FALCON – A VERSATILE TOOL FOR FUEL ROD BEHAVIORAL ANALYSIS

ANATECH CORP.

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Falcon is a fully-coupled, thermo-mechanical computer code designed to provide best-estimate light water reactor (LWR) fuel rod performance analyses. ANATECH originally developed the Falcon code under EPRI sponsorship and continues to improve the code by expanding the code's applicability through enhancements and additions to the code's numerous material property and behavioral models.

Unlike traditional fuel performance codes, Falcon is based on a two-dimensional finite element (FEM) computational framework that provides for a fully coupled thermo-mechanical solution capable of both steady state and transient analyses. This allows for computation of fuel and cladding deformation, up to and including extreme conditions such as cladding ballooning, to be computed as integral aspects of the thermo-mechanical FEM solution. Other key features include:

- A unique and effective implementation of fuel pellet smeared cracking and pellet/cladding contact logic,
- An integrated coolant channel model with full representation of the boiling regimes as well as an option for sodium coolant,
- An R-Θ plane, two-dimensional geometric modeling capability that permits detailed simulation of pellet-cladding interfacial forces including the effects of discrete pellet cracks, fuel pellet surface defects, cladding mechanical defects, etc.
- Three cladding failure models implemented to address:
  1. Pellet cladding interaction (PCI) related to the intergranular stress corrosion cracking (ISCC) failure mechanism under power ramp conditions,
  2. Cladding failure by ballooning and rupture under high temperature conditions associated with a loss-of coolant accident (LOCA), and
  3. Mechanical fracture and cladding failure resulting from pellet cladding mechanical interaction (PCMI) during rapid power ramps or power pulses associated with reactivity initiated accidents (RIA).

As an integral part of our development program, we routinely use a large verification and validation (V&V) database (currently at ~200 distinct cases) consisting of commercial, test, and instrumented fuel rods out to rod average burnups of ~70 GWd/tU to evaluate the code. This database also includes analytical and separate effects simulations designed to verify specific behavioral submodels. Results from evaluations by the developers, user community, and from the V&V program are used to demonstrate and verify the broad range of Falcon analytical capability and to provide guidance for future code development work.

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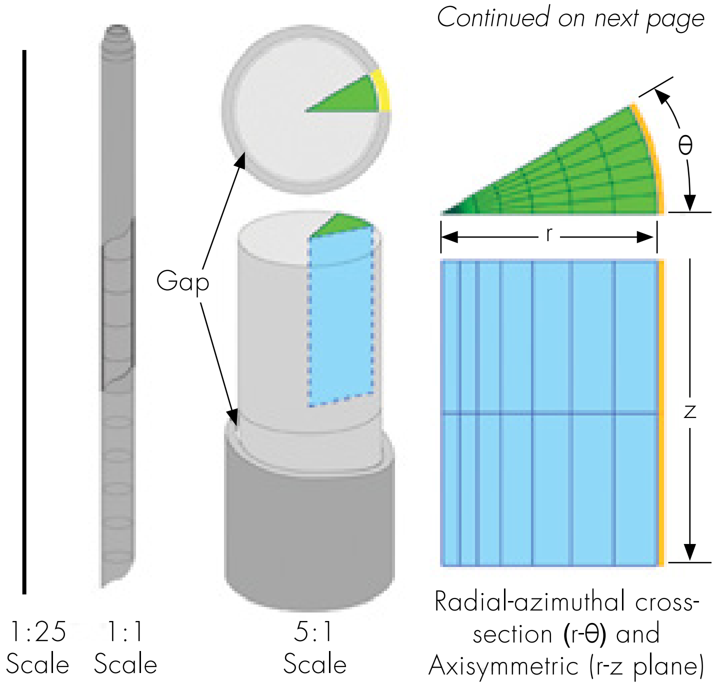
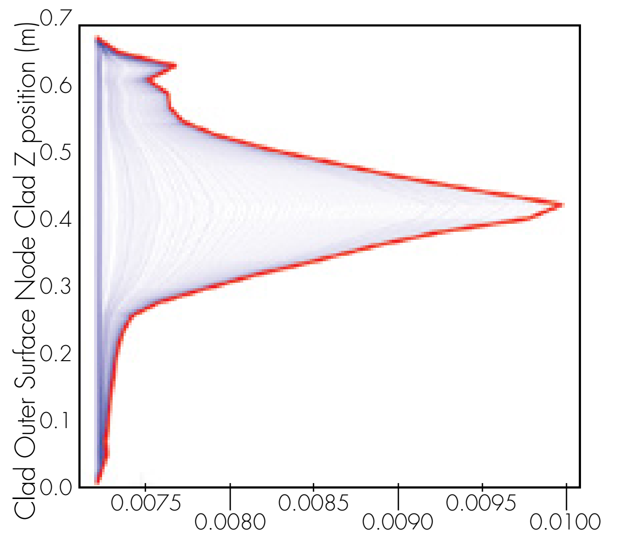


