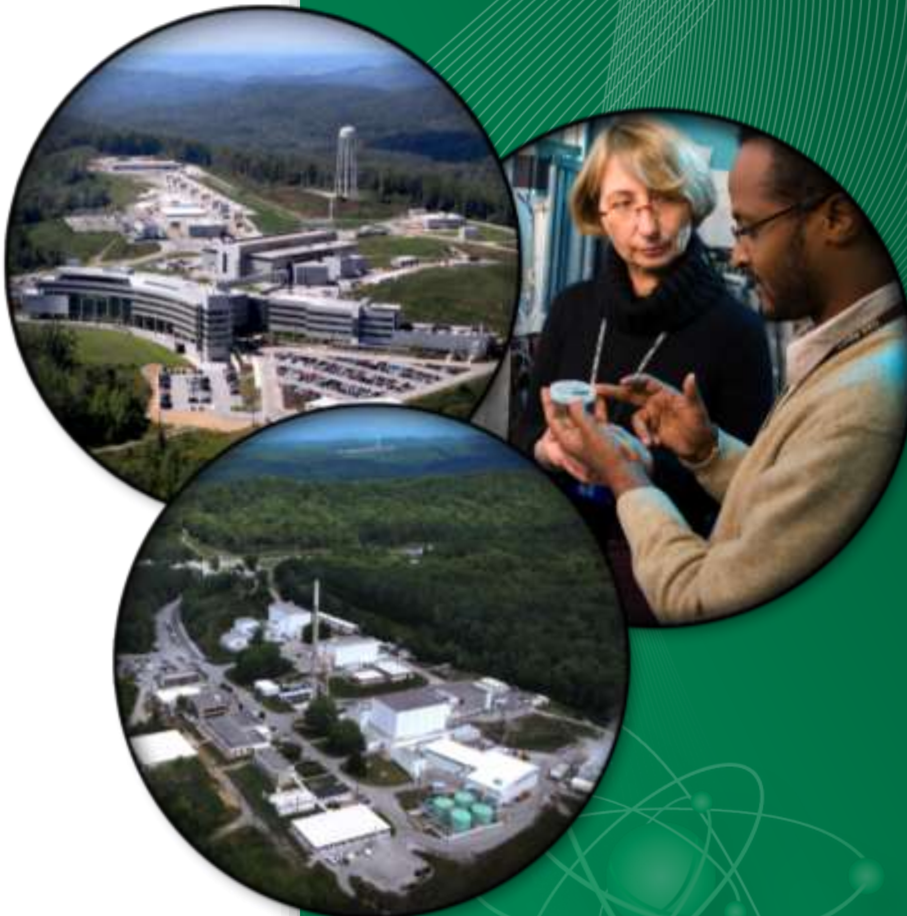
Target Engineering



Peter M. Rosenblad

Target Engineer

AAC Meeting, May 7-8, 2013

Topics

- Target Station Challenge – Robust Operation with Experimental Factors
- Capabilities and Limits of Present Target Design
- Target Development – Jet Flow Target
- Target Supply and Manufacturing
- Leak Detection
- Spare IRP Fabrication Update
- Aluminum Proton Beam Window (PBW) Update

Our Challenge: “Robust Operations” and World Record Power Levels

- BES Review Finding: “The Hg target system was described as ‘still an experiment.’ The target design/operation must evolve to provide for robust operation of the SNS facility”
- Meanwhile, near term customer expectation is @ 1.4 MW operation
- Long term expectation is higher

