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Re-aluminization of the 6.5m primary mirror at the MMT Observatory

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Abstract

The MMT Observatory (MMTO) initiated a series of coating process improvement projects after an issue with the coating system in 2010 resulted in blemishes on the 6.5m primary mirror coating. Formally started in 2013, these projects focused on four major tasks: 1) development of a software-based system to control the tungsten filament power sources, 2) characterization of an integrally wound tungsten and aluminum filament, 3) prevent stray molten aluminum droplets from contacting the isolation membrane separating the high and rough vacuum sections of the system, and 4) assemble a coating facility capable of performing full-scale system testing. The completion of these projects was realized with the successful re-aluminization of the MMTO primary mirror in 2016. With a focus on the implementation of the process improvements, the present state of the MMTO coating system is described along with data from the 2016 re-aluminization.

Keywords: Aluminization, physical vapor deposition, mirror recoating, MMT Observatory

1. Introduction

In the summer of 2016, the MMT Observatory's (MMTO) 6.5m primary mirror was successfully recoated with aluminum using a filament based physical-vapor-deposition process. This coating was the culmination of over three years of development work to improve the consistency of the coatings and to reduce the risks associated with the process. Issues with the 2010 re-aluminization prompted three main development projects: 1) change control of the power supplies used to heat the filaments from a manually operated control knob to an automated system, 2) change the manner in which the aluminum is loaded on the tungsten filaments, and 3) prevent any stray molten aluminum droplets from contacting the isolation membrane separating the high and the rough vacuum sections of the system. Since the MMTO primary mirror is coated while in the telescope (in-situ), the only practical manner to test the coating process and related equipment is off site. Based on the testing experience using a scaled-down system, the MMTO identified significant benefits in completing full-scale tests of the coating system before attempting a primary mirror coating. Since most of the required equipment was in long-term storage, resources were allocated to assemble a facility that would allow the entire coating system to be tested; this created a forth improvement project.

1.1 **Coating system description**

Due to space constraints at the summit of Mount Hopkins, the MMTO 6.5m primary mirror is recoated while mounted in the telescope. This requires the entire coating system to be transported and assembled on site for each coating. The primary mirror cell is converted to a vacuum vessel by replacing the lightweight-operational covers with vacuum-rated covers, and a vacuum chamber, also referred to as the bell jar, is lifted into the enclosure and mounted to telescope in front of the horizon pointing primary mirror. Additionally, all of the equipment needed to provide a vacuum for both the coating process and for differentially pumping on the mirror must be assembled on site. An isolation membrane fabricated from aluminized polyester sheet is used to separate the high vacuum applied to the optical surface of the

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[2] The MMT Observatory is a joint facility of the Smithsonian Institution and the University of Arizona.

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mirror from the rough vacuum applied to the back side of the mirror. Figure 1 illustrates the general arrangement of the equipment.

The coating system was designed to provide a 1000 Å thick aluminum coating through physical vapor deposition. Two hundred filaments are mounted in the bell jar and are arranged in ten arrays of twenty filaments each. The power to heat the filaments is supplied by ten commercial DC welders, Miller[3] Deltaweld 652, and each welder powers an array of filaments. For the previous primary mirror coatings, the electrical power to the filaments was adjusted through a control knob; this method of manual control contributed to a large amount of process variability.

Much of the design intent and early results of the MMTO coating system are described in the paper "In situ aluminization of the MMT 6.5m primary mirror" [1]. The 2010 coating illustrated some weaknesses in the system, and the coating process followed in 2016 was modified to address these issues.

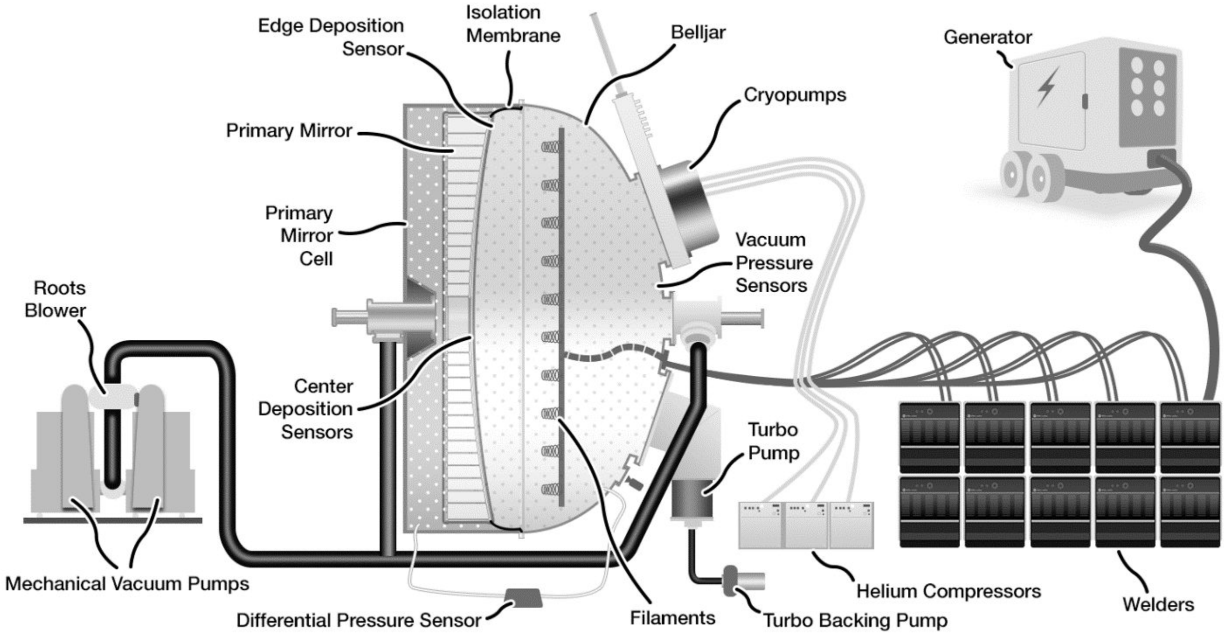

Figure 1 – MMTO coating system layout. The primary mirror and mirror cell remain in the telescope, and the coating system is assembled in place. The generator, the roots blower, and the mechanical pumps are located outside the telescope enclosure while the bell jar, the welders, and the high vacuum pumps (two cryopumps, the turbo pump, and the turbo backing pump) are located in the telescope enclosure. The isolation membrane around the perimeter of the mirror and a plug located in the cassegrain hole of the mirror separate the rough vacuum applied to the back side of the mirror from the high vacuum applied to the front surface of the mirror. When large pressure differences between the front and back sides of the mirror have the potential to develop (atmosphere to 260 Pa), only the mechanical pumps are used to differentially pump on the bell jar and the mirror cell. To help maintain the same pumping speed between the front and back side of the mirror, a 20 cm (8-inch) diameter orifice was installed in the roughing line (fabricated from 12" schedule 80 PVC pipe) routed to the bell jar. The orifice alone was not enough to maintain the specified pressure differential across the primary mirror, so a controllable air leak was introduced into the bell jar.

