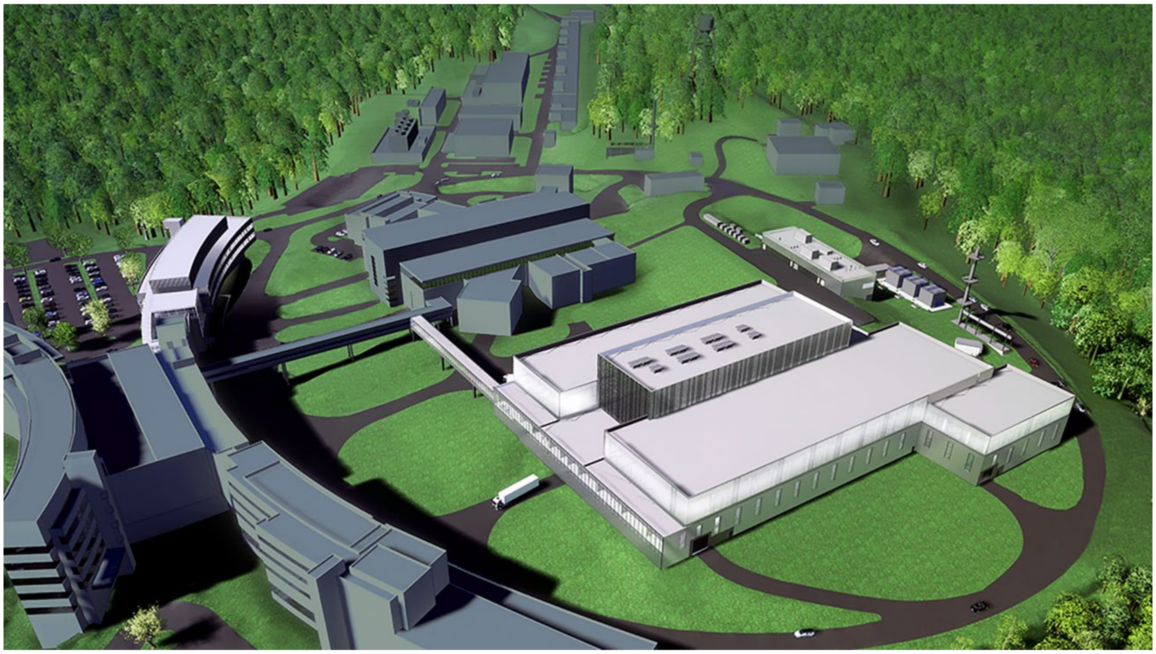
S07030200-TRT10000-R00

Second Target Station Project: Cylinder Moderator Prototype Manufacturing Report



Jim Janney

June 2023

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S07030200-TRT10000-R00

Second Target Station Project

CYLINDER MODERATOR PROTOTYPE MANUFACTURING REPORT

Jim Janney

June 2023

Prepared by
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US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

1. INTRODUCTION

The purpose of this report is to document the process and results of the Second Target Station (STS) Cylinder Moderator Prototyping project.

The motivation for the Cylinder Moderator Prototyping effort was to prove that the Cylinder Moderator could be manufactured within the tolerances required to meet the STS neutron production KPP. Additionally, the project offered the opportunity for establishing vendors capable of performing the required steps for manufacturing a moderator and allowing the MRA engineering team to become familiar with all necessary manufacturing processes.

In order to learn as mech as possible from the process, we elected to manage the project internally and subcontract for individual portions of the manufacturing scope. The high level manufacturing steps were as follows:

1. Machine weld samples and prototype parts
2. Machine filler metal shims
3. Dimensionally inspect all prototype parts
4. Clean all parts and shims
5. Weld sample parts
6. Weld hydrogen vessel prototypes
7. Inspect hydrogen vessel prototypes
8. Weld vacuum vessel prototypes
9. Inspect vacuum vessel prototypes
10. Final machine vacuum vessel prototype
11. Inspect final machined vacuum vessel prototype

The technical requirements for all manufacturing were contained in a single equipment specification, S07030200-EQ0001-R01. It should be noted that including all technical requirements for the project in a single equipment specification created significant confusion for vendors because the specification covered requirements for scope they weren't responsible for, even though the scope was clearly stated in the statements of work. It is advised to consider an approach that is more straightforward for vendors for future moderator procurements.

2. MANUFACTURING PROCESS

2.1 MACHINE WELD SAMPLES AND PROTOTYPE PARTS

The machining for the Cylinder Moderator Prototype project was supplied by Metalex Manufacturing per S07030200-SW0002 under PO 4000197021 for $198,700 (this PO also covered the final machining of the prototype). No other vendors bid on this project due to high demand for machining work at the time of bidding and significant documentation requirements. Confusion caused by the single equipment specification (see previous section) may have caused vendors not to bid as well. In future procurements, we will relax documentation requirements and make equipment specifications less confusing to attempt to increase interested vendors.

There was a design change notice just after placing the contract, S07030200-DCN10000, caused by a requested change by the EB welder to the EB shim thickness and hydrogen vessel backer size, which slightly changed the weld joint machining but did not impact cost or performance of the contract.

Metalex requested a number of small deviation requests at the beginning of the project (S07030200-DEV10000, S07030200-DEV10001, S07030200-DEV10002, S07030200-DEV10003), the only one of which may be relevant to future projects, increased an inside corner radius from 0.1mm to 0.13mm due to availability of cutters, although the original radius is technically feasible. The forged aluminum 6061-T6 material for machining these parts was supplied by Forge Products Corporation under PO 4000187312 which also supplied material for the Tube Moderator Prototype (note that there is some remaining unused material).

The manufacturing of the weld samples and prototype parts was overall very smooth. In general, these geometries were quite simple relative to Metalex's technical capabilities. Only one nonconformance report was produced, S07030200-NCR10000, which documented out of tolerance alignment bosses and a programming error which caused a step inside a beamtube. All other parts met required tolerances. The machining processes are documented in the machining report, S07030200-VST10008.

The tolerance alignment bosses required an extremely tight tolerance and were inaccessible from both sides of the part, creating problems in machining them to tolerance and in referencing other features to them. An alternative strategy should be considered for future Cylinder Moderator manufacturing (see recommendations).

2.2 MACHINE FILLER METAL SHIMS

The machining for the Cylinder Moderator filler metal shims was supplied by Meyer Tool (www.microwaterjet.com) per S07030200-SOW10001 thru the SNS manufacturing engineers' office for $2,330. This work required micro waterjet cutting of the shims in order to avoid contamination with standard waterjet or oxidation with laser cutting. The available shim stock did not match the shim stock dimensional requirements shown on the drawings as documented in S07030200-DEV10004. This scope of work was delivered with no issues. ORNL machine shop has since purchased a micro waterjet machine so future shims could be produced internally at ORNL. Future shim drawings and designs should be updated to use readily available shim stock sizes.

2.3 DIMENSIONALLY INSPECT PROTOTYPE PARTS

Although all parts were fully inspected by Metalex, we chose to use SNS Survey and Alignment (S&A) CMM to monitor prototype parts for weld distortion. We started by inspecting the prototype parts so that we could inspect with the same inspection program before and after welding. This work was mainly performed by Rich Schwartz of SNS S&A and was included in the hydrogen vessel and vacuum vessel dimensional inspection reports.

2.4 CLEAN ALL PARTS AND SHIMS

In order to prepare parts for EB welding, all parts to be welded and filler metal was cleaned and bagged by Astropak per S07030200-SOW10000 under PO2100004032 for $1,500. Representative samples of bulk Al 6061-T6 and Al 4047 filler shims were cleaned in both ½% sodium hydroxide and 10% nitric acid with 2% ammonium bifluoride (ABF) solutions for times of 1, 3, and 5 minutes. The samples cleaned in the sodium hydroxide solution all displayed some discoloration. The samples cleaned in nitric and ABF solution appeared clean although grain structure was subtly revealed at 3 minutes of time and plainly revealed after 5 minutes. Therefore, a 1 minute clean in nitric and ABF solution was chosen and documented in an approved cleaning procedure (S07030200-VST10000). This chosen cleaning method is very similar to the procedure used by HFIR before welding their cold source hydrogen vessel.

The parts were cleaned and bagged per the cleaning procedure as documented in S07030200-VST10001. This process was carried out with no issues. In the future the cleaning procedure should specify that each shim be bagged individually. For the prototype, the shims were bagged in groups of 4 so that they could not be opened individually before welding, although this did not seem to cause any problems for the prototype welding.

2.5 WELD SAMPLE PARTS

The welding for the Cylinder Moderator Prototype project was supplied by PTR-Precision Technologies, Inc. per S07030200-SW0003 under PO 4000197790 for $34,540. This contract covered the creation of welding programs and procedures through welding of samples and production parts welds. The welding of samples progressed rapidly in early November of 2022. 3 hydrogen vessel weld samples and 4 vacuum vessel weld samples were welded in order to develop final weld parameters. Excellent consistent penetration was achieved due to the constant weld cross sections and straightforward weld paths which made for simple weld development. The hydrogen vessel weld fixtures seemed to help reduce weld distortion and minimize part heating.

The weld parameters developed on the samples were used for welding PQR plates for mechanical testing to prove the required properties of each weld. Machining maps for creating the samples for testing are S07030200-M8U-8700-A10000 and S07030200-M8U-8700-A10001. The mechanical testing results were documented in PQR reports, which support the associated WOPQ and WPS for each weld. The document numbers are listed in Table 1.

Table 1. Cylinder Moderator Prototype Weld Qualifications

	WPS	WOPQ	PQR
Hydrogen Vessel Weld	S07030200-VST10002	S07030200-VST10003	S07030200-VST10004
Vacuum Vessel Weld	S07030200-VST10005	S07030200-VST10006	S07030200-VST10007

The only issue revealed was some minor over penetration through the weld backers which could lead to arc strikes on adjacent surfaces. Rather than develop more complicated welding programs or remachine parts with larger backers, other mitigation techniques were used to prevent arc strikes as detailed in the prototype welding sections. In the future, the vacuum vessel weld backer should certainly be made larger and hydrogen vessel weld backer enlargement should be considered.

2.6 WELD HYDROGEN VESSEL PROTOTYPES

The hydrogen vessel prototypes were welded on January 11th, 2023 and witnessed by Jim Janney and Daniel Lyngh. To mitigate the possibility of arc strike on the backing surface, ¼” 2017 aluminum balls (McMaster # 34665K31) were loaded into the production parts to protect the vessel body. 4 hydrogen vessels were successfully assembled and welded per WPS S07030200-VST10002. The shim fit up was extremely tight, and although this produced excellent welding results, assembly was difficult and required significant force. In the future, hydrogen vessel shim fit up should be reconsidered.

During this visit, it was discovered that the vendor’s weld operator had been final cleaning the parts and shims with alcohol prior to assembly during sample part welding, even though the specification stated the parts were to be unbagged immediately before assembly without additional cleaning. We elected to continue this practice during prototype welding as it had been successful during prototyping, but future moderator welding should consider removing this final cleaning step as it adds additional potential for weld contamination.

2.7 INSPECT HYDROGEN VESSEL PROTOTYPES

All 4 hydrogen vessels were cold shocked, leak checked, pressure tested, dimensionally inspected, and weld inspected at ORNL after return from welding. Cold shocking, leak checking, and pressure testing were performed by the SNS vacuum group and documented in report S07030200-TRT10001.

Dimensional inspection occurred next and was performed by SNS S&A and documented in S07030200-TRT10002. It was noted that hydrogen vessel #2 had significantly worse profile condition (maximum 0.18 mm away from nominal) than the other 3 because the lid was not fully seated during welding. All 4 hydrogen vessels shrank during welding, although the shrinkage in height was only .10-.13 mm when averaged for each vessel and was less than .023 mm radially. Worst case profile for the vessels was .1323-.1564 mm away from nominal not counting the weld bead and cocked lid. This is just above the assumed +/-.125 mm assumed for the MRA tolerance stack up and could easily meet the assumed tolerance by compensating for the weld shrinkage in the nominal parts. Future hydrogen vessel body parts should be made 0.12 mm taller than intended to compensate for weld shrinkage. Note, they also must be made 0.12 mm taller to compensate for thermal contraction upon cool down to their 20K operating temperature, so the total height compensation should be 0.24 mm.

Weld inspection consisted of visual testing (VT), penetrant testing (PT), and radiographic testing (RT), but ultrasonic testing could not be performed due to part geometry. All 4 vessels passed VT and PT but RT found a rejectable indication on hydrogen vessel 2 while no indications were found on the other vessels as detailed in S07030200-TRT10003. It is assumed that the rejectable indication was caused by bad fit up prior to welding which also caused the profile deviation. Future moderator welding should consider tooling to ensure proper hydrogen vessel fit up to avoid this issue.

2.8 WELD VACUUM VESSEL PROTOTYPES

Vacuum vessel welding occurred on February 27th, 2023 and was witnessed by Jim Janney. 2 hydrogen vessels were shipped back to PTR after their inspections for installation within the vacuum vessel assemblies.

During hydrogen vessel welding and inspection, a scheme for protecting the installed hydrogen vessel from over penetration during the vacuum vessel weld was created. Protecting from overpenetration of the vacuum vessel weld was difficult due to the small gap, only 3 mm. Shims were designed to be placed in the gap and protect the inner vessel from over penetration and then removed after welding. Shims and a shim form were designed (S07030200-M8U-8800-A10002, S07030200-M8U-8800-A10003, and S07030200-M8U-8800-A10005) and fabricated by TN Tool under the Basic Ordering Agreement (BOA).

These shims were formed and installed prior to assembly of the first hydrogen vessel within the vacuum vessel. Assembly of the hydrogen vessel within the vacuum body was quite finicky. It was very difficult to get the titanium pins to engage correctly and to be certain of proper engagement, and multiple attempts were necessary. The vacuum vessel lid was also similarly finicky to install with difficult engagement of the pins. The beam blocker shims made the pin installation slightly more difficult by adding one more element to monitor during assembly, but the pin installation is challenging regardless.

EB welding was performed using an existing CNC rotary table with a tilt axis. The vacuum vessel lid was clamped to the body during tack welding to ensure proper fit up for the full penetration pass. The clamps were removed after tacking was complete to allow for continuous welding of the full circumference. The full penetration weld was followed by a cosmetic pass which resulted in a smooth, even weld crown.

After welding, we attempted to carefully remove the weld shims; however, all 3 shims broke, trapping them between the hydrogen and vacuum vessels. Upon review of the photographs, it was discovered that the shims were incorrectly rotated, making removal more difficult than it needed to be. It was unclear whether the shims would be removable if the orientation was optimal, but we decided that for the second vessel we should perform welding without the shims.

The second vessel was assembled with some difficulty and then successfully welded. Because this vessel does not contain trapped shims, it was chosen for final machining to complete the prototype.
In the future, the alignment bosses should be adjusted so that the slotted side of the interface is on the part that will be lowered into place while the round side of the interface should be on the stationary part for minimizing assembly difficulty. The shims proved to be an unsuccessful solution for weld overpenetration. While there may be opportunity for making the shims successful, future moderator designs should feature a larger weld backer to remove the need for a shim.

