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ECCC RECOMMENDATIONS - VOLUME 3 Part V [Issue 1]

TESTING PRACTICES FOR THE GENERATION OF MULTI-AXIAL FEATURE SPECIMEN AND COMPONENT TEST DATA

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TESTING PRACTICES FOR THE GENERATION OF MULTI-AXIAL FEATURE SPECIMEN AND COMPONENT TEST DATA

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ABSTRACT

ECCC Recommendations Volume 3 Part V gives recommendations for the undertaking of creep testing of multi-axial feature specimens and component test specimens within ECCC. The recommendations for component testing are based on the responses to a Questionnaire circulated to organizations involved in the creep testing of components and an existing Code of Practice specific to tubular components [1]. The aim of the Questionnaire had been to establish a basis for the harmonization of testing procedures within Europe. The respondants to the Questionnaire indicated that their test practices for more complex component specimens aimed to comply, where practically possible, with the guidance given in [1]. The editors of this volume therefore acknowledge the input from [1] contained within these recommendations.

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CONTENTS

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1. INTRODUCTION

ECCC Volume 3 covers the recommendations for data acceptability criteria and the generation of creep, creep rupture, stress rupture and stress relaxation data within ECCC. In combination with other European and national standards, Volume 3 lays out testing practices for the production of acceptable creep data from the above tests.

Many creep tests are undertaken on multi-axial feature specimens and components representative of engineering structures.

Multi-axial feature specimen tests and component tests are conducted for a variety of reasons. For example they may be performed to directly evaluate the likely performance of engineering structures in service under closely controlled laboratory conditions or to provide the evidence to test the effectiveness of assessment procedures. In addition, multi-axial tests are performed to assess the applicability and effectiveness of:
- representative stress models to characterise material multi-axial rupture behaviour, and/or
- multi-axial rupture ductility models to characterise material multi-axial rupture behaviour.

With a small number of exceptions (e.g. [1-3]), multi-axial feature specimen and component tests are not covered by published standard procedures. WG4 was established with the objectives of:-

- Harmonisation of testing practices
- Harmonisation of the methods of analysis

This document is concerned with the first of these objectives. Although no guidelines existed for component testing, a code of practice for testing tubular components [1] has been in existence since 1989. This code of practice primarily addresses metallic test pieces of simple cylindrical geometry under conditions of constant temperature load. It does though indicate that the given recommendations should also be applicable to full size and scale model components subject to certain defined limitations to judge the extend of component and multi-axial feature testing and to establish the procedures being used in such testing, a questionnaire was circulated primarily to organisations within the EU states but organisations in the US and Japan were also contacted. In total eleven responses were received, all from Europe, with only seven of those still active in component creep testing. An overview of the responses to the questionnaire was prepared to evaluate the testing practices currently used and the extent of uniformity between them. It was found that most respondents were attempting to work to the recommendations contained within [1]. This document, Volume 3 Part V, has been prepared based on the overview of current practices [4] and the existing recommendations in [1].

2. SCOPE

The recommendations given in this document focus on tests undertaken at elevated temperature on components subject to internal pressure, external mechanical loading (axial, bending, torque) or combinations of such loads. The recommendations primarily cover metallic components or multi-axial feature test specimens. These are based on tests on tube/pipe, bends and nozzle/branch specimens but it is judged that they should equally apply to any oven heated components.

The objectives of the component and multi-axial tests are to assess the applicability and effectiveness of:-

- representative stress models to characterise material multi-axial rupture behaviour, and/or
- multi-axial rupture ductility models to characterise material multi-axial behaviour, and/or

- evaluate and validate the likely performance of engineering structures in service under closely controlled laboratory conditions.

3. DEFINITIONS AND TERMINOLOGY

The terms and terminology used in the design, execution and reportage of component and multi-axial feature specimen tests is detailed in Volume 2, Part V [5].

