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Integrated Thermal/Mechanical Analysis of Assembly and Irradiation of Annular, LEU-foil Based Target

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ABSTRACT

The thermal- mechanical safety analysis of a low- enriched uranium foil based annular target for molybdenum-99 production will be presented. The target constitutes a low enriched uranium foil sandwiched between two concentric aluminum tubes to form a composite cylindrical structure. A three- step numerical model is built using the commercial finite element code Abaqus FEA to simulate the assembly process, obtain the residual stresses, and simulate the in- vessel irradiation of the annular target. Due to the three- step modeling approach, the residual stresses from the assembly process are automatically used as initial inputs to the thermal- mechanical irradiation model. The safety acceptance criteria assumed that the thermally induced stresses and the temperatures in the cladding, after irradiation, would be within the yield strength and the melting point of the cladding material respectively. Discussions of the safety analysis results and the thermal- mechanical stress margins will be provided.

1. Introduction

The use of Technetium-99m (Tc-99m) in medical imaging is widely known. It is obtained by the radioactive decay of its parent isotope Molybdenum-99 (Mo-99). The bulk of the internationally produced Mo-99 is obtained from irradiated high enriched uranium (HEU) dispersion targets. To assuage proliferation concerns associated with the use of HEU (high concentration of uranium- 235) based targets, low- enriched uranium (LEU) targets are being starting to be used. Since the LEU has only a fraction of the U-235 content as HEU on a per unit weight basis, more LEU is required to achieve the same output of Mo-99. Hence, if LEU is used in a dispersion design, it is necessary to increase the number of targets processed. By switching to a monolithic uranium foil, the mean uranium-235 density can be equivalent to or higher than that of a dispersion target with the same volume [1].

A potential advantage to using an LEU foil based target is that it is possible to cut open the target cladding and remove the foil for chemical dissolution. Only dissolving the LEU, as opposed to the LEU and aluminum cladding as is done for dispersion targets, reduces the amount of liquid waste that needs to be processed. To keep the LEU foil from adhering to the cladding after irradiation, the LEU foil is wrapped in a nickel foil recoil barrier before being sandwiched between two concentric aluminum tubes [2-4]. The thermal/mechanical behavior of the composite target, from assembly through irradiation, needs to be carefully managed in order to establish that no fission products will be released to the environment and that material temperature limits will not be exceeded.

Two different techniques have been explored to assemble the annular targets: the draw-plug process [5] and the hydroforming process [6, 7]. These are illustrated in Figure 1. The assembly of the annular target begins by wrapping the LEU foil with nickel foil (~ 10-15 μm thick). Various metal foils (Zn, Al) have also been used as recoil barriers with different combinations of cladding materials [4]. The wrapped LEU foil with the recoil barrier is then inserted between two aluminum tubes (Al 3003-H14 or Al 6061-T6), that serve as the cladding. The hydroforming process involves the application of an internal pressure to the inner tube, causing it to expand and resulting in plastic deformation. The draw- plug process involves driving a plug made of D2 tool steel, through the inner surface of the inner tube, along its length. The assembly process is designed to plastically deform the inner tube radially and only elastically deform the outer tube, thereby contributing to a favorable stress state for disassembly. The purpose of the assembly process is to create a bonded composite structure by closing the macroscopic interfacial gaps.

