Mechanical Properties of Zircaloy - NORA

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Summary

The high temperature deformation model NORA has been developed for use in the SSYST computer code. As this code is used to perform whole core LOCA analysis the deformation model should not be time consuming. The model is an empirical one but its parameters have a physical background.

The model development is based on a data bank containing numerous well-defined deformation data from stress-strain, tensile and tube burst tests.

NORA-model consists of two parts, the description of deformation and of failure. The deformation properties rely mainly on uniaxial stress-strain and creep tests and it is postulated that this model can be applied to describe tube deformation as well. The basic equation is a power law strain rate equation. It has been proved that this equation is able to model the deformation behaviour in the whole range of temperatures ($600 \leq T(C) \leq 1200$) considered here. Yet of greater importance is the modelling of the changes of material properties due to phase transition, oxidation and strain hardening which are described by the model parameters.

The failure model is based on isothermal furnace heated tube burst tests. It is demonstrated that the broad scattering of burst strain of tube tests reported elsewhere is not only due to an azimuthal temperature distribution, but also to a dependence on the strain rate of deformation. This dependence has been modelled in a modified strain fraction rule for failure. Deformation and failure are therefore connected by the strain rate.

In parallel to this modified strain fraction rule, a model based on the life fraction rule has been developed for alternative use.

The influence of oxidation on the deformation has been derived from the pseudobinary Zircaloy-oxygen phase diagram using a homologous temperature. This model has been developed for homogeneously distributed oxygen, but it can also be applied to layered material with an average oxygen content lower than 0.8 wt %. The model can also be applied to the failure model, but only for material with homogeneously distributed oxygen. Due to outer or inner oxidation of the tube the oxygen is usually inhomogeneously distributed. Therefore an empirical function for strain reduction of oxidized material

has been established for the failure criterion.

Applying NORA model to tube deformation the axial and azimuthal distribution of temperature plays a most important part. The azimuthal temperature distribution reduces the circumferential strain. For this case NORA model has to be applied locally. The axial temperature distribution has an influence on the axial shape of ballooning. The shape modifies the tangential to axial stress ratio at higher strains.

As the temperature is the most sensitive parameter for deformation, differences between calculated and measured strain of tube burst tests are often caused by an unknown temperature distribution.

Releated references:

M. Boček
Creep Rupture at Monotonous Stress and Temperature Ramp Loading
I. Calculations
II. Application to Zircaloy
Journal of Nuclear Materials 82 (1979) 329-346

R. Meyder, W. Sengpiel
Probabilistic Analysis of PWR Fuel Rod Behaviour During a LOCA
Using the Response Surface Method
The European Nuclear Conference, Hamburg, May 6-11, 1979

S. Raff
Development of a Zry Deformation Model to Describe the Zry-4
Cladding Tube during Accidents
ENS/ANS International Topi al Meeting on Nuclear Power Reactor
Safety, Brussels, October 16-19, 1978

$$\dot{\varepsilon}_{pl} = \dot{\varepsilon}_R \left[\frac{\sigma - \sigma_S}{\sigma_R(T, O_2)} \right]^{n(T, O_2)}$$

$\sigma_S = f(T, \varepsilon, \dot{\varepsilon}, O_2)$ strain hardening

- data deduced from 1D tensile and creep tests in vacuum and air

- statistics

  maximum, expected value, minimum } for $\dot{\varepsilon}_{pl}$

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Deformation Model NORA Status September 79

