Thermo-mechanical response of LMFBR fuel elements using EAC with emphasis on the TRANSURANUS module

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1 ABSTRACT

The European Accident Code EAC is a multichannel modular computer code for simulating the initiation phase of low-probability whole-core accidents in LMFBRs, i.e. loss of flow (LOF) or transient overpower (TOP) events. The code presents itself as an informatic structure into which various stand-alone modules from the Joint Research Centre and from other laboratories have been included. Three phenomena mainly control the neutronic behaviour of the whole core, namely fuel pin behaviour, sodium thermohydraulics and fuel motion. Fuel behaviour, in particular, is computed by means of the TRANSURANUS program which is an advanced tool for fuel performance analysis, extensively used in both the LWR and the LMFBR areas.

Because of the modular structure of EAC, the computation of these interacting phenomena proceeds necessarily in a sequential manner, not only channel-wise but also time-wise. The purpose of this paper is to illustrate how the EAC approach remedies the usual drawbacks of a weak coupling, in particular as far as the strong interaction between fuel pin and coolant channel is concerned. Numerical results will be presented on the basis of an international benchmark exercise dedicated to a hypothetical LOF accident in the irradiated core of the fictitious 700 MWe EUROPE reactor.

2 INTRODUCTION

Following a decision of the European Council of Ministers in the late seventies, a Fast Reactor Safety Coordinating Committee was created with the aim of improving cooperation between national research activities in both analytical and experimental fields. The Joint Research Centre of Ispra was subsequently asked to develop a computer code system to predict the time-dependent whole-core behaviour of a fast breeder reactor during the initiation phase of low-probability accidents such as unprotected loss of flow (LOF) or transient overpower (TOP) accidents. This led to the first version of the European Accident Code, called EAC-1 (van Goethem et al., 1986). Similar to EAC-1, the presently developed version, called EAC-2, is composed of existing modules provided by the national laboratories and some others developed in the establishments of the JRC. The main modules are the following

1. the fuel behaviour module TRANSURANUS (Lassmann, 1986), which is an improved version of the URANUS code, developed at the Technical University of Darmstadt, the Karlsruhe Research Centre and at the JRC-Transuranium Institute (Lassmann, 1979; Preusser et al., 1983).
2. the heterogeneous sodium boiling code BLOW 3A (Bottoni et al., 1982), originating from the Karlsruhe Research Centre;
3. the fast-running finite element homogeneous sodium boiling model CFEM (Reynen et al., 1982);
4. the materials dynamics model MDYN which keeps track of the fuel motion in the pin and the fuel dispersion in the coolant after pin failure (still under development, Nguyen et al., 1987);
5. the static three-dimensional (r-z), diffusion and transport neutronics program HEXNOD which is based on the nodal approach;
6. a space-time kinetics calculation developed by the Université Libre de Bruxelles which will, in connection with HEXNOD, calculate the time-dependent behaviour of the reactor power distributions.

3 HEAT SOURCE TERMS, INITIAL AND BOUNDARY CONDITIONS

To reduce the number of spatial directions, the reactor core is currently modelled as a series of concentric annular regions in which the axial temperature distributions are identical for all pin elements. An annular region is then represented by a single fuel pin surrounded by an equivalent coolant flow area and bounded by a cylindrical layer of structural material such that the masses of the materials involved and the surfaces for heat exchange are representative of the real conditions.

During an unprotected accident, the LMFBR core can be considered as a tightly coupled closed-loop control system with several reactivity feedbacks governing the overall neutronics behaviour. Apart from the main positive feedback of sodium voiding, there can also be a temporary positive feedback due to fuel motion. All other feedbacks are negative for elevated powers: as such they tend to counterbalance the destabilizing positive effects just mentioned. As a typical result in a LOF driven TOP accident, such as those considered in the comparative exercise (Wider et al., 1986), the reactor power first slowly decreases to 90% of nominal value: then it starts rising very abruptly up to several hundreds nominal power and then drops quickly because of fuel dispersion effects after pin break-up (reactor shut-down).

The boundary conditions for modelling a reactor are dictated by design considerations, such as the in- and outlet pressure and the inlet temperature which are identical for all channels (lower and upper plenum conditions). This type of hydraulics boundary conditions, together with the need for a detailed boiling model (to compute accurately the voiding pattern), led us to discard the simple hydraulics model built in TRANSURANUS and to replace it by CFEM or BLOW mentioned earlier. In the present version of EAC, the inlet pressure is based upon the summation of a static pressure head plus a pump head term which can be time-dependent to simulate low-probability unprotected LOF accidents.

4 FUEL-COOLANT COUPLING MECHANISM

It is to be noted that, in the coolant, convective heat transfer is by far more significant than heat conduction. As a consequence, the hydraulics modules involve only z-dependent integrations. The axial distribution of the coolant temperature $\{T_m\}$, for example, is computed by solving the following thermal convection equation in the channel:

$$[C_m]\{\dot{T}_m\} + ([V]+[H])\{T_m\} = [H]\{T_c\} \qquad (1)$$

where $\{T_c\}$ is the outer clad temperature; $[C]$, $[V]$ and $[H]$ are the heat capacitance, transport and loss matrices, respectively, and the dot denotes the time derivative.

