DEVELOPMENT AND VALIDATION OF AN IMPROVED VERSION OF THE DART CODE

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ANL/USDOE and CNEA Argentina have been participating within a SisterLab Program in the area of Low Enriched Uranium Advanced Fuels 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 [1,2] optimization has been operative since February 8, 1999. Previously, as a part of this annex we developed a visual version of DART named FASTDART for silicide and U-Mo fuels that was presented at the RERTR Meeting in Las Vegas, Nevada [3].

This paper describes several major improvements in the FASTDART code: a thermal calculation subroutine, a fuel particle size distribution subroutine and several visual interfaces for thermal output plotting and particle size input.

Using the power history, coolant regime data and fuel dimensions, the new thermal subroutine is able to calculate at each time step the maximum temperature along the z-longitudinal axis as a function of plate/rod morphology (corrosion oxide, cladding, meat, aluminide particle layer, each radial shell of a central fuel particle, and particle center). Calculated temperatures at each time step are coupled to the DART calculation kernel such that swelling processes, volume phase fractions and meat thermal conductivity are calculated synergistically.

The new fuel particle size-distribution subroutine is essential in order to determine the evolution of the volume fraction of reaction product. This phase degrades the heat transport by a twofold mechanism: its appearance implies a diminution of aluminium phase and its thermal conductivity is lower than those of fuel and dispersant phase.

The new version includes the capability of plotting thermal data output by means of the plate/rod temperature profile at a given irradiation step, and displaying the maximum temperature evolution of each layer.

A comparison between the reaction layer thickness and matrix and fuel volume fractions of several RERTR-3 experiment miniplates and those calculated by DART THERMAL is included. A sound agreement was found which reveals an adequate DART THERMAL temperature calculation, since the layer grown depends strongly on temperature.

1 DEVELOPMENT OF A NEW THERMAL CALCULATION SUBROUTINE

This subroutine was programmed taking into account the following assumptions and limitations

- 1-D heat transfer
- Steady state reactor operating conditions
- DART THERMAL models Inlet coolant temperature and/or power changes as a suite of steady states (no transients)
- Neutronic flux cosine distribution along axial direction (i.e. no anisotropy is considered)

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The heat generated by nuclear fission inside fuel plates or rods is removed by means of a coolant stream circulating through the fuel assembly (FA). Heat transmission mechanisms are two. One considers no internal heat source, like in forced convection along fuel plate-coolant interface, conduction through external oxide layer and conduction through cladding. Special related issues related are:

- The dependence of coolant density and specific heat on temperature was modeled using the following fitting:

$$\rho(T)\ .\ Cp(T) \approx Amix\ cos\left(\frac{\pi}{wmix}(T - Tc)\right)^{*}$$

where Amix, wmix and Tc are constants.

- The coolant inlet temperature and the power density were used to state the equation of the coolant temperature *Tcool(z)* as a function of axial distance (z), that turns out to be

$$Tcool(z) = Tc + w/pi\ .\ arcsin\left\{\frac{q_m.2Lo}{V.Ac.Amix.wmix}\left[\sin\left(\frac{\pi.z}{2Lo}\right)+1\right]+\sin\left[\frac{\pi.}{wmix}(Ti - Tc)\right]\right\}$$

where

q_m : maximum linear power
Lo : extrapolated length
V : coolant velocity.
Ac : coolant channel cross section
Ti : inlet coolant temperature

By means of Dittus-Boelter equation the film coefficient *h(T)* was modeled. Some parameters are temperature dependant, so another fitting was used:

$$h(T) = \frac{V^{0.8}}{Dh^{0.2}}\ Ah\ sin[\frac{\pi}{wh}(Tcool(z) - xch)\ ]$$

where

x_{ch} , A_h:, w_h regression constants
V : coolant velocity.
Dh : hydraulic diameter

Oxide layer surface and cladding temperature were calculated using Fourier's Law.

Other heat transmission mechanisms include internal sources in the meat such as the reaction layer around a particle and the un-reacted portion of the particle. The thermal subroutine models each mechanism by taking into account the calculation of the meat thermal conductivity, the reaction layer (mostly considered to be $(U\text{-}xMo,Al)_3$ in the case of UMo fuel) and the fuel particle, divided into 50 equal volume shells. The particle thermal conductivity takes account of the effect of fission products. These temperature calculations are performed using Poisson's Law. The thermal subroutine finds the maximum temperature value for each region along the axial direction and the location of these maxima.