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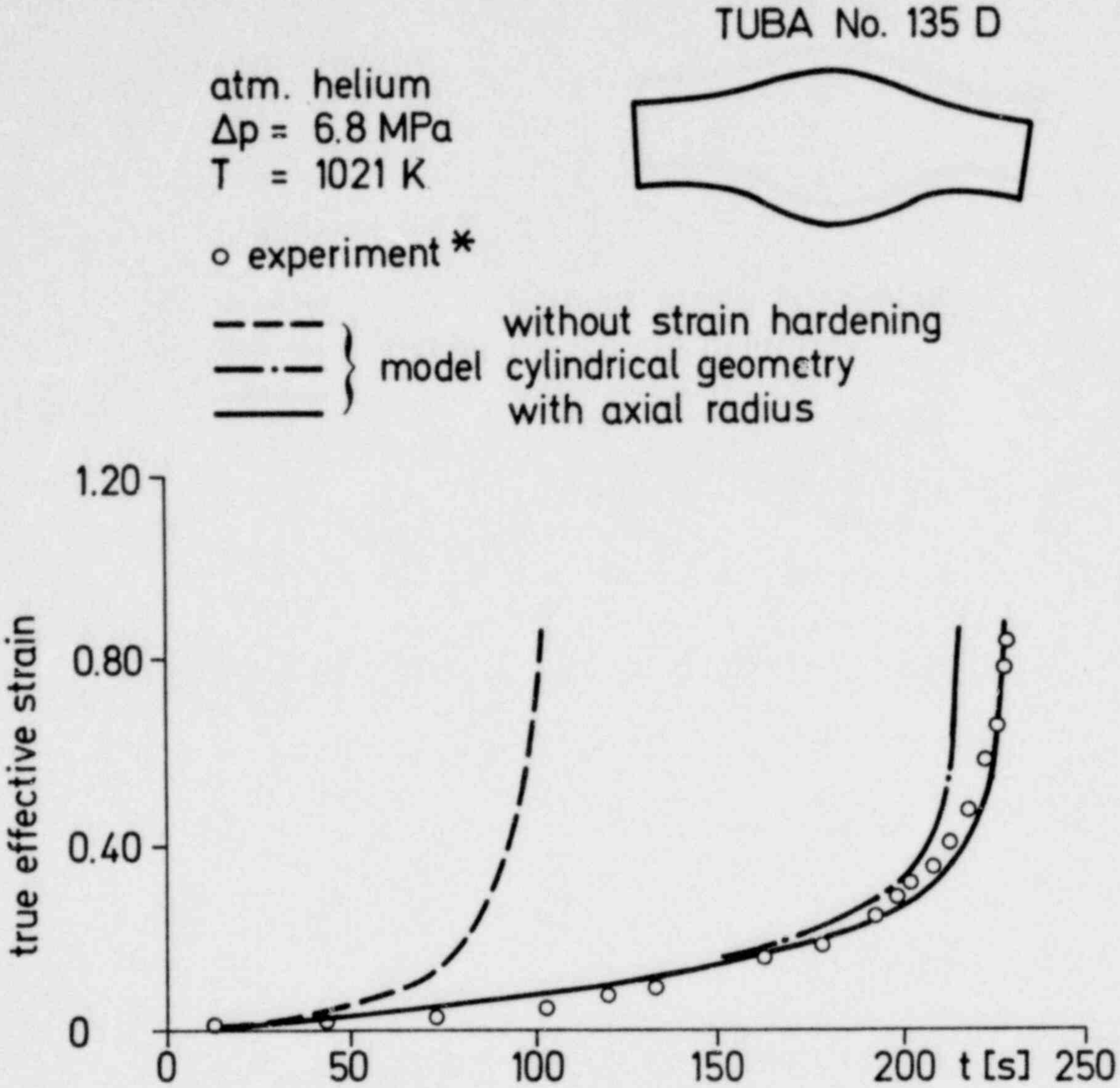

* P. Hofmann, KfK

Tube Burst Test in Inert Atmosphere

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HOMOLOGOUS TEMPERATURE T_H

$$T_H = \begin{cases} T/T_\alpha & \text{for } T \leq T_\alpha \\ \dfrac{T-T_\alpha}{T_\beta - T_\alpha} & \text{for } T_\alpha < T < T_\beta \\ T/T_\beta & \text{for } T \geq T_\beta \end{cases}$$

POSTULATE:

EQUAL T_H FOR EQUAL DEFORMATION PROPERTIES

E.G.

