University of Missouri Research Reactor (MURR)
Design Demonstration Element End Fitting Structural Rigidity Analysis

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University of Missouri Research Reactor (MURR) Design Demonstration Element End Fitting Structural Rigidity Analysis

prepared by
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**Acronyms and Abbreviations**

<table>
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<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ATR</td>
<td>Advanced Test Reactor, Reactor Technology Complex, INL</td>
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<tr>
<td>CAD</td>
<td>computer-aided design</td>
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<tr>
<td>FE</td>
<td>finite element</td>
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<td>FQ</td>
<td>fuel qualification</td>
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<td>FF</td>
<td>fuel fabrication</td>
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<td>FSI</td>
<td>fluid-structure interaction</td>
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<tr>
<td>DDE</td>
<td>design demonstration element tested as an experiment in a test reactor</td>
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<tr>
<td>HEU</td>
<td>highly enriched uranium with ≥ 20 wt% enrichment</td>
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<tr>
<td>INL</td>
<td>Idaho National Laboratory</td>
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<tr>
<td>LEU</td>
<td>low-enriched uranium with &lt; 20 wt% enrichment</td>
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<tr>
<td>MW</td>
<td>megawatts thermal</td>
</tr>
<tr>
<td>MURR®</td>
<td>University of Missouri-Columbia Research Reactor</td>
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<tr>
<td>RC</td>
<td>reactor conversion</td>
</tr>
<tr>
<td>SAR</td>
<td>safety analysis report</td>
</tr>
<tr>
<td>U-10Mo</td>
<td>uranium – 10 wt% molybdenum alloy fuel being developed as a monolithic metallic alloy fuel</td>
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<tr>
<td>USHPRR</td>
<td>U.S. high performance research reactor</td>
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## Definition of Terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tr>
<td>Bounding</td>
<td>A parameter value that has been technically determined to not be exceeded under given conditions, such as, for example, normal operating conditions.</td>
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<tr>
<td>Conservative</td>
<td>Method, or resulting parameter value, that is not best estimate and includes uncertainty or margin whether discretionary or due to conservative assumptions.</td>
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<tr>
<td>Fuel qualification</td>
<td>The process of designing, conducting, and evaluating experiments to ensure that the fuel is capable of performing without failure during reactor operations up to reported performance limits. Fuel qualification also includes measurements and reporting of fuel properties that can be used in performance and safety modeling.</td>
</tr>
<tr>
<td>Nominal</td>
<td>Value of a parameter under normal operating conditions.</td>
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Executive Summary

The University of Missouri-Columbia Research Reactor (MURR®) is one of five U.S. high-performance research reactors (USHPRR), plus one critical facility, that is actively collaborating with the National Nuclear Security Administration Material Management and Minimization Reactor Conversion Program to convert to the use of low-enriched uranium (LEU, < 20 wt% U-235) fuel. A new type of high-density LEU fuel, based on an alloy of uranium and 10 weight percent molybdenum (U-10Mo), is being qualified to allow the conversion to LEU of USHPRR. MURR has been working with the USHPRR Reactor Conversion (RC) Pillar at Argonne National Laboratory to perform fuel element design and fuel cycle performance analyses, steady-state thermal hydraulics safety analyses, and accident safety analyses in preparation for the conversion of MURR. The preliminary Safety Analysis Report (SAR) for conversion to LEU fuel was completed.

On the LEU U-10Mo fuel qualification side, mini-plate and large-plate irradiations have been successfully performed by the Fuel Qualification (FQ) Pillar at Idaho National Laboratory (INL), and more experiments are either ongoing or planned. As an additional experimental campaign, a full prototypic MURR element serving as the Design Demonstration Element (DDE) will be irradiated in the Advanced Test Reactor at INL, and a flow test for the MURR DDE will be performed to evaluate the hydro-mechanical stability of the MURR DDE before the irradiation experiment. (Throughout this report, MURR LEU fuel elements are referred to simply as LEU fuel elements or LEU elements, and the MURR DDE is referred to simply as DDE.)

As a part of the design of the DDE, an alternate new design for the end fittings must be considered to meet specific experiment needs, e.g., compatibility with the geometrical restrictions of the DDE testing location, and to allow for proper inspection of the test element during the experiments. Although the DDE bottom end fitting has a similar shape compared to the LEU bottom end fitting, the DDE top end fitting is considerably smaller than the LEU top end fitting in overall size and weight, and the vertical location of the MURR DDE fuel plates are closer to the top end fitting designed to facilitate channel gap probe measurements during the experiment. Consequently, the stiffness of the end fittings and the entire element could be affected compared to those of the LEU element.

The primary objective of this work is to assess the extent to which the stiffness (measured by means of maximum displacement) of the end fittings in the DDE contributes to the stiffness of the entire element, and how it compares to the equivalent stiffness of the end fittings in the LEU element. Structural analysis of both the LEU element and the DDE were performed using COMSOL 5.3a finite element software. Supporting combs are used on the leading and trailing edges of fuel plates for both the LEU element and the DDE. Therefore, simulations with and without combs are performed as two bounding boundary conditions on the leading edge of the fuel plates. Three types of loads are analyzed in this work: the hydraulic load due to the channel flow disparity-induced pressure differential, the thermal load due to the thermal expansion of the fuel plates, and a point load equal in magnitude to the LEU element’s weight.

For the hydraulic load response, when the plate's leading and trailing edges are constrained by the comb, the end fittings have a negligible effect on the overall element rigidity for both the LEU fuel element and the DDE (as compared to the cases without end fittings). When the constraints provided by the comb are neglected, the LEU element end fittings still had a negligible effect on the overall element rigidity, yet the DDE end fittings helped to reduce the maximum displacement by around 20% as compared to the DDE model without end fittings. This is because the distance between the fuel plate leading edge and the top end fitting is shorter for the DDE (0.5 inch) as compared to that of
the LEU element (2.25 inch). In short, the predicted maximum displacement for the DDE (with end fittings) is smaller than but comparable to that of the LEU element (with end fittings). For the thermal load response, no significant difference in the structural response was observed between the LEU element and the DDE, with or without the end fittings. The contribution of the end fittings to the element rigidity under the thermal load is insignificant (less than 6%). In the case of the point load considered in this study, the end fittings contribute significantly to the overall element rigidity. The predicted maximum displacement for the DDE (with end fittings) is comparable to that of the LEU fuel element, and the displacement magnitude is small for all cases.

