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Institut für Angewandte Reaktorphysik
Institut für Material- und Festkörperforschung

Multi-axial In-Reactor Stress-Rupture Strength of Stainless Steels and a Nickel-Alloy

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Introduction

In our cladding irradiation program we follow two lines of research. First, we have a fundamental program on the investigation of high temperature embrittlement by (n,α)-reactions and on mechanical property improvement by alloy adjustment and pretreatments. Second, we simulate the conditions of the fuel cladding with specially developed irradiation facilities to get reliable information for the final fuel-element design.

Within the scope of this second program we have tested small tubes of various alloys under constant pressure during irradiation in the temperature range of 600 to 700°C and measured the tangential strain afterwards.

The tested alloys were the German stainless steel, 16/13 CrNi, Inconel 625, 20/25 CrNi stainless steel and Incoloy 800.

Similar irradiations under multiaxial stress were performed earlier by others in Oak Ridge on the stainless steels, AISI 304 and 20/25 CrNi, and on Nickel-base alloys, Inconel 600 and Hastelloy N (1, 2, 3). In these irradiations, the main result was a considerable decrease of the tangential strain in comparison with the unirradiated specimens. The difference became smaller with increasing temperature; and at 850°C the unirradiated and irradiated 20/25 CrNi-tubes showed the same tangential strain (2). This same stainless steel showed nearly no difference in the stress-rupture strength between 550 and 850°C. However the neutron flux in these tests, was not very high (5×10^{12} fast neutrons/cm^2sec). In the other tests, also performed in the ORR-Reactor, the stress-rupture strength decreased up to as much as 30 %.

Experimental Conditions

Our irradiations were performed in the Belgian Material Test Reactor BR2. The fast neutron-flux was between 2.5 and 4.0 x 10^{14} n/cm^{2}sec and the thermal flux between 2 and 3.5 x 10^{14} n/cm^{2}sec, depending on the fuel-element position used. The irradiation facility was developed and constructed at the Karlsruhe Nuclear Center (4). The specimens had an outer diameter of 7.0 mm, a wall thickness of 0.4 mm and a length of 45 mm (Fig. 1). Each of the tubular specimens within a test capsule could be individually put under an internal pressure up to 500 atm. by controlled insertion of Helium. The temperature was kept constant during irradiations by an internal electrical heater. The specimen temperature was measured by three Chromel-Alumel thermo-couples, welded on the surface of the specimens. Eight of these specimens were placed one above the other in a capsule having an outer diameter of 17.4 mm. The control equipment was built in such a way that we can irradiate two capsules simultaneously. An identical test facility was built for unirradiated specimens.

The compositions of the alloys are shown in Table 1. The Inconel 625 specimens were tested in annealed condition (900°C - 1 h), the three other alloys were 10 % cold worked.

The diameter of the specimens was measured before and after irradiation with a micrometer. The accuracy of measurement of the irradiated specimens was not better than ± 5 %. The tangential stress was calculated with the well known formula for tubes of small wall thickness.

$$\sigma_t = \frac{p \cdot r_i}{s}$$

σ_t = tangential stress

p = inside pressure

r_i = inner radius

s = wall thickness

Experimental Results

The results for the investigated four alloys are summarized in Figs. 2 to 5.

16/13 CrNi: The stress-rupture strength of unirradiated and irradiated 16/13 CrNi stainless steel is given in Fig. 2. The stress-rupture strength decreased by about 40 % at 600°C and by about 50 % at 700°C. The ductility of the irradiated specimens was not decreased to the same extent. The unirradiated specimens showed a tangential strain between 0.3 and 1.75 % at 600°C, except after a rupture time of only 100 hrs., where 6.3 % was measured. In comparison the tangential strain of the irradiated specimens at 600°C was between 0.6 and 1.0 %. At 700°C the tangential strain of the unirradiated specimens increased with increasing rupture time from 1.75 (17 hrs.) to 3.8 % (1650 hrs.). The tangential strain of the irradiated specimens was between 0.3 and 1.5 %, independently of the rupture time.

