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Analysis of fuel rod behaviour under LOCA using the STAV-T fuel performance code

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ABSTRACT:
This paper shortly presents the methodology and models applied in the ABB Atom STAV-T fuel performance code for analysis of LWR fuel rod behavior under loss-of-coolant accidents. The code's applicability to predict fuel rod high temperature failure is illustrated by comparisons with exprimental data.

1 INTRODUCTION

The growing concern about loss-of-coolant accidents in the large-size light water reactor power plants that emerged in the sixties resulted in the US NRC acceptance criteria for emergency core cooling systems, defined in appendix K to the US Code of Federal Regulations, 10CFR50. These criteria, which have been adopted worldwide, did not only comprise limits on allowable local and global core damage under a LOCA, but also requirements on the evaluation models applied in predictive analyses.

The outlined methodology was focused mainly on large-break LOCA, and the analyses were to be made in a conservative manner in order to compensate for uncertainties about the physical processes involved. Since the early seventies, our knowledge about LOCA-related issues has gradually improved, and realistic phenomenological models have been formulated and verified with results from numerous research programmes.

Realistic best-estimate models are today replacing the conservative appendix K evaluation methods, leading us to better understanding of what actually occures in a nuclear power plant during various forms of power-coolant mismatch transients. However, the development of realistic best-estimate methods have been focused mainly on thermal hydraulics modelling, whereas the thermal and mechanical behaviour of fuel rods under LOCA has received less attention.

In the present paper, the introduction of physically based best-estimate models for analysis of fuel rod thermal-mechanical behaviour under loss-of-coolant events in the STAV-T fuel performance code is briefly described. Section 2 contains an overview of the STAV-T program, whereas important models used for clad high temperature degradation and failure are presented in section 3. The code's capability to predict clad high temperature rupture is finally illustrated in section 4.

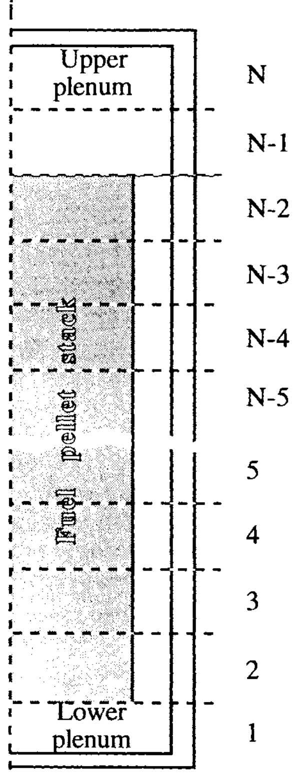
2 THE STAV-T FUEL PERFORMANCE PROGRAM

Analysis of LWR fuel rod behaviour under a postulated LOCA requires modelling of several transient and interacting phenomena, such as heat conduction in the fuel, heat transfer to the coolant, fission gas release, gas axial transport within the rod, extensive cladding deformation and cladding oxidation.

STAV-T is a 2D fuel rod analysis program, in which the coupled heat transfer and mechanical response of a LWR fuel rod is calculated within a finite element computational framework [*Massih et al 1993*]. The program is intended for analysis of fuel rod behaviour under transient and off-normal operational conditions, eg loss-of-coolant accidents.

Analyses can be performed in either an axisymmetric model of the entire fuel rod, or in a plane model of any cross section along the rod; figure 1. A combined analysis in both geometries is usually applied, in which the global fuel rod behaviour is first evaluated in the axisymmetric geometry, followed by a more detailed analysis of the peak power axial position in the plane model geometry.

Since the plane model need not be axisymmetric, the influence of fuel rod asymmetries or non-uniform cooling can be considered in the analysis. As illustrated in figure 2, the localized deformation leading to clad ballooning usually originates from such asymmetric effects.

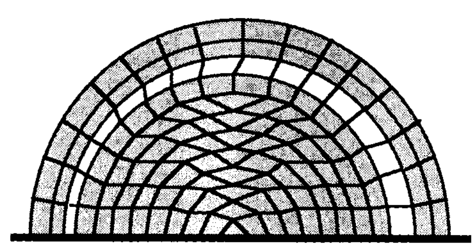


Fuel rod axisymmetric geometry

Fig 1. An axisymmetric model of the fuel rod is first used in the analysis, followed by a detailed modelling of the fuel rod peak power region in the plane geometry.

In the axisymmetric geometry, the rod is divided in N axial segments, with a maximum of N = 600. Each segment is assigned material properties and loads individually.

The plane model geometry need not be axisymmetric. Pellet-clad eccentricity, clad ovality and non-uniform cooling can thereby be considered in the analysis.


Plane cross-sectional geometry

A fundamental element in predicting the fuel rod behaviour under a LOCA is to accurately model the removal of stored energy and generated decay heat from the fuel to the coolant. The thermal analysis is performed in a finite element model of the deformed fuel rod geometry, where the time varying coolant conditions and the clad-to-coolant heat transfer coefficients are supplied from a separate thermal-hydraulic analysis. The pellet-clad gap heat transfer is evaluated by a phenomenological model, [*Forsberg & Massih 1988*], in which the influence of pellet-clad eccentricity is accounted for.

