Analysis of the NorthStar Inconel 718 Window

Experimental Operations and Facilities Division

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1 Introduction

NorthStar Medical Radioisotopes, LLC, is planning to produce the important medical radioisotope molybdenum-99 (Mo-99) through photonuclear reactions in molybdenum-100 (Mo-100). In this approach, a target comprising multiple thin disks of enriched molybdenum metal will be bombarded with a 40-MeV electron beam. Because enriched Mo-100 is expensive, there is a desire to utilize as much beam power as possible to achieve maximum production yield and minimize the size of the target. This requirement leads to very high beam power density (heat deposition in the target), which sets challenging requirements for cooling of the target. In the latest concept developed by NorthStar, a stack of target (sintered molybdenum) disks is irradiated from two sides by a 40-MeV electron beam, with a total power of 240 kW (120 kW from each side). As shown in Figure 1, the target disks are cooled by pressurized helium gas flowing through channels between the disks. A housing encloses the target disks and helium coolant. Thinned regions on opposite sides of the housing act as windows, forming the pressure boundary between the helium within the housing and the evacuated beam tube. A pulsed (50-Hz) 40-MeV electron beam is used, with 120 kW total power and a 10% duty cycle. The pulsing beam creates a corresponding cyclic thermal load within the window material.

Figure 1 The target housing, helium coolant flow, and direction of the electron beams

To examine the effects of the cyclic thermal load on the window, a combination of analyses was performed, including computational fluid dynamics (CFD) and finite element analysis (FEA). The analyses presented in this report were primarily performed using the finite element method. However, because of the curved surface of the window, CFD analysis was used to calculate the convective cooling boundary included in the FEA model. Transient thermal and structural models were used to explore the window geometry, including thickness, radius of curvature, and diameter, while staying within the temperature and stress limits of the material as well as maintaining mechanical stability (i.e., avoiding buckling).

Additionally, variations in the size and location of the electron beam were evaluated. Multiple parameters for the window and the electron beam were examined throughout the analysis. Upper and

lower bounds were established for the window geometry parameters, and limitations were established for the size and position of the electron beam.

2 Inputs

2.1 Geometry of the window

The housing has overall dimensions of 40 mm × 105 mm × 60 mm (see Figure 2), and the individual molybdenum disks are 29 mm in diameter and 0.5 mm thick, with a 0.25-mm gap between disks for coolant flow. The initial size of the analyzed window was 30 mm diameter, with a 0.3-mm thickness and a spherical radius of curvature of 50 mm.

Figure 2 The analyzed geometry, half-symmetric in the beam axis Z. A section view on the right shows flow channel detail

2.2 Material properties

For the CFD model, helium was modeled as an ideal gas with the properties summarized in Table 1.

Table 1 Properties of Helium in CFD Model

Property	Value
Molar Mass [kg/kmol]	4.00
Specific Enthalpy at STP [kJ/kg]	1558
Specific Entropy at STP [kJ/kg-K]	36.33
Specific Heat [kJ/kg-K]	5.24
Thermal Conductivity [W/m-K]	0.153
Dynamic Viscosity [Pa-s]	18.6×10^{-6}

The plots in Figure 3 represent the thermal and mechanical properties of Inconel 718 [3], which were used in all analyses presented in this report.

Figure 3 Thermal and mechanical properties of Inconel 718

2.3 Thermal load

Volumetric heat generation in the CFD and FEA models was based on a separate Monte Carlo calculation performed to determine the distribution of heat deposited in a 3-mm-thick disk of Inconel 718. Simulations were performed using Particle and Heavy Ion Transport-code System (PHITS 2.88). The beam has a Gaussian profile with a full width half max (FWHM) of 12 mm (see Figure 4).

There is significant variance in the values for heat deposition through the thickness of the material. Because the Monte Carlo calculation assumed a flat disk, the coordinates of the heat deposition data were transformed to match the spherical shape of the window.