As far as the thermal behaviour of the fuel pin is concerned, the heat is supposed to diffuse, by conduction, only in the radial direction so that only r-dependent integrations are involved in this case. At each axial station one has then to solve:

$$[C_p]\{\dot{T}_p\} + [K_p]\{T_p\} = \{Q_p\} \qquad (2)$$

where $[C]$ and $[K]$ denote the heat capacitance and conductance matrices, respectively; $\{Q_p\}$ is the heat source vector of the fuel pin, composed of the neutronic power produced in this channel plus the boundary condition originating from the coolant temperature $\{T_m\}$.

The interaction variables between the two phenomena are thus clearly T_c and T_m, and only a block solution of the two matrix equations (1) and (2) would give theoretically the right answer to the problem. Since this theoretical approach is not acceptable in a modular code, an alternative solution consists of introducing part of the fuel pin, namely the clad, in the hydrodynamical module. Doing so and assuming a linear dependence for both the heat flux determined in the fuel pin module and that which is effectively given to the coolant, leads to a new relationship between T_c and T_m:

$$\Delta\{T_c\} = \{\alpha\} - [\beta]\,\Delta(\{T_c\} - \{T_m\}) \qquad (3)$$

where Δ is the symbol of time increment whereas α and β are parameters depending on the current conditions of both fuel pin and coolant. In this way the coupling between fuel pin behaviour and hydrodynamics has been made about as strong as in the standard block solution procedure. This allows in particular to take large macro-time steps, which is of fundamental importance in a large modular system such as EAC.

If forced to decouple the two phenomena, there are two ways to solve at each time step the systems of Eqs.(1) and (2) in connection with the linear interaction model (3):

(i) first the fuel pin model TRANSURANUS is run; this approach requires to extrapolate $\{T_m\}$ which is a very sensitive quantity, mainly in the case of boiling and clad dry-out;

(ii) first the coolant model, CFEM or BLOW, is run; this alternative approach is based on an extrapolation of the cladding temperature $\{T_c\}$ or, if Eq.(3) is used, of the fuel-to-cladding heat flux which is a rather stable quantity. This is the approach chosen in EAC-2.

5 THE FUEL BEHAVIOUR MODULE TRANSURANUS

Of particular importance in the closed loop system of the whole core neutronic behaviour is the thermomechanical response of the fuel pin in terms of stresses, strains and gas release. There are mainly two reasons for this:

1. fuel heating gives rise to Doppler and fuel expansion reactivity effects which act as prompt negative feedbacks and which are highly important to counterbalance the destabilizing positive feedback effect of sodium expansion and voiding under hypothetical accident conditions;
2. the time and the location (relative core height) of the initial cladding rupture and the subsequent cladding rupture propagation are decisive for the further development of the hypothetical accident.

A failure near the midplane and no rapid failure propagation can lead to temporary reactivity increases due to in-pin fuel motions. A pin failure higher up will lead to negative reactivity effects due to in-pin motion and dispersion effects in the coolant channel.

For this reason, a very detailed description of the integral rod is necessary and this has been achieved by inclusion of the already mentioned advanced code TRANSURANUS, which has the following capabilities:

- steady-state and transient temperature calculations (finite element and finite difference techniques included);
- treatment of the thermo-hydraulics of the coolant;
- treatment of structures in a single pin experiment;
- detailed mechanical description of fuel and cladding;
- melting of fuel and cladding;
- boiling and evaporation of the coolant;
- coolant blockage;
- the code can be employed in different versions (as a performance code, as a statistical code and in a design version);
- it has a comprehensive materials data bank;
- it has a flexible structure;
- it has fast running algorithms.

The TRANSURANUS code has been successfully used to analyse FBR fuel rods (oxide, carbide) under steady state, off-normal and accident conditions. Of particular interest is its automatic time-step control mechanism, based on a micro/macro-timestep concept which was found to be very helpful in the coupling process with the EAC hydrodynamics and neutronics. This is best illustrated on the flowchart of the coupled computer system EAC-2 in Figure 1, which shows a series of innested iteration loops in which the thermomechanical part has a key role.

Another feature of interest in EAC-2 is the implementation of a 4th generation language interface to define the input data through a series of menus. This interface program has also been combined with an expert system in which the knowledge is represented by means of production rules in a NATURAL/ADABAS environment. As a result, a check is performed for inconsistencies in the input definition and the user is interactively informed about the corrections to be made (Delaval, 1987).