Both the pellet-clad and the clad-to-coolant heat transfer is largely affected by the fuel rod deformations, which must therefore be evaluated in tandem with the thermal analysis. An updated Lagrangian kinematical description of large deformations is used in the finite element mechanical analysis [*Bathe 1982*], since large cladding strains are expected in connection to clad rupture.

The fuel rod internal gas pressure is dependent on both the temperature distribution and the cladding deformation, and must therefore be evaluated together with the thermal and mechanical analyses. Fission gas release is calculated by a physically based model, in which a number of processes in the fuel are considered.

Axial gradients in both the gas pressure and composition due to the obstructive internal flow channel geometry are treated in a quasi one-dimensional finite volume model of the fuel rod. The conservation laws for mass and momentum in the multicomponent gas are solved by an implicit staggered mesh donnor cell technique, in which also isobaric gas mixing owing to multicomponent diffusion is considered.

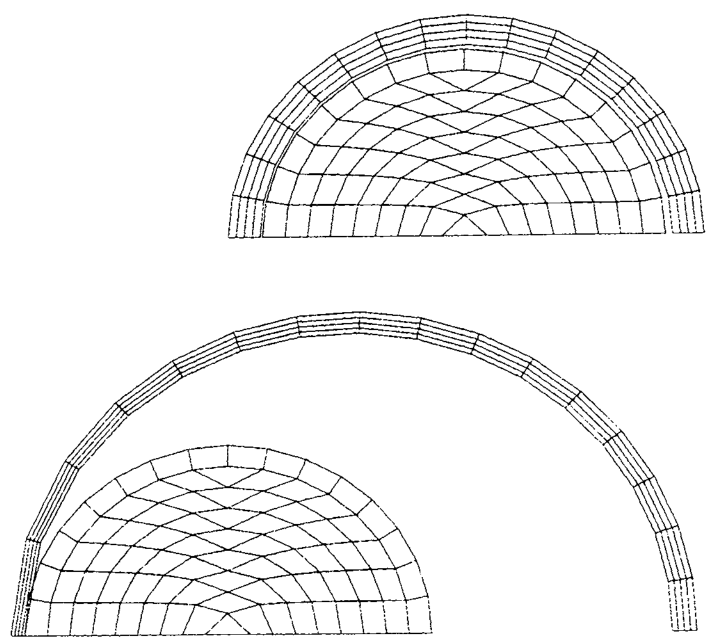


Fig 2. A PWR fuel rod cross section prior to and after a severe LOCA event. The asymmetric deformation is due to pellet-clad eccentricity, which leads to a localization of creep deformation to the warmer side of the cladding tube.

3 ZIRCALOY CLADDING HIGH TEMPERATURE DEGRADATION

At high temperature, the zircaloy cladding exhibits rapid oxidation and creep deformation. Modelling of these processes, which may ultimately lead to clad rupture, is crucial in the analysis of fuel rod behaviour under LOCA. Any attempt to model the clad high temperature behaviour is significantly complicated by the abrupt change in zircaloy thermal and mechanical properties at the α to β structural phase transition from a hexagonal closed packed to a body centered cubic lattice, and also by the strong interaction between clad oxidation, deformation and temperature:

- The oxidation kinetics is dependent mainly on temperature, but also on the rate of deformation through nucleation of cracks in the oxide layer.
- The rate of deformation is determined by temperature and mechanical loads, but is also influenced by the oxide layer thickness, especially in the β-phase region.
- The clad temperature is influenced by the exothermal oxidation, but also by the clad deformation, which leads to altered cooling conditions.

Separate but mutually interacting models have been formulated for clad oxiadation, creep and failure in the STAV-T program. They are briefly described in the following.

3.1 Cladding high temperature oxidation

High temperature oxidation of zircaloy in steam produces a material with a three-layer structure; an outer layer of partially cracked oxide, an intermediate layer of retained and oxygen stabilized α-phase, and the underlying bulk of β-phase zircaloy. The outer two layers are strong and brittle and have a pronounced strengthening effect on the bulk of soft zircaloy β-phase material.

The growth of the oxide and retained α-phase layer is calculated through:

$$\frac{\partial x_i}{\partial t} = \frac{A_i}{x_i} e^{-Q_i/RT} \tag{3-1}$$

where x_i is the oxide or retained α-layer thickness, T is the clad outer temperature and A_i and Q_i are temperature dependent parameters, tuned to experimental results, [*Biederman 1978, Leistikow 1987*]. Due to cracking, only part of the oxide layer is assumed to be load-bearing. The fraction of oxide assumed uncracked is dependent on the oxide layer thickness and the current rate of deformation.

