A 2D Transient Model for Gas-Cooled Fast

Reactor Plate-Type Fuel

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Abstract – *An accurate analysis of the thermal-mechanical behaviour of the fuel is particularly important for advanced reactor systems due to their increased safety requirements. The fuel types considered for advanced reactors may differ significantly from traditional designs, and so often the currently available codes cannot model such fuels without significant modifications. Thus, the adaptation and qualification of existing codes becomes an important requirement in the transient analysis of such reactors.*

The 2400 MWt helium-cooled (U-Pu)C-fuelled fast reactor is one of the most promising Generation-IV concepts. The design goal of the Gas-cooled Fast Reactor (GFR) is to combine a number of features, including flexible breeding parameters and high coolant temperatures. The high temperatures allow for both high thermodynamic efficiency and hydrogen production. Several new fuel designs are currently being considered within the GFR project. One of them, which is the reference design, is a ceramic plate matrix with a honeycomb inner structure containing small fuel cylinders. The fuel is mixed uranium-plutonium carbide, while the matrix material is silicon carbide.

A two-dimensional approach to the thermal-mechanical simulation of such fuel, taking into account the inner heterogeneity, is being developed at PSI, individual phases of the development involving benchmarking against detailed finite-element calculations. One of the distinctive features of the analytical scheme is taking into account the influence (on the transient temperature distribution in the fuel elements) of the elastic deformation and thermal expansion of the materials, as well of fuel swelling, fission gas release, and closure and reopening of the gas gaps Once integrated into the PSI transient analysis coupled code system "FAST", the resultant model will provide detailed fuel and matrix temperatures to determine neutronic feedbacks and to evaluate fuel integrity in a comprehensive manner.

The paper presents the development of the 2D thermal model for the GFR plate-type fuel, its integration into the transient analysis code system, as also the benchmarking of the model against 3D finite-element solutions obtained using the ANSYS[TM] code.

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I.   INTRODUCTION

The helium-cooled (U-Pu)C-fuelled fast reactor [1] is one of the most promising Generation-IV concepts [2]. The design goal of the Gas-cooled Fast Reactor (GFR) is to combine a number of features, including flexible breeding parameters and high coolant temperatures, allowing both high thermodynamic efficiency and the possibility of hydrogen production. The GFR core design is still under development; in particular, several options for the fuel design are being considered currently [3].

Presently, the reference design for the fuel elements is a thin (~1cm) SiC slab, formed by a honeycomb structure, both sides of which are covered by SiC walls (Fig. 1). Each cell of the inner structure encloses a fuel pellet. Thus, all these are separated from each other and the whole fuel element has no common gas plenum as in traditional fuel rods.

Such fuel is a technological and modelling challenge. Strictly speaking, each cell of the fuel has to be treated in 3D geometry, taking into account the influence of its neighbours. The present research aims at implementing a 2D approach to the thermo-mechanical GFR plate-type fuel simulation, which accounts adequately for the high degree of fuel heterogeneity. The methodology, currently developed for the thermal part, is benchmarked against finite-element solutions to verify the developed algorithms and evaluate the impact of the geometry changes made.

The resultant model has been integrated into the PSI transient analysis coupled code system "FAST" to provide detailed fuel and matrix temperatures to determine neutronic feedbacks, an important step towards the goal of evaluating fuel integrity for the GFR in a comprehensive manner.
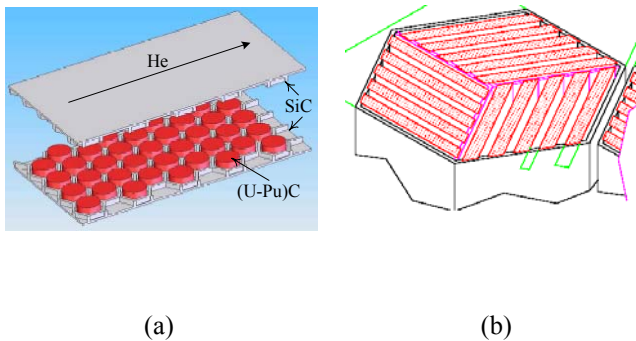

(a)   (b)

Fig. 1. GFR fuel element reference design: a) fuel plate; b) fuel assembly, view from above.

