Requirements for Extending the FAST Code for Transient Simulation of Nuclear Fuel

A. Prudil[1], B.J. Lewis and P. Chan
Chemistry and Chemical Engineering Department
Royal Military College of Canada, PO Box 17000, Kingston, Ontario, Canada
[1]Andrew.Prudil@rmc.ca

Abstract

The Fuel and Sheath modelling Tool (FAST) code is a finite-element model for the simulation of in-reactor fuel performance under Normal Operating Conditions (NOC) conditions. It has been tested and shows excellent agreement with other models and experimental results. This paper provides an overview of the steps necessary to extend the model for simulation of nuclear fuel during reactor transient or accident conditions. This would make the FAST code the first unified fuel performance model for CANDU fuel.

1. Introduction

Nuclear-fuel modelling codes have always been developed based on the computing resources available at the time. Until recently, this necessitated using one-dimensional representations of fuel-elements to reduce the computation expense of the models to manageable levels. One common method for reducing the complexity of fuel modelling codes has been to provide separate codes for NOC and transient/accident conditions. This is the case for both CANDU and LWR fuel modelling codes, where the steady-state (NOC) codes are used to provide initial conditions for the transient code analysis. The CANDU codes are ELESTRES and ELOCA, which are the NOC and transient codes, respectively, while the LWR equivalents are FRAPCON and FRAPTRAN.

NOC codes are required to model fuel performance for periods ranging from several days to more than a year for CANDU fuel performance analysis and more than 5 years for LWR fuel analysis. For this reason NOC codes such as ELESTRES and FRAPCON neglect many comparatively fast phenomena. For ELESTRES, these simplifications include using steady-state heat transfer and assuming a collapsed fuel sheath (as per design).

The transient codes, as the name suggests, are used for modelling the effects of fast transients such as loss of coolant accidents (LOCA) or power pulse phenomena in reactors. These codes are typically required to model fuel on the time-scale of several minutes. This is far shorter than may be required to achieve equilibrium; therefore, complete time-dependent models must be used. Because of the short time scale, transient codes make a number of assumptions regarding long time-scale phenomena. This includes neglecting fission gas release, fission product swelling and densification. As mentioned, both the ELOCA and FRAPTRAN codes utilizeNOC codes to establish the initial conditions prior to a transient simulation.

In the time since these models were created, advancements in both computer hardware and software have expanded modelling capabilities beyond previous limitations. The limitations imposed by RAM size, processing speed and data-storage continue to be pushed back allowing for the implementation of more computationally-expensive models. The availability of these computing resources has made feasible a new generation of modelling tools which require fewer simplifying assumptions and provide more accurate results than those previously available.

For example, the ELESTRES code uses a one-dimensional geometry for everything except for the solid-mechanics, which is based on a two-dimensional geometry. At RMC, fully coupled multiphysicsmodelling approaches have been used to develop two-dimensional fuel performance codes for NOC[1–4]. Recent work has improved these models by including detailed pellet and sheath geometriesand improved contact phenomena resulting in the Fuel And Sheath modelling Tool (FAST).The FAST code is a general purpose fuel performance code forNOC with an emphasis on modelling the deformation of the fuel pellet and sheath. The development work is now focused on extending the capabilities for accident and transient conditions.

2. Current Model

The capabilities of the FAST code is briefly summarized below, a paper entitled “Development of the FAST Code for Modelling CANDU Fuel” is also presented at this conference which includes more information.

The FAST code is a collection of separate effects models which have been coupled together and are solved simultaneously using the ComsolMultiphysics finite-element platform. The code includes models for deformation due to thermal-expansion, elastic strain, densification and swelling of the fuel, contact forces, internal gas pressure, external coolant pressure, as well as two sources of creep in the sheath. The temperature distribution in the fuel element is calculated including a heat source with flux depression and 1-dimensional models for the pellet-to-sheath gap and sheath-to-coolant heat-transfer. The pellet model includes models for the grain growth of UO_2 and a two-stage fission gas release model. The sheath model includes anisotropic thermal-expansion and creep.

