Numerical Prediction of LMFBR Fuel Rod Response Following from a Primary Loop Pump Seizure

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Abstract

This paper describes the fuel rod response in a LMFBR, following from a seizure in a pump of the primary loop. The analysis is carried out by means of the FENHT computer code, recently developed at the University of Bologna, in the frame of nuclear components accident behaviour. The code can predict pellet, gap and cladding temperature profiles, as well as the thermoelastic stresses in the cladding. The results show that the fuel and cladding temperatures and stresses do not exceed the safety margins, except a very thin region in the inner cladding for less than one second.

1. Introduction

The evaluation of the thermomechanical nuclear fuel rod performance during hypothetical accidents is very important to prevent cladding failures or fuel melting; in fact the knowledge of the temperature and stress distribution allows to predict if the design and safety margins can be exceeded. The solution of the thermomechanical problem presents some difficulties for its non linear character, due to the dependence of the materials properties on temperature. In the last years many computer codes (BACO,URANUS,TITUS,MSA,FEMAXI, ELESTRESS,...) have been developed to predict stresses and temperature in the fuel rod [1-4]. In many of these codes, to solve the set of transient non linear equations in cylindrical coordinates, the finite element method has been chosen. The usual following hypotheses have been applied to obtain the temperature and stress profile in the fuel rod [5]:

- stresses, strains and temperatures do not depend on the azimuthal coordinate and axial heat conduction is neglected;
- the fuel conductivity is a function of porosity;
- the gas in the gap is helium;
- the heat transfer inside the gap takes account of conduction and radiative heat transfer in the gas;
- the migration of fission gases, due to the high neutron flux, causes a cylindrical hole on the rod axis.

2. Mathematical model and numerical procedure

The temperature distributions in the fuel, gap and cladding are found by solving the set of transient non linear heat conduction equation in cylindrical coordinates, minimizing the thermal potential

$$I(T) = \int_A \left\{ \tfrac{1}{2} K_i \left(\frac{\partial T}{\partial r}\right)^2 + \varrho_i c_i \frac{\partial T}{\partial t} T - QT \right\} dA + \int_L \left(\tfrac{1}{2} hT^2 - hT_b T\right) dL \;, \quad i=f,g,cl. \tag{1}$$

The boundary conditions are included in the second part of the r.h.s. of the equation (1); all the thermal properties of the materials depend on the nodal temperatures. Subdividing the fuel pin in annular three-nodal finite elements and minimizing the potential (1) for every finite element, the heat transfer equation for the whole rod, in matricial form, becomes:

$$(|K| + |H|)\mathbf{T} + |C|\dot{\mathbf{T}} - \mathbf{F} = 0 \qquad (2)$$

where $|C|$, $|K|$, $|H|$ are respectively the capacitance, conductance and convective matrix, the vector $\mathbf{F}$ depends on the thermal exchanges on the boundary and the elements of the vector $\mathbf{T}$ are the nodal temperatures of the finite elements.
In the equation (2) the matrices $|K|$ and $|C|$ depend on the unknown nodal temperature T; so the vector $\mathbf{T}$ is found by an iterative procedure beginning from a trial temperature vector.
Equation (2) constitutes a set of first order non linear and non homogeneous differential equations; its solution is performed by the Crank-Nicholson integration method, since it is demonstrated to be unconditionally stable and to have no oscillating solutions (provided one chooses a time step smaller than a predetermined value depending on the maximum eigenvalue of the system).

The mechanical and thermoelastic stresses in the cladding are valued by the well known analytical solution in cylindrical coordinates:

$$\sigma_r = -\frac{1}{r^2}\frac{E\alpha}{1-\nu}\int_a^r \Delta T\, r\, dr + \left(1 - \frac{a^2}{r^2}\right)\frac{1}{b^2 - a^2}\frac{E\alpha}{1-\nu}\int_a^b \Delta T\, r\, dr - \frac{1}{r^2}\frac{b^2a^2}{a^2 - b^2}(P_e - P_i) + \frac{P_e b^2 - P_i a^2}{a^2 - b^2} \qquad (3)$$

$$\sigma_\theta = \frac{1}{r^2}\frac{E\alpha}{1-\nu}\int_a^r \Delta T\, r\, dr + \left(1 + \frac{a^2}{r^2}\right)\frac{1}{b^2 - a^2}\frac{E\alpha}{1-\nu}\int_a^b \Delta T\, r\, dr - \frac{E\alpha\Delta T}{1-\nu} + \frac{1}{r^2}\frac{b^2a^2}{a^2 - b^2}(P_e - P_i) + \frac{P_e b^2 - P_i a^2}{a^2 - b^2} \qquad (4)$$

$$\sigma_z = \frac{E\alpha}{1-\nu}\left(\frac{2}{b^2 - a^2}\int_a^b \Delta T\, r\, dr - \Delta T\right) \qquad (5)$$

where ΔT is the difference between $T_{cl}(r)$ and the cladding inner wall temperature.