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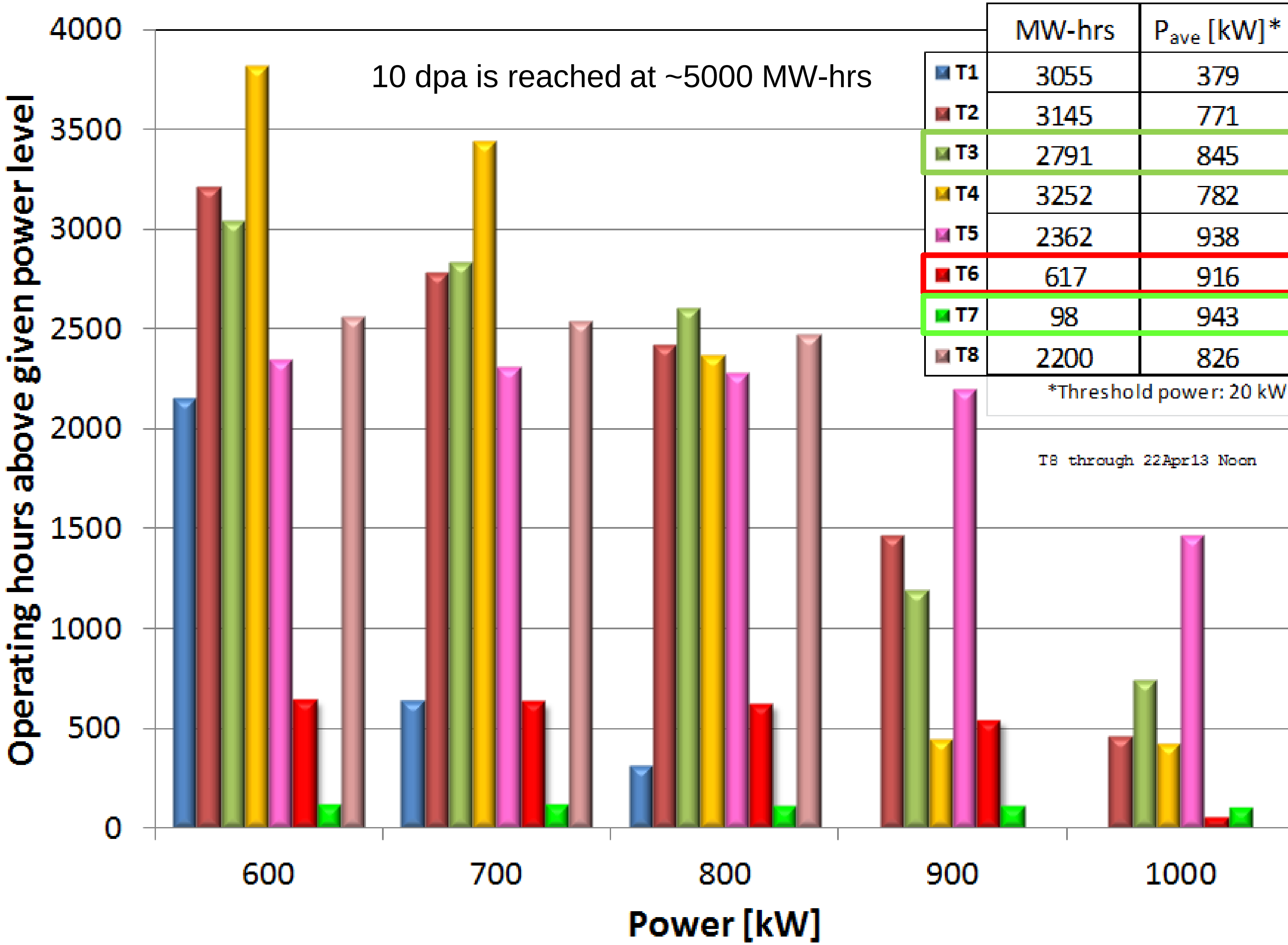
Target lifetime and power levels exceed initial expectations, but have room for improvement



	MW-hrs	P_{ave} [kW]*	
T1	3055	379	
T2	3145	771	
T3	2791	845	Cavitation / inclusions?
T4	3252	782	
T5	2362	938	
T6	617	916	Weld defect
T7	98	943	Weld defect
T8	2200	826	

*Threshold power: 20 kW

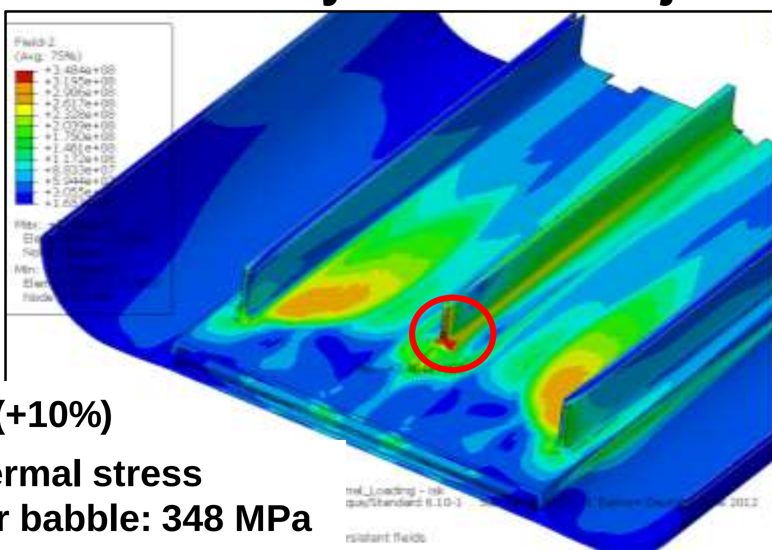
1100 → 1400 → ?