This model has evolved from previous treatments developed at the Royal Military College of Canada (RMC) developed by Morgan and Shaheen[1–4]. The model is a finite-element representation of a quarter cross-section of a fuel pellet and sheath in the radial-axial plane. The geometry includes the dishing of the pellet faces and chamfering of the pellet edges. The inclusion of these features allowthe model to predict circumferential ridging of the sheath during NOC.

The FAST code has been benchmarked against the ELESTRES-IST (Industrial Standard Toolset) and ELESIM fuel performance codes and validated against experimental post-irradiation data from six fuel elements. Through this validation the FAST code is shown to produce results in excellent agreement with other modelling codes and the experimental measurements. An analysis of the sensitivity of the model to the uncertainty in input parameters and the material properties has also been conducted.

3. Extension for Transient Conditions

The goal for the expanded model is to incorporate high temperature and transient models into the FAST code resulting in a single unified fuel performance code. A unified code offers several advantages over the use of separate codes for NOC and transient analysis. First, it allows seamless simulation of the transition between time scales. This allows the code to simulate multiple transitions between NOC and accident conditions which arenot currently possible using the ELESTRES and ELOCA codes. The flexible time-stepping also allows the model to incorporate more realistic element power histories. Second, it allows many phenomena to be considered simultaneously rather than based on limited and predetermined scenarios. Finally, a single code is easier to maintain as it also ensures consistency between the modelledNOC and transient phenomena.

The TRANSURANUS and FEMAXI codes are the only major fuel modelling codes that include integrated NOC and transient models. The TRANSURANUS code is developed by the Institute for Transuranium Elements (Europe) and the FEMAXI code developed by the Nuclear Safety Research Centre in Japan[5,6]. A number of other advanced codes are still underdevelopment which are also expected to include these capabilities such as the AMP[7] and BISION[8] codes from the USA CASL program.All of these codes were developed for LWR fuel and as such are not directly applicable to CANDU fuel. The FAST code would therefore be the first combined NOC and transient model for CANDU fuel.

In order to expand the FAST code for transient conditions, a number of upgrades and additions would be required:

1. The high temperature alpha-to-beta transition creep would need to be added to the code. The model for this creep mechanism requires calculating the alpha phase volume fraction of the sheath and therefore must be included in the model. A model for this type of creep is available from the work of Holt and Sills[9,10].

2. During accident conditions, the fuel sheath may reach temperatures high enough to undergo an oxidation reaction with the coolant water. This reaction produces a region of ZrO_2 which is brittle and can lead to enhanced crack propagation and strains due to lattice expansion. A model for the oxidation of the fuel sheath at high temperatures is available from the work of Iglesias *et al*.[11].

3. In the current model, the sheath-to-coolant heat transfer coefficient is constant. This parameter needs to be made as a variable to allow for the modelling of loss of coolant accidents. The sheath-to-coolant heat transfer coefficients are obtained from thermal-hydraulic codes such ASSERT or CATHENA and are considered inputs to the FAST code.

4. At elevated temperatures, the internal gas pressure of the element may exceed the coolant pressure. This results in a degradation of fuel-to-sheath thermal conductivity which further increases the temperature and pressure through positive feedback. Eventually, the sheath may lift-off from the fuel surface. This could lead to sheath ballooning phenomenon where the fuel sheath deforms locally, further weakening the sheath and accelerating the

deformation process. A model for this phenomenon is required to predict fuel failure due to sheath ballooning.

5. The radiative component of the heat transfer across the pellet-to-sheath gap is not considered for NOC since any heat transfer is dominated by the conductionmechanism. During accident conditions, however, such as a large break LOCA, however, the radiative component of the fuel-to-sheath heat transfer coefficient may become significant and must therefore be added to the model.

6. Modelling accident scenarios such as a loss of coolant accident is a highly non-linear problem. The high degree of non-linearity can be difficult for implicit time-stepping algorithms to model because the algorithm must transition from large time-steps during steady operation to short time-steps during the transient situation. This requires appropriate time-stepping parameters to maintain solution robustness while minimizing the computational time for the solution.

7. The fuel failure criteria must be added to the model so that it can be used to determine if the fuel fails during the simulation. The failure criteria relevant for CANDU fuel have been summarized by Lewis *et al*[12].