Figure 4 Monte Carlo calculation of heat deposition for 40-MeV electron beam in Inconel 718

3 CFD Analyses

A CFD model was created to model convective cooling for the window's spherical curvature. The window and targets are cooled with pressurized helium with an operating pressure of 2068 kPa (300 psi), a flow rate of 300 g/s, and an inlet temperature of 15°C. It was assumed that the helium flow into the housing is steady and fully developed. The coolant channels for the target disks (see Figure 5) were included in the model. First, the coolant gap between the window and the first target disk was adjusted until helium velocity was maximized without disrupting the flow pattern. Then, a transient analysis was run with volumetric heat generation for the duration of a single beam pulse.

Figure 5 Section view from the top of the window and coolant channels

3.1 Establishing initial conditions through steady-state analysis

To establish a stable flow pattern along the surface of the window, the size of the gap between the window and the first target disk was adjusted to increase coolant flow velocity while maintaining a stable flow pattern without separation or points of stagnation. Figure 6 shows window-to-target gap distances of (a) 0.25 mm, (b) 0.50 mm, and (c) 0.75 mm, respectively. At 0.25 mm, the gap is too small, leading to separation of flow and localized stagnation. At 0.50 mm, the flow separation has stopped. At 0.75 mm and beyond, the coolant velocity at the center of the window becomes too low to provide adequate cooling.

Figure 6 Streamline plots for window surface with gap distances of (a) 0.25 mm, (b) 0.50 mm, and (c) 0.75 mm

Nominal element size for the helium channel next to the window was 0.1 mm, with a minimum of five elements through the thickness of the channel. This gave an element size of 0.05 mm for the gap distance of 0.25 mm.

3.2 Calculating non-uniform convective coefficient through transient analysis

Having established a suitable coolant gap size, the steady-state solution from that model was then used as initial conditions for the next model for calculation of the convective boundary. The thermal load (previously shown in Figure 4) was applied and a transient analysis was run for the duration of a single beam pulse, 2 milliseconds. The resulting distribution of the convective boundary is shown in Figure 7.

Figure 7 Non-uniform convective boundary from CFD model

4 Finite Element Analyses

To reduce overall computation time, the remaining thermal analyses were completed in a transient finite element model, importing the convective boundary from the results of the previous CFD model. Multiple transient thermal/mechanical analyses were then performed, varying the thickness of the window to establish an upper limit on thickness based on temperature and a lower limit on thickness based on stress.

Temperature and stress limits were based on a temperature-dependent allowable stress curve, calculated using the method outlined in Section II of the ASME Boiler & Pressure Vessel Code (ASME BPVC) [2].

Additional analysis work included a pressure-only load case and use of an analytical solution to evaluate buckling. Stress analysis results were used to evaluate the fatigue life of the window.

4.1 Establishing failure criteria

Three limits were established as failure modes: a temperature-dependent allowable stress, a maximum temperature of the window, and a minimum number of cycles consistent with one year of operation. Although Inconel 718 is not included in the stress tables of Section II of the ASME BPVC, Section II of the code does provide a method for calculating allowable stress for unlisted materials. The allowable stress was calculated using the property data presented in Section 2.2, and the resulting curve is shown in Figure 8. The maximum temperature for the window, 550°C, was determined from the point where the allowable-stress curve has a sharp downward bend.

Figure 8 Calculated allowable stress for Inconel 718

4.2 Transient thermal analysis

Applying the heat deposition data, as was used in the CFD model, and the convective boundary from the CFD results, three transient thermal FEA runs were completed for window thickness values of 0.2, 0.3, and 0.4 mm, respectively. The transient thermal response is summarized in Figure 9. The range of time corresponds to 30 pulses of the beam. Figures 10 through 12 show temperature contours at the end of the 30th pulse and just before the 31st pulse (the high and low points in the cyclical steady solution).

Figure 10 shows the temperature contours for a window thickness of 0.3 mm. Table 2 summarizes the results for the three thickness cases. A thickness of 0.4 mm results in a peak temperature that exceeds the set limit of 550°C. A window with thickness less than or equal to 0.3 mm stays below the temperature limit, but, as will be shown later, a thickness of 0.2 mm is insufficient in terms of mechanical strength, based on allowable stress.

