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Past experience of FZJ on C/C mechanical testing for HTR Reactor development - Report of meeting and discussions with FZJ experts

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In the frame of the HTR-M program, CEA-DTEN has been charged of collecting data on the past experience of FZ Juelich related to the use of C/C materials in the frame of HTR development. This document reports briefly the results of different exchanges with experts of FZJ, more particularly Mr J. Linke we met during the technical workshop on C & SiC composites for nuclear applications, held at NRG-Petten, Netherlands (17-18 feb 2004).

FZJ experts have been questioned in order to obtain information concerning:

- the availability of nuclear grades of CMC and the evaluation of the different suppliers,
- the design and results of mechanical testing of C/C,
- the knowledge of environment effects (irradiation, atmosphere,...) on C/C.

Dr. Jochen Linke who was not personally involved in past HTR programs informed us that all activities in his institute related to High Temperature Gas Cooled Reactors have been terminated in the nineties. All experimental facilities have now been dismantled in FZJ. At present, Dr Linke is in charge of investigating plasma facing components (carbon based materials, miltidirectionnal CFC with high thermal conductivity, Si doped CFC, beryllium and tungsten alloys), in the frame of fusion-based rectors programs. Simulations of high thermal loads (20 MW/m^2) are performed is his laboratory on mocks-up containing C/C parts, and irradiation are carried out in experimental fission rectors. Recent results have been presented by Dr. Linke during the Workshop.

Dr. Manfred Rödig from FZJ developed in the beginning of the nineties a mechanical testing equipment for evaluating CMC. His study which deals with the tangential strength of C/C tubes is well described in the reference [1] (see annex).
In this publication, M Rödig reports the results of mechanical tests performed on commercial tubes of 330 mm diameter supplied by SIGRI (grade CC 2001 G). The C/C material was considered as a back-up solution for hot gas duct of HTR. Two mechanical testing methods were compared: burst tests where internal pressure was exerted either by a liquid or a gas and split disk test where the loading was applied by the contact two half-cylinder placed inside the tube. In all cases, the result allows to estimate the tangential strength conservatively. Indeed, a close analysis of the sample failure shows that bending load component under internal pressurization tends to enhance the failure of the tube which is not, in this case, submitted to a pure tangential stress. Furthermore, Mr. Rödig pointed out several problems encountered to manage the very coarse structure of CFC materials (large dimensions and large tolerances).

Dr. Rödig indicated that no further program of mechanical test on C/C materials has been performed since this early study and he confirmed that all equipments have been dismantled in FZJ. He mentioned two internal reports describing the experimental devices used at the end of the 80's at the FZJ in order to test CMC tubes (internal pressuring, bending, ...) [2,3]. This experience constitutes a valuable guideline for the development of mechanical tests on composite tubes.

We would like to thank Mrs Linke and Rödig for their collaboration.

[1] M. Rödig, W. Baur, B. Woschek: Burst Tests to Measure the Tangential Strength of CFC Tubes, IAEA Specialists Meeting on Status of Graphite Development for Gas Cooled Reactors, IAEA-Report IAEA-TECDOC-690, Wien Feb. 1993.

[2] B. Woschek, M. Rödig. Möglichkeiten zur Durchführung von Versuchen an keramischen Halbzeugen unter mehrachsiger Belastung bei hochen Temperaturen. Interner Bericht KFA – IRW – IB –10/86.

[3] B. Woschek, M. Rödig. Berstversuche zur Bestimmung der tangentialen festigkeit an Rohrabschnitten aus kohlenstoffaserverstärktem Kohlenstoff. KFA-IRW-TN-40/91

BURST TESTS TO MEASURE THE TANGENTIAL STRENGTH OF CFC TUBES

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Abstract

Carbon fiber reinforced composites (CFC) are considered as graphite/metal substitute material for certain structural components in modern HTR design. Internal pressure tests have been performed with tube segments made of CFC. The aim of the investigations was to value the failure of components under hoop stress and to compare the results to those obtained in relatively simple tests as split disk tests. The internal pressure was generated by gas and water.

The main problem in the experiments was to prevent leakage at the end of the tubes without applying uncontrolled bending moments. Design methods supported by finite element calculations, helped to reduce these bending moments which could not avoided totally however. Therefore the results of the burst tests must be considered as conservative. But compared to the split disk tests, the failure stress is twice as high as for the latter. Therefore it can be assumed, that for the given geometry, the split disk tests underestimate the tangential strength at least by a factor of two.