The FENHT (Finite Element Nuclear Heat Transfer) computer code has been applied to solve this thermomechanical problem.
The code assures the stability of the solution choosing the appropriate time step, and provides, in extremely low computer time, the transient distribution of temperature in the whole fuel rod and stresses in the cladding.

3. Pump trip and fuel rod response

The accidental transient here simulated is a pump trip, precisely a seizure of one of the primary loop pumps.
In order to check the fuel rod response in very severe conditions, two other accidents are hypothized to occur at the same time:

- the valve, positioned after the pump, does not shut off. In normal working the valve closure prevents the sodium flow from bypassing the core; due to a fault in the control circuit, the valve keeps open, so the sodium (removed from the core) goes up the tube of the seized pump and does not cool the fuel assemblies;
- due to a fault in the pump control circuit, the shutdown does not occur, it takes place only a few seconds later, when the increasing in outlet core sodium temperature starts an other different emergency system, operating the shutdown of the control rods.

In Fig.1 the sodium mean velocity and the fuel power density profiles are plotted; these are input data for the computer code (together with the sodium bulk temperature); the power density in the fuel, due to the neutron flux is assumed to be only time dependent; the power densities in the gap and in the cladding, due to γ heating, are considered negligible.
Fig.1 shows that the coolant velocity assumes a value equal to 56% of its initial value in only 1.3 s and the scram occurs only after 3.2 s from the accident start.
The initial value of the sodium mean velocity is 6.5 m/s and the initial value of fuel power density is 1500 MW/m^3.
All the properties of materials (UO_2, He, AISI 304 stainless steel and Na) are temperature dependent.

For the solution of this problem the following data have been assumed:

inner fuel radius = 2.21 10^{-4} m
outer fuel radius = 2.475 10^{-3} m
inner cladding radius = 2.555 10^{-3} m
outer cladding radius = 3.200 10^{-3} m
fuel rod pitch = 1.240 10^{-2} m
helium pressure in the gap = 0.1 MPa
coolant pressure = 0.4 MPa.

Furthermore the rod has been subdivided in seven finite elements in the fuel, one in the gap and three in the cladding.

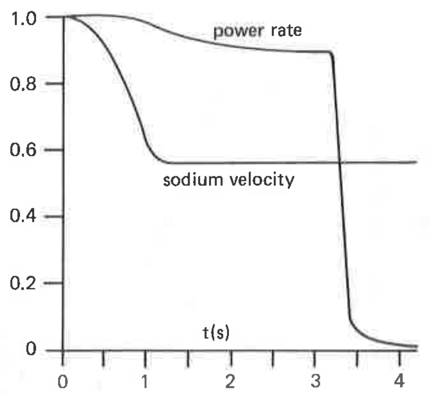

Fig.1. Dimensionless power rate and sodium mean velocity versus time, following from a pump trip.

In Fig.2 the fuel rod temperatures, predicted by the FENHT code, are plotted versus time; it can be seen that the inner fuel temperature decrease at first slowly, owing to the negative reactivity feedback, afterwards rapidly because of the scram. The other plotted temperatures, after a time period in which they increase continuosly, present a maximum (at the time 3.2 s for the outer fuel temperature and 3.6 s both for the inner and outer cladding temperatures) following the trend of the input sodium bulk temperature.

Hence the highest cladding temperature is reached in the inner surface (714 °C) at the time 3.6 s and exceeds the safety temperature that is 700 °C according to N.R.C..

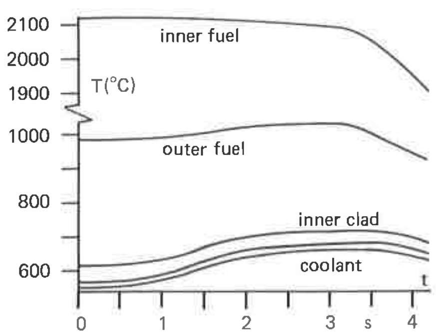

Fig.2. Fuel rod temperatures versus time, for the fuel, cladding and coolant.

The temperature profile in the fuel rod from the initial value to the final steady state (reached after about 20 s) is plotted in Fig.3 versus the radial coordinate, for various values of t. This graph shows in particular the considerable gap temperature step and the variation of the temperature gradient between the radii 1.3 and 1.7 due to the presence of a crack in the ceramic fuel.

The cladding radial, circumferential, axial and equivalent stresses are plotted in Fig.4 for the initial steady conditions versus the radial coordinate; the strongest equivalent stress, according to the Von Mises criterium, occurs in the walls of the cladding; by the inner wall, there is a thin region where the cladding gets exhausted, since the equivalent stress exceeds the allowable stress.

The Von Mises and Tresca equivalent stresses are shown in Fig.5; they are valued on the inner cladding wall, where they reach their maximum value.

In Fig.6 the equivalent Von Mises stress in the cladding is plotted versus the radial coordinate from the initial value to the final steady state for various time values; the stress decreases with time, in particular the thermal stresses disappear and only remain the mechanical stresses.

The results are in agreement with analogous predictions, the code convergence is secured with a computing time smaller than one minute an a 780/11 VAX computer.