II.   OVERVIEW OF THE CALCULATION ROUTINE, CODES AND ASSUMPTIONS

The reference GFR fuel element, as mentioned, is highly heterogeneous and, in specific terms, consists of a large number of honeycomb cells. For the 2400 MWt core design, the core consists of 397 fuel assemblies, each containing 21 fuel plates. Thus, the total number of fuel plates amounts to approximately 8000 (some assembly positions need to be reserved for control assemblies). Dimensions of the fuel plate are $7 \times 120 \times 1550$ mm. Each cell of the honeycomb structure has an across-flat of 3.7mm. This means that the total number of cells is about $1.2 \cdot 10^8$.

The basic goal for the code being developed, within the frame of the PSI FAST code system [4], is to combine a reasonable accuracy for the calculations with low CPU times. The original model was accordingly simplified to meet these requirements.

Each assembly is represented by a single fuel plate, the individual plates being assumed to be all subject to similar conditions. The plate is divided into several axial levels. Operating conditions are assumed to be constant within each level. As the height of each level is much greater than that of the individual cells within the honeycomb structure, it was decided to model a single cell with mirror boundary conditions per each axial level. The total amount of cells which need to be calculated is thus the number of fuel assemblies multiplied by the number of axial levels defined for the analysis.

The GFR fuel model has been developed on the basis of the coupled TRAC/AAA [5] (system thermal hydraulics) and FRED [6] (fuel pin thermal mechanics) modules, which are parts of the FAST code system.

The calculation routine is divided into two steps:
- "macro level calculation" – calculating the coolant temperature, power density and heat transfer coefficient distribution, as well as the point kinetics parameters based on the results of the "micro level calculation" (see below). This step is done by the TRAC/AAA code.
- "micro level calculation" – thermomechanical calculations, for each cell in the model, with the boundary conditions and power densities provided from the "macro level". This is necessary to capture the effect of the fuel heterogeneity and the evolution of the cell properties and dimensions with temperature and burnup. This step is done by the FRED code.

As shown in [7], a simplified 1D homogeneous model (stand-alone TRAC/AAA calculation) can be used for the thermal analysis of the GFR fuel during steady-state and transient operation. The difference in the peak fuel temperature between the homogeneous TRAC and

detailed ANSYS^{TM} model was obtained to be about several tens of degrees. However, as the feedbacks and fuel integrity are determined not only by the peak temperatures, an analysis which takes into account such effects as fuel and matrix thermal expansion, swelling, fission gas release, pellet-clad mechanical interaction, etc. is necessary, and this analysis requires a detailed heterogeneous (at least 2D) temperature distribution within the fuel cell, e.g. in order to correctly predict closing of the radial and axial gas gaps and corresponding boundary conditions for the pellet swelling, etc.

III. DESCRIPTION OF THE 2D FRED MODEL FOR CGFR FUEL

The present section describes the FRED code [6] adaptation for the thermomechanical calculation of a GFR honeycomb cell. As a full 3D model of the GFR hexagonal mesh, taking into account heat exchange with neighbouring cells, is too time consuming for a transient analysis code, a number of assumptions were made. One of them is that the 3D hexagonal GFR cell (Fig. 2a) can be reduced to the 2D cylindrical geometry shown in Fig. 2b, while preserving the volumes of the elements.
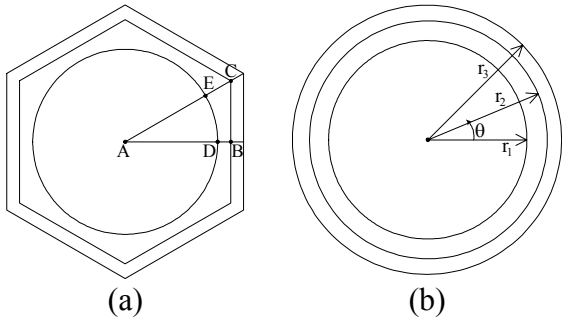

(a)   (b)

Fig. 2. Illustration of the development of the GFR cell model: (a) real geometry cross-cut; (b) 2D FRED model representation.

