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Development and testing of the FAST fuel performance code: Normal operating conditions (Part 1)

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HIGHLIGHTS

- FAST is a general purpose nuclear fuel model developed using Comsol Multiphysics.
- Presents the development of the FAST code for normal operating conditions.
- Multiphysics, multidimensional approach using commercial finite-element platform.
- Presents proof-of-concept comparison to experimental data and other CANDU fuel codes.
- Demonstrated improved agreement with the end-of-life sheath strain measurements.

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ABSTRACT

The Fuel And Sheath modeling Tool (FAST) is a general purpose nuclear fuel performance code. FAST includes models for heat generation and transport, thermal expansion, elastic strain, densification, fission product swelling, cracked pellet, contact, grain growth, fission gas release, gas and coolant pressure and sheath creep. The equations are solved on a two-dimensional (radial-axial) geometry of a fuel pellet and sheath using the Comsol Multiphysics finite-element platform. This paper presents the FAST code for normal operating conditions and results of the proof-of-concept testing against the ELESIM and ELESTRES-IST fuel codes as well as experimental data from seven irradiated fuel elements. In these seven cases, all of the codes were found to under-predict the measured average sheath strains. However, the FAST code was found to under-predict the mid-pellet sheath strains by a smaller margin than the other two codes. A larger data set is required to assess relative accuracy of the codes.

1. Introduction

Nuclear fuel is an important consideration for the design and operation of all nuclear reactors. Fuel design changes can be used to improve performance of existing reactors (e.g., mitigating reactor aging phenomena or power flattening), address environmental concerns (e.g., recycled fuel or actinide burning), address reactor safety concerns (e.g., hydrogen generation from cladding oxidation or higher melting temperature materials) or address operational issues (such as refueling interval). Additionally, the fuel matrix and fuel cladding are the first (of multiple) barriers to the release of fission products to the environment, making understanding the impact of fuel design particularly important. Computer modeling tools with predictive capability can be used to assess new designs to support fuel qualification. Computer models are necessary because of the high cost and difficulty associated with performing in-reactor measurements. These models, in effect, act as advanced interpolation (and in some cases extrapolation) tools to help bridge the gaps between the application (power reactors) and the experimental results (in- and out-reactor experiments).

Like all other computer programs, nuclear-fuel modeling codes must always be designed to accommodate the finite computing resources available to run them. In order to accommodate these limits, phenomena must be modeled using less computationally expensive approximations to obtain a model with

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acceptable fidelity within the constraints. This has historically favored the development of fuel modeling codes employing a fixed one-dimensional or quasi-two-dimensional representation of the fuel-element geometry. These codes typically also utilized many empirical correlations with limited coupling between phenomena. This is representative of many early codes such as GAPCON (Hann et al., 1973), FRAP-T (Thompson et al., 1975), and ELESIM (Notley, 1970) and to a lesser degree their successors FRAPCON (Berna et al., 1978), FRAPTRAN (Cunningham et al., 2001), ELESTRES (Tayal, 1987) and ELOCA (Sills, 1979).

In the time since these models were first developed, there have been many advancements in both computer hardware and software that have expanded modeling capabilities. This includes the development of higher frequency and higher capacity devices, the popularization of parallel computing, and the development of more efficient algorithms for solving systems of linear equations. These advancements have made feasible much more computationally expensive modeling codes which require fewer simplifying assumptions. These advanced codes have the potential of greater predictive capabilities and more diverse feature sets than those previously available. This has led to the development of a new fuel modeling paradigm employing features such as fully coupled multidimensional, multiphysics techniques and unification of normal and transient modeling domains into a single code. There are numerous examples of codes with one or more of these features, such as FALCON (Electric Power Research Institute (EPRI), 2004), TRANSURANUS (Lassmann, 1992; Lassmann et al., 1998), FEMAXI (Nuclear Energy Agency, 2011), and BISON (Hasen et al., 2009; Williamson et al., 2012).

