SIMPLIFIED THERMAL CREEP MODEL OF AN IRRADIATED FUEL PIN

Maurice DALLONGEVILLE, Cédric LANGLADE, Aravinda ZEACHANDIRIN
TN International (AREVA), France

ABSTRACT

TN International started recently a study of irradiated fuel claddings thermal creep in routine transport conditions to evaluate creep rupture risk of LWR fuel.

Fuel cladding thermal creep consists in local swelling of cladding parts submitted to internal pressure and high temperature. Cladding rupture occurs when a critical strain is reached. Creep rate is influenced by a combination of several parameters: temperature profile, stress level, irradiation and oxidation profiles. The study is focused on the hottest fuel pin during transport.

An axis-symmetrical finite elements modelling of a fuel pin is generally used with different temperature profiles, temperature evolutions, irradiation profiles and internal pressures. Thermal creep behaviour, described in creep laws, includes irradiation defects hardening recoveries with temperature. Claddings rupture criteria are based on a critical strain depending on irradiation damage and stress. The used creep laws and criteria have been developed by CEA R&D laboratories.

Analytical calculations are not possible because of creep behaviour non-linearity and large number of input parameters. Finite Elements Analysis (FEA) is very time-consuming and not flexible in practice. Therefore, TN International has developed a simplified FORTRAN calculation model.

The simplified modelling has the same input parameters as the FEA one. Cladding mesh has one element in thickness in order to calculate average stress. Axial mesh refinement is chosen to give good description of axial profiles of temperature and irradiation. Internal pressure is determined by thermodynamics balance. Creep laws and rupture criteria implementations permit to switch from one law to another one easily. Similarly to the FEA modelling, the rupture criterion consists in comparing at each integration point the local creep strain to the local limit strain. These calculations last only a few seconds versus several hours or days for FEA calculations.

This simplified modelling is under validation by comparison with FEA results. It should permit to make reliable calculations of rupture risk by thermal creep with large time and means benefits. With appropriate creep laws and rupture criteria, this method can be applied to closed casks vacuum drying, half-hour fire, routine transport lasting from a week to a year and interim storage.

INTRODUCTION

TN International (TNI) started recently a study of irradiated fuel claddings thermal creep in routine transport conditions to evaluate creep rupture risk of LWR fuel.

Fuel cladding thermal creep consists in progressive local swelling (Figure 1) of cladding parts submitted to high temperature and internal pressure of filling and fission gas. This swelling produces a decrease of the cladding thickness because of its circumferential stretching and potentially leads to a rupture with gas and fissile material release.

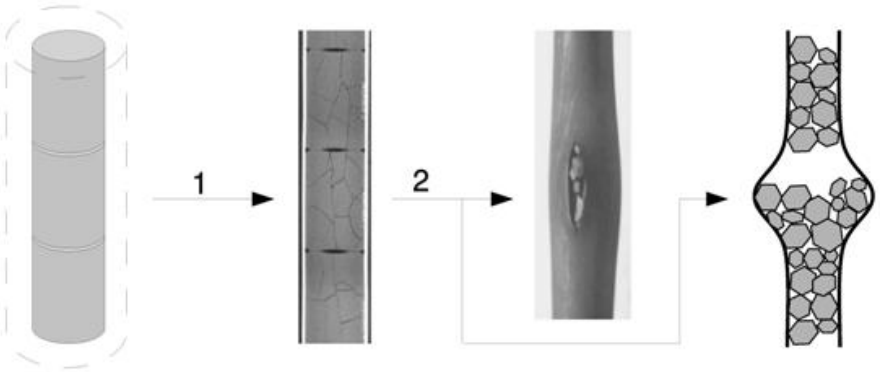

Figure 1: Creep deformation and rupture of irradiated fuel pins [1]

Analytical calculations are not possible because of creep behaviour non-linearity and large number of input parameters. In the early stages, TNI studied fuel cladding creep using finite elements analysis (FEA). This method was very time and cost-consuming, and not flexible in practice as it requires additional programming. Therefore, TNI has developed a simplified FORTRAN calculation model, which is described here.

