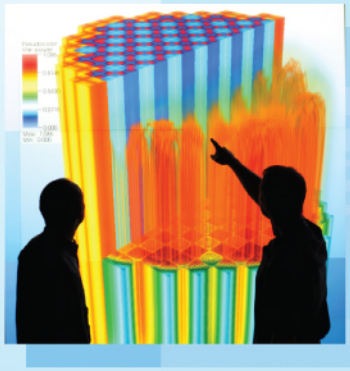
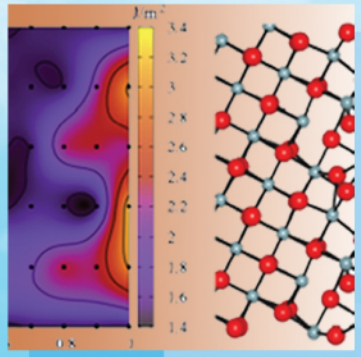
CASL-U-2014-0134-000

Power uprates
and plant life extension



Engineering design
and analysis

Science-enabling
high performance
computing



Fundamental science

Plant operational data

Consortium for Advanced Simulation of LWRs

Presentation Poster: Boron Tracking and Precipitation Model in CTF

Ana Jambrina Gomez
The Pennsylvania State University

August 4, 2014

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Boron Tracking and Precipitation Model in CTF

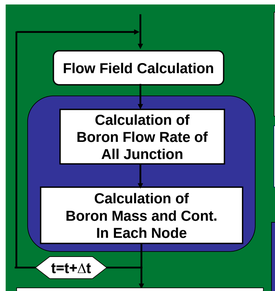
Ana Jambrina Gomez – The Pennsylvania State University

Mentor: R. Salko **With:** M. Avramova; K. Ivanov **Program:** NESLS. Consortium for Advanced Simulation of LWRs

MULTIDIMENSIONAL SOLUTE TRACKING AND PRECIPITATION MODEL BASED ON SUBCHANNEL APPROACH INTO CTF

Status of Recent Computational Models:
- System codes are limited solute transient model in 1-D
- Computational Fluid Dynamic models are computationally expensive

Measuring Boron Experimental Difficulties + Neutron Kinetics & Thermal-hydraulic Modeling Advances



Model Assumptions:
- Sufficiently dilute solute
- Negligible liquid property change by the presence of the solute
- No energy transfer by the solute
- Negligible inertia of the solute

ADDITIONAL FIELD EQUATION FOR THE SOLUTE CONSERVATION IS INCLUDED

Boron Tracking Model

$$\frac{\partial \rho_b}{\partial t} + \frac{\partial(\rho_b v_p)}{\partial x} = \frac{\partial}{\partial x}\left(D\frac{\partial \rho_b}{\partial x}\right) + S$$

Linearized Burguers Equation

$$\frac{\partial[(1-\alpha)m\rho_l]}{\partial t} + \nabla\cdot\left[(1-\alpha)m\rho_l\vec{V}_l\right] = S_m$$

NRC Codes

$$\rho_{b,L}^{n+1} = \rho_{b,L}^{n} - \frac{1}{V_L}\left(\rho_{b,j+1}^{n}V_{f,j+1}^{n+1}A_{j+1} - \rho_{b,j}^{n}V_{f,j}^{n+1}A_j\right)\Delta t$$

First Order Accurate Scheme

High-order accurate scheme models advection and physical diffusion

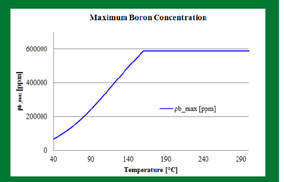
$$\rho_{b,j+1}^{n,L} = \rho_{b,L}^{n} + \left[\left(\frac{1}{2}\Delta x_L\right)\left(1 - \frac{v\Delta t}{\Delta x_L}\right) - \varphi_L\right]\bar{S}_L$$

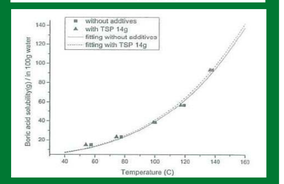
SECOND ORDER ACCURATE MODIFIED GODUNOV SCHEME

Boron Mixing Model – Cross Flow Mechanism

$$\frac{d\rho_b}{dt} + \frac{1}{A}\frac{d(\rho_b v_f A)}{dx} + \frac{1}{A}\sum_k(\rho_b W_f L_g)_k = 0$$

Axial Change and Total Transverse Gain





Boron Precipitation Model

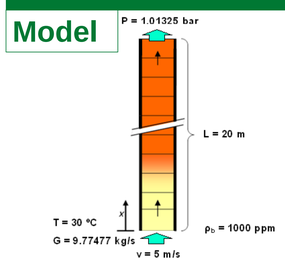
KIM AT *AL.* CORRELATION Maximum boron solubility → Applied to the entrained droplet field

Liquid Temperature > Temperature Range → The excess is precipitated and solute density is maximum

Kim et al.'s solubility correlation is derived in a temperature range (including the effects of buffer agents (tri-sodium phosphate (TPT)), which generate particulate oxide corrosion products and increase the risk of precipitation by chemical reactions with other dissolved materials.

