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Mock Target Window OTR and IR Design and Testing

FY17 NNSA Mo-99 Program
FY17 Northstar Activity 2 Report

Alexander Wass

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Introduction

In order to fully verify temperature measurements made on the target window using infrared (IR) optical non-contact methods, actual comparative measurements are made with a real beam distribution as the heat source using Argonne National Laboratory's (ANL) 35 MeV electron accelerator. Using Monte Carlo N-Particle (MCNP) simulations and thermal Finite Element Analysis (FEA), a cooled mock target window with thermocouple implants is designed to be used in such a test to achieve window temperatures up to 700°C. An uncoated and black-coated mock window is designed to enhance the IR temperature measurements and verify optical transmitted radiation (OTR) imagery. This allows us to fully verify and characterize our temperature accuracy with our current IR camera method and any future method we may wish to explore using actual production conditions. This test also provides us with valuable conclusions/concerns regarding the calibration method we developed using our IR test stand at TA-53 in MPF-14.

Geometry

The cooled mock target window design consists of a modified Inconel 718 window test piece or "coupon" that imitates the 12 mm window design and is fixed to the center of a water-cooled, 6" ConFlat (CF) aluminum 2219 vacuum flange. The CF flange contains a single 0.25 inch through-hole along the diameter of the flange (centered) to allow water to remove heat from the flange and coupon. Figure 1 shows a 3-D CAD model of the design using Solidworks. The coupon is attached to the flange via four SS 6-32 x 7/16" L socket head screws and lock washers. The coupon contains three 0.020" thermocouple holes to measure temperature 0.049 mm below the surface of the window center, and 0.067 mm below the opposite edges of the window. Three aluminum tabs are also screwed into the flange to clamp down the thermocouple wires during the experiment. Since the flange material is aluminum and not stainless steel, there are concerns of exceeding the melting temperature of aluminum (~600°C) at the coupon-flange interface. Therefore, a 0.020" wide, 0.030" deep horizontal slot is machined at the center of the flange surface at the coupon-flange interface in order to insert a thermocouple for temperature measurements. Lastly, two ¼" MNPT x ½" brass Swagelok tube

fittings are screwed into the water channel inlet and outlet. The overall dimension of the Inconel coupon is 1.6" x 0.944" x 0.175". The flange thickness is 0.83 inch.

Figure 1 – Final mock target window (flange and coupon) CAD model

Simulation

MCNP

MCNP simulations were performed by Michael Mocko at LANL on a basic design to determine the steady state heat generation within the Inconel coupon and aluminum flange when exposed to a 35 MeV and 4 mm FWHM electron beam achievable at ANL. A 2-D cross sectional view of the geometry can be seen in Fig. 2. The coupon was modelled as Inconel 718 and the flange was modeled as aluminum 6061. Results for power as a function of beam current and mass were provided for twelve cylindrical slices or segments of incremental radius through the center of the assembly. The power in the remaining material was provided as an additional segment. The flange was split into two equal segments axially due to its thickness (0.83"). The thermal power for each segment was then determined using Eq. 1,

$$Power = (Charge)(Repetition Rate)(35 MeV) \left(\frac{Power}{Current} \right) \quad (1)$$

where charge is determined from past beam operational data and is $\sim 3.25 \mu C$, and $\left(\frac{Power}{Current} \right)$ is provided in the MCNP results in $W/\mu A$. The total beam power is shown in Fig. 3. The total deposited power in the assembly is determined by adding all of the segmented powers together. The total deposited power in the mock window assembly is shown in Fig. 4 with increasing beam repetition rates. Both plots show a linear relationship with power and repetition rate, as expected. The deposited power translates into thermal energy within the coupon and flange assembly. These results show that 34% of the total beam power is

deposited into the flange and coupon. Also, 25% of the total deposited beam power is deposited in the coupon.

