Enhanced Engineering Analyses with Visualization of Geometry and Mesh-Based Data in Fulcrum

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INTRODUCTION

The Fulcrum graphical user interface (GUI) was initially released with SCALE 6.2 in March 2016 [1]. Fulcrum integrates input editing with job execution and output visualization in a single interface to simplify these tasks. Since its initial release, the Fulcrum GUI has been extended to become the Nuclear Energy Advanced Modeling and Simulation (NEAMS) Workbench [2] for use with tools external to SCALE. All Fulcrum capabilities are a subset of the NEAMS Workbench.

This paper presents two instances in which Fulcrum's visualization capabilities, available in Workbench, have enhanced engineering analysis in criticality safety. The first case presented is related to generating sensitivity coefficients within the TSUNAMI-3D sequence of SCALE 6.2.2 [3]. A brief synopsis of the TSUNAMI-3D theory is presented, along with the results demonstrating the advantages gained by visualizing the geometry and the mesh-based data together. The second case involves the analysis of a large array of waste drums with dissimilar contents. Fulcrum's capabilities allowed a more rapid, thorough investigation of unexpected results than possible with previously used tools.

Both cases presented here are real-world examples drawn from application work being performed at Oak Ridge National Laboratory (ORNL). Neither of these cases is hypothetical or a demonstration of a potential application of the visualization capabilities within Fulcrum. Rather, both examples are highlighting analysis improvements realized through the ability to visualize mesh-based data superimposed on the problem geometry. These cases involve different mesh-based quantities, but they can both be visualized within Fulcrum/Workbench.

TSUNAMI-3D THEORY

SCALE 6.2.2 includes two methods for calculating eigenvalue sensitivity coefficients using continuous-energy Monte Carlo. One method, known as CLUTCH, uses the F* function [4] to determine the importance of a fission location. This function is developed during the "skipped" generations of the calculation and tallied on a rectangular mesh covering the fissionable material in the model. After waiting for a certain number of "latent generations" to complete, the number of neutrons descended from each fission is tallied. Tallies made after waiting for larger numbers of generations are typically more accurate, but they also typically result in higher variance in the estimates of importance. This is because some fission chains die out and thus do not score. Typically, 2–10 latent generations are sufficient to achieve accurate sensitivities [4]. The number of latent generations one should wait before tallying neutron progeny is an important user input in the CLUTCH method.

A file containing the F* values in each voxel can be generated by TSUNAMI-3D for visualization. The F* function is the result of a Monte Carlo tally, so it has a stochastic uncertainty. The accuracy of the sensitivity coefficients generated in the calculation depends on the accuracy and uncertainty of the F* function [4].

U233-MET-FAST-006-001 APPLICATION

Sensitivity coefficients such as those generated by TSUNAMI-3D are useful in criticality safety validation and margin assessments. Therefore, sensitivity data were desired for the U233-MET-FAST-006-001 (UMF-006-001) case from the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook [5]. The critical experiment consists of a sphere of ^{233}U metal with a radius of approximately 4.2 cm reflected with a natural uranium sphere of radius 24 cm. The experiment was performed at Los Alamos in 1964 on Flattop.

Direct perturbation calculations are used in this process to confirm that TSUNAMI generates accurate sensitivity data [6]. Initial attempts to generate sensitivity data for UMF-006-001 did not result in good agreement with these direct perturbation calculations, so modifications to user input parameters were needed, such as modification to the number of latent generations used in tallying F*. The poor results applied specifically to the sensitivity of ^{238}U in the reflector. An examination of the F* function resulting from different numbers of latent generations is often helpful in this process and was undertaken in this case.

The CLUTCH calculation of sensitivities for UMF-006-001 was initially carried out with 2 latent generations. The F* function is shown in Fig. 1, and its relative uncertainty is shown in Fig. 2. The inner sphere of fissile material has much higher importance than the reflector, as expected. The relative uncertainties in the outer half of the reflector exceed 30%. Also, the difference between the TSUNAMI-calculated sensitivity and the direct perturbation result was larger than desired at 3% or approximately 6.5 standard deviations.