1.2 2010 Coating issues

Although the coating deposited on the primary mirror in during 2010 summer shutdown was serviceable, this coating suffered from two visibly pronounced brown blemishes on the mirror surface as seen in figure 2. These brown regions resulted from the isolation membrane being compromised when stray molten aluminum droplets from the filaments contacted and melted through the membrane. A subsequent analysis of the data from this coating indicated the damage occurred when the filaments were warming up and before aluminum started to be deposited on the glass substrate. Since

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[3] Miller Electric Manufacturing Company, Appleton, WI, USA, www.millerwelds.com

the process of preparing the mirror for another coating would require at least six additional weeks, the decision was made to operate with the coating as is until the exact cause of the blemishes could be identified and addressed in a future telescope shutdown.

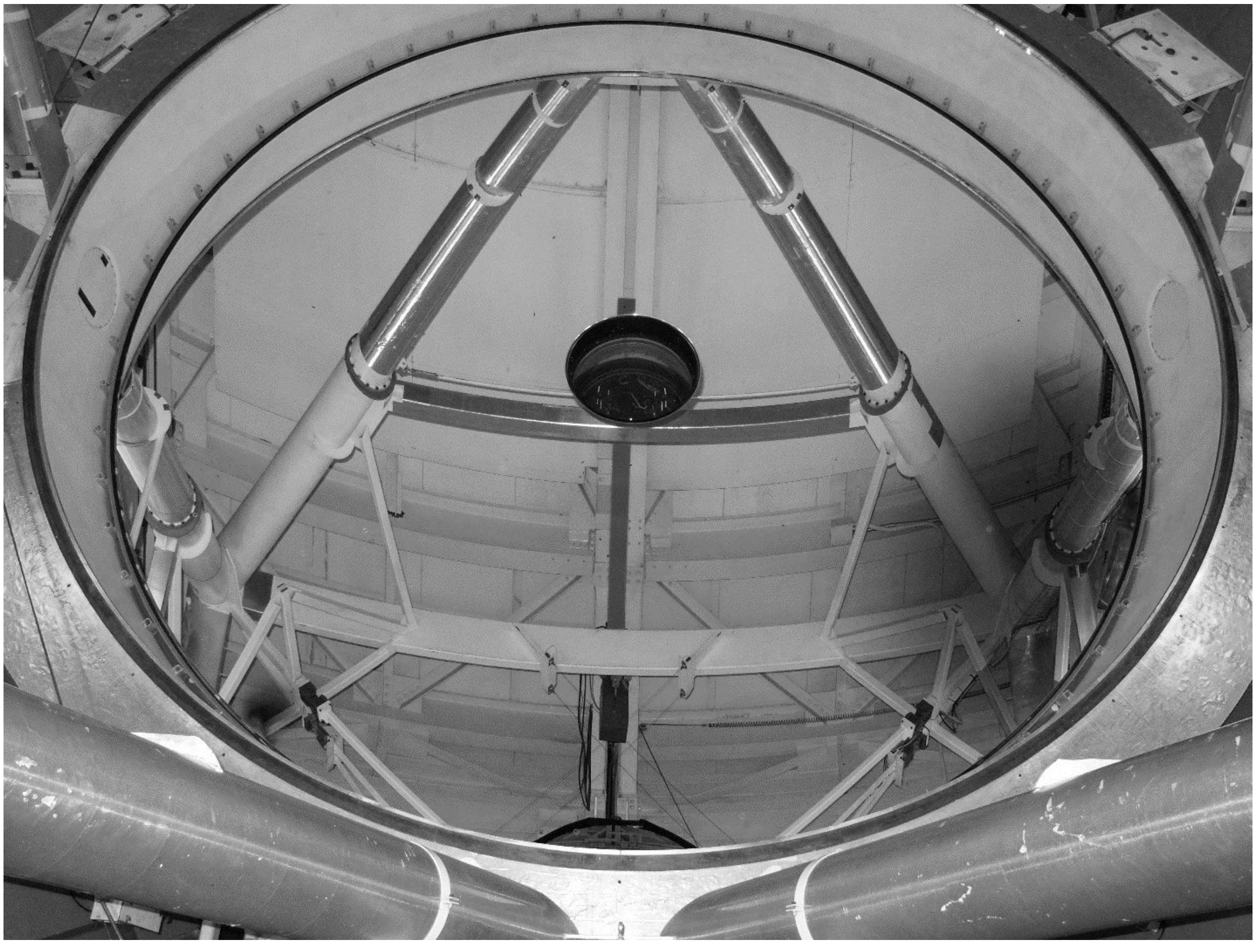

Figure 2 – MMTO 2010 mirror coating blemish. Two regions of the coating were contaminated. The largest brown spot is located around the 4 o'clock position (when looking at the surface of the mirror), and a smaller spot is located around the 7:30 position. A 0.61m (24-inches) wide x 6.1m (240-inches) long x 0.05mm (.002-inches) thick stainless steel sheet had been resting on the lower section of the isolation membrane (roughly between the 4:30 and 7:30 positions). This sheet prevented additional damage to the membrane and most likely greatly reduced the blemished area.

2. Control-software improvements

Initial testing of the software-based system for controlling the power to the filaments took place utilizing two welders powering four filaments (two filaments per array) in a 0.5m diameter coating chamber. Once some experience had been gained with the process, development of the control software continued using the same two welders to power forty filaments (twenty filaments per array) in a 2m diameter coating chamber. After the last round of testing in the 2m coating chamber was complete, a project decision was made to simplify the control system. During all of the testing in the 0.5m and 2m coating chambers, power to the filaments was controlled by software that was auto-generated from a simulation model. To represent the coating process, the model utilized a state machine to transition the filament warm-up through a series of states based on time, power supply voltage, power supply current, and the detection of the start of deposition. The details of this filament-control software are described in the paper, "Software framework for the upcoming MMT Observatory primary mirror re-aluminization" [2]. The software sections controlling the welders and handling the hardware interfaces (“alum-app”) proved to be difficult to support and needed a disproportionate amount of effort to handle even minor changes to the process. To simplify the system, the control of the filament power was converted to an open-loop system, where the command (welder command) to increase the output voltage of the welders is increased according to a predetermined voltage-versus-time profile. This profile was determined from the 2m chamber testing and then adjusted once during the full-scale system testing. Even though a significant effort was needed to rewrite the filament-power-control software, the new code is much more supportable, especially over the long term. Additionally, the software was written to readily handle changes to not only the heating profile but also the system hardware. Only minor changes were made to the software modules used to handle the data logging and the user interface (“node-server”).

3. Integrally wound tungsten and aluminum filament

For the full-scale system testing and the actual primary mirror coating, the 13H integrally wound tungsten and aluminum filament from Midwest Tungsten Service[4] was used. New filaments were installed for each test as well as for the primary mirror coating. The details of this filament are described in the paper, “Characterization of an integrally wound tungsten and aluminum filament for physical vapor deposition” [3].