In summary, for the three types of analyzed loads, no significant differences in the modes of deformation and their magnitude, and hence rigidity, were found between the DDE and the LEU fuel element.
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1 Introduction

The University of Missouri Research Reactor (MURR®) in Columbia, Missouri, is a multi-disciplinary research and education facility providing a broad range of analytical and irradiation services to the research community and the commercial sector. MURR is a 10 MW light water moderated and cooled reactor using highly enriched uranium (HEU, ≥ 20 wt% U-235) fuel [1].

MURR is one of five U.S. high-performance research reactors (USHPRR), plus one critical facility, that is actively collaborating with the National Nuclear Security Administration Material Management and Minimization Reactor Conversion Program to convert to the use of low-enriched uranium (LEU, < 20 wt% U-235) fuel. A new type of LEU fuel with very high density, based on an alloy of uranium and 10 weight percent molybdenum (U-10Mo), is being qualified to allow the conversion to LEU of USHPRR [2]. A detailed description of the preliminary MURR LEU fuel element design can be found in [3].

The conversion of USHPRR, including MURR, is carried out through four technical pillars led by several national laboratories: the Fuel Qualification (FQ) Pillar (Idaho National Laboratory or INL), Fuel Fabrication (FF) Pillar (Pacific Northwest National Laboratory), Reactor Conversion (RC) Pillar (Argonne National Laboratory), and Cross-Cutting (CC) Pillar (Savannah River National Laboratory). Working with the RC Pillar, MURR has completed performance and safety analyses for prototypic equilibrium fuel cycle operations with the current HEU fuel and following conversion to the LEU fuel with a power uprate from 10 MW to 12 MW [1]. Performance and safety analyses have also been completed which demonstrate satisfactory experimental performance and margins to safety for HEU and the preliminary LEU fuel element design [3] following a major facility upgrade [4]. Recently, the planning and safety analysis for the sequence of transition cores following conversion from HEU to equilibrium LEU operations have been completed [5].

On the LEU U-10Mo fuel qualification side, mini-plate and large-plate irradiations have been successfully performed by the FQ Pillar, and more experiments are either ongoing or planned. As an additional experimental campaign, a full prototypic MURR element serving as the Design Demonstration Element (DDE) will be irradiated in the Advanced Test Reactor (ATR) at INL, and the flow test for the MURR DDE will be performed to evaluate the hydro-mechanical stability of MURR DDE prior to the execution of the irradiation experiment.

As a part of the design of the MURR DDE, an alternate new design for the end fittings must be considered to meet specific experimental needs, e.g., compatibility with the geometrical restrictions of the MURR DDE testing location, and to allow for proper inspection of these test elements during the experiments. The conceptual design of the MURR DDE end fittings is substantially different from that of the end fittings in the MURR preliminary LEU fuel elements, with the MURR DDE top end fittings considerably smaller in overall size and weight, and the vertical location of the MURR DDE fuel plates closer to the top end fitting [6] designed to facilitate channel gap probe measurements during the experiment. Consequently, the stiffness of the end fittings and the entire element is affected.

Throughout the remainder of this report, MURR LEU fuel elements are referred to simply as LEU fuel elements or LEU elements, and MURR DDEs are referred to simply as DDEs.

The end fittings in the LEU element are designed primarily for proper handling. The stiffness of the end fittings also constitutes a fraction of the total stiffness of the entire fuel element. It remains to be confirmed to what extent the end fittings provide the structural rigidity necessary for the element to
properly respond to potential loadings. It is presumed that the bulk of the overall stiffness of the element is derived from swaging all fuel plates into the side plates of the element. However, the distribution of stiffness within different components of the LEU fuel element and the DDE has not yet been characterized.

The primary objective of this work is to assess the contribution of the DDE end fittings to the DDE stiffness, and how it compares to the stiffness contribution of end fittings in the LEU element. Since the design objective of the DDE is to be prototypic of the LEU element, it is important to assess the stiffness of the DDE relative to the LEU element to confirm the prototypic nature of the demonstration experiment.

It is expected that the primary sources of loads on the LEU fuel element and the DDE may come from the following:

- Fluid-structure interaction (FSI) effects (pressure differential acting on components of the element as well as flow-induced vibrations or motion of the DDE and LEU fuel element in the test reactor and MURR core, respectively).
- Irradiation and thermal effects (such as expansion caused by swelling of fuel plates or uneven temperature distribution).
- Handling accidents and related accidents like dropping of the element.

Proper characterization of the above-listed loadings and the deformations they cause would require a significant effort in the form of complex multiphysics analyses or experimental testing. However, to compare the relative stiffness of the LEU element and the DDE, a simplified approach was taken in this work by assuming small deformations and linear elastic properties of the materials. The consequence of these assumptions is the proportionality of the displacements to the magnitude of the load. That is, doubling the load causes doubling of the displacement, as long as the displacements stay within the linear elastic range. Identical loads can be applied to the components of the LEU element and the DDE, with or without end fittings. The comparison of displacements reported for these elements under such loads is used to estimate the differences in the stiffness and hence, the consequences of replacing the LEU element end fittings with the DDE end fittings. In this work, the above three sources of load were simplified to representative hydraulic, thermal, and point loads, respectively.
2 Model Development

2.1 Geometry

Isometric views of the geometries of the LEU fuel element and the DDE are shown in Figure 2.1. There are three major differences between the designs of the LEU fuel element and the DDE. First, the end fitting design is different. The LEU element has an identical design for the top and bottom end fittings, while the DDE adopts different designs for the top and bottom end fittings. As presented in Figure 2.2, the DDE top end fitting is simplified to allow the inspection of the channels with the channel gap probe during the irradiation test. The DDE bottom end fitting is similar in shape to the LEU element end fitting to not adversely affect the flow distribution. Any differences between the bottom DDE end fitting and the LEU element end fitting are dictated by specific experimental needs, such as element constraints in the test locations. Secondly, the axial location of fuel plates in the DDE is closer to the top end fitting (0.5 inch away from the top end fitting, 5.5 inch away from the bottom end fitting), while for the LEU element the fuel plates are equidistant from both ends (2.25 inch). This design modification was also made to facilitate the measurement of the channel gaps with a probe inserted from the top through the top end fitting. Finally, the overall length of the DDE (33.25 inch) is 0.75 inch greater than that of the LEU element (32.5 inch).