Inconel 625: Fig. 3 illustrates not only the influence of irradiation, but also the influence of the titanium- and aluminium-content, specimen dimensions and heat treatment of unirradiated Inconel 625. The unirradiated rod and sheet specimens were tested in the solution annealed condition (1 hr. - 1150°C), whereas the tubes, as mentioned before were annealed 1 hr. at 900°C. the highest stress-rupture strength was measured on the rod specimens with the highest titanium and aluminium contents. The higher stress-rupture strength of the sheet specimens with the lowest titanium and aluminium content, compared with the tube specimens, was probably influenced by the different heat treatment. The ductility of the various specimens was also influenced by the different titanium and aluminium contents. The highest ductility was measured on the sheet specimens. The lowest ductility was measured on the multi-axial stressed tube specimens and was found to be lower than expected from the strength hypothesis, which is 2/3 of the uni-axial strain. The discrepancy is, for the moment, not well explained.

Under irradiation and multi-axial stress we found a decrease of the stress-rupture strength of 40 % after 150 hrs. and 35 % after 1000 hrs. The low ductility of the unirradiated specimens (1.2 - 2.8 %) was further reduced to the range of 0.4 to 1.9 by irradiation.

<u>Incoloy 800:</u> The results are summarized in Fig. 4. The stress-rupture strength at 600°C was reduced by irradiation after a rupture time of 300 hrs. by 20 % and after 2000 hrs. by 30 %. At 700°C the reduction of 30 % was constant over the measured range. The most important result is the high ductility of this titanium and aluminium free Incoloy 800, in the unirradiated as well as in the irradiated conditions. The tangential strain decreased by irradiation at 600°C from 14 - 24 % to 3.0 % and at 700°C from 10 - 20 % to 2.5 - 4.7 %. Among the alloys tested, Incoloy 800 had the highest ductility but the lowest strength.

<u>20/25 CrNi:</u> The decrease of stress-rupture strength by irradiation at 600 and 700°C was 30 %. At 700°C however there was a tendency for a larger decrease at longer rupture times (Fig. 5). The decrease of the tangential strain with increasing rupture time of the unirradiated specimens we did not detect under

irradiation, since we have only few results under irradiation (0.4 - 1.0 %). But also the tendency was not apparent at 700°C of the irradiated specimens. While the tangential rupture strain of the unirradiated specimens decreases from 5.7 % after 10 hrs. to 1.1 % after 2000 hrs., the tangential strain of the irradiated specimens was 0.3 - 0.75 - 0.47 - 1.0 % with increasing rupture time. These results indicate that 20/25 CrNi is not a suitable cladding material for fast breeders since, in addition to the low strength under irradiation (600°C - 2000 hrs. - 9,5 kg/mm^2), the alloy has nearly no ductility in the irradiated condition.

Discussion of results

The test data illustrate two remarkable results:

1. Reduction of the stress-rupture strength from 20 to 50 % by irradiation.
2. Reduction of the tangential rupture strain to absolute values of 1.0 % (with the exception of Incoloy 800). This means that small intergranular cracks occur but no burst in the well known manner.

From theoretical considerations and in-pile-creep tests (5), it can be concluded that, within the test temperature range, the secondary creep rate is not changed by irradiation as long as no precipitation processes occur, since the concentration of thermal vacancies is much higher than the concentration of irradiation induced vacancies. The influence of irradiation must therefore lie mainly in the formation of intergranular cracks in the secondary creep stage.

Intergranular voids form under stress according to the mechanism of creep. They grow by diffusion of vacancies into these voids. At high enough applied stress their growth continues and failure will occur by linkage of the intergranular voids.

