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Direct Neutronics Modeling Approach for Deformed Core Analysis using PROTEUS

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Abstract – *Core deformation due to thermal expansion and irradiation induced swelling in sodium-cooled fast reactors (SFR) provides an important reactivity feedback effect during regular operation and accident scenarios. A new capability has been implemented in the PROTEUS-SN unstructured geometry neutron transport solver to directly simulate the neutronics behavior of deformed nuclear reactor configurations, including automatic updating of the local materials to account for mass and/or density changes. In this paper, PROTEUS-SN generates reference solutions for a series of contrived deformation states, which are then compared to solutions generated by conventional (indirect) modeling techniques that rely on structured grid neutronics codes and perturbation theory. The results show that PROTEUS-SN serves as a valuable tool to verify and/or assess conventional techniques for deformed core neutronics analysis.*

I. INTRODUCTION

Core deformation by thermal expansion and irradiation induced swelling in sodium-cooled fast reactors (SFR) provides an important reactivity feedback effect during regular operation and accident scenarios. As the reactor power increases, the grid plate expands and the assembly ducts bow, as guided by the core restraint system. As time proceeds, the assemblies contact each other at the above core load pad (ACLP) elevation and the reactor is "locked up" and unable to compact further [1], shown in Fig. 1. An SFR core is typically designed such that this locked up state provides negative reactivity relative to the colder temperature configuration, and any further temperature increases will result in further negative reactivity feedback.

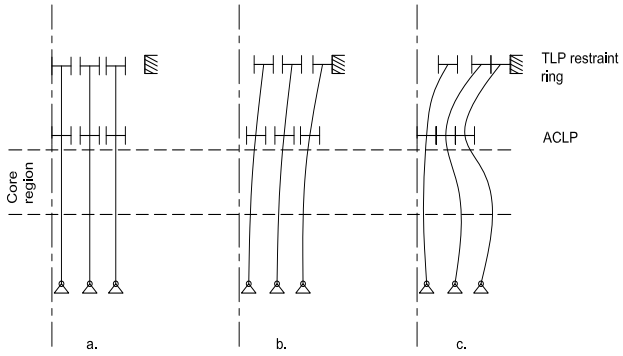

Fig. 1. Deformation States for a Limited Free Bow Restraint System showing a) Undeformed State, (b) Intermediate Deformation State, (c) Limited Free Bow State.

Conventionally, the reactivity feedback resulting from SFR core deformation is estimated using structured grid codes which cannot model the complex geometry deformations directly. Instead, perturbation theory is used to generate reactivity coefficients which are scaled with some representation of the deformation. The accuracy and predictive capability of these indirect methods are difficult to assess without a reference solution and/or experimental data.

Recent advancements in modeling and simulation have produced tools that can model complex deformed geometry configurations directly. In particular, a new capability was recently added to the PROTEUS-SN unstructured geometry neutron transport solver to directly calculate the reactivity feedback effect of core deformation. PROTEUS-SN models the deformed geometry directly and automatically computes the required material property changes to preserve mass (or other specified values) in the deformed configuration. The PROTEUS-SN direct solution therefore can be used to assess the accuracy and limitations of conventional approaches for modeling reactivity worth for core deformation.

In this work, we perform neutronics simulations of a variety of hypothetical core deformation states using PROTEUS-SN and make an assessment of conventional capabilities for computing reactivity worth of core deformation. The hypothetical core deformation states were not obtained using a structural mechanics code, and do not handle complex effects like duct contact. We propose inclusion of those effects and more precise core deformation states as future work.

II. DIRECT MODELING OF DEFORMED GEOMETRY WITH PROTEUS-SN

The PROTEUS-SN unstructured finite element mesh code [2,3] was developed at Argonne National Laboratory under the DOE Nuclear Energy Advanced Modeling and Simulation (NEAMS) program. The fully unstructured mesh capability differentiates PROTEUS-SN from most other high fidelity transport solvers which are limited to a semi-structured grid (regular repeated lattice with pins) and extruded geometry in the axial direction. Indeed, one of PROTEUS-SN's original intended applications was the direct modeling of structural reactivity feedback effects in sodium-cooled fast reactors. This section describes the newly developed capabilities of PROTEUS-SN to analyze deformed meshes in both multiphysics and standalone neutronics simulations.