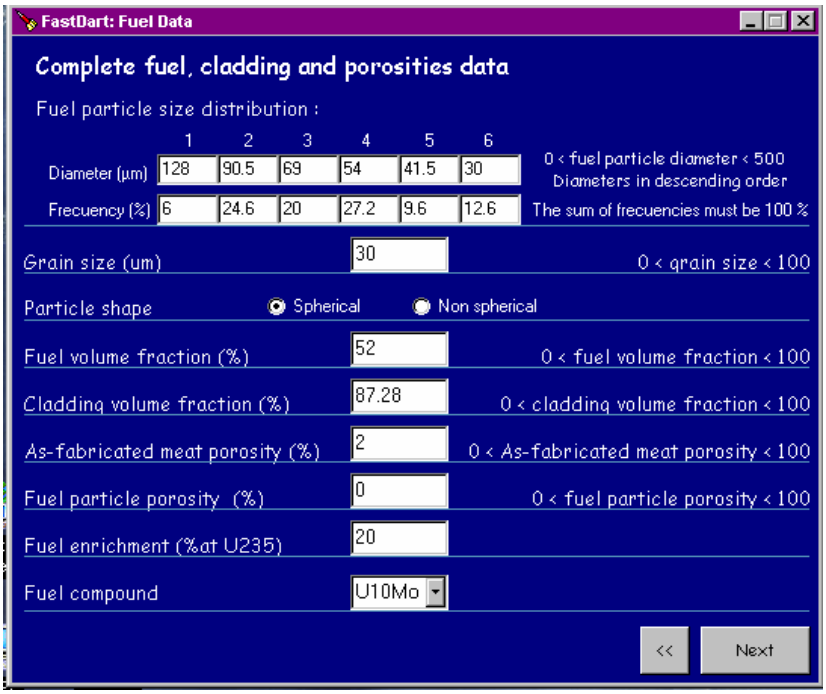
* Chemical Engineer's Handbook, R.H. Perry & C.H. Chilton McGraw-Hill Fifth edition