The embrittlement by various (n,α)-reactions during irradiation due to the bubble model is a well known process; so it is not necessary to discuss this problem in detail (6). The reduction of the tangential strain and the stress-rupture strength can be explained by the presence of helium in the 20/25 CrNi and Incoloy 800 alloys, with negligeable precipitation during irradiation. There was no difference in the structure of irradiated and unirradiated specimens and the fracture was in each case intergranular. The high ductility of the Incoloy 800 is probably coursed by the composition of the alloy (Ti- and Al-free).

For the complex alloys, Inconel 625 and 16/13 CrNi, an accelerated precipitation process by irradiation can be superimposed on the mentioned mechanism.

This combined mechanism can be the reason for the higher reduction in stress-rupture strength (40 - 50 %) while the two other alloys Incoloy 800 and 20/25 CrNi show a reduction of only 20 - 30 % and a smaller decrease with increasing rupture-time. Otherwise microscopic examination showed no difference in the structure of the irradiated and control specimens (Fig. 6). We hope to get more information by electronmicroscopic examination and the use of different heat treatments and compositions of the alloy. The higher reduction of strength can also be a simple function of the higher absolute strength of these solution hardening alloys.

The following conclusions can be drawn for the fuel-element design from the results of our investigations to date:

a.) Alloys with a tangential rupture strain of 1 % can only be compatible with the so called strong can concept, and for stress calculations for the moment we must take into account the 0.2 - 0.5 creep strength.

b.) With the collapsed can design ductility is the most important property. The tested titanium and aluminium free Incoloy 800 would have a good chance for this type of cladding.

The selection of a cladding material concerning composition and pretreatment cannot only be made by considering the technological problems of fabricating small tubes. One must also take into account its function as a fuel element cladding.

Summary

We have determined the stress-rupture strength and tangential rupture strain of four cladding materials under irradiation between 600 and 700°C. The tested alloys were the stainless steels 16/13 CrNi, 20/25 CrNi, Inconel 625 and Incoloy 800.

The irradiations were performed in the Belgian Reactor BR2 with a fast neutron flux between 2.5 and 4.0 x 10^{14} n/cm^{2}sec.

The stress-rupture strength was reduced between 20 and 50 % by irradiation. The highest decrease was measured on the complex alloys Inconel 625 and 16/13 CrNi. The tangential rupture strain was reduced to absolute values of 1 %, with expection of the titanium and aluminium free Incoloy 800 (2.5 - 4.7 %).

These observations can be explained on the basis of the mechanism of radiation damage involving helium produced by different (n,α)-reactions.

Acknowledgement

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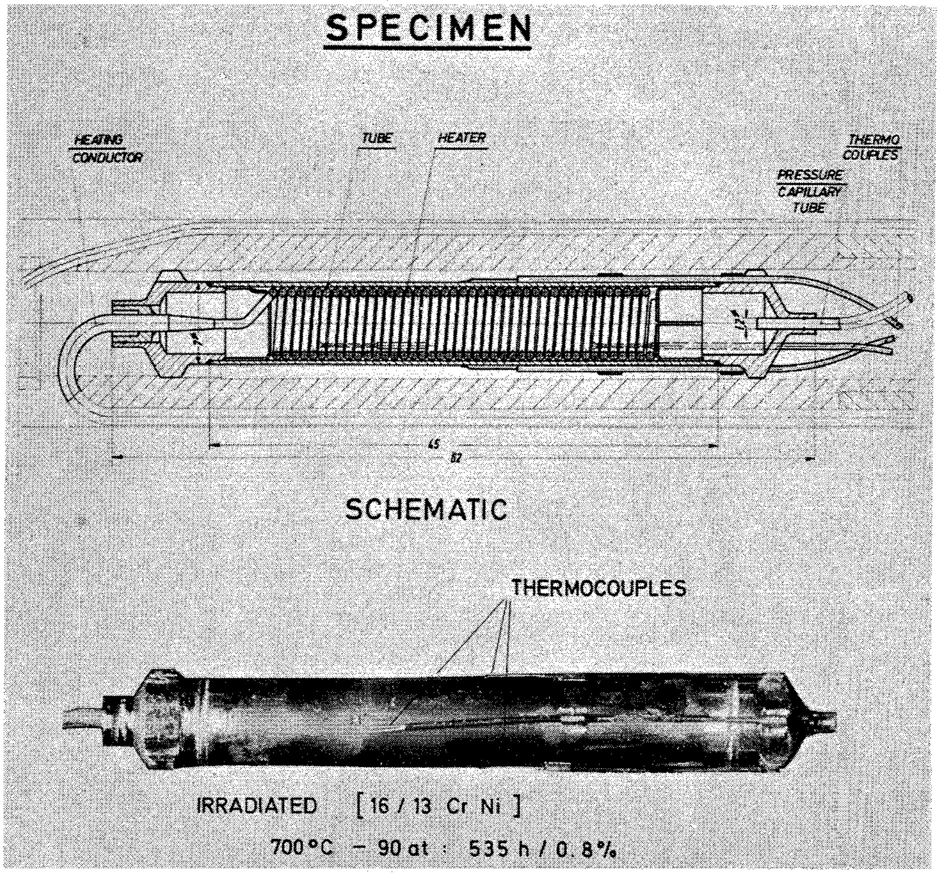