1. Multiphysics Capability

PROTEUS-SN is the neutronics module in the NEAMS-developed multiphysics toolkit SHARP [4], where it is directly coupled to the Diablo structural mechanics code [5] and Nek5000 thermal hydraulics code [6]. PROTEUS-SN provides power distributions, Nek5000 computes temperature distributions, and Diablo computes the structural deformation as shown in Fig. 2.

A coupled physics demonstration [7] using the SHARP toolkit was previously performed to compute the reactivity feedback resulting from thermal expansion of the Advanced Burner Test Reactor core [8] with a preliminary restraint ring design [9] using file based transfer for the structural deformation coupling and material adjustments. Since structural deformation inherently causes material changes including density changes, temperature changes, and mass changes (sodium backfill), an automated material processing capability was integrated into PROTEUS-SN to fully streamline the calculation of deformed mesh reactivity worth.

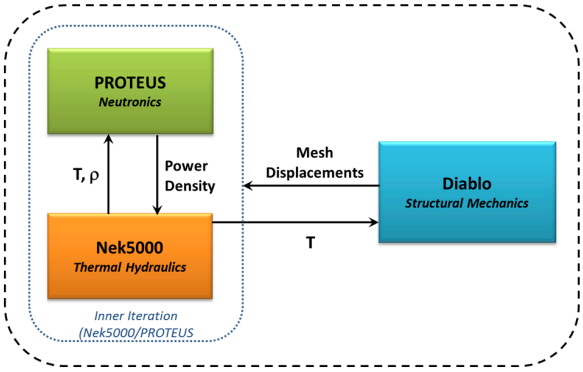

Fig. 2. Schematic of the SHARP Toolkit Workflow for Modeling Core Deformation.

2. Standalone Neutronics Capability

Due to the complexity in setting up detailed models for the three SHARP physics modules, a capability was developed in PROTEUS-SN to enable quick standalone neutronics simulations of deformed meshes by supplying the deformed mesh in addition to the base configuration input files. The deformed mesh and the undeformed mesh must have the same number of vertices, elements, and block definitions.

Given an undeformed and deformed mesh, PROTEUS-SN computes the volume change in each element block and alters the densities and compositions to define the deformed configuration. This process requires simple user input to indicate whether mass and/or density of constituent materials are to be conserved (for example, sodium coolant can backfill into the deformed domain but structural and fuel composition masses are always preserved). The treatment of various isotopes is controlled through composition model flags recognized by the code. So far, the mesh deformation capability has only been implemented for steady state calculations.

The deformed mesh is pre-generated using an external code (either a tool that applies an assumed deformation, or a structural mechanics code that computes the true deformation). Recently, a mesh utility code was created under the PROTEUS Mesh Toolkit [10] to deform 3D finite element meshes according to user-specified strain functions in the X, Y and Z directions. For simplicity, the X and Y strain functions can only vary with the Z-coordinate. While real assemblies can deform in more complex ways, this tool is intended to quickly manipulate a mesh into simple deformation states for scoping studies. A more advanced mesh deformation tool will be created in the future as this work progresses.

III. CONVENTIONAL MODELING APPROACHES OF DEFORMED GEOMETRY

Conventional neutronics codes are limited to structured grid geometry and are therefore not amenable to direct modeling of core deformation. Over the years, indirect procedures [11] have been proposed and/or developed to estimate the reactivity feedback due to core deformation using these structured grid codes.

1. DIF3D/SE2-ANL/PERSENT/NUBOW-3D Approach

One proposed procedure for computing the reactivity worth of the core deformation involves a series of individual physics simulations which are manually coupled as shown in Fig. 3.