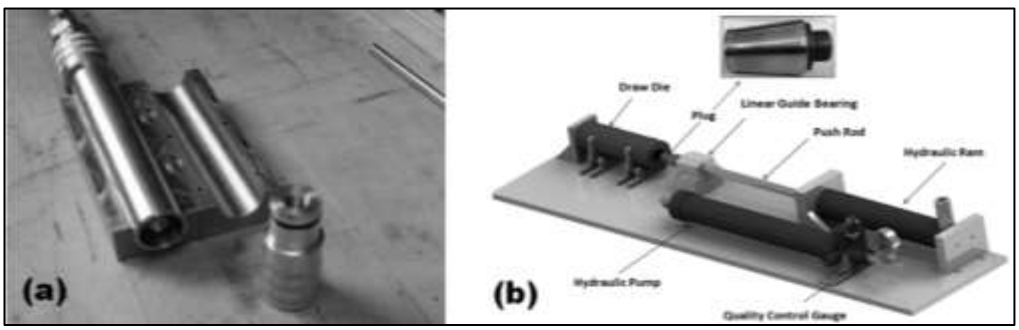

Figure 1. (a) Hydroforming assembly rig from [7]. (b) Draw- plug assembly device

2. Numerical Model

The numerical modeling procedure using the commercial finite element code Abaqus FEA [8], consists of simulating the assembly process, obtaining the assembled target dimensions, and the residual stresses. This is followed by an analysis step where the plug is removed from the simulation. The final analysis step simulates the in- vessel irradiation of the annular target. The analysis proceeds in a step- wise approach where the output of the first analysis step is the initial input to the second analysis step. Hence the residual stresses from the assembly process are automatically included as initial inputs in the irradiation model. The material properties used in the numerical model are provided in Table 1. Due to plastic deformation resulting from the assembly process, a true stress versus plastic strain material model [9, 10], as illustrated in Figure 2, is required for the Al 6061-T6 cladding and the uranium foil. The dimensions used in the numerical model are based on the Argonne National Lab (ANL) annular target design [11] and Al 6061-T6 is used as the cladding material. The numerical model was setup using the information provided in Figure 3. For the hydroforming assembly, an internal pressure of 36.4 MPa [7] was used, and for the draw-plug assembly a plug velocity of 0.16 m/s was applied to the base of the plug. It should be noted that this plug velocity depends on the target length and the largest diameter of the plug. The largest diameter of the plug used in this analysis is 26.619 mm (1.048 inch). This plug was selected based on the deformation required and the material being deformed (Al 6061-T6).

Table 1. Material properties used in the numerical model.

Property	Al 6061-T6	Uranium	D2 Steel
Density (Kg/m^3)	2700	19100	7700
Thermal Conductivity (W/mK)	167	27.50	20
Elastic Modulus (GPa)	68.90	208	210
Poisson's Ratio	0.33	0.23	0.30
Thermal Expansion Coefficient (K^{-1})	2.34×10^{-5}	1.39×10^{-5}	-------

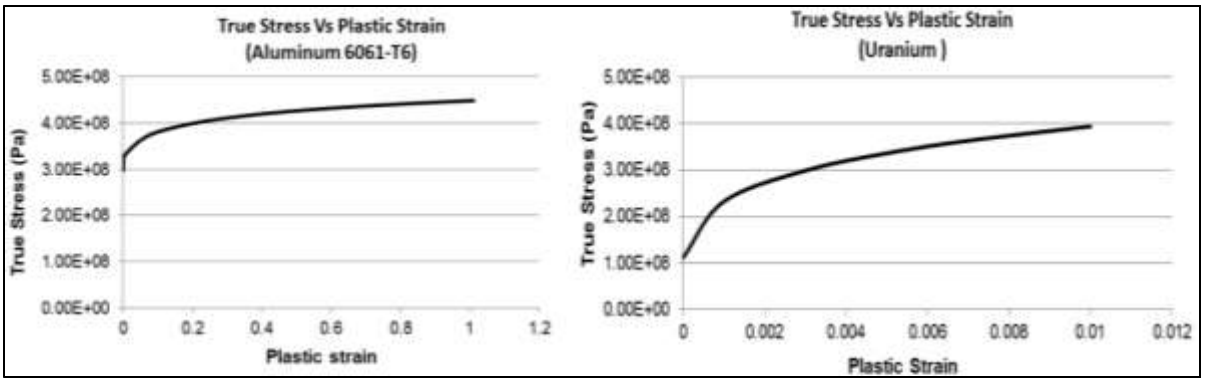

Figure 2. True stress versus plastic strain for Al 6061-T6 and uranium.