Figure 2 – Cross sectional view of the assembly geometry used in MCNP simulations (mm)

Figure 3 – Total beam power at increasing repetition rates

Figure 4 – Total beam deposited power within the mock target assembly

FEA

Steady state and transient thermal FEA simulations were performed using Solidworks 2016 (Simulation) with the MCNP simulation results included in the model. The same basic design from the MCNP simulation was used in order to maintain mesh quality by avoiding complex features. The goal for these FEA simulations was to determine the steady state mock window temperature at increasing beam powers (repetition rate) and to verify that the mock window does not reach above 700°C at a reasonable repetition rate. A reasonable repetition rate for this project is 30 Hz since it does not require as much energy to operate the electron accelerator, and is high enough so that the thermal pulse is much shorter than the thermal decay time constant of the assembly.

The mesh consisted of 739,089 nodes and 527,294 tetrahedral elements and can be seen in Fig. 5. The mesh size was reduced from 1.96 mm incrementally to 0.633 mm towards the center of the assembly in order to capture the large temperature gradients induced by beam heating. The materials consisted of Inconel 718 and aluminum 2219. The material properties of aluminum were set to the default constant values from the Solidworks library, whereas the Inconel 718 was custom added from data from Special Metals¹. Table 1 shows the material properties used in the FEA simulations. The thermal conductivity and thermal expansion coefficient of Inconel 718 were added as temperature dependent properties from 21°C and 93-760°C, respectively. An interesting thing to note is that the thermal conductivity of Inconel 718 almost doubles in this temperature range. Aluminum's thermal conductivity is about 7-15 times that of the Inconel alloy. This allows much more heat to be conducted away from the coupon.

¹ Inconel alloy 718, Special Metals Corporation, 2007, Retrieved from http://www.specialmetals.com/assets/smc/documents/inconel_alloy_718.pdf

Figure 5 - Mesh of simplified Al flange and Inconel coupon

Table 1: Material Properties Used in FEA Simulations

Material	Al 2219	Inconel 718
Thermal Conductivity [W/m-K]	170	11.4 to 23.2
Specific Heat [J/kg-K]	864	435
Thermal Expansion Coefficient [1/°C]	2.23E-05	1.32E-05 to 1.60E-05
Density [kg/m ³]	2840	8193

The boundary conditions were defined to match the experiment conditions as closely as possible. Although, the heat generation within the assembly was based on MCNP simulation, and not experiment results. Naturally, there was some error in this study. Also, conduction between the outer surface of the flange and the accelerator beam tube was not modeled. Therefore, we can expect slightly lower heat transfer and higher temperatures in the simulation, than the actual experiment. The inner surfaces of the assembly are exposed to vacuum, so no convective heat transfer conditions were added (there should be thermal radiation, but was not included in this study). The outer flange surfaces are exposed to atmosphere conditions (25°C), so a natural convection boundary condition of 5 W/m²-K was applied.

The convection heat transfer coefficient (HTC) of the cooling water was determined using several fundamental fluid equations. First, the Reynolds number is used in convection

fluid flow problems to characterize fluid flow as laminar, turbulent, or in a transition state. The Reynolds number for fluid flow in a circular tube is calculated by Eq. 2,

$$Re_D = \frac{\rho DV}{\mu} \quad (2)$$

where D is the inner pipe diameter, V is the mean fluid velocity, and μ is the dynamic viscosity of the fluid. The water density and viscosity were determined at a temperature of 25°C. The convective HTC is determined using Eq. 3,

$$h = \frac{Nu_D k}{D} \quad (3)$$

where k is the thermal conductivity of the fluid and Nu_D is the Nusselt number. The Nusselt number can be expressed using the Gnielinski correlation² which is valid for smooth tubes over a large range of Reynolds numbers and is shown in Eq. 4,

$$Nu_D = \frac{(f/8)(Re_D - 1000)Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)} \quad (4)$$

where Pr is the fluid Prandtl number and f is friction factor. The friction factor for smooth tubes is determined by Eq. 5.

