APPLICATION AND VALIDATION OF AREVA'S ADVANCED THERMAL-HYDRAULIC METHODS AND CODES FOR PWR LEVEL III CRUD RISK ASSESSMENT

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ABSTRACT

The current industry guidelines set by Institute of Nuclear Power Operations (INPO) and Electrical Power Research Institute (EPRI) require utilities to perform a crud induced corrosion and crud induced axial off-set risk assessment while undergoing any significant changes in the core operating conditions or the fuel design. The EPRI guidelines provide various levels of detail required in the crud risk assessment, of which Level III and Level IV have core neutronics and thermal-hydraulics coupled with the plant chemistry.

AREVA has developed a state-of-the-art process, based upon standard licensing methods and specialized applications, for evaluation of the risk due to crud induced corrosion and crud induced axial off-set. This streamlined process allows for evaluation of the crud risk for the full core subchannel by subchannel models, by applying local conditions on each fuel rod/subchannel, with axial nodes spanning scale of a several centimeters.

AREVA's tools are capable of performing a Level III risk assessment on any PWR reactor design, for uniform and mixed cores. These tools have been applied to B&W-177 FA, W-193 FA, CE-14x14 and CE-16x16 plants, and have been validated against the visual data of post-irradiation examinations from plants with known crud deposits.

This paper presents an overview of the thermal hydraulic portion of the AREVA Level III crud risk assessment methods and automation. The details of the plant chemistry process are provided in other publications.

Nomenclature

B&W	Babcock & Wilcox
CE	Combustion Engineering
CILC	Crud Induced Localized Corrosion
CIPS	Crud Induced Power Shifts
CST	Clad Surface Temperature
DUSG	Distance from Upstream Spacer Grid
EFPD	Effective Full Power Day
EPRI	Electrical Power Research Institute
FA	Fuel Assembly
FDIC	Fuel Deposit Interactive Chemistry
FR	Fuel Rod
HBC	Holloway, Beasley, and Connor
HF	Heat Flux
INPO	Institute of Nuclear Power Operations
LWR	Light Water Reactor
NOAK	N^{th} of a Kind
PLC	Pressure Loss Coefficients
PWR	Pressurized Water Reactor
KDV	Key Decision Variable
SGS	Spacer Grid Span
SRF	Steaming Rate Flux

KEYWORDS
EPRI, crud, risk assessment, steaming, Level III

I. INTRODUCTION

To achieve the goal of zero fuel failures, the current industry guidelines set by the Institute of Nuclear Power Operations (INPO) and the Electrical Power Research Institute (EPRI) require utilities to perform a crud induced corrosion and crud induced axial off-set risk assessment while implementing any significant changes in the core operating conditions or the fuel design [1] & [2]. The EPRI Guideline [2] describes the four levels of crud risk assessment along with details of analysis for each level. The guideline offers recommendations on the level of risk assessment appropriate for plant condition changes and measures to reduce the fuel crud deposit risk.

In accordance with the EPRI guidelines, AREVA has developed its own four level crud risk assessment methodology that is currently used to perform risk assessments for the Pressurized Water Reactor (PWR) cores. The details of AREVA's four level crud risk assessment are discussed in [3]. The level of analysis depth and detail of AREVA's four level crud risk assessment exceed the recommendations provided by the EPRI guidelines. The state-of-the-art assessment process developed by AREVA utilizes the standard licensing tools in conjunction with proprietary techniques to allow for performing the crud risk assessment in an efficient and effective manner. AREVA's Level III and Level IV crud risk assessment process couples the core neutronics and thermal hydraulics with plant chemistry. The thermal hydraulic component of the Level III calculations is performed on a subchannel node scale (scale of several centimeters) whereas the Level IV calculations are performed on fractions of a millimeter scale.

This paper provides details on the thermal hydraulic portion of the AREVA Level III crud risk assessment. Section II provides a high-level description of the analysis process. An overview of the sophisticated automation tool, AUTOCRUD, which couples multiple codes and interfaces used in the thermal hydraulics process to perform the Level III risk assessments, is provided in Section III. Also provided in Section III is the validation of crud deposition data from the thermal hydraulic models, with the Distance from Upstream Spacer Grid (DUSG) dependent heat transfer model implemented, against crud deposition visuals from a plant with known crud deposits. Finally, Section IV provides results for different plant types for which the assessment has been performed, including Babcock and Wilcox (B&W)-177 FA, Westinghouse (W)-193 FA, Combustion Engineering (CE)-14 x14, 217 FA and CE-16X16, 241 FA plants.

II. ANALYSIS PROCESS

AREVA crud analyses are typically performed for three cycles of operation in order to collect the complete life cycle of resident fuel for which the crud assessment is being performed; the cycle of interest, Cycle N, as well as the previous two cycles, N-1 and N-2, respectively. For instances where the current cycle has resident fuel reinserted from cycles beyond N-2, the data for reinsert cycles can be evaluated as necessary. The thermal hydraulic component of the Level III crud risk assessment is performed assuming absence of any crud on the fuel rod (FR) surfaces, called the 'clean rod' predictions.

The objective of the thermal hydraulic assessment is to determine the key decision variables (KDVs) on the 'clean rod' fuel rod surface and the coolant. The KDVs of interest are cladding surface heat flux (HF), cladding surface temperature (CST) and subchannel based steaming rate flux (SRF). Each of these KDVs is computed on a subchannel node scale for the entire core as a function of Effective Full Power Days

(EFPDs), with the key results provided to plant chemistry for further assessment. AREVA's plant chemistry assessment, not covered in this paper, incorporates the deposition of crud on the fuel rods as it progresses along its life cycle, and requires the coupling of neutronics, thermal hydraulics and plant chemistry. Plant chemistry determines the crud risk based on the KDVs mentioned here for the entire life of the fuel present in the core.

Figure 1 lists the schematic of AREVA's Level III crud risk assessment process. This paper focuses on the thermal hydraulic part of the assessment.

