MODIFICATION IN THE FUDA COMPUTER CODE TO PREDICT FUEL PERFORMANCE AT HIGH BURNUP

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Abstract

The computer code FUDA (FUel Design Analysis) participated in the blind exercises organized by the IAEA CRP (Co-ordinated Research Programme) on FUMEX (Fuel Modelling at Extended Burnup). While the code prediction compared well with the experiments at Halden under various parametric and operating conditions, the fission gas release and fission gas pressure were found to be slightly over-predicted, particularly at high burnups. In view of the results of 6 FUMEX cases, the main models and submodels of the code were reviewed and necessary improvements were made. The new version of the code FUDA MOD 2 is now able to predict fuel performance parameter for burn-ups up to 50000 MWD/TeU. The validation field of the code has been extended to prediction of thorium oxide fuel performance. An analysis of local deformations at pellet interfaces and near the end caps is carried out considering the hourglassing of the pellet by finite element technique.

1. INTRODUCTION

The Computer Code FUDA (Fuel Design Analysis) [1] is used to carry out design calculations and analyses for licensing submissions. The code is also used for fuel performance evaluation of operating pressurized Heavy Water Reactors (PHWRs) and feed back to designs [2,3]. Additionally the code is used for optimizing the fuel design and fabrication parameter for improved performance. Earlier the validation field of the FUDA code was limited upto a maximum burnup of about 15,000 MWD/TeU as obtaining in a PHWR for different parameters like fuel centre temperature, surface temperature, fission gas release, internal pressure, sheath stresses and strains.

FUDA-MOD 1 is originally based on FUDA MOD 0 [4]. The code is written in FORTRAN 77. It is running on Unix operating system on i860 workstation, on SINTRAN-III operating system on Norks Data Computer and as well as on PC-386/ 486 with MS.DOS operating system. The code consists of about 2000 lines. It can be linked with graphic package for pre and post processing. The code offers several options like different pellet geometries, different fuel and sheath materials, applications for PHWRs and LWRs, and analysis for load following or base load operations.

2. CODE DESCRIPTION AND MODELS

The computer code FUDA uses Finite Difference Method for temperature, thermal expansions, and sheath stress calculations. Local stresses and ridge analysis are carried out by finite element technique.

Fuel expansion is calculated using a two zone model in which the stresses in UO_2 are ignored. The model assumes that above a certain temperature, the UO_2 deforms plastically and below that temperature, it cracks radially and behaves as an elastic solid. The extent of plasticity is governed by the temperature of the UO_2, the stress imposed on it by sheath strength and the coolant pressure and is a function of time. In case of PHWR fuel element which uses a collapsible sheathing with low diametral clearances, the firm contact between the pellet and the sheath due to external pressure and diametral expansion, limits the relative fuel movement [5].

The fission gas generated is a function of burnup. The fission gas generated for each radial burnup zone is calculated as suggested by Southier [6]. A simple steady state and Transient Gas Release Model URGAS developed by K. Lassmann has been used for this analysis [7].

Fission gas pressure is calculated based on mass of the fission gas release, mass of the fill gas, available void volumes and temperature of storage locations.

Global sheath stresses and strains due to fuel thermal expansion, swelling and densification are calculated [8]. The creep and stress relaxation in the time zone at constant power operation is calculated using semi-empirical formula considering athermal and thermal creep including effect for irradiation. Fuel sheath interfacial pressure is then calculated based on gas pressure and strains. This shows whether the expanded fuel is touching the sheath or gas gap exists between them.