$$f = (0.79 \ln(Re) - 1.64)^{-2} \quad (5)$$

The water supply volumetric flow rate at ANL was determined using a mock cooling channel with similar dimensions to the flange cooling channel and was found to be 4.5 GPM. At this flow rate, the water HTC was determined to be ~37,000 W/m²-K. However, the HTC used in the FEA simulations was set to 40,000 W/m²-K (~5 GPM) because many of the simulations were performed before testing the water flow rate at ANL. Lastly, a thermal contact resistance was applied to the coupon-flange interface since no solid-solid interfaces allow perfect conduction. Although the coupon is composed of Inconel, only a stainless steel-aluminum contact resistance was found in literature. Thermal contact resistance for a stainless steel-aluminum interface was provided by Mills³ and is 3000-4500 W/m²-K. For this study, the average value of the contact resistance was applied and is 3750 W/m²-K (2.667e-4 m²-K/W).

² Incropera and DeWitt, Fundamentals of Heat and Mass Transfer, 7th Ed., Wiley, 2012, p. 545.

³ A. F. Mills, Heat Transfer, 2nd Ed., Prentice Hall, 1999, p.73

FEA Results

Thermal FEA simulations were performed at four increasing repetition rates (5, 15, 20, and 30 Hz) or beam powers. Since the beam power of the electron accelerator at ANL is adjusted via repetition rate, the following results are functions of repetition rate. Figure 6 shows a cross sectional view of steady state temperature at 30 Hz. The Inconel coupon experiences the highest temperatures in the assembly, with a sharp decrease in temperature through the interface. One can see that the window temperature far exceeds the 700°C constraint. The black dots in this figure show the locations of the thermocouples for the experiment. The naming convention is also shown where “Window Side” and “Window Center” describe the thermocouples just underneath the window edges and center, respectively.

Figure 6 – Cross sectional view of thermal FEA results at a repetition rate of 30 Hz. Black dots show locations of thermocouples beneath the window

The remaining steady state results for several thermocouple locations are shown in Fig. 7. Temperature increases linearly with repetition rate and beam power. The temperature at the window surface is about 10.7-27.4°C greater than at the center window thermocouple location due to conduction within the Inconel coupon. According to the thermal FEA results, the repetition rate should be between 15-20 Hz to achieve a window temperature of 700°C. Next, a transient simulation was performed with the steady state 30 Hz simulation set as the

initial condition. This simulates the time at which the beam is shut off. The assembly is no longer producing any thermal energy, and the temperature is decaying. Figure 8 shows the temperature decay at the window center thermocouple location. The temperature drops rather quickly and has an estimated thermal decay time constant of 4.44 s. The temperature reaches 99.3% of its steady state value after just 22.2 s.

Figure 7 – Steady state thermal FEA results

Figure 8 – Transient temperature decay from steady state beam off at 30 Hz

Experiment

Setup

Two experiments were performed at ANL using their 35 MeV electron accelerator. The first experiment consisted of an Inconel coupon without any additional surface treatments other than the stock machined surface. The second experiment consisted of a coupon with high temperature black paint applied to the window surface. Prior to the experiment, VHT (Very High Temperature) Flameproof Header Paint was sprayed onto the coupon surface in two coats and then heat treated according to the manufacturer's instructions. Both experiments were conducted in the same manner. The coupon and flange assembly was bolted to the end of the beam tube, and the cooling water flow rate was recorded using a visual flow meter. The beam was aligned to the center of the window, and the assembly was allowed to reach thermal equilibrium for each beam power and then allowed to cool. This occurred 8-9 times for each experiment.

Four 0.020" Type K thermocouples were used to measure temperature in the coupon and at the flange interface. The temperature at the back of the flange was also measured using a larger thermocouple. Figure 9 shows the flange assembly with the black-coated coupon before being bolted to the end of the beam tube. Figure 10 shows the installed flange with the cooling water hose attached. In this image, the cooling water flows from left to right.

A FLIR A655sc infrared (IR) thermal imaging camera with an 89 mm lens, located 2.5 m from the mock target window, was used to record the window surface temperature. An optical camera with similar distance was used for OTR purposes. Specifically, the OTR is used to aim and focus the electron beam on a reflective surface. Therefore, it is interesting to see if the non-reflective black coupon will produce an image of the beam profile.