4. Protection of the isolation membrane

During full-scale system testing, there was evidence of a small amount of stray aluminum droplets contacting the bottom of the vacuum chamber in an area that would correspond to the isolation membrane. These droplets were detected by lining the bottom section of the vacuum chamber with an aluminized polyester sheet, for the sheet would discolor in areas that had been in contact with any molten aluminum droplets. After each coating test, the marks on the sheet were typically less than 1.6mm in diameter, and generally a total of less than ten marks were detected. None of the detected aluminum drops penetrated the polyester sheet.

Since the presence of stray-molten aluminum could be anticipated during the primary mirror coating process and the issues associated with any damage to the isolation membrane were critical to the process, an aluminum shield was fabricated from UHV (ultrahigh vacuum) aluminum foil from All-Foils, Inc[5]. The final dimensions of the fabricated shield were 0.76m (30-inches) wide by 6.1m (240-inches) long, and the shield was installed by resting the foil on top of the lower section of the isolation membrane. This shield provided protection to about 30% of the isolation membrane but in an area most likely to be impacted by molten aluminum.

5. Full-scale system testing

In the process of coating another 6.5m mirror, the MMTO acquired the components necessary to create a complete vacuum chamber without the mirror cell. These components had been in long term storage at the Fred Lawrence Whipple Observatory[6] Base Camp facility in Amado, AZ. Assembly of the vacuum chamber at Base Camp started in the fall of 2015, and the first coating system test utilizing the new software-based system to control the power to all 200 filaments was performed on May 5th, 2016. This facility, as shown in figure 3, is only intended for system testing and was not designed to accommodate actual mirror coatings.

To prepare for a primary mirror coating during the summer of 2016, three full-scale-system tests were performed at Base Camp. The maximum filament current measured during the May 5, 2016 Base Camp test was below the maximum current the welders could supply, 990-amps. For the May 11th and June 23rd, 2016 tests, the command curve was adjusted slightly to provide more power to the filaments during deposition. Figure 4 shows the difference in the welder command between the May 5th and the June 23rd tests. The maximum filament current increased from 830-amps to 920-amps. A

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[4] Midwest Tungsten Service Inc., Willowbrook, IL, USA, www.tungsten.com

[5] All-Foils Inc., Strongsville, OH, USA, www.allfoils.com

[6] Fred Lawrence Whipple Observatory is operated by the Smithsonian Institution.

significant improvement in the deposition rate was realized, as the maximum deposition rate at a location corresponding to the vertex of the MMTO primary mirror increase from 32 Å/s to 47 Å/s, figure 5.

Figure 3 – MMTO full-scale coating test facility. There is enough electrical power available to run the vacuum pumps, but a mobile generator (in the long shipping container near the top of the image) was rented to provide power to the welders.

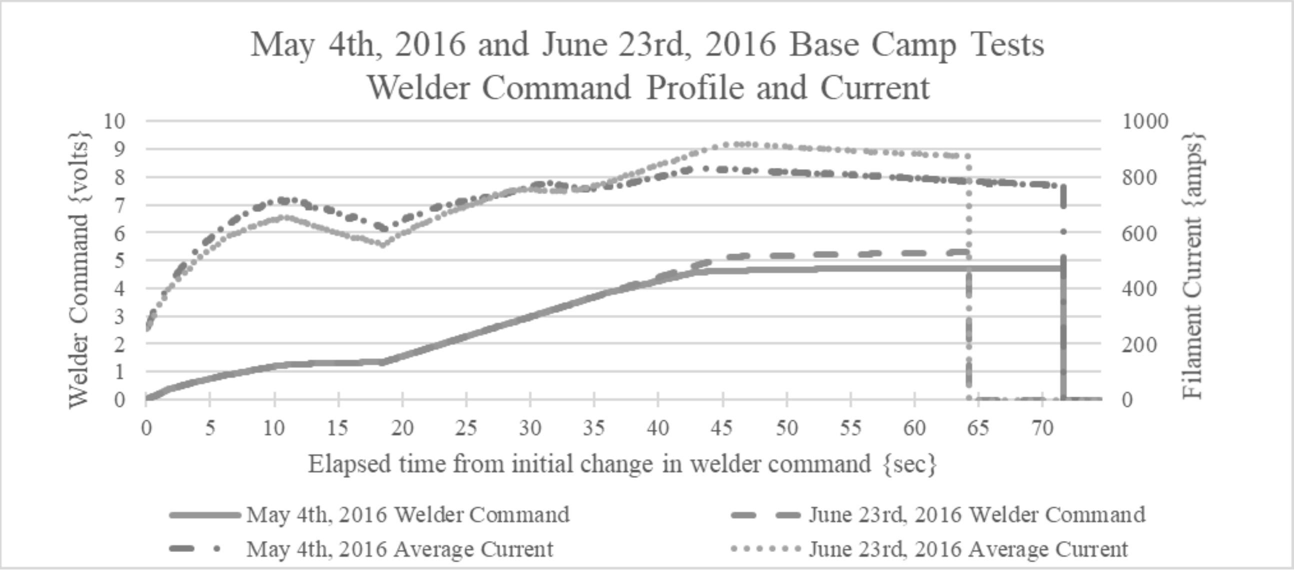

Figure 4 – Change in the welder command curve executed during full scale testing. The increase in the maximum welder command brought the system current closer to the 990-amp current limit of the welders.

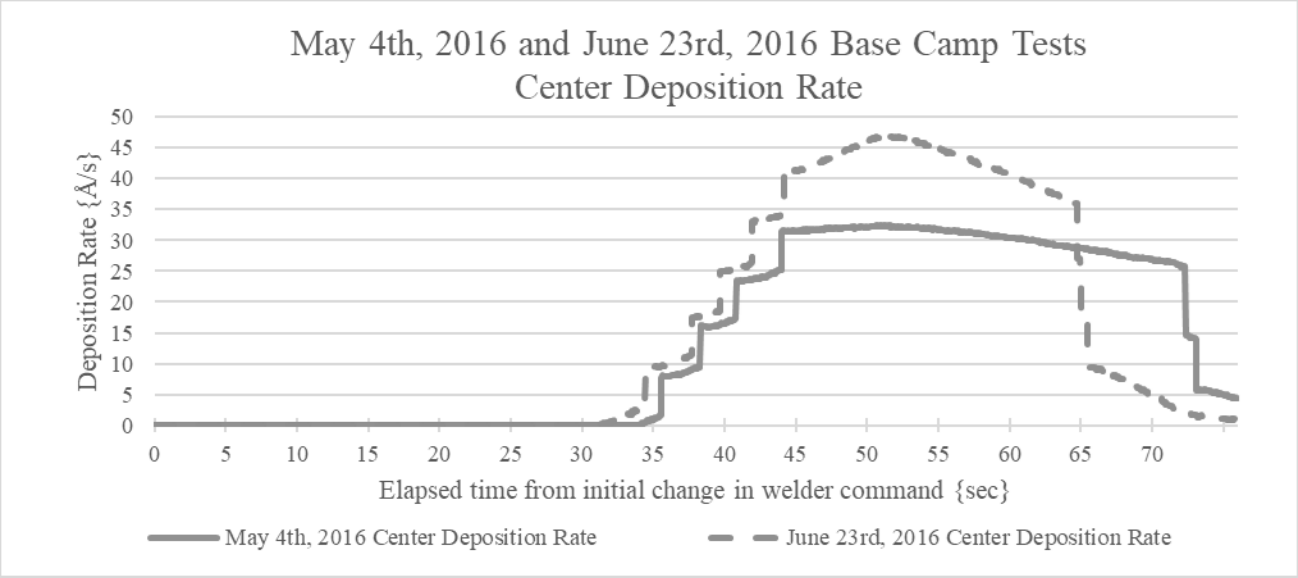

Figure 5 – Change in deposition rate after the welder command profile was adjusted. The additional power applied to the filaments increased the maximum deposition rate significantly, from 32 Å/s to 47 Å/s. The deposition rate towards the end of the process could probably be increased by having the welder command (shown in figure 4) ramp up again later in the process (possibly around 50 seconds after the initial change in the welder command).