Fig.: 1 tubular specimen, top: schematic, with a section of the irradiation capsule, bottom: irradiated 16/13-CrNi-stainless steel specimen

ALLOY	[WEIGHT - PERCENT]								
	C	Cr	Ni	Mo	V	Ti	Al	Fe	Nb/Ta
16/13 Cr Ni	0.08	16.9	13.6	1.2	0.6			BAL	0.7
INCONEL 625	0.03	21.82	BAL	8.7		0.21	0.15	2.94	3.64
INCOLOY 800	0.016	20.6	31.9					BAL	
20 / 25 Cr Ni	0.017	19.92	24.68					BAL	0.01

Table 1 : Composition of the Test Material

16/13 Cr Ni

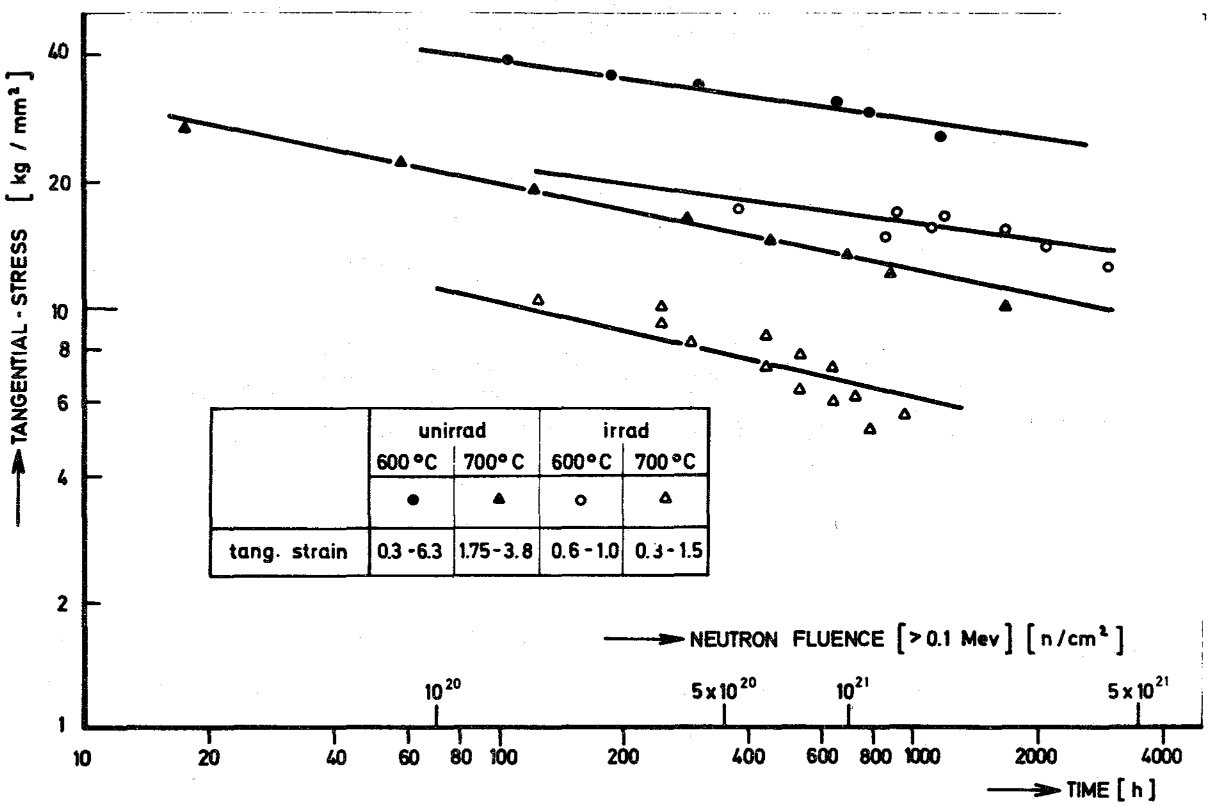


Fig. 2 : Multi-axial stress-rupture properties of unirradiated and irradiated 16/13 CrNi stainless steel tubes at 600 and 700°C