1. Aim

Carbon fiber reinforced composites (CFC) are considered as graphite/metal substitute material for certain structural components in modern HTR design. In a cooperation of the Institute for Reactor Materials and Sigri GmbH, internal pressure tests have been performed with tube segments made of CFC.

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The aim of the experiments was to measure the tangential strength in burst tests and to compare the results with those of less sophisticated experiments, as split-disk-tests (ASTM Standard D2290-69).

The split disk test is usually used for semi-empiric comparison of ring shaped testing specimens. The grips for these tests are two half-cylinders with an outer diameter corresponding to the inner diameter of the ring specimen to be tested (cp. Fig. 1). During the experiment the specimen is loaded by these half-cylinders. For the evaluation, a pure tangential tensile stress is assumed in both halfs of the ring-specimen. Therefore the ultimate tangential tensile stress (UTS) is:

$$UTS = F / (2 \cdot t \cdot l)$$

F: force
t: wall thickness
l: width of the ring

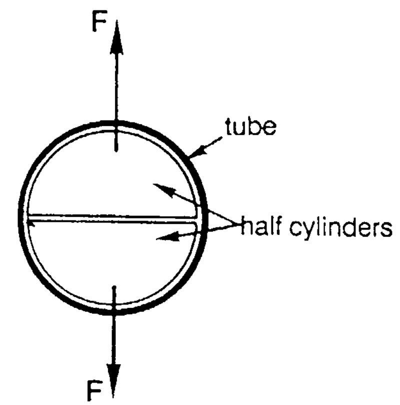


Fig. 1: Split disk test

In reality however the stress stage is more complicated and for the following reasons no pure tensile stresses can be assumed:

- For reasons of mountability the outer diameter of the grips has to be smaller than the inner diameter of the ring specimen to be tested.
- No ideal contact between grips and ring specimens is given due to surface roughness effects.
- The stress distribution is influenced by edge effects.

So the aim of the burst tests was to compare the results with those of the relatively simple split disk test and get an information on the grade of conservativity of the latter.

2. Tested Material and Specimens

The CFC material to be tested was CC 2001 G made by SIGRI. The technical data are given in Fig. 2.

The inner tube wall is a roving tissue of 0.2 mm thickness. Above this tissue are windings of carbon fibers under an angle of +/- 15° to the tangential direction. The outer wall consists of a layer of matrix material without reinforcement of fibers. This means, that the effect of reinforcement is given only in directions near to the tangential direction.

Material data:

Material:	Sigri CC 2001 G
final temperature treatment:	2000°C
density:	1.3 - 1.5 g/cm^3
bending strength (tang.):	280 - 350 MPa
tensile strength (tang.):	380 - 470 MPa
dyn. Young's modulus:	110 - 130 GPa

Tube dimensions:

outer diameter:	331 mm
wall thickness:	3 - 4.5 mm
length:	150 mm, 700 mm

Fig. 2: Technical data of CFC material CC2001G

The number of specimens tested are:

- 10 tube segments of 700 mm width (pressurized by water),
- 12 tube segments of 150 mm width (pressurized by gas),
- 15 split disk specimens of 6.3 mm width.

3. Burst Tests with gas as a pressurizing medium

It was intended to perform the experiments in such a way that by the sealing system no axial stresses were applied. In this case a uniaxial stress state would be achieved in the tube wall. The idea was to use a materials testing machine in closed loop operation so that only the sealing force was achieved. This concept of sealing is shown in Fig. 3.

The internal pressure was produced from a helium bottle (cp. Fig. 4). The needle valve behind the pressure reducer was used to shelter the pressure reducer from shocks during the failure of the tube. A filler body was brought into the tube specimen to reduce the released potential energy during failure. Four pairs of extensometers were mounted on the inside and on the outside of the tube in order to measure the change of the internal and the external diameter.

The failure stress of nine short tubes (length = 150 mm) is given in Fig. 9 (marked "2"). The mean values were:

mean failure stress: 249 MPa
standard deviation: 41 MPa
95%-confidence range for the mean value: 218...445 MPa

All specimens failed near to the edges of the tube.

The reason was, that the applied sealing force exceeded the failure stress of the tube in axial direction. To get the information about axial strength of the tube, pure compression tests were performed (cp. Fig. 5). It can be seen that from a stress of approximately 12 MPa irreversible deformations take place. So it must be assumed that near the edges a complex state of stresses occurs, and so the maximum hoop stress calculated from the burst pressure underestimates the tangential strength of the tube material.