5.1 Coating thickness radial variation

For the Base Camp tests, three deposition monitors were installed in the vacuum chamber on a fixture that approximated the optical surface of the MMTO primary mirror. For the first two tests, two of the deposition monitor crystals were installed at a location approximating the mirror vertex; this was done to replicate the coating system at the telescope in which two crystals would be installed near the vertex of the mirror in order to have redundant deposition rate and thickness measurements. The third crystal was installed at a location approximating the outer edge of the mirror at the 6 o'clock position (when facing what would be the optical surface). The full-scale tests at Base Camp were the first instance in which deposition data had been recorded at the outer edge of the mirror. During the first two full-scale tests, the coating thickness recorded near the edge of the mirror was roughly 75% of the center thickness. A visual inspection of the witness slides confirmed the applied coating was thinner at the outer edge than at the mirror vertex. Project deadlines did not allow sufficient time to investigate this issue, so a project decision was made to stop the coating process during next full-scale-system test when the center thickness was 1100 Å. This thickness was selected to help ensure the coating at the outer edge of the mirror would be thicker than 800 Å. In addition to increasing the target coating thickness for the June 23rd Base Camp test, the deposition monitor crystals were relocated to provide deposition measurements at three distinct radial locations: the mirror vertex, 2m from the vertex, and 3m from the vertex. The deposition data from these locations, figures 6 and 7, illustrate that the coating thickness can be expected to vary radially across the mirror. The recorded coating thickness at each location was: 1150 Å at the vertex, 1040 Å 2m from the vertex, and 830 Å 3m from the vertex. Based on these measurements, the coating thickness is probably reasonably uniform from the vertex to a radial distance of 2m, for the thicknesses measured at these locations are within 10% of each other. Similar to the first two full-scale tests, the thickness near the outer edge is 72% of the thickness measured at the vertex. The maximum deposition rate at each location varies in a manner similar to the thickness, for the maximum rates recorded were: 47 Å/s, 42 Å/s, and 33 Å/s, respectively. If resources are available before the next MMTO primary mirror coating, the facility at Base Camp will be used to determine the uniformity of the coating thickness provided by the existing system. Solutions to possibly improve the uniformity of the coating thickness may also be explored at that time.

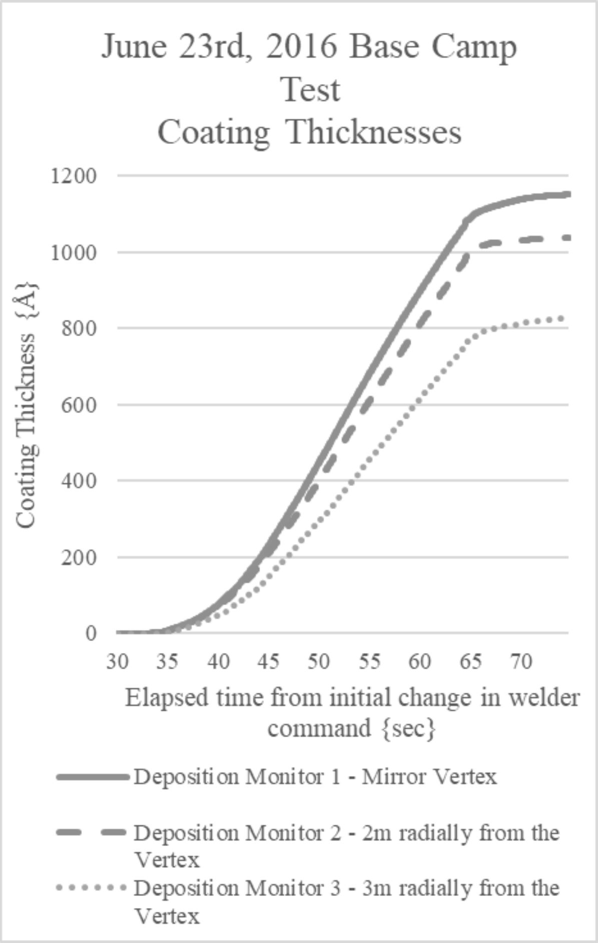

Figure 6 – Recorded coating thicknesses at different radial positions during the June 23rd, 2016 Base Camp test.

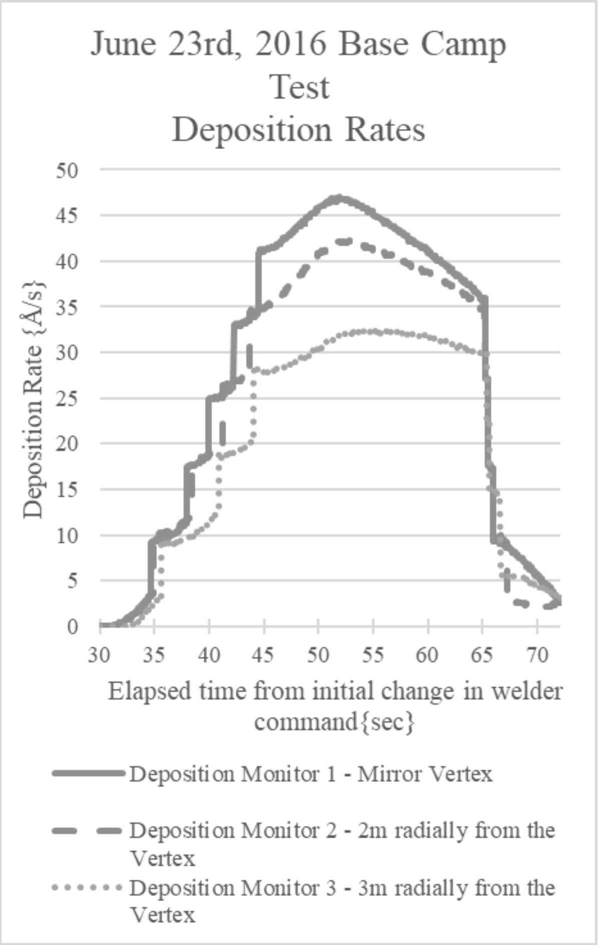

Figure 7 – Deposition rates at different radial positions during the June 23rd, 2016 Base Camp test.