PHYSICAL PHENOMENA

Generalities

In typical transport conditions, maximum fuel cladding temperature is reached at the centre of the fuel assembly located in one of the central lodgements of the cask basket. Indeed, basket wall temperatures are higher for central lodgements than for peripheral lodgements. The hottest fuel cladding can reach temperatures between 400 and 500 °C in transport conditions.

Creep rate is influenced by a combination of several parameters: temperature profile and evolution, stress level (from internal gas pressure), irradiation and oxidation profiles. In particular, the combination of the axial thermal profile features (maximum value and sharpness of the peak corresponding zone) and of the axial irradiation profile have a significant influence on the maximum radial cladding deformation obtained in relation to time and on its axial location. The cladding rupture occurs when a critical strain is locally reached.

The calculation of the cladding deformation, focused on the hottest fuel pin during transport, and the checking of its integrity on the concerned temperature and stress domains requires the knowledge of:

- A creep law validated for the material.
- A non-rupture criterion (based on a material rupture limit) that guarantees the cladding mechanical creep strength.

Parameters

The main parameters to consider as calculation hypotheses for irradiated claddings thermal creep study are presented here for a used PWR fuel pin.

- Geometry:

The geometry of a complete fuel pin is considered at 20 °C and 1 bar pressure.

- Mechanical characteristics:

Thermal and mechanical properties of Zircaloy cladding and fuel pellets are used. Fuel pellets are not explicitly modelled but they are taken into account in the free volume calculation.

The various possible zirconium-based cladding materials with associated composition, cold working and heat treatment, and consequently different in-reactor damage, lead to different thermal creep laws (and sometimes rupture criteria) that require to be dealt with separately.

- Displacement conditions:

The considered model is axis-symmetrical and the nodes situated on the revolution axis of cladding tube have nil radial displacements due to the axis-symmetry condition. One node of the lower plug is fixed.

- Temperature profiles:

Temperature axial profiles representative of 4 cycles irradiated fuel are imposed along the cladding, whose transversal sections are homogeneous in temperature during transport. These temperature profiles are crenels that are smoothed at their angles to simulate axial thermal conduction effects and to avoid creation of unrealistic local mechanical stresses.

Evolution of the temperature profiles for a given initial maximum cladding temperature is considered at 0, 4, 8 and 12 months, and permits to describe the fuel cooling in the cask. A linear interpolation of these temperature profiles is carried out for intermediate times.

- Fluence profile:

Fluence axial profiles permit to initialise the creep law irradiation variable in the model.

- Corrosion profile:

The consideration of axial profiles of claddings maximum outer corrosion permits to initialise the resistant cladding thickness in the model. The development of cladding outer oxidation during transport or storage is not considered because it is supposed that fuel assemblies are loaded in neutral atmosphere in the cask.

- Internal pressure at 20 °C :

The gas pressure is imposed on the inner side of the cladding tube and initialised at the standard absolute value at 20 °C or at higher value (study of the initial pressure influence) according to the calculation case. The pressure field stays perpendicular to the deformed mesh during time. Absolute pressure is updated at each calculation step taking into account the absolute temperatures and the associated local free volumes by the ideal gas equation.

The gas mole number is considered constant and no additional gas release is taken into account in the calculation of the thermodynamic balance.

<u>Thermal creep laws</u>

The thermal creep laws of irradiated Zircaloy claddings describe the deformation velocity $\nu^*(\sigma^*, T, \psi, \varepsilon^*)$ in relation to:

- loadings at time t:
    - stresses via the equivalent stress σ^*;
    - absolute temperature T.

- two internal variables rendering the material history:
    - the plastic equivalent deformation ε^*, which renders the isotropic cold-work hardening linked to the deformation;
    - the variable ψ, which renders the irradiation hardening linked to the density of irradiation defects.