2.9 INSPECT VACUUM VESSEL PROTOTYPES

After welding, the vacuum vessel prototypes were returned to ORNL for inspection. This inspection included dimensional inspection to evaluate weld shrinkage and leak checking. Both welded vessels were evaluated even though only one would go on to final machining. Both vessels passed leak check with no issues as reported in S07030200-TRT10004. Dimensional inspection was completed and showed weld shrinkages of 0.33 mm and movement of the inner vessel relative to the outer ring of 0.17 mm as shown in report S07030200-TRT10005. Future moderator designs should allow for weld shrinkage of the vacuum vessel, although the thermal contraction of the hydrogen vessel at operating temperature should also be accounted for. The movement of the inner vessel relative to the outer ring can be accounted for by leaving stock on the inside and outside of the beamtubes and outer ring prior to welding and post weld machining to final dimensions.

2.10 FINAL MACHINE VACUUM VESSEL PROTOTYPE

After inspection, vacuum vessel 2 was returned to Metalex for final machining. Final machining was completed quickly and was generally successful, although the assembly tolerances around the vacuum vessel were not met (S07030200-NCR10001) and will have to be relaxed for future moderators. The resulting tolerances can also be improved by leaving stock on the beam tubes in all areas that can be cleaned up after welding and by choosing datum features which can be accessed from both sides of the part. Using the outside cylinder of the vacuum vessel middle cylinder and the edge of one beam tube is suggested.

2.11 INSPECT FINAL MACHINED VACUUM VESSEL PROTOTYPE

After final machining, the final testing of the vessel could commence. First, cold shocking, leak checking, and pressure testing were completed at Metalex as documented on page 42 of submittal S07030200-VST10008. In addition to cold shocking, we also filled the hydrogen vessel with liquid nitrogen while allowing the vacuum vessel to remain at room temperature. The hydrogen vessel was then confirmed to still be rigidly located within the vacuum vessel by attempted manual manipulation. After these inspections were complete, the part was returned to ORNL for weld inspection. Weld inspection could not be completed prior to final machining because the excess material would make radiographic interpretation impossible. The weld inspection revealed no rejectable indications for VT, PT and RT (Report S07030200-TRT10006), although the RT has some sections where the images were difficult to interpret due to the part geometry. CT of the vacuum vessel weld is suggested for future moderators to reduce the difficulty of RT interpretation.

3. CONCLUSION

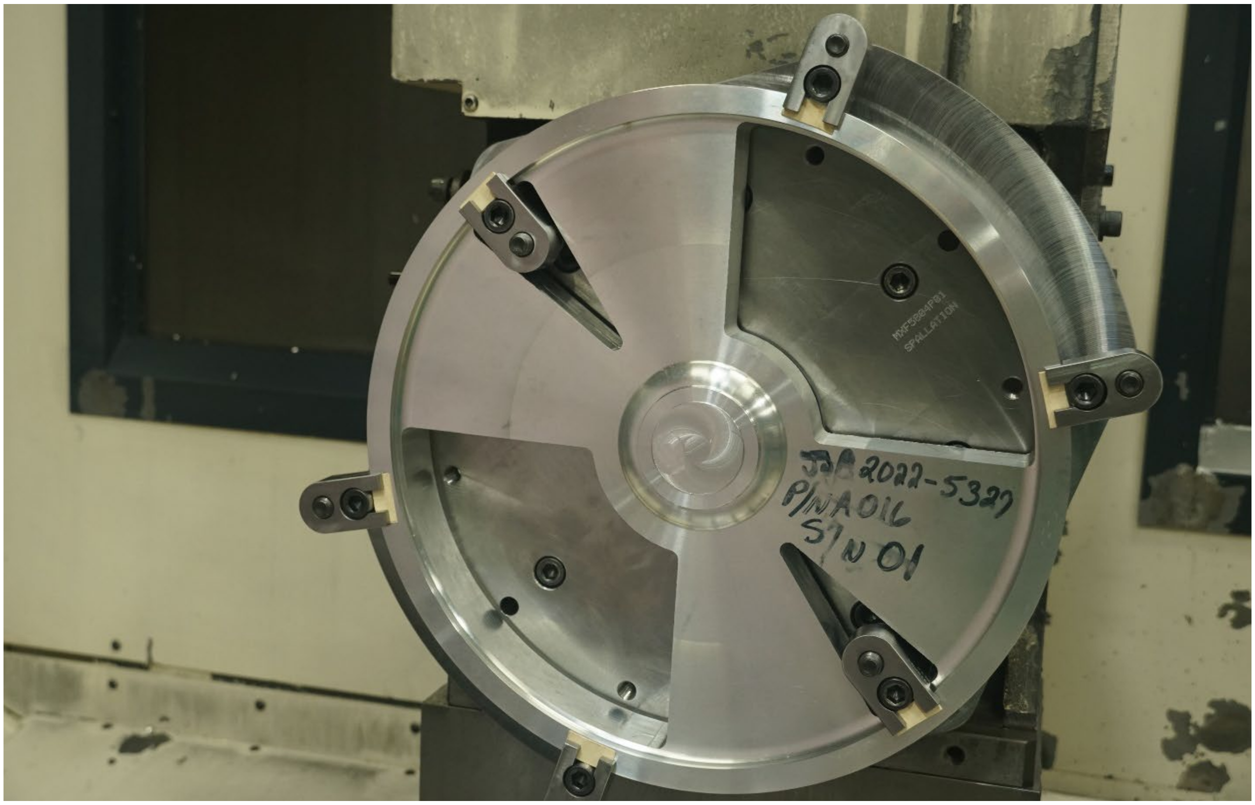
The Cylinder Moderator Prototype manufacturing was fully successful. The project was completed over 15 months, concluding in May, 2023, and produced a successful Cylinder Moderator Prototype while also enabling identification of many process improvements to be implemented in future moderator procurements:

- Larger datums accessible from both sides of the vacuum vessel body should used instead of small datum bosses utilized in the prototype design
- Weld filler shim and weld fit ups should be designed around available shim stock sizes
- Weld filler shims should be bagged individually after cleaning
- Electron beam weld backers should be enlarged to eliminate overpenetration
- Hydrogen vessel weld fit up should be reconsidered for easier assembly
- Hydrogen vessel bodies should be made 0.24 mm oversized in height to allow for weld shrinkage and thermal contraction at operating temperature
- An assembly tool should be created for fully seating hydrogen vessel lids prior to welding
- The hydrogen and vacuum vessel alignment bosses should be adjusted so that the slotted side of the interface is on the part that will be lowered into place while the round side of the interface should be on the stationary part for minimizing assembly difficulty
- Vacuum vessel bodies should be made 0.33 mm oversized in height to allow for weld shrinkage so that the fit with the hydrogen vessel is line to line at operating temperatures
- Machining stock should be left on the vacuum vessel body beamtubes and outer rings so that full clean up of these regions can be achieved after vacuum vessel welding
- CT scanning of the welded vacuum vessel should be used to inspect the vacuum vessel weld and to verify hydrogen vessel location within the vacuum vessel

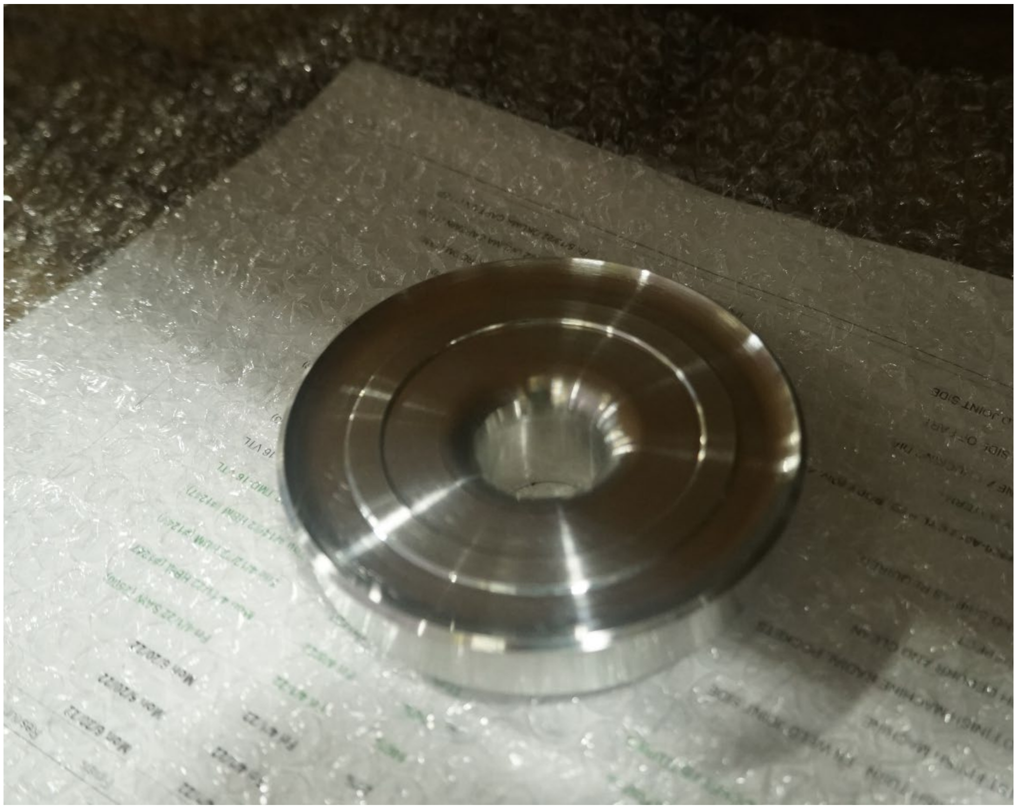
With the addition of the above process improvements, we are confident that the Cylinder Moderator Prototype manufacturing has established a path for successful Cylinder Moderator manufacturing during Moderator Reflector Assembly Fabrication.

APPENDIX A. PHOTOS

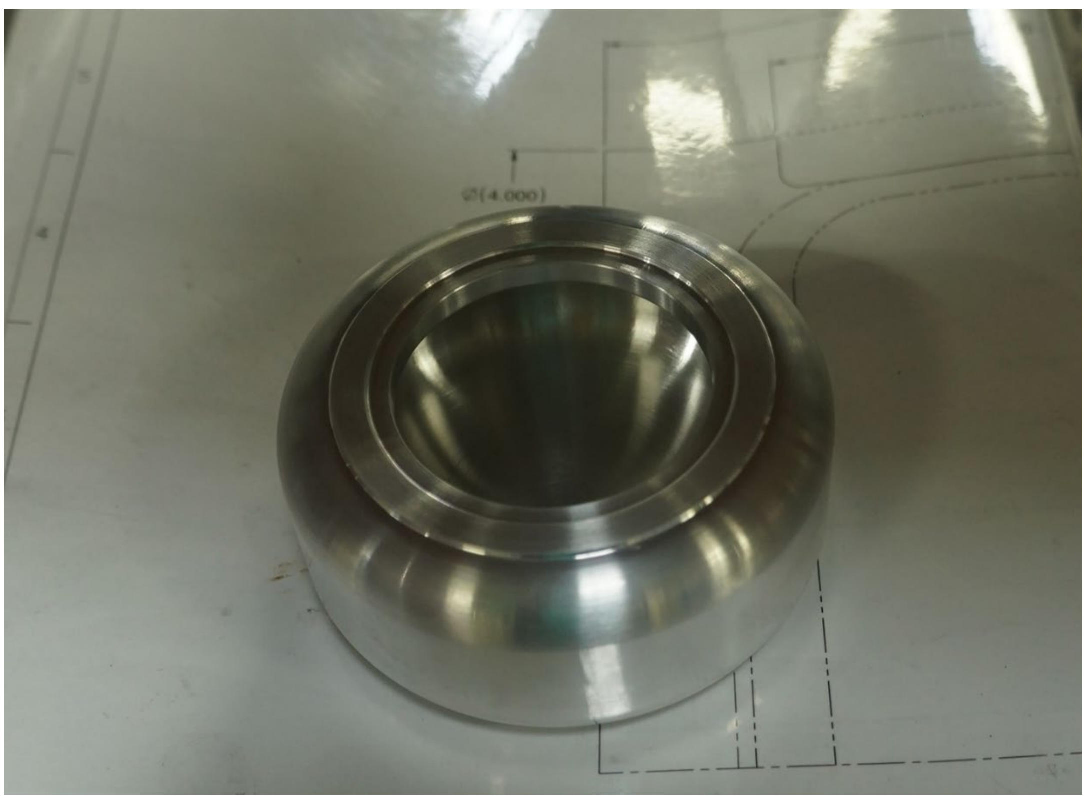
Parts at Metalex - May 26, 2022



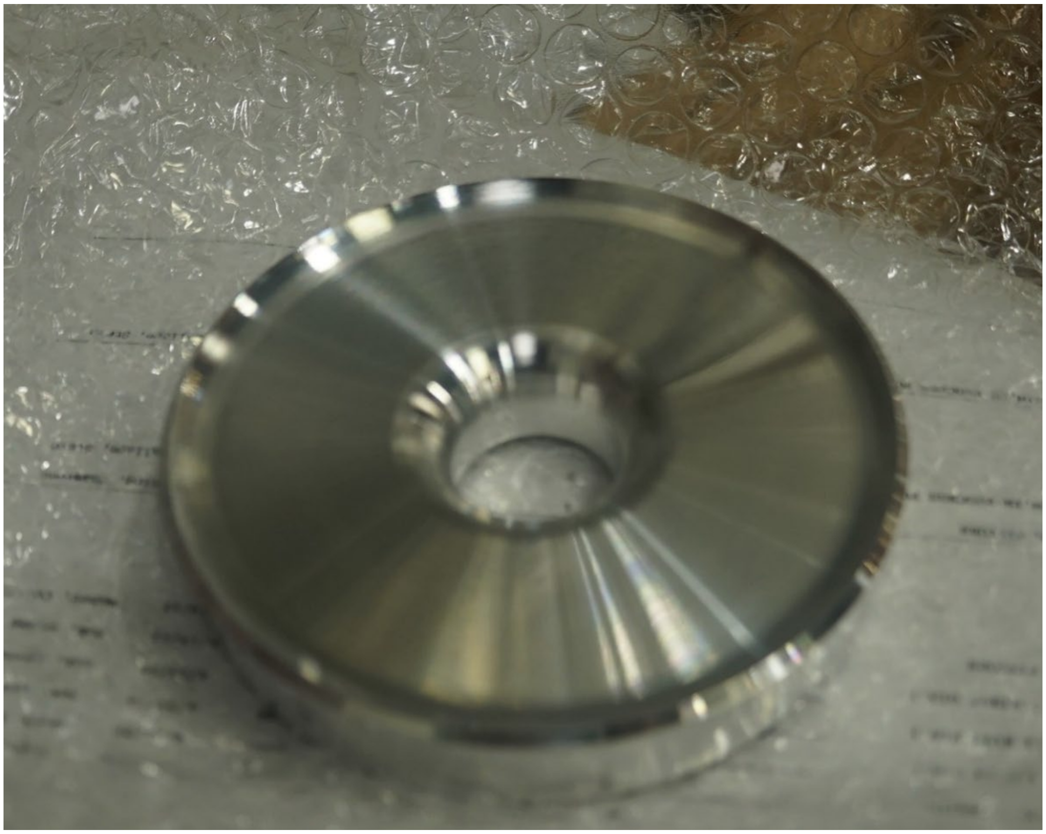
Vacuum vessel body on milling machine.



