A MULTI-PHYSICS CODE SYSTEM BASED ON ANC9, VIPRE-W and BOA FOR CIPS EVALUATION

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Abstract

This paper summarizes the development of a multi-physics code system for evaluation of Crud Induced Power Shift (CIPS) phenomenon experienced in some Pressurized Water Reactors (PWR). CIPS is an unexpected change in reactor core axial power distribution, caused by boron compounds in crud deposited in the high power fuel assemblies undergoing subcooled boiling. As part of the Consortium for Advanced Simulation of Light Water Reactors (CASL) sponsored by the US Department of Energy (DOE), this paper describes the initial linkage and application of a multi-physics code system ANC9/VIPRE-W/BOA for evaluating changes in core power distributions due to boron deposited in crud. The initial linkage of the code system along with the application results will be the base for the future CASL development.

Introduction

Crud Induced Power Shift (CIPS), previously referred to as Axial Offset Anomaly (AOA) [1, 10], is characterized as an unexpected downward shift in reactor core axial power distribution from predicted values during operation of a Pressurized Water Reactor (PWR), caused by the buildup of neutron absorbing boron compounds in crud deposited in the upper spans of fuel assemblies undergoing subcooled boiling. The Consortium for Advanced Simulation of Light Water Reactors (CASL), sponsored by the US Department of Energy (DOE), considers CIPS as one of the challenge problems that the industry must address for safer and more economical operation of PWRs. In order to better understand cause of CIPS and its effect on the reactor operation, Westinghouse in cooperation with Oak Ridge National Laboratories (ORNL), Sandia National Laboratories and Los Alamos National Laboratories is developing a multi-physics code system as part of the CASL program to account for feedbacks of thermal-hydraulic and chemical changes in the reactor core on power distributions. The first step of such development is to link existing neutronic code ANC [2], core thermal-hydraulic code VIPRE-W [3, 4], and coolant chemistry code BOA [4-6, 9, 10] for evaluating changes in core power distributions due to feedback of boron in the crud.

1. ANC/VIPRE-W/BOA Overview

ANC is a Westinghouse neutronic nodal code for predicting core power distributions under normal operation and accident conditions. ANC9 [5] is the new version of the Westinghouse ANC neutronic code, which contains many enhancements and new features including a model of grid spacers. The code uses the 3-D semi-analytic nodal expansion method, and is typically used with 2x2 nodes per assembly (X-Y direction) and 24 or more axial nodes. During feedback iteration, ANC9 reconstructs the nodal cross-sections based on the nodal history and the local conditions, such as temperatures, moderator density, and boron concentration. For a standalone calculation, ANC9 employs a simplified thermal-hydraulic model to provide node average fuel and moderator temperatures at steady state conditions.

In a linked calculation, the core thermal-hydraulic (T/H) calculation is performed using VIPRE-W [3], the Westinghouse version of the VIPRE-01 code [4] developed from several versions of COBRA under the sponsorship of the Electric Power Research Institute (EPRI). Steady state or time-dependent conservation equations of mass, axial and lateral momentum and energy are solved for fluid enthalpy, axial flow rate, lateral flow and momentum pressure drop. VIPRE-W contains many enhancements for PWR design calculations, including options of fuel boiling duty calculation, a grid heat transfer model and data interface with ANC and BOA for CIPS risk assessment.

The BOA code [6, 9, 10] was developed under EPRI sponsorship from the BOB code [7]. It predicts corrosion product deposition on the fuel rods and boron accumulation within the deposits. From a neutronic point of view, due to the large absorption cross-section of B10, the boron deposited in the crud will induce a considerable nodal cross-section change and essentially impact the core reactivity and the node-wise power distribution. During reactor operation, it takes some time for crud deposits containing B10 to thicken sufficiently to cause CIPS. Significant CIPS has usually been observed in the second half of the reload cycles. However, due to the complexity of the crud deposition model and lack of communication between different physics codes, it has been a challenge to the standard core design codes to directly follow the B10 deposition and account for the impact.

The code linkage among ANC9, VIPRE-W and BOA is based on a proven data interface architecture that has been recently developed for linking ANC9 with VIPRE-W. The new data interface is established between BOA and ANC9 for boron distribution in the core to complete the data interface loop among the three codes. A feedback model for boron deposited in crud has been developed and implemented in ANC9 to account for the crud impact based on the boron deposition distribution calculated by BOA. The multi-physics code system provides a new capability for modelling boron and crud effect leading to CIPS. The code predictions are being compared with core parameter measurements of a plant operating cycle that experienced significant CIPS.