4. MULTI-AXIAL TESTING

4.1 General

Existing procedures are already available for a number of multi-axial feature specimen tests (e.g. [1-3]). The adoption of these is currently recommended for ECCC purposes.

4.2 Circumferentially Notched Round Tensile Testpieces

The procedure for testing circumferentially round tensile (CNRT) testpieces is comprehensively covered elsewhere [2]. In principle, there are two main types of CNRT testpiece, i.e. v-notched and Bridgman (semi-circular) notched.

V-notched CNRT testpieces have traditionally been employed as a means of characterising notch strengthening or notch weakening behaviour in materials used for a wide range of high temperature applications. Until recently, the v-notched geometries defined in different standards were not exactly the same (e.g. [6,7]). Following an initiative taken by ECCC-WG1, a new standard European geometry (the E notch) has been devised which bridges the dimensions formerly defined in BS and DIN standards (Appendix A[1]) [8,9].

The use of Bridgman (semi-circular) notched CRNT testpieces are more appropriate for tests involving notch root strain measurement [2]. The spectrum of geometries which can be derived based on the Bridgman notch geometry provides a wide range of stress states.

4.3 Thin Walled Tube Testpieces

Guidance for testing thin walled tube testpieces, subject to internal pressure, end loading and/or torsional loading is given elsewhere [1,3], and the reader is referred directly to these testing procedures.

4.4 Compact Tension Testpieces

The compact tension testpiece geometry is not commonly used for multi-axial specimen testing, but is the recommended configuration for the LICON methododology [10]. Compact tension testpieces are more commonly used for fracture mechanics testing and high temperature procedures involving this geometry are defined elsewhere [11,12].

5. COMPONENT TESTING

5.1 Component Types

Ref. 4 identified three generic geometry types that were subject to elevated temperature testing:-
- Tube/pipe
- Bend
- Nozzle/Branch

[1] NB, in Appendix A, the E notch is referred to as the A notch

Welds may or may not be included in these geometries as an integral part of the component under test.

Other specific geometries were tested by organisation involved in elevated temperature component testing [4]. It is judged that application of the recommendations contained within this document will bring best practice to the testing of components other than those listed above.

5.2 Test Facility

5.2.1 Heating System

The heating system should provide a uniform temperature, within defined limits, over the test section of the test specimen. Generally the specimen will be contained within an electrical resistance oven with a minimum of three zone control or a fan assisted system. However, other heating methods can be used that are shown to comply with the defined temperature limits.

Ref. [1] recommends a limit for tubular specimens of ±0.25% of the absolute temperature (K).

Practical experience of those involved in component testing [2] has shown that ± 3°C (or K) is achievable for such tests.

Regardless of the accuracy achieved, it is essential to record the magnitude and duration of any excursions outside the specified temperature limits.

A temperature measuring system is required, usually thermocouples, in sufficient numbers and location to determine the magnitude of any thermal gradient present during testing.

The thermocouples should be of a type and composition suitable for the temperatures of the test. Calibration and use of the temperature measurement system should be in accordance with BS1041 [13].

5.2.2 Environment

The environment inside and outside the component will be dictated by the specific requirements of the test. Where there are no specific environmental conditions relating to the simulation of service conditions, it is recommended that a high purity inert gas be used as the internal pressurising medium. Generally components are tested with an external air environment [4] but where the component is thin walled and oxidation would have a significant influence of creep life of the component, an inert environment should also be used for the outside of the component.

5.2.3 Loading (Mechanical)

Component testing is undertaken with the component subject to internal pressure, axial tension, moment or torsional loading or a combination of such loads. Application of mechanical loading must be by a system capable of achieving the desired level without overshoot.

The loading system should be capable of maintaining a constant load to a predetermined accuracy. It is preferable that control of the load is automatic, although manual control may suffice provided the tolerance limits are maintained. Ref. 1 requires the internal pressure in tubular specimens to be maintained to an accuracy of ±0.5%. It is recognised that for complex components it may be difficult or impractical to achieve this level of accuracy. Ref. 2 indicates organisations involved in the testing of components are generally operating to a practical limit of <±1.0% for all load types. It is essential to record the magnitude and duration of any excursions outside the specified temperature limits. Calibration of all loading systems should be against certified load measuring equipment and generally follow the procedures of BS 1610 [14].

