

INTRODUCTION

On the invitation of the Government of Poland the International Atomic Energy Agency (IAEA) convened from 20-23 June 1988 in Cracow the Specialists' Meeting on "High Temperature Metallic Materials for Gas-Cooled Reactors". The meeting was held in the framework of the International Working Group on Gas-Cooled Reactors and hosted by the Institute of Nuclear Physics.

The Specialists' Meeting was organized in conjunction with an earlier meeting on this topic held in Vienna, Austria, 1981, which provided for a comprehensive review of the status of materials development and testing at that time and for a description of test facilities.

This meeting provided an opportunity

- (1) to review and discuss the progress made since 1981 in the development, testing and qualification of high temperature metallic materials,
- (2) to critically assess results achieved, and
- (3) to give directions for future research and development programmes.

In particular, the meeting will provide a forum for a close interaction between component designers and materials specialists.

The meeting was attended by 48 participants from France, People's Republic of China, Federal Republic of Germany, Japan, Poland, Switzerland, United Kingdom, USSR and USA presenting 22 papers. The technical part of the meeting was subdivided into four technical sessions:

Components Design and Testing - Implications for Materials
Microstructure and Environmental Compatibility
Mechanical Properties
New Alloys and Developments

At the end of the meeting a round table discussion was organized in order to summarize the meeting and to make recommendation for future activities. This volume contains all paper presented at the meeting.

SUMMARY OF SESSIONS

COMPONENTS DESIGN AND TESTING — IMPLICATIONS FOR MATERIALS

(Session I)

The four papers in this session span the whole range of potential HTR applications ranging from the steam cycle to the process heat systems. Also included are some of the material questions relating to the Japanese Very High Temperature Test Reactors.

The first paper presented by Mr. Bodman covers the whole range of materials applications from 250°C to 950°C and therefore embraces the steam cycle, steam reforming and process heat systems. The paper presents a good summary of the data available on the main high temperature structural alloys, Alloy 800 and Inconel 617. Some data is also given on the proposed control rod alloy DIN 4981 showing how a special version has been developed (DIN 4981-KA) to improve post irradiation tensile ductilities.

In the case of Alloy 800 emphasis is given to presenting the data available on the creep behaviour and the influence of C, Al and Ti on the creep strength obtained from more than 250 heats and heat treatments. As a result of this, three variants of the alloy have been defined basically representing high, intermediate and low temperature versions. One comment to make is that the high temperature version, designated Alloy 800-HT and recommended to be used above 700°C would appear to be equivalent to Alloy 800H which is the specification chosen from the steam generator material of the US Modular HTR design where the temperatures are expected to be well below 700°C. Data is also given on the tensile and fatigue perspective of Alloy 800.

In relation to the process heat applications, some creep data on Inconel 617 is presented but this material is more extensively covered in another paper during the meeting.

In the paper, mention is also made of the coatings required to prevent wear on components:

Cr_{23}C_6 up to 850°C and 2rO_2 (Y_2O_3) for temperatures up to 1000°C.

The paper presented by Mr. Shenoy concerns itself only with the steam cycle application and specifically with the US version of the Modular HTGR. From the materials viewpoint the relatively modest requirements in terms of the operating conditions are to be remarked upon and thus the need to employ only well established materials in the design. Nevertheless, it is somewhat surprising to see the design side still asking for data for component development. Mr. Shenoy does in fact point out that the ASME Boiler and Pressure Vessel Code whilst including the proposed materials of construction (Alloy 800H, SA 533 B, low carbon steel and 2 1/4 Cr - Mo steel), does not include environmental effects such as corrosion, thermal ageing and irradiation. However, a wealth of data already exists on these topics from the extensive programmes on HTR worldwide over the past 25 years and a useful topic for discussion would be to what extent is new data required.

The two papers presented by Mr. Hada represent a contrast to that of Mr. Shenoy in that they concentrate on the very high temperature applications, above 900°C.