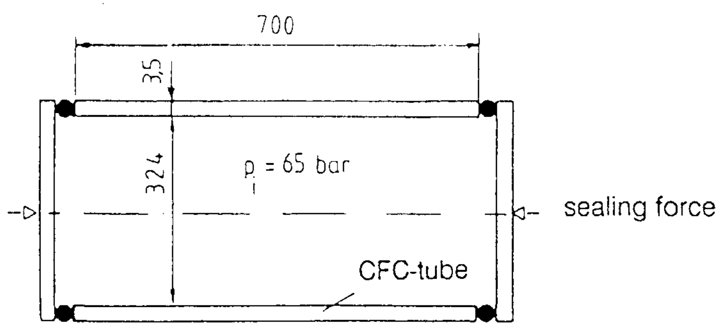


Fig. 3: Sealing by O-rings

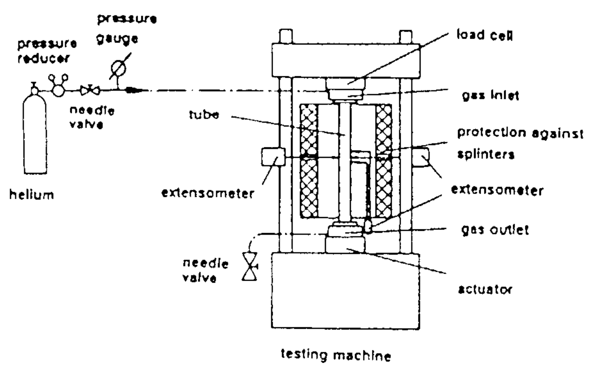


Fig. 4: Gas pressuring system

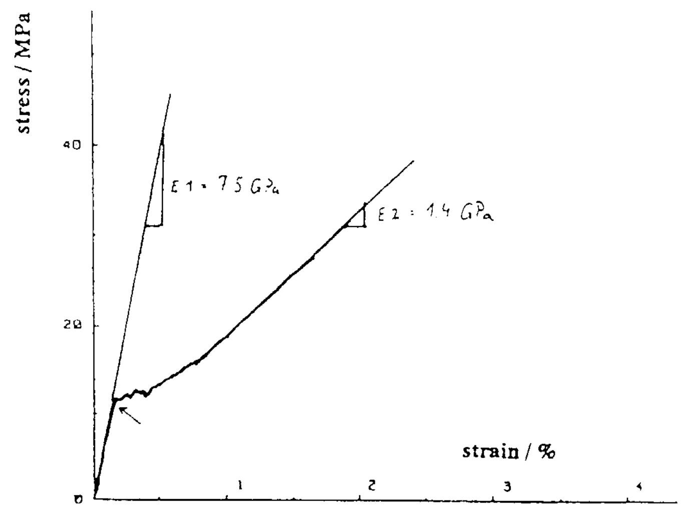


Fig. 5: Stress strain diagram for a tube under axial compression

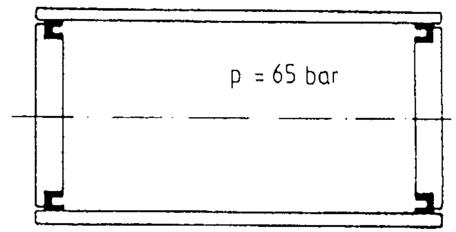


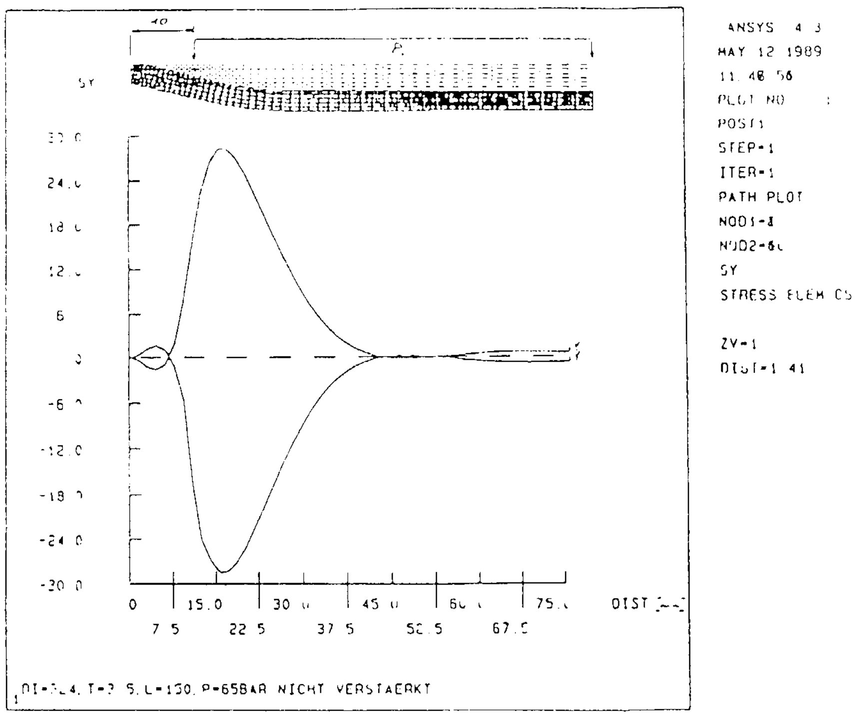
Fig. 6: Lip sealing concept

4. Burst Tests with water as a pressurizing medium

Due to the experimental problems described in chapter 3, another testing technique was developed. Lip sealings were used to avoid damage of the tube while applying the sealing forces (cp. Fig. 6). Now it was no longer necessary to perform the experiments in a testing machine and water could be used as a pressurizing medium.

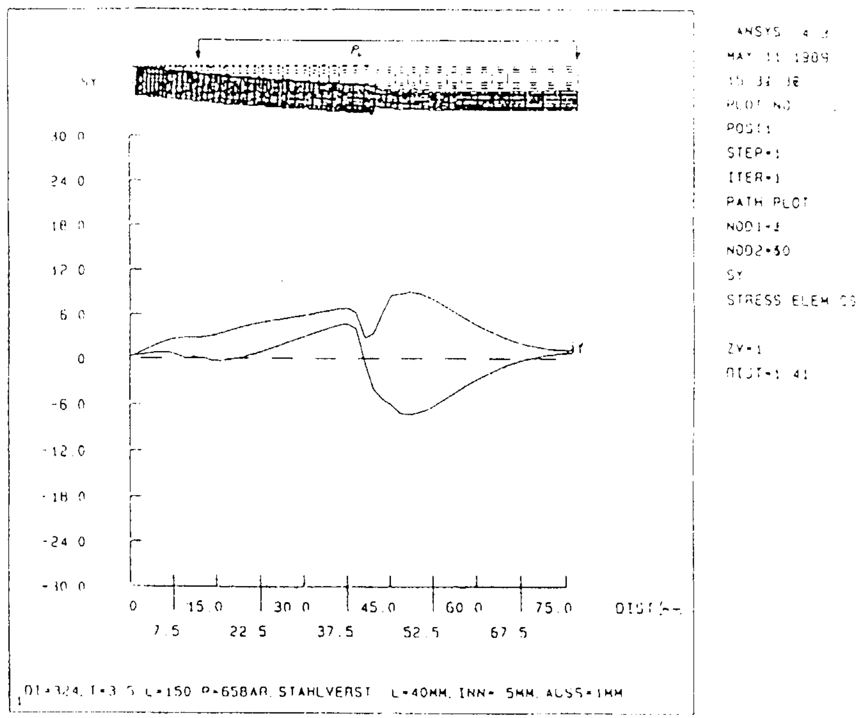
In the first two tests it was found that the tubes were destroyed near the edges as well. The results for these two tubes are shown in Fig. 9 they are marked by "3a".

In order to understand these phenomenon, an analysis of the deformations and stress distributions was performed with the finite element code ANSYS. In Fig. 7 the distribution of axial stresses in the tube wall is shown. An internal pressure of 65 bars was assumed which is the approximate mean burst pressure. About 16 mm from the tube edge, a maximum of the bending stress of 28 MPa is found. This is compared to the results of the simple axial compression test (cp. Fig. 5).



outer diameter: 324 mm, wall thickness: 3.5 mm, length: 150 mm
no reinforcement sheets

Fig. 7: Axial stress in the inner and outer tube wall (without reinforcements)