As the FRED code was originally developed for conventional fuel rod analysis, other modifications were made to introduce the new cladding layers below and above the fuel column (pellet). The heat transfer scheme also changed, as the coolant flows along the "top" and "bottom" (in terms of the original FRED geometry, while the pellet axis is oriented horizontally within the GFR fuel plates) flat ends. Heat flux from the radial surface is set to zero to represent the mirror boundary conditions (no heat exchange with neighbouring cells). The mechanical part is correspondingly changed according to the new fuel cell / coolant arrangement.

To better demonstrate the difference of the GFR fuel nodalization (Fig. 3a) from the conventional scheme, a traditional fuel pin diagram is shown in Fig. 3b.
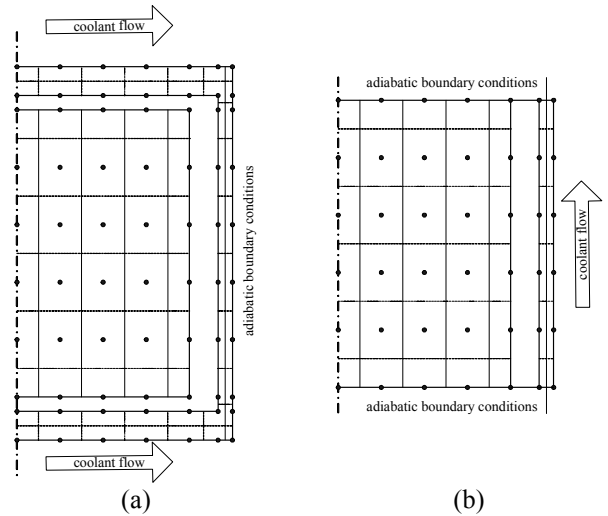

(a)   (b)

Fig. 3. Nodalization scheme for the FRED calculations: (a) GFR scheme; (b) conventional fuel pin scheme.

Summarizing the aforesaid, the new FRED model is a fuel pellet enclosed in a cylinder of structural material closed from both flat ends. Radial and axial gas gaps are initially open, and the model has a rotational symmetry as well as symmetry about a plane normal to the Z-axis and placed at the half-height of the cell. The radial boundary is adiabatic, with heat being removed from the flat ends.

IV. COUPLING BETWEEN TRAC/AAA AND FRED FOR THE GFR FUEL

To obtain boundary conditions for the heat fluxes on the GFR fuel element surfaces, a heat structure in slab (X-Z) geometry is specified in the TRAC code for each simulated fuel element, while (as described above) the FRED representation describes a more detailed (2D) set of separate fuel cells with one representative cell for each axial level of the TRAC model. Hence, if there are N TRAC heat structures (representing, for example, N fuel plates with different powers or geometries) each with M axial layers, then N×M cells will be calculated in FRED, each with appropriate boundary conditions, viz. heat transfer coefficient and bulk temperature for the corresponding axial coolant level taken from the TRAC calculation. The temperatures inside the fuel cell calculated by FRED are then used by the TRAC heat structure model for calculating heat fluxes.

The schematics of the GFR fuel and the corresponding TRAC and FRED models are presented in Fig. 4.
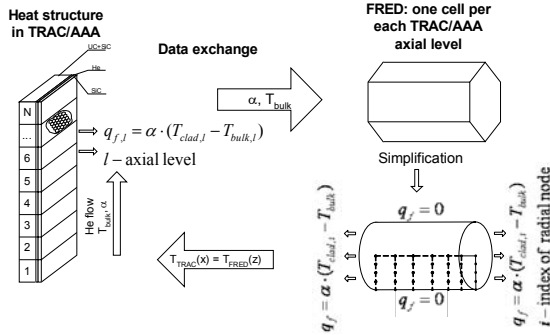

Fig. 4. Coupled TRAC/FRED modelling for the GFR fuel.