We still have lofty long term power goals for the target system

- Accelerator's present capability is 1.4 MW
  - With energy and current upgrades: 2.8 MW is possible
    - To be shared with STS (SP ≤ 500 kW; LP ~ 1 MW)
- Mercury target shroud radiation damage limit is 10 dpa (administrative)
  - Is reached at ca. 5000 MW-hrs
  - Tensile testing data may lead to a higher limit
- FTS systems were generally designed for 2 MW
  - Ultimate power capacity may be higher
    - Review of operational data and refinement of engineering work
- *Beam-induced cavitation damage may shorten target life and limit maximum power without mitigation*

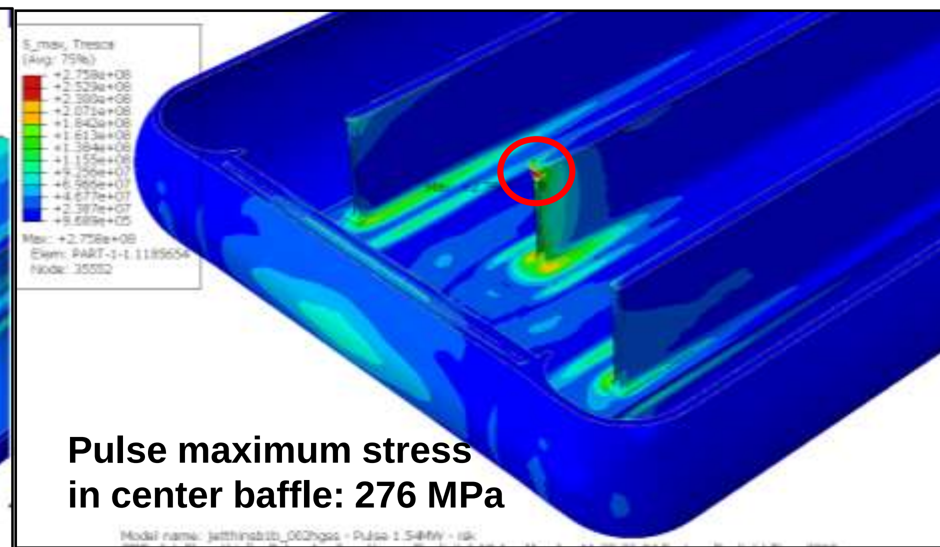
The present (and new jet flow) target design is limited to 1.4 MW

- Radiation damage: 10 dpa on water-cooled shroud
- Engineered for 1.4 MW
- Cavitation based lifetime is unknown
- Challenged by thermal & pressure pulse stresses
    1. Center baffle
    2. Beam entrance window
    3. Front body – transition joint



1.4 MW (+10%)

Max. thermal stress
in center babble: 348 MPa



Pulse maximum stress
in center baffle: 276 MPa

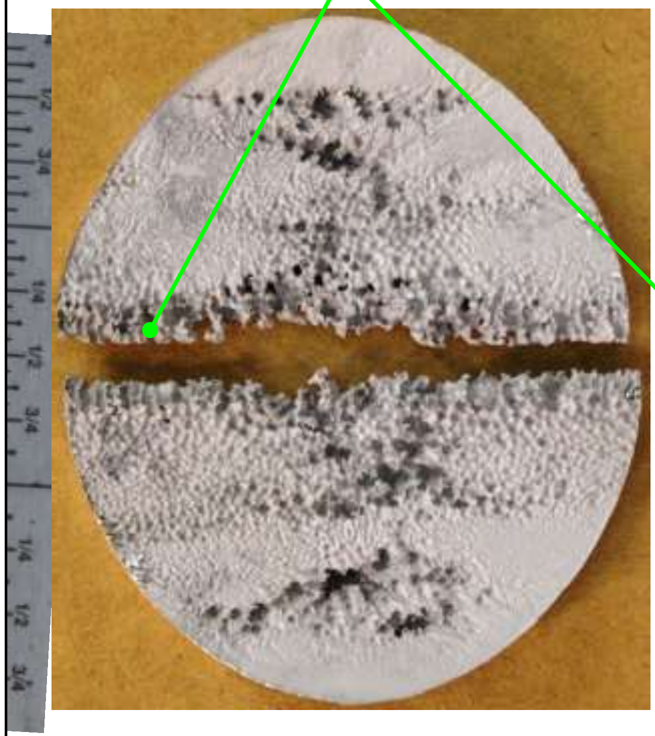
Damage to inner vessel wall at center surface facing bulk mercury

