INL/CON-22-66408-Revision-0

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August 2022

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http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Proceedings of the ASME 2022
29th International Conference on Nuclear Engineering
August 8-12, 2022, Shenzhen, China

ICONE2022-93700

SUMMARY OF GEOMETRIC PARAMETERS AND THEIR EFFECTS ON PERFORMANCE OF U-10MO FUEL PLATES

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ABSTRACT

A monolithic plate-type fuel system has been under development to convert high-performance test reactors from highly enriched uranium to low-enrichment uranium fuels and is now moving into the qualification phase, a predecessor to the timely conversion of the target reactors. To qualify this fuel system, the plates must meet safety standards and perform well in a reactor. The plates must maintain mechanical integrity, exhibit geometric stability, and have stable and predictable in-reactor behavior. The requirement to maintain mechanical integrity under normal operating conditions is primarily demonstrated by successful testing. However, each high-performance reactor employs a distinct design, resulting in distinct plate geometries, with unique features, attributes, irregularities, and tolerances. Due to the abundance of such distinct geometric varieties, a single "generic" plate geometry capturing all extremes is not achievable. It is also impractical to test each of these proposed designs in a reactor. This limitation necessitates cautious evaluations since the thermomechanical response of a plate with a certain geometry may not be representative for a plate with a significantly different geometry. To address concerns related to in-reactor plate performance, large set of sensitivity studies were performed. These parametric studies aimed to better understand irradiation performance, while evaluating the sensitivity of results to various modeling inputs, including geometric, operational, and material parameters. This work studied selected geometric parameters based on provided fuel specifications and performed a series of parametric simulations. The resulting temperature, displacement, and stress strains were comparatively evaluated to determine the effects of various geometric parameters. This draft provides a "high-level summary" of our parametric sensitivity studies and summarizes the key findings.

Keywords: U-10Mo, monolithic fuel, geometric parameters

1. INTRODUCTION

The main objective of the Office of Material Management and Minimization is to achieve a permanent threat reduction by minimizing and eventually eliminating use of highly enriched uranium around the world. This objective is being fulfilled by several subprograms: reactor conversion, material removal, and disposition. Reactor conversion programs aim to develop technologies to convert test reactors to operate with a proliferation-resistant, low-enriched uranium (LEU) fuels. Although many test reactors can be converted with existing licensed LEU fuels, several high-power reactors in the U.S. require higher density fuels in a monolithic form.

Using a foil fuel form creates several fabrication challenges and distinct parameters related to the fabrication process. The abundance of such parameters raises concerns about their implications on performance.

All USHPRRs have released proposed designs for LEU monolithic fuel reactor cores. While these designs may have some changes, they are sufficiently mature to be used in proposing specific fuel plate geometries for consideration in fabrication and development efforts. The list below summarizes current fuel element designs, as described in Reference [1]:

- ATR (Advanced Test Reactor): Modified ELF design, no burnable absorbers, 19 unique plate types [2, 3]
- HFIR (High-Flux Isotope Reactor): Graded fuel zone with burnable absorbers, complex geometric design [4]
- MITR (Massachusetts Institute of Technology Reactor): 19B25 design concept, without fins, 3 unique plate types [5]
- MURR (Missouri University Research Reactor): CD35 design concept, employs 23 unique plate types [6]
- NBSR (National Bureau of Standards Reactor): 34 plates per element, one unique type [7].

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These unique designs necessitate nearly 50 distinct LEU fuel plate geometries. Consequently, a single generic plate geometry representing all the extreme points in this design matrix is not realistic. Because given parameter extremes could yield entirely different fabrication difficulties, as well as entirely different in-reactor performances, the presence of many distinct geometric features raised concerns that dimensional variations could lead to a vastly different in-reactor performances.

To address those concerns, proposed plate designs should be benchmarked for projected design variables. However, it is virtually impractical to test each of these design parameters in reactor settings. Instead, simulations can provide a timely and cost-effective means to evaluate the in-reactor performance of plates with variations in operational parameters, fuel plate design, material property, geometric irregularities, etc.

