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DART-TM: A THERMOMECHANICAL VERSION OF DART FOR LEU VHD DISPERSED AND MONOLITHIC FUEL ANALYSIS

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ABSTRACT

- A collaboration agreement between ANL/USDOE and CNEA Argentina, in the area of Low Enriched Uranium Advanced Fuels has been in place since October 16, 1997 under the "Implementation Arrangement for Technical Exchange and Cooperation in the Area of Peaceful Uses of Nuclear Energy". An annex concerning DART code optimization has been operative since February 8, 1999. Previously, as a part of this annex a visual thermal FASTDART version was developed that includes mechanistic models for the calculation of the fission-gas-bubble and fuel particle size distribution, reaction layer thickness, and meat thermal conductivity. FASTDART was presented at the last RERTR Meeting that included validation against RERTR 3 irradiation data. The thermal FASTDART version was assessed as an adequate tool for modeling the behavior of LEU U-Mo dispersed fuels under irradiation against PIE RERTR irradiation data.

- During this past year the development of a 3-D thermo-mechanical version of the code for modeling the irradiation behavior of LEU U-Mo monolithic and dispersion fuel was initiated.

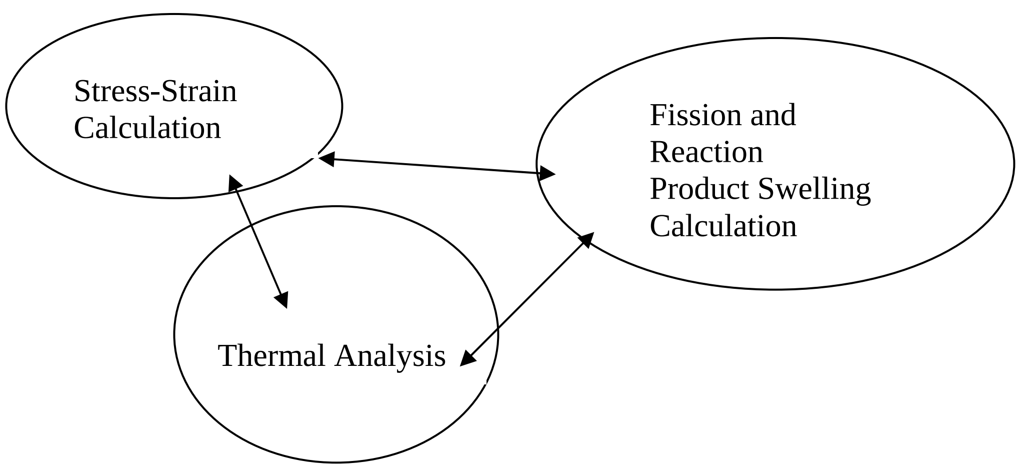
Some preliminary results of this work will be shown during RERTR2003 meeting.

INTRODUCTION:

The FASTDART [1,2] thermal subroutine is able to calculate, at each time step, the maximum temperature point along the z-longitudinal axis, and several temperature values across the meat, from cladding-meat interface to meat centerline. Calculated temperatures at each time step are taken into account to get swelling predictions, reaction layer depths and volume phase fractions by coupling temperatures to the DART calculus kernel. Reasonable agreement with RERTR 3 PIE data was found which reveals an adequate DART temperature calculation.

The 3-D DART-TM thermo-mechanical code, currently under development, is based upon a preexisting finite element elastic code named TERMELAS, and on FASTDART that provides temperature and irradiation effect modeling subroutines. Using a given power history, coolant regime data and fuel plate dimensions, DART-TM calculates at each time step the fission product swelling, the temperature distribution on the nodes of each layer (oxide, cladding, U-Al reaction product and fuel) and the effect of temperature and swelling on stresses and strains. The capability of plotting calculated thermal and stress distributions is also under development.

