BG9600365

Assesment of VVER Fuel Condition in Design Basis Accident

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This paper gives a review of design and experimental studies of fuel behaviour in design basis accidents relevant to a fuel cladding temperature rise.

The VVER fuel conditions is assessed based on calculations by the RAPTA code developed at ARSRIIM. The first version of the code appeared in late 70-ies [1]. Nowadays the fifth version of the code, specifically RAPTA-5, has been developed. Compared to the preceding version [2] the code comprises new models: non-axisymmetrical local ballooning of cladding, cladding straining within a fuel bundle taking account of mutual effects. The models of cladding straining and rupture, cladding material oxidation and oth. have been backfitted with due account for new experimental data.

To prepare a new version of the code the newly developed and backfitted models were tested using experimental data. For instance, the serviceability of the calculation of the process of non-isothermal high temperature oxidation of Zr-1%Nb alloy was determined by comparing with the relevant experimental data [3]. As a whole the codes verified by comparing with the results of experiments with fuel bundles as well as with design data obtained using other codes.

RAPTA-5 code performs interrelated thermo-mechanical calculations of a fuel conditions taking account of high temperature interactions. The results of code calculations are:

- temperature field of a fuel rod including assessments of power density due to chemical interactions;
- stress-strained condition of cladding including determination of location, time and strain of rupture;
- assessment of the extent of chemical interactions (cladding material oxidation, cladding-fuel interaction etc.);
- assessment of hydrogen release;
- assessment of cross section blockage.

The input data for the RAPTA code are results of calculations of neutron physics and thermal hydraulics parameters of the core: power density of fuel, coolant condition (composition, pressure, flow rate), etc. The calculations of this kind are executed by the chief designer of a reactor unit, i.e., OKB Hydropress.

The main result of the calculations of fuel rod condition in design basis accidents is the check-up of the ability to meet the criteria for the emergency core cooling system acceptance:

- not to exceed the temperature of UO_2 melting down at any point in the core;
- not to exceed the fuel cladding temperature of 1200°C;
- local depth of fuel cladding oxidation must not exceed 18% of the initial wall thickness;
- a fraction of reacted Zr must not be higher than 1% of its mass in fuel claddings. There are also requirements placed on the maximum blockage of a core;
- the feasibility of discharging a core and its components after a design basis accident. For accidents relevant to a quick reactivity increase the specific threshold energy of fuel rupture must not be exceeded at any moment of life.

Comparison between the above criteria in terms of fuel for VVER type reactors with those for PWR's demonstrates the full coincidence in the set of the criteria. In many cases also quantitative parameters agree.

The process describing models designed for the RAPTA-5 code are based on dependences and constants derived experimentally using commercially produced materials, fuel rod simulators, fuel bundles. The major processes are

- cladding material straining and rupture;
- high temperature interaction of a cladding material with steam, a spacer grid material (stainless steel) and UO_2 (in case of a contact);
- UO_2 - steam interaction have been studied in a wide range of temperatures and rates of temperature - force loading.

The unique method (continuous weighting of a specimen) used for studying the oxidation of a cladding material [4, 5] revealed same specific features. For instance, upon rather long-term holding the "weight gain - time" curves show a transition. The metallographic analysis confirmed the relationship between accelerated oxidation and oxide film separation. The ranges of this effect in terms of temperature - time have been revealed.

Another specific feature of oxidation is relevant to the process of oxidation during cladding material straining [6]. Based on the generated experimental data to be used for design calculations, a set of conservative dependences was recommended for the description of oxidation kinetics. For the temperature range of 900 - 1200°C and the interaction time up to 900 *sec* the following dependence is a conservative one:

$$\Delta m/A = 920 \cdot \exp(-10410 / T)\ t^{1/2} \qquad (1)$$

where: $\Delta m/A$ - is the specific weight gain, *mg/cm²*, T is temperature in K, and t - time, *sec*.