The first paper deals with a proposal for the development of a high temperature design code, needed because the existing Code, N47, only applies to temperatures up to about 800°C. The proposal is made to extend the Code to 1000°C taking the premise that the failure modes defined in fixing Code N47 will also apply at higher temperatures. The paper considers application to Hastelloy XR and concludes that the critical issues in this case are

- (i) the effect of dynamic re-crystallisation at high strain rates (ie tensile and fatigue properties)
- (ii) the low creep resistance of Hastelloy XR.
- (iii) the loss of ductility after prolonged ageing.

Some proposals on the approach to these issues are made in the paper.

The second paper presented by Mr. Hada relates to the helical design of heat exchanger proposed for the Experimental Multi-purpose HTGR and the High Temperature Engineering Test Reactor. The paper identifies the most critical factors relating to materials behaviour and examines the application to Hastelloy XR.

It is concluded that in the case of this material the critical properties are those of creep strain and creep rupture due to the relatively poor creep strength of Hastelloy XR at the very high temperatures involved. As a result the need is to accurately evaluate the creep strength at very low stresses and this is a key part of the test programme in Japan.

MICROSTRUCTURE AND ENVIRONMENTAL COMPATIBILITY

(Session II)

In the first part of the session a survey on creep corrosion behaviour of Alloy 617, Alloy 800H and the Austrian type of 800H was given. It was reported that structural changes occur in the environment of operation. Especially the relationship between microstructure and relevant creep properties was discussed. Based on very detailed experimental results the limits of steady state dislocation creep were shown. Due to the influence of the environment of operation and the mechanism of carburization respectively decarburization in special environments various dislocation mechanism occur and the "normal" creep-curve changes. The formation of anisotropic subgrains leads to loss of ductility and reduces the expected lifetime of a component.

During discussion mainly the consequences to component behaviour, lifetime prediction and technical design were mentioned. An important statement was: Designers have to understand and to learn, that the proposed material at high temperature under operation conditions is "living", not steady, and is changing its microstructure.

In the second part of session the thermal stability of "normal" and modified heats of Alloy 617 and other high temperature candidate alloys was reported. In different laboratories and in various test atmospheres a lot of experimental results were collected and the effect of the influence of impurities in the cooling gas (Helium) to the mechanical properties of material was studied.

Main results are: the gas-metal-interaction is depending on the gas-composition, especially on ratio of CO, H₂O, H₂, CH₄. It's possible to determine the corrosion behaviour of most candidate materials, the results were summarized in stability diagrams, and it is possible to define the range of gas-composition, in which also at the highest temperatures (near 950°C) stable corrosion behaviour occurs.

A special method for experimental determination of critical CO-partical pressure for a given material was reported: the measuring of the so-called Alf-point by HTMP-laboratory.

In the discussion mainly the possible difficulties were mentioned regarding controlling the gas-composition in all parts of a running reactor. It is expected that the protective range of operation is able to be kept by dotation of the gas, in order to ensure a component life-time of around 100.000 hours.

MECHANICAL PROPERTIES

(Session III)

In this Session there were 3 presentations concerning mechanical properties of high-temperature metallic materials, especially the transferability of the data from standard specimens to tubes in both the experimental and the analytical aspects. And the results of round robin fracture toughness tests on Alloy 800H were also presented.

1. Creep and Fatigue Crack Growth in Tubes of HTR Components
M. Rödig (Nuclear Research Center Jülich, FRG)

Experiments have been performed on the transferability of fatigue-and creep-crack growth data from standard specimens to tubes.

In the fatigue crack growth experiments, a tube of Alloy 800 with an external 180° crack was loaded in 4 point bending at 550°C . The comparison of the da/dN vs K relations for standard specimens and the tube showed a poor agreement. The reason was thought to be in too conservative assumptions in the calculation of the K values.

In the creep crack growth experiments, tubes of Alloy 800 with an external 360° crack were loaded by axial tension and internal pressure at 800°C . The comparison of the da/dt vs C^* relations for standard specimens and tubes showed a good agreement.

There were a question and an answer concerning the crack depth measurement method. And there was a comment that the asymmetric crack growth observed in the experiments might be a hint for the validity of the leak before break criteria.