Fundamental geometric modeling approach applied in Falcon[2]

APPLICATIONS

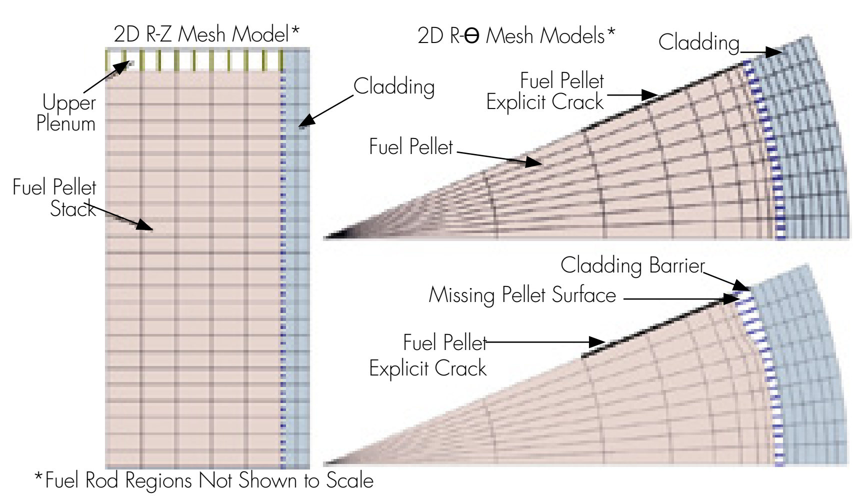
Developers and users around the world have applied Falcon extensively in the last 10 years for numerous commercial and test fuel rod analyses, as well as supporting computations for spent fuel rod assessments. In many of these cases, Falcon has provided an enabling and unique capability to address a specific modeling requirement. Examples of Falcon applications are listed below.

- Fuel rod research and development program evaluations
  - Numerous Halden Instrumented Fuel Assembly (IFA) experiment analyses. Recent examples include:
    - IFA-650 – LOCA analyses
    - IFA-742 – utilizing Falcon's unique post primary defect analysis capability
  - Analysis of Studsvik Cladding Integrity Project (SCIP) test rod experiments
  - Evaluation of proposed accident tolerant fuel rod designs
    - SiC and TZM molybdenum composite cladding materials
    - Doped-pellet cladding hour-glassing and ridging evaluations