V. INITIAL GEOMETRY OF A CELL

The geometry of a GFR hexagonal cell, as used in the calculations, is described in Table I.

Table I

Geometry of the benchmarked cell.

Parameter	Value, mm
Fuel pellet height	5.9
Fuel pellet radius	1.6
Minimal radial gas gap	0.05
Lateral gas gap	0.05 (each)
Radial wall thickness	0.2
Fuel element thickness	7.0
Cell outer across flat	3.7
Lateral wall thickness	0.5

VI. BENCHMARKING THE RESULTS AGAINST FINITE-ELEMENT SIMULATION

Due to the current lack of detailed knowledge regarding the behaviour of the novel GFR fuel type, as also of corresponding experiments, a series of benchmark calculations have been performed using the finite-element ANSYS^{TM} code [8].

This benchmarking was divided into two steps. Firstly an axisymmetric 2D R-Z model (analogous to the FRED model) was developed to verify the algorithms implemented in FRED. The next step was the modeling of the actual 3D cell (Fig. 5), to investigate the correspondence between 2D and 3D geometries.
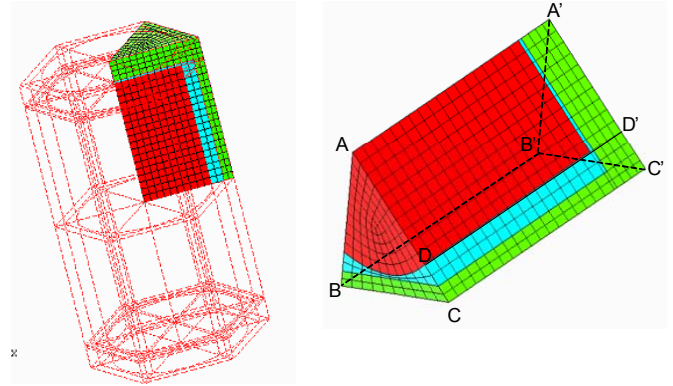

Fig. 5. 3D finite-element model of a cell.

Boundary conditions were imposed on the surface A'B'C' (Fig. 5) by specifying the bulk helium temperature and heat exchange coefficient taken from the TRAC/AAA calculations, while zero heat flux was assumed for all other surfaces. Furthermore, steady-state parameters were used for comparison during the benchmarking, viz.:

- temperature field in the open gap (both gaps) regime;
- temperature field in the closed gap regime;
- deformation of the SiC matrix and the fuel pellet;

An important phenomenon leading to gap closure is fuel pellet swelling under neutron irradiation. However, this algorithm was not implemented in the ANSYS^{TM} model for benchmarking (and was switched off in the FRED model). In order to force the gap closure, the fuel pellet thermal expansion was increased by a factor of two, while other properties were kept unchanged [9, 10].

VI.A. Temperature field

As the ANSYS^{TM} 3D model does not have rotational symmetry, the temperatures on the fuel pellet radial surface (line BB') (see Fig. 5) may be considered, for example, for the locations where the radial gas gap is maximal and minimal. These values are indicated by "max gap" and "min gap" in the following figures.

Two calculations were made with different power densities, respectively, to test the algorithm in the regimes of the open and closed axial gaps. The radial gap remains open in both cases.