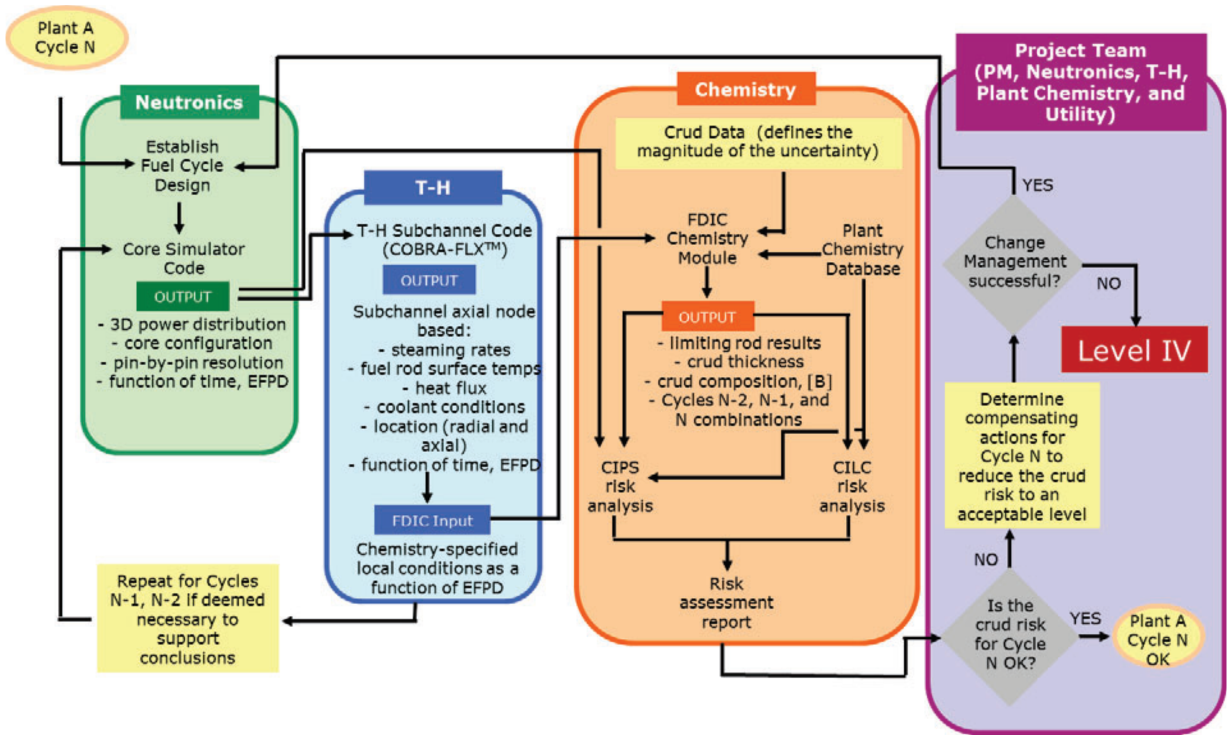

Figure 1: AREVA Level III Analysis Schematic

The neutronics supplied plant parameters and the core data listed in Figure 1, for the required cycles, feed into the thermal hydraulics analysis. The thermal hydraulic analysis uses the automation code, AUTOCRUD, to generate multi-cycle 'clean rod' life history for every single fuel rod/subchannel in the core. A key subset of these data points, defined using a selection process defined by plant chemistry, for the Crud Induced Power Shifts (CIPS) and the Crud Induced Localized Corrosion (CILC) are used as an input to the plant chemistry module called Fuel Deposit Interactive Chemistry (FDIC). This set of data points, generated for both CIPS and CILC risk, are based on the life time history of the KDVs (HF, CST and SRF) for the fuel present in Cycle N. The generation process for the limiting thermal hydraulic input data to plant chemistry is the same for the CIPS and the CILC risk. Plant chemistry utilizes its own differentiation process for the thermal hydraulics supplied CIPS and CILC data.

III. THERMAL HYDRAULICS MODELING

III.A. Automation

The Level III crud risk assessment is performed using AUTOCRUD, AREVA's state-of-the art automation tool with enhanced capabilities to generate multi-cycle fuel rod life history, interface with chemistry analysis tools, as well as produce high resolution visual images. AUTOCRUD combines the PWR subchannel simulation code COBRA-FLX™ [4] with other in-house tools and interfaces.

The COBRA-FLX™ code is based on COBRAIIIC/MIT-2 [5]. It includes versatile computational capabilities to cover the full spectrum of thermal hydraulic analyses for both safety and non-safety applications needed to support AREVA's global thermal hydraulic needs. The code is approved in the US by the Nuclear Regulatory Commission for use in licensing applications. In this application, COBRA-FLX™ is used to calculate the aforementioned KDVs.

In addition, COBRA-FLX™ contains a specialized solution algorithm that allows the subchannel/fuel rod calculations to be performed fast enough to evaluate local conditions that combined with the automation capabilities of AUTOCRUD, allows for evaluation of many discrete time intervals over multiple cycles. One of the key benefits of the automation tool is the reduction of total analysis time for 'Nth of a Kind' (NOAK) assessment. This allows AREVA and utilities to proactively perform risk assessments during the core design process, and even evaluate multiple core designs to select the optimal design based upon comparative analysis of the KDVs.

The process schematic of AUTOCRUD is presented in Figure 2.