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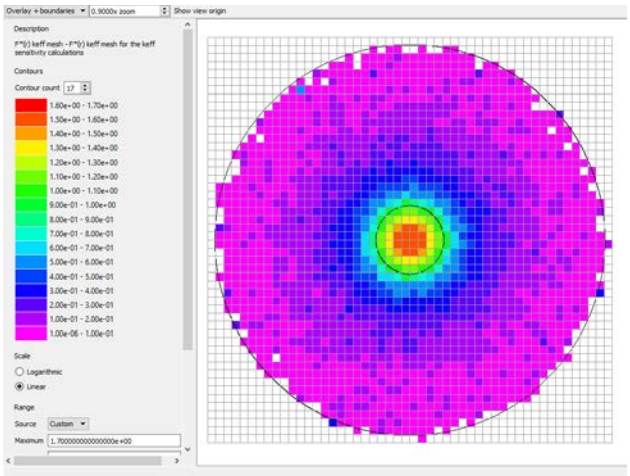

Fig. 1. F* function for UMF-006-001 with 2 latent generations.

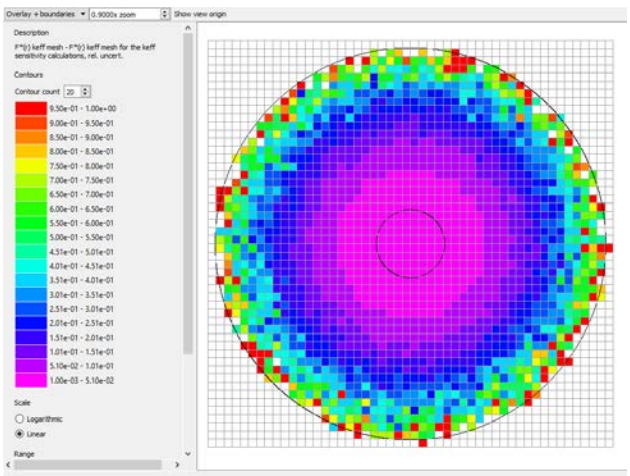

Fig. 2. Relative uncertainty in F* for UMF-006-001 with 2 latent generations.

The number of latent generations was increased to 5, and the calculation was rerun to improve the TSUNAMI result. Unexpectedly, the agreement with direct perturbation results became much worse. The misprediction in the sensitivity of the ^{238}U in the reflector increased to 7.7%, or 17 standard deviations. This outcome required investigation. The F* function considering 5 latent generations is shown in Fig. 3, and the relative uncertainty of the function is shown in Fig. 4. The outer regions of the reflector have no F* values, indicating that no fissions occurred in those regions during the calculation of the F* function. Figure 2 clearly indicates that the outer third to half of the reflector has extremely large uncertainties, ranging from 30% up to 100%. These results indicate that the F* function is not well converged in the reflector.

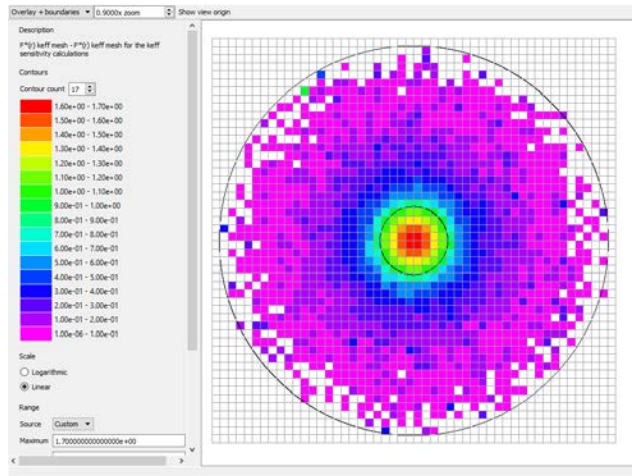

Fig. 3. F* function for UMF-006-001 with 5 latent generations.