Vacuum vessel lid finished with lathe work and ready for milling of pockets.

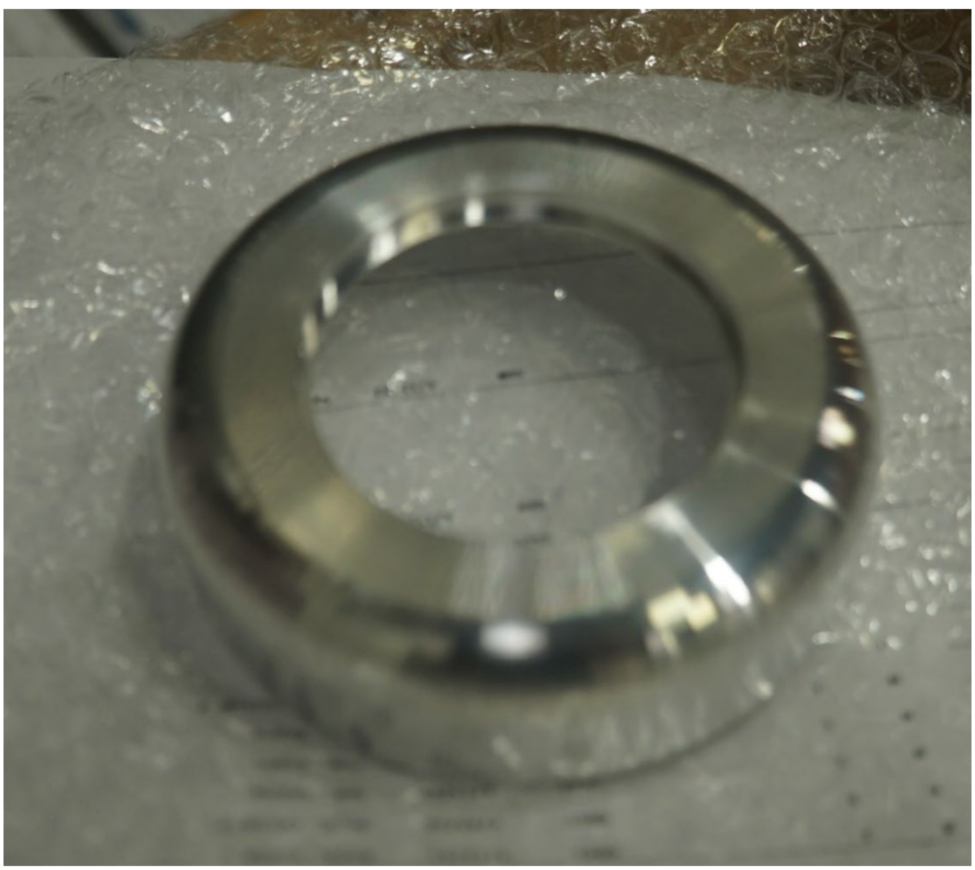


Hydrogen vessel body finished with lathe work and ready for milling.

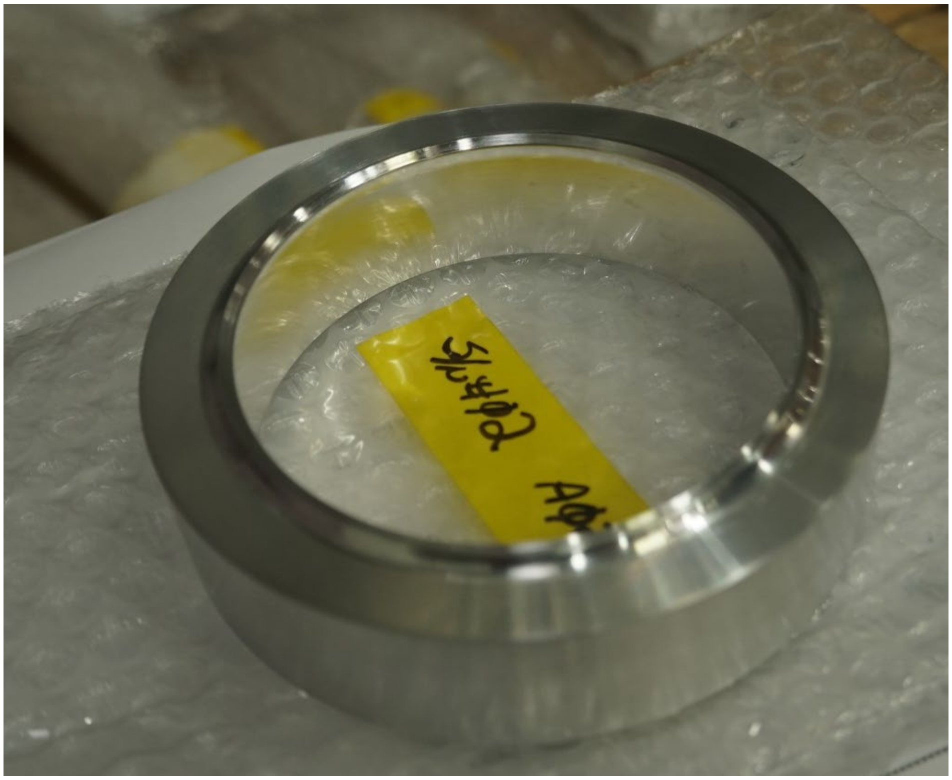

Finished sample vacuum vessel lid.


Finished sample vacuum vessel lid.

Finished sample hydrogen vessel body.

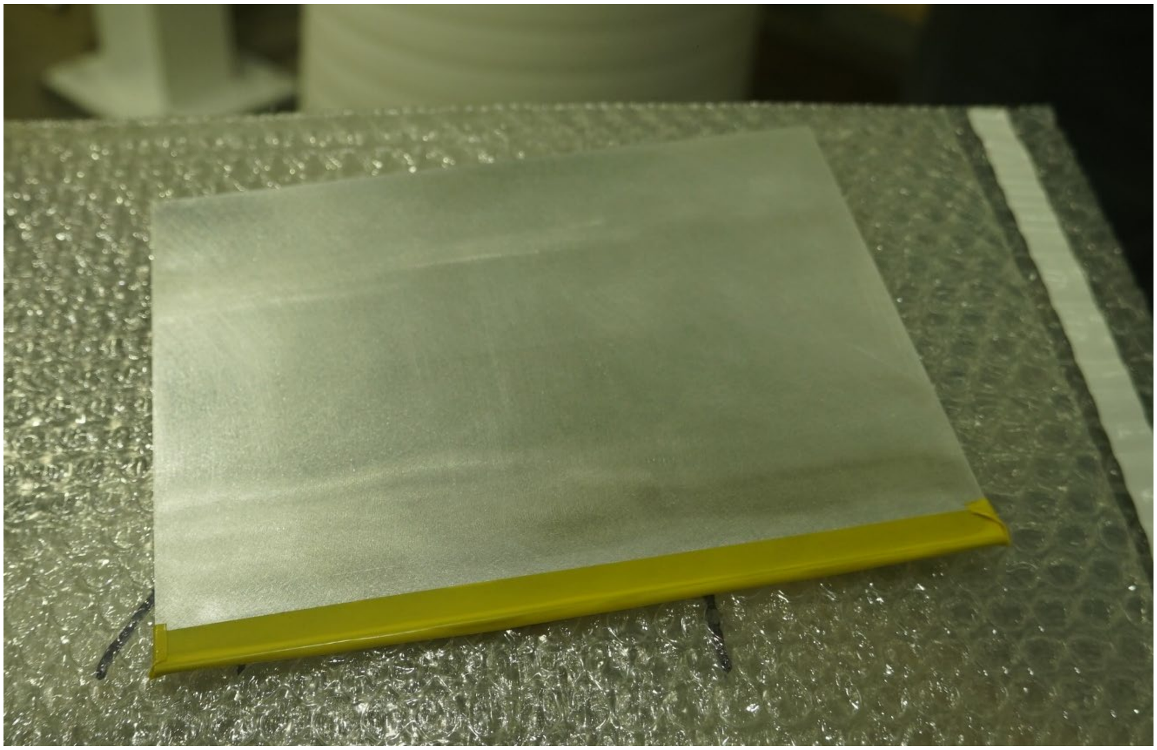


Finished sample hydrogen vessel body.



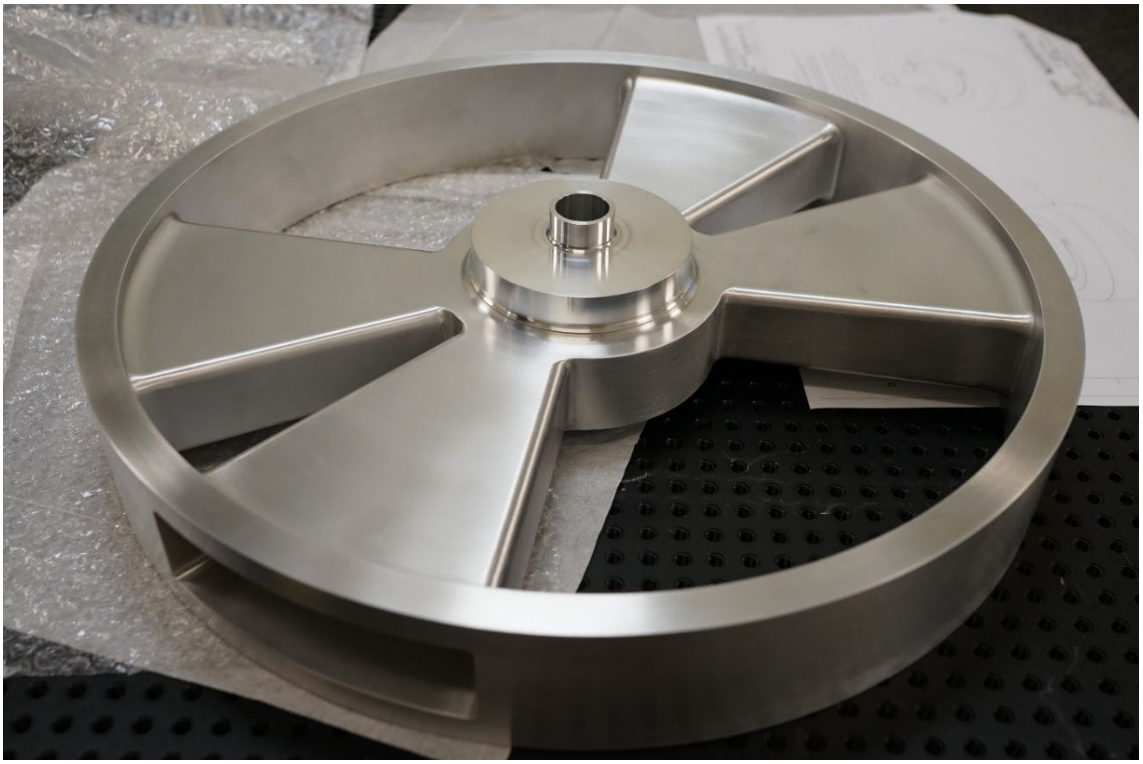
Finished sample vacuum vessel body.

Finished sample hydrogen vessel lid.

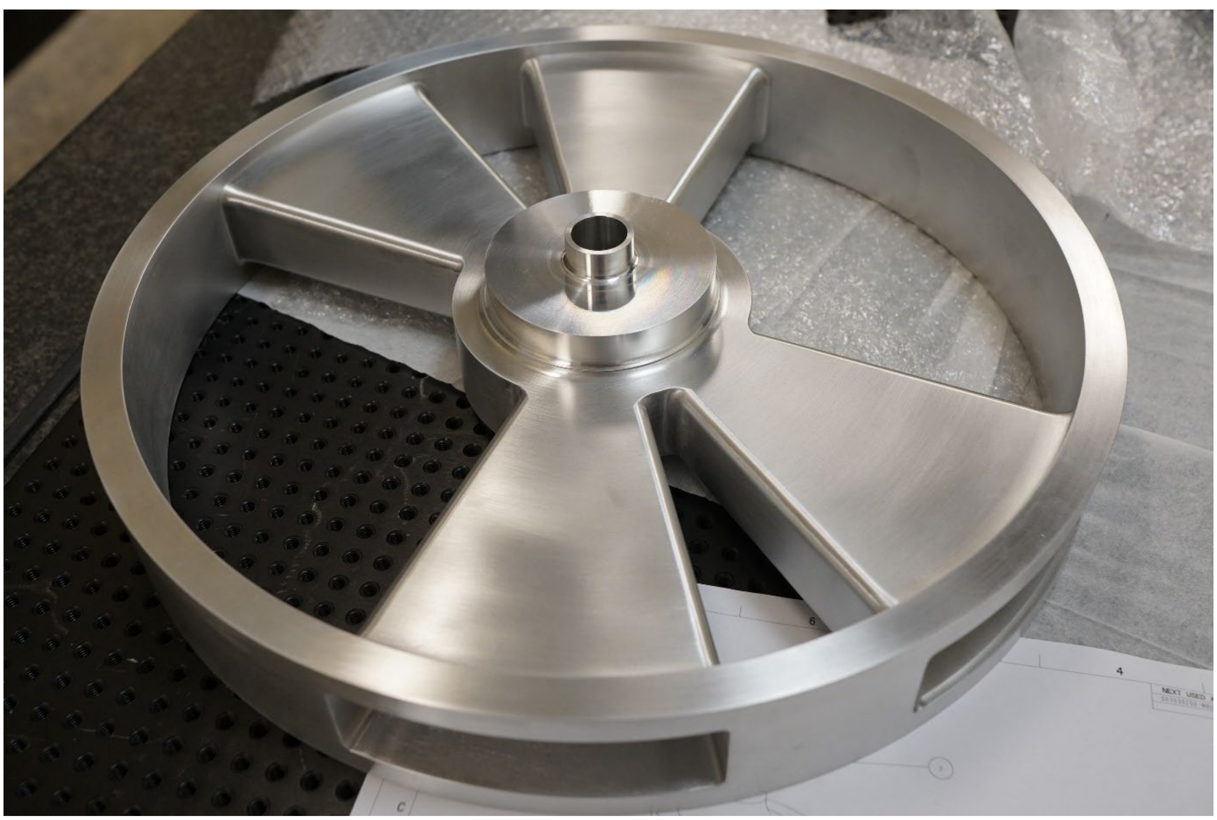

Finished PQR plate without backer.

Finished hydrogen vessel lid.

Receipt of Parts at ORNL – August 10, 2022



Testing fit up of vacuum vessel body to lid at receipt.



Testing fit up of vacuum vessel body to lid at receipt.


Testing fit up of vacuum vessel body to lid at receipt.


Vacuum vessel body at receipt.