When a component is subject to a cyclic test, the loading system should be capable of applying the required waveform and frequency within the practical load limit of ±1.0% or better.

5.2.4 Instrumentation

5.2.4.1 Strain

High temperature strain gauges and extensometers can be used to obtain deformation data from the test piece on a continuous basis. This instrumentation is for monitoring purposes only and is not used as part of the control system.

The instrumentation should be applied and used in accordance with the manufacturer's instructions. All instrumentation should be suitably calibrated with extensometers specifically in accordance with BS EN 10291 [8]. The accuracy of the strain readings will be dependent on the selected method and the nature of the test in question. The effect of long term changes in accuracy of the specific device used should be established prior to testing. The change in long term accuracy should be significantly less than the anticipated creep strain in the component.

Intermittent strain measurements on the specimen can be made using creep pips or micro or macro surface indentations on the specimen. An accuracy of <±0.5% should be achieved using suitably calibrated equipment.

The frequency of measurements will be determined by the requirements of the test.

5.2.4.2 Crack Monitoring

Instrumentation can be applied to components for use in the detection of initiation and/or the monitoring of crack growth. Both DCPD and ACPD can be used for detection of initiation and monitoring of cracks. Devices for the measurement of COD can be used for monitoring crack growth.

The measurement system should be suitably calibrated and applied and operated following the manufacturer's instructions.

5.2.5 Monitoring System

The monitoring system should be fully automatic and record all test parameters. The resolution of the system should match that of the measuring instruments and should be accurate to within <±1% of full scale deflection and preferably within <±1% of the measured signal when all sources or error are taken into account.

The system should be capable of varying the frequency of measurement to allow for the possible changing conditions within a given test (e.g. primary and secondary creep) and between types of component test. The minimum frequency for both measurement and data storage should be hourly.

5.3 Test Procedure

5.3.1 Determination of Test Loads

Where test loadings are not dictated by the simulation of service condition, it will be necessary to determine the correct level of loading for the required test duration. This is not an easy task for complex components under multiple forms of loading. Equations for rupture stress are given in [1] for simple tubes subject to internal pressure loading.

For other more complex components subject to internal pressure and external loading, skeletal point or reference stress methods should be used to determine the level of loading for the required test duration. The R5 document [7] gives guidance on determining the reference stress in complex components. For complex components subject to internal pressure plus external loading, a finite element stress analysis will generally be necessary to determine the load levels for the required test duration.

Where welds are part of the test section in the component, it is important to take account, where possible, of the relative creep rupture properties of the components of the weldment when determining the test loadings.

5.3.2 Test start up and scheduled /unscheduled interruptions

The start up of creep tests on component specimens subject to multiple loadings gives practical difficulties in the simultaneous application of the load, It is recommended that the basic guidance given in [1] should be followed where appropriate and practical:-

- Leak testing the system prior to test should be done at room temperature and at a pressure that will not result in the material yield stress being exceeded anywhere in the test component.
- Heat up the component to temperature with no mechanical loading applied
- Once at temperature, the component can be loaded with the various mechanical loadings in sequence.
- Temperature gradients should be minimised during start up.
- Loads should be applied as rapidly as possible without overshooting the predetermined test level.

Start up durations will tend to vary depending on the complexity of the component being tested. Amongst organisations involved in component testing, start up could be from 4-48 hours [4]. Allowing for the complex geometries involved in component testing, it is recommended to make the heat up and soak periods as short as possible commensurate with minimising thermal gradients and operating within the temperature limits described in section 5.2.1.

Scheduled and unscheduled restarts should be treated in the same manner as the original start up.

On completion of the test, the system should be closed down in a controlled manner:-

- Switch off the heating system.
- Reduce mechanical loads to zero.