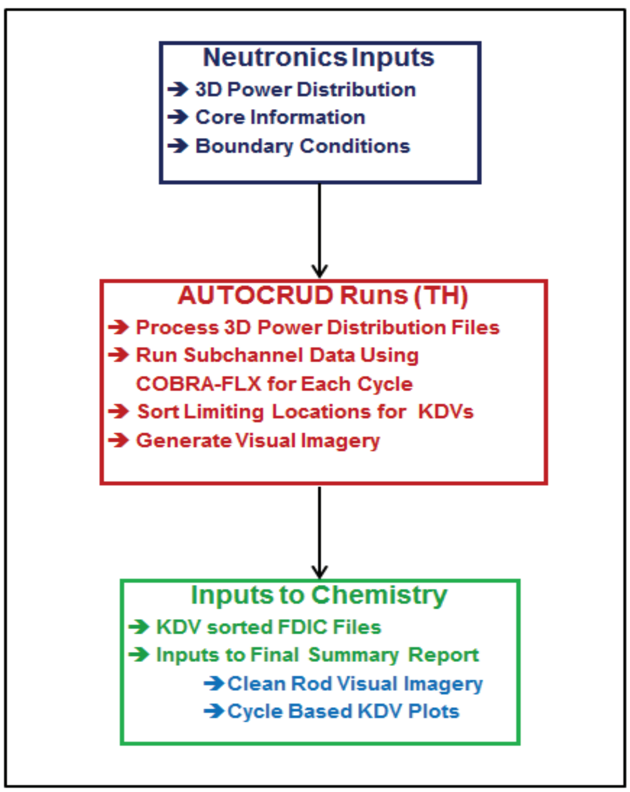

Figure 2: AUTOCRUD Process Schematic

III.B. Core Model Development

A typical subchannel-by-subchannel COBRA-FLX™ model used in the thermal hydraulic analysis is shown in Figure 3. The model here is based on a uniform (non-mixed) core of an operating B&W-177 plant. The schematic in Figure 3 contains both, the full core model and an expanded view of a single fuel assembly. The model has 40276 subchannels and 36816 fuel rods, where the unheated rods are color-coded with the red rods denoting unheated control rod guide tubes and the green (cyan) rods denoting unheated instrument guide tubes.

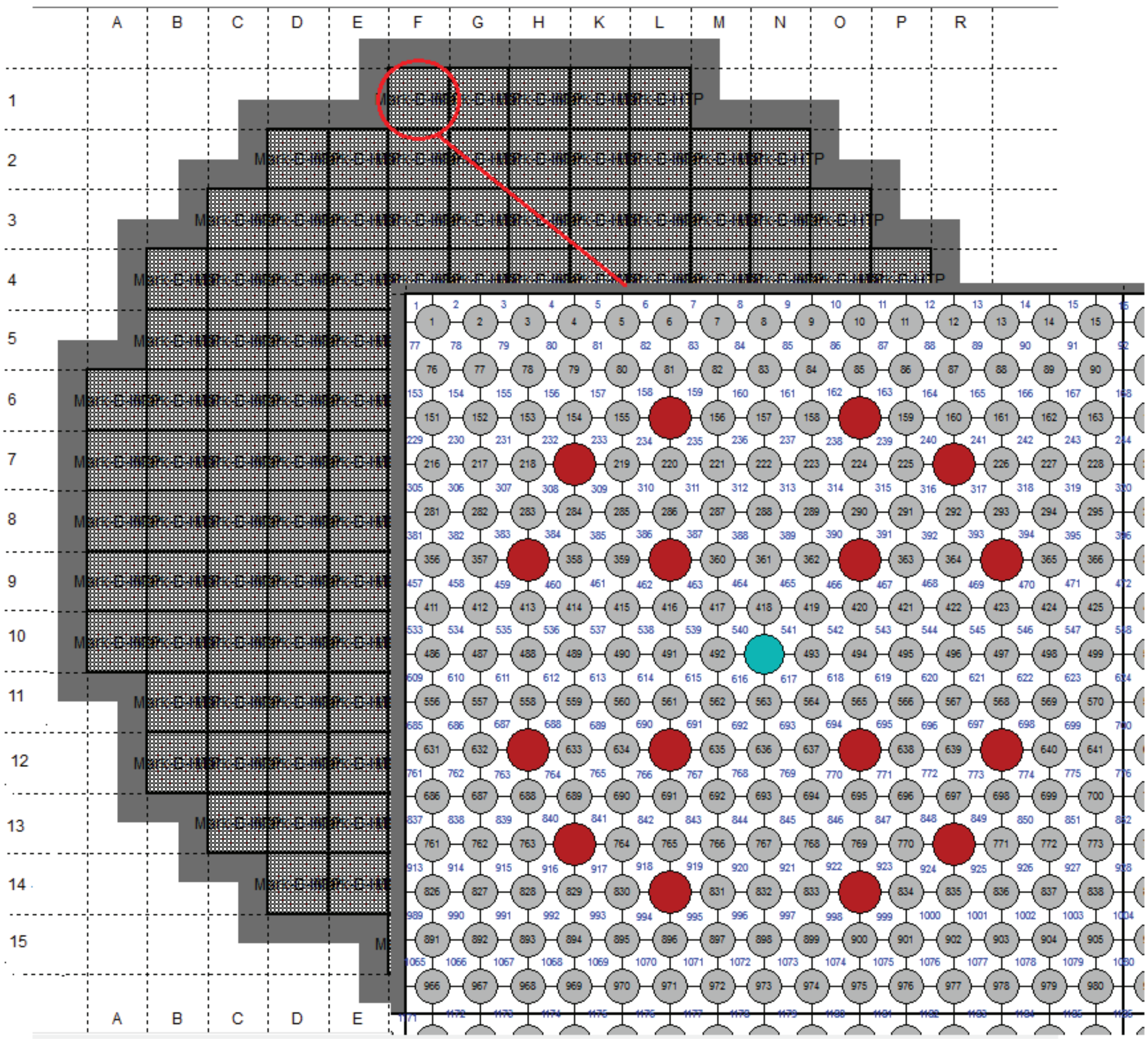

Figure 3: COBRA-FLX™ Full Core Detailed Model

The boundary conditions for the core power level, the core inlet flow rate, the inlet coolant temperature, and the core exit pressure used in COBRA-FLX™ are based on cycle specific measurements from the plant where possible. The COBRA-FLX™ code is also capable of modeling end of cycle maneuvers such as a power coast down or core average temperature reductions, where applicable. It should be noted that only a single model is required with all variation in boundary conditions managed by the AUTOCRUD automation.

Although AUTOCRUD is capable of generating the KDVs for every single fuel rod/subchannel combination in the core over all axial heights, only a subset of the data over the limiting axial range is supplied to plant chemistry for further analysis. Generally, the locations of maximum KDVs occur in a span of a few axial nodes within the fuel assembly allowing for further refinement of the data.

For example, the analysis performed in Figure 4 showed that the maximum steaming rate flux for the plant being analyzed was within axial locations of spacer grid span (SGS) 2, which is the span between grids 5 and 6.

