



Assessment of the analysis capability for core-wide PWR pellet-clad interaction screening of Watts Bar Unit 1

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ABSTRACT

This article demonstrates the application of the Virtual Environment for Reactor Applications simulation environment to screen for pellet-clad interaction amongst the core-wide fuel rods within a pressurized water reactor, with emphasis on the multi-dimensional analysis capabilities of the BISON fuel performance code. The VERA codes utilized in this effort include the BISON fuel performance code and the VERA sub-element, which combines the MPACT neutron transport code and the COBRA-TF thermal-hydraulics code. This effort has involved screening Cycles 6 and 7 of Watts Bar Unit 1, which were selected on the basis that pellet-clad interaction failures had occurred during reactor start up in both cycles, despite the moderate power levels. These failure instances at Watts Bar Unit 1 offered an interesting test of the code's veracity and a particularly challenging condition for this assessment.

1. Introduction

1.1. General perspective

Pellet-clad interaction (PCI) is a failure mechanism in light-water reactor (LWR) fuel rods that occurs as a reaction to a strong pellet-cladding mechanical interaction (PCMI) in the presence of an aggressive corrosive environment and is driven by two forms of pellet damage: (1) a radial crack in the pellet causing stress concentration on the clad inner surface, or (2) a similar pellet crack in combination with a missing pellet surface (MPS). The terms SCC-PCI and MPS-PCI are used to describe these two cladding failure mechanisms, respectively, and the analysis described in this article covers both mechanisms.

Fuel performance codes capable of modeling these failure mechanisms must have finite-element-based, multi-dimensional analysis capabilities. As a full 3-D code, BISON represents the ultimate simulation tool, both in its material and physical behavior capabilities and in its finite-element versatility with spatial representations. The code can operate in full 3-D mode, as well as in reduced 2-D modes (e.g., axisymmetric radial-axial [R-Z] or plane radial-circumferential [R-θ]), to suit the application and to allow treatment of global and local effects. For example, under steady-state power operation, a global response that is compatible with neutronics depletion calculations can be appropriately treated as an axisymmetric 2-D R-Z simulation, whereas SCC-

PCI and MPS-PCI calculations can be performed in detailed 2-D R-θ models or as full 3-D models. The amount of detail in the 2D R-Z and 3-D simulations can vary over a wide range: for example, in modeling of the fuel pellets, one can choose models as a smeared column, as individual pellets, or as a combination of both.

Traditionally, PCI analysis capabilities in fuel performance codes have been decoupled from neutron transport and thermal hydraulics methods, although some important feedback phenomena in depletion calculations (e.g., fuel temperatures) have been lacking. This institutionalized the separation between the two methods and built nearly impenetrable virtual walls in the path of coupled methodologies—until recently. The Consortium for Advanced Simulation of Light Water Reactors (CASL) has since developed the Virtual Environment for Reactor Applications (VERA), which has the capability to simulate the physical phenomena of nuclear reactors using coupled multi-physics models (Godfrey and Lee, 2016).

The purpose of this paper is to assess VERA capabilities by conducting core-wide PCI screening analysis of Cycle 6 and 7 of Watts Bar Unit 1. Both Cycle 6 and 7 reported the presence of fission products in the coolant during the reactor startup; the release of fission products into the core provides evidence of a cladding breach. With the occurrence of fission products in the coolant coinciding with the reactor startup, the failure mechanism is directly related to failure by PCI. VERA was used to conduct a quarter-core R-Z evaluation in order to

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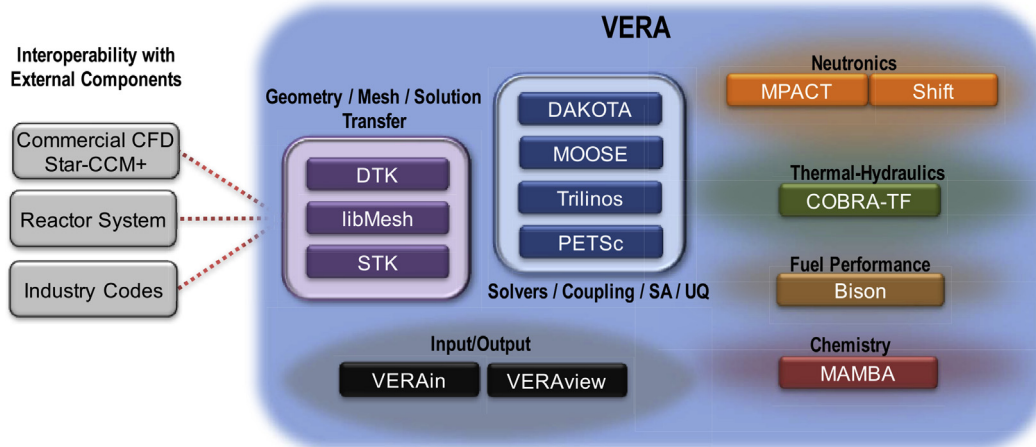


Fig. 1. VERA consists of several single physics code packages, ranging for core neutron transport to coolant chemistry, that are coupled together with an interface, e.g. common input (Godfrey and Lee, 2016).

determine the limiting rods from the startup of Cycles 6 and 7. Following the quarter-core assessment with a one-way coupling between neutronics/thermal hydraulics and fuel performance for screening, the BISON fuel performance code was used to conduct local effects assessments on the limiting rods in order to determine the rod with the highest probability of failure.