VI.A.(a) Open-gap regime

The plots below (Fig. 6 and Fig. 7) show the steady-state temperature distributions as a function of z-

coordinate (in terms of the FRED geometry) at different positions within a cell (with both gaps open), viz. the centreline of the cell; line, coincident with the fuel radial boundary; line, coincident with the cladding inner boundary; line, coincident with the cell outer boundary.
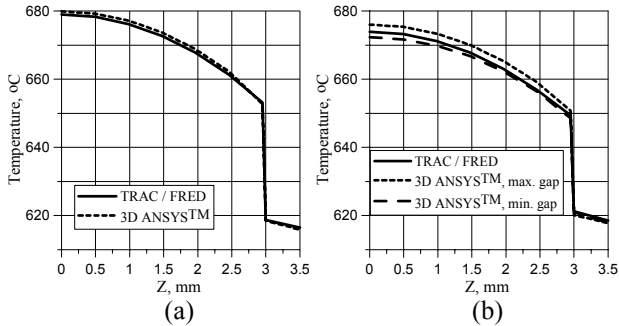

Fig. 6. Cell temperature distributions (with open gaps) for (a) cell centreline, (b) fuel radial boundary.
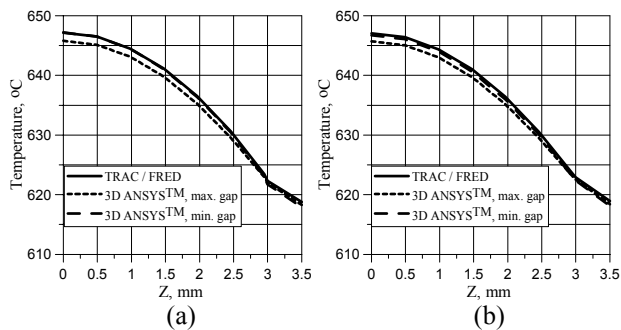

Fig. 7. Cell temperature distributions (with open gaps) for (a) inner clad surface, (b) outer clad surface.

As one can see the FRED results for temperatures in the open-gap regime, are in very good agreement with the benchmark solution.

VI.A.(b) Closed gap regime

The plots below (Fig. 8 and Fig. 9) show the same temperature distributions as considered above, but this time for the case of closed axial gap.

(a)   (b)

Fig. 8. Cell temperature distributions (with closed axial gap) for (a) cell centreline, (b) fuel radial boundary.

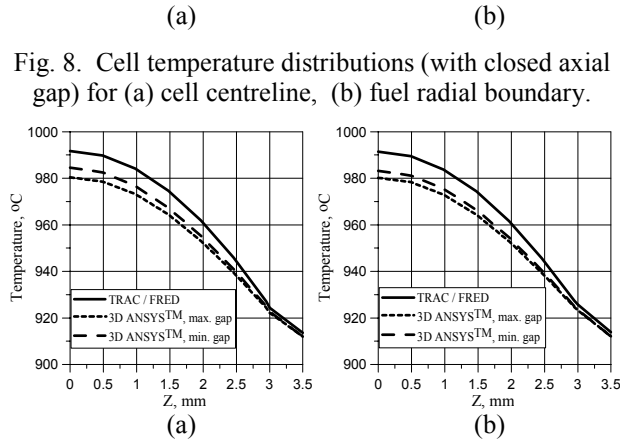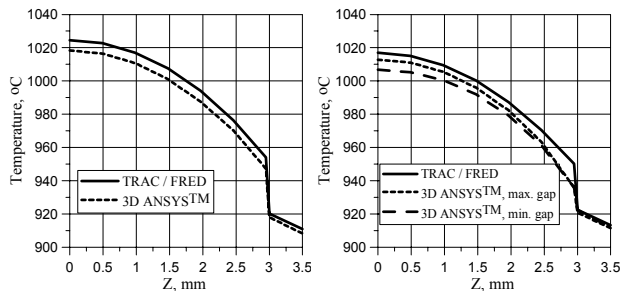(a)   (b)

Fig. 9. Cell temperature distributions (with closed axial gap) for (a) inner clad surface, (b) outer clad surface.