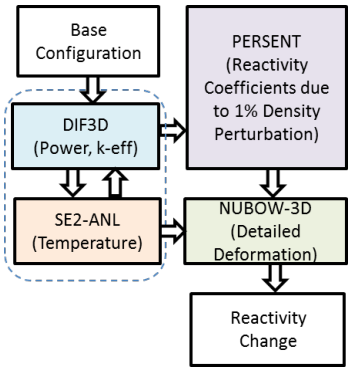

Fig. 3. DIF3D/SE2-ANL/PERSENT/NUBOW-3D Calculation of Core Deformation Reactivity Feedback.

First, the neutron/gamma ray distribution of the base configuration is solved using the DIF3D [12,13] neutronics code to obtain the power distribution, including gamma heating. Given the power distribution, the SE2-ANL code [14] computes the assembly pin, coolant, and duct temperatures. Iterations between DIF3D and SE2-ANL are repeated as necessary to converge the temperature and

predicted power distribution. The NUBOW-3D code [1] calculates the detailed assembly deformation due to thermal expansion and irradiation swelling based upon a given reactor state change. In particular, for each assembly, NUBOW-3D calculates a new pitch (expansion/contraction) and center coordinate (translation) at various axial nodes. It also computes the local density changes $\Delta D_{m,i}$ (m=material, i=spatial region) due to the deformation.

First order perturbation theory is assumed to describe the reactivity response between the undeformed and deformed state, and the perturbation theory code VARI3D [15] or PERSENT [16,17] is used to compute the mesh-wise instantaneous reactivity coefficients $\frac{\partial \rho}{\partial D_{m,i}}$ for 1% changes in the fuel, sodium, and structural densities while keeping the original base mesh constant. Consistent with linear perturbation theory, the fuel, sodium, and structural perturbations are computed independently. NUBOW-3D combines the mesh-wise reactivity coefficients with the computed density changes to estimate the total reactivity change as:

$$\Delta\rho_{\text{NUBOW}} = \sum_{m=fuel,sod,struct} \sum_{i=1}^{N} \left(\frac{\partial \rho}{\partial D_{m,i}} \right) \Delta D_{m,i} \,. \qquad (1)$$

In this *indirect* procedure, the perturbation is assumed to be small, and the coupling effects of simultaneously perturbing different isotope densities are neglected. Geometry changes are entirely ignored in the reactivity worth computation, isotope mass is *not* conserved when computing the reactivity coefficients, and the NUBOW-3D calculation is limited to $1/12^{th}$ core symmetry (typically inconsistent with the full core DIF3D and SE2-ANL calculations). In reality, the geometry change cannot be decoupled from the density change as done in this method. Unfortunately, the geometry change cannot be easily "added" back in to correct errors in this method because it is already partially accounted for in the density change. So, while a very accurate representation of the deformation can be calculated in NUBOW-3D, it cannot be fully accounted for in the neutronics part of the calculation due to structured grid requirement on DIF3D when calculating density reactivity feedback coefficients.

2. DIF3D/SAS4A/SASSYS-1 Approach

The DIF3D/SAS4A/SASSYS-1 workflow, shown in Fig. 4, also relies on the DIF3D structured grid code. First, the neutron/gamma ray distribution of the base configuration is solved using DIF3D. A second DIF3D calculation is then performed for a uniform radially 1% dilated geometry where all solid material densities are adjusted accordingly to preserve mass. Ideally, the liquid coolant densities are maintained in order to simulate sodium backfill into expanded regions, but this is a very small effect for small deformations. The eigenvalue difference in these two calculations (base vs. uniformly dilated) produces a single reactivity coefficient which is the reactivity introduced for a 1% increase in assembly pitch, $\frac{\partial \rho}{\partial r_{dilation}}$ This value can be converted to units of \$/m^2, \$/m or \$/degree K based on different conversion factors (volume, area, expansion coefficient of grid plate material).