As a supplement to the information obtained from irradiation testing, a significant number of sensitivity studies have evaluated a plate's sensitivity to various input variables. These included geometric, operational, and material-property-related parameters.

This document will provide "*a high-level summary*" for the first set of sensitivity studies solely focusing on geometric features. The parametric studies on plate geometry have been used to evaluate the effects of various dimensional parameters on performance, including (1) foil flatness, (2) diffusion barrier thickness, (3) foil corner shapes, (4) size effects, (5) plate curvature, (6) fuel thickness, (7) foil centering, (8) foil tilting, (9) burred foil, and (10) foil waviness.

The modeling section below provides a brief overview of the base model we created. The results section provides a brief discussion of the problems, the motivation for the sensitivity studies, the activities we performed, and a summary of our key findings.

2. FINITE ELEMENT MODEL

We modeled plates by parametrically varying geometric features and dimensions and then simulated them using projected irradiation parameters. The resulting distortions, stress strains, and temperature fields were comparatively evaluated to assess the plate's sensitivity to specific geometric variations and nonuniformities.

The models were fully coupled thermal-structural interactions with user-defined parameters. For this work, we created a fully coupled 3D model of a monolithic plate capable of evolving the mechanical and thermal properties of the constituent materials with irradiation time and burnup.

For a conservative evaluation, plates were evaluated at a high power with high burnup. The average fission power density was 32,776 W/cm^3 (sampled from a high-power experiment), the average fission density at end of life was 7.7E+21 f/cm^3, nearly resulting in a full burnup, and finally, the average fast neutron flux was 2.220E+14 n/cm^2-sec. The fission density in the fuel zone was taken as a constant (i.e., no fission profile, constant local to average ratio, L2AR) to avoid any possible artificial effects that could be created by a nonuniform fission power distribution in the fuel zone.

The fuel material in this study was U-10Mo. Behavioral models for the fuel zone included elasticity, plasticity, thermal expansion, irradiation creep, volumetric swelling, modulus degradation, and thermal conductivity degradation due to a porosity increase. The thermal and mechanical models were based on temperature- and burnup-dependent data.

The cladding material in this study was aluminum 6061-O. The diffusion barrier was ASM Grade 702 commercially pure zirconium. Cladding and diffusion barrier behavioral models included elasticity, plasticity, neutron hardening, thermal expansion, and thermal creep. Thermal and mechanical models were based on available temperature-dependent data.

Details on material properties and behavioral models are not the focus of this work and therefore will not be discussed here. If needed, properties, behavioral models, and tabulated data can be found in the article that discusses the base model [8] and the U-Mo qualification report [9, 10].

3. RESULTS AND DISCUSSION

3.1 Foil Flatness

Monolithic plate fabrication involves multiple stages, including co-rolling, cold and hot rolling, edge trimming, and Hot Isostatic Pressing (HIP) processing. Although the miniplates are fabricated flat, achieving a perfectly flat foil inside the cladding can be a challenge. Examinations showed that, occasionally, the foils inside the cladding can form a slight curved profile, consequently shifting from the centerline, as schematically shown in Figure 1.

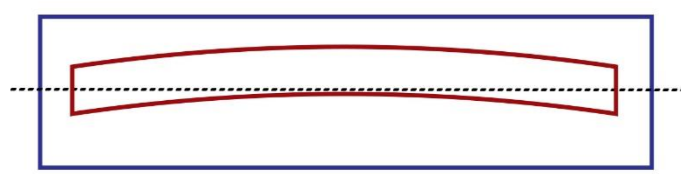

Figure 1. Foil flatness

This geometric irregularity caused some concerns about irradiation performance in case a flat foil inside the cladding is not achieved during fabrication. To address these concerns and characterize possible effects, we performed a set of parametric simulations. Between the simulations, the curvature of the foil inside the cladding varied from a perfectly flat setting to a limiting case. The limiting case was the minimum allowable cladding thickness defined by the specification, which was 0.152 mm in this study. All geometric specifics were unchanged, except the foil flatness inside the cladding. For the fabrication and irradiation models, we simulated six distinct curvatures.