The development of new, very high-density fuels, to fulfill the demands of the RERTR program, is focused on U-Mo based fuels, particularly on the advanced monolithic fuel. To assess the irradiation behavior and lifetime issues a consistent effort on modeling is needed. This modeling must take into account the thermal and elastic stresses and strains, plastic phenomena associated with creep, as well as the synergies between these phenomena. This situation can be sketched in the following scheme:



In order to have the capability of assessing fuel plate lifetime issues, an appropriate way to design and develop an accurate model of the monolithic fuel undergoing irradiation is to construct this scheme within a 3-D thermal-mechanical formulation which steps through time. That is the reason why the authors have chosen a finite element approach to this problem. To this end, an existing 3-D finite element code named TERMELAS is taken as the stress and strain core calculator that exchanges thermoelastic and swelling data with DART to achieve the modeling goal.

DESCRIPTION AND PROPOSED MODEL:

As discussed above, in order to assess the irradiation and lifetime issues of monolithic fuel it is necessary to take into account the thermal and elastic stresses and strains and plastic phenomena associated with creep. Thus, the development of a thermal-mechanical version of DART (DART-TM) has been initiated.
In the following, the thermal-elastic treatment will be described. The introduction of plastic phenomena will be discussed in a future paper.

The strong coupling between the thermal, stress and swelling issues become apparent as soon as it is considered that fission releases a given amount of heat per unit time. Fission also generates a given yield of fission products, particularly, fission gas retained inside the fuel grains and on grain boundaries. Additionally, the neutron flux interacts with atoms of the crystalline structure of the meat and cladding generating interstitials and vacancies that result in creep and associated plastic flow of the material. These mechanisms contribute to increased stresses and strains in the meat and cladding materials by both thermal expansion and swelling. In turn, the swelling degrades the thermal conductivity of the monolithic material. The joint effect of all these phenomena is the buildup of strain within materials undergoing irradiation. To keep track of this kind of coupled evolution we present a model on which the ongoing work is based.

The modeled temperature field is given by:

$$-\nabla.[k_F(T)\nabla T] = q_V \qquad \text{in } \Omega$$

$$-k_a \frac{\partial T_a}{\partial n} = -k_b \frac{\partial T_b}{\partial n} \qquad \text{on } \Gamma_D$$

$$-k \frac{\partial T}{\partial n} = h_c(T - T_e) \qquad \text{on } \Gamma_R$$

$$-\nabla T(0) = 0 \qquad \text{on meat centerline}$$

where q_V stands for the power density source, k_* for the thermal conductivities, h is the convection heat transfer coefficient (determined by Dittus-Boelter equation), the boundary Γ_D represent the interface between the cladding and the monolithic fuel, the boundary Γ_R is defined by the surface in contact with the coolant, and coolant regime. The last equation reflects an axisymmetrical assumption to reduce the amount of nodes (and computational time) demanded by the calculation.

In order to find the irradiation induced strain, it is necessary to solve the mechanical equilibrium equation:

$$\nabla.\sigma + \rho f_V = 0$$

where $\rho = \rho(x)$ is the density of the material , f_V is given by volumetric forces and the stress tensor σ is given by the linear elastic law $\sigma = C(\varepsilon + \gamma + \alpha\ \Delta T)$, where α is the thermal expansion coefficient, γ is the contribution of swelling due to fission and reaction products and ΔT is the thermal jump regarding the zone where the material is free of stress. $\varepsilon = \nabla^S u$ .is the symmetric part of the strain field.

Under a variational technique applied to the total potential energy, and a finite element discretizing method (Galerkin scheme), the preceding equation system is transformed into a set of linear equations:

$$M_T\ T = F_T$$
$$M_\sigma\ U = F_\sigma$$

where M_σ and M_T are known as the system stiffness matrixes and U and T are the corresponding nodal displacement and temperature vectors, F_T y F_σ are the charge vectors for the displacement and temperature system and will be given by the usual integral of finite elements.

While the right side temperature vector is given by the coolant-fuel assembly plate contact conditions, the displacement vector F_σ will be given by the contribution of surface charges, fuel swelling and thermal expansion term.

Once the geometry is established using a Computer Aided Description (CAD), the 3-D calculation scheme consisting in a loop between FEM mesh generation, fission and reaction-product swelling, thermal conductivity evolution and FEM thermal calculation, and FEM strain calculation and analysis is entered within an algorithm required in order to reach a given accuracy for each time step.