Eq. (1) is an analogue of Baker-Just dependence recommended for PWR cores with fuel cladding in Zry-4. It is to be noted that Eq. (1) and other relations that enter into the set of conservative dependences for VVER cores give an assessment of oxidation with a margin also in case of fuel cladding straining.

The strain property of a cladding material were studied both in initial tension and in experiments with cladding and fuel rod simulators. The investigations performed with iodine containing environment in a cladding (the concentration of 1 mg/cm^3) show that the effect of iodine takes place up to 700°C. The availability of iodine lowers the rupture strain of cladding.

Cladding-spacer grid material interaction was studied using diffusion pairs in vacuum as well as cladding and spacer grid simulators in steam. It is shown that steam available in a system has a significant effect on the minimum temperature of eutectics formation [7].

UO_2-steam interaction depends significantly on oxygen potential and steam composition. At the standard composition of steam and temperatures typical of design basis accident UO_2 does not essentially react with steam.

In the problem relevant to properties of fuel and structural materials a special position is taken by the mechanical properties of high temperature oxidized fuel claddings, since this issue is closely related to the margins in the acceptance criterion in terms of cladding material oxidation. Recently papers have appeared [8, 9] that question the validity of the criterion. Tests were conducted for compression of oxidized cladding section in the direction normal to the axis of the specimen symmetry. Similar results were published by us earlier [10]. However, these results cannot be related to the needed experimental validation of the criterion, since, first, the experiments were performed at room temperature. Second, this does not comply with actual scenarios of design basis accidents, and as has been mentioned in [11] the chosen type of cladding loading does not comply with the loads experienced by fuel rods in accidents and subsequent fuel handling, shipping included.

The experiments carried out in Russia using oxidized specimens (cladding sections, cylindrical microspecimens, rings) demonstrated a significant increase of ductility with temperature.

Most dangerous for fuel rods during accidents are modes of core flooding with cold water. Fig. 1 shows the results of testing for thermal resistance of fuel simulators. The vertical line is a boundary of an allowable region of oxidation, namely 1200°C; the sloping line is a boundary of 18% oxidation of a cladding material. The experimental data shown by Fig. 1 pertain to cladding testing without axial limitation of relocation. The recent similar data on axially limited relocation indicate with in this case too there is the needed margin for oxidation. All these results were obtained for indirectly heated fuel claddings which is basic since at significant oxidation (more then 1%) experiments with directly heated claddings (by passing directly electrical current through a specimen) give large uncertainties in terms of temperatures.

Taking account of the commercial introduction of new Zr alloys as cladding materials in the IAEA framework recommendations are to be issued in terms of methodology support of determining the fuel acceptance criteria.