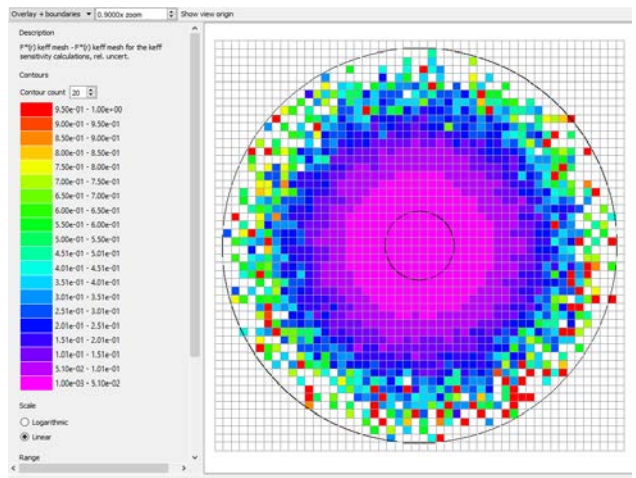

Fig. 4. Relative uncertainty in F* for UMF-006-001 with 5 latent generations.

Comparisons of Figs. 1 and 3 and Figs. 2 and 4 demonstrate that the increase in the number of latent generations reduced the accuracy and reliability of the F* function for this system. This is atypical behavior, but it can occur in a relatively small system with a fast neutron energy spectrum. These systems have very high leakage rates, and fissions that occur near the periphery have fewer progeny than the fissions occurring in the center of the system. The number of fission chains that completely die out increases when the number of latent generations is increased from 2 to 5. This explains the result and ultimately led to the use of the iterated fission probability method to generate accurate sensitivity results for this problem. An accurate diagnosis of this problem would have been significantly more difficult without the ability presented by Fulcrum to visualize the F* mesh. Analysis that may have required hours and would likely have involved discussions with the theory expert could instead be performed almost instantaneously by comparing

Figs. 1–4. It is difficult to overemphasize the utility of visualization capabilities in performing engineering analyses.

WASTE DRUM ARRAY ANALYSIS

The analysis of a large array of drums containing waste that may be emplaced in a salt formation repository was performed at ORNL. Initial models included a large, homogenous array of drums containing waste material and neutron absorbing material. Some number of drums without the neutron absorber material may exist, so consideration of these drums was also necessary. When these drums were incorporated into the existing array, the calculated k_{eff} increased more than expected. KENO also generated warning messages indicating that some geometric regions of the problem (units) containing fissionable material did not have any fissions occur in them. These messages can indicate a source convergence problem, so further investigation of the problem was warranted.

The expanded analysis began with the generation of a fission source map file within KENO. This map was created by specifying the *cds=yes* parameter in the parameter block and adding a grid geometry for tallying the source. This grid geometry was added in its own block in the KENO input, and it provided a Cartesian mesh on which the fission neutron production can be tallied. A mesh tally file was generated and returned to the user; this file can be opened in Fulcrum and overlaid on the geometry in the geometry viewer. Source maps were generated for the nominal case, with the homogeneous array and the heterogeneous case containing the drums without neutron absorbing material.

The fission source map for the nominal case is shown in Fig. 5. The source appears to be well converged, and the center of the array has the highest fission density. The fission density is fairly constant along the long axis (Y) of the array through its middle portion. This is because the leakage from the ±X faces (left and right in Fig. 5) and ±Z faces (in and out of the page in Fig. 5) is essentially constant along the Y axis, and there is no leakage in the remaining direction for the drums in this central portion of the array. Establishing that the nominal result is correct was important in this case because the magnitude of the difference was unexpected and could have been a result of a problem with the nominal calculation.