2. Fracture toughness of Alloy 800H at Room Temperature
K. Krompholz (Paul Scherrer Institute, Switzerland)

Within the round robin test concerning fracture toughness testing on Alloy 800H at room temperature, different evaluation methods (i.e. ASTM E813-81 and ASTM E813-87) were compared. The results were obtained on the three point bend type specimen (25mm x 25mm x 100mm) and on the 1-CT specimens 20%- and 40%- sidegrooved.

In no case a valid J_{IC} -value was obtained for this material. This was due to the thickness of the plate. The J-integral R-curve for the 1-CT 40% sidegrooved specimens is lower than the curve for the 1-CT 20% sidegrooved specimens. For design reasons, both ASTM E813-81 and ASTM E813-87 for the 1-CT 20% sidegrooved specimens can be applied. For the three point bend type specimen without sidegrooves ASTM E813-81 should be preferred.

there were questions and answers concerning the narrow scatter, material dependence and applicability of J-integral R-curves in design rule.

3. Fracture Mechanical Characteristic Values(J-integral) with Transference to Components(Tubes) by an Analytical Method
G. Ullrich (Paul Scherrer Institute, Switzerland)

A comparison of J-integral values from experiments on tubes with optical detection and finite element calculations with those obtained from a simple analytical method was performed.

Since an excellent agreement was obtained, the analytical method delivers a simple tool to estimate J-integral values from simple load vs load point displacement diagrams of small specimens and components which can be produced by a simple test machine.

There were a question and an answer concerning the application method of a linear description like Boltzmann equation to inelastic analysis.

Though the test data of the components or of J-integral R-curves may not be applicable presently in design rule, the problem concerning the transferability of the data from standard specimens to the real components of the nuclear plants is very important. So additional work is expected to be performed widely furthermore.

NEW ALLOYS AND DEVELOPMENTS

(Session IV)

The following is the list of contributions:

1. B. Huchtemann - A New Alloy Thermon 4972 / NiCr 22 Co 12 Mo / for High Temperature of Components Gas-Cooled Reactors
2. W. Pelz, W. Schendler, H. Weber - Comparison of Mechanical and Corrosion Behaviour of Alloy 800 H and the New Alloy AC 66
3. C. Breitbach, F. Schubert, H.J. Seehafer, H. Nickel - Experimental and Theoretical work for the Analysis of Creep Ratcheting and Creep Buckling of HTR-components
4. H.-J. Lehman, M. Becker, M. Ludeke - Development and Validation of an Improved Creep-Fatigue Interaction Rule for Lifetime Determination of High Temperature Components
5. H. Fricker, G. Ullrich, H.P. Alder - Wear Stresses in Ceramic Layers at Elevated Temperatures under Helium Atmospheres
6. E.V. Kuznetsov, T.B. Tokareva, A.V. Ryabchenkov, O.V. Novichkova, Ju.D. Starostin - Promising Materials for HTGR High-Temperature Heat-Exchangers.

Three papers (Nos. 1, 2 and 6) were discussing new or alternative alloys that have been developed to improve the performance of existing alloys with application experience. Some developments try to avoid the element Cobalt for primary circuit materials, mainly by using Tungsten as an alloying element. The creep resistance is claimed to be as good. One of the new alloys seems to form fairly stable protective oxide layers, also with low oxygen pressures. A modification of the widely used Alloy 800 by adding the rare earth element Cerium, apparently has higher corrosion resistance than the basic alloy. However, the problem, with oxidation of Cerium in the weldments requires further development.

The papers 3 and 4 presented studies on the mechanical behaviour of VHTGR Components. Investigations into the ratchetting mechanism revealed that the creep rate by primary loads such as pressure can be increased considerably by the presence of alternating thermal loads. Creep buckling of oval cylindrical components have been investigated by both theory and experiment with fairly good agreement. Furthermore, the well-known creep-fatigue interaction rule on the basis of a linear damage concept has been modified by a proposition to introduce cycle number influences into the creep damage term of the equation.

Paper No. 5 presented tests that were performed to assess the behaviour of Ceramic Layers on metallic components in helium atmospheres. The loadings of friction in these tests were partly static with slow movement - and partly dynamic with vibration. It was found that most layers were not as stable as expected, with some discrepancies left in the interpretation of results of different test facilities.