The modeling experience of fuel element units operation under MSC. MARC&MENTAT 2008R1

A.A. Bochvar High-Technology Research Institute of Inorganic Materials, 123060, Moscow, Russia (VNIINM)

Abstract

MSC Software is leading developer of CAE-software in the world, so behaviour of fuel elements modeling with MSC.MARC use is of great practical importance.

Behaviour of fuel elements usually is modeled in the elastic-viscous-plastic statement with account on fuel swelling during irradiation. For container type fuel elements contact interaction between fuel pellets and cladding or other parts of fuel element in top and bottom plugs must be in account.

Results of simulated behaviour of various type fuel elements – container type fuel elements for PWR and RBMK reactors, dispersion type fuel elements for research reactors.

1. Introduction

The specific feature of the MSC.MARC [1] software is the feasibility of solving fully coupled highly non-linear problems that investigate the thermomechanical behaviour of a design with due account for automatic contact interactions between unlimited number of bodies having changeable properties without any simplifications of geometrical shapes. The more so, MSC.MARC 2008 has easy to control and simple interface and upon modeling multicontact interactions as distinct from other CAE systems. MARC does not need any special «interface» or «intermediate» elements between contacting bodies or surfaces.

The authors accomplished modeling PWR fuel element components under some reactor operating condition that in needed for preliminary designing. The feasibility in principle is shown and examples of modeling in the MSC.MARC software medium are given pertaining to the following problems [2]:

- thermomechanical multicontact interactions between fuel pellets and a plug fitting under unsteady-state operation conditions (start-up and power density peaking conditions);
- influence of cracked fuel fragments on stresses and strains;
- instantaneous cladding collapse in 3D statement;
- technological operation of fuel column lock placing into cladding;
- technological operation of fuel pellet pressing during manufacturing in 3D statement.
In all the instances discussed below the fuel pellet material is uranium dioxide, the material of the claddings and end pieces is zirconium alloy E110 [3].

Also stress and strains modeling for research reactor dispersion fuels developed by VNIINM are given. Analysis of calculations results allows selecting the best version for further development and in-pile research.

2. Modeling thermomechanical multicontact interaction between fuel pellets and plug fitting under non-steady-state operation conditions

With using of **MSC.MARC** behavior of local areas of fuel elements under non-steady-state operation conditions such as start-up conditions, conditions of power density peaking, **LOCA** and **RIA** conditions can be modeled. In simulating as an example consideration was given to a local area of the bottom plug fitting of a fuel element with three pellets under conditions of power density peaking; its virtual model is shown in figure 1. Multicontact interaction was modeled with account for the isotropic creep and plasticity of materials, temperature dependence of material properties, changes in power density and boundary conditions vs time with account for the wedging of the third pellet from the plug fitting.

It has been assumed that at the moment of power density peaking the radial fuel-cladding gap as well as significant stresses in the plug fitting clad are not available 20% power risk from 180 W/cm after 20 sec. is modeled using heat transfer for the fuel-cladding gap coefficients values from integral code **Start** (developed by VNIINM). First using thermal option the temperature field in the bottom plug fitting was simulated. Then using Coupled, Contact and Pre-State options (to account for the obtained temperature values) the non-steady state related thermomechanical multicontact problem was solved to investigate the conditions of power density peaking. Figures 2-4 illustrate the results of modeling which evidence that the temperature and stress values do not exceed the critical ones for the cladding material. The values of the hoop stresses at the pellet joints under consideration are shown in figure 5. It is seen that values of the hoop stresses at the pellet joints might increase by 10 MPa.
Figure 1 – Virtual image of PWR fuel bottom plug fitting

Figure 2 – Distributions of temperatures (°C) in bottom plug fitting at end of power density peaking

Figure 3 – Distributions of axial stresses (MPa) in bottom plug fitting at end of power density peaking
2.1 Influence of Fuel Fragment Cracking for stress and strains in fuel cladding

In the operation process the cracking of fuel is possible in various directions which breaks the integrity of pellets and might influence the distribution of stresses and strains in fuel cladding. To assess the influence of cracking the above presented procedure is used, however, for the plane-stress deforming. Of the feasible configurations of pellet cracking shown in figure 6 two extreme cases were considered: with a single radial crack (figure 7) that as a rule has the most intensive influence on stresses and strains of a cladding and with randomly cracked fuel.