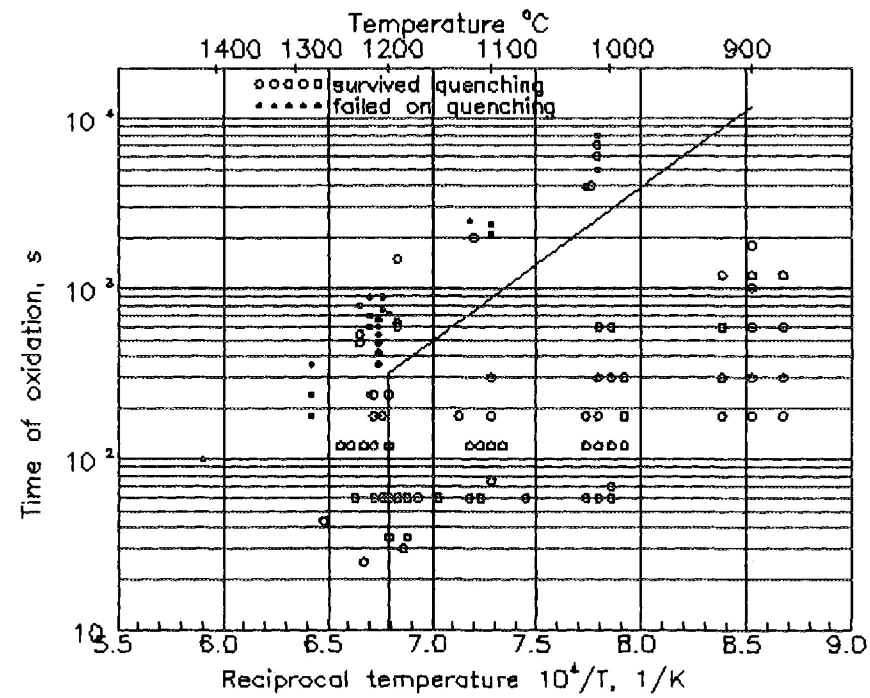

Figure 1 Testing of dummy fuels by thermal shock (cladding 9.1×7.74 mm, Zr1%Nb)

Conclusions

1. The fuel condition in design basis accidents is assessed on the basis of the verified code RAPTA-5.
2. The code manes use set of high temperature physico-chemical properties of the fuel components as determined for commercially produced materials, fuel rod simulators and fuel rod bundles.
3. The VVER fuel criteria available in Russia for design basis accidents do not generally differ from the similar criteria adopted for PWR's.

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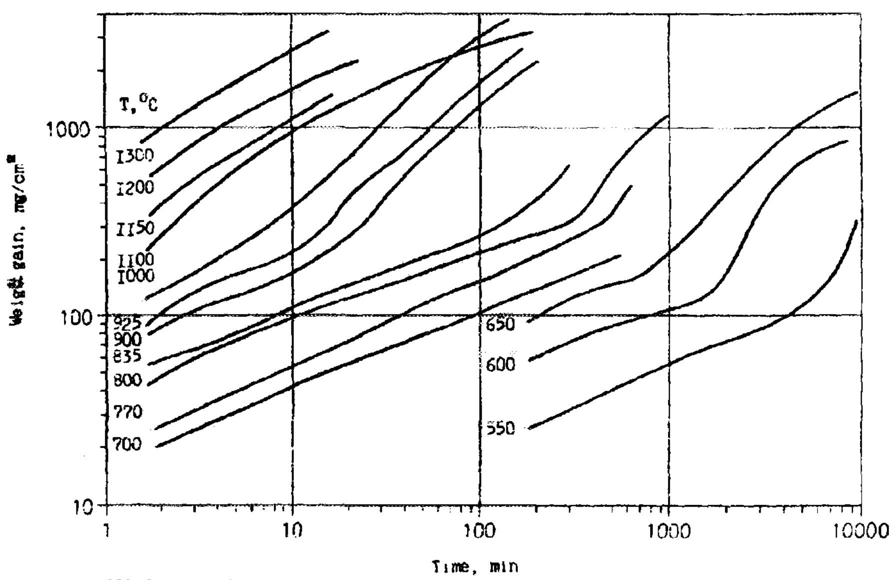
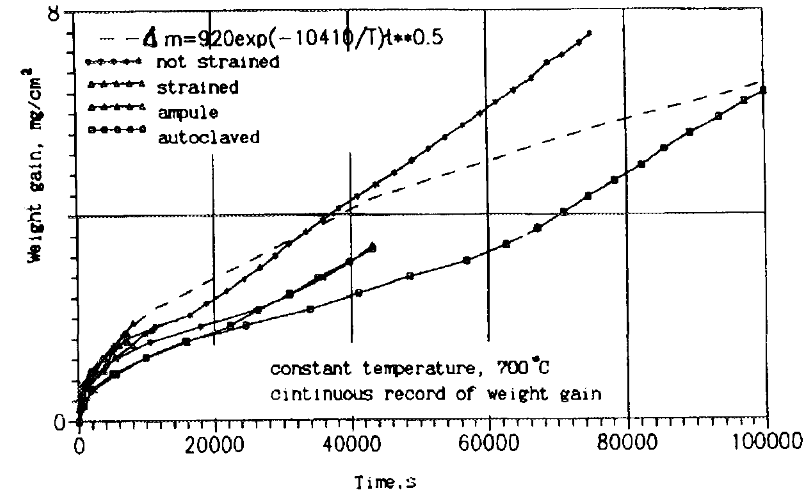
Note by the Publisher