The general form of the (secondary) creep term of the law is similar to the ones mentioned in [2], [3] and [4].

At the loading beginning, the equivalent deformation ε^* is nil and the irradiation hardening variable ψ is equal to the final cladding in-reactor irradiation fluence profile ϕ_t (z), where z is the axial position, or to a corresponding constant.

Creep rupture criterion

The limit elongation of irradiated Zircaloy claddings is generally established in relation to stress and irradiation variables:

$$\varepsilon^* \leq \frac{1}{2m}\exp(-a.(F(\psi))^b), \text{ with } m = m_0 \frac{\sigma^* / \sigma_C}{th(\sigma^* / \sigma_C)}.$$

ε^* and σ^* are the same as in the creep law, and σ_c is a threshold stress depending on the temperature and on the irradiation hardening.

This criterion is a generalization of a similar formulation [4] for high-tin Zircaloy 4 in which $F(\psi) = \phi_t$. The coefficients of limit equivalent deformation for high-tin Zircaloy 4 are also given in [4]. It should normally be used with circumferential stress and strain but, in fact, using equivalent values is simpler and is slightly more conservative.

The criterion used in creep calculations permits to determine the duration until cladding creep rupture. However, included in cases of cladding rupture, the calculations are generally carried out for one year to obtain the theoretical maximum elongation upon this period.

The limit equivalent deformation is calculated from the criterion formula and from the cladding stresses and irradiation variables obtained by the mechanical calculation. It is compared to the cumulated creep deformation at each time-step for all integration points along the cladding. The corresponding differences are margins that should stay negative to avoid a cladding rupture risk.

The non-rupture criterion can be checked for local parameters, or more conservatively, for semi-local parameters (envelope on whole cladding), or even more conservatively, for global values (envelope on whole cladding and plugs).

FORTRAN MODEL

Thermal creep calculations by FEA are usually carried out with a Finite Element code completed by an additional programming of data, laws and criteria generally written in code-specific and / or FORTRAN language. Because of the non-linearity of creep laws, FEA are time and cost-consuming.

The necessity to have a simpler model to check FEA results, and also, to produce results on other cases with close configurations has led TNI to explore the possibility of a simplified calculation program, which would nevertheless includes many interactions between the various parameters effects.

Therefore, TNI is currently developing a simplified creep model with similar functional calculation capacity to FEA codes, and including the axis-symmetrical mechanical calculation of claddings thermal creep and the associated additional programming. This calculation model is aimed to be quicker than FEA codes and to have a good precision.

Calculation principles

The modelling takes into account main phenomena, parameters, and their interaction. It has exactly the same input parameters values and precision level than the FEA model. The main calculation principles applied to develop this simplified model are:

- **Preliminary filtering of the initialisation profiles**:

The input profiles are given by linear segments and the associated axial positions are used to produce the minimum effective meshing generation. A preliminary work carried out on the data profiles permits to simplify them to eliminate un-necessary intermediate points and to manage the very close points (merging of points is done if distance differs from less than a minimum gap).

- **Meshing generation:**

The selected nodes coming from the geometry and various « filtered » profiles are used and completed by intermediate nodes created on the basis of a maximum mesh element length.

Axial mesh refinement is chosen to give good description of temperature and irradiation axial profiles. Cladding mesh has one element in thickness in order to stay simple and calculate average stress.