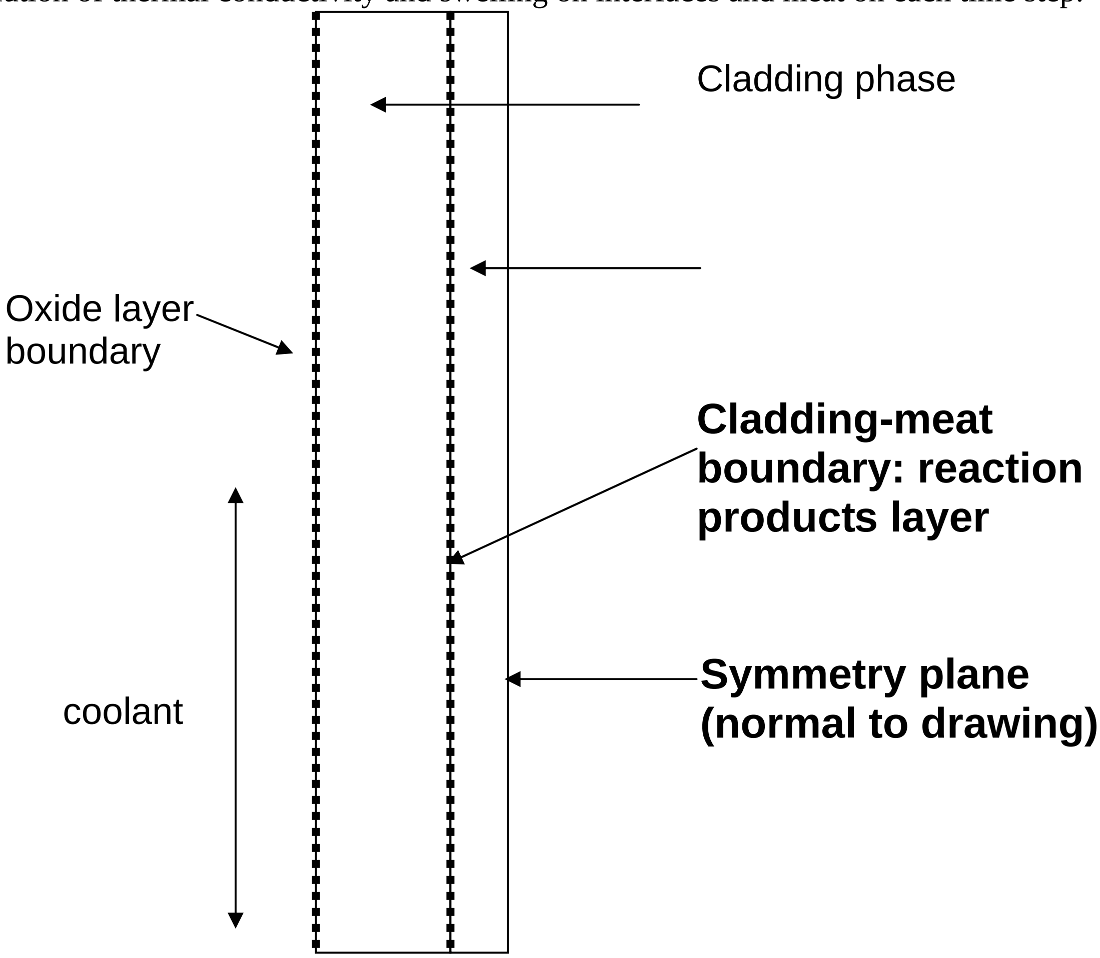
MODELING ASPECTS AND RESULTS

The region under modeling represents the ¼ part of the whole plate, due to geometric symmetry and also due to thermal and mechanical restrictions. It can be seen in Figs.1 and 2 the graphical representation. The dashed lines represent growing boundaries along the irradiation (oxide layer and reaction products layer). The boundary conditions in these symmetry planes are, the already mentioned nullity of the thermal gradient on the longitudinal axis (for the thermal calculation) and the nullity of the displacement in the normal direction to the symmetry plane for the stress calculation. The face in contact with the coolant has a mixed gradient-value boundary condition. The plate displacement and thermal gradient on the wrapping part of the structural frame are

$$\nabla T(0) = 0 \qquad U.n = 0 \qquad k\nabla T = h(T - T_e)$$

nulls.

A model representing ¼ of a plate is achieved. Several subroutines give to 3-D code the evolution of thermal conductivity and swelling on interfaces and meat on each time step.