Both the start up and shut down histories should be recorded as for the actual test period (section 5.2.5).

5.3.3 Inspection Methods

Inspection of the component for damage may take place during scheduled interruptions of the test period and during the final post test examination. The inspection methods employed may depend on the purpose of the specific test.

During scheduled test interruptions, the following methods may be used as a means of detecting damage in the component:-

- Visual inspection
- Magnetic Particle (MPI) or Dye Penetrant (DPI) inspection
- Ultrasonic examination
- Metallurgical replication

- X-ray
- Dimensional measurements (e.g. creep pips)

On completion of the test, post test examination may, in addition to the above test, consist of some or all of the following methods:-

- Final dimension survey
- Hardness survey across test section, especially welds
- Metallography of damaged areas by optical, SEM or TEM microscopy
- Map of cracking with depth and length at each location
- Chemical analysis

5.3.4 Safety

Tests conducted at high temperature, especially under internal pressure, have the potential to store large amounts of energy. Unintended release of this energy either by leak of break has the potential for injury to personnel of damage to the test facility and equipment (e.g. by release of hot gas, specimen fragmentation or noise). Every effort should be made to reduce the level of energy stored in the test system by minimising internal volume, e.g. by the use of internal filler bars of other material.

The location of test equipment and operating procures should be assessed to minimise possible dangers and protect personnel and equipment from deleterious effects.
Guidance on such matters is given in the High Pressure Safety Code [16].

5.4 Reporting

A final report should be prepared that fully describes the test results. The following information should be included as a minimum record of the test:-
(i) The objective of the test.
(ii) A description of the test component that shall include:

- a drawing of the test component.
- manufacturing procedures used in the fabrication of the component including the weld procedure if the weld is part of the component under test.
- measured dimensions before test.
- grade of material and chemical composition.
- material test certificates.
- specimen description as marked on test component.

(iii) The test conditions should be listed including:

- test temperature, T
- test pressure, p
- internal pressure medium
- external environment
- external mechanical loading (magnitude and direction of application), F_A, τ, M_i, M_o
- Description of the cyclic loading cycle, where appropriate, including rate of loading and duration of any hold at maximum load.
- Method used to determine loading conditions.

(iv) Description of the loading rig and the load control system and the monitoring equipment.
(vi) The test results should be described including:

- total duration of test or to rupture t, t_u
- time to reach test temperature
- soak time prior to application of load
- cooling time following each test period
- strain measurements , at initiation, at rupture ε, $\varepsilon_{i,\ u}$
- time to initiation of first damage t_i

- dimensional measurements including final measurements at end of test
- crack growth data where appropriate
- crack depth, initiation, rupture a_i, a_u
- crack length, initiation, rupture c_i, c_u

(vii) All deviations out with the intended test condition limits should be recorded stipulating the magnitude and duration of deviation. Unscheduled interruptions should also be detailed. A statement should be made as to whether or not the test complies with the recommendations of this volume.

6. REFERENCES

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APPENDIX A

THE EFFECT OF NOTCH GEOMETRY ON STRESS RUPTURE PROPERTIES
DEVELOPMENT OF THE A NOTCH

G Granacher and P F Morris

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2. The Effect of Notch Geometry on Stress Rupture Properties

This work was carried out in conjunction with WG1 and the data presented from testing carried out at IfW-TU Darmstadt in Germany and Corus, Swinden Technology Centre, in the UK. The testing at IfW-Darmstadt covered a range of steels and nickel based alloys, while the UK test programme was limited to X19 CrMoVNbN 11 1 material and was carried out within WG3.4.

Currently notch geometries used in various countries are different which could pose problems when comparing data from different sources and compiling data sets in order to determine standard properties. Examples of the UK and German notches are contained respectively in BS3500 : Part 1 : 1969 and National Annex 1 : 2001-1 to DIN EN 10291 2001 and are shown in Figure 1. The UK and German notches have elastic stress concentration factors, K_t, values of 4.2 and 4.5 respectively. Representing the notch geometry by two parameters: the ratio of the sample diameter to the net section diameter and the ratio of the net section diameter to the notch radius an average notch geometry, designated Type A, has been defined based on the geometric means of these ratios for the two notch types. This results in a K_t value of 4.4.