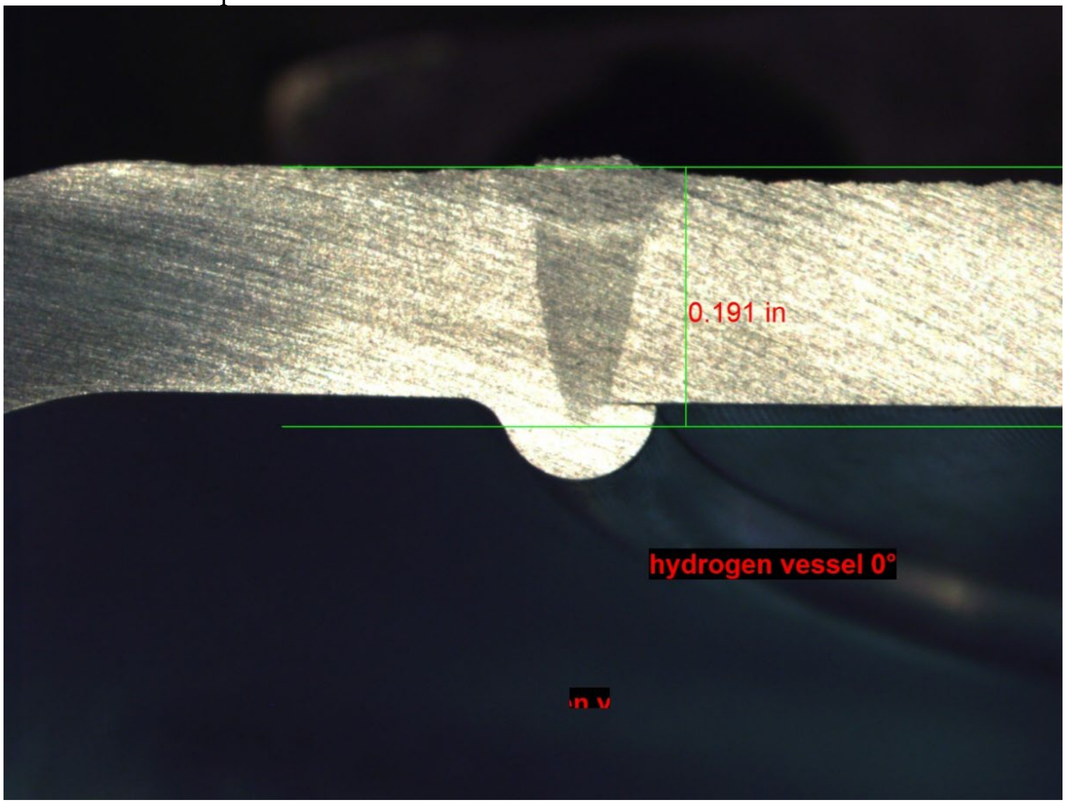

Vacuum vessel lid at receipt.


Hydrogen vessel lid at receipt.

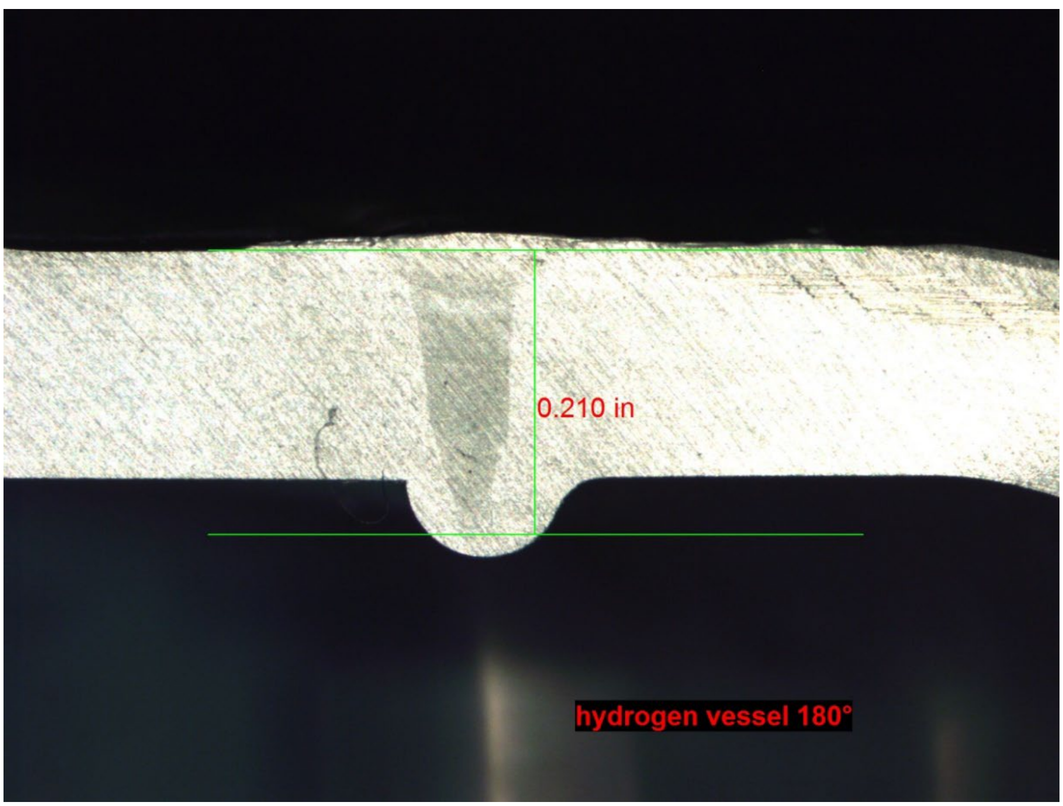
Hydrogen vessel body at receipt.

Hydrogen vessel body at receipt.

PTR Weld Development Photos

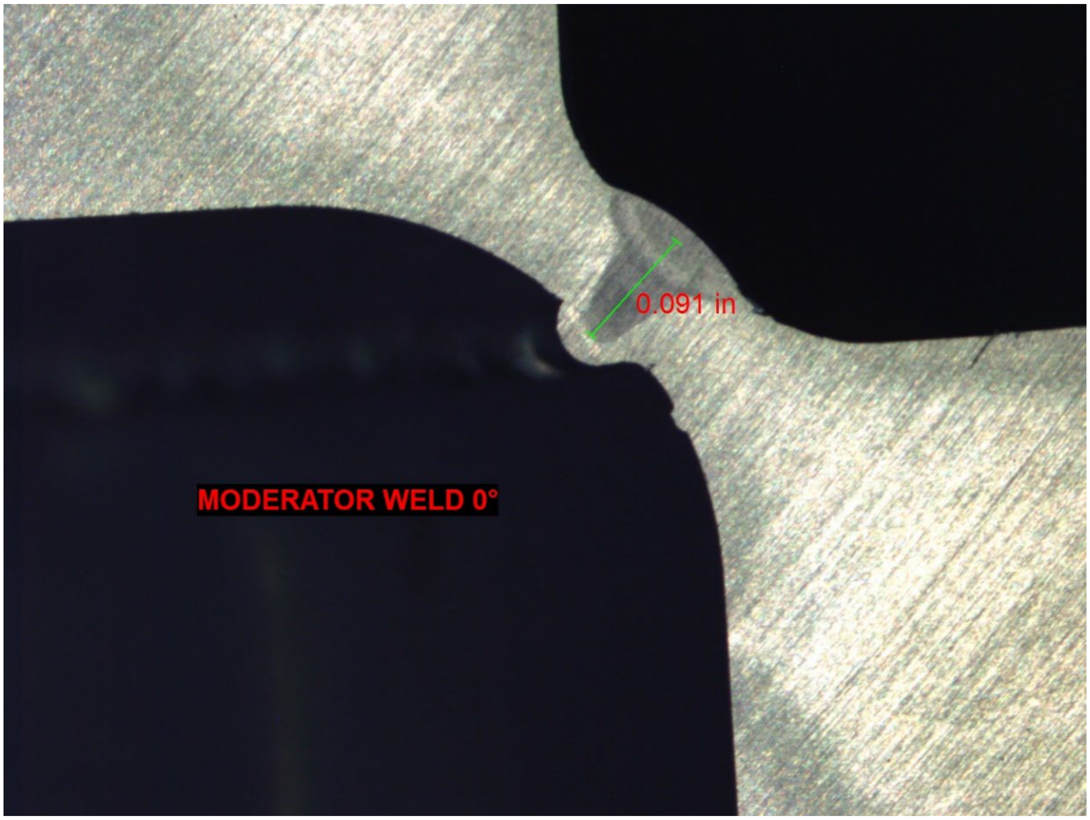


Hydrogen vessel weld section at start of weld.

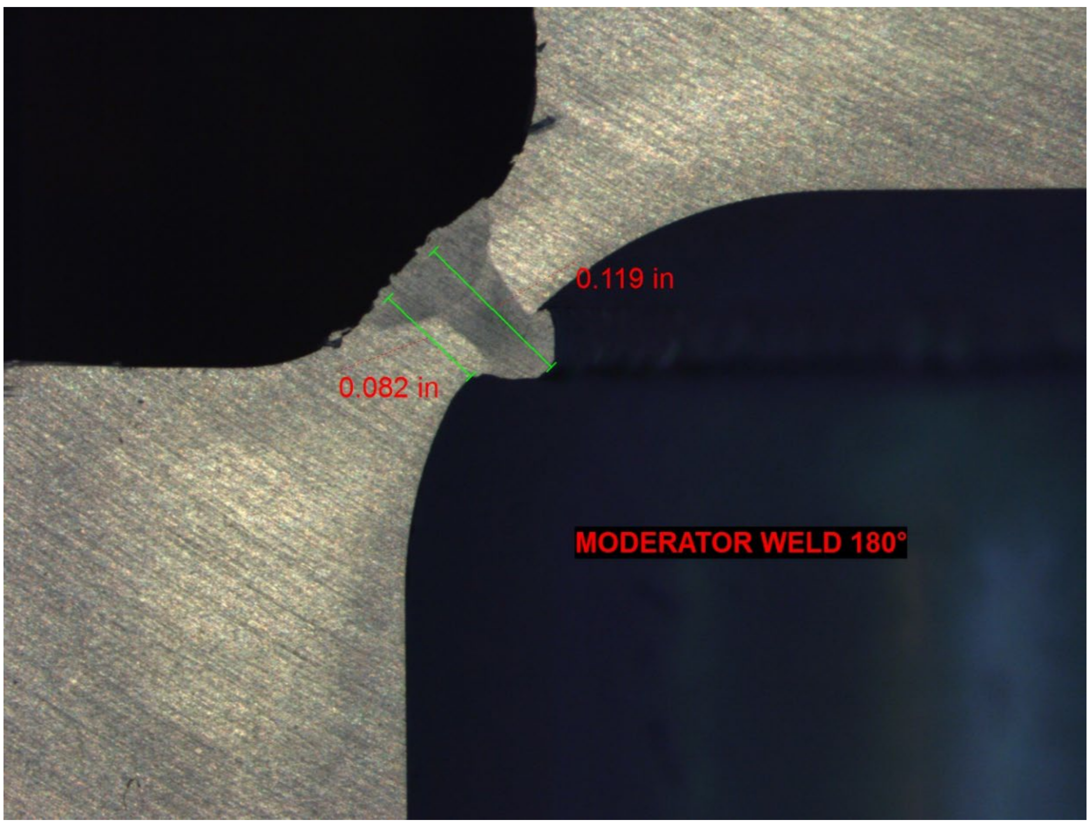


Hydrogen vessel weld section 180 degrees from start of weld.


Intermittent over penetration of hydrogen vessel sample weld.



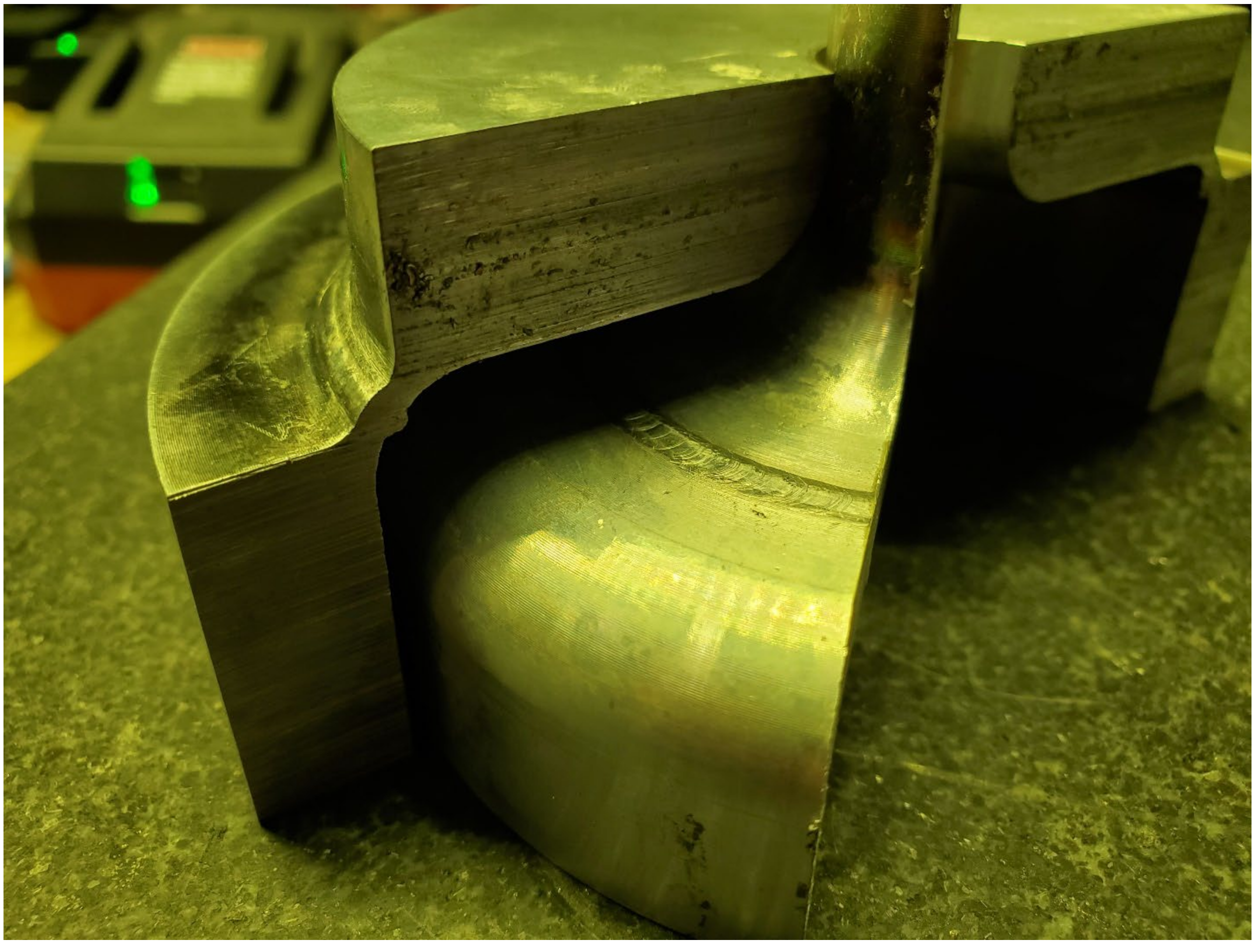
Vacuum vessel weld section at start of weld.