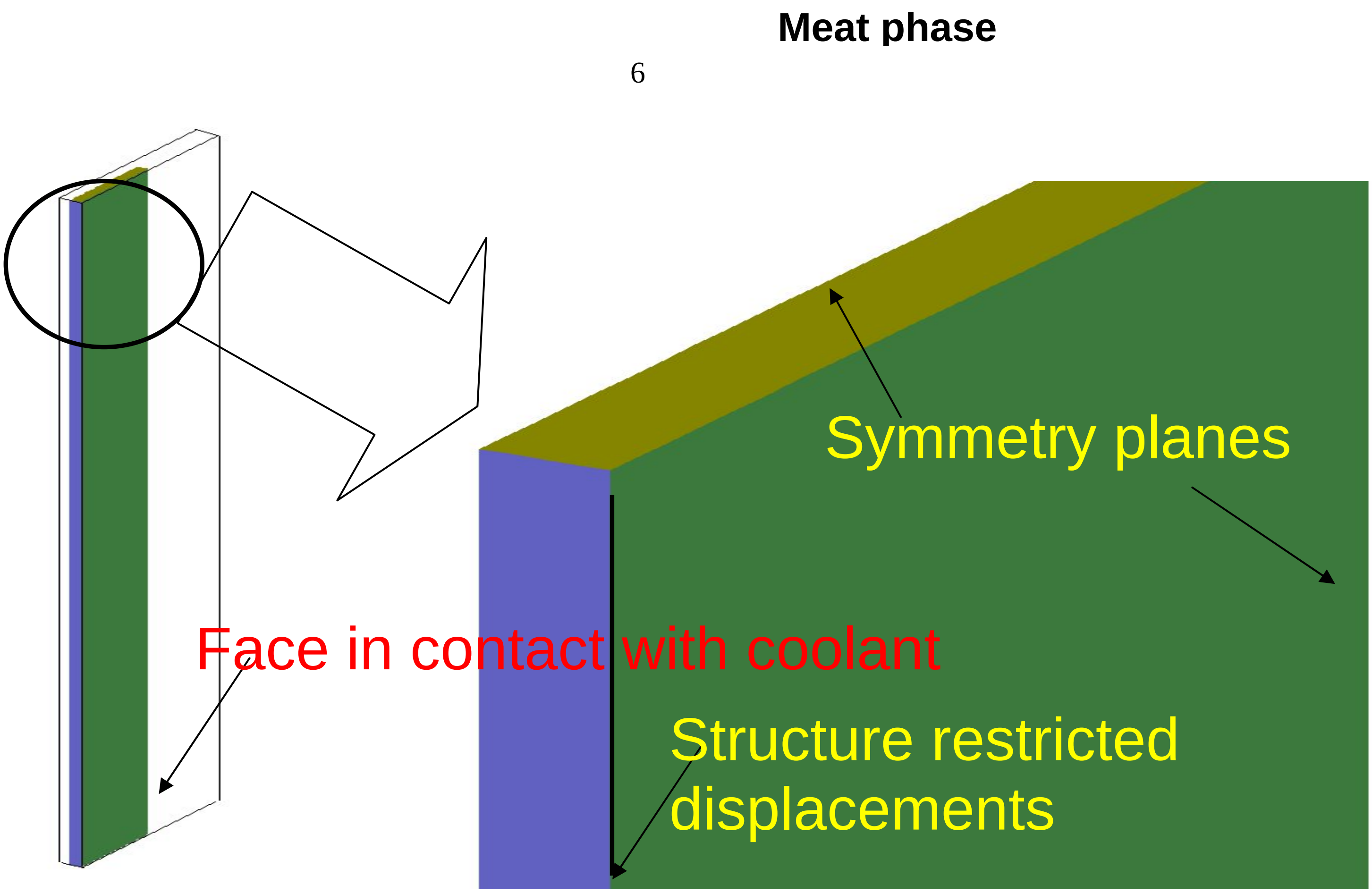