Four finite element (FE) models were developed in COMSOL Multiphysics 5.3a software [7] for this analysis to represent the LEU element and DDE with and without the end fittings. The models were based on the technical drawings of the LEU element [3] and the DDE [6]. Figure 2.3 presents isometric views of all four models used in this study: the LEU element, the LEU element without the end fittings, the DDE, and the DDE without the end fitting.

![Figure 2.1. Isometric view of (a) LEU element and (b) DDE](image)
Figure 2.2. Top views (a, b, c) and side views (d, e, f) of LEU element end fittings and DDE end fittings.

Figure 2.3. Isometric views of four geometry models: (a) LEU element, (b) LEU element without end fittings, (c) DDE, and (d) DDE without end fittings.

There are multiple small-sized geometry features in both the LEU element and the DDE design. For example, the thickness of the fuel plate is slightly smaller than the width of the slots in the side plates for the purpose of swaging. Usually, it is unfeasible as well as unnecessary to resolve all these geometric details, and a simplification of the geometry is needed when a global response of structures is studied. In the current model, the fuel plates and side plates are assumed to be perfectly bonded, and the presence of the grooves in the side plates is neglected. Also, the structure of the bolts, nuts, and rollers in the end fittings is simplified to a filled roller with a perfect bond at the interface with the end fitting. Rivets are used to connect the side plates and end fittings for both the LEU element and the DDE. The strength of the rivet connection is not a subject of this study. Instead, perfect bonding is assumed at the contact interface between the side plates and the end fittings, which is
achieved by the continuity feature in COMSOL. This ensures continuity of displacement field across the interface of the side plates and end fittings. In addition, the comb structure is also simplified, which will be discussed in detail in Section 2.5. The comparison between the computer-aided design (CAD) model of the LEU element and the corresponding simplified geometry for the COMSOL model is shown in Figure 2.4.

![Diagram](image)

*Figure 2.4. (a) CAD model of LEU element and (b) simplified LEU element geometry.*

### 2.2 Boundary Conditions and Loadings

Three different loading cases were considered in this study:

1. Hydraulic force due to pressure differentials. A lateral loading representative of hydraulic forces was applied to the fuel plate.
2. Thermal load. A representative thermal load was applied to all plates in the elements to analyze the structural response of the elements and the influence of the end fittings on that response.
3. Point loads on a resting surface (end fitting edge, etc.) as a surrogate to model external forces due to resting mass.

The LEU element is not fully constrained in the reactor. It can move or expand within the small gaps around it. The DDE will be constrained in a testing basket, with the top and bottom end fittings positioned in the basket by spring-loaded screws and the corresponding contact features of the basket. There is a 0.04-inch-thick gap between the side plates of the DDE and the basket, which is the same as the nominal gap between the side plates of two neighboring LEU elements when inserted in the MURR core [8].

As outlined above, there are notable differences in how the two elements are constrained. Exact replication of the mechanical constraints of the LEU element (which can move within the gaps between elements) in the FE model is difficult due to the nonlinearities introduced by the boundary conditions. Moreover, the purpose of this study is to compare the relative stiffness of the LEU element and DDE under the same load types and identical or equivalent boundary conditions. Therefore,
identical mechanical constraints were used in the models of both the LEU element and the DDE. This modeling choice is meant to primarily prevent the models from rigid body motions in the simulations and to facilitate the comparison of the relative stiffnesses of the elements.

2.2.1 Mechanical Constraints Applied
The response of a MURR element to a specific load depends on what kind of mechanical constraints are applied to it. As discussed previously, mechanical constraints used in this work are intended to only prevent rigid body motions. Specifically, as shown in Figure 2.5, the following three constraints are applied (superposed) in all cases:

(a) No displacement in z-direction (axial direction) along the two bottom edges of the side plates;
(b) No displacement in x-direction (parallel to one side plates) along the front vertical edge of one of the side plates, as highlighted in Figure 2.5 (b); and
(c) No displacement in x and y-directions along the front vertical edge of the other side plate, as highlighted in Figure 2.5 (c).

![Figure 2.5. Schematic of mechanical constraints configuration for Cases (a), (b), and (c) from left to right.](image)

2.2.2 Hydraulic Load
For the purpose of this report, the hydraulic load refers to the flow-induced pressure differential acting on the fuel plates. The flow-induced pressure differential results from the flow disparities caused by differences in the thicknesses of surrounding coolant channel gaps, turbulent fluctuations in the flow, or both. This pressure differential, when acting on the fuel plates, may cause deflection. In the previous efforts [9], preliminary FSI simulations were performed for MURR on a geometry of a single LEU plate and two channels surrounding it. The simulated plate represented plate 22 of the LEU element, and the channel gap thickness disparity was determined on the basis of the channel gap tolerances.
In the current work, the pressure differential distribution extracted from that analysis [9] is applied to plate 22 for the hydraulic load case. As shown in Figure 2.6, the pressure differential peak at the plate’s leading edge decreases in magnitude by more than half within a short distance downstream from the leading edge and then decreases almost linearly, reaching zero at the trailing edge. The assumed pressure differential contour acting on plate 22 of the LEU element model is presented in Figure 2.6 (b). Since the coolant in the MURR core flows in the downward direction, the leading edge is located at the top in that figure.

Note that only the pressure differential on plate 22 has been analyzed in previous efforts [9], and predictions of the pressure differential distribution for other plates and side plates are not available at this time. In that work, the pressure differential on plate 22 was obtained by assuming the maximum possible (within manufacturing and assembly tolerances of +/-8 mil) channel gap thickness disparity for the channels adjacent to that plate and nominal dimensions for other channels in the element. When nominal dimensions for the channels are used, the channel gap thickness disparity either does not exist or is very small. Thus, the hydraulic load for plates in such geometric configuration is expected to be small as compared to the load applied on plate 22 in the most limiting configuration. Although such limiting conditions can be created for each plate in MURR element, the prior study only focused on plate 22 as having the span smaller only from that of plate 23 and being thinner than plate 23. The pressure differential load applied to plate 22 is shown in Figure 2.6. The distribution of the load on plate 22 in COMSOL model is shown in Figure 2.7. The load direction is towards the center of the arc.