2. Code Linkage Approach

Boron deposited in the core affects the core neutron and heat flux distribution. The heat flux distribution affects local thermal-hydraulic conditions and sub-cooled boiling rates. The sub-cooled boiling rates affect crud and boron deposition. Therefore it is necessary to involve multiple physics components to accurately simulate the CIPS phenomena. The development of the multi-physics code system in this work focuses on interactions between core power distribution and boron in crud deposit in a CIPS analysis.

Accurate prediction of power distributions in core experiencing CIPS by the neutronic code ANC requires communication between ANC, VIPRE-W, and BOA so that the core power distribution, thermal-hydraulic data and boron in the crud distribution information can be determined consistently between the codes. ANC accounts for the effect of thermal-hydraulic conditions and boron in the crud through feedback models by correcting the cross-section in each node or fuel rod (i.e. pin) when needed. In turn, ANC provides BOA and VIPRE-W with predicted core soluble boron levels as well as the detailed power node-wise and pin-wise distributions, respectively.

Due to the different interaction time-scales of power to thermal-hydraulic and temperature to corrosion deposition, different schemes are implemented for ANC/VIPRE-W coupling and VIPRE-W/BOA/ANC coupling.

Westinghouse developed the linkage of ANC and VIPRE-W in the 1990s [8]. Because the impact of power and thermal-hydraulic (i.e. temperatures and moderator densities) results is almost instantaneously, the data transfer between ANC and VIPRE-W follows immediately the update of power distribution or thermal hydraulic results. This iterative process is established in through the feedback model and the iteration continues till all the convergence criteria are met.

The deposition of corrosion products and boron on the fuel impacts the core reactivity and power distribution in two major aspects. The crud deposited on the cladding surface adds thermal resistance from cladding to coolant and therefore leads to a higher local fuel temperature. The second effect comes from the boron accumulated in the deposit. Due to the large thermal absorption cross-section of B10, the local boron accumulation directly contributes to the total absorption cross-sections. Compared to the boron contribution, the impact of the overall thermal conductivity change is relatively small. Therefore, the change of the fuel temperature due to the crud is not modelled in this initial linkage of the codes. For a fuel node with crud deposition, based on the B10 concentration in the crud, the node absorption cross-sections are adjusted using the following expression:

$$\Sigma_{a,g}^{Correct} = \Sigma_{a,g}^{NoCrud} + N_{B10}^{Crud}\sigma_{a,g}^{Crud} \tag{1}$$

Here $\sigma_{a,g}^{B10}$ is the B10 microscopic absorption cross-section at energy group "g", N_{B10}^{Crud} is the B10 number density accumulated in the crud. $\Sigma_{a,g}^{Correct}$and $\Sigma_{a,g}^{NoCrud}$ are respectively the node macroscopic absorption with and without crud boron correction.

Fig. 1 shows the linkage among ANC9, VIPRE-W, and BOA codes. Since any change in heat flux distribution quickly affects the local thermal-hydraulic conditions, ANC and VIPRE-W must be coupled relatively tightly. However, crud and boron deposition change over much larger time scales. Therefore it is assumed that the deviation of the calculated boron deposition due to the change of the core condition within a burnup step is negligible if the burnup step is chosen to be sufficiently small. In practice, the core power, temperature, and moderator density distributions at the beginning of the time step are taken to predict the core crud/boron deposition and the coupling between ANC and BOA is structured outside of the ANC/VIPRE-W feedback iterations, linked using dash lines in the figure.

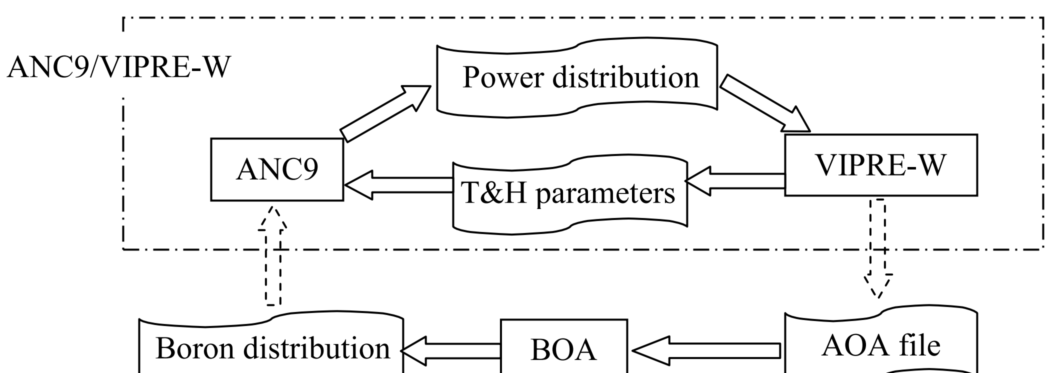

Figure 1 Illustration of ANC/VIPRE-W/BOA linkage.