Additional figures were presented by the authors at the Seminar, that were not mentioned in the text. As we consider them important for understanding of the discussed phenomena, these pictures are next included without specific order or numbering. Their captions, however, correspond to certain paragraphs in the text above.

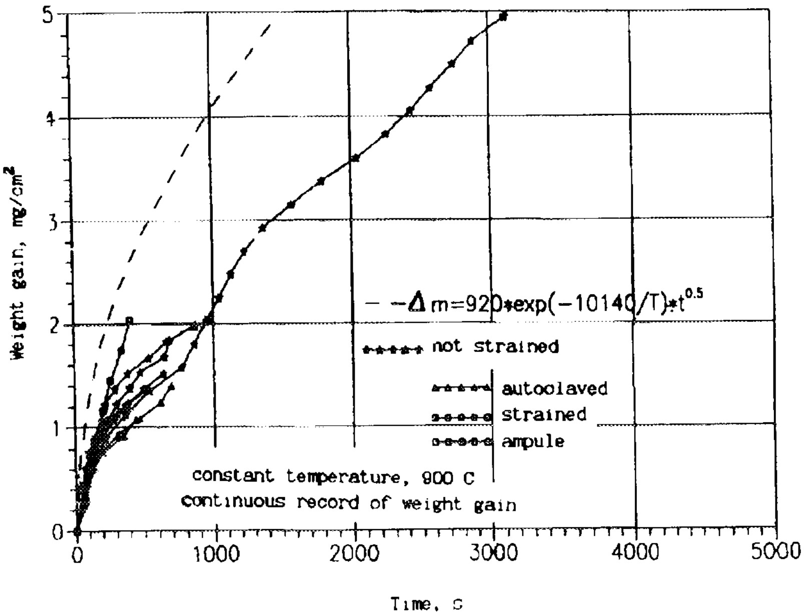


Weight gain of VVER-type claddings as oxidized in steam at athmospheric pressure

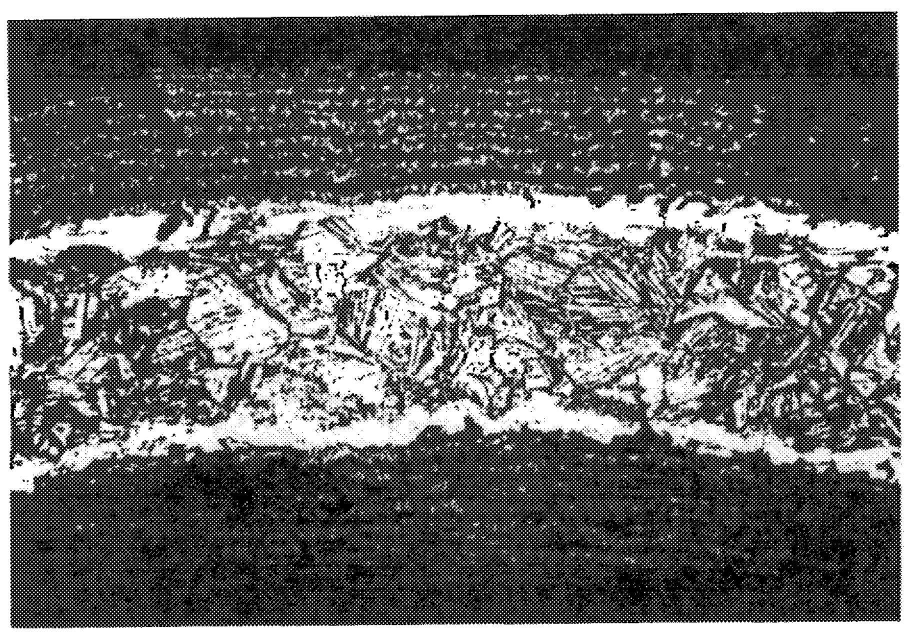
Weight gain of tubular samples 9.15×7.72 as oxidized in steam