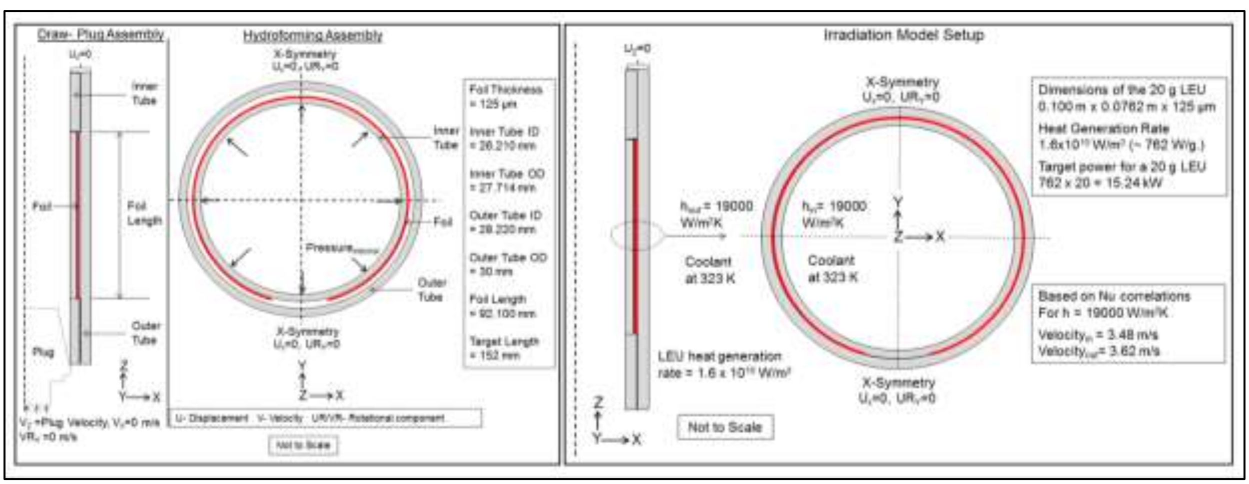

Figure 3. Illustration of the numerical model setup for the assembly and irradiation modeling.

The nickel foil was excluded from the analysis as its thickness is lesser than the LEU foil itself. Due to the non- availability of any fission gas data at the time the analysis was compiled, it was not possible to include any fission gas pressure or a thermal contact resistance model in the analysis. However, the procedure to estimate the fission gas pressure and hence develop a thermal contact resistance model to be used in the thermal- mechanical analysis of an annular target has been outlined and presented elsewhere [12]. The finite element meshes used in the planar hydroforming model [7] and the axisymmetric draw-plug model are illustrated in Figure 4.

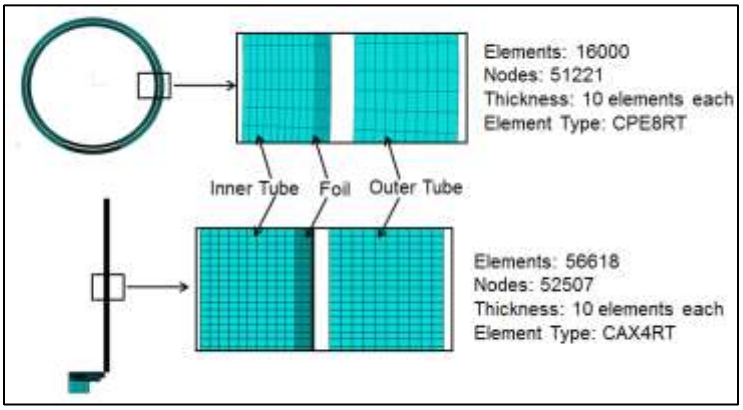

Figure 4. Finite element meshes used in the planar hydroforming model and the axisymmetric draw-plug model.