6 NUMERICAL RESULTS AND CONCLUSIONS

At this phase of the code development, numerical results are presented in regard with the LOF driven TOP exercise, previously mentioned, for which a pre-irradiation period of 6601 hours has been assumed with slightly rising power till the nominal value of 45,000 W/m in the central channel. Figure 2 gives an overview of the hydraulics and the fuel pin thermal behaviour in the irradiated channel No.2 at elevated powers during a simulated accident. Of particular importance for the neutronics balance are the fuel axial elongation and the mean fuel temperature which both produce negative feedback effects, needed to counterbalance the positive destabilizing feedback due to the channel voiding.

As a conclusion it is to be noted that the introduction of TRANSURANUS into the European Accident Code meant significant improvement. Not only the various thermal feedbacks but also the time and location of clad failure are now better predicted and this is crucial for the follow-up of the hypothetical accident, that is: the fuel ejection and dispersion in the coolant channel which eventually lead to reactor shut-down. Although the stand-alone version of the TRANSURANUS code has already been extensively validated, it is still planned to compute a series of CABRI experiments in order to further improve EAC-2 and to make it a fully reliable investigation tool for fast reactor whole-core safety.

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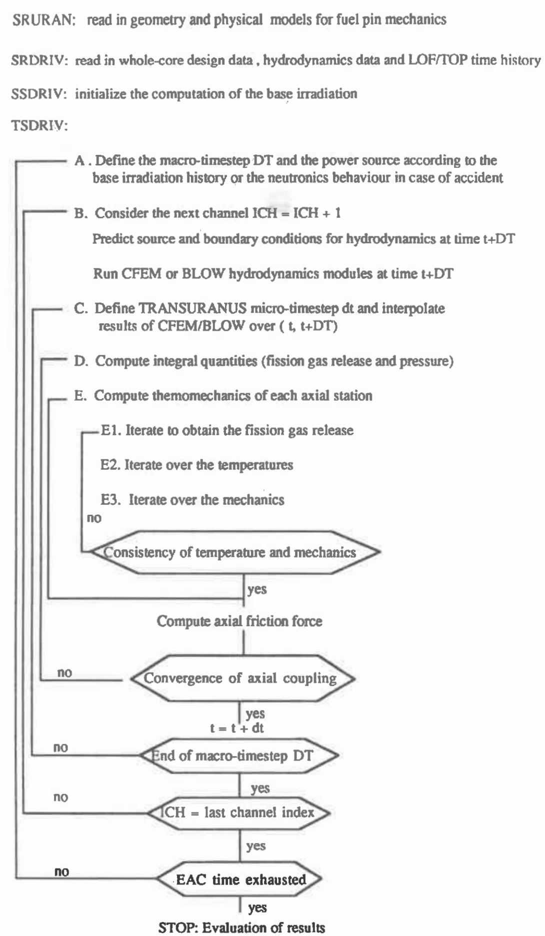

Figure 1 - Flow-chart of EAC-TRANSURANUS

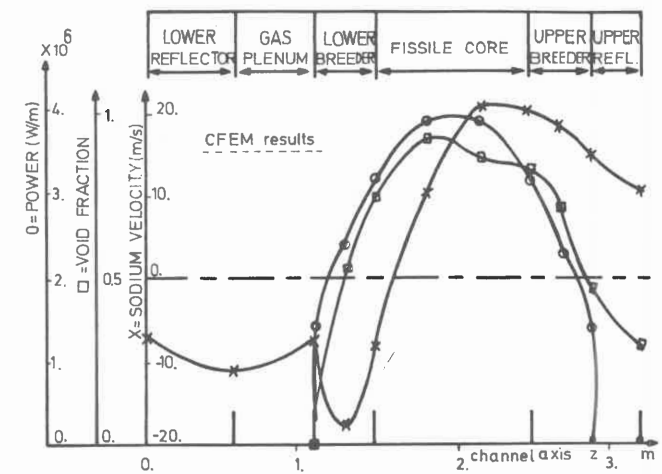

FIGURE 2-a) Sodium boiling during a reactivity ramp using EAC 2 (time 18.344 s, channel 2, comparative LOF exercise)

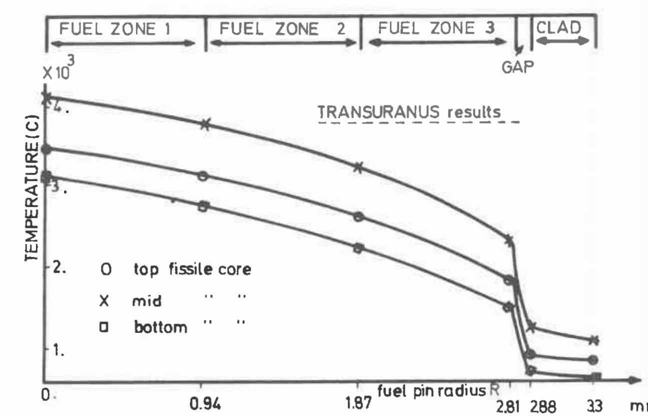

FIGURE 2-b) Fuel pin thermal behaviour under the above mentioned conditions