6. Primary mirror coating

After the glow discharge cleaning and a short period pumping on the bell jar with the one working cryopump, the bell jar pressure stabilized at 9.5×10^{-3} Pa (7.1×10^{-5} torr). Since the pressure seemed to have reached a lower limit, the coating process was initialized. Unfortunately, two coating sequences were necessary in order to reach the desired aluminum film thickness.

6.1 First coating sequence

The first coating sequence was started at 11:35 on September 2nd, 2016, and the process was progressing similar to the testing at Base Camp. However, measurements from one of the center deposition monitors (center2) were very noisy and obviously erroneous. The control system was designed to terminate the process when one of the two center deposition monitors determined a coating thickness of 1100 Å had been reached. Unfortunately, these erroneous readings caused the center2 monitor to log an overall thickness that was significantly higher than the actual coating, and once this monitor reached the 1100 Å set point, the center2 monitor terminated the process early. Other than the early termination, the deposition rates and average array power look very similar to the results from the Base Camp tests, figure 8. The recorded thickness from the working deposition monitor located at the mirror vertex was 717 Å; the edge thickness monitor recorded 573 Å. The bell jar vacuum rose to 1.8x10^{-2} Pa (1.3x10^{-4} torr) during the start of deposition and then recovered before the process ended, figure 9.

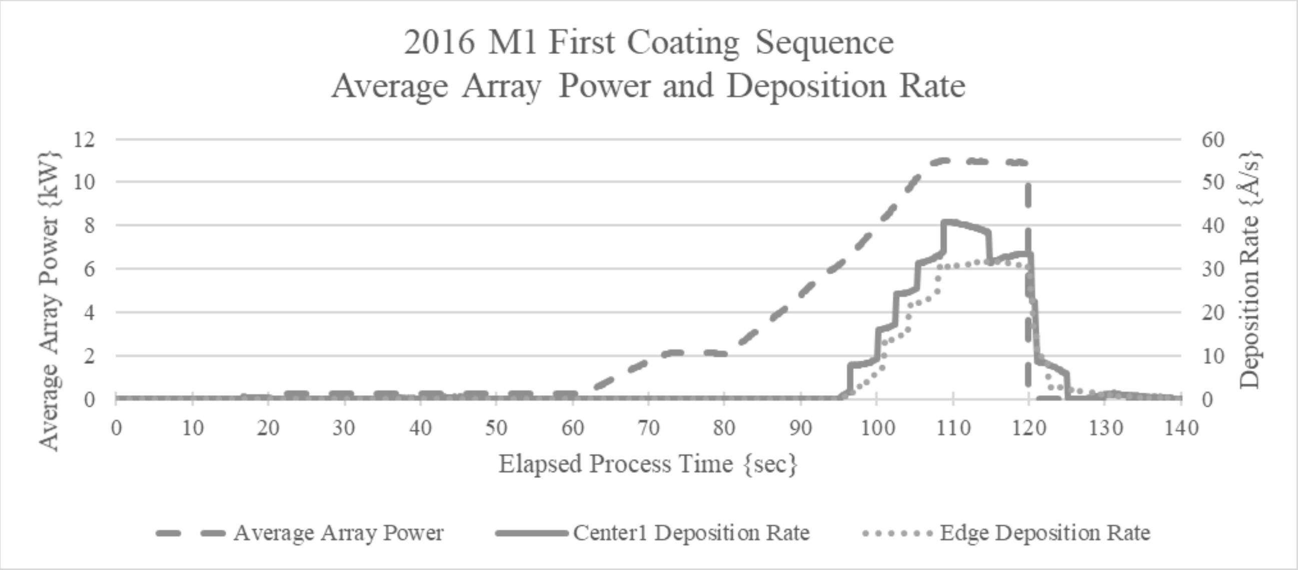

Figure 8 – Array power and deposition rates from the working deposition monitors for the first primary mirror coating sequence. The graphed array power is the average of the ten arrays. The maximum deposition rates were 41 Å/s at the center and 32 Å/s at the edge.

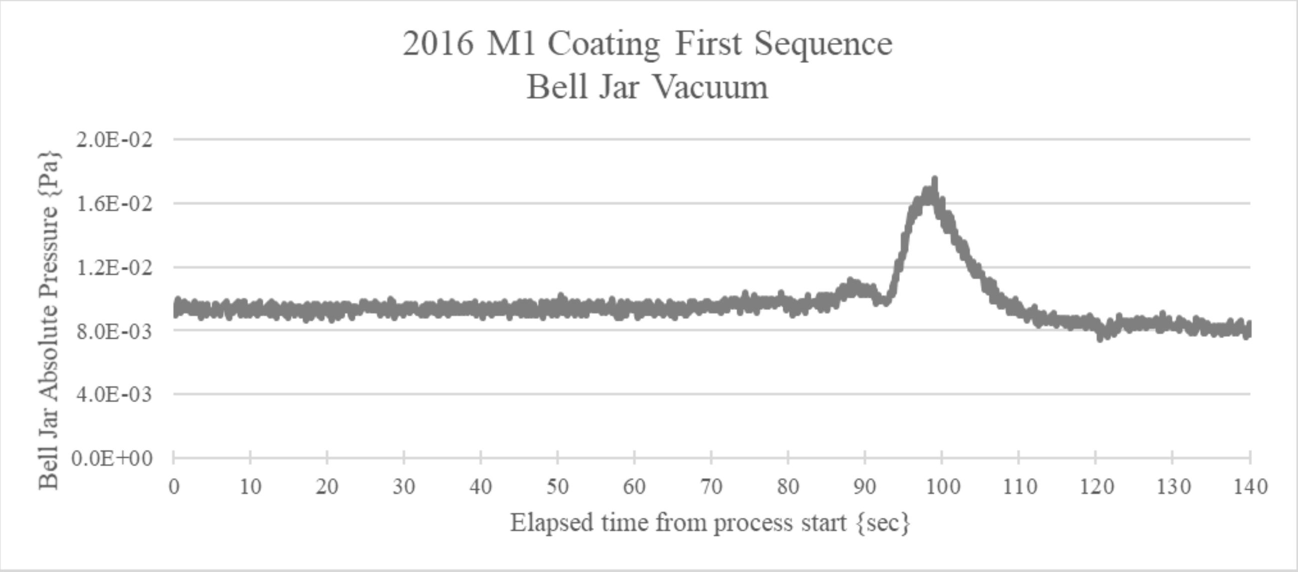

Figure 9 – Bell jar vacuum during the first primary mirror coating sequence. The bell jar vacuum degraded to 1.8x10^{-2} Pa (1.3x10^{-4} torr) and then recovered before the coating process was stopped.

6.2 Second coating sequence

After the first coating sequence was terminated, the bell jar vacuum stabilized at 1.1x10^{-2} Pa (8.1x10^{-5} torr), and the process was restarted in order bring the coating thickness up to the target value. Deposition rates were slightly lower than desired, figure 9, but the thickness at the mirror vertex increased to 1140 Å. The final thickness at the edge was 960 Å;

this was better than Base Camp testing would have predicted (85% of the thickness at the vertex). The bell jar vacuum only rose to $1.4x10^{-2}$ Pa ($1.1x10^{-4}$ torr) during this coating sequence.