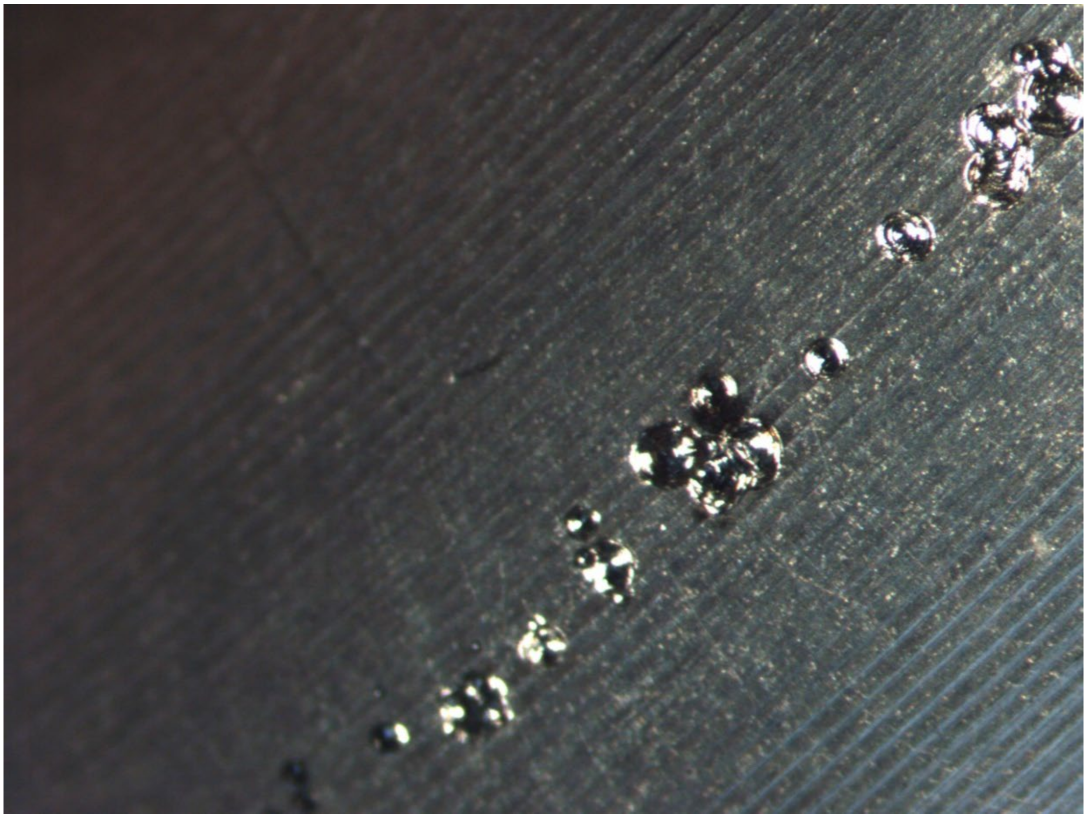


Vacuum vessel weld section 180 degrees from start of weld.

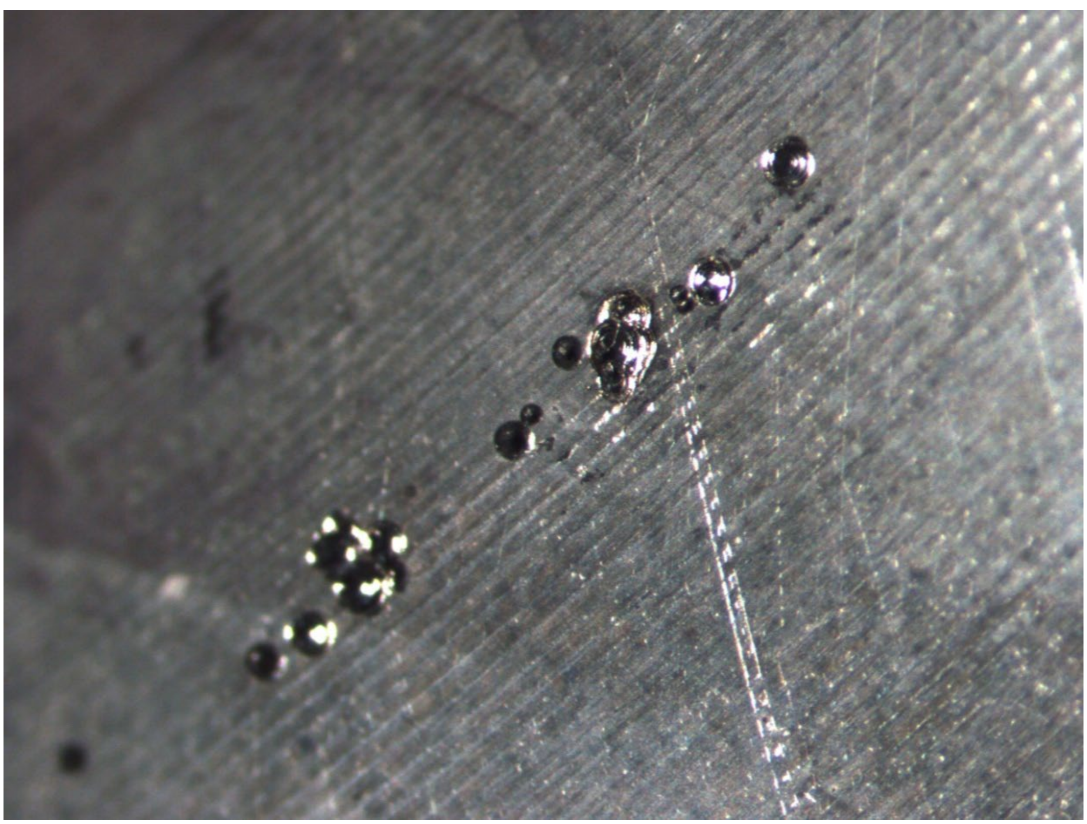
Over penetration of vacuum vessel weld backer resulting in melting of backer.


Over penetration of vacuum vessel weld backer resulting in melting of backer.

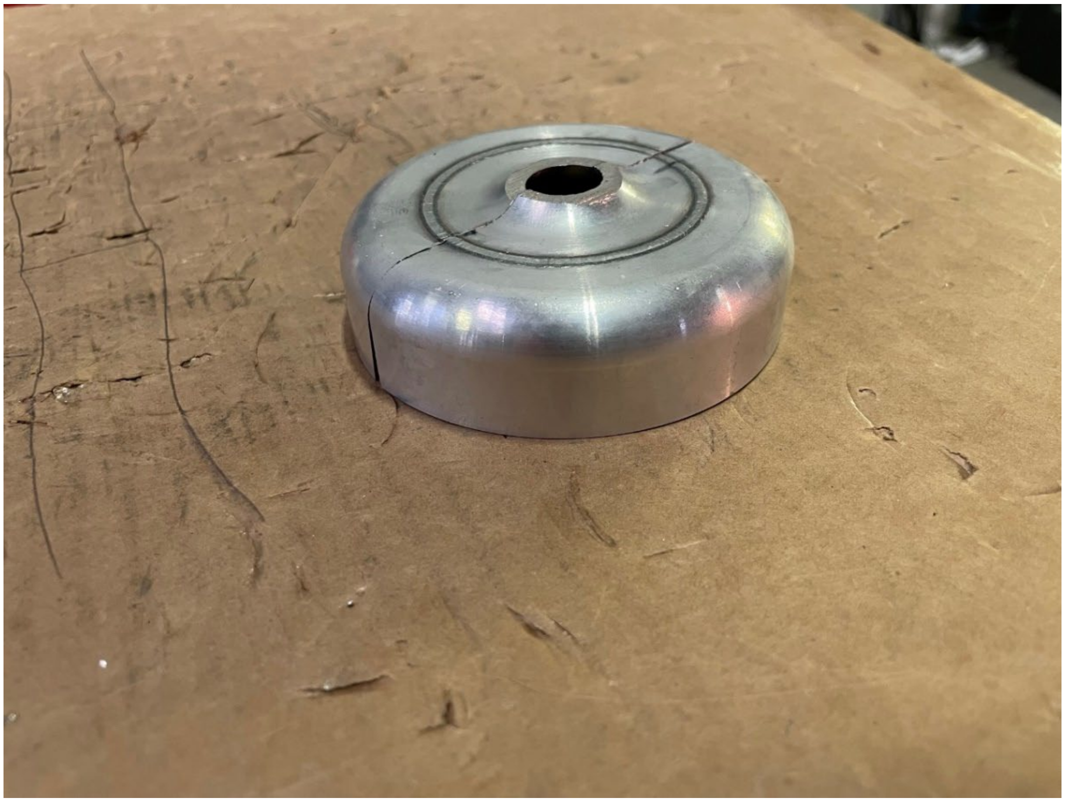

Already welded sample hydrogen vessels were placed inside sample vacuum vessel welds during welding to determine the effect of overpenetration.



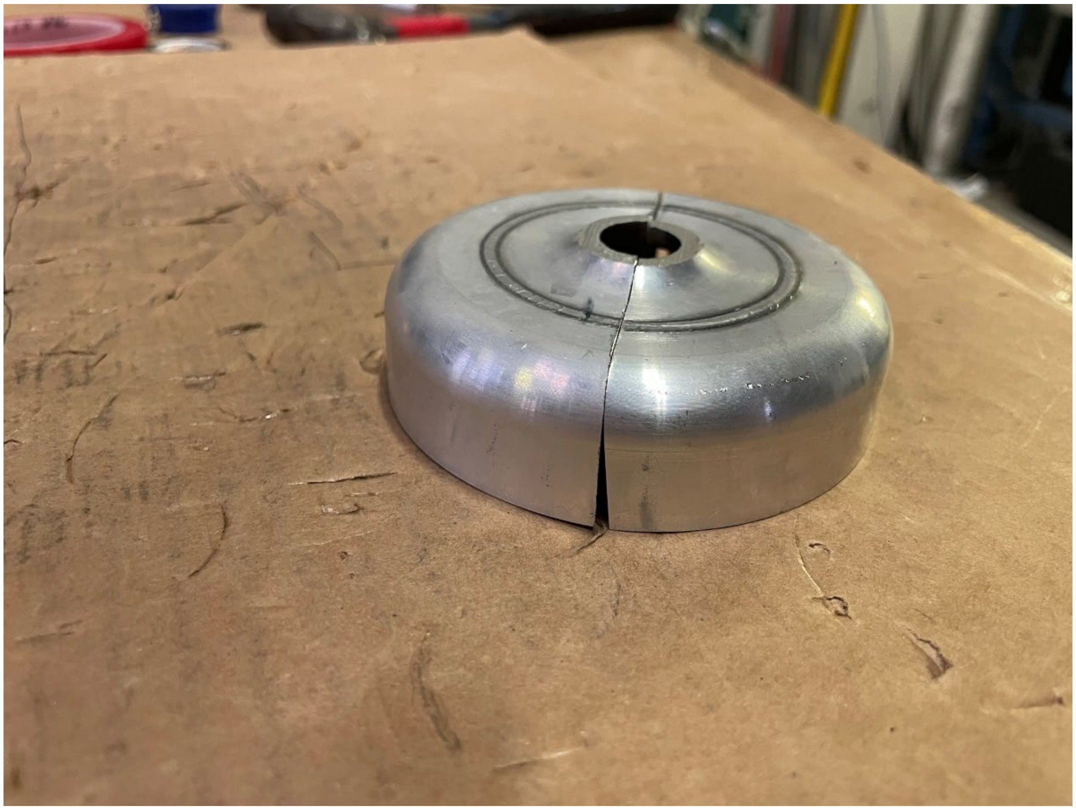
Beam strikes on the hydrogen vessel sample due to overpenetration of the vacuum vessel weld.



Beam strikes on the hydrogen vessel sample due to overpenetration of the vacuum vessel weld.


Beam strikes on the hydrogen vessel sample due to overpenetration of the vacuum vessel weld.


Beam strikes on the hydrogen vessel sample due to overpenetration of the vacuum vessel weld.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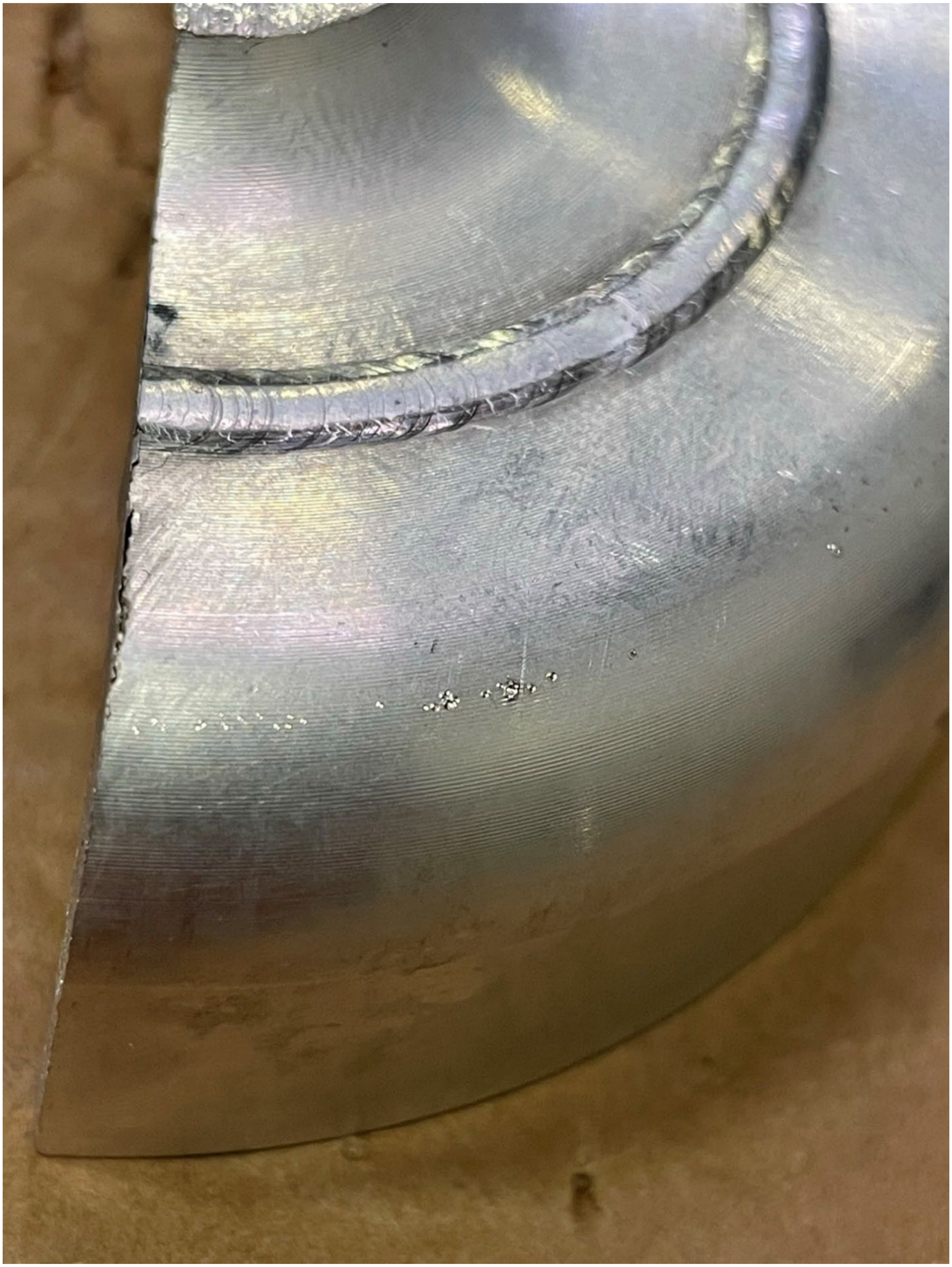