The fission source map for the heterogeneous array is shown in Fig. 6. The location of three of the four seven packs is clear in the figure. A fourth seven pack was located in the lower left-hand corner of the array to ensure that the group of unpoisoned drums in the corner is not the most reactive configuration. The drums without neutron absorbers were shown to be markedly more reactive than the other drums, which caused the fission source to be highly peaked near those locations. Some drums near the edge of the array were so far removed from these arrays that no fissions occur there in the converged source. This was the source of the warning messages in KENO. As in the previous example, the analysis of these results was completed rather promptly once the fission source was visualized. In fact, these results indicate that a more reactive configuration would result from the unpoisoned drums being located in the center of the array away from the walls. The fission density distribution for that configuration is shown in Fig. 7. The relocation of the drums increased k_{eff} by approximately 3% Δk. The visualization of the fission densities in Fulcrum allowed a more complete understanding of the system and a more accurate and conservative analysis. It also allowed the analyst to have confidence that a limiting configuration had been identified and to understand the interactions among the different elements of the array.

CONCLUSIONS

Two demonstrations are presented in this paper regarding the effectiveness of Fulcrum's visualization capabilities. Both cases involved actual applications from work being performed at ORNL in two very different aspects of criticality safety. The analyses were expedited by Fulcrum's ability to impose mesh-based results on the problem geometry. This type of analysis was not directly possible with tools that were previously available. This new capability in Fulcrum, and thus also the NEAMS Workbench, results in easier, more thorough analysis of real-world systems.

ACKNOWLEDGMENT

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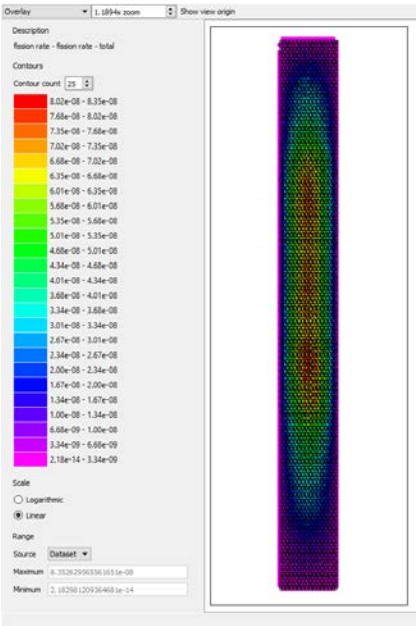

Fig. 5. Nominal case fission density.

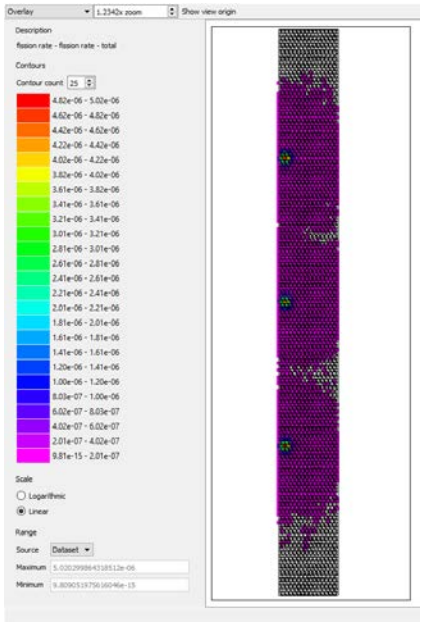

Fig. 6. Fission density with unpoisoned drums on the side of the array.

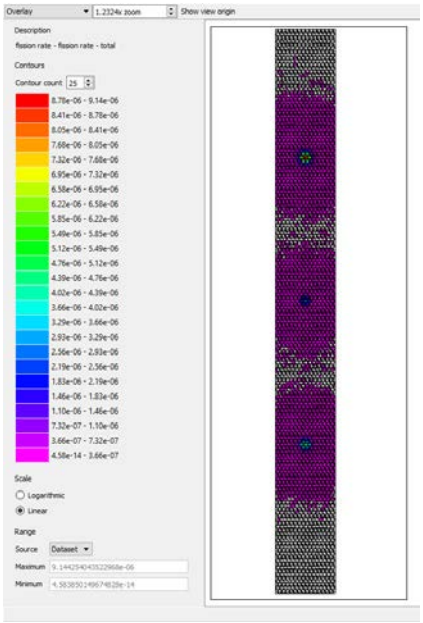

Fig. 7. Fission density with unpoisoned drums in the center of the array.