VERIFICATION: ANALYTICAL TEST – MODIFIED GODUNOV VS. UPWIND SCHEME –

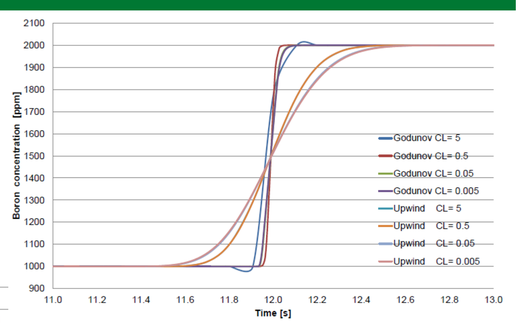
Model

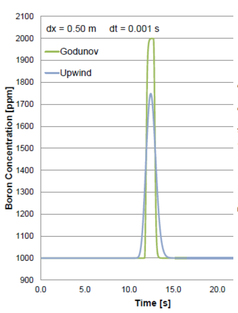


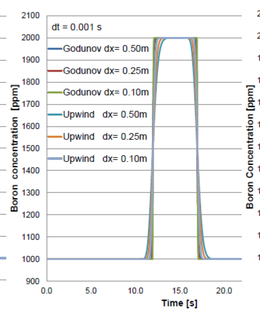
In order to measure how well the numerical schemes can predict the exact solution of an analytical equation, the pulse function is used.

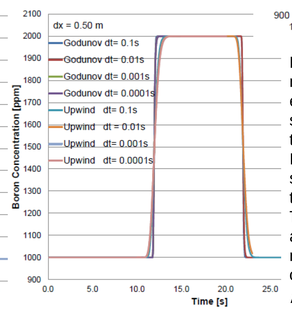
The transient was started as the 30 ºC single-phase 1000 ppm borated water injection with a speed of 5 m/s. was inserted from the bottom section of 20 m unheated vertical pipe with 50 mm hydraulic diameter. The outlet pressure is set as 1 atm. The pulse function was applied at 10 s with a variable duration of 1 s, 5 s and 10 s.

Not only it has been wanted to compare the behavior of the modified Godunov and upwind schemes; also was made a sensitivity analysis considering the parameters related with the CFL (Courant Number Limiting Condition).









Besides reducing the numerical error in each time step, the modified Godunov model gives information about the physical effect of the turbulence in flow field. Thus, the modified Godunov scheme provides more realistic results compared to the first and the second order accurate models.

It is shown the boron concentration evolution for different pulse sizes for both schemes, as well as, a sensitivity analysis over the mesh size and timestep size.

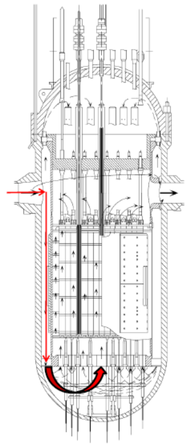
The discretization in time and space not only affects the accuracy of the solution, also determines the stability of the numerical analysis, which is a necessary condition to the convergence and non-oscillatory behavior of the method.

Analysis over Pulse Size, Mesh Size and Timestep Size

VERIFICATION: BORON DILUTION TRANSIENT SCENARIO

GSI 185 Accident: Control of Recriticality following Small-Break LOCAs in PWRs

Assumptions and Scenario Formulation

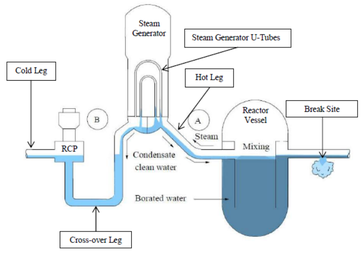


Westinghouse 4-Loop Reactor Vessel: Condensate Slug Path

In the final phase of this study, the verified CTF code is employed in the simulation of a series of boron dilution transients using the Purdue MOX core model. Heterogeneous boron dilution transient scenarios are simulated in order to fully exercise and demonstrate the boron tracking capability of CTF.

The condensate slug entrance radial location is first varied assuming that a SBLOCA occurred while the reactor was at full power operation. The most limiting radial entrance location is determined from these results and most extreme case is considered where actuation of a main reactor coolant pump drives a single condensate slug into the core at the most limiting entrance location at a high velocity.

The current scenario is largely based on an accident sequence postulated in NRC Generic Safety Issue - 185, "Control of Recriticality following Small-Break LOCAs in PWRs" While the reactor is at full power operation, the primary loop boron concentration is approximately 1680 ppm with control rods withdrawn.



Simplified Diagram of Boron Dilution Due to Reflux Condensation in Post-SBLOCA Conditions

In order to build a post-SBLOCA boron dilution transient simulation scenario, a number of assumptions and simplifications must be made.