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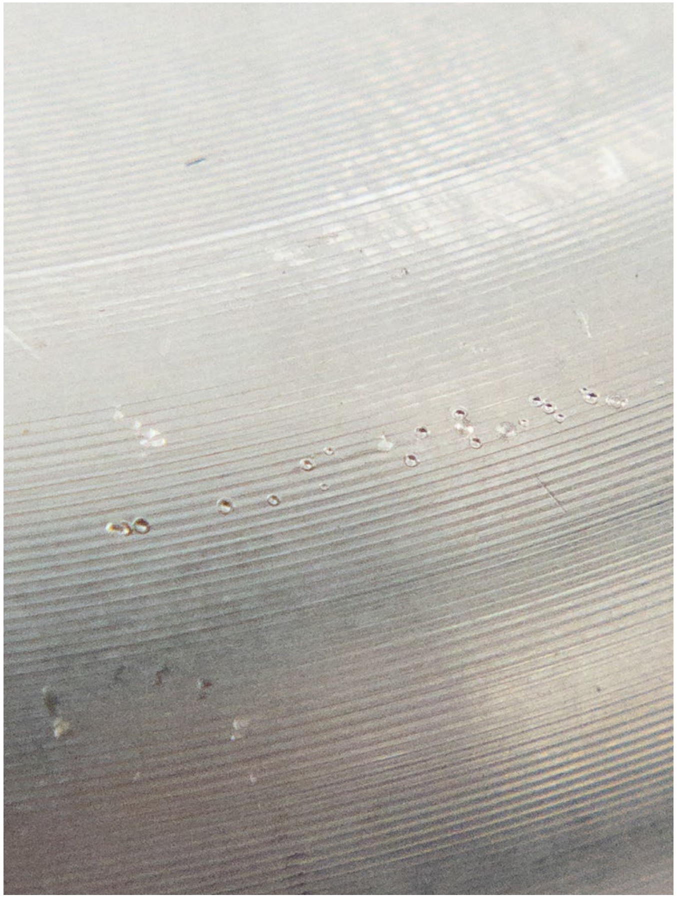
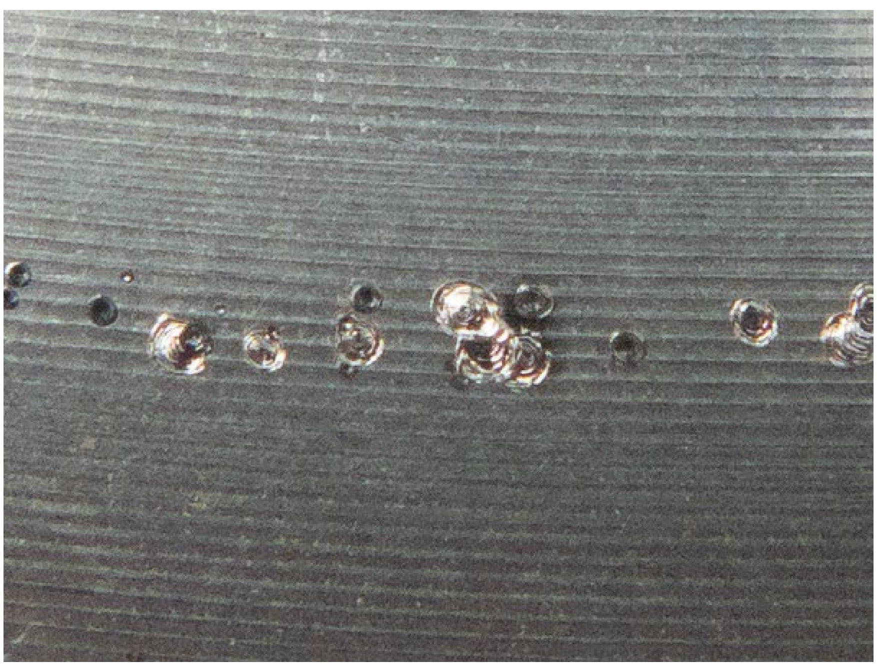
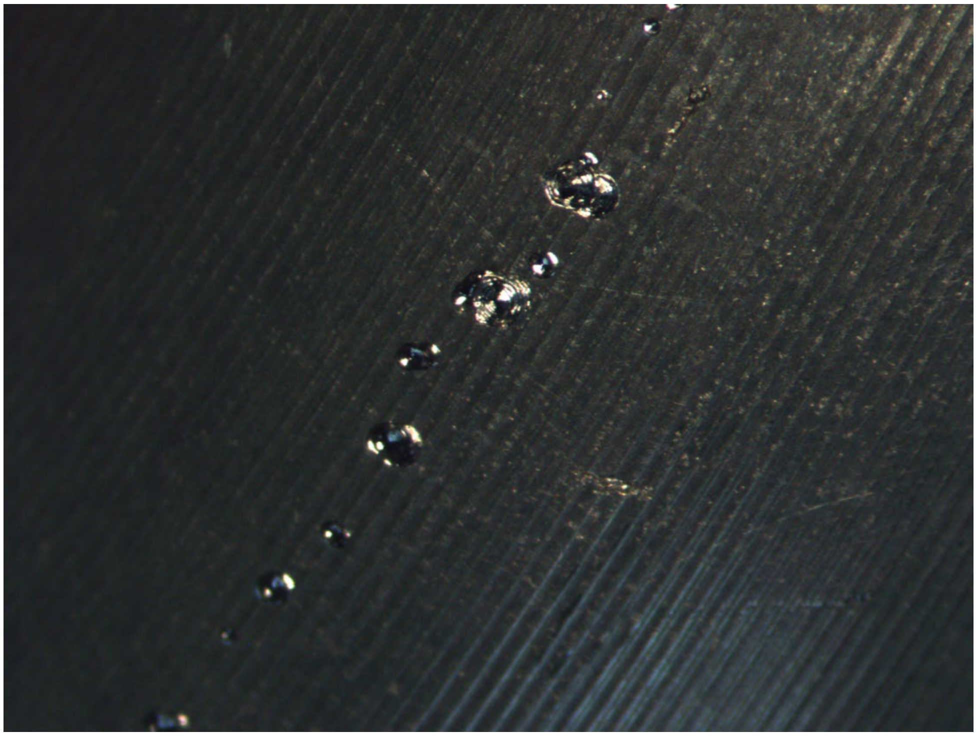

Beam strikes on the hydrogen vessel sample due to overpenetration of the vacuum vessel weld.


Beam strikes on the hydrogen vessel sample due to overpenetration of the vacuum vessel weld.

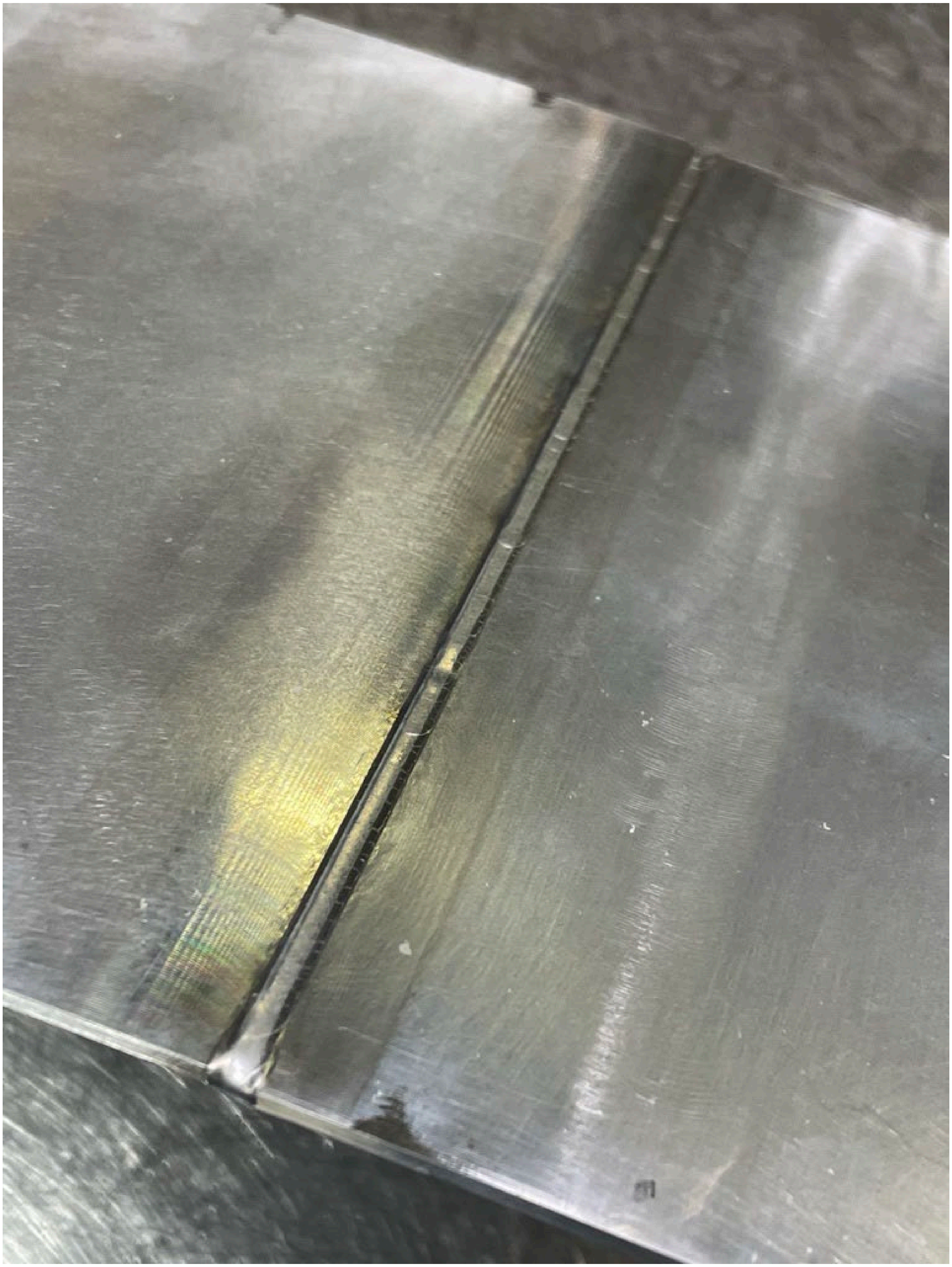

Beam strikes on the hydrogen vessel sample due to overpenetration of the vacuum vessel weld.

Beam strikes on the hydrogen vessel sample due to overpenetration of the vacuum vessel weld.

Hydrogen Vessel and Development Welding at PTR

Four completed hydrogen vessels.

Loading vacuum vessel weld sample into EB weld machine.


Completed PQR plate weld.

Completed hydrogen vessel.

Completed hydrogen vessel.

Completed hydrogen vessel.

Hydrogen Vessel Leak Checking at ORNL

Beam Blocker shims and forming tool

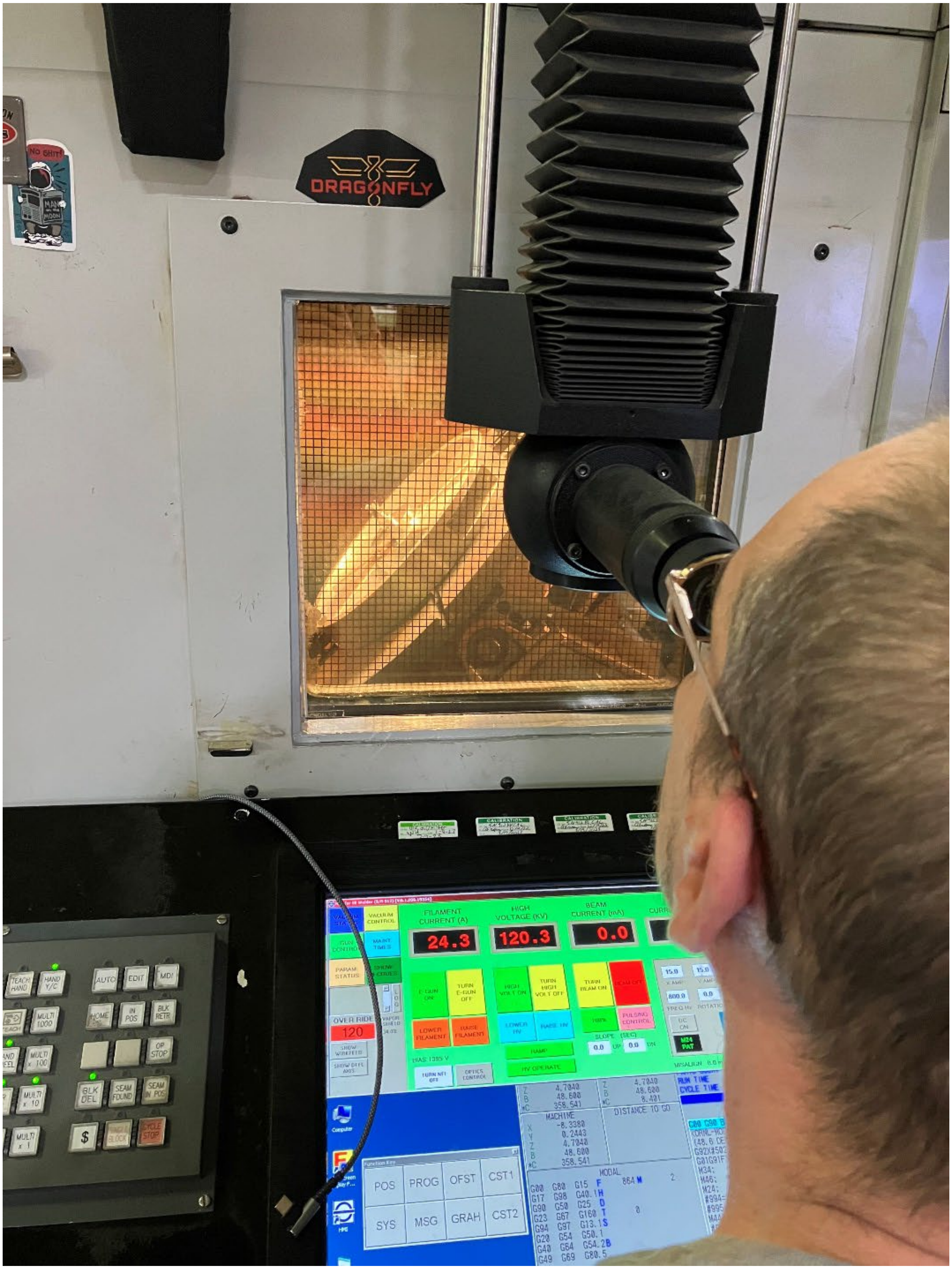
Vacuum Vessel Welding at PTR

Hydrogen vessel with beam blocker shims installed.