3. Results

Figure 5 illustrates that small microscopic gaps do exist close to the recess edges after the assembly process is complete. However at the mid-length of the target there are no gaps and the assembly process reinforces the interfacial bond. In Figure 5, the post assembly hydroforming contour has been obtained from [7].

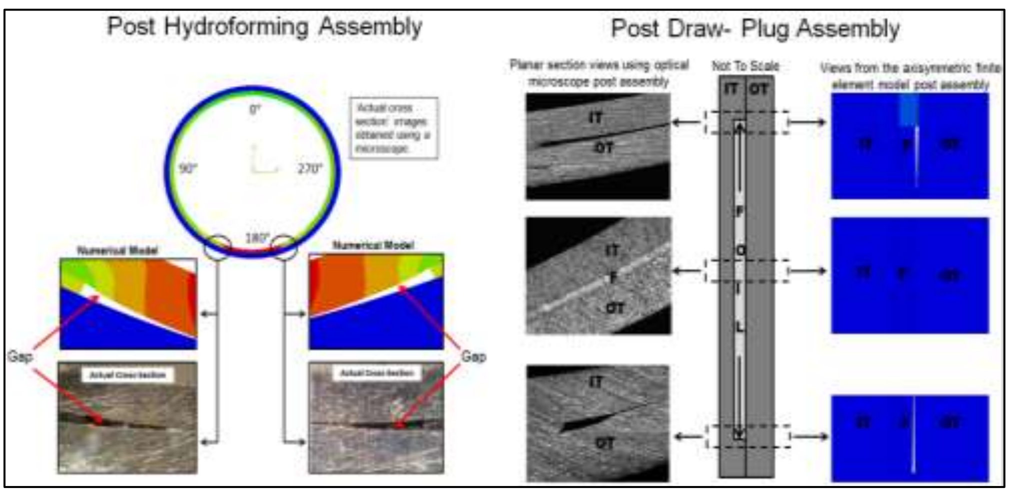

Figure 5. Presence of microscopic gaps at the recess edges after the assembly process.

The variation in equivalent plastic strain across the thickness of the annular target assembly at half its length has been provided in Figure 6. For isotropic hardening and von Mises plasticity, the equivalent plastic strain is given by $\sqrt{(2/3)d\varepsilon^{pl} : d\varepsilon^{pl}}$. It is a scalar measure of the components of plastic strain and a value greater than zero indicates material yielding. Figure 6 also shows that there is zero plastic strain in the outer tube after the assembly process. This shows that the applied hydroforming pressure and the draw plug size used, are adequate to plastically deform the inner tube and only elastically deform the outer tube. However, post-irradiation there is some amount of plastic strain in the outer tube.

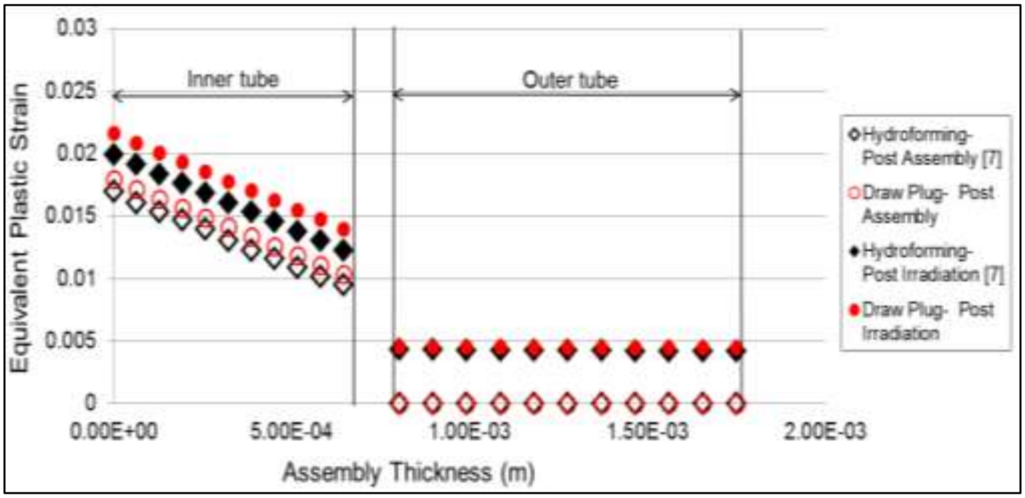

Figure 6. Variation in equivalent plastic strain at half the longitudinal length of the target.