To obtain the pressure differential distribution for all 23 plates and side plates, a full-element computational fluid dynamics analysis is required, which is planned for another activity, but is out of the scope of this work. Therefore, in this work, the hydraulic load is only applied to plate 22, as shown in Figure 2.7. The load direction is towards the center of the arc.
2.2.3 Thermal Load

This analysis considers the effects of thermal expansion of the fuel element components during irradiation. The fluid flow and heat transfer are not considered in this analysis, and the temperature field is needed as the model input to characterize the thermal strain in the components of the fuel element.

The input temperature field is obtained with the use of PLETMP/ANL [10] for the element with the highest temperature in the LEU core (reference core 7X, beginning-of-life, fresh element X1, as explained in [5]). For that reason, a larger thermal strain is expected compared to other conditions of the fuel elements, and the analysis is conservative in terms of thermal expansion effect.

In the PLTEMP/ANL model, the fuel core and cladding were modeled separately in the thickness direction. In the COMSOL model, the temperature in the fuel plate was averaged in the fuel thickness direction by averaging the fuel core and cladding temperatures weighted by heat capacity (J/K) of each component. Also, in the PLTEMP/ANL model, the plate was divided into nine (9) stripes in the azimuthal direction and 24 axial nodes, so the temperature distribution for each plate is represented by a total of 216 data points. These temperature data points are interpolated in COMSOL to obtain the input temperature field for the thermal load cases, as shown in Figure 2.8. The temperature of the top and bottom end fittings is assumed to be the inlet and outlet coolant temperature, respectively, and the average coolant temperature is used to represent the side plate temperature distribution.

For the calculations presented in this report, the strain reference temperature was assumed to be 20°C. After applying the imported temperature distribution and solving the COMSOL solid mechanics model, the displacements due to the thermal load in the element can be calculated.
2.2.4 Point Load

For the point load cases, a force with a magnitude equal to the LEU element weight (121.35 N) was applied to the lip of the side plate, along the direction normal to the surface, as shown in Figure 2.9. Note that the weight of the DDE element is slightly different from the LEU element weight, but the same load magnitude (equal to the LEU element weight) is used for the analyses of both the LEU element and DDE for the comparison purpose. For the LEU element, the load was applied to the top end of the side plate (Figure 2.9 (a)). For the DDE, two cases were considered in which the load was applied to the top and bottom ends of the side plate (Figure 2.9 (b) and (c), respectively). The need for the two cases arises from the differences in the distance from fuel plates to the side plate lip for the top and bottom ends. Additionally, cases without the end fittings were analyzed to better understand the influence of the end fittings on the response of the elements.
2.3 Material Properties

During the early phase of operation, the increased temperature of the fuel relative to the reference temperature causes thermal strain. Elastic, unirradiated properties govern the behavior of the fuel elements at that stage. Many thermal and mechanical properties of the aluminum cladding and the fuel core subsequently change as a result of irradiation. The yield strength of aluminum is greatly affected by this process [11]. During the irradiation process, the fuel core also undergoes swelling. Subsequently, owing to the amount of fuel core swelling, the cladding frequently experiences plastic deformations. Irradiation and thermal creep in the fuel core and Zr interlayer, respectively, further change the state of stress in the fuel core, the interlayer, and the cladding, and the interface between them. These effects are quite complex to model and are analyzed under another Reactor Conversion Project activity [12] [13]. They are not the subject of the present work, which focuses only on the relative rigidity of the fuel elements, encompassing the linear elastic effects only.

In this work, the elastic properties of aluminum alloy (AA6061) are used to represent the whole element. The only material properties governing the elastic range of response are the Young’s modulus, the Poisson’s ratio, and the coefficient of thermal expansion. The Young’s modulus (in GPa) is estimated using the formula derived in [14]:

\[ E_{AA6061} = 54.9 + 1.07 \times 10^{-1}T - 2.03 \times 10^{-4}T^2, \]

where the temperature \( T \) is in K. For the hydraulic load cases, the room temperature of 20°C is used as a reference temperature, which results in a Young’s modulus of 68.82 GPa. For the thermal load cases, the Young’s modulus varies with the input temperature field. The Poisson’s ratio and the coefficient of thermal expansion were assumed as constant, at 0.33, and 2.3×10^{-5} [1/K], respectively [11].

2.4 Meshing and Sensitivity Analysis

As shown in Figure 2.10, different meshing approaches are used for the fuel plates and the end fittings. For meshing of the fuel plates and side plates, the hexahedral elements were generated by sweeping the surface mesh in the cross section. This meshing technique is preferred over free tetrahedral meshing because the total count of the elements can be kept lower and the quality of the mesh in that portion of the model can be more tightly controlled. For such a swept-based mesh, each edge must have the number of elements defined by the user. For the end fittings, due to the complicated geometry, the tetrahedral elements were used. Therefore, the mesh is not conformal at the interfaces between the end fittings and side plates, and the identity boundary pair is used to enforce the perfect bonding between end fittings and side plates. The mesh sensitivity analysis was performed in two steps. The mesh sensitivity analysis for the fuel plates was performed first, followed by the end fitting mesh sensitivity analysis.
2.4.1 Mesh Sensitivity Analysis for Fuel Plates

The mesh sensitivity analysis for fuel plates (including side plates) is performed for the cases of the LEU fuel element and the DDE without the end fittings (cases (b) and (d) in Figure 2.3). Four different mesh settings with various numbers of elements in the plate thickness direction (1, 2, 3, and 4), the plate span direction (30, 50, 60, and 70), and the plate axial direction (100, 150, 175, and 200) are analyzed. The maximum displacement of the fuel plates is the parameter of interest.

The comparison of the plate displacement for different mesh settings and all load cases is shown in Table 2.1. The cell filled by 'N/A' indicates the represented mesh and load combination is not analyzed because mesh convergence is reached and further running these cases is not needed. The cell filled by '-' represents the finest mesh analyzed for each load and is used as the reference cases for the percentage difference calculation. With the selected mesh settings of the LEU element and the DDE, which are bolded and gray-shaded in the table, the model predicts maximum displacements that are very close (< 0.5% difference) to the displacements predicted with the finest mesh for all types of load cases investigated.

Note that the quadratic discretization is used in the solid mechanics models. Thus, the number of degrees of freedom in the model is over an order of magnitude larger than the total number of elements.