Figure 9 Pulsed-beam temperature response for three window thicknesses

Figure 10 Temperature contours at high and low points in the thermal cycle for 0.3-mm thickness

Table 2 Peak Temperatures for Three Values of Window Thickness

Window Thickness [mm]	High Point [°C]	Low Point [°C]
0.4	684	605
0.3	521	438
0.2	366	276

4.3 Steady-state structural analysis

The stress contour plots for a window thickness of 0.3 mm are shown in Figure 11. The maximum stress occurs on the helium side along the circular edges of the window. As window thickness decreases, the effects of thermal loading on stress at the center of the window decrease, but the stress due to internal pressure begins to increase at the edges of the window. Table 3 summarizes the maximum stress values for all three window thicknesses.

Figure 11 Variation in von Mises stress due to cyclic thermal loading for 0.3-mm-thick window

Table 3 Maximum Stress for Three Values of Window Thickness

Window Thickness [mm]	High Point [ksi]	Low Point [ksi]
0.4	92.9	86.5
0.3	77.5	74.6
0.2	95.9	92.7

4.4 Buckling analysis

4.4.1 Finite element eigenvalue buckling analysis

The spherical shape of the window adds to its structural rigidity but also presents a potential problem of elastic instability in the form of buckling or snap-through. To evaluate this problem, a static structural model was run without thermal load and with internal pressure only. The von Mises stress contour is shown in Figure 12. The results of the static structural analysis were then passed to an Eigenvalue buckling analysis as a pre-stress load.

Figure 12 Von Mises stress for internal pressure load only

The first-mode shape from the buckling analysis is shown in Figure 13. This solution corresponds to an internal pressure of 1410 psi, a factor of 4.7 above the nominal operating pressure. However, this solution was not considered sufficiently conservative, as it assumes ideal geometry.

Figure 13 First-mode shape from Eigenvalue buckling analysis

4.4.2 Correlation for critical buckling pressure

A more conservative calculation was identified in an algebraic expression built upon theoretical and experimental data [4]. Using this correlation for shallow spherical caps (Eq. 1), solutions were plotted in Figure 14 to compare the variations in thickness, T , and radius of curvature, R . As is illustrated, the critical buckling pressure is more sensitive to thickness than radius. However, as was shown previously in the finite element thermal model, increasing the thickness is not practical. Decreasing the radius of curvature, though, would be a viable method of increasing the window's resistance to pressure.

The algebraic expression for critical buckling is defined as

$$P_{CR} = 0.075 E n_o^{-4} \lambda_o^{4.15} e^{-0.095 \lambda_o} \quad (1)$$

where geometric parameters n_o and λ_o (all others being illustrated in Figure 15) are defined as

$$n_o = \frac{a_o}{T} \quad (2)$$

$$\lambda_o = \frac{1.82 a_o}{T \sqrt{R/T}} \quad (3)$$

Figure 14 Critical buckling pressure (PCR) as a function of shell thickness for multiple spherical radii

Figure 15 Geometric parameters for spherical cap equations

4.5 Fatigue life evaluation

To estimate the fatigue life of the window, results were considered from the nominal case with a 0.3-mm thickness and radius of curvature of 45 mm; the mean stress is 76 ksi with a stress amplitude of 2.9 ksi, as can be determined from the high and low stresses shown in Figure 11. The maximum temperature in this region is 400°C.

Those data were then compared to the fatigue curve from the ASME BPVC for nickel-chromium-iron alloys (Figure 16) for temperatures not exceeding 800°F (427°C). This curve is adjusted for the effects of high mean stress. The red line represents the analysis result for alternating stress, which would indicate an infinite life.