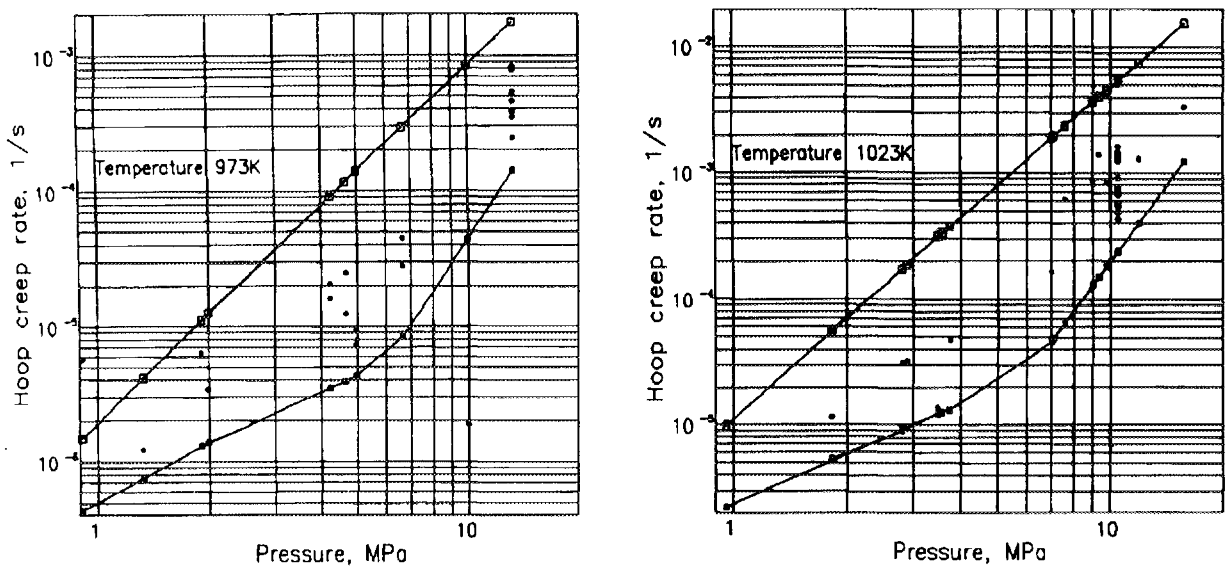
Weight gain of tubular samples 9.15×7.72 as oxidized in steam