- **Overall calculation on a whole fuel pin (Figure 2):**

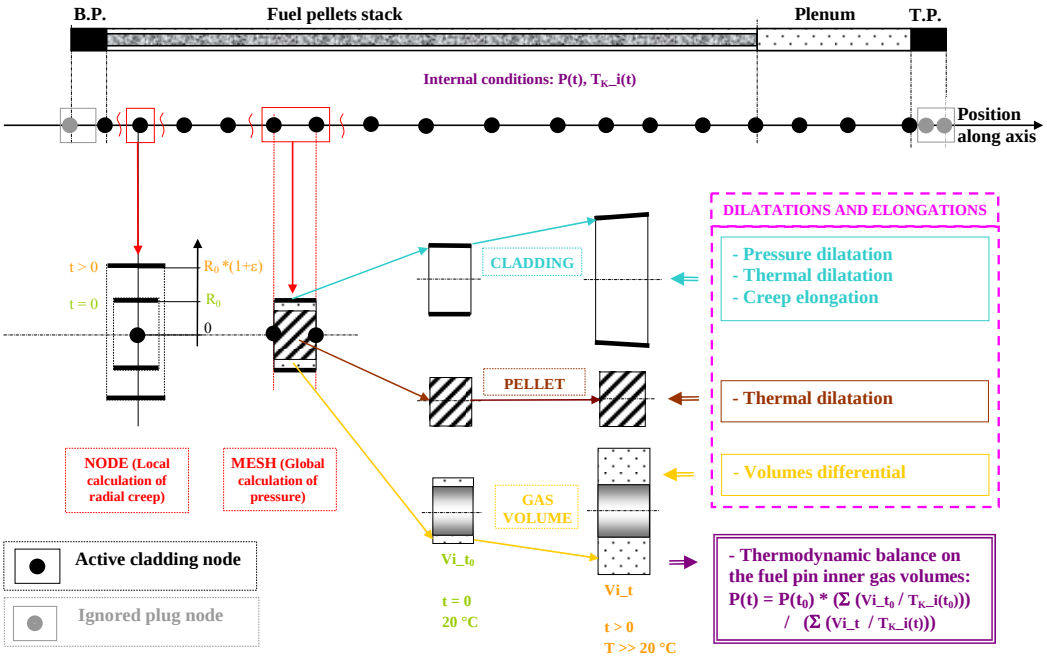

Figure 2: Overall calculation of a fuel pin

Parallel creep calculations at cladding nodes permit to determine the deformations and the volumes in deformed geometry, and then, to update internal pressure by integration of the gas state equation for a constant number of gas moles (as in the additional coding in FEA). The local free volumes are

calculated by subtracting the expanded cladding internal volume and fuel pellets external volume on each mesh, and they are updated at all iterations.

- **Iterative resolution:**

The numerical scheme used (an iterative parabolic time integration method for functions of several parameters) permits to obtain a very good consistency with the time evolution of the various calculated parameters and with the use of a variable time-step. This later one produces a significant improvement of the calculation velocity as soon as the increase is a few percents high from time-step to time-step.

All cross-depending functions are developed versus time, which is simpler to calculate and consistent, and the simultaneous convergence process with integration of the parabolic time derivatives of functions guarantee a very good consideration of the mutual interactions of functions and of their actual time evolutions. Moderate time-step variations (below about 10 %) permit a good precision of the numerical scheme.

- **Recommended maximum time-step:**

A « recommended maximum » time-step selected at all calculated times upon all calculated nodes is the minimum value among several types of calculated time-steps. The maximum time-step necessary to avoid calculation divergence in the irradiation variable equation is reduced with security margins and then compared to a maximum time-step necessary to keep a good precision of the numerical scheme. The resulting time-step is finally compared to an « experience feedback » time-step. This latter logically proposes a low initial value followed by an exponential evolution until an asymptotic limiting value. The « maximum recommended » envelope time-step finally retained guarantees a significant margin for the known divergence risks and it includes optimisation knowledge.

- **Algorithms and equations:**

The general algorithm of the simplified program presented in Figure 3 shows the iterative solving of the main equations at each time-step and details the elementary initialisations and calculations used. The physical parameters concerned are the cladding un-corroded thickness and outer diameter, and the fuel pin relative internal pressure.