LOCA analysis showing cladding ballooning computed by Falcon

- Regulatory support focusing on postulated accident analysis (RIA and LOCA)
  - Analytical support to the EPRI Fuel Reliability Program Fuel Safety Licensing Working Group
  - Development of the technical bases for the fuel acceptance criteria for RIAs
  - Analysis and design support for the NRC-ANL LOCA test program
  - Assessment of experimental data for evaluation of the impact of burnup on the cladding embrittlement criteria (10 CFR 50.46) for LOCA events
  - Support for the topical report for NRC submittal for Safety and Licensing for Burnup Extension
- PCI risk reduction
  - Analytical support for the development of EPRI's Fuel Reliability Guidelines: PCI[1] (PCI-GL) to provide utility operating guidance for the reduction of fuel rod failures due to PCI across the entire US PWR and BWR nuclear fleet
  - Fuel rod analyses for multiple commercial utilities
    - plant and cycle specific PCI failure margin evaluations
- Post fuel rod failure forensic analysis
  - Falcon has been applied for numerous post failure fuel rod analyses to determine root cause and develop mitigating strategies to limit or eliminate fuel rod failures
    - Example: evaluation of Braidwood and Byron mid-cycle fuel rod failures determined by post irradiation examination (PIE) to be due to Missing Pellet Surface (MPS) manufacturing defects
- Spent fuel analysis
  - Analysis support for characterization of failure mechanisms, associated failure criteria, and response analysis of spent fuel systems subjected to normal and hypothetical transport accident conditions (10 CFR 71)
  - Support for the development of technical bases for high burnup spent fuel rod dry storage acceptance criteria
- Support for development of next generation 2D and 3D nuclear fuel behavior codes
  - Model development, benchmarking, and evaluation supporting Department of Energy (DOE) research programs
    - Consortium for Advanced Simulation of Light Water Reactors (CASL)
    - Nuclear Energy Advanced Modeling and Simulation (NEAMS) development program

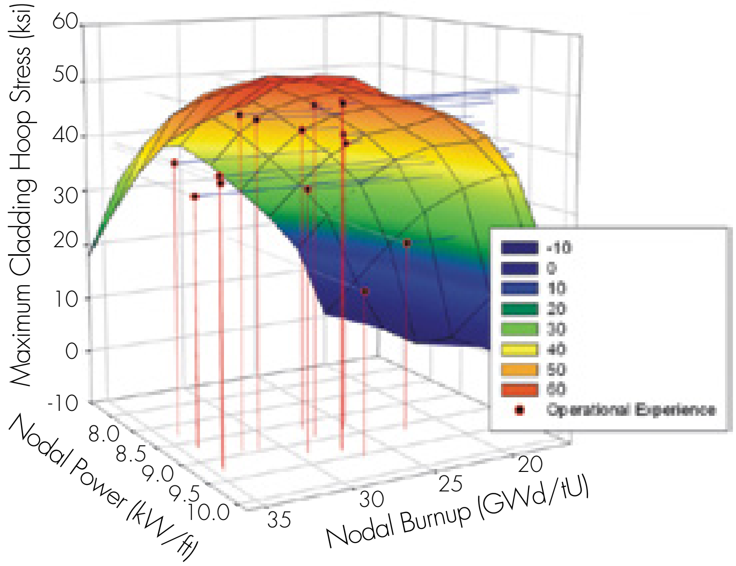


Typical Falcon Fuel Rod Models

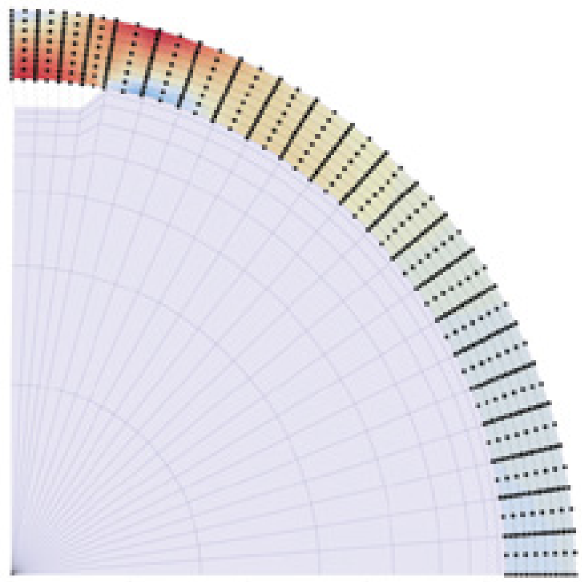
UNIQUE AND ENABLING CAPABILITY

One area of special significance that highlights Falcon's unique and enabling capabilities is fuel rod analysis for mitigation of fuel rod failure due to PCI. As noted in addition to being the analytical tool used to develop the PCI guidelines, Falcon has been used by ANATECH for direct support to a number of nuclear utilities to provide operational guidance for increasing fuel reliability and reducing or mitigating the potential for fuel rod failures due to PCI. These analyses have included plant and cycle-specific analyses applied to the following areas:

- Alternative cycle start-up strategies to limit cladding stresses during reactor start-up
  - For example, revised power ramping strategies, insertion of constant power holds, reduced extent of prior cycle coastdown, and reducing the extent of power increase on startup,
- Evaluation of changes in plant operation on PCI failure margin from unanticipated plant operational events, varying coast down strategies, and different fuel vendor/utility power ascension strategies, and
- Evaluation of fuel design changes on PCI failure margin
  - For example, new or improved fuel design features, advanced lead test assemblies, alternate vendor fuel designs, etc.

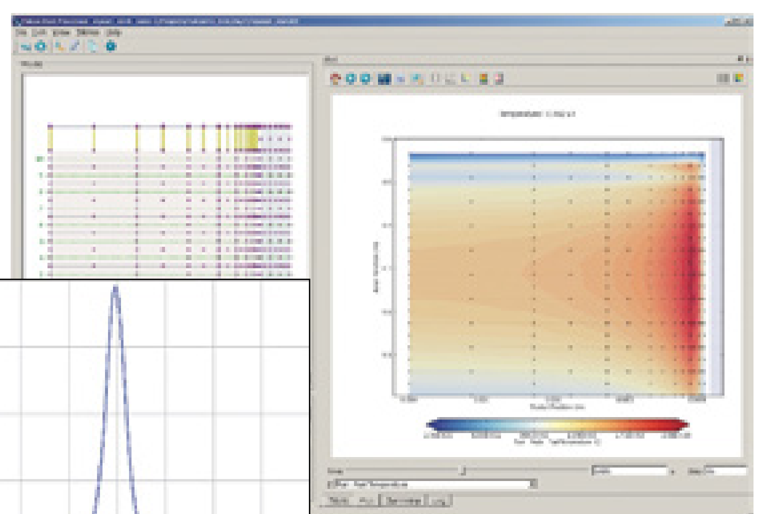


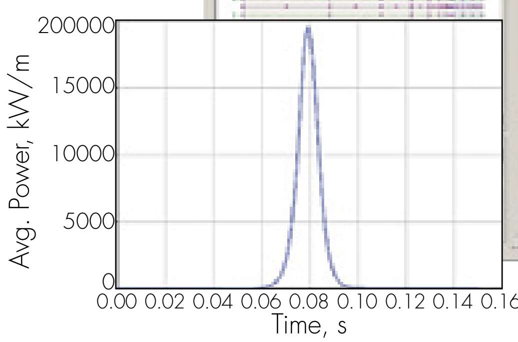
Power and burnup dependent bounding analysis


MPS model showing grid deformation and cladding hoop stress distribution

Recent notable examples of the application of Falcon by ANATECH for utility support in this area include cycle-specific and start up strategies for Exelon (Braidwood and Byron), Southern Nuclear Company (Farley and Vogtle), Progress Energy (Shearon Harris and H. B. Robinson), Xcel Energy (Prairie Island), and Constellation Energy Nuclear Group (Calvert Cliffs ramp rate evaluation for a new fuel supplier). In terms of successes, all of these utilities have benefited from the insight Falcon provides. Exelon, who has contracted ANATECH for over 10 years, has not experienced any PCI-related fuel failure issues at either Braidwood or Byron since employing Falcon for these types of analyses.

Falcon is the only analytical tool available across the industry that can perform these type of analyses. This "real world" application has resulted in a measurable reduction in fuel rod failures due to PCI and has provided sound technical bases for revision of operating procedures for startups and other power ascension maneuvers at nuclear utilities throughout the country.





Falcon RIA Analysis: FEM mesh, power pulse, and fuel temperature distribution

REFERENCES

1. Fuel Reliability Guidelines: Pellet Cladding Interaction, EPRI, 1015453, Final Report, November 2008
2. Fuel Reliability Program: Falcon Fuel Performance Code, Version 1.2, EPRI, 1022711, User Guide, September 2012