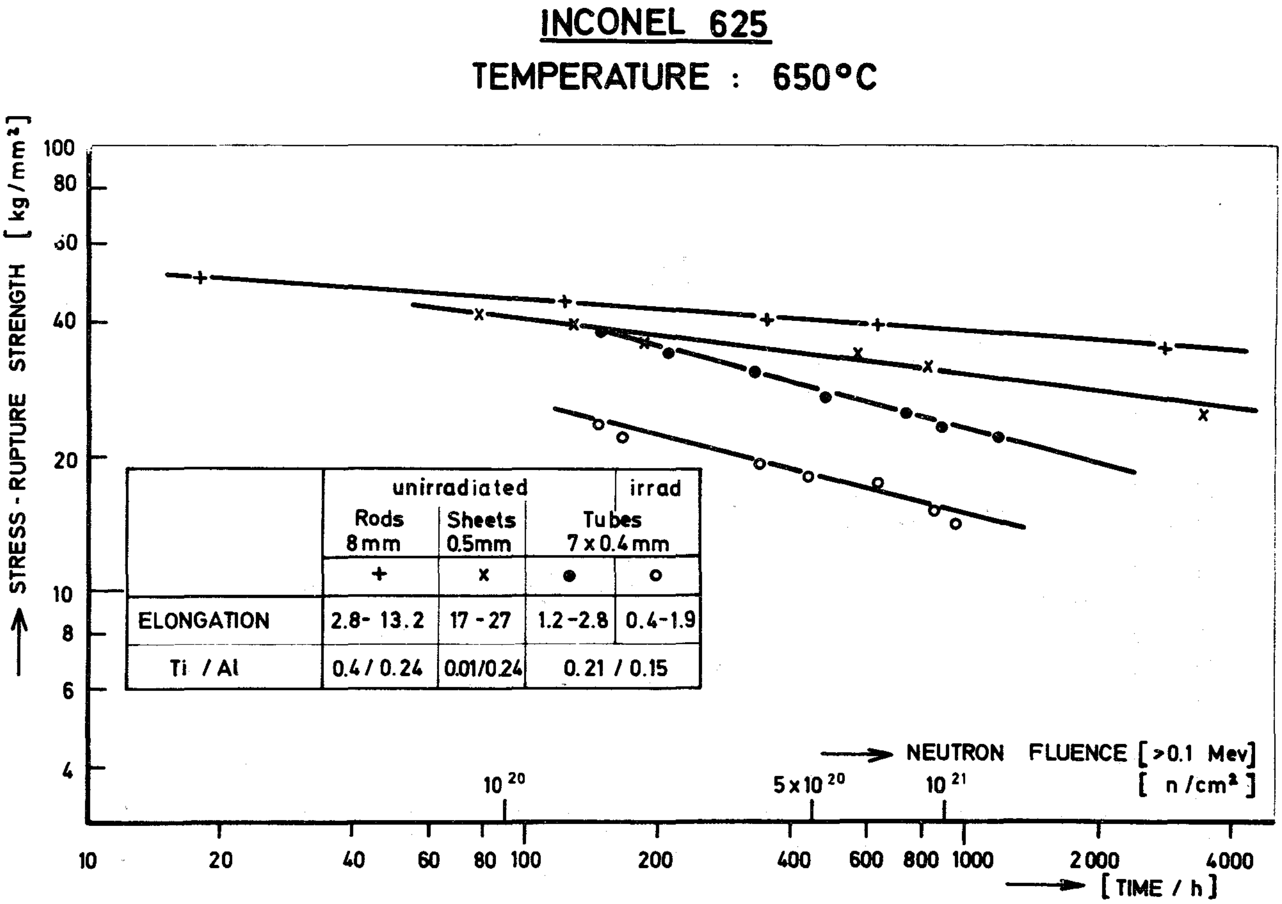