1.2. Modeling and simulation tools: VERA analysis codes

The core-wide PCI screening analysis described in this article is a multi-disciplinary activity performed using the VERA simulation environment developed by CASL. VERA is comprised of codes used collectively for nuclear reactor modeling and simulation. This work uses the MPACT neutron transport solver, the CTF thermal hydraulics solver, the MAMBA coolant chemistry package, and the BISON fuel performance code, all of which are briefly described below. Fig. 1 shows the components of VERA.

1.2.1. MPACT

The MPACT neutron transport solver, a collaborative effort between the University of Michigan (UM) and Oak Ridge National Laboratory (ORNL), provides pin-resolved flux and power distributions (MPACT Theory Manual, 2013). To solve 3-D problems, MPACT employs the 2-D/1-D method, which decomposes the problem into a 1-D axial stack of 2-D radial planes (Collins et al., 2016). Typically, the 2-D Method of Characteristics (2-D MOC) is used to solve each radial plane, and 1-D nodal methods are used to solve axially along each rod. While there are a variety of axial solvers available, the nodal expansion method (NEM)-P₃ solver is the default, which wraps a one-node NEM kernel to handle the intranodal flux distribution (Stimpson et al., 2014). These 2-D and 1-D solvers are coupled together through transverse leakage terms to ensure neutron conservation, and they are accelerated using a 3-D coarse mesh finite difference (CMFD) method.

1.2.2. COBRA-TF

COBRA-TF (CTF) is a sub-channel thermal hydraulics code being developed by ORNL and North Carolina State University (NCSU) specifically for LWR analysis (Avramova, 2009). CTF simulates two-phase flow with a three-field representation—liquid, droplet, and vapor—assuming that the liquid and droplet fields are in dynamic equilibrium, leaving two energy conservation equations. CTF provides significantly higher resolution and physics detail than MPACT's internal thermal hydraulics solver (Simplified TH), though this added resolution does result in longer execution times.

1.2.3. MAMBA

MAMBA is a coolant chemistry code developed by Los Alamos National Laboratory. MAMBA estimates the growth of CRUD (corrosion-related unidentified deposits) on the clad surface of each fuel rod and tracks the precipitation of isotopes from the coolant that make up the CRUD layer. Because Cycle 7 of Watts Bar Unit 1 is known to have issues with CRUD-induced power shift (CIPS), the VERA analysis used MPACT/CTF/MAMBA, whereas Cycle 6 only used MPACT/CTF because CIPS is not a significant factor in that cycle.

1.2.4. BISON

The BISON fuel performance code, which has been developed by Idaho National Laboratory (INL), provides single-rod fuel performance modeling capability that enables users to assess best-estimate values of design and safety criteria and the impact of plant operation and fuel rod design on the thermo-mechanical behavior of PCI failures in pressurized water reactors (PWRs) (Montgomery, et al., 2012; Montgomery, et al., 2014). PCI is controlled by the complex relationship between the mechanical, thermal, and chemical behaviors of a fuel rod during operation. Consequently, modeling PCI failure requires an integral fuel performance code to simulate the fundamental processes of these behaviors. BISON is built on INL's Multiphysics Object Oriented Simulation Environment (MOOSE) (Montgomery, et al., 2012; Montgomery, et al., 2014), which uses the finite element method for geometric representation and a Jacobian Free Newton-Krylov (JFNK) scheme to solve systems of partial differential equations (Gaston, 2009). For this work, BISON uses a 2-D azimuthally symmetric (R-Z), smeared-pellet thermomechanical fuel pin model with output data from VERA, which generates the time-dependent power shape and moderator temperature inputs needed for BISON. The BISON analysis described in this article addresses the PCI behavior of Cycle 6 and Cycle 7 of the Watts Bar 1 nuclear reactor.

2. Generation of standalone BISON inputs

XML2MOOSE is a pre-processor program that began as part of the development of Tiamat—a driver program that handles the code coupling between MPACT/CTF/BISON (Clarno, et al., 2015; Pawlowski, et al., 2015; Clarno, et al., 2015). When running cases through VERA, the user interfaces with a single ASCII input file, which is then converted to an extensible markup language (XML) file that interfaces with several other codes. However, codes like CTF and BISON have additional preprocessors that convert the XML file into their own native input file formats. XML2MOOSE takes a template BISON input and populates it accordingly with options that are entered in the VERA

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