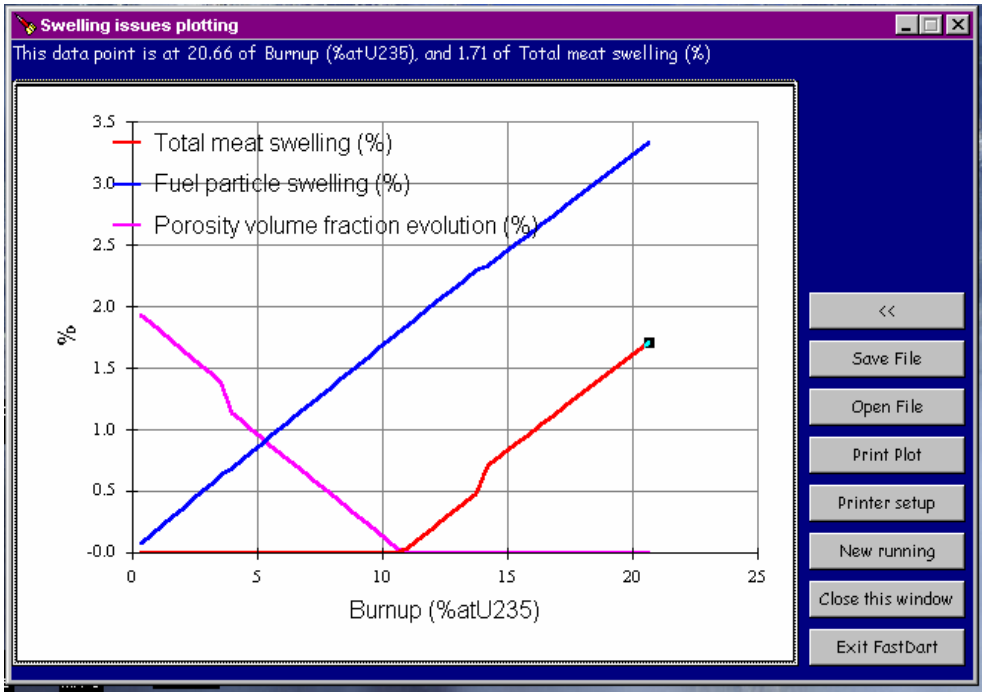
2 PARTICLE SIZE DISTRIBUTION MODELLING

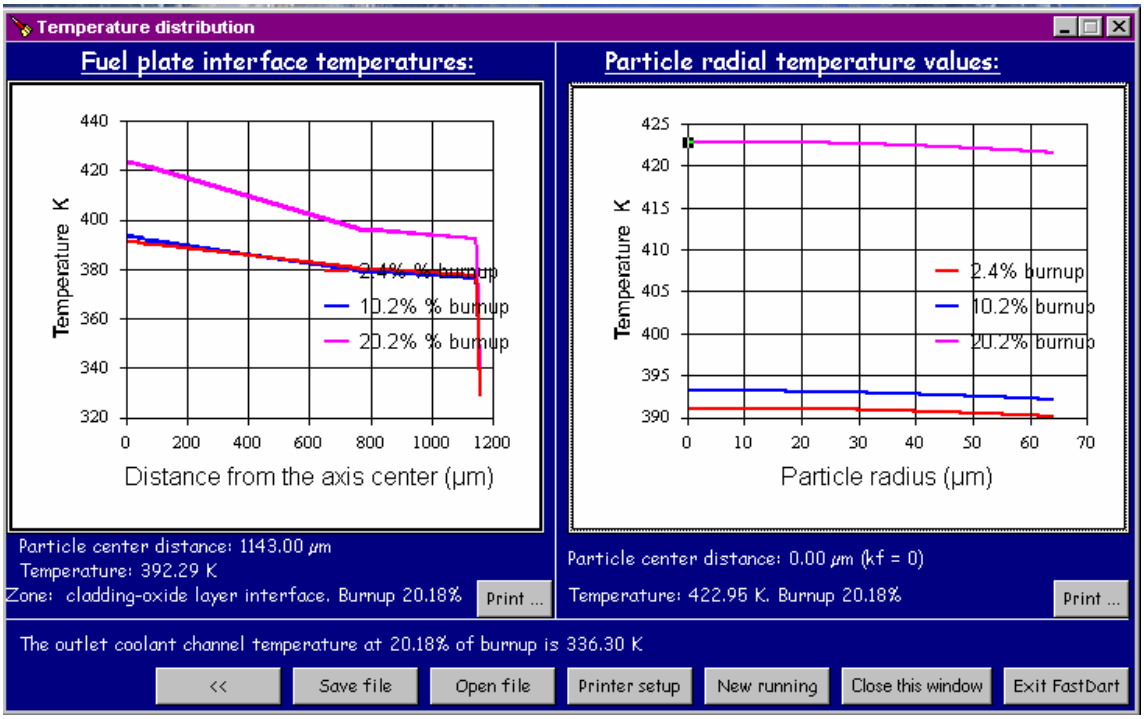
In order to consider the important effect of the interdiffusion of matrix Al and fuel particle U on the thermal performance of different kinds of fuels, a new particle size distribution formulation was incorporated into the DART code complex. This formulation also takes into account matrix-particle contiguity as well as the extrusion of matrix aluminium due to the swelling fuel particles. DART is able to predict the complete or partial alumization of particles in order to keep an adequate tracking of meat constituent volume fractions.

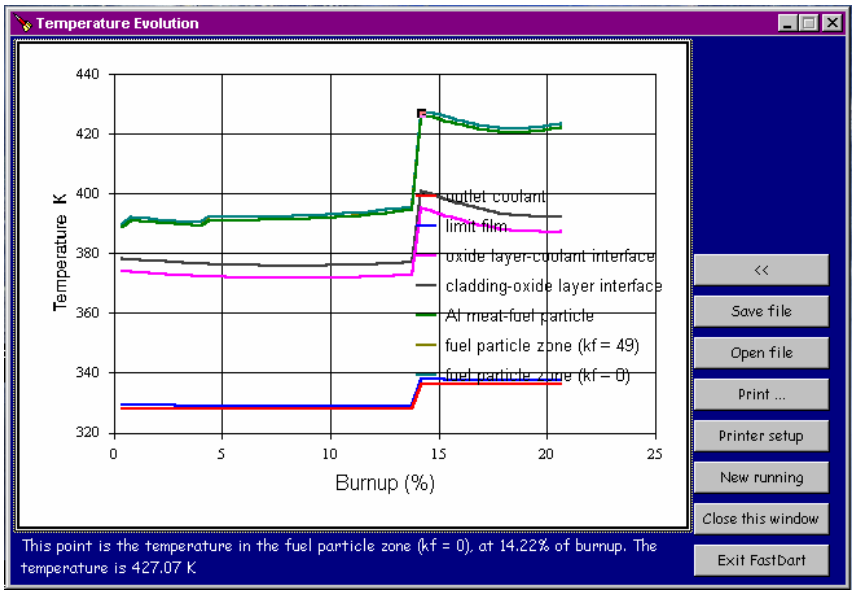
3 IMPROVED USER FRIENDLY INTERFACES

DART THERMAL has a complete set of input-output graphic interfaces that greatly facilitates case definition and extraction of information from the simulation. Several examples are shown, corresponding to case selection, fuel data input, calculation of meat swelling and temperature distribution and evolution.