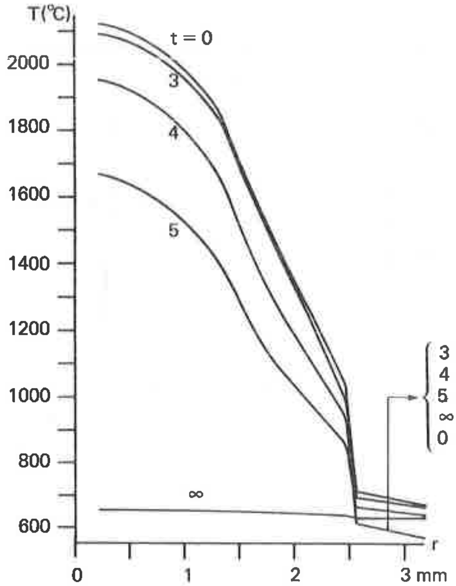

Fig.3.Radial distribution of the fuel rod temperature for different time values.

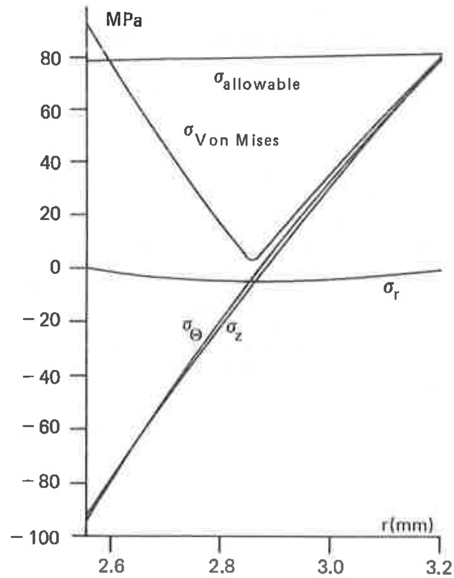

Fig.4.Initial steady state radial distribution of the stresses in the cladding.

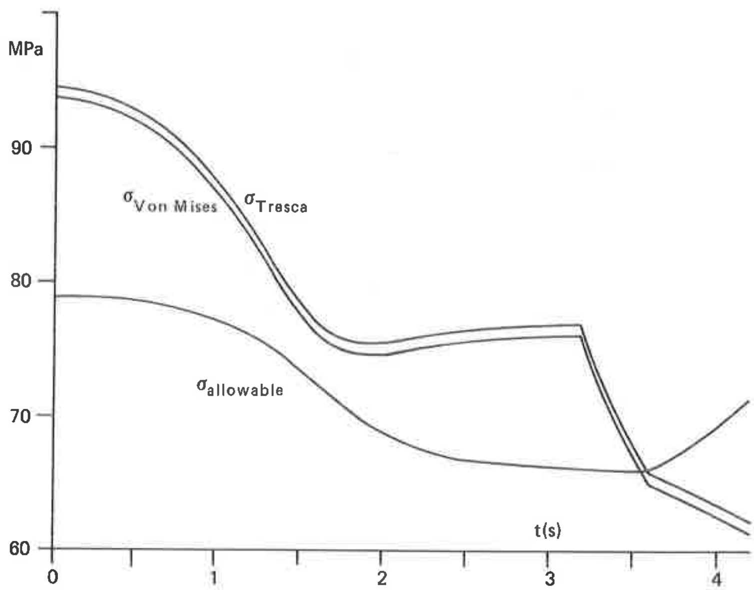

Fig.5.Allowable,Tresca and Von Mises stresses versus time in the inner cladding wall.

Nomenclature

a inner radius of the finite element
b outer radius of the finite element
c specific heat
E Young modulus
h coolant-cladding heat transfer coefficient
K thermal conductivity
P pressure
r radial coordinate
t time
T temperature
α coefficient of thermal expansion
ν Poisson ratio
ρ density
σ stress

Subscripts

b bulk (coolant)
cl cladding
e external
f fuel
i internal
g gap
r radial
z longitudinal
θ azimuthal

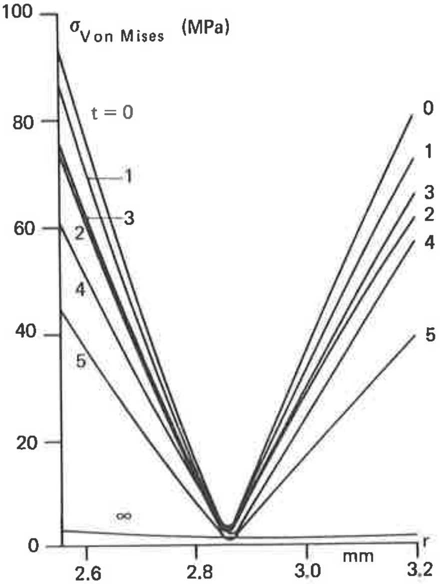

Fig.6.Radial distribution of the Von Mises stress in the cladding for different time values.

Acnowledgement

This work was performed with the financial support of the C.N.R..

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