The results revealed that the stress and strains induced by the fabrication process are not considerably affected by the flatness of the foil. The effect of flatness on peak irradiation stresses was minimal. There is a slight increase in temperature for the case with the maximum curvature.

The major impact was on the displacement characteristics. Even though, the total swelling strain is not affected by the curvature, the final shape of the foil varied for different curvatures. While the case with a flat foil produces a symmetrical swelling, as soon as a foil curvature is introduced, preferential swelling occurred. A thickness increase (i.e., material relocation) was more pronounced on the thin-cladding side. This caused the plate centerline to shift from its initial position. Furthermore, when a curvature is present, the peak displacement locations of the foil moved from the edges toward the inside.

3.2 Zr Diffusion Barrier Thickness

Although the specification indicates that the nominal diffusion barrier thickness is 0.0254 mm, post-fabrication and post-irradiation examinations have revealed that the zirconium thickness over the fuel zone can vary, sometimes considerably. These observations raised concerns that the nonuniform diffusion barrier thickness could lead to performance issues. Another concern is that having different zirconium thicknesses in fabricated plates could produce a behavior that differs from one plate to another. This purpose of this study to address these concerns.

To quantify the possible effects, a series of simulations were performed. In the simulations, the thickness of zirconium diffusion barrier was varied between the bounding values. All geometric parameters were unchanged, except for the Zr diffusion barrier thickness. Our simulations considered nine different Zr thicknesses, ranging from 0.00 mm (no zirconium) to 0.05 mm (2× nominal thickness). We comparatively evaluated the results to determine the sensitivity of the plate's performance to the changes in diffusion barrier thickness.

Fabrication simulations showed that the fuel zone and cladding stresses of a plate without a diffusion barrier would be higher. Post-HIP residual stresses implied that the presence of a diffusion barrier with a nominal thickness (0.0254 mm) would reduce the stresses, roughly 20 MPa in the cladding and 60 MPa in the fuel. As the Zr thickness increases, fabrication stresses of the fuel zone would decrease. Cladding stresses were insensitive to changes in Zr thickness. Irradiation simulations showed that the zirconium thickness has little or no effect on in-reactor and shutdown stresses for the fuel elements.

3.3 Foil Corner Shapes

Although the fuel zone of the final designs is expected to have square corners, some experimental mini plates were fabricated with different corner profiles for various reasons. Common corners profiles employed in previous experiments are "*90-degree squared*," "*rounded*," and "*45-degree chamfer*." In the blister test, we observed occasional blisters around the perimeter of the fuel zone, sometimes around the fuel corners. Furthermore, edge and corner peaking in the fuel zone can be problematic. These observations raised concerns that the selected fuel zone corner shape could lead to performance issues.

To address these concerns, we evaluated fuel plates for three distinct corner shapes previously employed in experimental plates. For the baseline case, we simulated a fuel zone with a squared corner. The simulations were then repeated for two additional corner shapes, while keeping all other parameters the same. Then, we comparatively evaluated temperature, displacement, and stress-strain fields from the simulations.

The fabrication simulation results showed that the shape of the fuel corners would not affect the post-fabrication stress-strain magnitudes. Irradiation simulations showed that the foils with sharp, chamfered, and rounded corners would have stresses with comparable magnitudes. A similar result was noted for the cladding stresses. Although, a slight difference in magnitudes was observed, the difference was insignificant. Deformations and temperatures were not affected by the corner shape either. The results have implied that, unless edge peaking occurs, the corner shape would not have detrimental effects on performance.

3.4 Size Effects

Geometric features and dimensions of the plates specific to target reactors vary significantly. As a result, proposed plate designs have different length, width, and thickness ratios. There are concerns if these distinct geometric ratios would have any effect on irradiation performance.

Furthermore, smaller, "down-scaled" fuel size plates, so-called "mini plates," are often employed by the program for experimental purposes. The results from these mini-plate experiments are often used to develop behavioral models for the fuel system. This necessitates an evaluation if the models developed by using the results from mini-plate experiments are applicable for full-size plates.