Figure 16 Fatigue curve from ASME BPVC

Near the center of the window, cyclic loading occurs at a slightly lower stress (maximum stress of 68 ksi and a stress ratio of greater than 0.9), but at a higher temperature of 521°C. The additional fatigue curve data [3] shown in Figure 17 are for unnotched and notched specimens at up to 1000°F (538°C). The red

lines represent the analysis results. Both plots include fatigue data up to $\sim 3 \times 10^7$ cycles, and the range of the plots is up to 1×10^8 cycles (555 hours of operation). Five thousand hours of continuous cycling at 50 Hz is 9×10^8 cycles.

Figure 6.3.5.1.8(c). Best-fit S/N curves for unnotched Inconel 718 sheet at 1000 F, long transverse direction.

Figure 6.3.5.1.8(d). Best-fit S/N curves for notched, $K_t = 3.0$, Inconel 718 sheet at 1000 F, long transverse direction.

Figure 17 Fatigue curves for Inconel 718 sheet from MIL-HDBK-5J [3]

4.6 Gigacycle fatigue discussion

Materials typically thought of as having an endurance limit, such as steels, have a body-centered cubic crystal structure. Also, strain aging appears to be common for ferrous metals but uncommon for nonferrous metals.

However, regardless of crystal structure, as the number of load cycles progresses from 10^6 to 10^9 , the failure mode for cyclic loading changes from initiation of cracks at the surface to initiation of cracks from below the surface, originating from inclusions or pores within the material [5]. The drop in fatigue stress limits from 10^6 to 10^9 cycles is large for nickel-based alloys.

The effects of radiation damage on the fatigue life of Inconel are not known. However, Gaganidze et al. [6] made this summary observation regarding radiation damage of martensitic steels: The increase of the elastic part of the cyclic deformation and related reduction of the inelastic strain in the irradiated state compared to the reference unirradiated state for common total strain amplitudes can yield an increase in fatigue lifetime. In contrast, radiation hardening induced enhancement of the stress state might lead to enhanced damage evolution and hence to lifetime reduction especially at high strain ranges.

5 Variation in electron beam parameters

5.1 Beam size

Three beam widths were examined in total. Analysis results previously shown in this report were based on a beam size of 1.2 cm FWHM. Two additional cases were run, assuming more focused beams of 1.0 cm FWHM and 1.1 cm FWHM. The Gaussian distribution of heat deposition is shown in Figure 18.

Figure 18 Gaussian beam profiles analyzed

The previous transient thermal finite element model was run with the adjusted beam profiles. The analyses were interrupted after the temperature exceeded the limit of 550°C. The peak window temperature results are shown in Figure 19.

Figure 19 Peak window temperature over time for varying beam size

5.2 Beam position

Heat deposition from a 12-mm FWHM beam was placed off-center of the window. The amount of offset ranged from 1.0 to 2.5 mm. The peak window temperatures are shown in Figure 20. An offset of 1.5 mm exceeds the temperature limit of 550°C.

Figure 20 Change in maximum window temperature from beam hitting window off center

6 Summary

The analysis work presented in this report demonstrated the significance of window geometry and beam parameters. Keeping within the established failure criteria, based on material properties of Inconel 718, resulted in tight limits on window thickness and beam size. The initial CFD work established limits on the gap size between the window and the first target disk as related to cooling the window with pressurized helium gas, the gap parameter being sensitive to changes on the order of $<100\text{ }\mu\text{m}$. The thickness of the window was examined using FEA, and limits for thickness changes with respect to maximum window temperature and stress were found to also be on the order of $<100\text{ }\mu\text{m}$. An algebraic expression was identified and showed that radius of curvature could be modified to increase resistance to snap-through without increasing thickness.

Cyclic variation in window stress from the pulsing beam was low, and this observation would normally indicate an adequate lifetime for a component. However, owing to the unusually high number of cycles involved (on the order of 10^9 for practical usage), prediction of failure of the window due to fatigue from thermal cycling requires further study.

Finally, variation in the electron beam size and position was analyzed. A minimum beam size was determined as 12 mm FWHM. A more focused beam would exceed the temperature limit of 550°C . Drifting of the beam position away from the window center began to cause thermal problems at 1.5 mm from the window center.

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