FastDart: Fuel Data
Complete fuel, cladding and porosities data
Fuel particle size distribution :
1 2 3 4 5 6
Diameter (µm) 128 90.5 69 54 41.5 30
0 < fuel particle diameter < 500
Diameters in descending order
Frecuency (%) 6 24.6 20 27.2 9.6 12.6
The sum of frecuencies must be 100 %
Grain size (um) 30
0 < grain size < 100
Particle shape
Spherical
Non spherical
Fuel volume fraction (%) 52
0 < fuel volume fraction < 100
Cladding volume fraction (%) 87.28
0 < cladding volume fraction < 100
As-fabricated meat porosity (%) 2
0 < As-fabricated meat porosity < 100
Fuel particle porosity (%) 0
0 < fuel particle porosity < 100
Fuel enrichment (%at U235) 20
Fuel compound U10Mo
<<
Next


Swelling issues plotting
This data point is at 20.66 of Burnup (%atU235), and 1.71 of Total meat swelling (%)
Total meat swelling (%)
Fuel particle swelling (%)
Porosity volume fraction evolution (%)
%
Burnup (%atU235)
<<
Save File
Open File
Print Plot
Printer setup
New running
Close this window
Exit FastDart


Temperature distribution
Fuel plate interface temperatures:
Temperature K
Distance from the axis center (μm)
2.4% % burnup
10.2% % burnup
20.2% % burnup
Particle center distance: 1143.00 μm
Temperature: 392.29 K
Zone: cladding-oxide layer interface. Burnup 20.18%
Print ...
Particle radial temperature values:
Particle radius (μm)
2.4% burnup
10.2% burnup
20.2% burnup
Particle center distance: 0.00 μm (kf = 0)
Temperature: 422.95 K. Burnup 20.18%
Print ...
The outlet coolant channel temperature at 20.18% of burnup is 336.30 K
<<
Save file
Open file
Printer setup
New running
Close this window
Exit FastDart


Temperature Evolution
Temperature K
Burnup (%)
outlet coolant
limit film
oxide layer-coolant interface
cladding-oxide layer interface
Al meat-fuel particle
fuel particle zone (kf = 49)
fuel particle zone (kf = 0)
This point is the temperature in the fuel particle zone (kf = 0), at 14.22% of burnup. The temperature is 427.07 K
<<
Save file
Open file
Print ...
Printer setup
New running
Close this window
Exit FastDart

4 VALIDATION OF DART THERMAL CALCULATION AGAINST RERTR 3 EXPERIMENT

In order to validate the thermal models, the authors have performed simulations in order to compare DART THERMAL outputs to PIE data belonging to the RERTR 3 irradiation experiment. These simulations are currently in process. Recent results for two RERTR-3 miniplates are shown in the following table.

RERTR 3 EXPERIMENT	V07 U10Mo n-PLATE		S03 U6Mo n-PLATE	
	PIE	DART	PIE	DART
ALUM. VOL.% (EOL)	32,6%	34,2%	6,3%	6,0%
AVG.MEAT SWELLING %	2,3%	1,7%	7,7%	7,6%
REACTION THICKNESS (µm)	3,50	4,24	13,00	15,24

The calculation of the reaction product layer thickness is strongly dependent on the temperature. The agreement shown in the above table between the measured and calculated reaction layer thickness indicates that the maximum temperatures are being calculated satisfactorily. As the meat swelling and thermal conductivity are strongly coupled to the heat transfer calculation, the reasonable agreement between calculated and measured quantities shown in the table indicate that the DART thermal and swelling models are behaving satisfactorily. Subsequent to complete validation against RERTR-3 and RERTR-5 miniplate data DART-THERMAL will be used to analyse various fuel type/fuel geometry conditions, such as irradiation of U-10Mo monolithic fuel rods.

1. The DART Dispersion Analysis Research Tool: A Mechanistic Model for Predicting Fission- Product-Induced Swelling of Aluminum Dispersion Fuels. J. Rest, ANL-95/36. (1995).

2. *DART Model for Irradiation-Induced Swelling of Uranium Silicide Dispersion Fuel Elements*
J. Rest and G. L. Hofman. Nuclear Technology, Vol. 126, pp. 88-101 (April 1999).

2. *FASTDART: A Fast, Accurate and Friendly Version of DART Code*
J. Rest and H. Taboada (Comision Nacional de Energia Atomica)
Paper presented at 23rd Intl. Mtg. on Reduced Enrichment for Research and Test Reactors,
Las Vegas, Oct. 1-6, 2000.