2.4.2 Mesh Sensitivity Analysis for End Fittings

The mesh sensitivity analysis for end fittings is performed for the cases of the LEU fuel element and the DDE with the end fittings (cases (a) and (c) in Figure 2.3). Different mesh settings (predefined meshing options in COMSOL) ranging from coarser to finer are analyzed. The maximum displacement of the plates is the parameter of interest.

The comparison of the plate displacements for different mesh settings and all load cases is shown in Table 2.2. With the selected mesh settings for the LEU element and DDE, which are bolded and gray-shaded in the table, the model predicts maximum displacements that are very close to the displacements predicted with the finest mesh for all types of load cases investigated. The cell without
number entered (filled by 'N/A') indicates the represented mesh and load combination is not analyzed. Note that for the DDE under hydraulic load, the extra fine mesh is needed. This is because the top end fitting of the DDE is close to the maximum load position, and its mesh density affects the maximum displacement more than for other load cases.

### Table 2.1. Mesh sensitivity of the fuel plates.

<table>
<thead>
<tr>
<th>Case</th>
<th>Number of elements in direction of</th>
<th>Number of elements $\times 10^6$</th>
<th>Degrees of freedom $\times 10^6$</th>
<th>Difference of max. displacement relative to the finest mesh</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thickness</td>
<td>Span</td>
<td>Axial</td>
<td></td>
</tr>
<tr>
<td>(b) LEU w/o end fitting</td>
<td>1</td>
<td>30</td>
<td>100</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>50</td>
<td>150</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>60</td>
<td>175</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>70</td>
<td>200</td>
<td>2.29</td>
</tr>
<tr>
<td>(d) DDE w/o end fitting</td>
<td>1</td>
<td>30</td>
<td>100</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>50</td>
<td>150</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>60</td>
<td>175</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>70</td>
<td>200</td>
<td>2.44</td>
</tr>
</tbody>
</table>

a 'N/A' indicates the mesh and load combination is not analyzed because mesh convergence is reached and further running these cases is not needed.
b '-' represents the finest mesh analyzed for each load and is used as the reference cases for the percentage difference calculation.

### Table 2.2. Mesh sensitivity of the end fittings.

<table>
<thead>
<tr>
<th>Case</th>
<th>End fitting element density</th>
<th>Element number of end fitting $\times 10^3$</th>
<th>Difference of max. displacement relative to the finest mesh</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Point load</td>
</tr>
<tr>
<td>(a) LEU</td>
<td>coarser</td>
<td>54</td>
<td>-1.26%</td>
</tr>
<tr>
<td></td>
<td>coarse</td>
<td>90</td>
<td>-0.37%</td>
</tr>
<tr>
<td></td>
<td>normal</td>
<td>190</td>
<td>-0.15%</td>
</tr>
<tr>
<td></td>
<td>fine</td>
<td>384</td>
<td>-0.02%</td>
</tr>
<tr>
<td></td>
<td>finer</td>
<td>1223</td>
<td>-</td>
</tr>
<tr>
<td>(c) DDE</td>
<td>coarser</td>
<td>11</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>coarse</td>
<td>47</td>
<td>0.17%</td>
</tr>
<tr>
<td></td>
<td>normal</td>
<td>51</td>
<td>0.39%</td>
</tr>
<tr>
<td></td>
<td>fine</td>
<td>65</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>finer</td>
<td>109</td>
<td>-b</td>
</tr>
<tr>
<td></td>
<td>extra fine</td>
<td>201</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>extreme fine</td>
<td>328</td>
<td>N/A</td>
</tr>
</tbody>
</table>

a 'N/A' indicates the mesh and load combination is not analyzed because mesh convergence is reached and further running these cases is not needed.
b '-' represents the finest mesh analyzed for each load and is used as the reference cases for the percentage difference calculation.
2.5 Effects of Comb on Plate Displacement

For both the LEU element and the DDE, supporting combs (made of AA6061) are present on the leading and trailing edges of the fuel plates. As shown in Figure 2.11, the comb is installed in the center of the span to reduce the deflections in the fuel plates and to maintain the spacing in between the plates. The comb is connected to the plates by a pin that goes through all plates. However, the comb slots (where the fuel plates slide in) are 0.006 inch thicker than the plates [3]. The thickness of plates 1 to 22 is 0.044 inch, and the corresponding slots’ gap thickness is 0.050 inch. The thickness of plate 23 is 0.049 inch, and the corresponding slot’s gap thickness is 0.055 inch. Therefore, if it is assumed that the plate is perfectly centered in the comb slot, there will be a gap of 0.003 inch for deformation or expansion of the plate with limited restrictions provided by the comb. As a result, if the plate displacement is very small (i.e., less than 0.003 inch), the effect of the comb could be negligible, and if the displacement is large, the support from the comb should be considered, as the displacement has an upper limit defined by the size of the slots.

In this work, the simulations with and without the combs are performed as two bounding cases. For the simulation cases with the combs, the gaps between comb and plates are neglected and a perfect bond between the comb and plates is assumed, ensuring continuity of the displacement field between them.

![Figure 2.11. LEU fuel element with supporting comb.](image-url)
3 Results

3.1 Hydraulic load

3.1.1 Maximum Displacement and Distribution

The distribution of assumed hydraulic load varies only in the axial direction (along the flow). It has a peak at the plate’s leading edge and decreases along the flow, following the curve shown in Figure 2.6. Therefore, the supporting effect provided by the comb modeling at the leading edge can significantly affect the character and magnitude of the plate deflection.

Figure 3.1 shows the displacement field caused by the hydraulic load in four models: the LEU fuel element, the DDE, and the equivalent models without the combs. As shown in Figure 3.1, for the LEU fuel element and the DDE without the combs, the maximum displacement occurs at the leading edge. Note that the maximum displacement (shown in Table 3.1) in the model of the DDE without the comb is about 16% smaller than the maximum displacement in the model of the LEU fuel element without the comb. This is because the distance between the top end fitting and the fuel plates in the DDE is smaller than that in the LEU fuel element (0.5 inch vs. 2.25 inch), so the DDE end fitting can provide more support through the side plates to reduce the plate deflection. For the DDE and the LEU element with the comb, the maximum displacement occurs at around one quarter of the plate length downstream from the leading edge, and the maximum displacement magnitude is similar for both the LEU fuel element and DDE models.