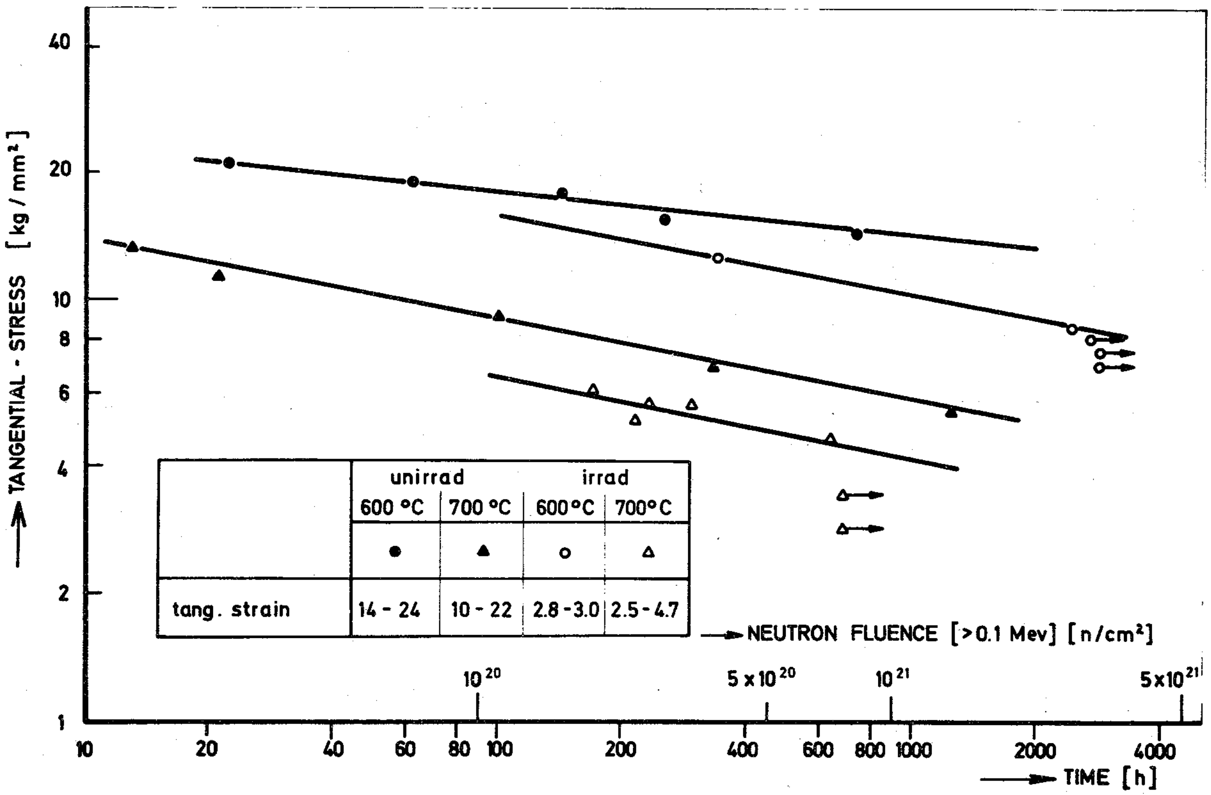