A test programme was set up to determine whether the different notch geometries produced any significant difference in the stress rupture properties, particularly when determining whether materials are notch sensitive.

A range of materials was examined showing both essentially notch neutral and also notch weakening behaviour. It should be pointed out that it was difficult to obtain materials showing notch weakening and the steels in the current programme which exhibited this type of behaviour should not be considered typical of current commercial production.

Details of the materials tested are shown in Table 1 and the heat treatment details are shown in Table 2. A range of stress rupture tests, both plain and notched were carried out for all the materials giving rupture lives from 1,000 up to 14,000 hours for notched samples and up to 26,000 hours for plain samples. BS, DIN and Type A notch geometries were tested. (For Inconel 625 no failures have occurred after 16,000 hours and the tests are continuing.)

The results of the German testing are shown in Figure 2 and the UK testing in Figure 3. The data are plotted on a logarithmic time axis and comparison made between the failure times for the plain, t_u, and the notched samples, t_{un}, for each of the three notch geometries under consideration. Most of the material used in the test programmes was not produced recently. In the case of the German data much of the testing was completed in the 1980's or earlier. Hence repeat tests on plain samples were carried out and, where possible, two samples were tested for each notch geometry. For the UK programme only one plain sample and one for each notch geometry was tested.

To help in interpreting the results a scatter band in time of $\pm 30\%$ is indicated in the diagram. For the German data, Figure 3, material with notch neutral behaviour, in cases 1 to 3 the different notch geometries all gave rupture lives within the $\pm 30\%$ scatter band with no systematic variation in rupture lives between the different notch geometries. (For case 4, Inconel 625, all the notched tests are still running so no comment can be made for this material.)

For the materials showing notch weakening, for cases 5, 6 and 8, in all except one case the different notch geometries again give results within the $\pm 30\%$ scatterband, and no systematic variation between them. (The exception was one of the DIN test pieces for case number 5. Here a third test has been started to check the result.)

For case 7, the X19 CrMoVNbN 11 1 material tested at 550°C, the data for the different notches showed a very wide scatter, well in excess of the $\pm 30\%$ scatterband within which the data for the other cases were contained.

The UK testing programme provided further data, for the X19 CrMoVNbN 11 1 material in the notch weakening condition. These provided additional tests at 550°C and also at 575°C, which was not included in the German programme. These data are shown in Figure 3. In three of the cases the failure times for the different notches lay within the $\pm 30\%$ scatter band. However for two cases 9 and 13, one tested at 550°C and one at 575°C the scatter was greater than this. Despite the large scatter for this material at these temperatures, again there was no systematic difference apparent in the failure times for the different notch geometries.

Thus the indications from this limited test programme are that using these different notch geometries does not, in general, lead to any significant difference in notched creep properties and there should, in principle, be no objection to incorporating notch geometry A into ECCC recommendations for notch creep rupture testing and its inclusion in future revisions of EN 10291 should be considered.

