EUROPEAN COMMISSION
5th EURATOM FRAMEWORK PROGRAMME 1998-2002
KEY ACTION : NUCLEAR FISSION

HTR-M

European Project for the development of HTR Technology - Materials for the HTR

CONTRACT N°
FIKI-CT-2000-00032
&
FIK1-CT-2001-00135

Proposed creep rupture test conditions for the HTR-M irradiation experiment on a modified 9Cr-1Mo steel weld

by

R D W Bestwick

NNC Ltd, UK

Dissemination level: CO
Document Number: HTR-M 03/08-D-1 4 78

Proposed creep rupture test conditions for the HTR-M irradiation experiment on a modified 9Cr-1Mo steel weld

by

R D W Bestwick

C6463/TR/023
Issue 02
September 2004

DOCUMENT ISSUE RECORD
(engineering documents)

Adding value through knowledge

Document Title :	Proposed creep rupture test conditions for the HTR-M irradiation experiment on a modified 9Cr-1Mo steel weld
Project Reference:	64631

Purpose of Issue : Final Issue

Security Class : Commercial in Confidence

Issue	Description of Amendment	Originator/ Author	Checker	Approver	Date
01	First Issue				
		R. D. W. Bestwick	D. Buckthorpe	T. Lennox	Aug. 2003
02	Final Issue including comments from HTR-M partners	R. D. W. Bestwick	D. Buckthorpe	T. Lennox	September 2004

Total number of pages:	Intro:	(i)-(iv)	Text	1-5	Tables	T1	Figures	F1	Appendices	-

Previous issues of this document shall be destroyed or marked **SUPERSEDED**

Distribution: S. Casalta (EU), HTR-M Partners via SINTER Website,

NNC: A. Braithwaite, D. Buckthorpe, R. Bestwick, A Stuart, EDMS Registry

3050aOct99 Controlling procedure - QP11, QP40 DSC Ref

Table of Contents

List of Tables

List of Figures

1 Introduction

This document responds to Action 6/7 from the HTR-M and M1 progress meeting of June 2003 (Ref. 1) by proposing creep rupture test conditions (test temperature and stress levels) that are compatible with:

- the test programme for the HTR-M irradiation experiment (Ref. 2) on specimens representing various parts of the welded joint;
- steady state and transient conditions in HTR vessels;
- the creep strength of modified 9Cr 1Mo steel before and after irradiation.

A single test temperature is first proposed. A method is then described for selecting the stress levels to be used for the tests on each part of the weld.

2 Design of the irradiation experiment

The design of the irradiation experiment provides for two groups of 32 creep rupture specimens. The first group is to be used during the HTR-M project for tests of up to 3000 hours duration while the second group is to be saved for long-term tests proposed for the 6th Framework programme. Each group contains one set of 16 irradiated specimens and one set of 16 control specimens. Each set of 16 specimens contains 4 sub-sets.

A. 4 base material specimens (remote from the weld).
B. 4 cross weld specimens.
C. 4 all weld metal specimens (weld longitudinal orientation).
D. 4 all weld metal specimens (weld through thickness orientation).

In view of the small number of specimens in each subset, conditions have to be selected carefully to ensure that planned tests are completed within the HTR-M timescale. According to the HTR-M programme most of the control tests will have been completed before the tests on irradiated material start. Lot specific data will therefore be available when conditions for the tests on irradiated material are selected. In addition to assessments of the effects of irradiation and specimen location on creep rupture strength the HTR-M results are required to provide a sound basis for planning the long-term tests.

3 Steady state and transient conditions

Under normal operation modified 9Cr-1Mo steel in the beltline region of a GT-MHR reactor pressure vessel is subject to a steady state stress intensity of approximately 160 MPa at temperatures of up to approximately 450°C. Efforts are being made to reduce the normal operating temperature. It was proposed in Ref. 3 that vessel temperatures be limited to 435°C to ensure that RCC-MR design stresses were controlled by tensile properties rather than creep rupture data which are well established only at temperatures of 500°C and above.

Creep strength and any effects of irradiation will therefore be most important during transients. These may involve temperatures of 550°C for hundreds of hours and relatively high levels of primary stress.

4 Creep strength and the effect of irradiation

Ref. 4 provides the following correlation, based on the Larsen-Miller parameter (LMP), for the mean rupture strength of modified 9Cr-1Mo base material to RCC-MR specifications.

$$LMP = T\,(26.4 + \log_{10} t_r) = a_o + a_1 \log_{10}\sigma + a_2 (\log_{10}\sigma)^2 + a_3 (\log_{10}\sigma)^3 \qquad (1)$$

T = test temperature in K, t_r = rupture time in hours, and σ = stress in MPa.
$a_0 = 43713.32$, $a_1 = -19904.054$, $a_2 = 10530.178$, $a_3 = -2372.5767$.

The standard deviation of a_0 was 394.136. 95% confidence limits on a_0 and LMP were based on 1.96 standard deviations. The upper and lower bound values of rupture life are therefore obtained by multiplying/dividing the mean value of t_r by a temperature dependent factor (div 95%) that decreases from 10 at 500°C to 6.2 at 700°C.