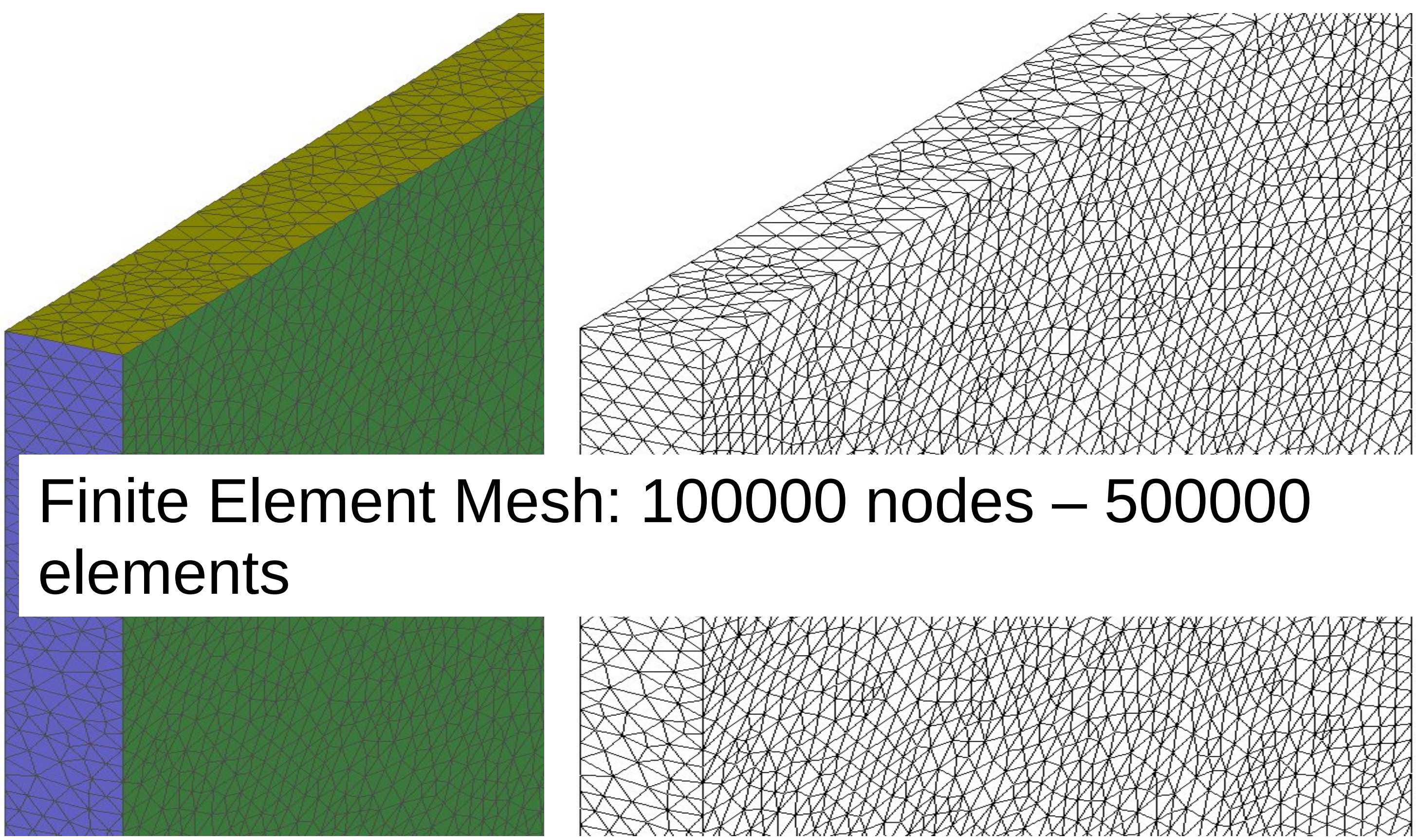