Table 3.1 presents the maximum displacements calculated for all considered models subject to a hydraulic load. For the cases with the comb, all four geometries (LEU, LEU without end fittings, DDE, and DDE without end fittings) predict a very similar value of the maximum displacement (near 0.62 mil; 1 mil = 0.001 inch) at a similar location, which means that the effect of the end fittings on plate displacement under hydraulic load is negligible.

For the geometries without the comb, i.e., Case (a) (LEU) and (b) (LEU without end fittings) in Table 3.1, the analysis predicts nearly identical maximum plate displacement, indicating that the end fittings of the LEU element do not noticeably affect the plate displacement under the selected hydraulic load. For Cases (c) and (d) in Table 3.1, the model of the DDE with end fittings predicts around 20% less maximum displacement than the model of the DDE without end fittings. The DDE end fittings help reduce the maximum displacement, while the end fittings in the LEU fuel element model appear to not have such influence. It is concluded that this is caused by the varying distance between the end fittings and fuel plates in the DDE and the LEU fuel element, that is, 0.5 inch and 2.25 inch, respectively, in case of the top end fittings.

Note that the maximum displacement predicted for all cases is in the range of 0.6 to 1.1 mil, which is smaller than the 3-mil gap between the comb slot walls and the plates. Therefore, it is possible that for some plates in the actual fuel elements, the comb’s supporting effect on the plate leading edge could be limited, given the small magnitude of plate displacement and the gap between the plates and the walls of the comb slots. However, it should be mentioned that this activity aims at comparing the relative differences in displacement between the DDE and LEU elements to evaluate the equivalency of their structural response under the selected loads. Thus, the plate displacement magnitude predicted here may not be conclusive, given the assumptions and simplifications adopted (e.g., applying load on plate 22 only), but the relative stiffness is conclusive, owing to the linear elastic effects.
Figure 3.1. Plate 22 displacement field distribution under hydraulic load: (L-comb) LEU element with comb, (D-comb) DDE with comb, (L-nocomb) LEU element w/o comb, (D-nocomb) DDE w/o comb.

Table 3.1. Maximum displacement under hydraulic load.

<table>
<thead>
<tr>
<th>Load</th>
<th>Case</th>
<th>Fuel element type</th>
<th>With comb</th>
<th>Without comb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximum displacement (mil)</td>
<td>Difference relative to LEU</td>
</tr>
<tr>
<td>Hydraulic load on plate 22</td>
<td>a</td>
<td>LEU</td>
<td>0.619</td>
<td>0.0%</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>LEU w/o EF</td>
<td>0.619</td>
<td>0.0%</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>DDE</td>
<td>0.620</td>
<td>0.2%</td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>DDE w/o EF</td>
<td>0.621</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

Figure 3.2 shows a cross-sectional distribution of displacement for LEU fuel elements (a) with and (b) without the comb. The displayed cross section is at the axial location of maximum displacement for both cases. Although the hydraulic load was only applied to plate 22, the surrounding plates are also deforming as a result of the deformations in the side plates. The maximum plate displacement occurs at plate 22, as expected. The reason that cases with comb predicts a smaller maximum displacement than cases without comb is that the comb structurally connects the leading-edge center of plate 22 (where load is applied) with that of other plates, and the other plates provide support through the comb to limit the displacement of the plate 22 leading edge.

In summary, if one assumes that the plate leading edge is constrained by the comb, the end fittings have a negligible effect on the element rigidity under the assumed hydraulic load applied to plate 22 for both the LEU element and the DDE. Considering the gap of 3 mil between the plates and the corresponding comb slots, and neglecting the comb constraint, the presence of the end fittings...
reduces the maximum displacement by 20% for the DDE, while for the LEU fuel element, the influence of the end fittings on the maximum displacement (and stiffness) is small (2.2%). This result occurs because the DDE top end fitting is closer to the maximum displacement location (plate leading edge) than that of the LEU fuel element. The predicted maximum displacement for the DDE (with end fittings) is smaller than but comparable to that of the LEU element.

(a) Cross-section at axial position of max. disp. LEU with comb  (b) Cross-section at axial position of max. disp. LEU w/o comb

Figure 3.2. Cross-sectional distribution of displacement of LEU (a) with comb and (b) without comb.

3.2 Thermal Load

As discussed in Section 2.2.3, the thermal load is represented by considering the thermal expansion (thermal strain) of the element. Since the fluid flow and heat transfer are not considered in this analysis, a temperature distribution calculated using the PLTEMP/ANL model of MURR is used as the model input.

3.2.1 Maximum Displacement and Its Distribution

Since the applied mechanical constraints only prevent rigid body motion, the strain of the element due to thermal load occurs in the axial/vertical (z axis) and horizontal (x and y axis) directions. The displacement distribution in the model of the LEU element (with comb) is shown in Figure 3.3 (a). Note that the displacement distribution in the DDE is very similar to that of the LEU element, and the displacement distribution in the LEU element is presented as an example. The maximum displacement occurs at the top of the element because most of the displacement magnitude is from the expansion in vertical direction due to thermal load of the element and the element’s bottom edges are constrained in the z direction. However, from the thermal hydraulics safety analysis viewpoint, the fuel plate displacement in the plate thickness (radial) direction is of more interest, as it is related to the channel gap thickness and the cooling capability of the channel. Therefore, the displacement field is decomposed into vertical displacement (w) and radial displacement \((u^2+v^2)^{0.5}\), where \(u, v\) is the displacement along x-direction and y direction, respectively. Both components are presented in Figure 3.3 (b) and (c), respectively. Figure 3.3 (b) shows that the maximum vertical displacement due
to thermal expansion is smaller than 36.0 mil for the LEU element. Figure 3.3 (c) shows that the maximum radial displacement is 13.7 mil, occurring at plate 23 with the axial location around one third of the plate’s length from its trailing edge.

Figure 3.3. Displacement distribution in LEU element with comb under thermal load.