$$T_H = \frac{T}{T_\alpha (O_2)} = \frac{T_e}{T_\alpha (O_2=0)} = \text{CONSTANT}$$

$$T_e = T_\alpha (O_2=0) \cdot T_H$$ = EFFECTIVE TEMP. USED IN NORA

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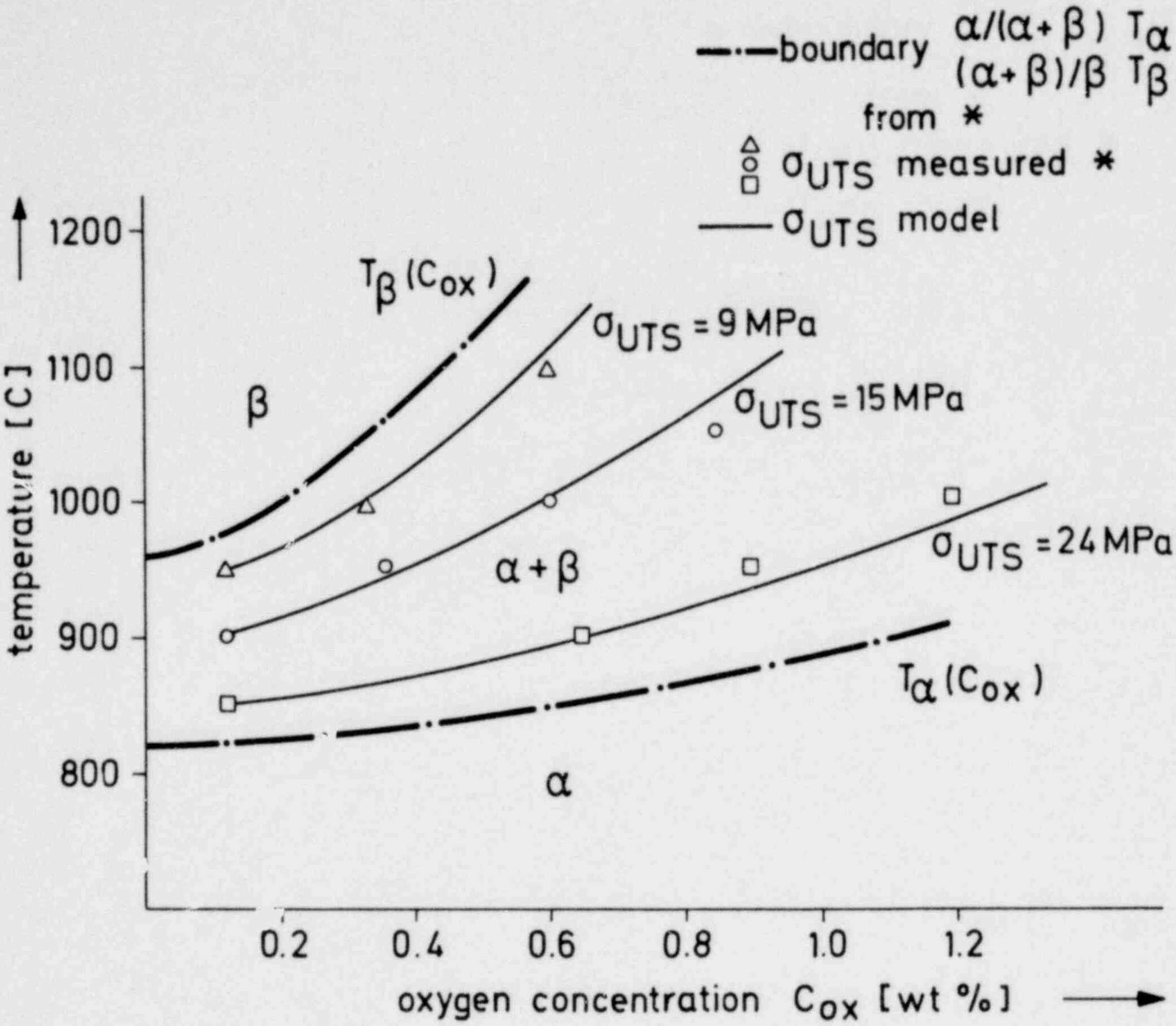
Model for Oxygen