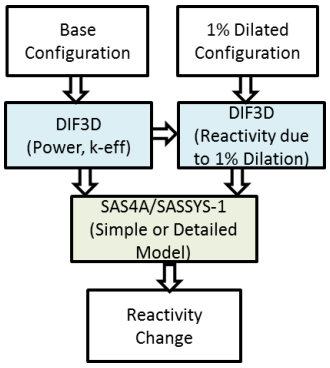

Fig. 4. DIF3D/SE2-ANL/PERSENT/NUBOW-3D Calculation of Core Deformation Reactivity Feedback

A SAS4A/SASSYS-1 [18] calculation is performed to calculate the temperature distribution in the core and the resulting radial expansion reactivity feedback using either a "simple" or "detailed" model.

In the simple model, the reactivity feedback is determined by two values: the temperature of the grid support plate (which anchors the bottom of the assembly) and the temperature of the above core load pad (ACLP) (located somewhere above the active core). These two values are linearly interpolated to estimate the radial expansion in the middle of the active core zone, $\Delta r_{\text{linear average}}$. The displacement is then multiplied by the reactivity coefficient from DIF3D to obtain the reactivity change:

$$\Delta\rho_{\text{SAS,simple}} = \frac{\partial \rho}{\partial r_{dilation}} \times \Delta r_{\text{linear average}} \qquad (2)$$

The simple model does not explicitly account for assembly bowing but attempts to determine a reasonable average core deformation.

In the SAS4A/SASSYS-1 detailed model, significantly more complex equations are introduced to attempt to calculate a single representative deformed assembly shape. It is difficult to know how well the SAS4A/SASSYS-1 detailed shape would agree with NUBOW-3D data (considered very accurate) and it certainly cannot model assemblies with different deformation shapes simultaneously like NUBOW-3D can. However, it is ideally more accurate than linearly interpolating for a single expansion value for the entire core as done in the simple model. The single reactivity coefficient for uniform dilation

is converted into an axially dependent reactivity coefficient using the normalized power distribution in the active core $p_i(z)$ as an importance function:

$$\frac{\partial \rho}{\partial r}(z) = \frac{\partial \rho}{\partial r_{dilation}} \times p_i(z) \quad (3)$$

The axially-dependent deformation shape is then weighted with axially-dependent reactivity coefficients to obtain the reactivity change:

$$\Delta\rho_{\text{SAS,detailed}} = \sum_z \frac{\partial \rho}{\partial r}(z) \times \Delta r_{SAS}(z) \quad (4)$$

One caveat of this model is that it only models the deformation of a single assembly and applies that shape to the whole core, so different assembly bowing shapes within the core cannot be simultaneously accounted for.

3. Grid Plate Expansion-Only Approach

In this method, no attempts are made to calculate the true deformation in the active core. Instead, the entire core is assumed to expand uniformly with the grid plate, and deformation at the grid plate is scaled with the reactivity coefficient from a 1% uniform radially dilated configuration as in the DIF3D/SAS4A/SASSYS-1 approach.

$$\Delta\rho_{\text{GPE}} = \frac{\partial \rho}{\partial r_{dilation}} \times \Delta r_{gridplate} \quad (5)$$

IV. DEFINITION OF MODELING APPROACHES USED

In this paper we assess methods for modeling core deformation reactivity feedback using a series of contrived, hypothetical deformation states. *The contrived states were not computed with structural mechanics calculations and are not claimed to be true deformation states in this reactor*. Studying the performance of these methods for contrived deformation states is still instructive because it exposes the weaknesses and strengths of the methods under different conditions. Plausible values and shapes for bowing in the core and grid plate expansion were used. The conventional multiphysics procedures were simplified to eliminate structural mechanics and temperature feedback codes, and instead use the hypothetical deformation states, as follows.

Method A: The deformation state is modeled directly using PROTEUS-SN, including deformed geometry and automatic density adjustments with sodium backfill into expanded regions. The results from this method were considered as reference solutions in this paper.