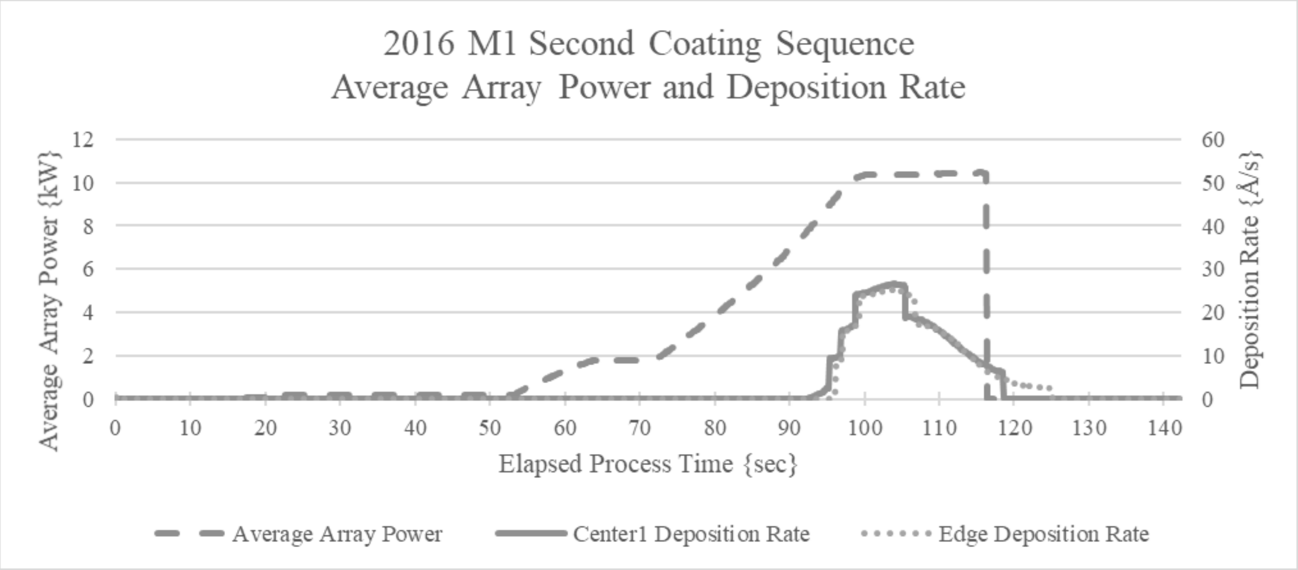

Figure 10 – Array power and deposition rates for the second primary mirror coating sequence. The graphed array power is the average of the ten arrays. The maximum deposition rates were 27 Å/s at the center and 25 Å/s at the edge.

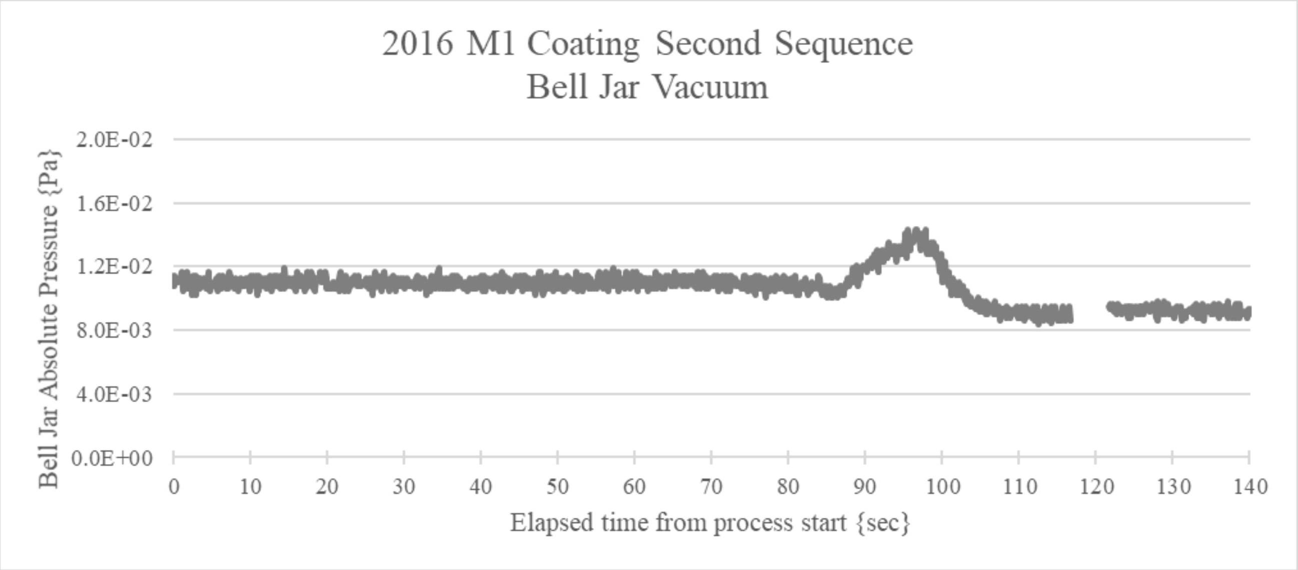

Figure 11 – Bell jar vacuum during the second primary mirror coating sequence. The bell jar pressure rose to $1.4x10^{-2}$ Pa ($1.1x10^{-4}$ torr) during the coating process. For unknown reasons, logging of the vacuum data sensors stopped briefly when the filament power was shutoff.

6.3 Process parameter comparison between the two coating sequences

Since the welders are voltage-controlled power supplies and the same welder-command profile was used for both coating sequences, the average array voltage was very similar between the two coating sequences, figure 12. However, the average array current was different, figure 13. This could be attributed to the aluminum being better distributed on the surface of the tungsten wire at the start of the second coating sequence (pre-wetted filaments).