Fig.: 3 Uni- and multi-axial stress-rupture properties of unirradiated and irradiated Inconel 625 at 650°C

INCOLOY 800



<u>Fig.: 4</u> Multi-axial stress-rupture properties of unirradiated and irradiated Incoloy 800 tubes at 600 and 700°C

20 / 25 Cr Ni

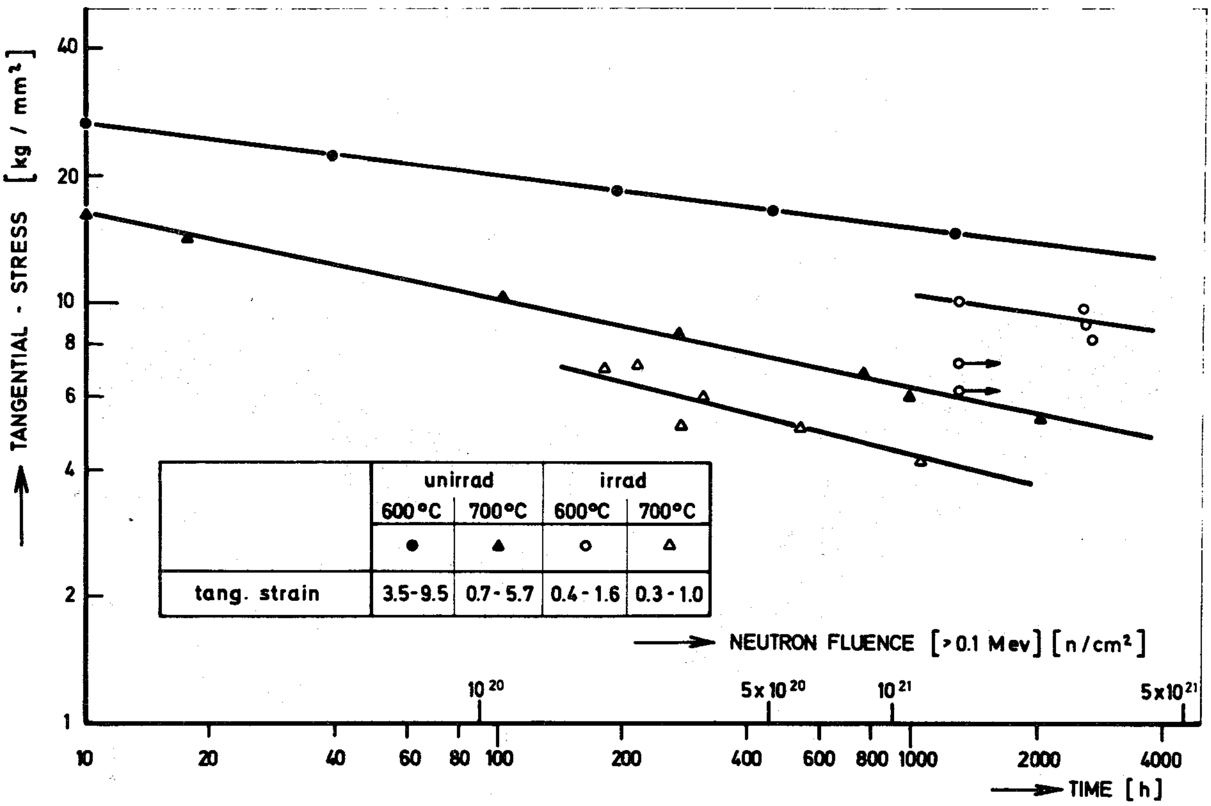


Fig.: 5 Multi-axial stress-rupture properties of unirradiated and irradiated 20/25 CrNi stainless steel tubes at 600 and 700°C