Figure 9 – Black-coated coupon and flange assembly prior to installation

Figure 10 – Installed flange assembly at the end of the beam tube with water hoses

Results

The cooling water flow rate was measured before each experiment. The first experiment with the uncoated coupon had a flow rate of 4.5 GPM, which corresponds to a HTC of $\sim 37,000 \text{ W/m}^2\text{-K}$. The second experiment with the black coupon had a flow rate of 4.1 GPM ($\sim 34,000 \text{ W/m}^2\text{-K}$). The electron beam energy for the uncoated and black coupon was 35.2 and 34.9 MeV, respectively. The beam size was 4.5 x 5.5 mm and 5.0 x 5.0 mm, respectively. The electron beam power was recorded for both experiments and plotted in Fig. 11. Beam power is linearly proportional to the repetition rate, and there was little difference in the results for each experiment.

The steady state thermocouple results for both experiments can be seen in Fig. 12. As expected, the temperature in all locations increased linearly with repetition rate. At 30 Hz, the Inconel mock window center reached 690°C and 715°C for the uncoated and black coupons, respectively. Also, the flange-coupon interface reached 303°C and 328°C for the uncoated and black coupons, respectively. These temperatures are well below the melting point of aluminum, so there were no concerns of melting during the experiment. One should note that the black-coated coupon achieved higher temperatures than the uncoated coupon at all thermocouple locations above a repetition rate of 15 Hz. At 30 Hz, the uncoated coupon left and right side window temperatures were 75°C and 71°C less than the black-coated coupon, respectively.

Figure 11 - Average measured beam power for uncoated and black-coated coupon tests

Figure 12 - Steady state thermocouple results for the uncoated and black-coated coupons

The temperature results from the thermocouples were recorded for the entire duration of the second experiment with the black-coated coupon. Unfortunately, the transient temperature results for the first experiment were not recorded, only the steady state results. Figures 13-20 show the transient temperature results for each repetition rate. As expected, the temperatures at the center of the assembly (center of beam) fluctuate more than at low repetition rates. The amount of fluctuation decreases as the repetition rate increases. Once the highest repetition rate was achieved (30 Hz), the rate was ramped down to 8 Hz to verify

that similar temperatures were achieved in the mock window target as before. Figure 21 shows the transient temperature results at this power level. The steady state window temperature at the center was about 40°C greater than the first recording shown in Fig. 15. It is hypothesized that the black surface finish experienced some degradation from the high energy electron interactions, causing a fluctuation in temperature.

Once the beam was shut off when thermal equilibrium was achieved in the target, the temperature of the target and flange decayed. The rate of temperature decay can be expressed using the thermal decay constant. Assuming a lumped thermal capacitance model, the thermal decay constant is determined from the transient thermal equation⁴ shown in Eq. 6,

$$\frac{T - T_{\infty}}{T_i - T_{\infty}} = e^{-t/\tau} \quad (6)$$

where T is the solid's current temperature, T_i is the initial temperature, T_{∞} is the steady state temperature, and τ is the thermal time constant. The thermal decay time constant at repetition rates of 2, 8, and 30 Hz were 32.5, 35.5, and 38.7 seconds, respectively.

Figure 13 - Thermocouple results for black-coated coupon at 2 Hz (218.6 W)

⁴ Incropera and DeWitt, Fundamentals of Heat and Mass Transfer, 7th Ed., Wiley, 2012, p. 282.