A common trait of most fuel modeling codes is that they have been developed as purpose-written, standalone, computer programs in which the physical models are included along with the numerical methods directly in the source code. This architecture offers some advantages, particularly in terms of computational efficiency, protection of intellectual property, and guarding against accidental modification. The main disadvantage of this architecture is that significant modifications are difficult, and generally require editing the source code. Thus, in order to model non-standard fuels or geometries the end-user would have to have intimate knowledge of the internal structure of the code, and access to the source code. An example of this would be modeling a pellet with a blind-hole using the ELESTRES code. This would require modifying the source code to accept new inputs, utilize a new mesh, and apply additional boundary conditions. This can make most existing fuel codes difficult to use for research-oriented applications, in which it is desirable to simulate the performance of novel fuel designs and experimental configurations.

An alternate architecture has also emerged which provides greater separation of the modeling tasks from the numerical solution tasks. The two main advantages of this architecture are a reduction in the difficulty associated with modifying the model and the ability to use an existing numerical solution infrastructure. This is the methodology employed by the FAST code (the subject of this work) and the BISION code (Hasen et al., 2009; Williamson et al., 2012).

The FAST model has been developed on the Comsol Multiphysics (v.4.4) finite-element platform. A significant reduction in development time and cost was achieved by utilizing the built-in pre-and-post-processing tools for various tasks such as building model geometry and finite-element meshes, solving linear systems and graphing results, rather than developing custom tools for the same task. The Comsol platform is extremely flexible, allowing the solution to a wide range of ordinary, and partial differential equations with arbitrary coupling of the dependent variables. These equations are represented in either strong or weak form and are automatically discretized as part of the solution process, making them easy to modify as needed. A drawback of this implementation is that the FAST code requires a Comsol installation and a license to run.

The FAST code is comprised of mechanistic and empirical separate effects models (also called phenomena or physics models) coupled together to obtain a simultaneous solution. This code has evolved from fully coupled two-dimensional (radial-axial) models developed previously (Morgan, 2007; Shaheen, 2011). The FAST code has four broad motivations, which have guided the design decisions:

- Support modeling of CANDU fuel (i.e. solid UO_2, collapsible zircaloy-4 sheathing).
- Improve prediction of sheath strain including circumferential ridging effects to support predictions of Stress Corrosion Cracking (SCC).
- Serve as a flexible research tool which can be adapted for fuel design optimization, experimental design/analysis, and prototyping new material/phenomena models.
- Utilize non-proprietary models where available to limit intellectual property issues.

Section 2 of this paper summarizes some of the key theory employed in the FAST code for modeling CANDU fuel under normal operating conditions (NOC). In order to apply the code to other fuel types, modification would be necessary to account for differences in fuel designs and irradiation conditions. For example, LWR fuel would require models to account for the difference in flux depression, length of fuel elements/pins and cladding corrosion. Section 3 presents a proof-of-concept validation of the FAST model with comparisons to experimental measurements and Canadian industry standard codes. Section 4 presents the ongoing and future development of the code as well as some potential applications.

2. Model development

The behavior of nuclear fuel during irradiation is a complicated multiphysics problem involving many branches of science and engineering. The geometry employed in the FAST code is described in Section 2.1. Phenomena models are summarized in the following Sections 2.2–2.5. The references to the material property models used in the FAST code are provided in Section 2.6. A complete description of the FAST code, including implementation details, is available in reference (Prudil, 2013).

2.1. Model geometry

The model geometry consists of one half-pellet in the radial-axial plane (axisymmetric) with an accompanying sheath (see Fig. 1). This includes options for a central hole as well as dishing and chamfering of one or both ends of the pellet. The model assumes that the single pellet is representative of all pellets within an element. This is equivalent to assuming no strong axial dependence of the irradiation conditions over the length of an element ($\sim$0.5 m in length). This allows a periodic boundary condition to be applied which bounds the model in the axial direction. The boundary conditions required to implement this periodicity are described in details in Section 2.3.1.

A sample mesh has also been included in the right-hand side of Fig. 1. It is worth noting that the default geometry and mesh can be modified as needed using the Comsol Graphical User Interface (GUI) or by importing CAD or mesh files generated by other software packages.