FLOW CHART

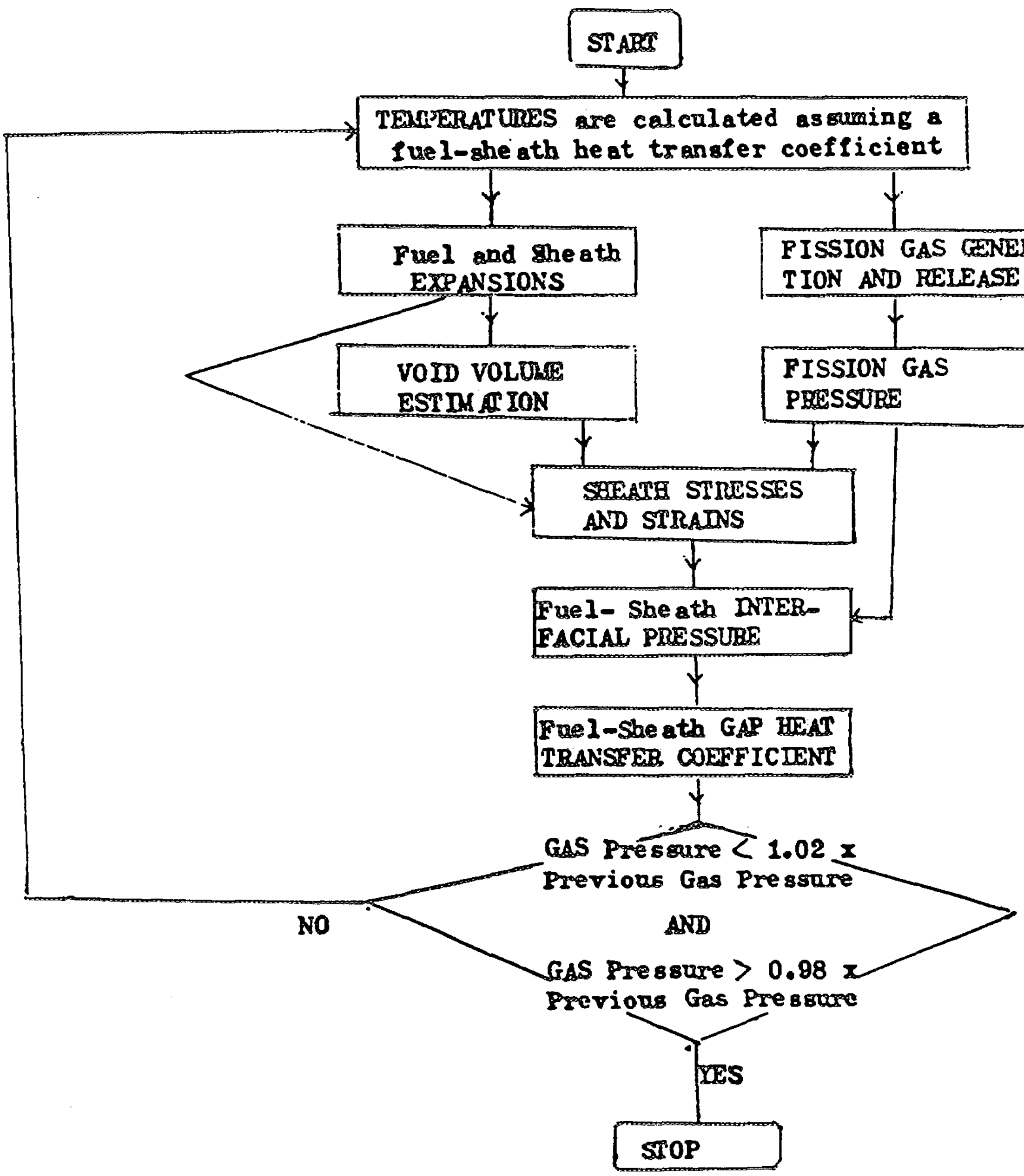

FIGURE - 1

Using global diametral changes, local deformations of the pellet and sheath are calculated considering hourglass phenomenon of the pellet. Finite element method using axisymmtric 8-noded isoparametric elements is used for calculating deformation, stresses and strains in pellet and in sheath [9].

The radial temperature distribution across the pellet and sheath are calculated for the given inputs of linear heat rating, coolant temperature and heat transfer coefficient. The components of the fuel-sheath heat transfer coefficient across the gas filled fuel-sheath gap through the solid-solid contact points are calculated using Ross and Stoute equation [10]. The gap conductance model URGAP by K. Lassmann has been referred for this purpose [11].

Using the new fuel-sheath heat transfer coefficient, new temperature distribution across fuel and sheath are calculated and the cycle is repeated iteratively. The iteration is terminated when two successive calculations of internal gas pressure agree within 5%. For any power change, the above iterative procedure is repeated for a given time zone till the required convergence is obtained. For improving accuracy, the pellet is divided into 100 rings radially and all the parameters are calculated for each ring. The radial flux depression in the element is taken into account in estimating powers in different rings. For radial flux depression calculation two options are available. The first one is using Bessell function with an inverse diffusion length, kappa value. The second option is using an equation fitted to the results of the neutron-physics code. This takes into account variation with burnup. Axial flux gradient in the fuel element can be handled by splitting the element into a number of equal lengths and considering each as being at an uniform power output [3] (Fig.1).

The following are the main models used in the code:

2.1 Flux depression in the pellet: The local flux perturbations affecting fuel design are radial flux depression through the bundle and flux peaking at the interface between adjacent fuel bundles in a channel. The radial distribution of flux is a function of pellet diameter, UO_2 enrichment and burnup and plutonium build up. Two options are included in this model viz., (i) Bessel function based and (ii) Based on PHWR physics codes which varies with burnup.

2.2 Film heat transfer co-efficient: Depending on the coolant condition and environment, sheath-to-coolant heat transfer is calculated. For forced flow through rod bundles, Dittus-Boelter equation is used. For BWRs, Jens-Lottes correlation is used.

2.3 Fuel-sheath gap heat transfer coeff.: Pellet clad gap conductance is calculated by Ross and Stoute model taking care of the physical gap existing between the pellet and the clad. Pellet-clad gap conductance consists of three parts

$$hg = hs + hf + hr$$

a) Conduction through solid-solid contact points (hs)

b) Convection through solid-gas interface (hf) and

c) Radiation exchange between pellet outer surface and clad inner surface (hr)

URGAP, a gap conductance model developed by K. Lassmann has been made use of for this analysis [11].