Figure 14 - Thermocouple results for black-coated coupon at 5 Hz (547 W)

Figure 15 - Thermocouple results for black-coated coupon at 8 Hz (886.9 W)

Figure 16 - Thermocouple results for black-coated coupon at 12 Hz (1312.8 W)

Figure 17 - Thermocouple results for black-coated coupon at 15 Hz (1646.7 W)

Figure 18 - Thermocouple results for black-coated coupon at 20 Hz (2204.3 W)

Figure 19 - Thermocouple results for black-coated coupon at 25 Hz (2733.4 W)

Figure 20 - Thermocouple results for black-coated coupon at 30 Hz (3297.1 W)

Figure 21 - Thermocouple results for black-coated coupon at 8 Hz (869.5 W)

IR Thermography

The mock window surface temperatures were recorded using an infrared camera. The resulting temperature of the target is hugely dependent on the target's surface emissivity, as well as the transmission through objects such as viewing windows. Without knowing these values, the IR camera is useless in obtaining accurate temperature results. Therefore, previous experiments were conducted at LANL that were intended to determine these IR thermography parameters as close to the actual experimental setup at ANL as possible. They determined a surface emissivity of 0.52 for the uncoated Inconel mock window center, and a transmission of the entire camera path (reflected off two mirrors and passing through a zinc selenide window), of 0.372. The emissivity of the black-coated mock window was never experimentally

determined, so a value of 0.9 was assumed. These parameters were input into the FLIR ExaminIR camera software for this experiment in an attempt to achieve accurate temperatures.

The camera calibration settings were also adjusted to the appropriate lens size and temperature range. For example, the calibration setting used for the uncoated mock window from 2 to 12 Hz was "FOL89, NOF, 100-650°C". From 15 to 30 Hz, the calibration setting was "FOL89, NOF, 300-2000°C" to account for higher surface temperatures. The calibration setting used for the black-coated mock window from 2 to 5 Hz was "FOL89, NOF, 100-650°C". From 8 to 30 Hz, the calibration setting was "FOL89, NOF, 300-2000°C".

Figure 22 shows the IR steady state temperature results compared to the actual temperatures for the uncoated and black-coated mock window surfaces at increasing repetition rates. The uncoated mock window IR temperatures were 87-186°C less than the thermocouple results and the black-coated mock window IR temperatures were 82-740°C greater than the thermocouple results. At 30 Hz, the uncoated mock window IR temperature was 535°C and the black-coated window was 1455°C, thus, the surface condition plays a large role in the IR temperature results. After 30 Hz, the repetition rate was decreased back to 8 Hz for the black-coated mock window to see if there was any variation in the IR results after being heated. The IR results only changed by 2.1°C, thus, the black coating was still intact. Figure 23 shows the IR temperature contours for the uncoated and black-coated mock windows (shown rotated). The uncoated coupon shows much higher temperatures just above the mock window cutout. This is most likely due to differences in surface finish from the machined window cut, versus the smooth flat surface. Whereas, the black-coated coupon IR temperature results are more uniform since the surface finish is the same throughout.

Figure 22 - Center window surface IR temperatures for the uncoated and black-coated targets using previously determined IR software settings

Figure 23 – IR temperature results of uncoated (left) and black-coated (right) mock window targets at 30 Hz using previous IR parameters

Since the IR temperature results were too inaccurate for our requirements, the emissivity and/or transmission were adjusted until the IR results matched the thermocouple temperature measurements. For the uncoated mock window, the emissivity was changed from 0.52 to 0.223 for the first calibration setting from 2 to 12 Hz. The emissivity was increased to 0.422 for the second calibration setting from 15 to 30 Hz. The transmission was not changed (0.372). For the black-coated mock window, the emissivity was changed to 0.659 for the first calibration setting from 2 to 5 Hz. The emissivity was increased back to 0.9 for the second calibration setting from 8 to 30 Hz. The transmission was increased to 0.96 for both calibration settings. Figure 24 shows the new IR results compared to the thermocouple results for both windows. The uncoated mock window IR temperatures are now within 24°C of the thermocouple results and the black-coated mock window IR temperatures are now within 0.5-40°C of the thermocouple results. More importantly, the new IR temperatures are within 0.1 and 0.5°C for the uncoated and black-coated coupon temperatures at 30 Hz corresponding to window temperatures of 690 and 715°C, respectively. This change in temperature can be seen in Fig. 25. The largest temperature changes occur between calibration settings at 15 and 8 Hz for the uncoated and black-coated windows, respectively.