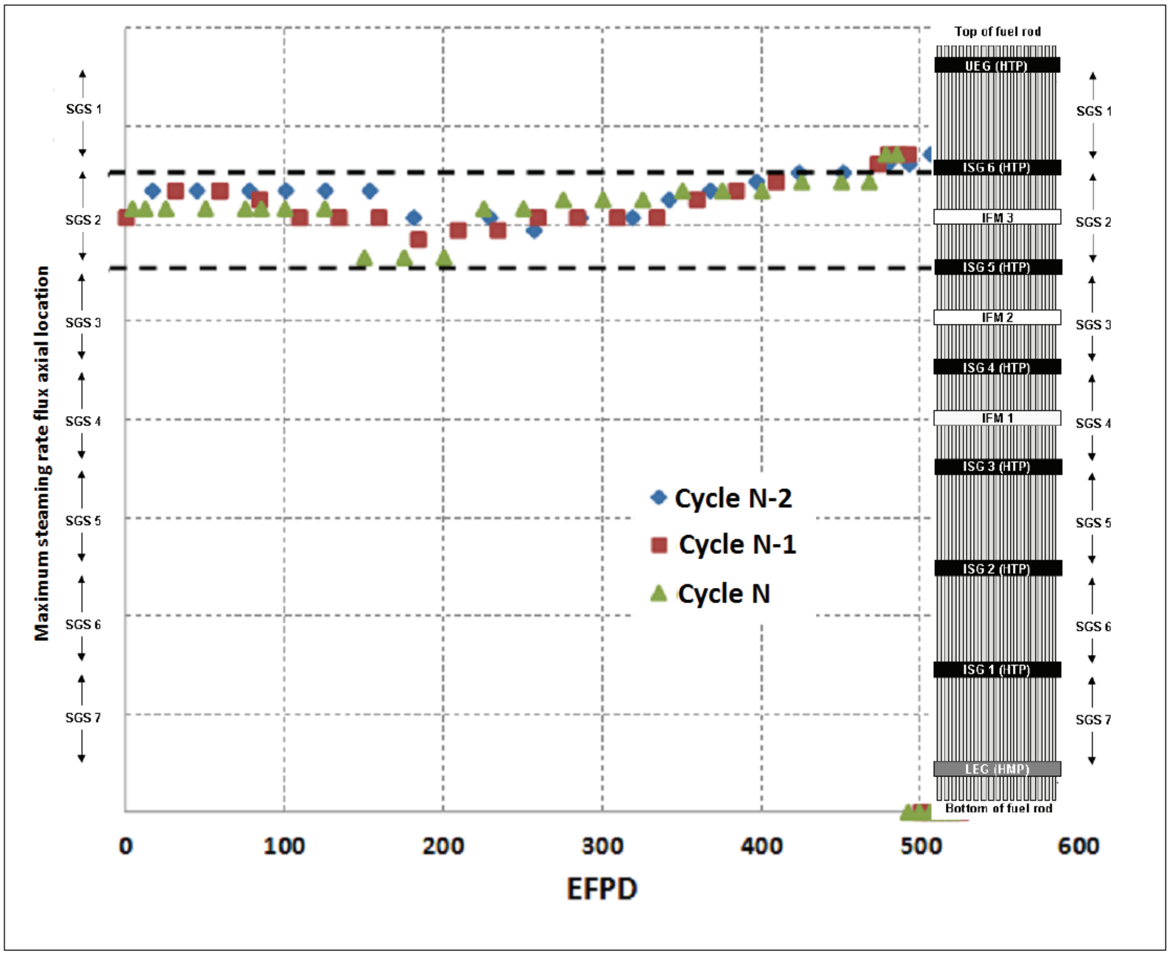

Figure 4: Axial Height of Limiting Key Decision Variable.

III.C. Modeling Updates

Early validation of the AREVA Level III crud risk assessment process was performed on a B&W 177 fuel assembly plant with measured crud deposition. The details of the validation were presented in [6]. Insights gained during the validation resulted in refinements in the models and processing to more accurately predict the crud deposition.

The original COBRA-FLX™ modeling did not include a distance from upstream spacer grid (DUSG) dependent heat transfer model. It has since been determined that the use of a DUSG model would allow the crud risk assessment process to produce a more realistic comparison to the crud visuals. The revised benchmark, with the Holloway, Beasley, and Connor (HBC) correlation [7] implemented in the COBRA-FLX™ models, showed better predictions for the crud deposition. The HBC correlation modifies the single-phase convective heat transfer coefficients for turbulent flow through the rod bundles downstream of the spacer grids. The correlation is based on air flow and is dependent only on the spacer grid pressure loss coefficient (PLC). It indicates heat transfer enhancements for up to 10 hydraulic diameters immediately downstream of the spacer grids. The HBC correlation for the heat transfer enhancement downstream of the spacer grid is,

$$\frac{Nu_{avg}}{Nu_{fd}} = 1 + \left(0.8K_g - 0.4\right)e^{0.25z/D_\infty}$$

where

$Nu_{avg} = Avg.\ Nusselt\ number$,

$Nu_{fd} = Fully\ developed\ Nusselt\ number$,

$K_g = Pressure\ Loss\ Coefficien\ t$,

$z = Axial\ (stream\ wise)\ coordinate\ \ direction$,

$D_\infty = Hydraulic\ diameter\ of\ \ Subchannel$,

Details of the HBC correlation development can be found in Reference [7].

Less crud deposition was predicted immediately downstream of the spacer grids, as indicated by lower clad surface temperature (CST) values in that area. The CST values downstream of spacer grids in SGS 1, 2 and 3, which are in nucleate boiling regime, are not impacted by HBC the model. A comparison of the HBC and non-HBC model for a wall fuel rod /subchannel of a B&W-177 plant is presented in Figure 5.