Lower bound values determined from equation (1) were specified in EFR design rules (Ref. 5) and included in the 2003 edition of RCC-MR.

In Ref. 6 it was shown that the upper and lower bounds of equation (1) encompassed collected rupture data for all weld metal specimens. Collected results on cross weld specimens were also encompassed at applied stresses exceeding approximately 200 MPa. At lower stresses a significant proportion of results fell below the base material lower bound. This reduction in strength was considered in Ref.7 to be associated with the existence of a weak intercritical heat affected zone (so called Type IV cracking).

Minimum stress to rupture values were proposed in Ref. 7 for use in the ASME code and compared with RCC-MR minimum values in Ref.3. They are consistent with the following correlation from Ref. 8.

$$\log_{10} t_r = C_h + A_1\,\sigma + A_2 \log_{10}\sigma + A_3 /T \qquad (2)$$

$A_1 = -0.0231\ \sigma$, $A_2 = -2.385$ and $A_3 = 31080/T$.

The parameter C_h is described as a 'lot constant'. Ref. 8 gives a mean value of $C_h = -23.737$. The minimum values tabulated in Ref. 4 are obtained with $C_h = -24.247$ which corresponds to dividing the mean value of t_r by a temperature independent factor of 3.24. This factor is much less than that associated with equation (1). ASME practice appears to be based on 95% of results exceeding the minimum stress to rupture whilst the 95% confidence limits in RCC-MR practice correspond to 97.5% of the results exceeding the minimum stress to rupture. The lower bound is therefore set at 1.65 standard errors in ASME rather than 1.96 standard errors. The use of 1.96 standard errors with equation (2) would reduce the minimum value of C_h from –24.247 to –24.343 and increase div 95% 3.24 to 4.04, still much less than the values associated with equation (1).

A database (Ref. 9) generated independently at approximately the same time as Ref. 8 was used in Ref. 10 to compare four parametric equations of the form:

$$P(T, \log_{10} t_r) = f(\sigma).$$

The four equations and the values of div 95% given in Ref. 10 were:

- a Larson-Miller equation similar in form to equation (1) but rearranged so that mean values and 95% confidence limits were obtained for $\log_{10} t_r$ rather than the Larson-Miller parameter: div 95% = 4.03;
- a 'modified' Orr-Sherby-Dorn (OSB-ORNL) equation identical in form to equation (2): div 95% = 4.01;
- an 'original' Orr-Sherby-Dorn equation with f (σ) in the form of a third order polynomial: div 95% = 4.04;
- a Manson-Haferd equation with $P(\sigma) = (\log t_r/t_a)/(T-T_a)$ and f(s) = in the form of a third order polynomial: div 95% = 3.72.

It therefore seems that values of div 95% from similar databases are little affected by the choice of $P(T, \log_{10} t_r)$ or f (σ) at least when it is based on a direct determination of the standard error of $\log_{10} t_r$.

The higher value of div 95% from the more recent database of Ref. 4 appears from an inspection of plotted data at various temperatures to reflect the dispersion of the data. It is not clear why the modest increase in the size of the Ref. 4 database (427 test results compared with 220 results in Ref.10) should cause such an increase in div 95%. Some aspects of the statistical treatment in Ref. 4 are beyond the scope of this note but may be worth further examination within the framework of the HTR-M database activity.

Despite the above reservation, equations (1) and/or (2) provide the best available basis for planning the control tests in the HTR-M creep rupture programme in the absence of lot-specific test data from qualification or production activities.

Figure 1 shows mean rupture lives from equations (1) and (2) at four temperatures. The two equations agree closely at 650°C but the ASME equation predicts longer lives at lower temperatures, by a factor of up to 3 for long times at 500 and 550°C. The HTR-M tests involve relatively short times. Under these conditions the discrepancy between the two equations is smaller and less than the standard deviation associated with the equation (1). It is also worth noting that except for the Manson-Haferd equation, predictions in Ref. 10 agree closely with those from equations (1) and (2).

5 Proposed test conditions

5.1 Test temperature

A test temperature of 550°C is proposed. It is relevant to HTR transient conditions and is judged to be high enough for possible effects of irradiation and/or Type IV cracking to be observed at least in the long-term 6th Framework tests. At 550°C discrepancies between the RCC-MR and ASME rupture strength equations are not severe for times up to 3000 hours. This may ease the task of selecting stress levels for the HTR-M control tests as described below.

5.2 Applied stresses in the HTR-M control tests

It is proposed to select stress levels for each of the four sub-sets of 4 specimens to give target rupture times of 100, 300, 1000 and 3000 hours. This should be done using both equation (1) and equation (2) with appropriate values of the lot constant C_h in equation (2) and treating a_0 as a lot constant in equation (1). The default values C_h =-23.737 and a_0 = 43713.32 should be used for the first (100 hour) test in each subset unless qualification or production data on a relevant product are available and suggest different values.

Table 1 shows an example of the application of equations (1) and (2) for a single material. Stresses for each test are chosen initially using the default values of C_h and a_0. It is recommended that, as in the example, tests be carried out in order of decreasing stress. Wherever possible the stress for a given test should take into account measured values of C_h and a_0 from the previous test in the sub-set.