One of the FRED calculational procedure assumptions is that all the axial levels remain flat during the deformation. Consequently, the axial contact occurs over the entire flat end of the pellet. The finite-element model treats the deformations more accurately, with a part of the surface being in contact and the rest not. Fig. 10 shows the flat end of a pellet in the ANSYS modelling. The orange coloured part of the surface is in contact with cladding, for the given boundary conditions and heat generation rate.
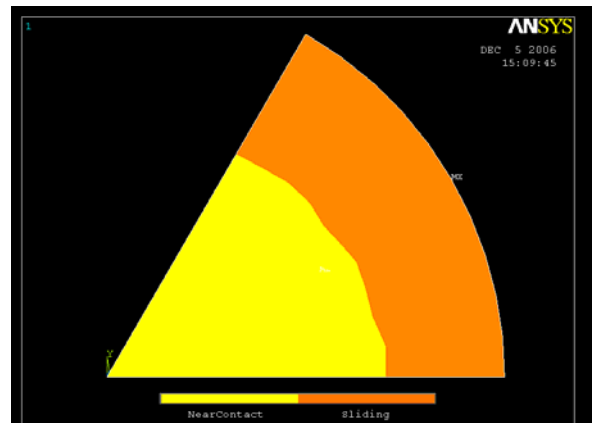

Fig. 10. Typical axial contact status in ANSYS model

The different areas of contact surface in the two models, and as consequence the different contact pressures, result in discrepancies in the heat transfer coefficient between fuel and cladding. Nevertheless, the influence (~5ºC) is not very significant, so that fuel peak temperatures remain in acceptable correspondence.

VI.B.   Deformations of the pellet and matrix

The ANSYS[TM] and FRED predictions have been compared for the pellet deformation in the open and closed gap regimes. Accurate prediction of the material displacement is especially important for GFR safety analysis, because of the impact of reactivity effects due to core expansion.

The variation of the inner gas pressure was assumed to be caused by the change of the inner free volume and temperature distribution. The FRED predictions for the inner gas pressure agree very well with the ANSYS[TM] results. For example, in the open gap regime, the two codes predicts 5.69 MPa and 5.72 MPa, respectively; for the closed gap regime (characterised by a higher power), the corresponding values are 8.64 MPa and 8.65 MPa.

The deformations of the fuel and SiC structure have been assumed to be driven by the thermal expansion and elastic deformation.

The plots below show the deformation of the fuel pellet in greater detail. The comparisons are made for the relative axial and radial deformations of the fuel pellet, elongations for different radial positions being shown in Fig. 11a and radial deformation versus height in Fig. 11b. As one can see, the correspondence between the two different sets of results is quite good in each case. This means that geometry change is well predicted by the simplified FRED model.
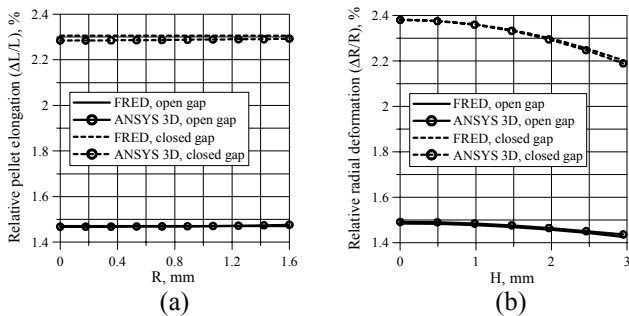

Fig. 11. (a) Fuel pellet elongation and (b) radial deformation, calculated by FRED and ANSYS for the open and closed gap regimes

VII. MODELLING OF TRANSIENT PROCESSES

In order to illustrate the ability of the coupled TRAC/FRED code to simulate time-dependent processes, a simple transient was analysed. The power density was linearly ramped during first 30 seconds, then remained constant for next 30 seconds and finally was ramped down to zero level (Fig. 12a). Such power history allows the modelling of both open and closed axial gap regimes (see Fig. 12 b).
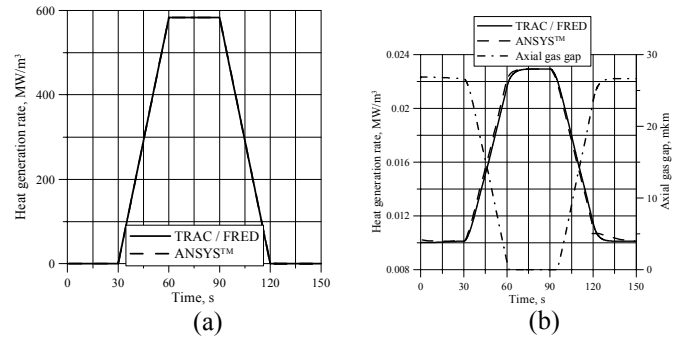