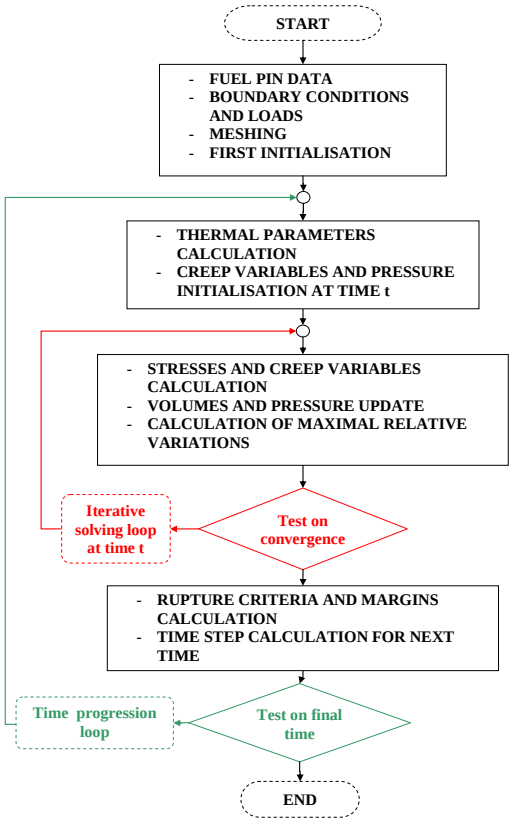

Figure 3: Equations solving

The claddings stresses inducing thermal creep are developed from hydrostatic and deviator stresses. The stress / strain equations consider the incompressibility deformation relationship and the Sodenberg creep deformation relationships during a time-step. Associated to some further simplifications of formula, this system of equations leads to a simplified model for creep resolution:

- Relationship during time-step: $\Delta\varepsilon_{éq}^{fl} = \dot{\varepsilon}_{eq}^{fl} \times \Delta t$.

- Ratios of equivalent to circumferential values: $\sigma_{eq} = \sqrt{\frac{3}{4}} \times \sigma_{\theta\theta}$ and $\varepsilon^{fl}_{\theta\theta} = \sqrt{\frac{3}{4}} \times \varepsilon_{eq}$.

Use of equivalent stresses for the rupture criterion

The rupture criterion [2] must be applied in principle with use of the average effective circumferential deformation and average stress ($\sigma_{eff} = \sigma_{\theta\theta} - \sigma_{rr}$) in the cladding thickness. However, corresponding equivalent Von Mises stress and strain were used instead as they are easier to obtain and give consistent results with the previous criterion.

Software characteristics

The thermal creep program is robustly written in FORTRAN 77. Creep laws and rupture criteria implementation permit to switch easily from one cladding material to another one because of the organisation with sub-programs and use of general formulas with numerous input data.

The main electronics files generated in use concern the data, calculation listing, mesh, initial conditions and calculation results. The calculation results are analysed extensively in spreadsheets graphs (more severe curves in relation to time, axial profiles at several times, time curves at several axial positions). Results comparisons are also available on spreadsheets graphs (more severe curves in relation to time or axial profiles at several times) between a case calculated by this program and another case (same program and different hypotheses, or same hypotheses and calculation by FEA).

Typical calculation duration for a given case is a few seconds for the calculation, about five times more to write the output files and a few minutes for results transferring in spreadsheets graphs and visual exam. Comparatively FEA calculations of similar cases last from several hours to a few days and visual transfer for exam in spreadsheets graphs lasts currently a few hours.

The FORTRAN program can be applied to all thermal creep calculations in a closed cask (routine transport lasting from a week to a year, vacuum drying, un-flooding during some hours, regulatory half-hour fire, and interim storage) provided that adequate creep laws and rupture criteria are available.

It will also permit to carry out studies necessary to support safety demonstrations either with:

- a simplified envelope approach expressed in maximum fuel pin temperature for several fuel pins types,
- or a direct approach realised by complete creep calculations carried out for each case.