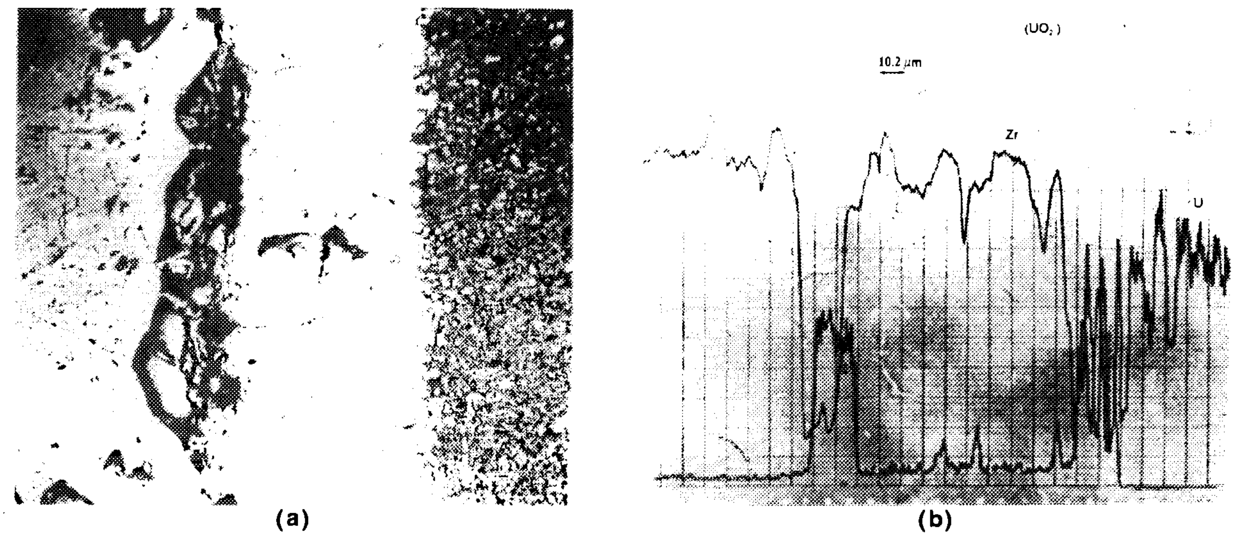
Microstructure of steam oxidized specimen



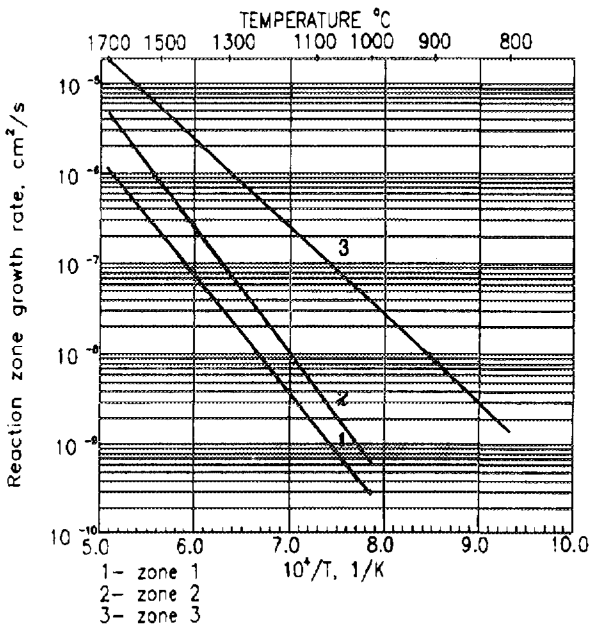
T=1000 °C, τ=8040 s



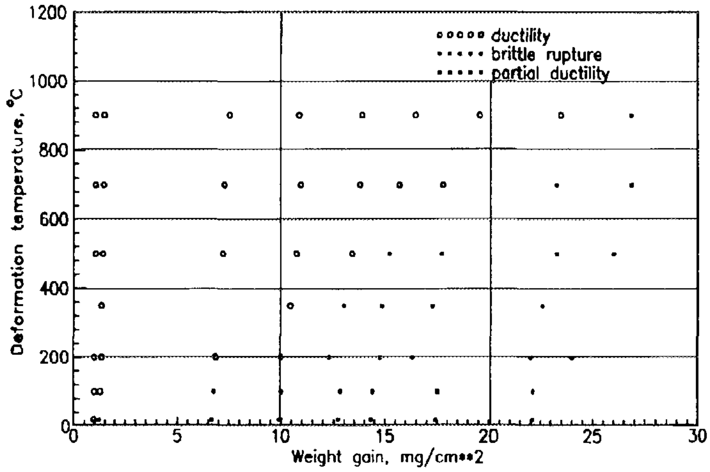
Dependence of creep rate on internal pressure (hot, undeformed clad):
• • • experimental data; □□□ calculated (1983); ■■■ calculated (1986).



