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SIMULATE-3K Explicit Fuel Pin Modeling in RIAs

Gerardo M. Grandi, Kord S. Smith

Studsvik Scandpower, Inc. 504 Shoup Ave., Suite 201, Idaho Falls, ID 83402 U.S.A
Gerardo.Grandi@studsvikscandpower.com

INTRODUCTION

SIMULATE-3K (S3K) is a best-estimate nodal reactor analysis tool[1] that employs advanced core neutronics coupled with detailed thermal-hydraulic channel models. Faithful modeling of assembly-by-assembly neutronic and thermal-hydraulic effects, including assembly pin power reconstruction, permits application of S3K to a wide class of LWR core transients. Utility licensing approval from the U.S. NRC has been obtained for reactivity insertion accidents (RIA) and S3K has been employed in support of dynamic rod worth measurements (DRWM).

Recently, there has been considerable focus on the licensing basis for RIA limits, which impacts both pressurized water reactor (PWR) and boiling water reactor (BWR) RIA analyses. In Europe and Japan, exposure-dependent RIA fuel enthalpy criteria have been adopted. Similarly, a recent NRC recommendation for an interim RIA acceptance criterion has also proposed exposure-dependent limits on fuel enthalpy rise. One consequence of these new criteria is that more detailed analysis of RIA events may be required because fuel pins with highest enthalpy may no longer be the most limiting.

This paper describes recent extensions to the S3K fuel pin modeling to enhance applications to RIA scenarios with exposure-dependent fuel failure criteria (FFC).

MODELING ENHANCEMENTS

For purposes of modeling thermal hydraulic feedback effects, S3K historically has modeled all fuel pins within a node by the average pin. The average fuel pin was supplemented in the original S3K by tracking of the peak (hot) pin - permitting accurate estimation of peak fuel pin enthalpies. The capability to explicitly represent every fuel pin in the reactor core has been recently added to S3K. This capability is referred to as the explicit fuel pin conduction model.

Model Assumptions

- Fuel pin heat sources are taken directly from time-dependent pin-by-pin energy deposition rates.
- Channel thermal hydraulic conditions for the bulk fluid (i.e., coolant temperature, quality, and void fraction) are assumed to be the same for all pins within a node (whole- or quarter-assembly radially and ~ 15 cm axially).
- Fuel pin and cladding material properties are computed using pin-by-pin burnups and temperatures.
- Heat transfer regime and heat transfer coefficients are computed for individual fuel pins

Modeling Details

Each fuel pin is divided into 12-50 axial nodes, and axial heat conduction within a fuel pin is neglected. Radial symmetry within a fuel pin is assumed, permitting the heat conduction equations to be written as a function of radial position. Each pin is subdivided into equal volume radial rings (typically 10), and each ring's material properties are temperature and burnup dependent. Temperature-dependent properties for UO_2 and Zircaloy are tabulated using MATPRO data.[2] The burnup dependence of fuel conductivity uses the model of Wiesenack.[3] The pellet/clad gap conductance is modeled as a primary function of fuel burnup and temperature, and as a secondary function of fuel pellet cracking, fuel pellet irradiation swelling, fuel pellet and clad thermal expansion, clad creepdown (caused by irradiation at high pressure), and gas gap composition changes which result from fission gas release.

The fuel pin heat source is modeled as the sum of two components: the prompt fission heat and the decay heat. Decay heat is modeled by using the ANSI/ANS-5.1 23-group data. S3K treats both the energy deposited within the fuel pellet and within the coolant (due to prompt neutron slowing down and gamma attenuation). The radial distribution of heat source within a fuel is modeled explicitly as a function of fuel pin exposure through the use of pre-computed tables generated with CASMO-4.[4] This model is important since the radial distribution of heat source peaks at the outer edge of a fuel pin and the relative peaking increases substantially with fuel burnup.

Improved Analysis Capabilities

With the new explicit fuel pin conduction models, S3K can now explicitly follow the complete radial distribution of fuel pin temperatures and enthalpies (in every fuel pin) throughout a transient. This new modeling capacity eliminates the need for traditional modeling limitations resulting from such things as:

- Pre-selecting and lumping of thermal hydraulic channels
- Assuming known/fixed radial peaking shapes
- Assuming known/fixed pin-to-box factors
- Assuming known/fixed fuel pin conductivity
- Assuming known/fixed pin/gap conductance
- Assuming fixed intra-pin energy deposition shapes

At the end of a transient simulation, S3K compares individual fuel pin temperatures and enthalpies to the fuel safety criteria provided by the user. Detailed information is then summarized, including core-wise and assembly-wise maximum and limiting values and the total number of fuel pins failing the safety criterion.

EXAMPLE

A PWR rod ejection accident (REA) in a typical UO_2 core at hot zero power (HZP) conditions was analyzed by ejecting a peripheral rod from fully inserted to fully withdrawn in 0.1 sec (assuming no reactor scram). Fig. 1 displays the computed peak fuel pin enthalpy versus pin exposure for every assembly in the core, as well as the typical Japanese FFC. Note that the maximum enthalpy rise in the core (~75 cal/g) does not violate the FFC. However, the enthalpy rise in several depleted assemblies close to the ejected rod does violate the FFC. There are three fuel assemblies containing pins exceeding the FFC and 335 individual fuel pins exceeding the FFC.

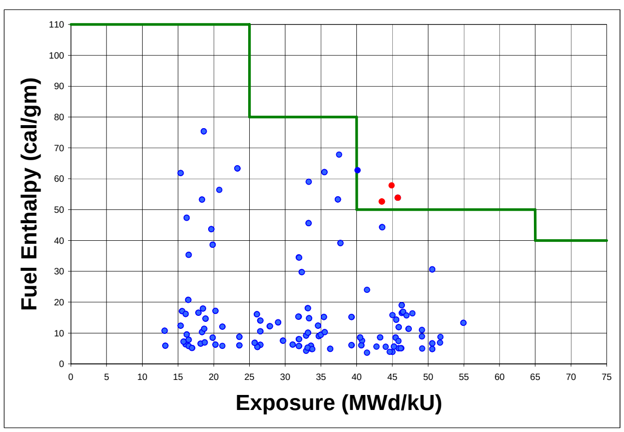

Fig.1. Fuel Enthalpy Increase vs. Pin Burnup.

SUMMARY

The S3K explicit pin model permits direct computation of fuel pin temperatures and enthalpies for all pins in a reactor core. This capability eliminates many of the traditional assumptions made in RIA analyses. Consequently, this analysis capability presents the safety analysis engineer with an opportunity to recapture margin that might otherwise be lost by the use of needlessly conservative modeling assumptions.

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