Vacuum vessel body being indicated in on rotary table.

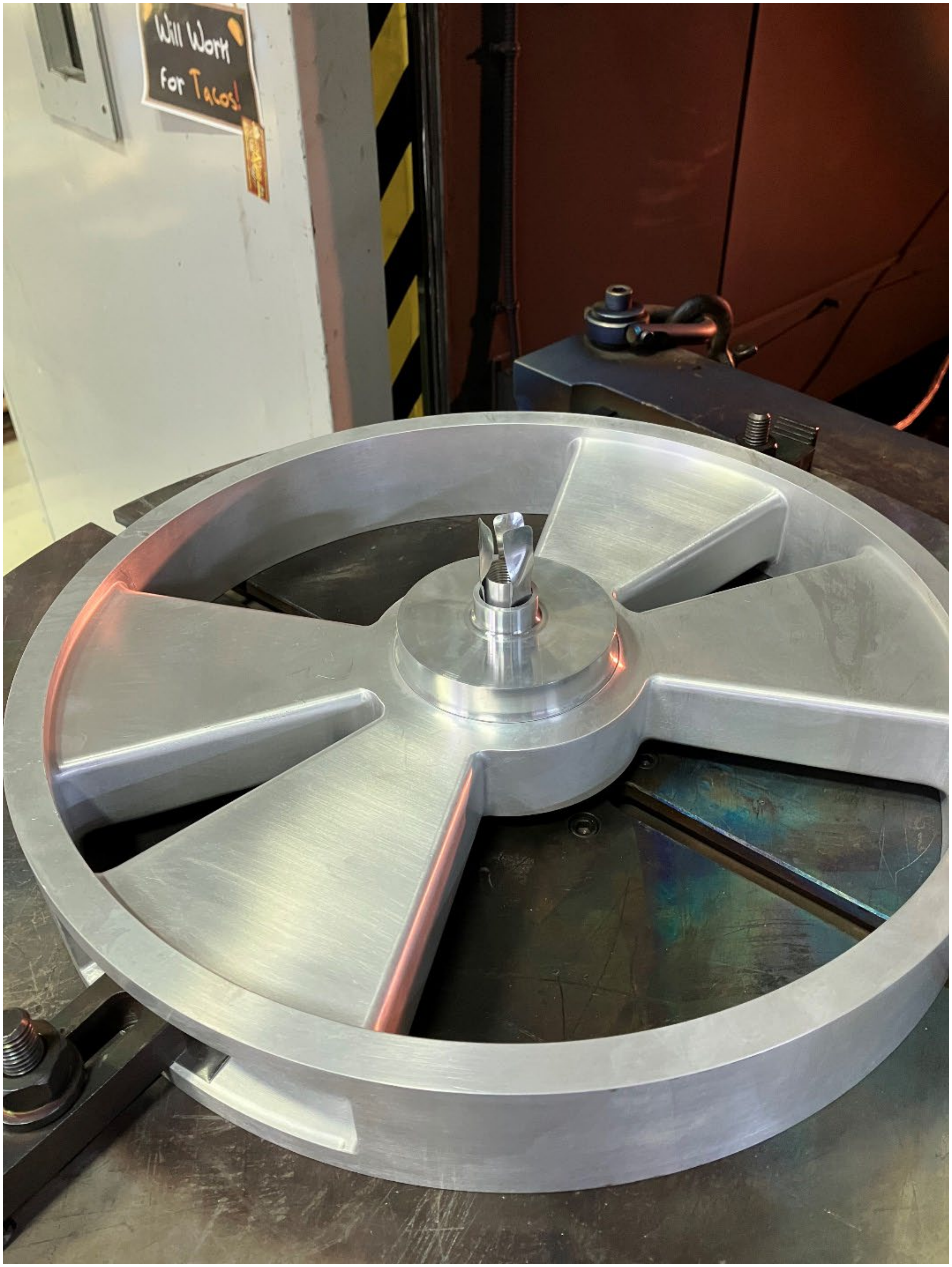
Hydrogen vessel with beam blocker shims installed into vacuum vessel body.


Vacuum vessel lid installed and clamped down for tacking.



Vacuum vessel welding in the EB weld chamber.

Vacuum vessel welding in the EB weld chamber.

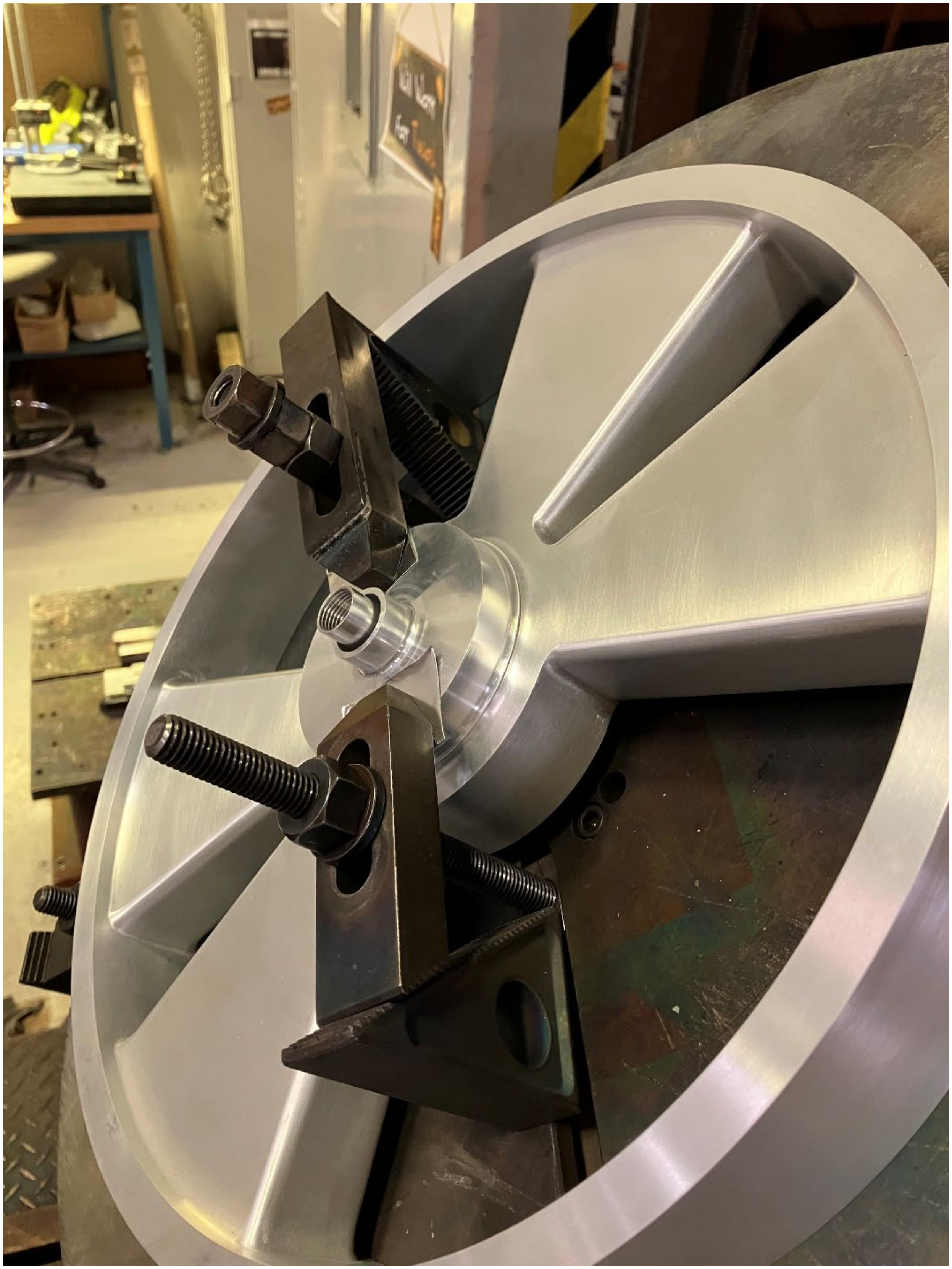


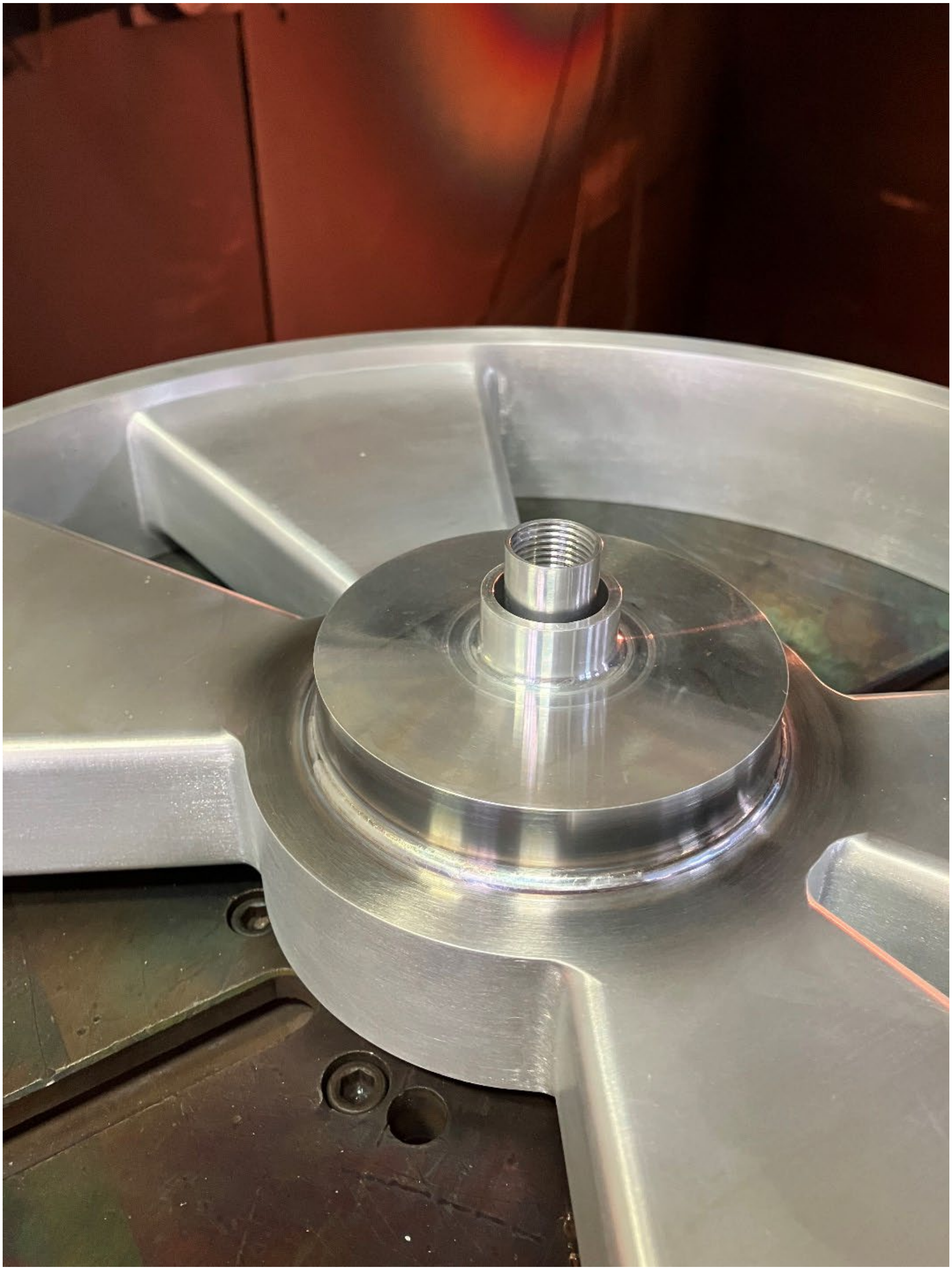
Vacuum vessel weld completed and cooling down.

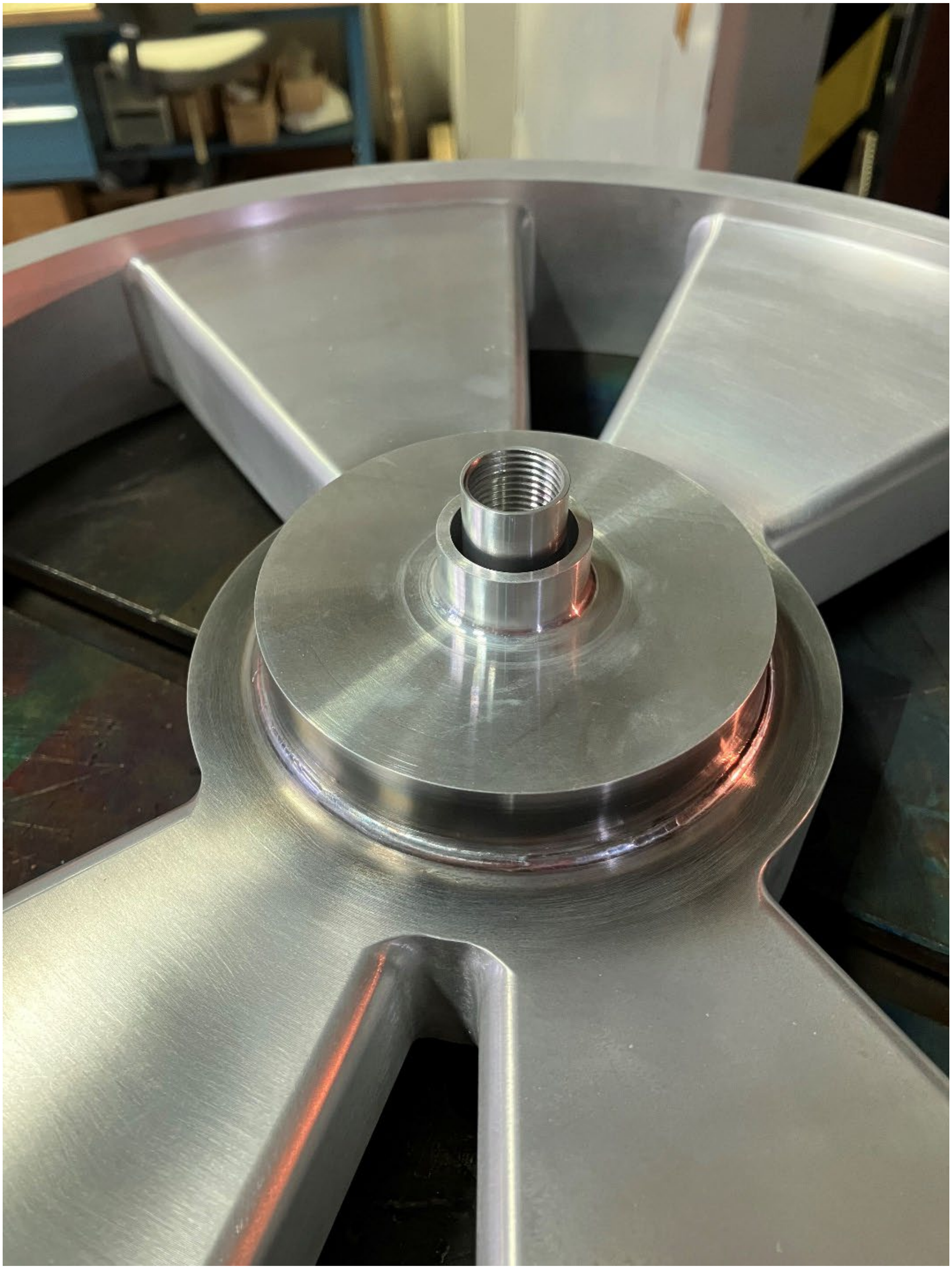

Vacuum vessel weld completed and cooling down.