Method B: The base geometry is modeled with PROTEUS-SN using the modified compositions corresponding to each deformed state. This is *unphysical* (the deformed compositions cannot exist simultaneously with the base geometry) but this calculation approach sheds light on the source of errors in Method C, which follows.

Method C: The DIF3D/SE2-ANL/NUBOW-3D approach is emulated by using the deformation state and corresponding local density changes in place of NUBOW-3D. The local density changes are processed with mesh-wise reactivity feedback coefficients calculated by PERSENT to compute the total reactivity feedback using Eq. (1). See Fig. 5 for a flowchart of the workflow.

Method D: The DIF3D/SAS4A/SASSYS-1 "simple" radial core expansion approach is emulated by linearly interpolating the deformation values at the top and bottom of the active core to estimate the core-midplane value, which is then used in Eq. (2). See Fig. 6 for a flowchart of the workflow. We note that sodium backfill was not accounted for in the 1% dilated configuration, but the reactivity worth of a core-wide 1% sodium density change in these states is very minor (<1 pcm) so this simplification is negligible. (The DIF3D/SAS4A/SASSYS-1 "detailed" procedure is not emulated in this work because it fundamentally requires computation of an approximate deformation shape by SAS4A/SASSYS-1.)

Method E: The grid plate expansion-only approach is emulated by using the deformation at the grid plate in Eq. (2) to compute reactivity worth as shown in Fig. 6. Values are omitted for deformation states without grid plate expansion.

Method F: A hybrid approach is introduced where the exact average core deformation (defined by the integral of the assembly pitch change over active core height, divided by the active core height) was used in Eq. (2) as shown in Fig. 6. In reality, the exact average core deformation would only be known if a code like NUBOW-3D were used to calculate the deformation, and this can be considered a hybrid method between the SAS "simple" model and the NUBOW-3D approach.

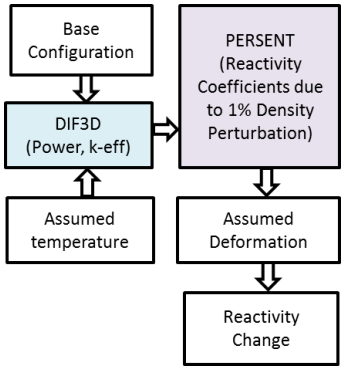

Fig. 5. Method C Workflow: Emulates DIF3D/SE2-ANL/ PERSENT/NUBOW-3D.

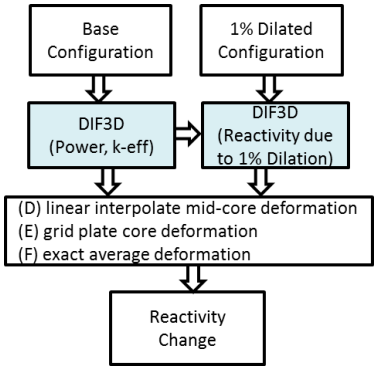

Fig. 6. Method D, E, F Workflows: Emulates SAS4A/ SASSYS-1 Simple Method, Grid Plate Expansion-Only, and new Hybrid Method.

V. CALCULATION OF RADIAL CORE EXPANSION REACTIVITY FEEDBACK IN THE ABTR DESIGN

The Advanced Burner Test Reactor (ABTR) core design [8,9] shown in Fig. 7. has 199 assemblies with 14.685 cm pitch arranged in a hexagonal grid with 9 rings. The core contains fuel, control, shield, and reflector assemblies which extend axially from 0.0 cm to 345.68 cm elevation. The active core is located between 110.54 cm and 194.95 cm elevation. The above core load pad (ACLP) is assumed to be located at 200.0 cm elevation (there is no detailed design for the core restraint system in the ABTR).