The comparison of radial displacement distribution in the LEU model with and without the comb is shown in Figure 3.4. For the case with the comb, the maximum radial displacement occurs at the axial location around one third of the plate’s length from the trailing edge, and the displacement is outward. For the case without the comb, the maximum displacement occurs at the trailing edge, and the displacement is inward (toward the center of the arc-shaped fuel plate). Note that the displacement distribution is similar between the cases with and without the comb except near the trailing edge. Under the constraint configuration and the applied thermal load, the fuel plate deflects inward at the trailing edge and deflect outward at other locations, this should be because the non-uniform temperature field (see Figure 2.8) and the constraint configuration applied in this work. The presence of the comb would limit the trailing edge displacement, which makes the maximum displacement to occur at the axial location around one third of the plate’s length from the trailing edge. The direction of displacement is more visible in Figure 3.5 and Figure 3.6, which show the cross section of radial displacement distribution for the LEU and DDE models without comb at different vertical locations. Note that the deformation is scaled up by a factor of 20 for visualization purpose.

Figure 3.6 (a) shows the cross section at the trailing edge, where the maximum inward displacement occurs. Figure 3.6 (b) is at 0.25 m above the trailing edge, and the displacement is outwards at this position, with the magnitude slightly less than the trailing-edge inward displacement. For the models with supporting comb considered, the displacement at the trailing edge is limited by the comb, and the outward displacement around 0.25 m above the trailing edge becomes the maximum.
Figure 3.4. Radial displacement distribution of LEU element, (a) with comb and (b) without comb

Figure 3.5. Cross-sectional distribution of Radial displacement magnitude for LEU element without comb (deformation scaled by factor of 20 for visualization purposes)
Figure 3.6. Cross-sectional distribution of radial displacement magnitude for DDE without comb (deformation scaled by factor of 20 for visualization purposes)

The results in the form of maximum displacements for cases under thermal load are summarized in Table 3.2. Cases (a) to (d) represent models of the LEU element, LEU element without end fittings, DDE, and DDE without end fittings, respectively. The first four rows are the results for the model with supporting comb considered, and the remaining rows are the results for the model without supporting comb considered. While the maximum displacement occurs at the top of elements (as mentioned above), because of the thermal expansion in the vertical direction, the radial displacement is of more interest. Therefore, the maximum radial displacements are presented in Table 3.2, along with their differences from the LEU element results (Case a).

For the cases with combs, the maximum radial displacement occurs at one third of the plate length from the trailing edge (Figure 3.4 (a)). The maximum displacement values are very close to each other (less than 2% difference) for cases with and without end fittings for both the LEU element and the DDE. This finding indicates that the contribution of the end fittings to the element rigidity under this thermal load is insignificant for both the LEU element and the DDE.

For the cases without the combs, the maximum radial displacement occurs at the trailing edge (Figure 3.4 (b)). Under this condition (without the comb), the effect of the end fittings is slightly more noticeable. The maximum radial displacement for cases without the end fittings can be up to 5.6% greater than that for cases with the end fittings for both the LEU element and the DDE.

In summary, for the cases analyzed, no significant difference between the LEU element and the DDE in structural response under the simulated thermal load was observed. Also, the contribution of the stiffness of the end fittings to the stiffness of the overall element under the thermal load was found to be not substantial.
Table 3.2. Maximum displacement results under thermal load.

<table>
<thead>
<tr>
<th>Leading/trailing edge support condition</th>
<th>Case</th>
<th>Fuel element type</th>
<th>Max. displacement (mil)</th>
<th>Max. radial displacement (^a) (mil)</th>
<th>Difference of radial disp. relative to Case (a) LEU model</th>
</tr>
</thead>
<tbody>
<tr>
<td>With comb</td>
<td>a</td>
<td>LEU</td>
<td>35.9</td>
<td>13.7</td>
<td>0.0%</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>LEU w/o EF</td>
<td>36.4</td>
<td>13.9</td>
<td>1.7%</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>DDE</td>
<td>37.6</td>
<td>13.7</td>
<td>-0.1%</td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>DDE w/o EF</td>
<td>37.6</td>
<td>13.9</td>
<td>1.6%</td>
</tr>
<tr>
<td>Without comb</td>
<td>a</td>
<td>LEU</td>
<td>35.9</td>
<td>14.9</td>
<td>0.0%</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>LEU w/o EF</td>
<td>36.3</td>
<td>15.7</td>
<td>5.6%</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>DDE</td>
<td>37.5</td>
<td>15.3</td>
<td>2.9%</td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>DDE w/o EF</td>
<td>37.5</td>
<td>15.7</td>
<td>5.4%</td>
</tr>
</tbody>
</table>

\(^a\) The maximum radial displacement does not occur at the top of the element (as it does for the total displacement), it occurs at the trailing edge for the cases without comb and occurs at the axial location around one third of the plate’s length from the trailing edge for the cases with comb.

### 3.2.2 Channel Gap Thickness Reduction

It should be noted that the maximum radial displacement of 13.7 mil for the LEU element does not necessarily imply that the coolant channel gap thickness could change by 13.7 mil. As shown in Figure 3.6, for channel 23, which is bounded by plates 22 and 23, the channel gap thickness change is expected to be smaller than the value of the plate-23 radial displacement (maximum of 13.7 mil), because both plates 22 and 23 are deforming concurrently in a similar way.

To evaluate the effect of thermal expansion on channel gap thickness reduction, the channel-23 gap thickness distribution of the LEU element and the DDE under thermal load is presented in Figure 3.7. The changes of channel 23 gap thickness compared to the initial (nominal) thickness of 93 mil for all cases are listed in Table 3.3.

For the cases without the comb, the minimum channel gap thickness occurs at the trailing edge because of the inward displacement of plate 23 at this position. The value is around 2.4 mil smaller than the nominal value (93 mil) for all four cases. The maximum channel gap thickness is about 1.6 mil larger than the nominal value. For the cases with the comb, the trailing edge plate displacement is limited by the comb, and the minimum channel 23 gap thickness occurs at the upper part of the plate, with the value of 0.81 mil (less than 93 mil). The maximum channel gap thickness occurs at a position similar to that of the cases without the comb, and the magnitude is also similar. The magnitude of channel thickness change due to the thermal load is small compared to the fabrication tolerance (8 mil) of MURR LEU element [1].

There are almost no differences in the channel 23 gap thickness reduction among the four elements analyzed (LEU element and DDE, both with and without end fittings), indicating that the effect of the end fittings, as well as the difference in the design between the DDE and the LEU element, on the channel 23 gap thickness change due to thermal expansion is negligible.
Figure 3.7. Channel 23 gap thickness distribution under thermal load.