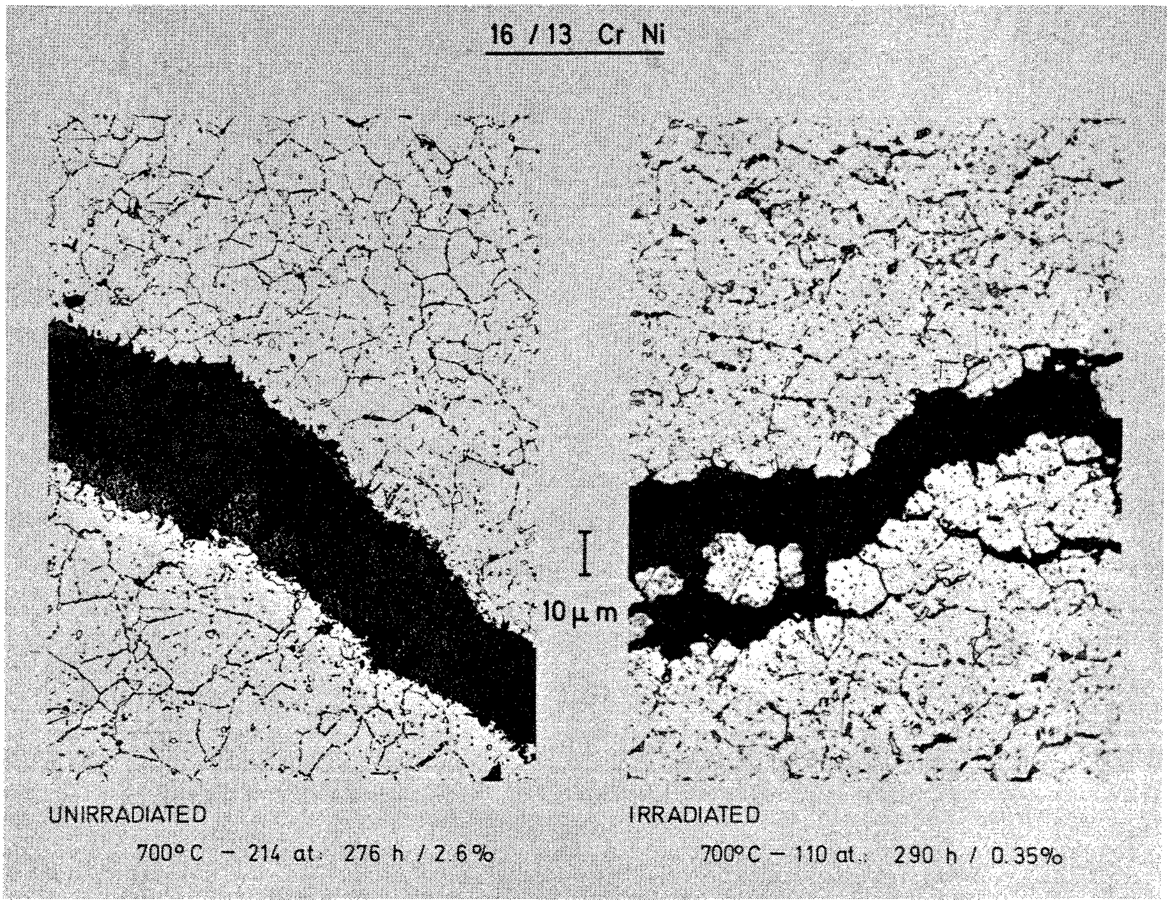


Fig.: 6 Photomicrographs of 16/13 CrNi tubing, fracture section
left: unirradiated, right: irradiated