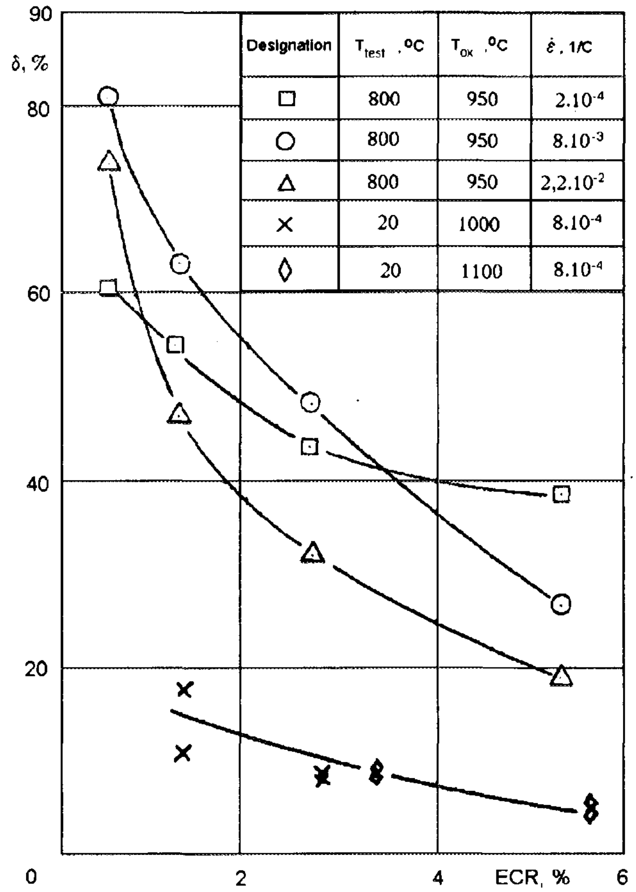
Reaction zone of Zr1%Nb / UO_2 couple (1500°C, 15 min, 300×) - (a); Zr and U contents (b).



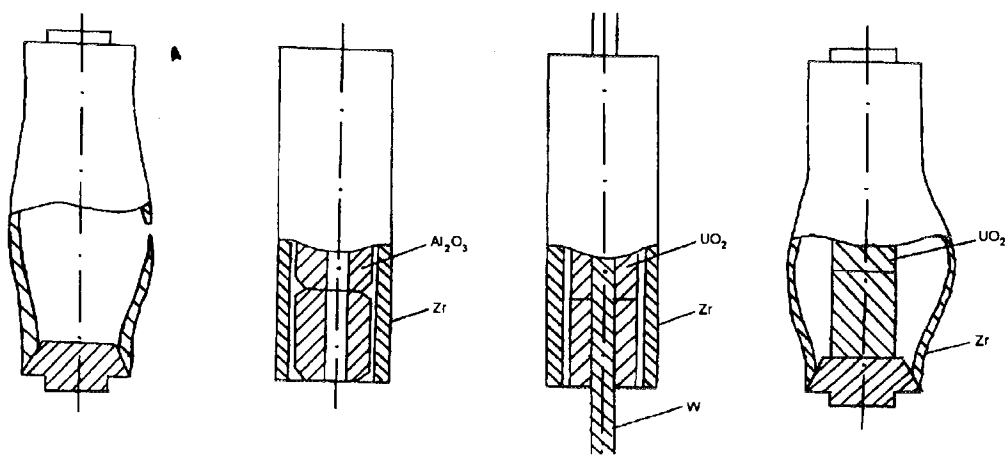
Reaction zone growth rates of Zr1%nb/UO_2 couple



Ductility of steam-reacted Zr1%Nb claddings. Ring compression results.



Per cent elongation in active tension of cylindrical microspecimens



Schematics of dummy fuel rods (see also Fig. 1 in the text).