In the example case the ‘errors’ in the estimated rupture lives do not lengthen the overall timescale of the programme. Much larger factors could occur in practice (up to a factor of 8.7 for equation (1)). A rupture time approaching 1000 hours for Test 1 is not a serious problem – it simply becomes Test 3. A very short rupture time for Test 1 (say 20 hours) is probably the worst case. Larger time steps then become necessary for the subsequent tests and rupture life predictions may be less accurate. It may then be useful to consider relationships between the rupture time and the time to 1% strain, the time to the end secondary creep (or 0.2% tertiary creep) or the minimum creep rate. These may give early warning of gross ‘errors’ in the estimated rupture lives provided that appropriate parameters are measured and recorded during testing.

6 Conclusions

1. A test temperature of 550°C is recommended for HTR-M creep rupture tests on modified 9Cr-1Mo steel, consistent with the design and objectives of the HTR-M irradiation experiment.
2. A method based on RCC-MR and ASME master curves is proposed for selecting stress levels for tests lasting nominally 100, 300, 1000 and 3000 hours on base material, weld metal in two orientations and cross weld tests.
3. A stress of 272 MPa is proposed for the first (100-hour) test on each lot of material in the absence of relevant, lot specific data.
4. A method of refining rupture stress estimates for subsequent tests as rupture data accumulate has been proposed.

7 References

1. D Buckthorpe et al. Minutes of the 5th HTR-M plus M1 meeting. Document No. HTR-M-03/07-M-0-0-xx. (available on SINTER).
2 J Hegeman. Current status of HTR-M WP 1. Ibid. Attachment 7. (available on SINTER).

3 C Escaravage. HTR-Compared properties of pressure vessel candidate materials. Document No. HTR-M-02/02-D-1-1-41. (available on SINTER).
4 I Curbishley et al. Tensile and stress rupture properties of modified 9Cr steel. CEC Study Contract RA1 0199 UK. Final Report, January 1995.
5. C Escaravage. Design Properties of modified 9Cr-1Mo steel. DCRC Report No. 11, Rev. C. EFR Associates Document No. B4 015 1078 C. December 1998.
6. A A Braithwaite et al. Tensile and stress rupture properties of modified 9Cr-1Mo steel welds. CEC Study Contract RA1 0214 UK. Final Report, January 1996.
7. Letter from C R Brinkman (ORNL) to C Hoffman ABB Combustion Engineering.
8. C R Brinkman et al. Long-term creep rupture behaviour of modified 9Cr-1Mo steel - base and weldment behaviour. Document No. ORNL/TM10504, November 1987.
9. D S Wood et al. Final report on data collection relating to the stress rupture properties of 9-12% Cr steels. CEC Study Contract RAP 092, October 1987.
10. D S Wood et al. Extrapolation of stress rupture data on 9 to 12% Cr steels. Final Report on CEC Study Contract RA1-0106-UK, December 1988, also published as CEC Report EUR 12388 EN 1989.

Table 1. Example of prediction method (contains fictitious test results)

Before Test 1

Test No.	θ°C	σ MPa	ASME prediction		RCC-MR prediction		Test result		
			C_h	t_r	a_0	t_r	t_r	C_h=	a_0=
1	550	272.00	-23.737	87	43713.32	118			
2	550	252.50	-23.737	292	43713.32	308			
3	550	231.50	-23.737	1097	43713.32	898			
4	550	213.00	-23.737	3579	43713.32	2392			

After Test 1

Test No.	θ°C	σ MPa	ASME prediction		RCC-MR prediction		Test result		
			C_h	t_r	a_0	t_r	t_r	C_h=	a_0=
1	550	272.00	-23.737	87	43713.32	118	205	-23.363	43910.15
2	550	260.00	-23.363	432	43910.15	368			
3	550	244.00	-23.363	1177	43910.15	820			
4	550	228.00	-23.363	3242	43910.15	1870			

After Test 2

Test No.	θ°C	σ MPa	ASME prediction		RCC-MR prediction		Test result		
			C_h	t_r	a_0	t_r	t_r	C_h=	a_0=
1	550	272.00	-23.737	87	43713.32	118	205	-23.363	43910.15
2	550	260.00	-23.363	432	43910.15	368	450	-23.345	43981.76
3	550	244.00	-23.354	1202	43945.95	907			
4	550	229.00	-23.354	3106	43945.95	1962			

After Test 3

Test No.	θ°C	σ MPa	ASME prediction		RCC-MR prediction		Test result		
			C_h	t_r	a_0	t_r	t_r	C_h=	a_0=
1	550	272.00	-23.737	87	43713.32	118	205	-23.363	43910.15
2	550	260.00	-23.363	432	43910.15	368	450	-23.345	43981.76
3	550	247.00	-23.354	995	43945.95	779	750	-23.477	43932.49
4	550	228.00	-23.395	3011	43941.47	2042			

Figure 1. Mean values of rupture stress from ASME and RCC-MR analyses