With the linkage, ANC9 will directly read in the B10 distribution file generated by BOA code and, based on the information, correct the nodal cross-sections using Equation (1).

3. Initial Evaluation of Boron/Crud Feedback Effect

3.1 Case Description

A series of cases was run as part of an initial study to ascertain the impact on the core-wide power distributions from the boron distribution within the crud layer. A sample model was generated for a typical reload cycle of a Westinghouse 3-loop PWR core. Various boron distributions as a function of cycle depletion were modelled to determine the interaction of the depletion feedback effects along with the boron distribution within the crud layer.

- The first case was a nominal all rods out, hot full power depletion with no boron distribution within the crud layer as a reference calculation.
- A second depletion case assumed a boron distribution within the core to slightly reduce the core axial offset at 6000 MWd/mtU and then the boron distribution held uniform for the remainder of the cycle.
- The third case started as the second case, but then varied the amount of boron in the crud distribution as a function of cycle burnup to attempt to keep the core-wise axial offset at a constant negative value.

A second series of cases was run to show the instantaneous impact of the variation of the boron content within the crud layer. These cases evaluated the impact of gradually increasing the total boron content within the crud layer on the core-wide parameters of boron concentration and axial offset, along with the impact on the core peaking factors.

3.2 Results Comparison

The cases described above demonstrate the strong depletion feedback effect. The depletion feedback effect is related to the change in the axial burnup distribution in the core. Since the reactivity decreases with depletion, especially after the burnout of the burnable absorbers, there is a reactivity shift within the core that tends to pull the core power distribution to the regions with lower burnup. This effect tends to "heal" the deviation caused by a constant reactivity perturbation and the core axial offset will tend toward its natural state. Also, the forcing function to hold the axial offset at a more negative value than natural will have to keep getting stronger to have the same impact.

Figure 2 shows the two different forcing functions created by a boron distribution within the crud. The solid line represents the total amount of boron to keep the axial offset approximately uniform after 8000 MWd/mtU. As can be seen the amount increases substantially with burnup. Figure 3 shows the impact of the axial offset as a function of burnup, Note the end of cycle burnup point used the same boron holdup mass as the case at 18,000 MWd/mtU. The dramatic shift upwards at that point demonstrates the depletion feedback effect is strong, even with a large boron holdup mass.

Also seen in Figures 2 and 3 is the impact of holding the boron holdup mass at a constant value, as shown in the dashed lines. The impact of the boron distribution in the crud initially reduces the core-wide axial offset, but leaving the value constant allows the core the quickly return to its natural state.

Note that neither of these cases considers the depletion of the B10 in the boron holdup in the crud layer. Any depletion of the B10 would only increase the impact of the effects demonstrated in these cases.

The second series of cases run were investigating the impact of the boron distribution within the crud layer on the core at a fixed point in life. Figure 4 shows the impact on the core-wide axial offset and the soluble boron concentration as a function of the boron holdup mass. As expected these functions are linear and demonstrate the strong impact on the core axial offset and the critical boron concentration of the small amount of boron within the crud layer.

Figure 5 visualizes the impact on the core power distribution from the boron in the crud layer. Since the crud deposition tends to be related to the amount of subcooled boiling, the layer is focused in the high power assemblies. When the boron content in the crud layer is increased, the average power in the higher power assemblies is decreased. Therefore, as shown in Figure 5, the peak fuel rod to core average power (FDH) decreases with increasing boron mass within the crud layer. However, since the non-uniform axial distribution of the boron content within the crud layer, the axial power distribution becomes more skewed and hence the peak pellet to rod average power (FZ) increases as the boron content increases. The combination of the two factors (FDH and FZ) is related to the peak pellet power (FQ) within the core. The FQ is initially flat, or decreasing, but then starts monotonically increasing with the boron mass increase.