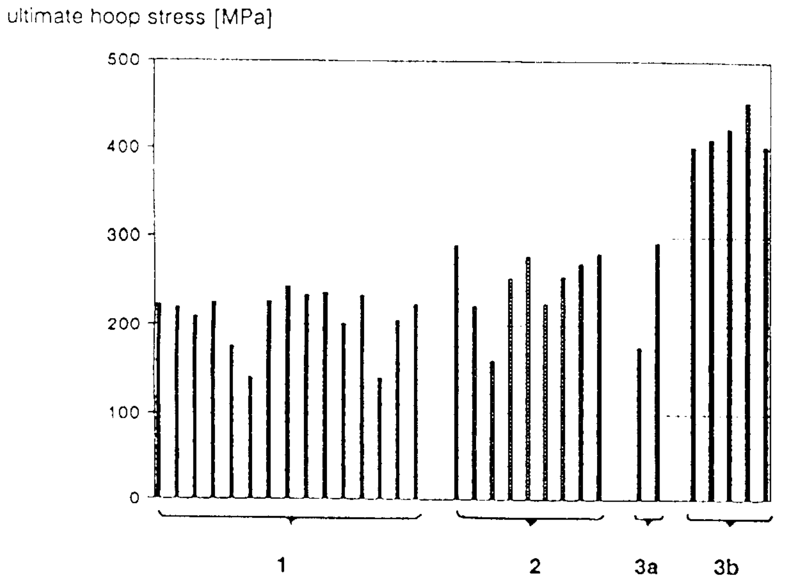


outer diameter: 324 mm, wall thickness: 3.5 mm, length: 150 mm
Inner reinforcement: steel 0.5 mm thick, 40 mm long
outer reinforcement: steel 1 mm thick, 40 mm long

Fig. 8: Axial stress in the inner and outer tube wall (with reinforcements)

The reason for the high axial stresses now is the large difference in axial and tangential stiffness of the tube. The small part of the edges of the tube, which is not pressure loaded remains on its position while the pressure loaded part gets a radial deformation (cp. top of Fig. 7). The result is a high curvature in axial direction near the edges which leads to the bending stresses. To avoid the curvature, it was necessary to reinforce the tubes by metal sheets in the region near the sealings.

A finite element study has been performed in order to estimate the influence of the reinforcements. Calculations were made for several widths of the reinforcement zone, for reinforcements on the inner and/or the outer tube wall, and for reinforcement materials of different stiffness. Fig. 8 gives the final configuration of the reinforcements (inside: 40 mm long, 0.5 mm thick, outside: 40 mm long, 1 mm thick, sheet material: steel). The finite element calculation shows, that the axial stresses are drastically reduced by the reinforcement.



1: split disk tests

2: burst tests (series 1):
tube length: 150 mm
pressure medium: gas

3: burst tests (series 2)
tube length: 700 mm
pressure medium: water
a) without reinforcements
b) with reinforcements

<u>Fig. 9:</u> Experimental results for all specimens

In burst test with tubes reinforced by steel sheets a much higher failure stress is found (cp. Fig. 9 - results are marked "3b"). Mean values were:

mean failure stress: 419 MPa
standard deviation: 21 MPa
95 % confidence range for the mean value: 393...445 MPa

5. Result of Split Disk Tests and Discussion

Nine split disk tests have been performed. The results are given in Fig. 9 (marked by "1"). Mean values are:

mean failure stress: 210 MPa
standard deviation: 33 MPa
95 % confidence level for the mean value: 192...228 MPa.

The failure strength of the tubes pressurized by gas (249 MPa) lies approximately 20 % higher than the split disk test. This difference however is not significant according to the 95 % confidence limit. For the tubes reinforced by steel sheets, significantly higher failure stresses are found. The final stresses are nearly as double as high as for the tubes without reinforcement. This confirms the result of the finite element calculation on the influence of reinforcements. But it must be mentioned, that by the reinforcement bending moments can be reduced but can not be totally avoided. Therefore it must be mentioned, that the failure stresses found in these experiments are still below the true tangential strength and hence conservative. Therefore it can be assumed, that for the given geometry, the split disk test under-estimated the tangential strength at least by a factor of two.

DISCUSSION

Questions or Comments **Name:** R. Judge

1 Did you use strain gauges on the specimens?

No - But extensemeters were used to measure the change in diameter.

2 Did you consider loading by rubber membrane?

We considered rubbermembrane loading, but we did not use it because we were afraid of edge effects.