To address these concerns, we performed a set of parametric simulations. For this, we parametrically varied the plate geometry to reveal if the plate size has any effects on irradiation performance. Specifically, the length and width of the plates were increased by 5× their nominal values. The plates were simulated for same irradiation parameters. The resulting plate temperatures, deformations, and stresses were comparatively evaluated.

Evaluations of plates with various lengths have revealed no considerable changes in temperature, stress, and deformation characteristics because of a length increase. Furthermore, the swelling and creep results in the longer plates showed no significant difference, implying that plate length should not be a factor.

For plates with various widths, an evaluation of the results has implied similar results for wider plates. No significant changes in temperatures, stress and thickness increase were found for plates with different widths.

The only considerable difference was the centerline shift for the wider plates. Although the magnitude of the shift was small for the cases we evaluated, the trend of the profiles has implied that the wider plates could become more inclined to buckling-type deformations, if nonlinearities are present. The results have implied that the deformations of wider plates should be evaluated carefully to ensure that channel gap are not restricted to a critical value.

3.5 Plate Curvature

Unique needs of target reactors necessitate distinct plate dimensions and geometrical features. Although MITR plates have a flat profile, the plates of MURR, NBSR, ATR and HFIR are curved with specific operational parameters. Figure 2 illustrates this geometric configuration.

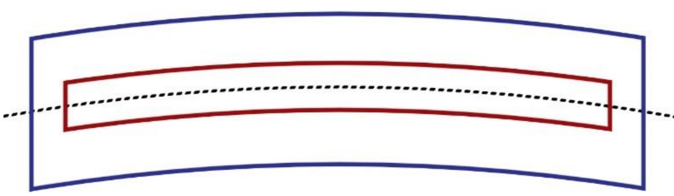

Figure 2. Plate curvature

There are concerns that the extremes of a given irradiation parameter specific to the target reactor could yield entirely different performance on a curved geometry. There are also questions regarding the stability of curved plates and their ability to maintain the channel thickness during irradiation.

To address these concerns and evaluate if plate's curvatures have any effects on overall performance, the plates with distinct curvatures were simulated. While all geometric parameters (width, length, and thickness) of the plates were kept constant, we varied the curvature radius between the bounding values. The plates were simulated for the same irradiation parameters. We comparatively evaluated the resulting temperature, deformation, and stress-strain characteristics with those from a flat plate.

The results have indicated that peak stresses in the fuel, diffusion barrier and cladding materials would not be affected by the radius of the plate's curvature. Although stress profiles at the centerline and plate surface showed slight variations, the magnitudes of these differences were small. Comparative evaluations of stresses showed that the plate curvature would not be important for the stresses exerted on the fuel elements.

Similar trends were observed for temperatures. A comparative evaluation of temperature results for fuel centerline, cladding surface and global maximums indicated that the temperatures are not affected by the curvature of the plates under normal operational conditions.

Although the effects of curvature on stresses and temperatures were insignificant, presence of a curvature influenced the deformation characteristics. For deformations, we examined multiple output variables, including total thickness increase, swelling, irradiation creep, and centerline movement. The overall deformation profile trends were comparable to each other, regardless of plate's curvature. This implied that the plate curvature is not an influential factor for the total thickness increase of the fuel. In addition, the total swelling and creep strains were found to be relatively insensitive to the magnitude of the curvature.

The results clearly showed that a centerline relocation would occur on curved plates, indicating the presence of preferential deformations. This phenomenon consequently caused shifts in the plate centerline. The magnitude of centerline shift increased with increasing plate curvatures. The trends of the profiles showed that the plates with tighter curves (i.e., smaller curvature radius) would have a greater degree of centerline movements. Centerline shift was found toward the center of the curvature (i.e., reducing the curvature, flattening the plate).

Simulations considered symmetric cooling conditions. Restricting one of the cooling channels during operation could create an asymmetric cooling setting, causing thermal gradients. The presence of thermal gradients could magnify the centerline shifts discussed above, eventually leading to structural instabilities.