Table 1 : CHEMICAL COMPOSITION OF TEST MATERIALS

No.	Identifier	Test Material	Chemical Composition in mass-%																
			C	Si	Mn	P	S	Co	Cr	Mo	Cu	Ni	Nb/ Ta	Ti	N	Al_{tot}	B	V	W
1	320b JL	X19 CrMoVNbN 11 1	0.18	0.34	0.52	0.015	0.012	-	11.34	0.20	0.07	0.65	0.39	-	0.069	0.025	0.005	0.26	-
2	320I OW	X19 CrMoVNbN 11 1	0.18	0.28	0.52	0.021	0.002	-	10.49	0.63	0.09	0.69	0.45	-	0.07	0.012	0.009	0.20	-
3	39cAKU	Inconel 617	0.06	0.12	0.05	0.003	0.002	12.0	22.1	9.02	0.01	bal.	0.01	0.42	0.032	1.23	0.002	-	-
4	40aAKV	Inconel 625	0.02	0.13	0.05	0.002	0.007	-	22.3	8.97	0.03	bal.	3.58	0.19	-	0.14	-	-	-
5	113c KX	40 CrMoV 4 7	0.38	0.20	0.56	0.010	0.024	-	0.95	0.61	0.17	0.13	-	-		0.021	-	0.31	-
6	17h ON	21 CrMoV 5 11	0.21	0.40	0.33	0.010	0.008	-	1.28	1.13	-	0.25	-	-	0.007*)	0.040*)	-	0.35	
7	320b JL	X19 CrMoVNbN 11 1	See 1																
8	329h ANU	X19 CrMoVNbN 11 1	0.17	0.42	0.42	0.013	<0.003	0.03	10.72	0.66	0.07	0.36	0.30	0.002	0.061	0.016	0.002	0.20	0.03
9	A8R3	X19 CrMoVNbN 11 1	0.22	0.33	0.60	0.013	0.005	-	10.87	0.66	0.04	0.41	0.41	-	0.055	0.007	0.0015	0.22	-
10	A8R4	X19 CrMoVNbN 11 1	0.19	0.28	0.64	0.020	0.008	-	11.00	0.69	0.11	0.36	0.41	-	0.054	0.007	0.0005	0.20	-
11	A8R4	X19 CrMoVNbN 11 1	See 10																
12	A8R4	X19 CrMoVNbN 11 1	See 10																
13	A8R2	X19 CrMoVNbN 11 1	0.21	0.28	0.60	0.013	0.003	-	11.07	0.69	0.07	0.56	0.44	-	0.062	0.003	0.0010	0.23	-

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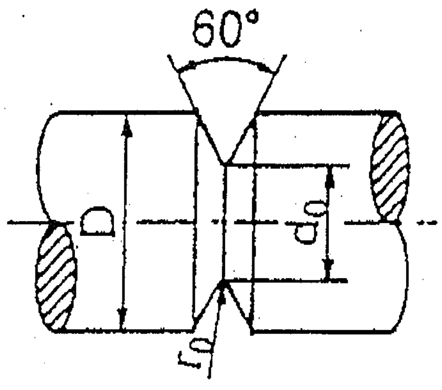
Table 2 : HEAT TREATMENT OF THE TEST MATERIALS

No.	Identifier	Test Material	Heat Treatment
1	320b JL	X19 CrMoVNbN 11 1	1050°C h/air + 720°C 4 h/air
2	320i AOW	X19 CrMoVNbN 11 1	1100°C 65 min./air + 670°C 4.5 h/air + 620°C 24 h/air
3	39c AKU	Inconel 617	1170°C 75 min./water + 1200°C 70 min./water
4	40a AKV	Inconel 625	1120°C 80 min.
5	113c KX	40 CrMoV 4 7	930°C 2 h/water + 700°C 4 h + 830°C 2/air + 680°C 4 h/air
6	17h ON	21 CrMoV 5 11	900°C 1 h/oil + 700°C 2 h/air
7	320b JL	X19 CrMoVNbN 11 1	See No. 1
8	329 ANU	X19 CrMoVNbN 11 1	1150°C/oil + 690°C 7 h/air
9	A8R3	X19 CrMoVNbN 11 1	1120°C 2 h/fan cool + 705°C 4 h/air + 700°C 2 h/air
10	A8R4	X19 CrMoVNbN 11 1	1120°C 1.5 h/oil + 700°C 6 h/air + 650°C 2 h/air
11	A8R4	X19 CrMoVNbN 11 1	See No. 10
12	A8R4	X19 CrMoVNbN 11 1	See No. 10
13	A8R2	X19 CrMoVNbN 11 1	1150°C 2 h/fan cool + 700°C 4 h/air + 700°C 2 h/air