* Garde et al., ANL

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Pseudobinary Zry-Oxygen Phase Diagram with Curves of Equal Ultimate Tensile Strength (UTS)

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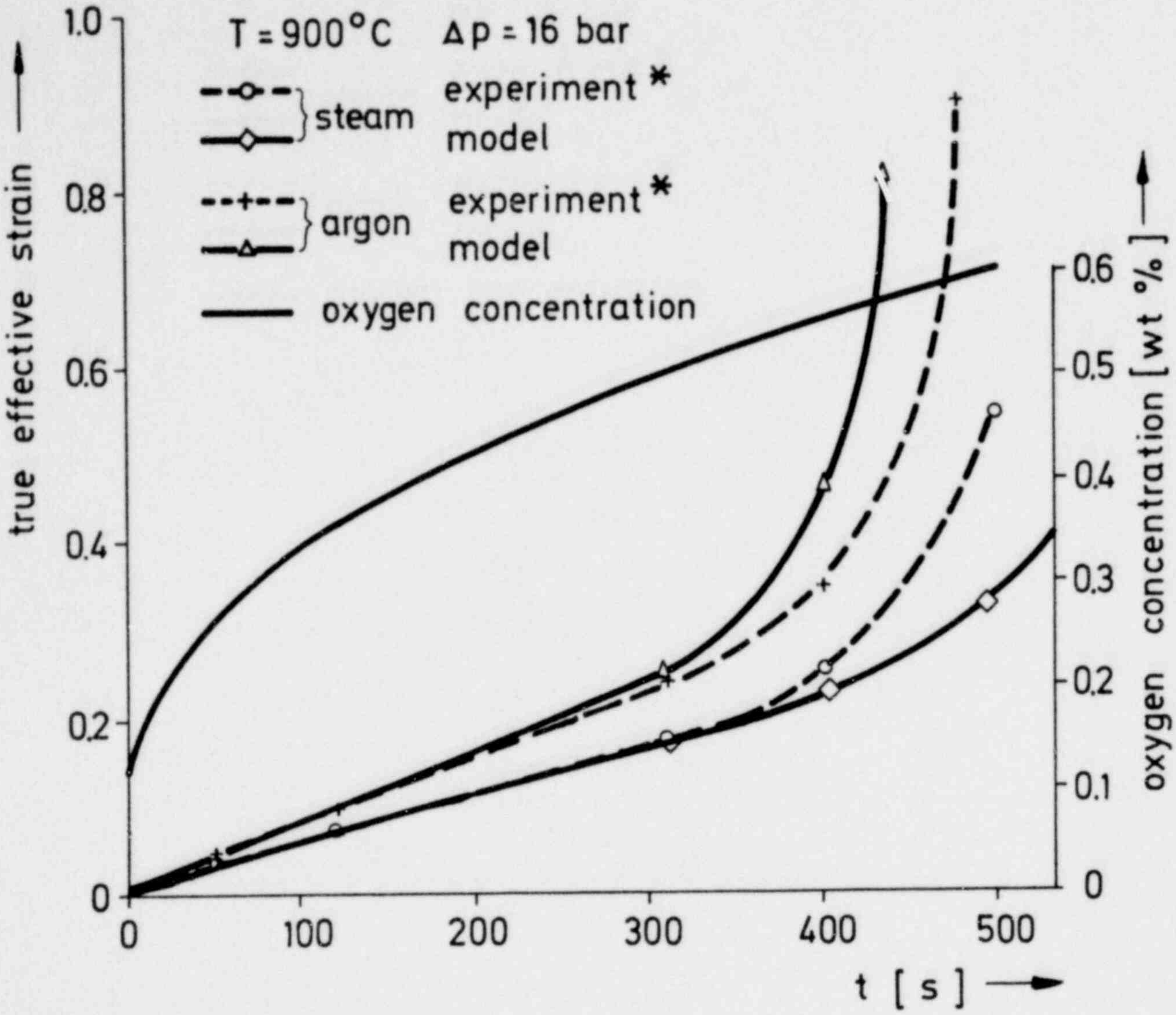