3.6 Fuel Thickness

Target reactors will have plates with different fuel and plate thicknesses, resulting in distinct fuel-to-cladding thickness ratios. Also, different foil thicknesses within the fuel plate will likely affect deformations, stresses, and operational temperatures. This raised concerns that the plate performance could be affected by the fuel thickness and fuel-to-cladding thickness ratios.

To address these concerns, fabrication, irradiation, and shutdown stages were simulated for various fuel thicknesses. While keeping the plate thickness constant, we varied the fuel zone thickness according to design specifications. The bounding fuel thicknesses were 0.203 mm as a minimum (projected for ATR) and 0.635 mm as a maximum (projected for MITR).

Results revealed that plates with thicker fuels have higher temperatures, deformations, and stresses at shutdown. We expected this finding, as plates with thicker fuels would generate a higher heat for same volumetric heat generation rate.

To exclusively investigate the effects of fuel thickness, we performed a second set of simulations, scaling operational parameters by prorating volumetric heat generation rates.

The fabrication simulations indicated that the HIP stresses in the fuel zone decrease with an increasing fuel thickness, while the cladding stresses experience a slight increase. Also, slightly higher plastic deformations in the cladding were observed for plates with thicker fuels.

Irradiation simulations have shown that the fuel centerline temperatures increased with an increasing fuel thickness. This increase in pre-shutdown temperatures led to a considerable increase in fuel stresses at reactor shutdown. Results also showed that fabrication stresses in the fuel would be relieved and that the fuel zone would be essentially stress free during the entire irradiation process, regardless of the fuel thickness or fuel-to-cladding thickness ratios simulated.

Developed at the reactor shutdown, the stresses in the fuel zone were mainly affected by pre-shutdown temperatures, plate deformations, and property degradation. The results showed that shutdown stresses in the fuel zone would be higher for plates with thicker fuels. Finally, the overall displacement magnitudes were higher for the thicker fuels under the same fission density. Based on the increasing thickness of the plates, the coolant channel reduction was greater for plates with thicker fuels.

3.7 Foil Centering

An offset fuel foil within the cladding has the potential to impact the shape, residual stresses, and cladding integrity during fabrication and irradiation. Although the fuel foil should be centered, fabricating plates with a perfectly centered fuel is not always possible. Previous post-fabrication and post-irradiation examinations have revealed that some plates had off-centered foil. Figure 3 illustrates that geometric configuration.

These observations raised concerns that an off-centered foil has potential impacts on performance. To address these concerns, we simulated the fabrication, irradiation, and shutdown stages for various fuel offset positions within the fuel plate. The fuel foil position was varied from the center position to the maximum offset position as determined by the minimum allowable cladding thickness. The resulted distortions, stress-strain fields and temperature profiles were evaluated on selected locations to make a comparative assessment.

Fabrication simulations indicated that the thermal expansion mismatch causes warping during fabrication as the fuel plate is cooled from the HIP temperature when the fuel is not centered. Even if the model is constrained during cooling to simulate the effects of the rigid HIP can surrounding the fuel plate during cooling, warping is observed as soon as the constraints are removed.

Irradiation simulations revealed that the fuel offset causes virtually all irradiation-induced swelling to occur on the thin-cladding side of the plate, resulting in a preferential thickness increase for even the smallest offset we considered. If the fuel offset is large, the entire plate could warp. In such cases, the total surface displacement is the sum of the displacement caused by the plate warping and thickness increasing by fuel swelling. It should be noted that asymmetric fuel swelling could reduce the coolant channel gap more than anticipated.

The thin-cladding side of the plate deforms to accommodate the preferential fuel swelling, resulting in increased plastic strains on the thin-cladding side, particularly around the perimeter of the fuel. The magnitude of the total swelling is approximately the same for all offset values. Fuel offset does not significantly increase the peak cladding stresses in the thin-cladding side; although, peak cladding stresses decrease in the thick cladding side. Stress variations within the fuel as a function of offset are relatively minor. Fabrication stresses do not have a large impact on the final stress state after irradiation. Temperature variations resulting from fuel offset are small and generally under 5°C.