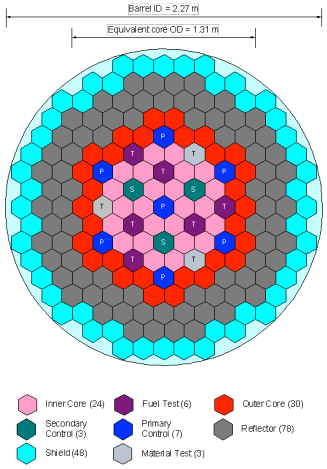

Fig. 7. Core Map of the Advanced Burner Test Reactor.

1. Base Configuration

The base configuration with homogenized assemblies was simulated with PROTEUS-SN and DIF3D-VARIANT using the P1 scattering approximation, 41 axial zones (8-10 cm each) and a 21 energy group cross section data file from previous studies of the ABTR. The base configuration neutronics models in DIF3D and PROTEUS-SN are entirely consistent. The choice of energy groups is not important to this study since the two codes use the same energy group structure and multigroup cross section data. The eigenvalues summarized in Table I are consistent within the 100-200 pcm expected difference due to different chi fission distribution treatment in the two codes.

Table I. Eigenvalues Computed for the Base Configuration.

Code (Options)	**Base Configuration Eigenvalue**
DIF3D-VARIANT (040601 space approximation)	1.02087 (P3) 1.02226 (P5) 1.02273 (P7)
PROTEUS-SN (quadratic FEM, 6 elements per assembly, L7T7 cubature)	1.02119

2. Description of Hypothetical Deformation States

Several hypothetical (contrived) deformation states were considered in this work and depicted in Fig. 8. The deformations were contrived rather than computed because the core restraint system for ABTR was not fully designed, detailed knowledge of deformation states in other reactors is limited and/or proprietary, and high fidelity multi-physics modeling to compute the exact state is impractical for this assessment. The hypothetical states were chosen to be *representative* of generic sodium-cooled fast reactor limited free bow and free bow concepts, and should not be taken by the reader to be a direct result of physical transients in this (or any) reactor.

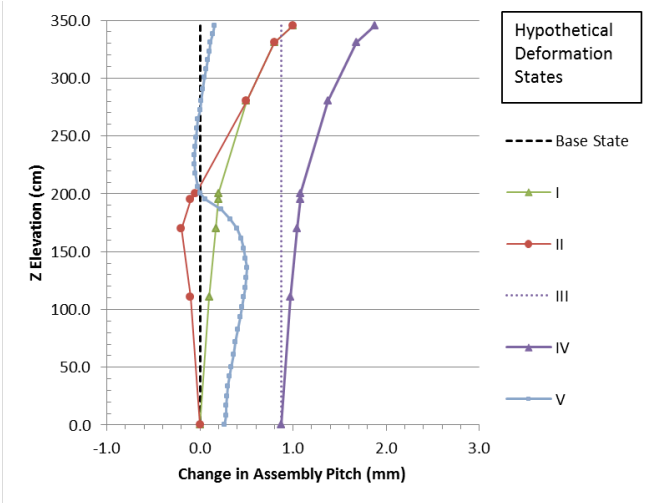

Fig. 8. Hypothetical Radial Core Deformation States Applied for ABTR Analysis.

In Fig. 8, the change in assembly pitch [units of millimeters] is plotted at different axial elevations of the core for each hypothetical state. Each deformation curve is applied uniformly across all assemblies within an axial

plane (this is a simplification from real deformations that actually makes it easier for conventional codes to model). The maximum expansion in the active core zone is 1.075 mm in the most extreme case (corresponding to 0.7% increase in the assembly pitch).

State I is a hypothetical free flowering shape that neglects grid expansion effects. State I can alternatively be interpreted as the change between two S-shaped deformation curves at hot conditions due to an increase in the power/flow ratio [20].

State II is a hypothetical early state in a limited free bow design exhibiting inward contraction in the active core and neglecting grid plate expansion. This state could possibly occur during startup for a brief period of time before the reactor is "locked up", but it does not persist.

State III is a hypothetical uniform grid plate expansion state in which the core deforms uniformly by 0.596%, corresponding to a 330 K increase in inlet temperature, i.e. cold to hot condition [9].