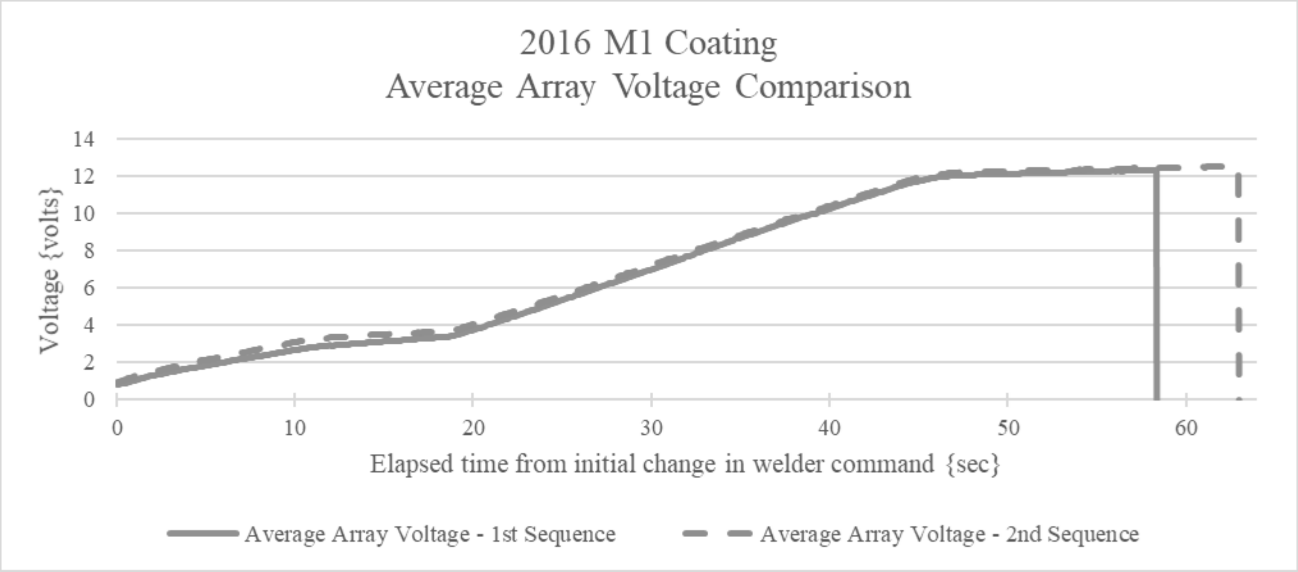

Figure 12 – Array voltage for both primary mirror coating sequences. The graphed array voltage is the average of the ten arrays measured at the electrical feedthroughs on the bell jar. The same welder command profile was used for both coating sequences.

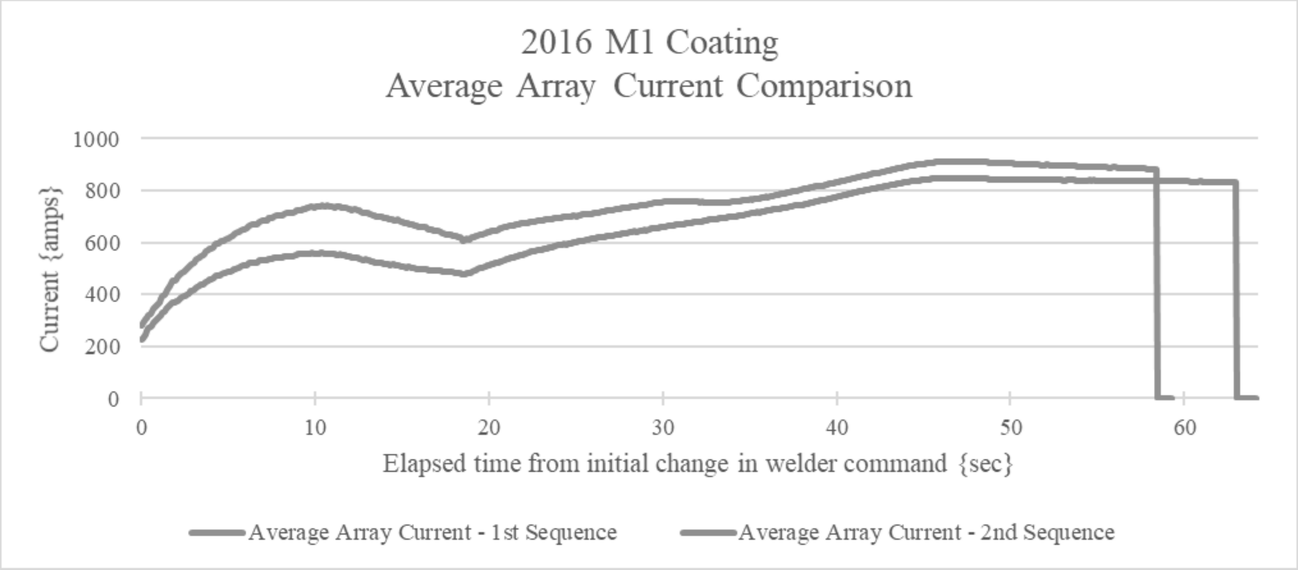

Figure 13 – Array current for both primary mirror coating sequences. The graphed current is the average of the ten arrays. The reduced current for the second coating sequence can be attributed to the filaments being “pre-wetted”. In other words, the filaments started the coating process with a thin layer of aluminum distributed almost uniformly on the tungsten wire rather than the aluminum wire being a distinct strand in the filament.

6.4 Coating inspection

After a three-day holiday weekend, the bell jar was opened on September 6th, 2016 to reveal a high quality coating. A few cleaning marks (small localized spots where the coating appears hazy under certain lighting angles) were present, especially in the 3 o’clock position (when facing the optical surface) of the mirror. This area is near the east access platform and is where personnel leave the mirror surface at the end of the cleaning process. In two places, a very small region (approximately 2cm wide x 8 cm long) near the outer edge of the mirror was not coated with any aluminum. These bare areas were most likely shadowed from the filaments by the isolation membrane or the aluminum shield.

Witness slides from both the center and the perimeter of the mirror were completely opaque, so the slides appear to be consistent with the recorded thickness measurements. While a tape test was not performed on the primary mirror, no adhesion issues were noted when the tape test was performed on randomly selected witness slides. Figure 14 shows the MMTO primary mirror after all of the coating equipment had been removed from the telescope.

Figure 14 – MMTO primary mirror shortly after being recoated in 2016. This image was taken after all of the coating equipment had been removed but before the telescope was returned to normal operations.

6.5 AC power from the mobile generator set

During the first coating sequence, a Fluke Corporation[7] 435 power analyzer was used to record the incoming AC power to the welders from the rented 1250 kVA generator set. Figure 15 shows the peak current for each phase throughout the coating process. With a maximum recorded current of 480 amps at 480 volts, the generator set could potentially be downsized for future coatings. While this unit was anticipated to have much more capacity than required, a key factor for selecting this specific generator set was the short wheelbase trailer the unit was packaged on; this allowed straightforward transportation to and from the summit of Mount Hopkins.

6.6 Effectiveness of the aluminum shield

An inspection of the aluminum shield installed over the lower half of the isolation membrane shows a minor amount of molten aluminum contacted the shield; figure 16 shows one of the larger marks (approximately 1.6mm in diameter) indicated on the shield. None of the molten aluminum droplets penetrated the aluminum shield, and no damage to the isolation membrane was observed.