* S. Leistikow, KfK

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Tube Burst Tests in Argon and Steam

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$$FFR = \int_{\tau=0}^{t} \frac{\dot{\varepsilon}(\tau)^{K(T)}}{FF[T(\tau), O_2]} d\tau$$ relative failure function

$$FF(T, O_2) = \int_{\tau=0}^{t_B} \dot{\varepsilon}(\tau)^{K(T)} f(T, O_2)\, d\tau$$ failure function

$$FFR \begin{cases} < 1 & \text{no rupture} \\ = 1 & \text{rupture} \end{cases}$$

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Failure criterion
(modified strain fraction rule)

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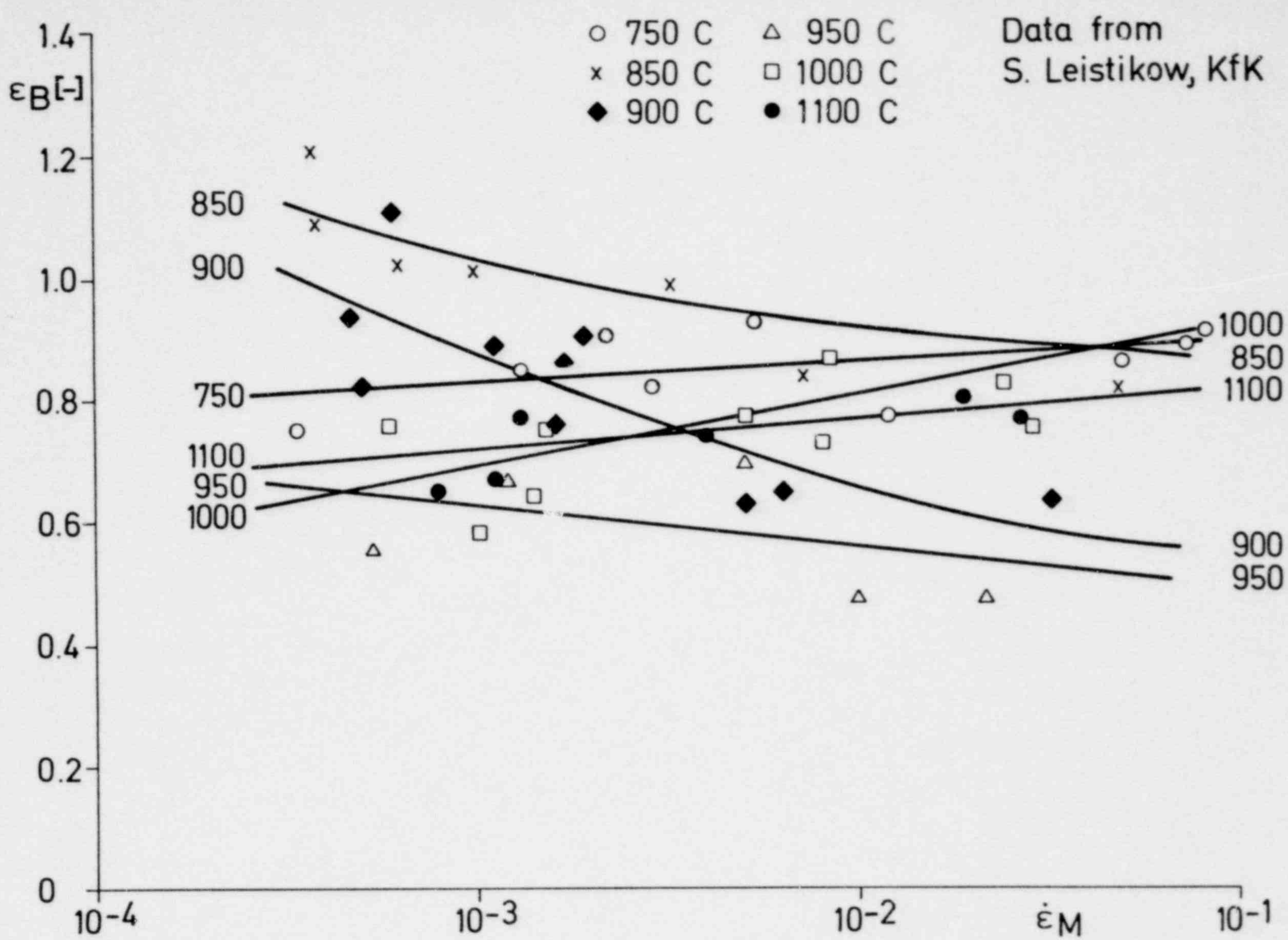