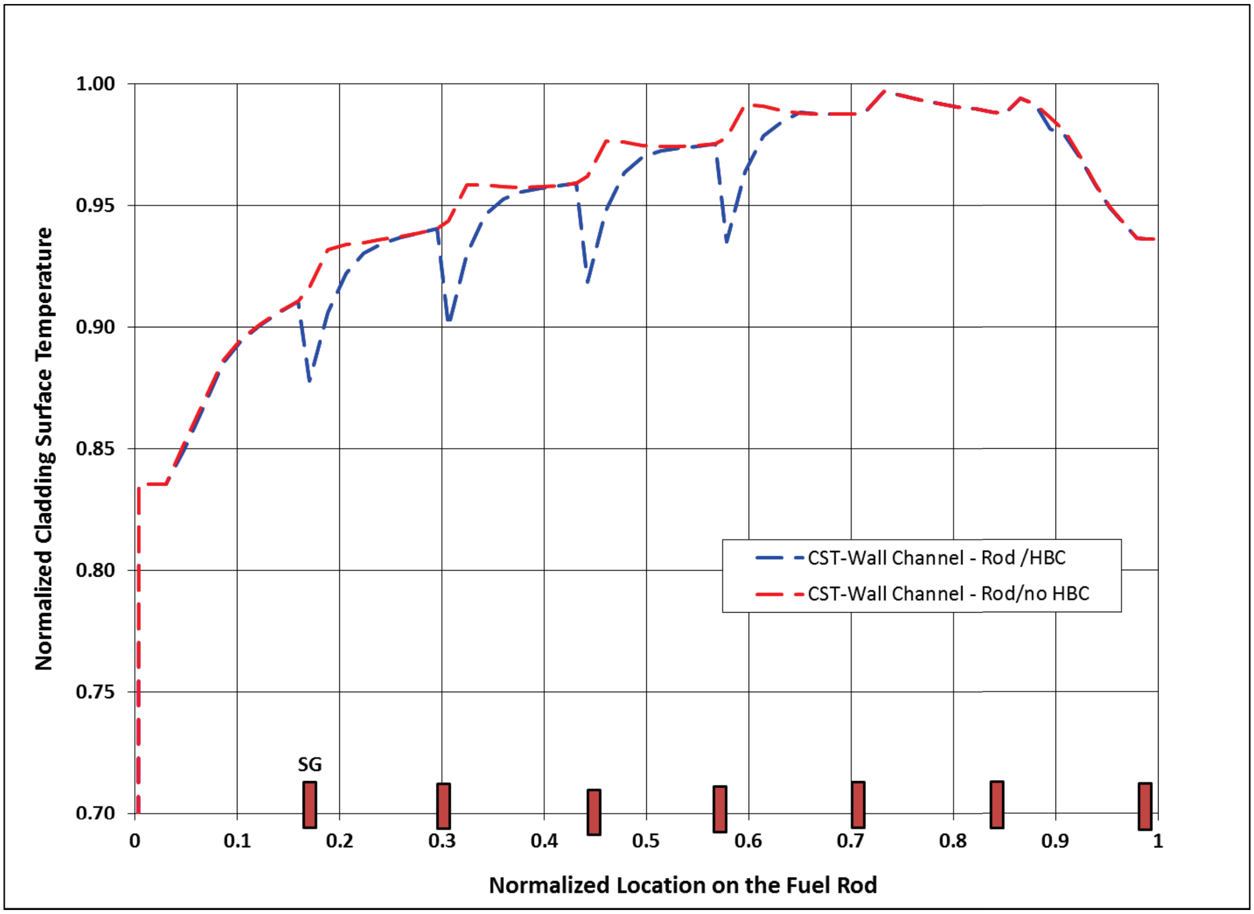

Figure 5: CST as a Function of Fuel Rod for HBC and Non-HBC Model.

Based on Figure 5, the HBC model is predicting lower CSTs downstream of the spacer grid in the regions where forced convection heat transfer occurs. The difference in the CST values decreases until the end of the spacer grid span where both models are predicting the same CST. The lower CSTs predicted downstream of the spacer grids matches the crud visual data from a B&W-177 plant.

In Figure 6, crud is the light-colored material on the surface of the fuel rods and starts downstream of the spacer grid. The crud visuals show little or no deposition immediately downstream of the spacer grid as predicted by the HBC model in the benchmarks.