3.8 Foil Tilting

Fabrication specifications provide information for proper "foil-positioning" requirements. Although the specifications may change based on new findings, they are sufficiently established. From a mechanical perspective, a perfectly aligned fuel foil within the cladding is desirable once the plate emerges from the HIP process. However, achieving a perfect alignment may not be feasible every time. Previous post-fabrication and post-irradiation examination have revealed that some plates had a tilted fuel zone, essentially causing an angle between the cladding and foil. Figure 4 illustrates that geometric configuration.

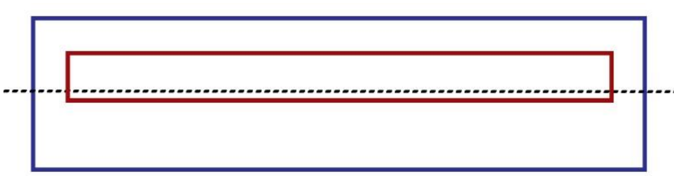

Figure 3. Foil centering

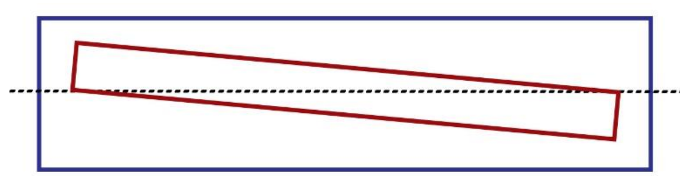

Figure 4. Foil tilting

The observation of such geometric nonlinearity raised concerns that tilted fuel within the cladding could affect the overall irradiation performance and eventually cause thermomechanical issues. To address these concerns, we simulated the plate for distinct fuel alignment settings and assessed the effect of tilted fuel through a comparative evaluation of plates with angled fuel and the baseline case with a perfectly aligned configuration.

In the comparison of plate temperature, although there are slight differences between the cases, the difference was insignificant (under 5°C). The results implied that both the peak temperatures and their locations would not be considerably affected by the tilted foils.

In a comparison of equivalent stresses, the results have implied that a tilted foil would not have a significant effect on the stresses. Although changes in stresses were too insignificant to make a distinction between the cases, the degree of tilting had implications on the deformation magnitudes. The results indicated that the bulging magnitude is slightly higher at the thin-cladding side, implying the presence of a preferential swelling. For the case with tilted fuel, the peak displacement increased roughly 45% compared to the baseline case (centered and aligned) because more material relocation can occur toward the thin-cladding side, as the fuel would experience less resistance from the thinner cladding side.

3.9 Burred Foil

As discussed previously, fuel foil fabrication involves multiple stages prior to the HIP process, including co-rolling, cold and hot rolling, and trimming. Edge trimming is done by shear cutting to bring the foil dimensions to the desired length and width. Ideally, the foils have uniform edging. However, the shearing process can cause geometric nonlinearities. Examinations showed that the foils inside the cladding can have burred edges, running around the perimeter of the foil, where the shear cutting process was performed. Figure 5 illustrates that geometric configuration.

The presence of such geometric nonlinearity raised concerns that edge burring of the fuel causes performance issues. To address these concerns, we simulated the plates for various burred foils. Inside a flat cladding, the degree of burring varied from perfectly flat foil to a limiting case.

Temperature evaluations have shown that burred edges and the degree of edge burring would not cause considerable effects on temperature magnitudes and profiles.

The results showed that displacements are slightly affected by the degree of burring. Around the burred edges, displacements were greater.

An examination of stresses indicated that fuel stresses would increase slightly around the burred edge. We expected this, as the tip of the burred edge would act as a stress raiser. Although fuel edges experience a slight stress increase, a degree of burring would not affect the stresses in the cladding and diffusion barrier.

3.10 Foil Waviness

Although multiple rolling passes should produce relatively uniform and flat fuel foils prior HIP processing, perfectly flat foils within the cladding after HIP processing may not be always achievable. Since the fuel foil is relatively thin, even small shifts from the centerline cause a wavy foil profile. Figure 6 illustrates that geometric configuration.