burst strain for Zry-4 stove heated capsules, inert

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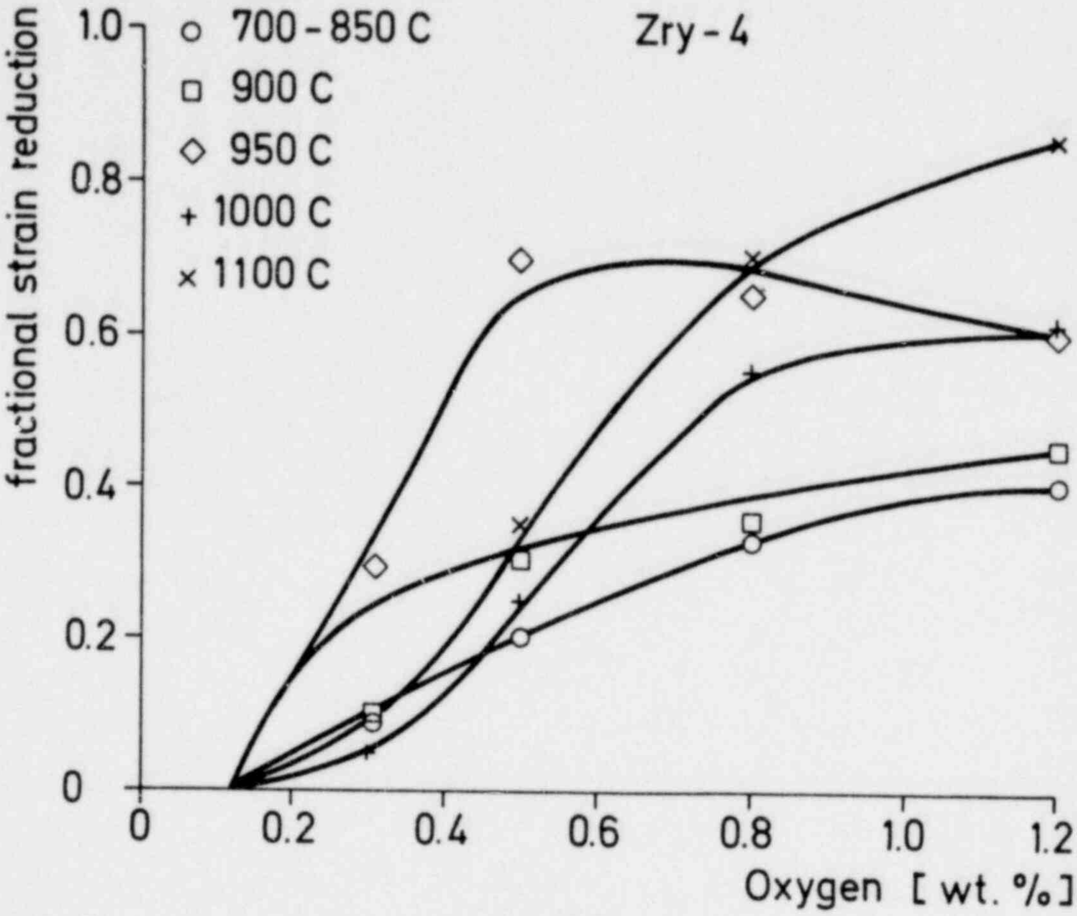