Figure 7 illustrates the variation of residual hoop stresses after the assembly process and the post- irradiation hoop stress margins in the annular target. It can be concluded that the residual hoop stresses alleviate some of the post-irradiation stresses. This is favorable from a structural safety standpoint. Since the geometry of the draw-plug model is axisymmetric in this analysis the von Mises stress distribution after irradiation has also been presented for the draw-plug assembled target in Figure 8. In Figure 7 and Figure 8 the overall stress state of the target is lesser than the yield point of the Al-6061 T6 (based on Figure 2). Therefore it is unlikely that the annular target under consideration would fail structurally under the assumed operating conditions in this analysis.

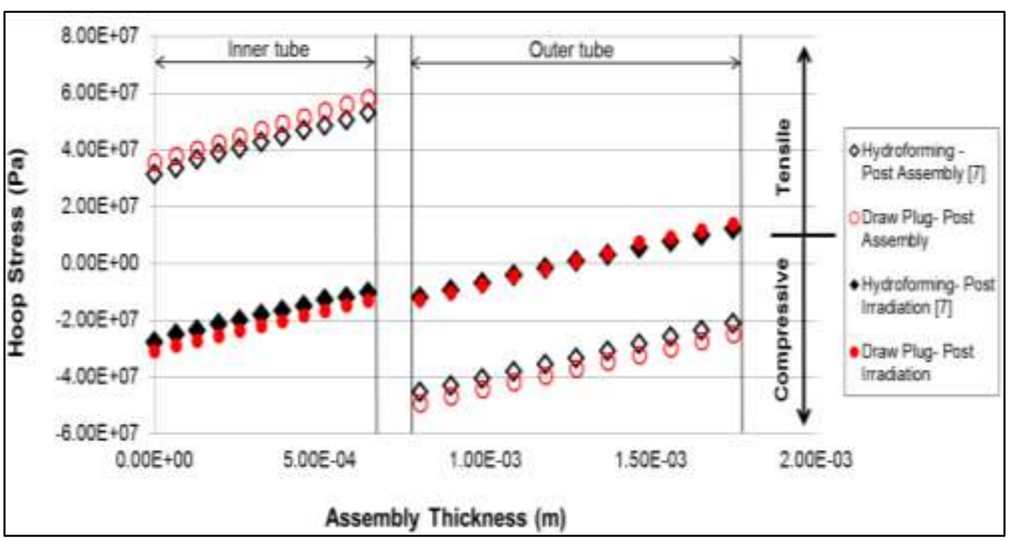

Figure 7. Hoop stresses at half the target length after assembly and irradiation.

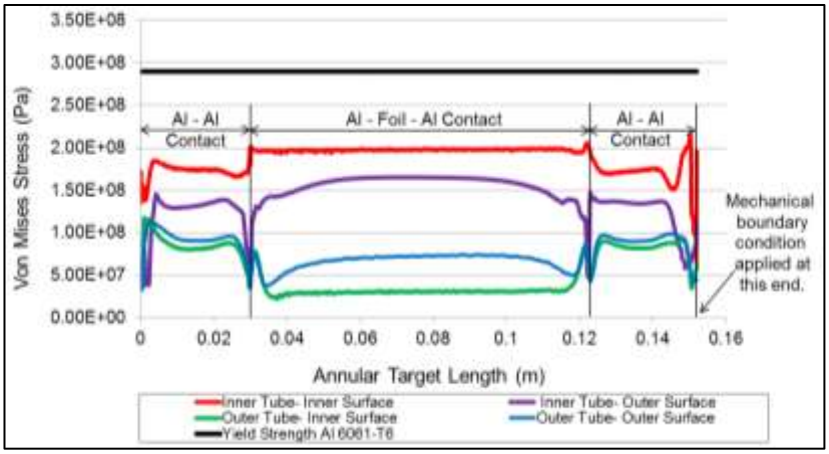

Figure 8. Post- irradiation von Mises stress state for the draw-plug assembled annular target.