8. After adding the new separate effect models to the FAST code it must be revalidated for both NOC and transient conditions. Although the changes are not expected to significantly influence the results of the NOC simulations, this must also be validated through comparisons with post irradiation measurements and by code-to-code comparison. The transient models can be validated against experimental data as well as code-to-code comparisons with ELOCA.

Once these tasks have been completed, the FAST code would have includedthe mostimportant phenomenafor the modellingof transient CANDU fuel behaviour.

4. Discussion and Conclusions

The FAST code for NOC application has been tested and shows excellent agreement with other models and experimental results.FAST has many potential applications, including its ability to assess advanced fuel designsand determine the effect of new separate effects models which can easily be implemented within the multiphysicsarchitecture of the code.

Thedevelopment tasks necessary to include transient functionality have been identified and are progressing well as a thesis project. The development of FAST code into a unified NOC and transient fuel performance tool will further expand its potential applications for CANDU fuel analysis.

5. Acknowledgements

The authors would like to acknowledge the support of our colleagues at RMC as well asA. Williams,B. Leitch and J. Baschuk fromCRL for discussion on fuel modelling. Funding for this work was provided byNSERC, UNENE andCOGthrough the Industrial Research Chair (IRC) program and an ORF grant.

6. References

[1] D. Morgan, “A thermomechanical model of CANDU fuel,” MASc Thesis, Royal Military College of Canada, Kingston, Ontario, 2007.

[2] K. Shaheen, “A mechanistic code for intact and defective nuclear fuel element performance,” Royal Military College of Canada, Kingston, Ontario, 2011.

[3] K. Shaheen, J. S. Bell, A. Prudil, and B. J. Lewis,, “Modelling CANDU Fuel Element and Bundle Behaviour for Performance of Intact and Defective Fuel,” in *Proceedings of the International Conference on the Future of Heavy Water Reactors*, Ottawa, Ontario, 2011.

[4] K. Shaheen and B. J. Lewis, “Platform-Based Modelling of Intact and Defective Fuel Behaviour,” in *Proceedings of Top Fuel 2009 Conference*, Paris, France, 2009.

[5] K. Lassmann, “TRANSURANUS: a fuel rod analysis code ready for use,” *Journal of Nuclear Materials*, vol. 188, pp. 295-302, Jun. 1992.

[6] Nuclear Energy Agency, “FEMAXI-6, Thermal and Mechanical Behaviour of LWR Fuel Rods,” *Organization for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA)*, 16-May-2011. [Online]. Available: http://www.oecd-nea.org/tools/abstract/detail/nea-1080. [Accessed: 09-Aug-2011].

[7] B. Philip, K. Clarno, and W. Cochran, “Software Design Document for the AMP Nuclear Fuel Performance Code,” Oak Ridge National Laboratory, Oak Ridge, Tennessee, ORNL/TM-2010/34, Feb. 2010.

[8] G. Hasen, C. Newman, and D. Gaston, “BISON: An Implicit Solution Framework for Fuel Performance Simulation,” presented at the Material Model ing and Simulation of Nuclear Fuels, Albuquerque, New Mexico, 2009.

[9] H. E. Sills, “ELOCA: Fuel element behavior during high-temperature transients.” Chalk River Nuclear Laboratories, Atomic Energy of Canada Limited, Mar-1979.

[10] H. E. Sills and R. A. Holt, “NIRVANA□: a high-temperature creep model for zircaloy fuel sheathing.” Atomic Energy of Canada Limited, 1979.

[11] F. C. Iglesias, D. B. Duncan, S. Sagat, and H. E. Sills, “Verification of the from model for zircaloy oxidation during high temperature transients,” *Journal of Nuclear Materials*, vol. 130, pp. 36-44, Feb. 1985.

[12] B. J. Lewis, F. C. Iglesias, R. S. Dickson, and A. Williams, “Overview of high-temperature fuel behaviour with relevance to CANDU fuel,” *Journal of Nuclear Materials*, vol. 394, no. 1, pp. 67-86, Oct. 2009.