State IV is a hypothetical grid plate expansion plus free flowering shape in which the grid plate expands due to a 330 K increase in inlet temperature, and the core continues to bows outward as the axial elevation increases.

State V is a hypothetical limited free bow "S-shape" curve, similar to Fig. 1(c), where the grid plate expand according to a 100 K temperature increase, the active core continues to bow outward as the axial elevation increases until assembly movement is restricted at the ACLP elevation.

3. Calculated Reactivity Feedback Results

The reactivity worths for core deformation states I, II, and III were computed with the direct approach with PROTEUS-SN (Method A) and the emulated NUBOW-3D approach (Method C) and summarized in Table III.

Examining the PROTEUS-SN (Method A) reference values, we see that the reactivity worths for state I (-70 pcm) and state II (+69 pcm) are nearly identical in magnitude and opposite in sign because the deformation shapes within the active core are similar but in opposite directions. These similar values are consistent with the reactivity worths computed by PERSENT which are negligible outside the active core. The computed reactivity worth of state III (-413 pcm), the uniform grid plate expansion case, is much higher in magnitude than in state I and state II (-70 and +69 pcm respectively) which is also expected.

Method C exhibits large, consistent 35-40% errors relative to the reference solution. This non-conservative bias subsequently introduces more negative reactivity feedback from the core deformation in a transient analysis. At first this result was surprising, as Method C uses the exact, detailed deformation data to process the density change reactivity feedback coefficients. However, the density change reactivity feedback coefficients are estimated using the initial base geometry only, which is a critical flaw in this approach. We were able to verify the cause of the error in Method C by running PROTEUS-SN simulations of the base configuration mesh with the perturbed densities (Method B) which produced nearly identical results to Method C. This confirms that Method C is modeling the reactivity change of an unphysical configuration: that of the deformed material densities in undeformed base geometry.

The conclusion drawn from Table III is that the original DIF3D/SE2-ANL/PERSENT/NUBOW-3D approach is expected to have large errors in the prediction of core deformation reactivity worth for nearly all scenarios because the perturbation theory DIF3D/PERSENT calculations fundamentally ignore part of the geometry change by using the base mesh. However, the geometry change is partially accounted for by collapsing the expected detailed density changes against the deformation, making it difficult to modify the procedure to further account for the geometry change. Density and geometry changes are fundamentally coupled and attempting to separate out the effects in the different stages of the approach causes large errors.

Table II. Computed Reactivity Worths for ABTR Deformation States using Method C.

Predicted Reactivity Worth of Deformation (pcm) and Relative Error from Reference Solution (%)			
Method	**I**	**II**	**III**
A.PROTEUS-SN (Reference)	-70	+69	-413
B. PROTEUS-SN (Density Change Only, Base Mesh)	-97 (+39%)	+98 (+43%)	-574 (+39%)
C. Density Reactivity Coefficients Collapsed with Exact Shape	-95 (+35%)	+98 (+43%)	-558 (+35%)

Table III. Computed Reactivity Worths for ABTR Deformation States.

Predicted Reactivity Worth of Deformation (pcm) and Relative Error from Reference Solution (%)					
Method	**I**	**II**	**III**	**IV**	**V**
A. PROTEUS-SN (Reference)	-70	+69	-413	-483	-195
D. Linearly-Interpolated Mid-Core Deformation	-71 (+1%)	+47 (-32%)	-414 (0%)	-485 (0%)	-124 (-36%)
E. Grid Plate Expansion Only	N/A	N/A	-414 (0%)	-414 (-14%)	-124 (-36%)
F. Exact Average Core Deformation	-71 (+1%)	+71 (+3%)	-414 (0%)	-485 (0%)	-194 (-1%)

The reactivity worths for deformation states I-V are computed with Methods D, E, and F in Table III. Examining

the reference value for state IV, which is a superposition of the state I and state III deformation shapes, we observe that the reactivity worth of this case is also the superposition of the reactivity worths of those two calculations. This suggests that, at least for these simple perturbations, radial core deformation causes highly linear changes in reactivity, and the reactivity coefficients predicted by simple methods could potentially be accurate for a large regime of perturbations.