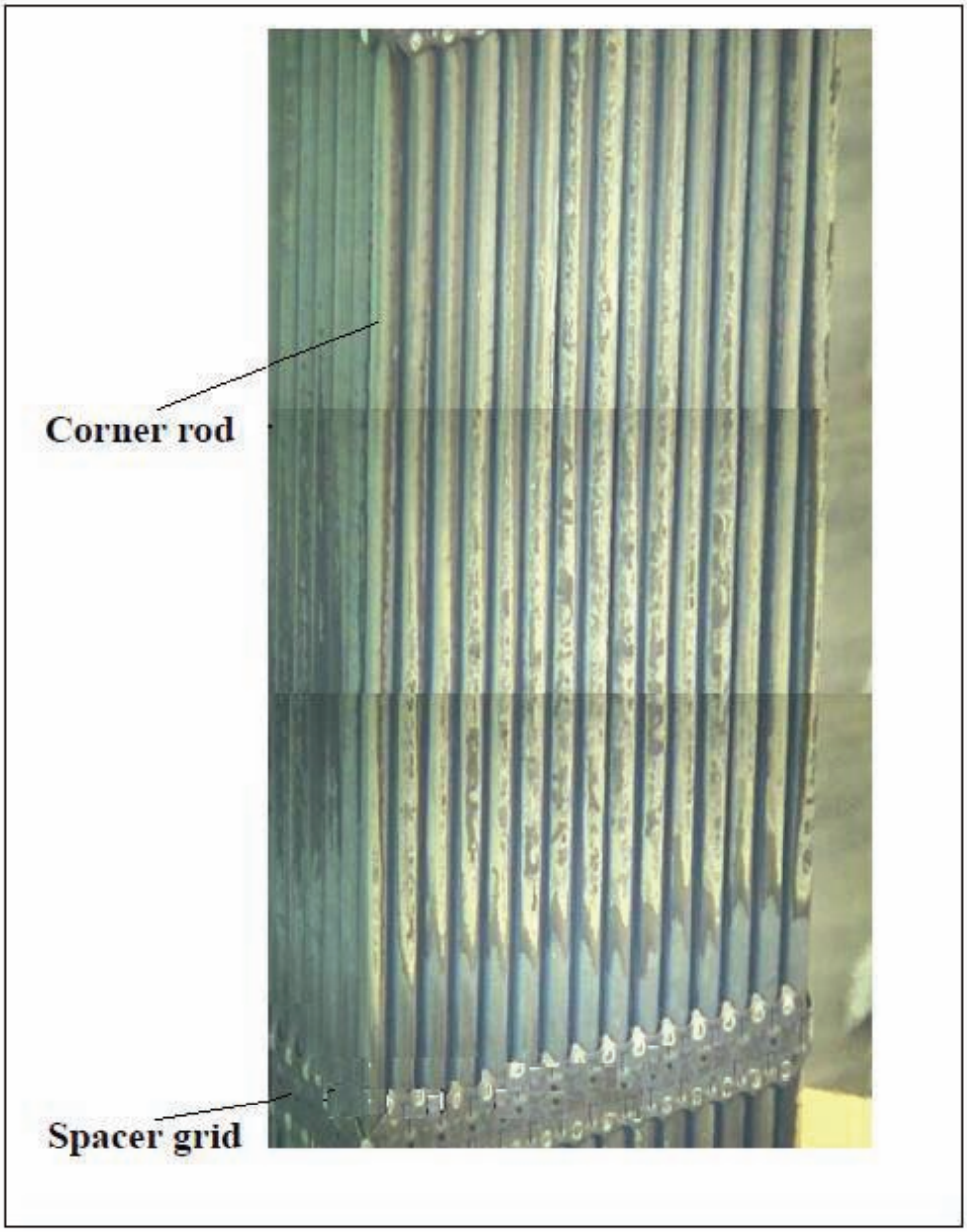

Figure 6: Crud Deposition Visuals from B&W 177 FA Plant.

III. LEVEL III EVALUATIONS & RESULTS

The modeling upgrades and automation allow the Level III risk assessment to be performed in more efficient and precise manner. The Level III risk assessments have been performed on the B&W-177, W-193, CE-14x14 and the CE-16x16 plants using AUTOCRUD. The automation tool helps analyze the multiple cycles of full core data for several different core loading plans, allowing AREVA and their customers to optimize the loading plan for the lowest crud risk based on the KDVs.

Figure 7 shows the life time values for steaming rate flux for a full core B&W-177 plant. The lifetime steaming rate values, over EFPD for all cycles, show that highest steaming rates were observed at the periphery of the fuel assemblies (shown in red). The higher steaming rates on the periphery are based on distribution of the flow resistance. This data coincides with the crud deposition pattern from crud visuals which is heavy on the periphery of the fuel assemblies.

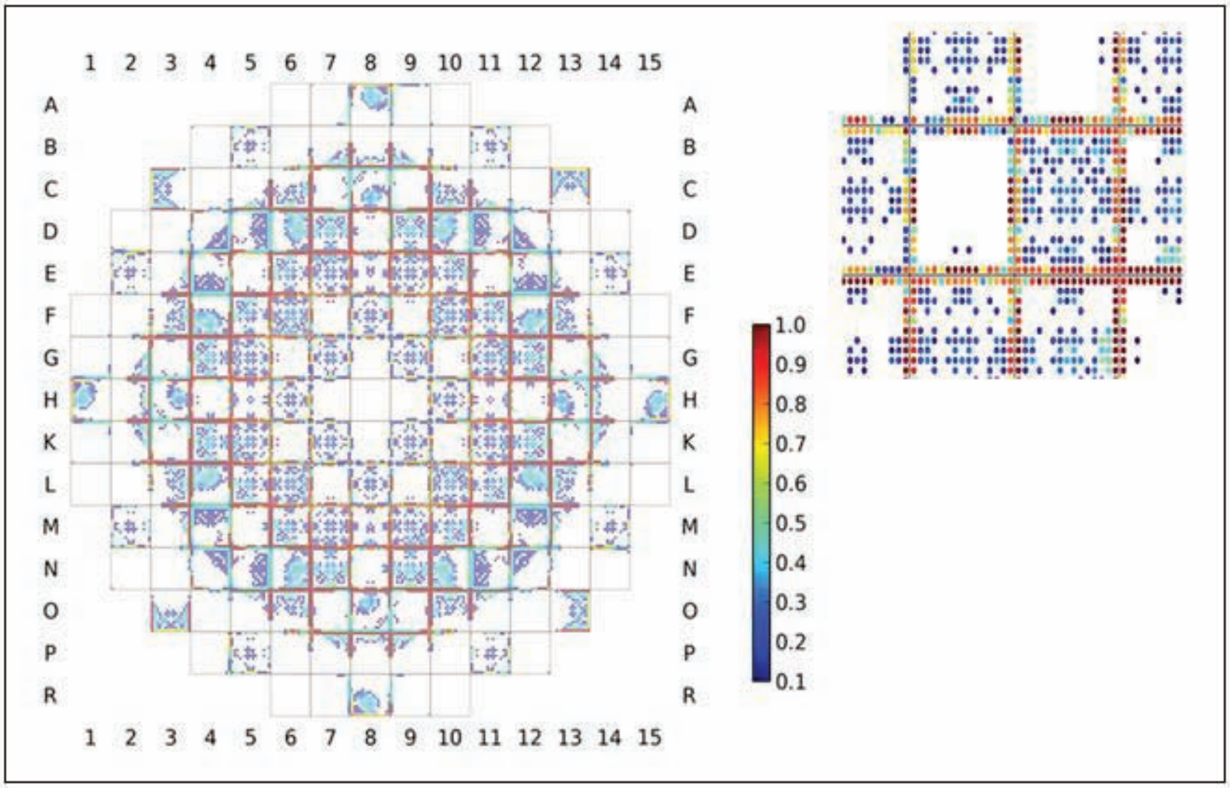

Figure 7: Lifetime Integrated Steaming Rate Fluxes for B&W 177 Plant.

Figure 8 presents the comparison of normalized SRF as a function of EFPD for three cycles of operation for a W-193 plant. The cycle being analyzed has fuel from two prior cycles, thus the N-2 and N-1 cycles were also analyzed to get the complete life history of the resident fuel.

Figure 9 presents the comparison of normalized CST as a function of EFPD for cycles for three cycles of operation for a CE -14x14 plant.