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re!ative strain reduction due to steam oxidation for composite material

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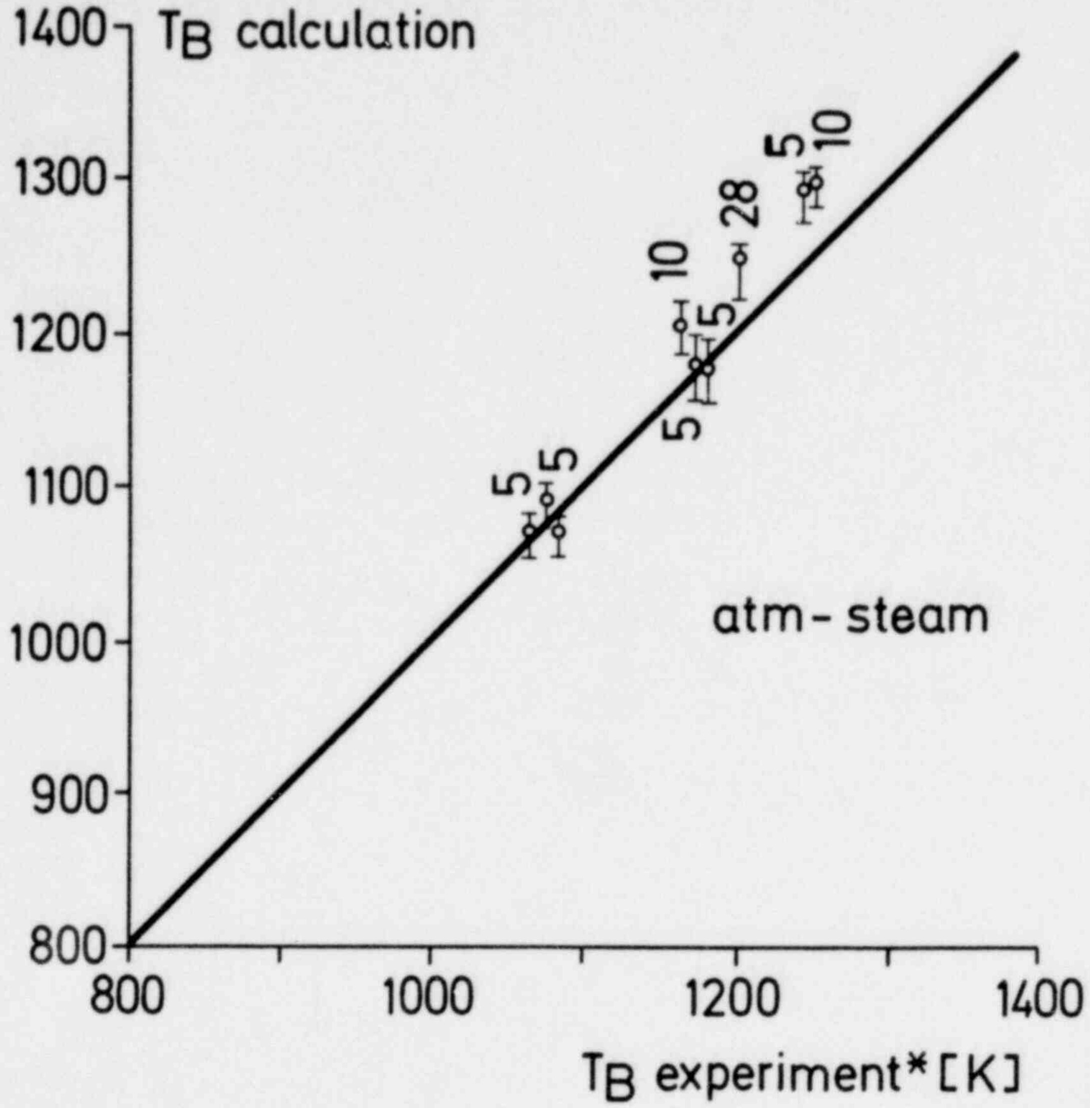