Qualification plan

The program qualification plan, currently under development, consists of:
- Functionality tests concerning input and output data.
- FORTRAN programs checks on the physical equations and numerical schemes aspects.
- Comparisons with already available FEA calculations.
- Several analyses of differential modifications tests of the FORTRAN program models.
- Sensitivity studies on all involved physical parameters, in particular to show the interest or not to model them, and their acceptable simplification level in the model.

APPLICATION EXAMPLE

Preliminary comparative application case is carried out for a fuel pin coming from a 900 MWe reactor with the simplified program developed by TNI and with the FEA code CAST3M (see users section of http://www-cast3m.cea.fr/cast3m/index.jsp).

Data

A case with initial maximum temperature of 450 °C is studied here and the associated temperature axial profile is presented in Figure 4.

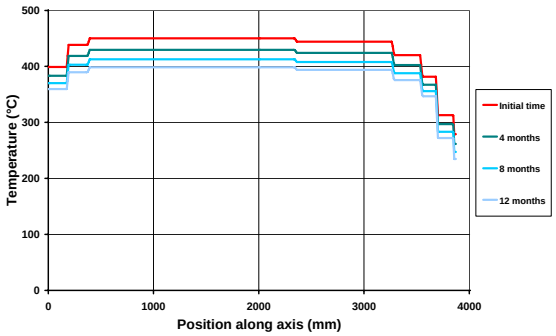

Figure 4: Temperature profiles for 450 °C

In this application case, the data and the boundary conditions (presented above) come from a 17x17 PWR used fuel pin. The cladding material is high-tin Zircaloy-4 (Zr4). The cladding irradiation fluence corresponds to a 4 cycles in-reactor irradiation.

The outer thickness of corroded cladding is not differentiated from sound metal, in accordance with the creep laws establishing. The standard internal absolute pressure used is 62 bars. FEA calculations use fast initial time-steps variation in stages on the first thirty hours while the FORTRAN program time-steps increase regularly.

The used creep laws and criteria have been developed by CEA R&D laboratories. Thermal creep behaviour used for high-tin Zr4 material includes irradiation defects recoveries with temperature but does not include cold-work hardening recoveries. It was established from tests on 4 cycles irradiated claddings with temperature conditions from 450°C to 600°C and with a stress domain from about 30 MPa to 130 MPa.

Creep margins to rupture are established with local deformations and rupture criterion values for the simplified model and presented on curves versus time for points with minimum local margin. Local, semi-local and global margins to rupture are established for FEA creep calculations and give similar results with the corresponding gradation of conservatism.

The rupture parameters of the FEA curves presented versus time are the maximum cladding deformation, the semi-local and global criterion, and the minimum local margin (established from FEA local deformation and criterion not shown here).

Results

Principal results of this 450 °C case are presented for both models on the following figures:

- Internal pressure profile in relation to time (Figure 5) and equivalent stresses axial profile at several times (Figure 6) :

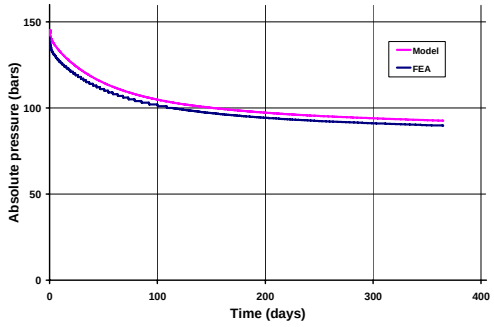

Figure 5: Internal pressure for 450 °C

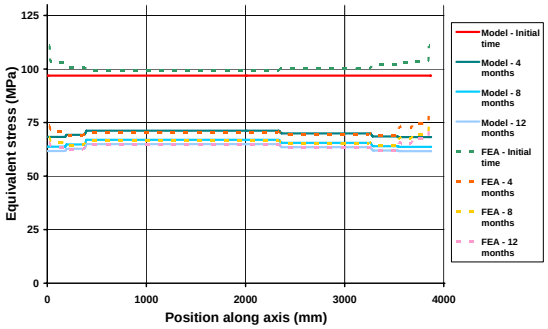

Figure 6: Equivalent stress for 450 °C

- Maximum cumulated equivalent deformation axial profile at several times (Figure 7) and deformation / criterion / margin to rupture in relation to time (Figure 8) :