Figure 24 – Center window surface IR temperatures for the uncoated and black-coated targets using updated IR software settings

Figure 25 – Temperature change between updated IR results and center window thermocouple results ($T_{IR} - T_{thermocouple}$)

OTR Imaging

Optical transmitted radiation images were recorded throughout the experiment for beam position and shaping purposes. A Basler acA640-120gm camera with a Nikon ED AF Nikkor 180 mm lens was used to capture these images. An enhanced OTR image on the uncoated and black-coated mock windows can be seen in Fig. 26. As expected, the OTR image on the uncoated surface was much brighter than the black surface. The OTR on the black surface, although very dim in this image, was still apparent during the experiment, and beam positioning was successful. The brightness of the OTR image on the black surface increased as beam heating progressed. Since the black coating was sprayed on, we expect that some degradation of the paint occurred, causing the matte surface to become more reflective. After inspecting the black mock window surface post-experiment, it showed some mild discoloration, especially in the center of the beam shown in Fig. 27. Also, the black paint was discolored above the mock window where high temperatures were seen in the IR results. However, there was no chipping or peeling of the black paint. The uncoated mock window showed no visible discoloration or surface corrosion.

Figure 26 – OTR image centered on the uncoated (left) and black-coated (right) mock windows at 30 Hz

Figure 27 – Uncoated (left) and black-coated (right) mock windows after beam heating.

Simulation & Experiment

The thermal FEA results shown in a previous section are compared to the experimental results. The steady state mock window and flange temperatures are compared in Fig. 28. The window center temperature at the thermocouple location from the simulation was 375°C greater than the experimental result at 30 Hz. The flange-coupon interface temperature from the simulation was 141°C less than the experimental result. A large difference in the thermal decay of the coupon was also seen. Figure 29 shows the thermal decay at the mock window center from beam shut off to ambient temperature. The thermal decay time constant from the FEA thermal simulation was 8.7 times greater than from the experiment. This large difference in results is contributed by many factors. These include the Inconel-aluminum thermal contact resistance at the interface, which depends on the surface finish and amount of clamping force applied, the flow rate of the cooling water, the beam location and size, and the extra stainless steel material from the beam tube where the aluminum flange was bolted.

Figure 28 – Steady state results of simulation and experiment

Figure 29 - Thermal decay of window center from simulation and experiment

Conclusion

The designed water cooled flange successfully cooled the Inconel mock window while being exposed to a beam power of 3297 W. The mock window reached a desired max temperature of 715°C, while the aluminum flange reached 328°C at the interface. However, the IR results using the original emissivity and transmission parameters were not accurate enough for our application. The uncoated mock window IR temperatures were 87-186°C less than the thermocouple results and the black-coated mock window IR temperatures were 82-740°C greater than the thermocouple results. At 30 Hz, the actual window temperature results were 690 and 715°C for the uncoated and black-coated mock windows, respectively. These large discrepancies in IR temperature are not useful in providing accurate temperatures until the surface emissivity and transmission are determined for the specific application. Therefore, the mock window emissivity and transmission determined from the IR test stand results at TA-53 are not accurate enough for the IR thermography performed at ANL. Although, the IR camera can still be used for monitoring sudden changes in temperature caused by a catastrophic event, which requires operator intervention.

As expected, the OTR images were bright and clearly visible on the uncoated mock window surface. On the black-coated mock window, the OTR images were dim, yet visible, and allowed us to position and shape the beam successfully. The black coating did not chip or flake off of the surface, but discolored. This proves that beam alignment is still possible on a black-coated surface.

Future Studies

We propose to perform a similar experiment using the same water cooled flange design, with an additional thermocouple clamped to the back side of the flange within a machined cutout. This will provide more accurate results, instead of just taping a thermocouple to the surface. The surface finish on the mock window should be applied using different methods in order to determine a more robust finish. Also, in-beam heating of heavily oxidized windows should be performed to determine the surface effects on the temperature results using conventional and IR methods.

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