Vacuum vessel weld completed and shims unsuccessfully removed (broken off at lip).

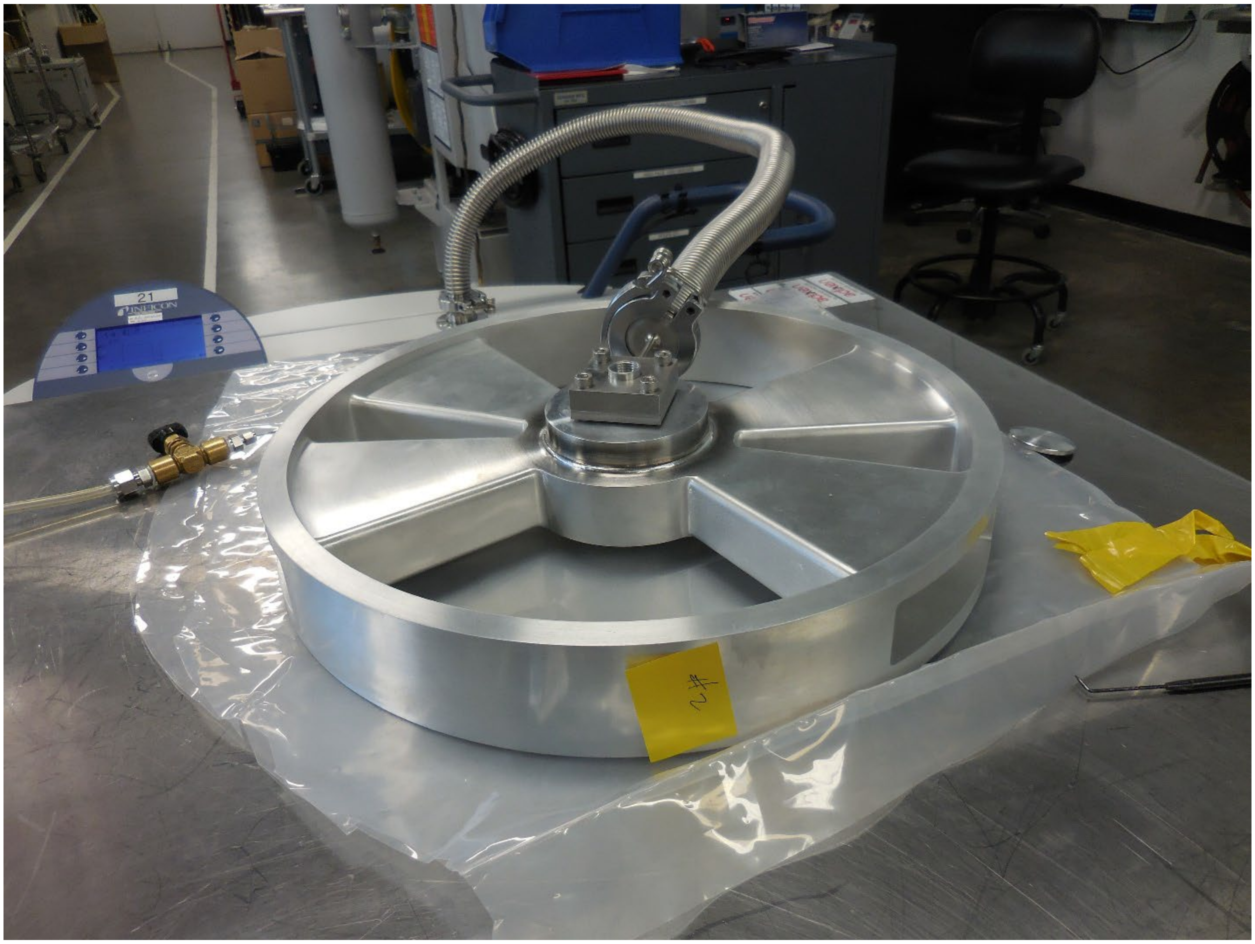
Tedious installation of titanium spacers onto hydrogen vessel.


Vacuum vessel with no beam blocker shims being loaded into EB weld machine.


Vacuum vessel weld completed and cooling down.


Vacuum vessel weld completed and cooling down.

Vacuum Vessel Leak Checking at ORNL prior to post weld machining.



Final Machining at Metalex

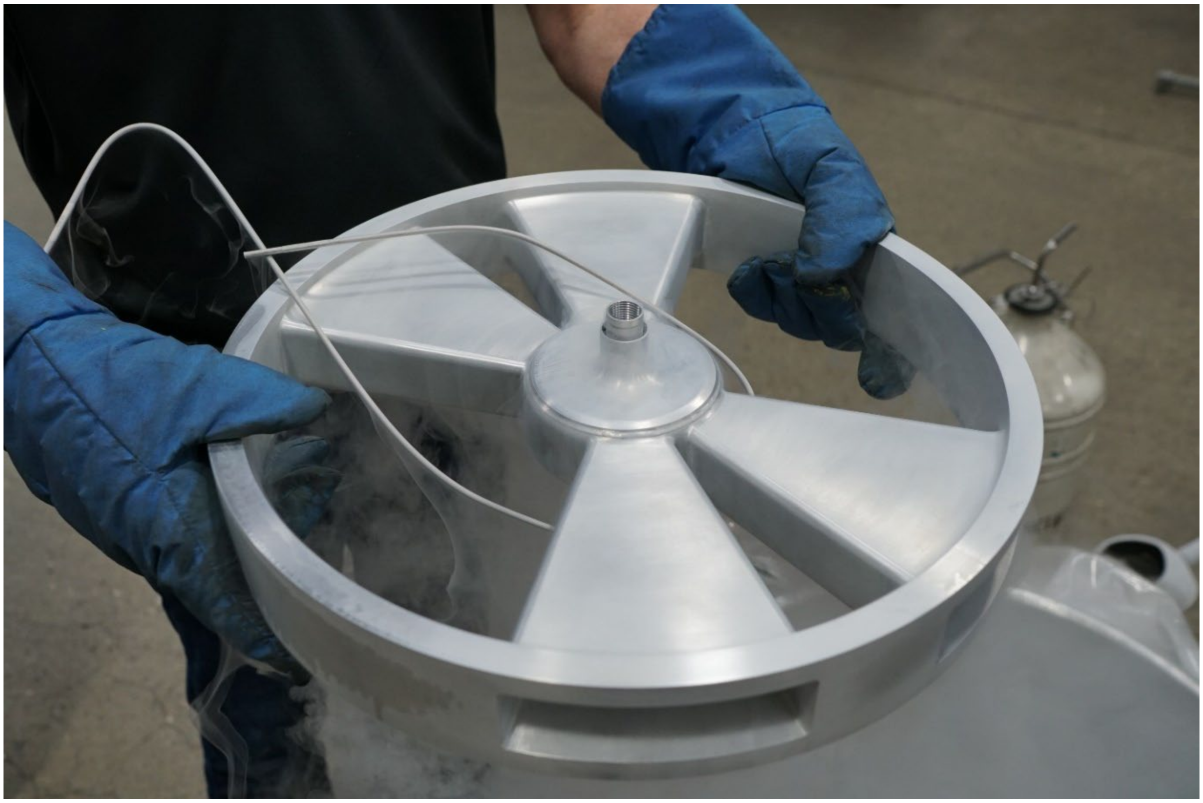
Vacuum vessel undergoing post weld machining at Metalex.

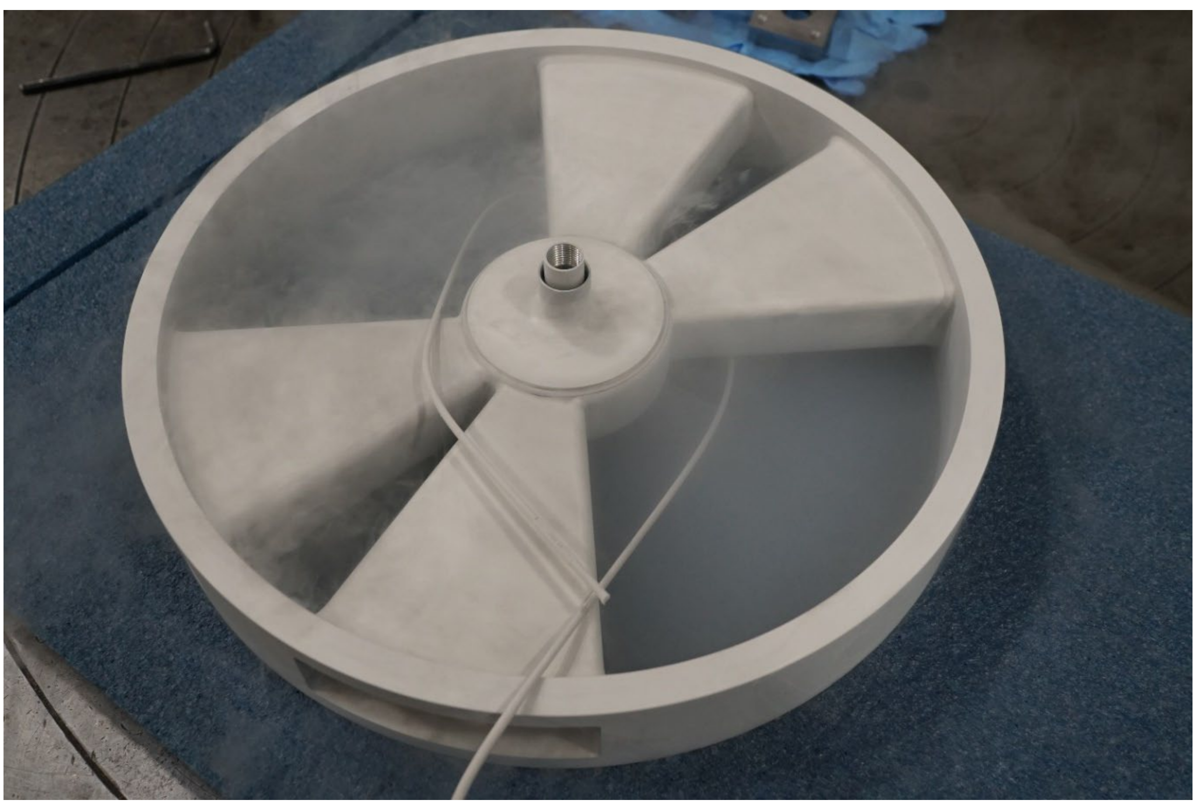
Vacuum vessel after post weld machining completed at Metalex.

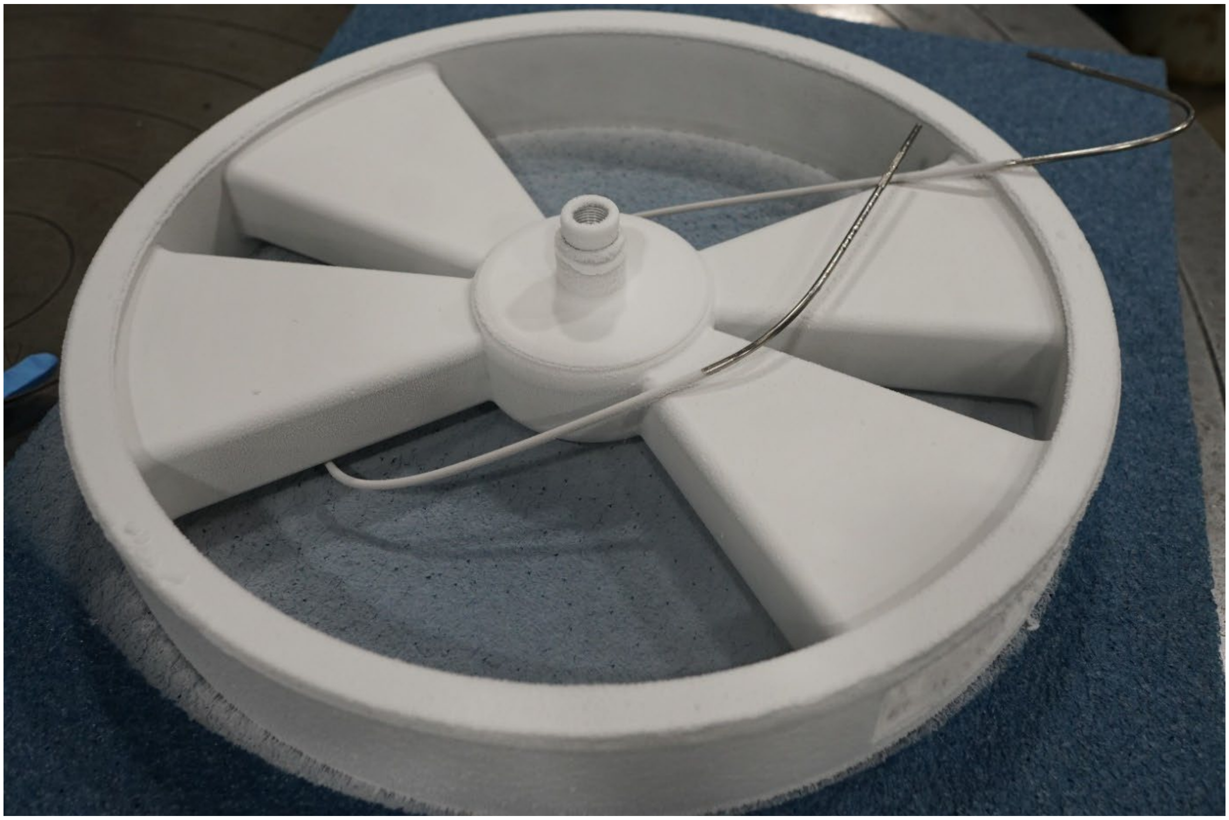
Final Testing at Metalex


Cold shocking in LN2 at Metalex.


Cold shocking in LN2 at Metalex.


Warming up after cold shocking.


Warming up after cold shocking.


Warming up after cold shocking.

Vacuum vessel pressure testing set up.

Vacuum vessel pressure test at test pressure.

Vacuum vessel leak checking at Metalex.

Final Machined Cylinder Moderator Prototype Receipt