In contrast to the large errors in Table III, we see that Methods D, E, and F perform much better for the hypothetical states considered.

Method D emulates the DIF3D/SAS4A/SASSYS-1 "simple" radial expansion model by linearly interpolating the core deformation from the core bottom and top data points. It produces excellent results for the deformation states I, III, and IV which follow a linear deformation pattern from grid plate to top of the core. However, Method D cannot account for the bowing shapes in states II and V, which have large errors. State II is not expected to be a persistent shape in the reactor and so the underestimation of positive reactivity feedback here is not important. In state V, Method D underestimates the negative reactivity feedback but is still, importantly, conservative. SAS4A/SASSYS-1 has a more "detailed" radial expansion model that could not be assessed within the scope of this paper. However, the "detailed" model will certainly show large improvements over the "simple" model if its representative assembly model corresponds to the average core deformation.

Method E accounts for grid plate expansion only, and is conservative for the cases shown. However, if the active core deforms by a smaller amount than the grid plate, then this method is not conservative. Therefore, the accuracy of this method is considered lower than Method D.

Method F is a proposed method that does not currently exist: it uses the exact average core expansion value, which is not currently known with traditional methods, and processes it in a similar manner to the SAS4A/SASSYS-1 "simple" model. This method correctly captures all five of the reactivity worths within 3% error, at a fraction of the computing cost required for the PROTEUS-SN reference solution. However, the choice of how to calculate the detailed core deformation is an outstanding question: is the current "detailed" model in SAS4A/SASSYS-1 sufficient, or is a code like NUBOW-3D or Diablo required? The answers to these questions will depend on the true core deformation states.

In summary, the results show that the structured geometry DIF3D method with 1% uniform dilation to generate a singular reactivity coefficient is extremely accurate when the average core deformation is known or can be estimated accurately. The conventional multi-step method C may have large errors if the geometry change is not properly modeled in the calculation of core deformation reactivity worth. The assessment of these techniques was made possible by the new capability developed in PROTEUS-SN to analyze deformed core geometries directly. Based on the results shown here, we believe PROTEUS-SN is a valuable tool for both direct assessment of deformed core configuration as well as verification of simpler approaches which may be adequate for many deformed configurations.

VI. CONCLUSIONS

A new capability has been introduced in the PROTEUS-SN unstructured geometry transport solver which enables the direct computation of reactivity feedback due to core deformation. PROTEUS-SN was used to generate reference solutions for a variety of contrived core deformation states in order to assess the accuracy and limitation of several legacy techniques.

For small core deformations, legacy techniques using a structured geometry neutronics code can be very accurate for certain deformation states, particularly those in which the active core region deforms relatively linearly along the axial direction. For curved/bowed configurations, the conventional approaches capture the correct reactivity worth only if the average deformation in the core can be accurately calculated. Therefore, there is certainly a need for methods like the DIF3D/SAS4A/SASSYS-1 detailed radial core expansion model, but it is inconclusive whether modeling a single representative assembly is sufficient for a wide variety of cases.

Due to the simplistic and hypothetical nature of the deformation states studied in this work, we recommend pursuing studies of real NUBOW-3D or Diablo-based deformation states for a given reactor design which address complex bowing effects like assembly duct contact. Analysis of these geometries can be done directly in PROTEUS-SN including direct modeling of the explicit geometry, provided that a mesh can be created. In addition to calculating the reactivity change due to deformation, PROTEUS-SN can also provide detailed estimates of local power distributions which will differ from conventional approaches, particularly if the assembly ducts and inter-assembly sodium channels are modeled explicitly. Therefore PROTEUS-SN can produce reference solutions for detailed distributions and integral parameters in deformed core configurations.

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