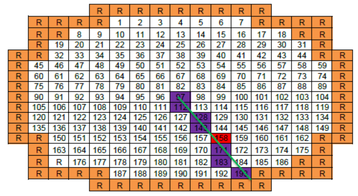
To determine the most limiting entrance location of the condensate slug, eight cases are simulated in which the entrance locations are varied from the core periphery to the core center region. Based on the assumed path of the condensate travel depicted, the condensate slugs are centered on the fuel assemblies.

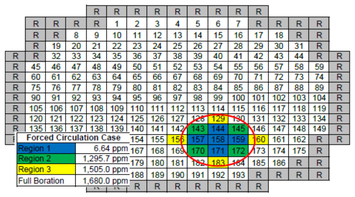
The condensate slug is assumed to have a circular cross section of the same inner diameter as the cold leg pipes. The resultant boron concentration is discretized in the same manner as the CTF sub-channel discretization using an area-weighted boron distribution to calculate the regional boron concentrations.

A more severe boron dilution transient would occur if forced circulation were started by actuation of a RCP.

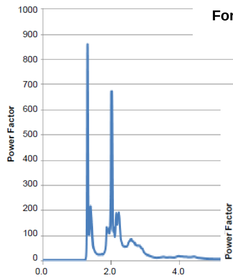
Selected Boron Dilution Transient Input Conditions	
Parameters	**Value**
Control Rod States	All Rod In
Linear Power Initial Condition [kW/m]	0.38259
Inlet Coolant Enthalpy Boundary Condition [kJ/kg]	1267.74
Outlet Coolant Pressure Boundary condition [bar]	190.55
Initial System boron Concentration [ppm]	1680
Condensate Boron Concentration [ppm]	0
Forced Circulation Case	
Total Coolant Mass Flow [kg/sec]	4010.35
Inlet Condensate Slug Boron Concentration [ppm]	6.64

Purdue UO_2 MOX Core Benchmark

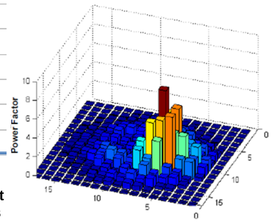




Condensate Slug from Cold Leg Inlet 23° counter-clockwise from the 270° direction
Actual Slug Boundary (assuming 27.5 in diameter)
Fuel Assemblies Represent Centered Condensate Entrance Locations
Limiting Case: Greatest Power Peaking Factor (Subchannel ID: 158)



Forced Circulation Limiting Case Power Factor vs. Time



Radial Power Distribution at Peak Core Power, t = 1.31 s

Results and Analysis

The start of a reactor coolant pump would drive the mass of deborated condensate through the cold leg and reactor vessel and into the core at a much higher velocity. The resulting insertion of positive reactivity would be much more rapid and the power level of the core would be able to increase further before prompt feedback reduces the power level again.

It is found that the power spike was more intense with a peak power factor of 859.014 at time 1.31 seconds. The pulse width is also very short with at full width, half maximum of approximately 0.025 seconds. This larger spike is due to the condensate slug being able to enter further into the core before significant Doppler feedback was able to bring the power level back down again.

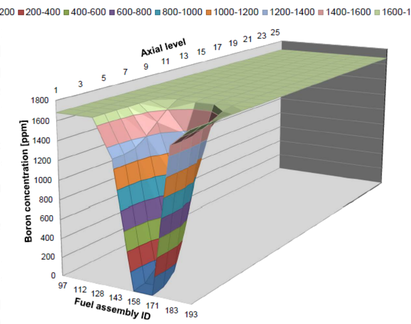
As predicted, at the time of peak core power, the condensate slug has entered further into the core than in the natural circulation case which contributed to the more rapid and higher power increase.

The borated slug that enters the core inlet takes the cross sectional shape of the cold leg pipe in the axial direction. The resulting reactivity change was more rapid with the core power peaking with a higher power factor of 859.014 attained at 1.31 seconds.

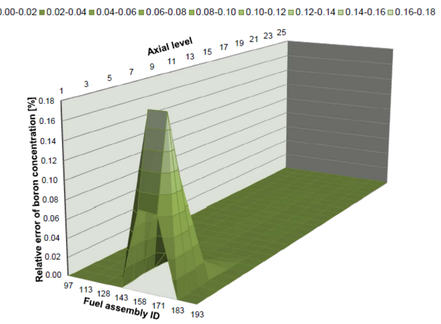
The boron transport model added to CTF greatly enhanced the overall capabilities of the code, in order to predict the boron concentration.

The CTF prediction of the transport of the condensate slug along the core.

The boron concentration relative error distribution, with a maximum value of 0.18% between the simulations using CTF/NEM (PSU) and CTF (CASL) validates the implementation of the boron tracking model in CTF code.



Boron Concentration Distribution in Subchannels Located along Condensate Slug at Peak Core Power, t = 1.31 sec



CTF/NEM vs CTF : Boron Concentration Relative Error Distribution at Peak Core Power, t = 1.31 sec

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