* S. Leistikow, KfK

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Temperature Ramp Burst Tests in Steam
Δp constant

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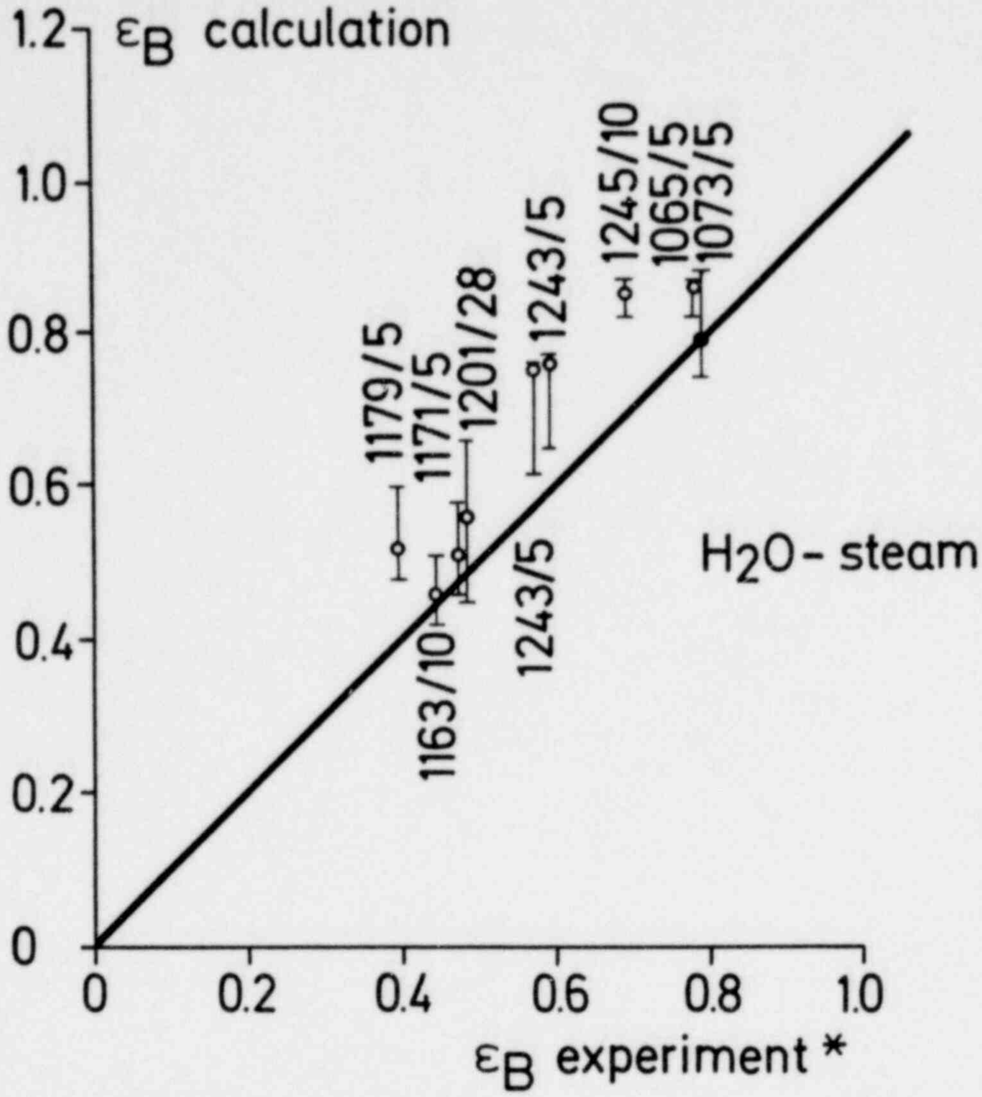

* S. Leistikow, KfK

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Temperature Ramp Burst Tests in Steam Δp constant

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