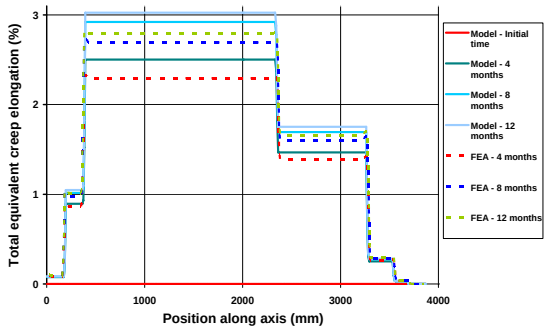

Figure 7: Cumulated equivalent deformation for 450 °C

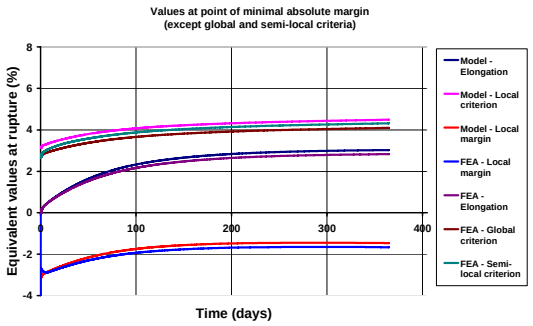

Figure 8: Deformation / criterion / margin to rupture for 450 °C

There is no rupture risk for a one year transport (typical transport duration is about a week) and the minimum deformation margin against rupture is still 1.66 % at end of the year.

Comparison with FEA calculations

Consistency of results:

Discrepancies on the creep amount results between the FEA calculation and the FORTRAN model are small and show that the TNI model permits to carry out low cost studies with an already good accuracy. Furthermore, this program can still be optimised as it is not yet fully validated.

The values determined by the TNI program are mainly average values within cladding thickness, while FEA results are maximum values within cladding thickness, which are then potentially situated on other radial positions. However, for comparison purpose, the TNI program can also show stresses and irradiation variables post-treatment estimations at inner and outer cladding radius.

Programs possibilities:

Creep calculation with the FEA code CAST3M involves the basic mechanical program and an additional programming in FORTRAN and specific CAST3M language that define input data, specific equations for irradiation variable and thermodynamic balance for internal pressure calculation, as well as the instructions for results presentation. FEA calculations and output analysis are long, leading to particularly prohibitive costs and deadlines.

The calculation model of the FORTRAN program integrates all the system equations in an optimal way and uses an efficient numerical scheme. Data are in an external input file read by the

FORTRAN program when running. The overall program is particularly simple to understand and check. So it can easily be corrected and developed. It runs fast and its output analyses chain developed with spreadsheets is efficient.

Consequently, the simplified model is more adapted to a daily use than the FEA one, which is more pertinent for indirect validation of the FORTRAN program (when there is no convenient test result) or for independent comparative calculations that may be required in some projects.

CONCLUSION AND PERSPECTIVE

Currently, the FORTRAN modelling gives good results because, although simplified, it nevertheless takes into account main thermal creep phenomena, parameters, and their interactions. The principle used for modelling is very efficient and the actual program, which still has a significant progression margin, is open to further updates and developments (e.g.: introduction of the cladding dynamic outer oxidation during the transport, or a secondary plenum in the bottom part of fuel pins).

The FORTRAN simplified program is now under validation and will permit to make reliable evaluations of LWR fuel pin rupture risk by thermal creep with large time and means benefits. It uses generic thermal creep laws and can be applied to closed casks routine transport lasting from a week to a year, vacuum drying, half-hour fire and interim storage with appropriate creep laws and rupture criteria.

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