Table 3.3. Channel 23 gap thickness change due to thermal load.

<table>
<thead>
<tr>
<th>Leading/trailing edge support condition</th>
<th>Case</th>
<th>Fuel element type</th>
<th>Channel 23 gap thickness change (mil)</th>
<th>Ratio to nominal gap thickness of 93 mil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Min.</td>
<td>Max.</td>
</tr>
<tr>
<td>With comb</td>
<td>a</td>
<td>LEU</td>
<td>0.81</td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>LEU w/o EF</td>
<td>0.81</td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>DDE</td>
<td>0.81</td>
<td>1.62</td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>DDE w/o EF</td>
<td>0.81</td>
<td>1.63</td>
</tr>
<tr>
<td>Without comb</td>
<td>a</td>
<td>LEU</td>
<td>2.44</td>
<td>1.59</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>LEU w/o EF</td>
<td>2.42</td>
<td>1.59</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>DDE</td>
<td>2.43</td>
<td>1.58</td>
</tr>
<tr>
<td></td>
<td>d</td>
<td>DDE w/o EF</td>
<td>2.41</td>
<td>1.59</td>
</tr>
</tbody>
</table>

3.3 Point Load

The displacement distributions in the models of the LEU element and the DDE under the point load described previously in Section 2.2.4 are presented in Figure 3.8. The structural response of the elements under the point load is very localized, and the maximum displacement occurs near the load position.

The maximum displacements obtained for all considered geometries in simulations with the point load are shown in Table 3.4. The displacement magnitude for all cases is very small (less than 1 mil). Note that for the model of the DDE, the displacement caused by applying the load at the top end (Case 3) is smaller than the displacement in the model in which the load was applied to the bottom end (Case 3b). This is because the DDE fuel plates are located closer to the top end and therefore provide more structural support near that location. This effect is more significant for the DDE without end fittings (Cases 4 and 4b). In addition, since the point load response is a local effect, the difference...
in maximum displacement between cases with and without the combs is insignificant, as shown in Table 3.4. However, the difference in maximum displacement between the cases with and without the end fittings is significant because the absence of the end fittings changes local structure substantially and the stiffness of the side plate lip under the point load decreases as a result of this change. However, the displacement magnitude is still smaller than 1 mil, even without the end fittings. Further evaluation of the difference in structure behavior between DDEs and LEU elements will be conducted in other tasks of the LEU conversion study.

In summary, although end fittings contribute significantly to element rigidity (measured by maximum displacement in comparison to the no end fitting cases) under a point load, the structural performance of the DDE is not substantially different from that of the LEU element. The predicted maximum displacement obtained in the model of the DDE (with end fittings) is comparable to that of the LEU fuel element, and the displacement magnitude is small for all cases under a load equivalent to the weight of the LEU element.

Figure 3.8. Displacement distribution under point load in the models of (a) LEU fuel element and (b) DDE.

Table 3.4. Maximum displacement for cases under point load.

<table>
<thead>
<tr>
<th>Load</th>
<th>Case</th>
<th>Fuel element type</th>
<th>With comb</th>
<th>Without comb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximum displacement (mil)</td>
<td>Percentage relative to LEU case</td>
</tr>
<tr>
<td>Point load (on top end)</td>
<td>1</td>
<td>LEU</td>
<td>0.13</td>
<td>0.0%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>LEU w/o EF</td>
<td>0.34</td>
<td>164.0%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>DDE</td>
<td>0.11</td>
<td>-15.7%</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>DDE w/o EF</td>
<td>0.15</td>
<td>13.8%</td>
</tr>
<tr>
<td>Point load (on bottom end)</td>
<td>3b</td>
<td>DDE</td>
<td>0.15</td>
<td>13.5%</td>
</tr>
<tr>
<td></td>
<td>4b</td>
<td>DDE w/o EF</td>
<td>0.77</td>
<td>489.6%</td>
</tr>
</tbody>
</table>
4 Conclusions

The preliminary design of the MURR LEU fuel element and the conceptual design of the MURR DDE are different in terms of the structure and position of the end fittings. The geometry of the DDE top end fitting is modified to allow for instrumentation access during the irradiation test. Also, the fuel plates in the DDE are closer to the top end fitting and further from the bottom end fitting than in the LEU fuel element to facilitate channel gap probe measurements.

Simplified structural analyses of both the LEU fuel element and the DDE were performed to evaluate the relative contribution of the end fittings to the overall stiffness of the element, and to determine whether the structural response of the DDE is similar to that of the LEU fuel element under the selected loads.

A supporting comb is used on the leading and trailing edges of fuel plates for both the LEU fuel element and the DDE. The simulations both with and without the combs were performed as two bounding situations. For the simulation cases with the combs, the gaps between the comb and plates were neglected and perfect bonding between comb and plates was assumed.

Three typical loads were analyzed in this work: the hydraulic load due to the pressure differential induced by flow disparities, the thermal load on the fuel plates, and a point load with magnitude equal to the LEU element weight.

For the hydraulic load response, if the plate leading edge is assumed to be constrained by the comb, the end fittings have a negligible effect on the element rigidity for both the LEU element and the DDE. If the comb constraint is neglected, the effect of the end fittings is less significant for the LEU element compared to the DDE. The LEU element end fittings help reduce the plate maximum displacement by around 1% as compared to the LEU element without the end fittings, while the DDE end fittings help reduce the plate maximum displacement by 20% as compared to the DDE without the end fittings. This result is due to the different distance between the plate leading edge (where maximum displacement occurs) and the top ends of the DDE (0.5 inch) as compared to that of the LEU element (2.25 inch). In short, the predicted maximum displacement for the DDE (with end fittings) is smaller than, but comparable to, that of the LEU element.

For the thermal load, no significant difference in structural response is observed for either the LEU element or the DDE, with or without the end fittings. The contribution of the end fittings to the element rigidity under the thermal load is insignificant.

In the cases with the point load, the end fittings contribute significantly to the fuel element rigidity (measured by maximum displacement in comparison to the no end fitting cases), as expected. The predicted maximum displacement for the DDE (with the end fittings) is comparable to that of the LEU element, and the displacement magnitude is small for all cases.

In summary, for the three types of loads analyzed, no significant difference in rigidity was found between the MURR DDE and the MURR LEU element and the conceptual design of the DDE end fittings was found to be adequate.
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References