It is evident from figures 7-9 that under the considered conditions of power density peaking a radial crack might increase hoop stresses by 20 MPa. Cracks available in large quantities substantially lower down the cladding load.
3 Modeling instantaneous cladding collapse

Stress and strains calculations for cladding stressed with outer pressure is needed to assess possibility of instantaneous cladding collapse. With MSC MARC it is possible to model loss of cladding stability using **Buckle** option. As an example cladding area without initial ovality under outer pressure 12 MPa with fixed ends is considered. The example of hoop stresses calculation (with enlarged strains shape) for static equilibrium form and for last loss of stability form is illustrated in figures 10 and 11.
4. Modeling behaviour of fuel column fixing lock

PWR fuel elements make use of a spring lock for fixing a fuel column that has compensating and fixing groups of coils (see figure 12). The compensating group of the coils is the main element of the fixing lock. It ensures the needed force for compressing the fuel which prevents the loss of tightness by the fuel column in the process of all technologic operations including transportation and loading into a reactor as well as in the operation process. The fixing group of coils promotes the guaranteed wedging of the fixing lock in the cladding to avoid the fixing lock relocation within the cladding during technologic operations and in the operation process.
4.1 Modeling behaviour of compensating part of fixing lock

Stresses and Strains of the coils in the compensating part of the fixing lock was obtained for two loading stages:

- fixing lock positioning in fuel element at the total compression of 22 mm followed by 3h increase of compression to 42 mm corresponded to reaching the terminal power;
- compression increase to 67 mm by swelling during 25000 hours with account for creep of fixing lock material.

The axial relocation $U$ was specified depending on the current coil compression value: $U_Z = -d_l/n_k$, where $d_l$ – current coil compression value; $n_k$ – number of coils.

Distribution of tangential stresses in cylindrical coordinates is shown in figures 13 and 14. It might be seen that spring compressed and for 25000 hours maximal tangential stresses decreased in 2,5 times. In this case Reaction Force $Z$ which corresponds to the compression force increases to reach 40 N and the slowly goes down to 16 N with account for creep of fixing lock material.
4.2 Modeling technologic process of fixing lock installation into cladding

Experience of modeling technologic process of fixing lock installation into cladding shows that modeling near to technologic process is possible one (see figure 15) but it needs too much resources for the present. So now we use simplified procedure of modeling of fixing lock installation into cladding in accordance with computers resources. We use option **DYNAMIC TRANSIENT** with **3D-solid** elements of **type 7** and options with account of geometric non-linearity of fixing lock and cladding. For contact interaction option **CONTACT** is used. Results of calculations at previous step transfers to next one with use of option **PREVIOUS ANALYSIS STATE**. Modeling is divided into several steps, one after another for the virtual image (see figures 16-17).

Step 1. Fixing part of fixing lock stretching for its diameter decreasing on fixing part stress value.

Step 2. Cladding pulling over stretched fixing lock, initial velocity specifies depend on this stress, friction, fixing lock and cladding length.

Step 3. Top and bottom parts of fixing lock unfixing and following self-installation for elastic forces till equilibrium friction forces (cladding and fixing lock) vs elastic ones.

Step 4. Compensating part coils axial relocation specifies with compression value assessed during installation for efficiency of fixing part testing (lack of displacement for all or several fixing part coils).

For this procedure’s verification installation of fixing lock of fuel rod was modeled. Calculations were done for fuel rods with X-ray photographic research of fixing lock position in cladding. Modeled installation fixing lock position is shown in figures 18, 19 compared with X-ray photograph of fixing lock installed in cladding. Fixing lock fixing part installation step is in good agreement with results of modeling. Distribution of tangential stresses in experimental fuel rod cladding after fixing lock installation is shown in figure 20. Hoop stress values don’t exceed 102 MPa. Distribution of tangential stresses in fixing lock coils after its installation is shown in figure 21. Their values don’t exceed permissible limit. Therefore with account of experimental and modeled results simplified procedure of modeling may be used to assess stresses and strains in cladding and fixing part of fixing lock by fixing lock installation.
Figure 15 – Real scheme of modeling technologic process and fixing lock for RBMK fuel element

Figure 16 – Fixing lock stretching and cladding pulling on (steps 1 and 2)
Figure 17 - Fixing lock self-installation for elastic forces with following additional pressing for lack of displacement test (steps 3 and 4)
Figure 18 - Modeled installation fixing lock position

Figure 19 - X-ray photograph of experimental fuel element

Figure 20 - Distribution of hoop stresses (MPa) in experimental fuel element cladding after fixing lock installation

Figure 21 - Distribution of tangential stresses (MPa) in fixing lock coils
5. Modeling of technological operation of fuel pellet pressing during manufacturing

Modeling is aimed at assessment of relative distributions of density, stress and strains in fuel pellet during pressing. Such assessment might optimize geometric pellet configuration (face incline, hole depth) and technological operation of pressing itself. We consider simplified process of one-side pressing with account of friction for option Material powder display. For modeling of process we use Solid-type elements (type 7), rigid-surfaces and Material-powder, Mechanical, Contact - rigid-velocity options. Virtual image of technological operation of fuel pellet pressing is shown in figure 22. Modeling distribution of relative density is shown in figure 23. Figure 23 shows that relative density is changing during pressing from initial value 0.7 to 0.98.