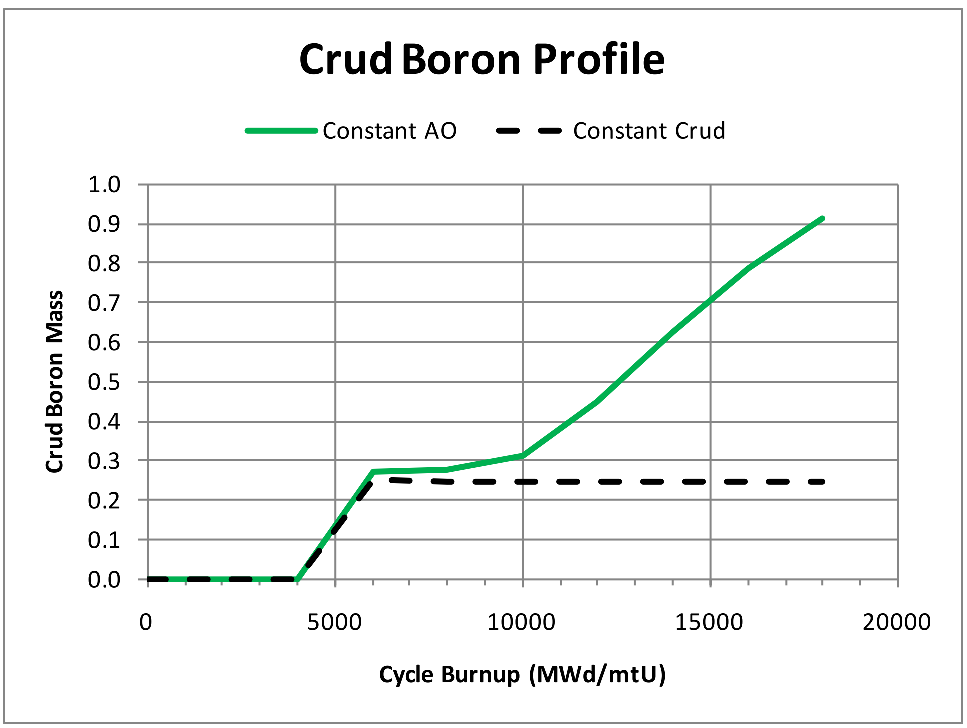

Figure 2 Two Different Crud Boron Profiles versus Cycle Burnup

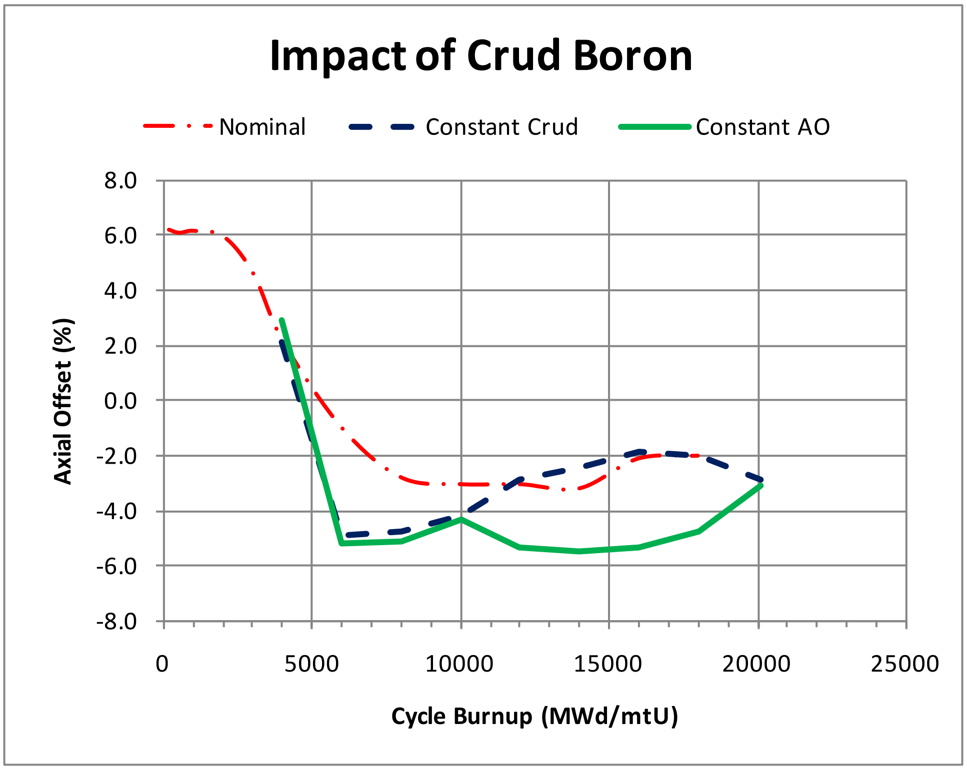

Figure 3 Impact of Different Crud Boron Profiles

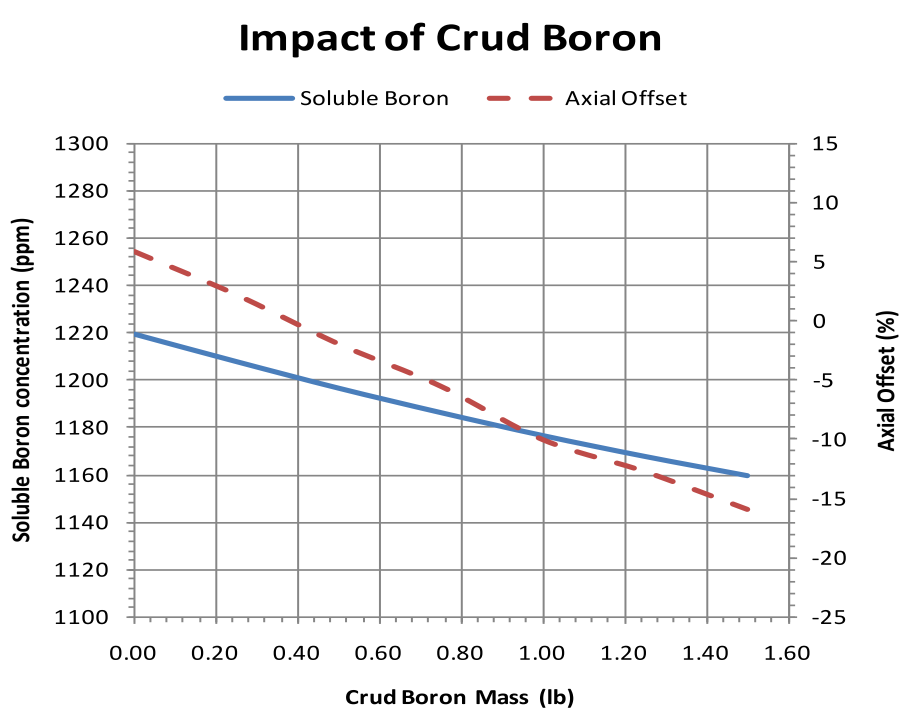

Figure 4 Sensitivity to Crud Boron Mass

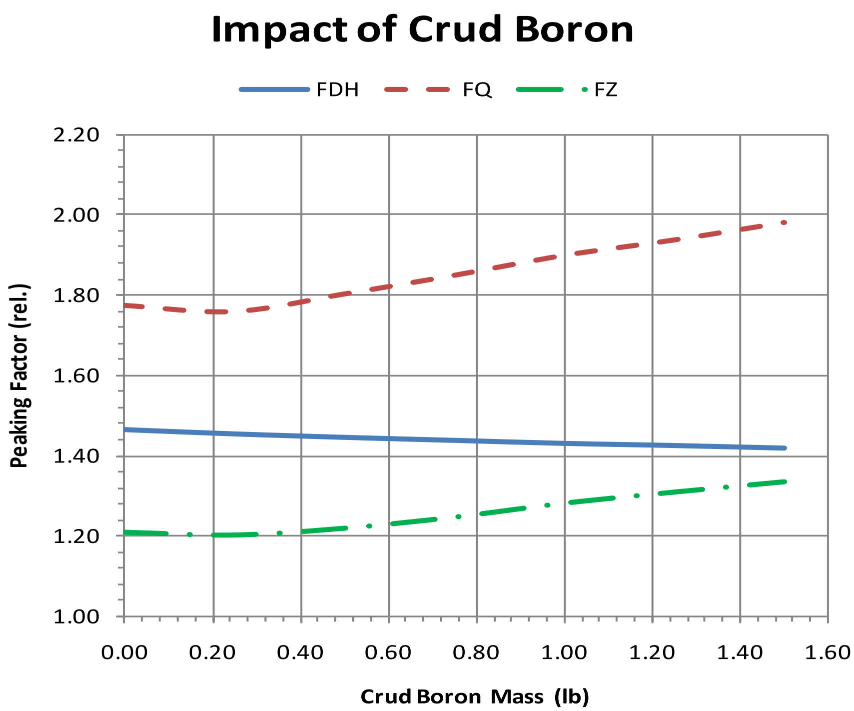

Figure 5 Peaking Factor Sensitivity to Crud Boron Mass

4. Conclusion

A coupled linkage among ANC9, VIPRE-W and BOA has been developed for the analysis of CIPS within PWR cores. Initial analyses have demonstrated sensitivities of core power distribution associated with the boron distribution within the crud layer, and the importance of the coupled feedback effect to fully understand the phenomenon of CIPS and its impact. The linked code system will be applied to investigation of CIPS occurrences in previous operating cycles of several PWRs. The improved capability based on the linked code system will provide greater assurance that the reload fuel management and plant chemistry management are sufficient to minimize the impact of CIPS on operating reactors.

5. References

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