3.2 Cladding high temperature creep

The high temperature creep behaviour of zircaloy is governed by the volume fractions of α- and β-phase material, which in the STAV-T program are calculated through a viscous model. In the single phase regions, the creep strains ε^c_α and ε^c_β are expressed as:

$$\begin{aligned} \varepsilon^c_\alpha(t) &= \varepsilon^p_\alpha\left(1-e^{-t/\tau}\right) + \dot{\varepsilon}^s_\alpha t \\ \varepsilon^c_\beta(t) &= \dot{\varepsilon}^s_\beta t \end{aligned} \tag{3-2}$$

where the parameters ε^p_α, $\dot{\varepsilon}^s_\alpha$, $\dot{\varepsilon}^s_\beta$ and τ are dependent on temperature and applied stress.

In the mixed phase region, the creep is considered to be governed by α- and β-phase secondary creep acting in parallel, and a contribution from phase boundary sliding, acting in series with the secondary creep rate:

$$\varepsilon^c_{\alpha\beta}(t) \quad = \quad \dot{\varepsilon}^s_{\alpha\beta} t \quad + \quad \dot{\varepsilon}^b_{\alpha\beta} t \tag{3-3}$$

The mixed phase secondary creep rate $\dot{\varepsilon}^s_{\alpha\beta}$ in (3-3) is calculated from the single phase secondary creep rates in (3-2) by assuming that the two phases have the same strain rate. The stress is thereby redistributed, so that the stronger phase takes the larger share of the applied load.

3.3 Cladding high temperature rupture

High temperature cladding rupture is predicted by a burst stress criterion, in which clad failure is assumed as soon as the local hoop stress reaches a critical burst stress. The burst stress, σ_B, which is dependent on temperature *T* and clad oxygen content *Ox*, can be written as:

$$\sigma_B \quad = \quad Max\left[\ \sigma_{B\min}, a\exp\left(-bT - c\left(Ox - 1.2\cdot 10^{-3}\right)^d\right)\ \right] \tag{3-4}$$

where *a, b, c, d* are positive parameters that vary widely with temperature in the α-to-β phase transition temperature region. σ_{Bmin} is the minimum stress required for clad rupture in steam environment, which has been determined to 4.5 MPa, [*Leistikow & Schanz 1987*].

4 VALIDATION OF THE CLAD HIGH TEMPERATURE RUPTURE MODEL

Data from several different experimental studies have been used for verification of the STAV-T code in fuel rod analysis under LOCA conditions. The experimental data base covers burst tests performed with both unirradiated and irradiated Zr-4 cladding materials, and it also comprises materials from several different vendors. The test conditions in these experiments are summarized in table 4.1.

Table 4.1 Summary of experimental conditions

Experiment:	Material:	Heating:	Heating rate:
Leistikow & Schanz	Unirradiated Zr-4	Induction	5 K/s
Markiewicz & Erbacher	Unirradiated Zr-4	Internal+Shroud	1 K/s
Karb et al	Irradiated Zr-4	Internal	6-20 K/s
Chapman et al	Unirradiated Zr-4	Internal	20-30 K/s

The STAV-T program was used to simulate these burst tests. Comparisons of calculated clad deformation and time to rupture with the experimental data were made. The result is depicted in figure 3. As can be seen from the figure, the time to cladding failure is fairly well predicted for all the data sets, whereas the predicted burst strain showed somewhat higher deviations from the experimental results. It should be noticed, however, that the measured failure strain exhibited strong variability also under identical test conditions.

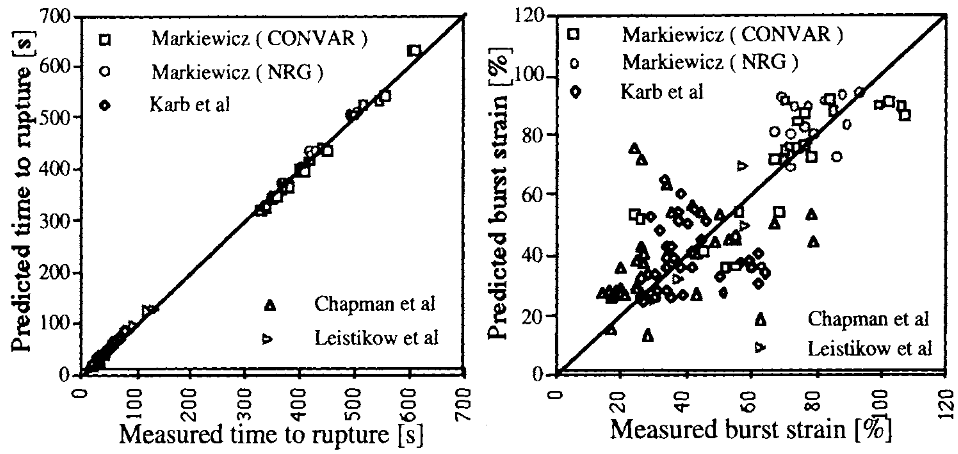


Fig 3. Calculated time to clad rupture and clad hoop strain at rupture compared with experimental results for various Zr-4 clad materials and test conditions.

5 CONCLUSIONS

The presented physically based models for zircaloy high temperature oxidation, creep and rupture have been implemented in the ABB Atom STAV-T transient fuel performance code and validated with respect to numerous experimental data. The code's ability to predict cladding high temperature rupture is satisfactory.

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