The heat transfer coefficient between the sheath and the pellet is a function of:

- radial gap/contact-pressure between the pellet and the sheath;
- the composition of gases inside the fuel element and gas pressure and
- the initial roughnesses of the surfaces of the sheath and of the pellet.

However, all these quantities are time-dependent, and consequently the quantitative data are uncertain because:

(1) Gap width and contact pressure are determined by uncertain fuel densification and swelling effects as well as by relocation effects (displacement of broken fuel fragments), apart from thermal expansion;

(2) gas pressure and gas composition depend on fission gas release, which is also uncertain.

(3) the surface characteristics change due to creep effects and chemical reactions, again in a manner which cannot be specified accurately.

In view of uncertain input parameter, more complicated models would not provide any better quantitative information. URGAP model is a simplistic heat transfer model for use in fuel rod modelling. URGAP model has been used in TRANSURANUS code. This model consists the gases helium, argon, krypton, xenon, nitrogen, hydrogen, oxygen, carbonmonoxide, carbon dioxide and water (steam). It considers the fuel surfaces UO_2, (U, Pu)O_2, UC, (U, Pu)C, UN,(U, Pu)N and the cladding surfaces Zr, ZrO_2, Fe, fuel, Fe_3O_2.

2.4 Fuel Thermal Conductivity: Thermal conductivity variation with temperature and porosity is considered. The low temperature radiation damage is considered by assuming the UO_2 conductivity below 500°C as constant. Pellet temperature profile is calculated by dividing pellet into a number of concentric rings, normally 100. Temperature is calculated from surface to centre using finite difference method.

2.5 Fission Gas Release: There are two models incorporated in FUDA for fission gas release.

i) Temperature dependent release mechanism.

ii) Physical model based on diffusion and grain growth mechanism - Both equiaxed and columnar grain growth are treated. Equiaxed grain growth is calculated based on local temperature, UO_2 enrichment and grain size. Fission gases are assumed to diffuse through UO_2 grains, the amount of diffusion being dependent amongst others on local temperature and grain diameter. The bubbles accumulated on the grain boundary grow in size and coalesce before releasing to the gap through the tunnels/cracks [12].

URGAS, a Simple steady state and Transient Gas Release Model by K. Lassmann has been used for numerical treatment and implementation of diffusion model of fission gas release [7]. URGAS is a simple gas release model based on the concept of an effective diffusion coefficient. The model is defined by an incremental algorithm that can accommodate temperature and burnup dependent diffusion parameters as well as a variable power history. By choosing the appropriate effective diffusion coefficient gas release from all fuels like oxide, mixed oxide, carbide, nitride can be modelled. It is in reasonable agreement with the ANS-5.4 model which has been validated against a large data base, but overcomes the problem of large storage requirements faced by ANS-5.4.

In view of the results of the FUMEX (Fuel Modelling at Extended Burnup) cases, the above modified models were implemented in the code. In particular fission gas release model URGAS by K. Lassmann is made use of to take into account the higher burnup effects based on physically based models. The code resulting from the implementation of these modification, namely FUDA-MOD 2, is now able to predict fuel performance parameters for burnups upto 50000 MWD/TeU.

3. VALIDATION

Validation field consists of different parameters like fuel centre temperature, surface temperature, fission gas release, sheath strain (plastic upto a burnup of 50,000 MWD/Te U against end of life parameters measured after irradiation experiments. Variation of fission gas pressure with burnup is compared with available instrumented data from irradiation experiments. The different parameters are also compared with results obtained with other similar computer codes like ELESIM, ELESTRES etc.

The validation is based on, power reactor data, comparison with other codes, literature on results of inpile experiments conducted abroad and inpile experiments conducted in India and post irradiation examination.

Special irradiation experiments were carried out in power reactors with various design and fabrication variables such as fully annealed cladding, high grain size UO_2 pellets upto 400 microns and thorium bundles [13,14,15]. The validation field of the code has also been extended to these special irradiations including predictions of thorium oxide fuel performance. Thorium is being irradiated in research reactors DHRUVA and CIRUS. In KAPP-1 35 bundles of Thorium dioxide have been introduced into initial core for the purpose of flux flattening. Before this, ThO_2 bundles were test irradiated in MAPS-1 reactor to prove the design of the bundles. The calculations and analyses for licencing submissions for thorium bundles were also carried out using FUDA.

4. CONCLUSIONS:

1. FUMEX bench marking exercise for fuel performance codes has helped considerably in improving various models and submodels used in FUDA.

2. The gap conductance model URGAP by K. Lassmann has been used for prediction of fuel-sheath heat transfer coefficient in modified version of FUDA, viz, FUDA-MOD 2.

3. The Fission Gas Release Model URGAS by K. Lassmann has been used for prediction of fission gas release by diffusion mechanism.

4. The code has been updated, with improved models, to predict fuel performance parameters for burnups upto 50000 MWD/TeU.

5. With new version of the Code FUDA-MOD 2, the accuracy of Prediction of parameters compared to experimental results of FUMEX benchmarking exercises has been significantly improved.

6. The validation field of the code has been extended to special irradiation experiments in power reactors including thorium oxide fuel.

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