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[7] Fluke Corporation, Everett, WA, USA, www.fluke.com

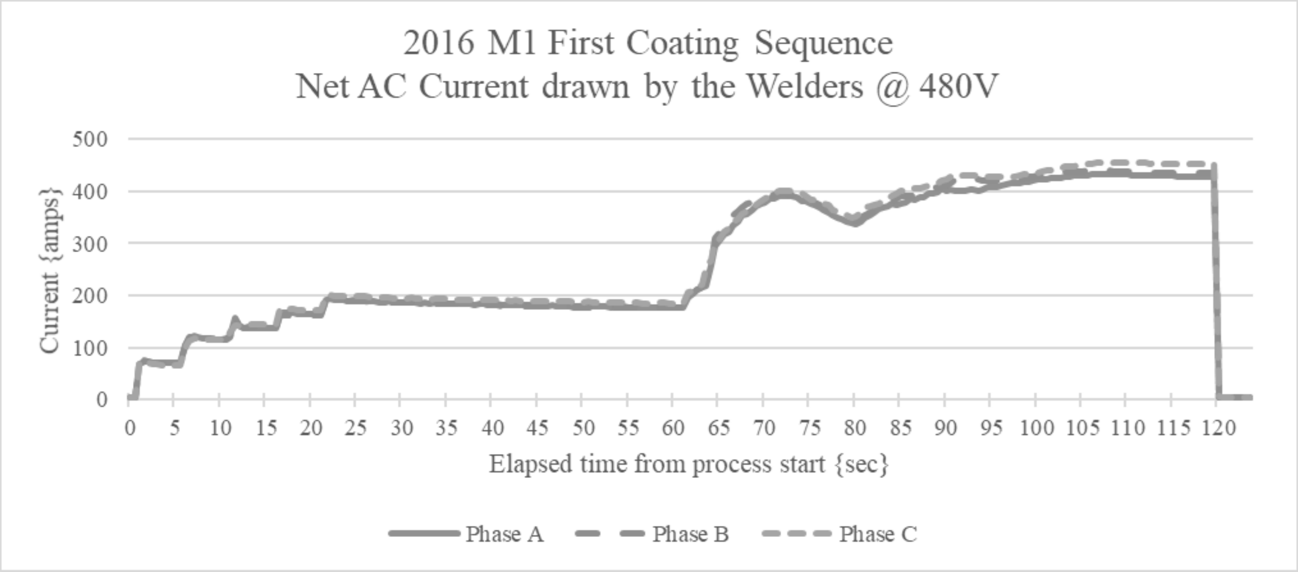

Figure 15 – Current drawn by the ten welders during the first coating sequence. The power from the generator set to the breaker panel for the welders was delivered via seven 4/0 cables, two for each phase and a ground. The current probes for each phase were wrapped around both wires of the respective phase.

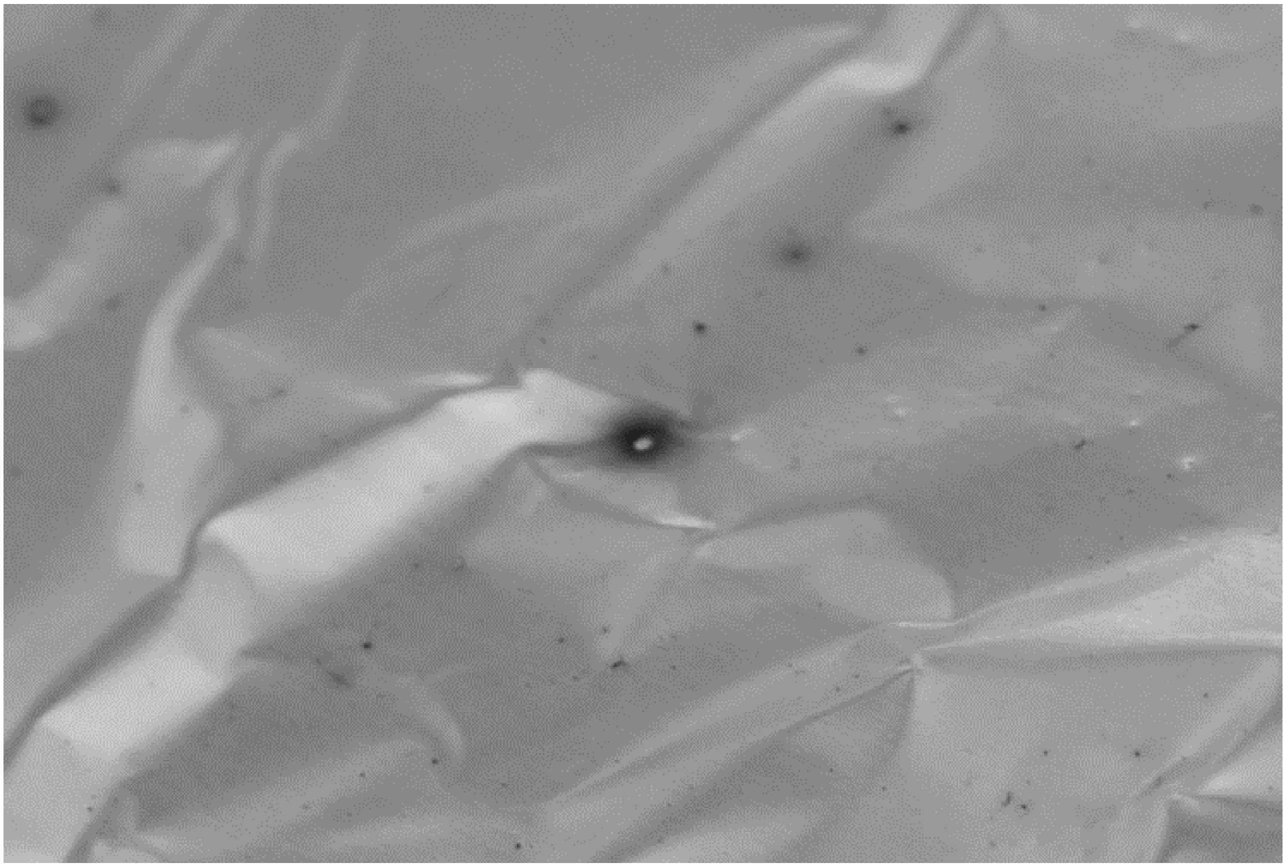

Figure 16 – Discoloration on the isolation membrane shield. These areas indicate places where molten aluminum contacted the shield at some point in the coating process. The isolation membrane itself did show any evidence of molten aluminum contacting it.

7. Conclusions

The development projects undertaken by the MMTO before the primary mirror recoating process was started had a profound impact on the success of the 2016 coating. Development of the open-loop-control system simplifies the manner in which power to the filaments is applied, and the open-loop software is able to provide a very consistent process. While the filament heating curve has not been optimized, any control system changes that can replicate the welder command profile should be relatively straightforward to incorporate. The full-scale test facility at Base Camp gives the MMTO the ability to verify the equipment operation as well as test process changes before the system is assembled at the telescope. Some tweaks to the welder-command profile may take place during future testing at Base Camp in order to improve deposition rates, but any changes made to the profile would be minor.

Even with the new filaments and control system, stray aluminum droplets were still present during the coating process. Although the amount of and the size of the droplets have been greatly reduced, the aluminum shield protecting the isolation membrane will remain a critical item for future MMTO primary mirror coatings. Some effort must be spent before the next coating to identify the cause of the noisy and erroneous deposition monitor readings, and this work may include deploying alternate deposition monitors. However, the overall re-aluminization process is sufficiently developed, and the 2016 coating results should be repeatable for future primary mirror coatings.

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