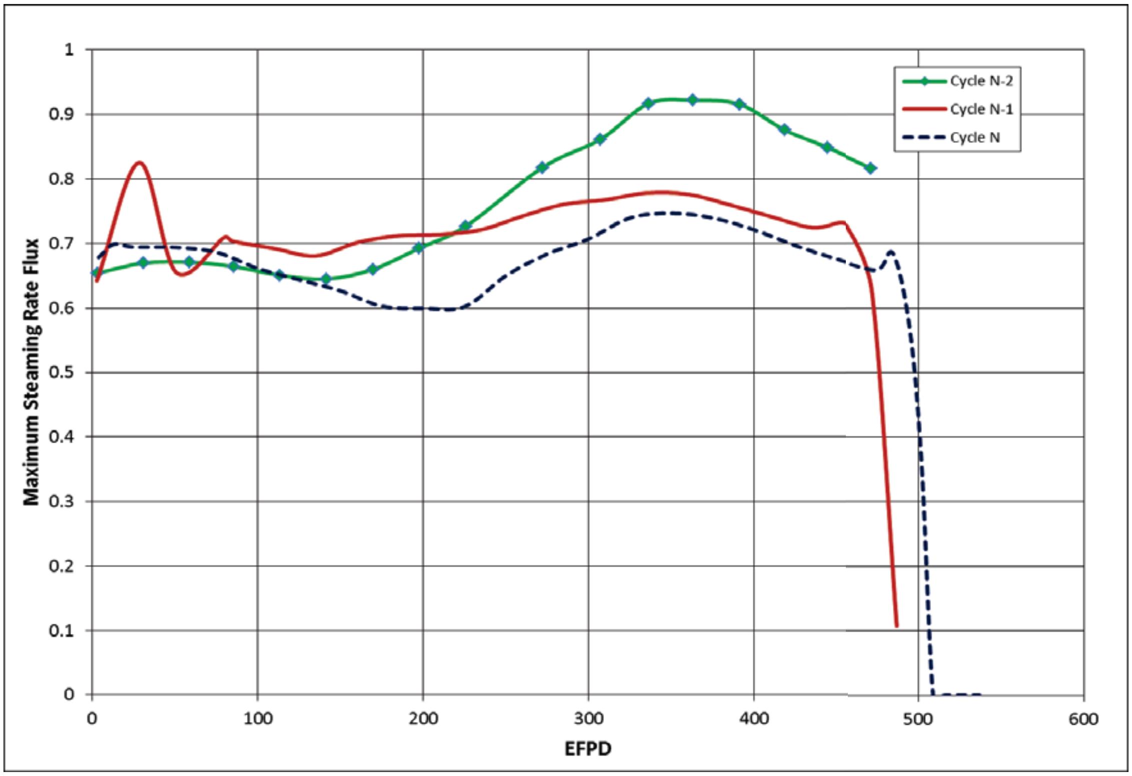

Figure 8: Normalized Steaming Rate Flux as a Function of EFPD for W-193 Plant.

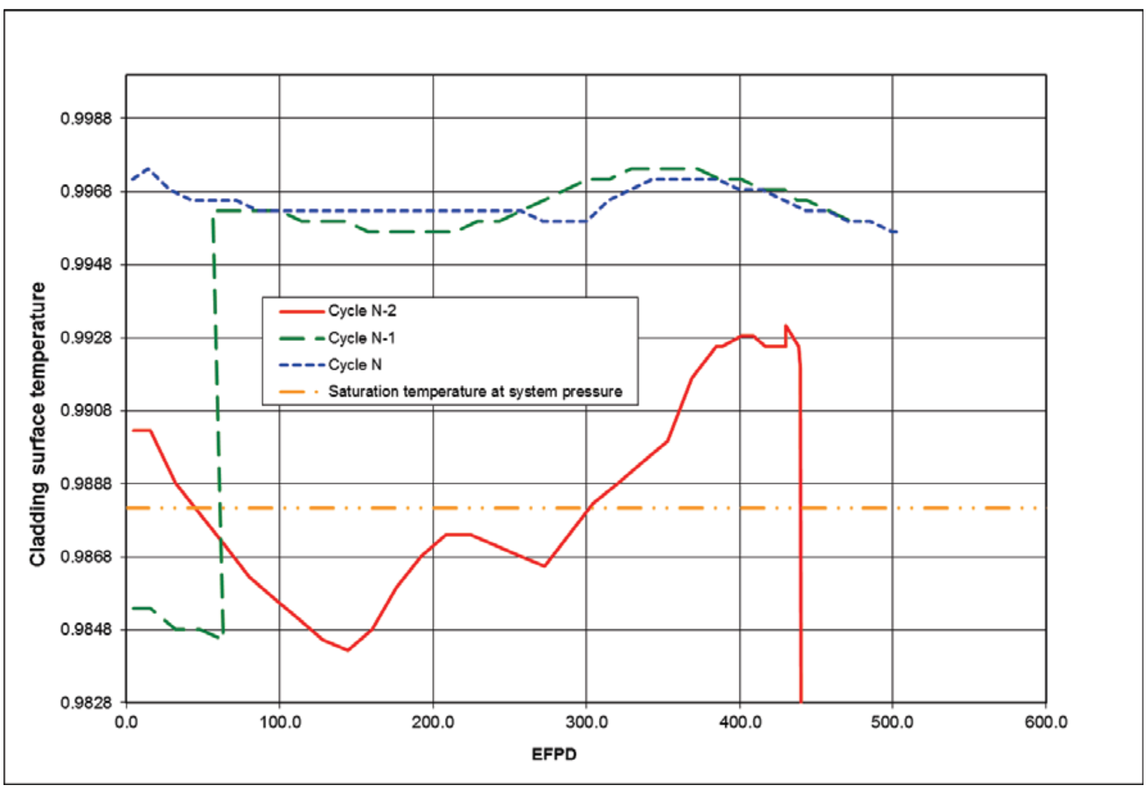

Figure 9: Normalized Clad Surface Temperature as a Function of EFPD for CE-14x14 Plant.