![Virtual image of technological operation of fuel pellet pressing](image1)
![Modeling distribution of relative density in the end of pressing](image2)
6 Simulating of Research Reactor Fuel Elements

In the frame of the International Program RERTR the work is in progress to license U-Mo alloy base dispersion fuel. VNIINM develops new rod type fuel elements for research reactors.

The appearance of rod type fuel element illustrated in figure 24 [5,7].

![Design of rod type fuel element](image)

Figure 24 - Design of rod type fuel element

Analysis of results of postirradiation examination was shown that at high burnups a substantive U-Mo fuel – Al matrix interaction is observable [4-7]. This interaction leads to heat conductivity decreasing, open porosity and fission gas products release in central areas of fuel meat. On account of such fuel behaviour cladding failure is possible with fission product release into coolant.

One way to decrease U-Mo fuel – Al matrix interaction is monolithic fuel element development. VNIINM develops rod type fuel elements with aluminum [8] and zirconium alloys claddings and cylindrical rod of U-Mo alloy. It is known that no interaction between zirconium alloys (one side) and aluminum matrix and U-Mo alloy (another side) for cladding temperatures. So in 2 variants fuel U-Mo rod coated with additional zirconium alloy E110 cladding preventing U-Mo fuel – aluminum alloy interaction. Cross sections of developing fuel elements are shown in figure 25.

The stress and strains for rod type fuel elements was modeled using **MSC. Marc Mentat** with account on irradiation condition in MIR reactor till 80 % fission of U-235 atoms (see figure 25). The problem is resolved in the elastic-viscous-plastic statement with account on fuel swelling during irradiation.
Figure 25 - Cross sections of developing monolithic fuel elements. Monolithic fuel rod is shown by yellow colour; cladding of aluminum alloy – green; zirconium alloy cladding – blue; aluminum alloy with silicon (matrix) – grey. Upper figures shows initial cross sections; lower ones – deformed under irradiation cross-sections.

Distribution of hoop stresses across additional and basic claddings sections for fuel elements with cladding of aluminum alloy is shown in figure 26, for fuel elements with cladding of zirconium alloy is shown in figure 27. It is evident that additional cladding not only prevents U-Mo / Al interaction but also decreases basic cladding strain. That is important because basic cladding is main barrier to fix fission products in fuel meat.
Figure 26 – Distribution of hoop stresses across claddings sections
Cross sections strain parameters are shown in table. It is evident that the least cladding strains are for cross-form fuel element with cladding of zirconium alloy E110. This fuel element was chosen for further development and irradiation examination in MIR reactor.
### Table - Cross sections of fuel elements strain parameters

<table>
<thead>
<tr>
<th>Fuel element type</th>
<th>Increase of cross section square, $\Delta S/S, %$</th>
<th>Increase of outer diameter, $\Delta D/D, %$</th>
<th>Increase of square size (or inner diameter), $\Delta d/d, %$</th>
<th>Highest value of hoop stress at outer/inner cladding surface, $\varepsilon_{\text{max}}, %$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Additional cladding</td>
</tr>
<tr>
<td></td>
<td>4.9</td>
<td>1.6</td>
<td>3.8</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>4.6</td>
<td>1.6</td>
<td>3.1</td>
<td>13.7/22.4</td>
</tr>
<tr>
<td></td>
<td>4.9</td>
<td>1.7</td>
<td>3.8</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>5.7</td>
<td>1.4</td>
<td>8.3</td>
<td>14.4/20.4</td>
</tr>
</tbody>
</table>

### Conclusion

The usage of **MSC.MARC** allow to model behaviour of various type fuel elements – container type fuel elements for PWR and RBMK reactors, dispersion type fuel elements for research reactors. Results of modeling are in use for fuel elements designing including experimental fuel in-pile examinations and serial fuel elements exploitation.
References

1. MSC.MARC&MENTAT. Лицензионное свидетельство EC 9068 от 15 мая 2000.

2. Кузнецов А.В., Каширин Б.А., Новиков В.В., Медведев А.В. Опыт моделирования поведения элементов конструкции твэлов ВВЭР в среде MSC&MARC. Доклад на международной конференции по вопросам обеспечения безопасности АЭС с ВВЭР, Подольск, Россия, май 2007.

3. Ю.К. Бибилашвили. Свойства материала оболочек и топливных таблеток твэлов реактора ВВЭР. ВНИИНМ № 312-0-001, Москва, 1983.