Such a wavy profile could cause a nonuniform orientation within the cladding, consequently leading to off-centered foils and variable cladding thicknesses. Because uneven cladding thicknesses could generate a preferential swelling, there are questions if the waviness of the foil could cause potential issues during an operation.

To address these concerns, we simulated the plates with various foil profiles and assessed the effects of the wavy foil within the cladding through a comparative evaluation of a fuel plate with a wavy foil and the baseline case with flat and center-aligned foil.

The comparative temperature evaluation indicated that effects of foil waviness on temperature characteristics, including the magnitudes and shapes, would be minimal.

We observed a similar result for the stress characteristics. The comparison of equivalent stresses from all cases evaluated in this work indicated that foil waviness would not have considerable effects on stresses in the fuel, cladding, diffusion barrier, and interfaces.

Although temperature and stress results were not affected by the waviness, we noted effects in deformation characteristics. The simulations have revealed that the asymmetry of the foil profile influences the overall deformation to be asymmetric. When asymmetry in the profile is present, deformation patterns become asymmetric and plate tilting occurs. This is due to the uneven wave profiles with respect to the midplane. Regardless of the

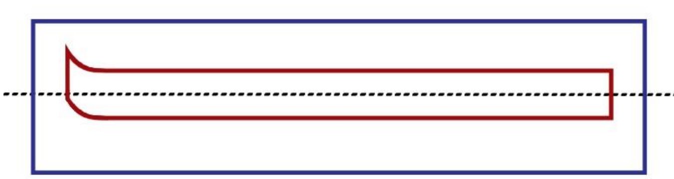

Figure 5. Burred foil

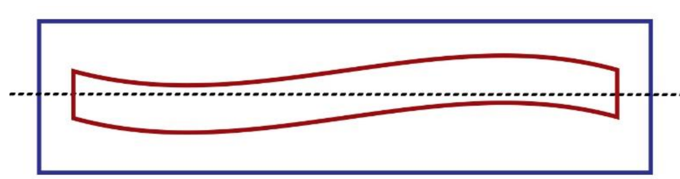

Figure 6. Foil waviness

profile, we observed peak deformations in regions where the cladding is thinnest. These observations are somewhat consistent with other parametric sensitivity studies, which have revealed the presence of a preferential swelling and larger displacements that would occur towards to the thinner cladding side.

4. CONCLUSIONS

There are specifications for an acceptable “foil-positioning” requirement. The fuel specification provides several real-life misalignment examples. Based on these examples given by the fuel specification, there are concerns that the presence of such nonuniformities and misalignments within the cladding could cause thermal and mechanical issues during service.

To address these concerns, this draft studied the effects of such nonuniformities and variation in geometric parameters on the performance of the U-10Mo fuel system. We performed a set of simulations considering the range of geometric parameters and comparatively evaluated the resulting plate temperature, deformation, and stress characteristics. This article gave a “high-level” summary of parametric sensitivity studies focusing on plate geometry and the motivation for the sensitivity studies and the key findings.

Simulations provided a better understanding for the performance of the plates. Compared to each other, we found several parameters unimportant, while others exerted more influence on overall performance. For instance, a foil off center or the curvature of a plate would have important implications on deformations, though we found the shape of foil corners unimportant for its performance.

Although this study has revealed valuable information about the performance of plates in support of qualification efforts, it would be helpful to perform the analysis for combined effects, such as off-centered and tilted foil in a curved plate. Because maintaining a geometric stability and an efficient heat removal are performance requirements, it is also critically important to evaluate the actual plates from target reactors for a given specification, as the target reactors will be employing different designs with distinct geometric features, dimensions, and nonuniformities.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy, Office of Material Management and Minimization, National Nuclear Security Administration, under DOE-NE Idaho Operations Office Contract DE-AC07-05ID14517. This manuscript was authored by a contractor for the U.S. Government. The publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for U.S. Government purposes.

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