The thermal safety criterion dictates that the temperature of the cladding must remain below its melting temperature at all times. The temperature variation across the thickness of the assembly at half the target length has been compared for the two modeling approaches in Figure 9. In both cases, the maximum temperature is found to be lesser than the melting temperature of the Al 6061-T6 (855 K) thereby satisfying the assumed thermal safety criteria.

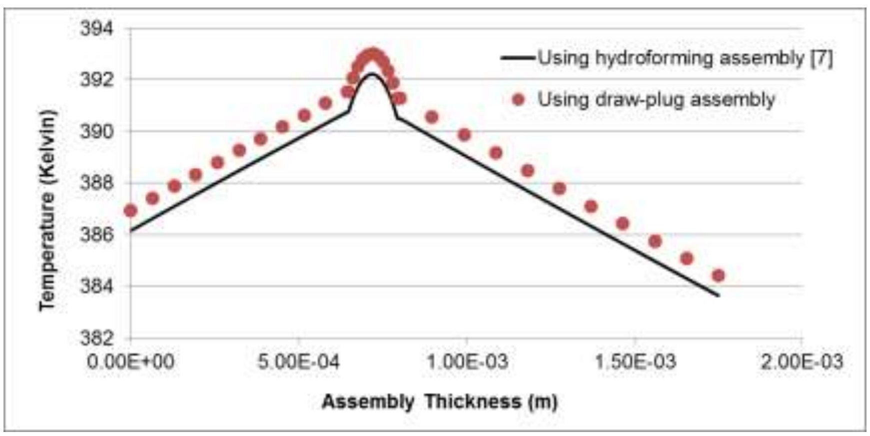

Figure 9. Temperature distribution across the annular target thickness at half its length.

4. Conclusions

An approach to integrate the assembly and the irradiation modeling for the thermal-mechanical safety analysis of a LEU foil annular target has been presented in this paper. Two assembly procedures – hydroforming and the draw- plug approach, have been considered. Both these assembly approaches were used to analyze the thermal-mechanical behavior of a LEU foil based annular target using the commercial finite element code Abaqus FEA [8]. A three-step analysis, consisting of an assembly step, a pressure relaxation step and an irradiation step was used in the numerical model. For the hydroforming model, an internal pressure of 36.4 MPa [7] was used. For the draw-plug model, a 26.619 mm plug (1.048 inch) was used and a longitudinal velocity of 0.16 m/s was applied to the base of the plug. In both the models, the thermal boundaries and loading conditions were the same in the final analysis step. The applied LEU heat generation rate of 1.6 x 10^{10} W/m^3 corresponds to a heat flux of 100 W/cm^2 incident on the outer surface of the inner tube and the inner surface of the outer tube. The model did not consider the nickel foil, the fission gas pressure and the thermal contact resistance.

The results from the hydroforming based approach [7] have been presented relative to the thermal-mechanical results from the draw-plug based approach. The analysis results indicate that the draw-plug based approach slightly over predicts the strains, stresses and temperatures. The residual stresses from the assembly process were found to alleviate some of the post irradiation stresses. From a safety standpoint, the stress margins and the cladding temperatures were found to be within the yield strength and the melting point of the Al 6061-T6 respectively. Therefore, it is unlikely that the target design considered in this analysis would fail under the assumed operating conditions and safety criterion.

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6. References

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