Visual images for KDVs at the desired EFPD are generated, typically at every ~50-100 EFPD for each of the cycles being analyzed during the Level III analysis. These images help visualize the behavior of the core throughout its lifetime. These visual images are of great help in identifying core behavior as a function of time and location in the core. They also help identify the remedial steps needed to reduce crud risk based on the comparison of KDVs for the cycle being analyzed to the past cycles, typically current Cycle N to Cycles N-1 and N-2. These steps include proactively making necessary changes to fuel cycle design even before the final risk analysis is performed by the plant chemistry.

Comparison of visual imagery for normalized SRF as a function of EFPD for three cycles of operation for a B&W 177 plant is presented in Figure 10. It can be seen from the figure that Cycle N has lower maximum SRF values at 250 EFPD compared to Cycle N-1, but higher SRF values compared to Cycle N-2. Similar behavior throughout the life of the cycle would indicate lower crud risk for Cycle N compared to Cycle N-1, while higher risk compared to Cycle N-2.

Recommendations to optimize the core design for the steaming values are made for the cases where significantly higher KDVs are observed for the current cycle compared to the previous cycles.

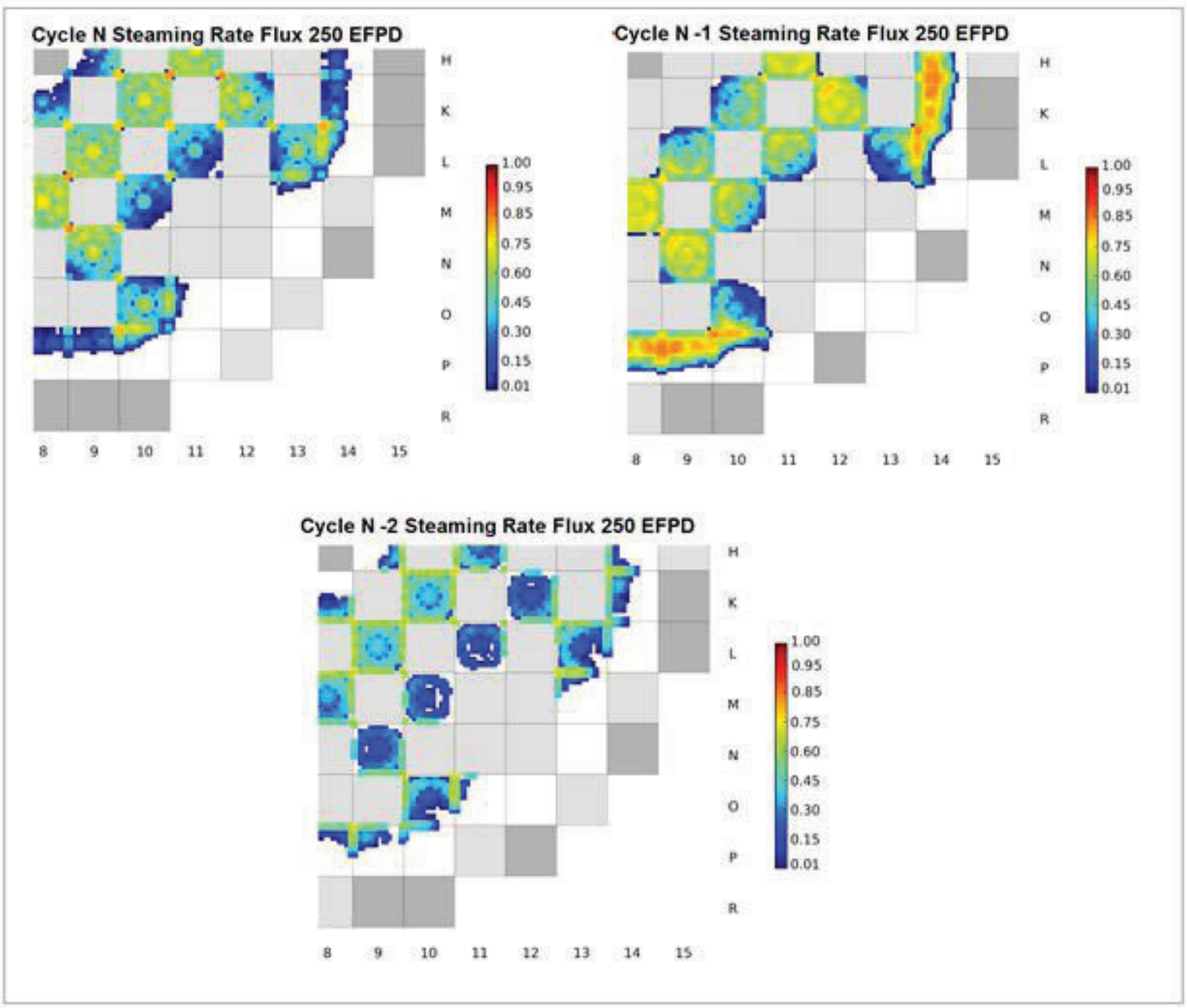

Figure 10: Steaming Rate Flux as a function of EFPD for B&W 177 Plant

IV. SUMMARY AND CONCLUSIONS

Based on the guidelines provided by EPRI, AREVA has developed a highly sophisticated Level III process that performs crud risk assessment for both CIPS and CILC risk. The thermal hydraulics part of the analysis, coupled with neutronics and the plant chemistry, is automated and is capable of analyzing multiple cycles of full core data to provide in-depth and accurate crud deposition predictions. AREVA's Level III risk assessment tool, AUTOCRUD, which couples multiple codes and interfaces including COBRA-FLX™, reduces the total thermal hydraulics analysis time, allowing for optimization of core design and even for the lowest crud risk based on comparative analysis of KDVs.

Implementation of the HBC heat transfer model in COBRA-FLX™ demonstrated improved crud deposition predictions downstream of the spacer grids. This is indicated by lower CSTs downstream of the spacer grid compared to the non-HBC model. The results from HBC implementation agree with the crud visuals.

Results from Level III analyses performed for several different PWR designs are presented, showing the depth and the versatility of the AREVA tools capable of performing the assessment on any known PWR reactor designs.

Future code development plans include integration of AUTOCRUD into ARTEMIS™, the 3D core simulator within the AREVA's advanced code system for Light Water Reactor (LWR), ARCADIA®, and addition of enhanced capabilities to model different methods of fuel shuffle from cycle to cycle.

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