Type	DIN	BS	A
D/d_0	1.25	1.41	$\sqrt{1.25 \cdot 1.41} = 1.33$
d_0/r_0	50	35	$\sqrt{50 \cdot 35} = 42$
K_t *)	4.5	4.2	4.4

$$^{*)}\ K_t = 1 + \left(\frac{1}{2} \cdot \frac{r_o/d_o}{D/d_o - 1} + 2 \cdot \frac{r_o}{d_o} \cdot \left(1 + 2 \cdot \frac{r_o}{d_o}\right)^2 \right)^{-\frac{1}{2}}$$

FIGURE 1: GEOMETRIES OF TESTPIECES FOR NOTCH TYPES DIN, BS AND A.

no	identifier	test material	T (°C)	σ_0 (MPa)	% t_u for -3 % σ_0
A) Approximately neutral notch behaviour					
1	320b JL	X 19 CrMoV NbN 11 1	600	123	12
2	320i AOW	X 19 CrMoV NbN 11 1	600	199	20
3	39c AKU	Inconel 617	600	296	21
4	40a AKV	Inconel 625	900	14.0	10
B) Clear notch weakening					
5	113c KX	40 CrMoV 4 7	550	147	9
6	17h ON	21 CrMoV 5 11	550	196	5
7	320b JL	X 19 CrMoV NbN 11 1	550	308	30
8	320h ANU	X 19 CrMoV NbN 11 1	600	160	19