Fig. 1 Scheme of a transversal cut of a plate showing phases and interfaces

Figs. 2 and 3 Symmetry representation of a plate and nodal mesh



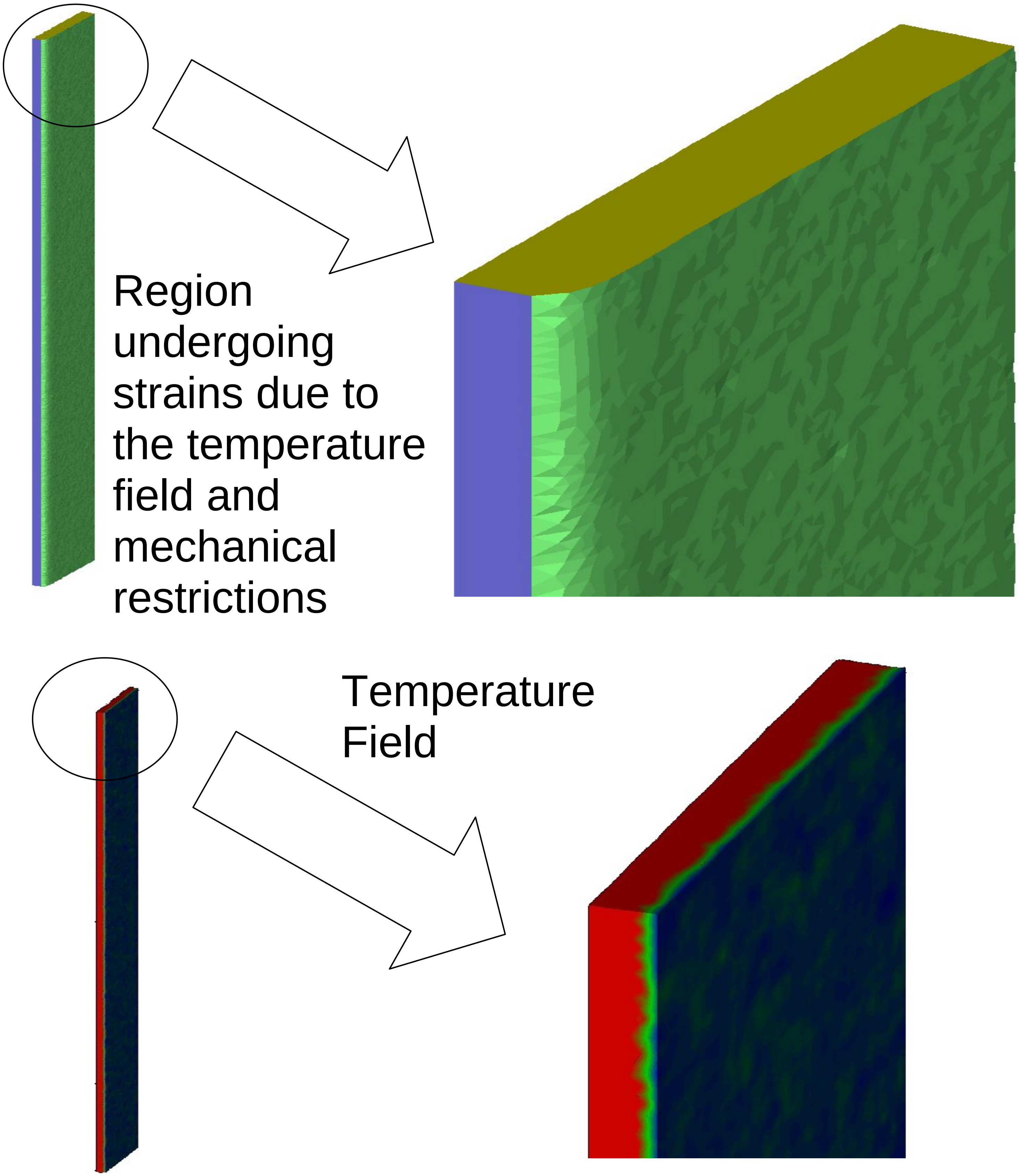


Fig. 4 and 5 Strain and temperature field representation

CONCLUSIONS:

In order address life-time issues associated with advanced very high-density monolithic fuel development, a new DART 3-D thermo-mechanical code, DART-TM is being developed. DART-TM is based upon an existing 3-D FEM thermal-elastic code named TERMELAS. DART-TM couples the thermal and stress evolution calculated by TERMELAS to the fission and reaction product swelling calculation provided by the FASTDART. This synergy includes models of oxide and reaction product layer growth and thermal conductivity evolution. The resulting code will undergo benchmarking and validation exercises. Subsequently, the introduction of plastic behavior due to creep phenomena will be implemented and the resulting code validated against experimental data.

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