Fig. 12. Power density (a), fuel pellet elongation and gas gap (b) evolution in the power ramp transient calculated by 3D ANSYSTM and 2D FRED for the GFR fuel
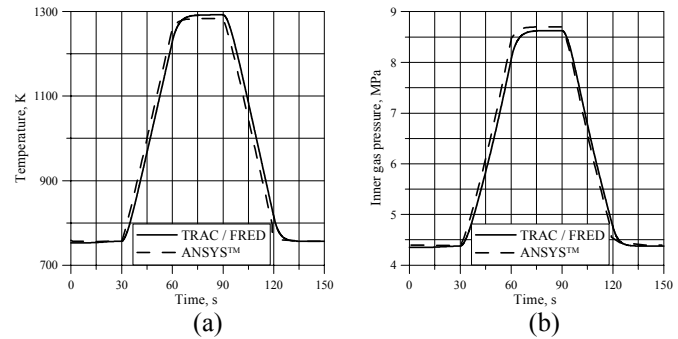

Fig. 13. Peak fuel temperature (a) and inner gas pressure (b) evolution in the power ramp transient calculated by 3D ANSYSTM and 2D FRED for the GFR fuel

The results provided by both of the codes are in a very good agreement. Thus such important parameters as deformations and temperature field which influence the reactivity feedbacks are well predicted by the FRED code.

VIII. CONCLUSIONS

The present study examines the reference Generation-IV Gas-cooled Fast Reactor (GFR) fuel design, which is significantly different from traditional fuel rods. This refers both to the geometry and the materials used. Each cell of the honeycomb SiC matrix (enclosed by thin walls on both sides) encloses a (U-Pu)C fuel pellet. The fuel element no longer has rotational symmetry and, moreover, is highly heterogeneous. Currently available codes cannot model such fuels without considerable modifications. The development of a simplified approach to treat the GFR fuel heterogeneity, in the context of thermal-mechanical analysis, has currently been addressed.

The overall procedure is based on coupling the TRAC (system thermal-hydraulics) and FRED (finite-difference thermal-mechanics) codes, the first of which provides the heat generation rate distribution and thermal boundary conditions, while the latter performs thermal and mechanical analysis including such effects as swelling, fission gas release, creep etc. This scheme was already developed and tested for conventional fuel pin designs.

The aim of the research has been to apply the algorithms implemented in FRED to GFR analysis, without significant modifications. Thereby, certain assumptions have been necessary concerning the fuel geometry and the interdependence of the honeycomb structure cells. The principal simplifications made are:

- The original 3D hexagonal cell geometry is reduced to a 2D axisymmetric one.
- Neighbouring cells are assumed not to influence each other.

To assess the influence of the simplifications on the thermal-mechanical GFR fuel behaviour, and to verify the applicability of the algorithms originally developed for traditional fuel, finite-element benchmarking analysis has been carried out using the ANSYS[TM] code.

Two finite-element models were created:

- A 2D axisymmetric model to verify the FRED algorithms;
- A 3D model to verify how closely the results of the 2D analysis correspond to the "real" geometry.

For the thermal analysis, a good correspondence has been obtained between the FRED and 2D ANSYS[TM] models, as well as between the 2D and 3D geometries. Thus, average fuel and matrix temperatures are well predicted, which is important for reactivity feedbacks calculations (Doppler effect).

Dimensions of the pellet and structures are mostly driven by thermal expansion and elastic deformation, and corresponding predictions are also in good agreement between FRED and ANSYS[TM].

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