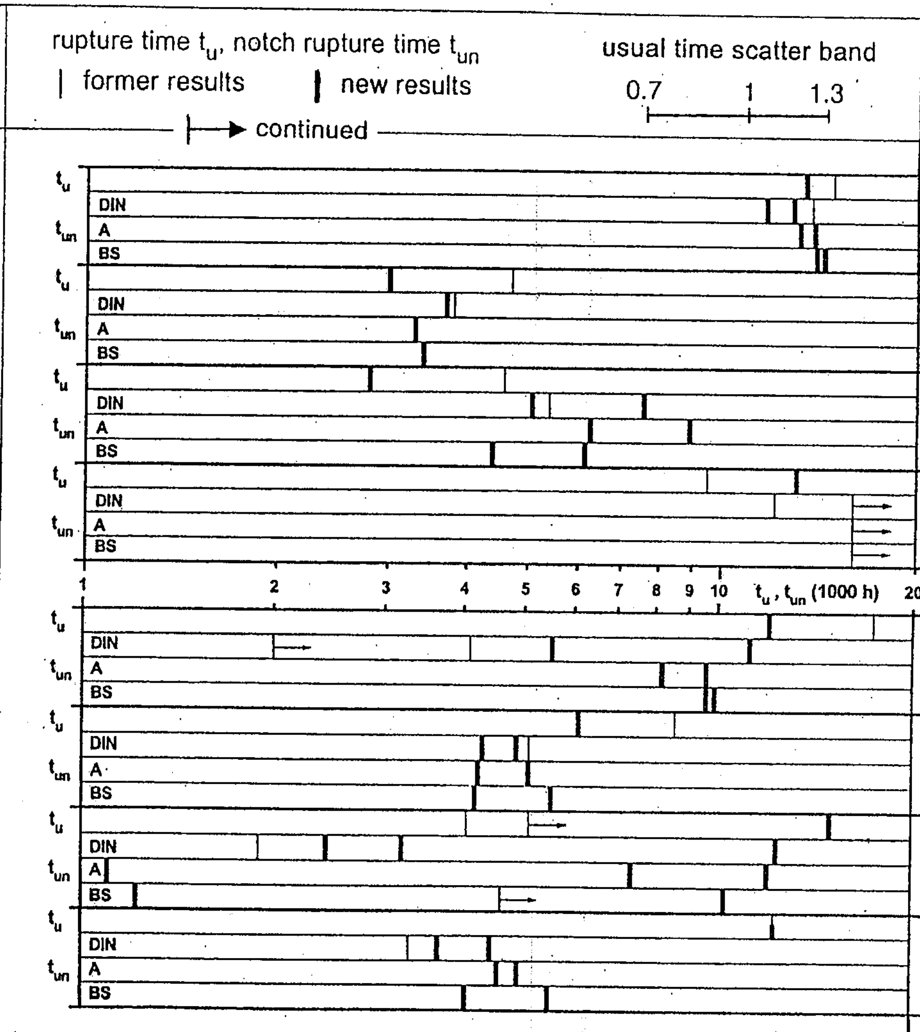
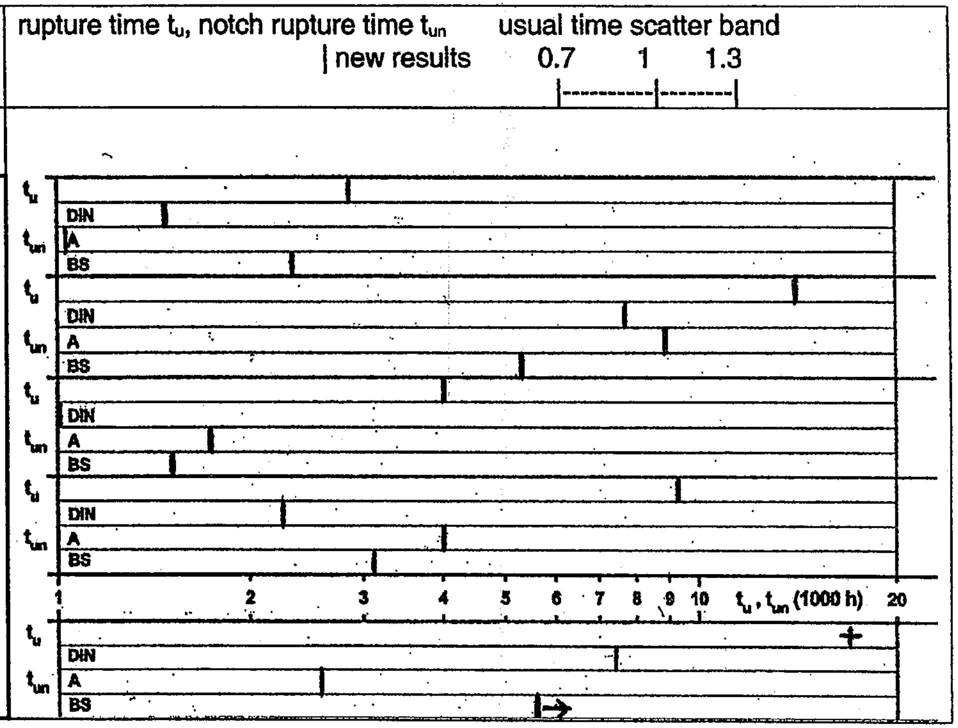


FIGURE 2: RUPTURE TIMES FROM THE FORMER AND NEW CREEP RUPTURE TESTS ON PLAIN AND NOTCHED SAMPLES WITH BS, DIN AND A TYPE NOTCHES – GERMAN TEST PROGRAMME

No.	Identifier	Test Material	T (°C)	σ_0 (MPa)
A) Clear Notch Weakening				
9	A8R3	X19 CrMoVNbN 11 1	550	278
10	A8R4	X19 CrMoVNbN 11 1	550	278
11	A8R4	X19 CrMoVNbN 11 1	575	247
12	A8R4	X19 CrMoVNbN 11 1	575	216
13	A8R2	X19 CrMoVNbN 11 1	575	170



+ failed at 26,000 hours

FIGURE 3: RUPTURE TIMES FROM THE CREEP RUPTURE TESTS ON PLAIN AND NOTCHED SAMPLES WITH BS, DIN AND A TYPE NOTCHES – UK TEST PROGRAMME