T4

T2

d at B&W

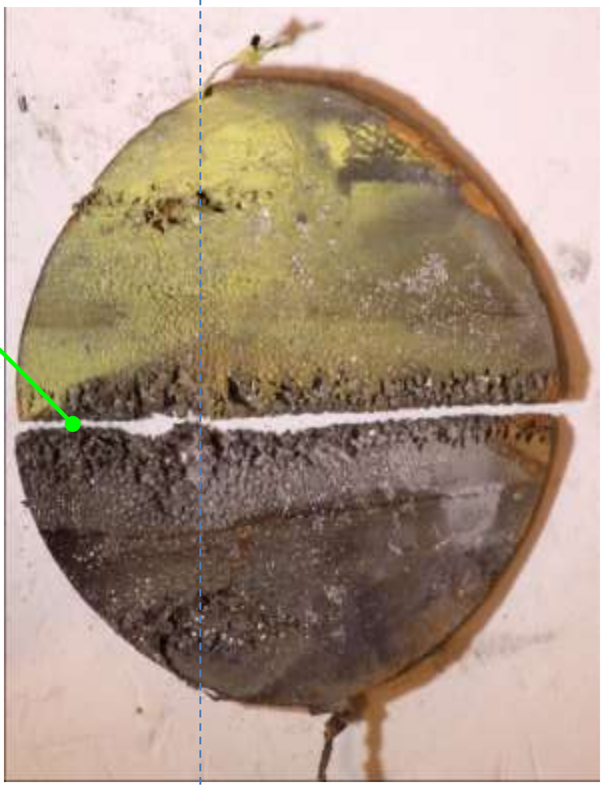
Horizontal “V” of aggressive erosion



T3

Fractured across full width of inner window

(cut missed target center by ~ 13 mm)



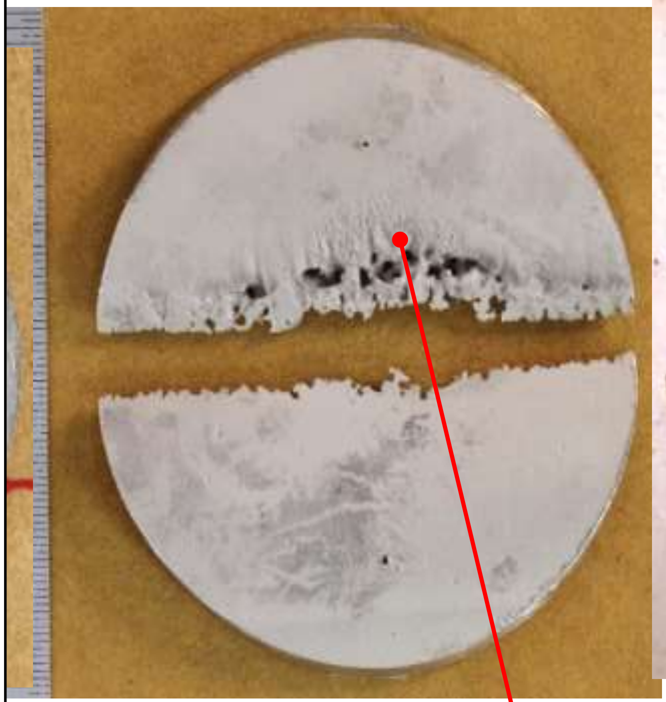
All specimen diameters are 60 mm, except T2 is 57 mm. Views oriented as during operation.

Damage to inner vessel wall at center
surface facing mercury channel

- Much less erosion vs. bulk side
- Elongated pits

T4

T2



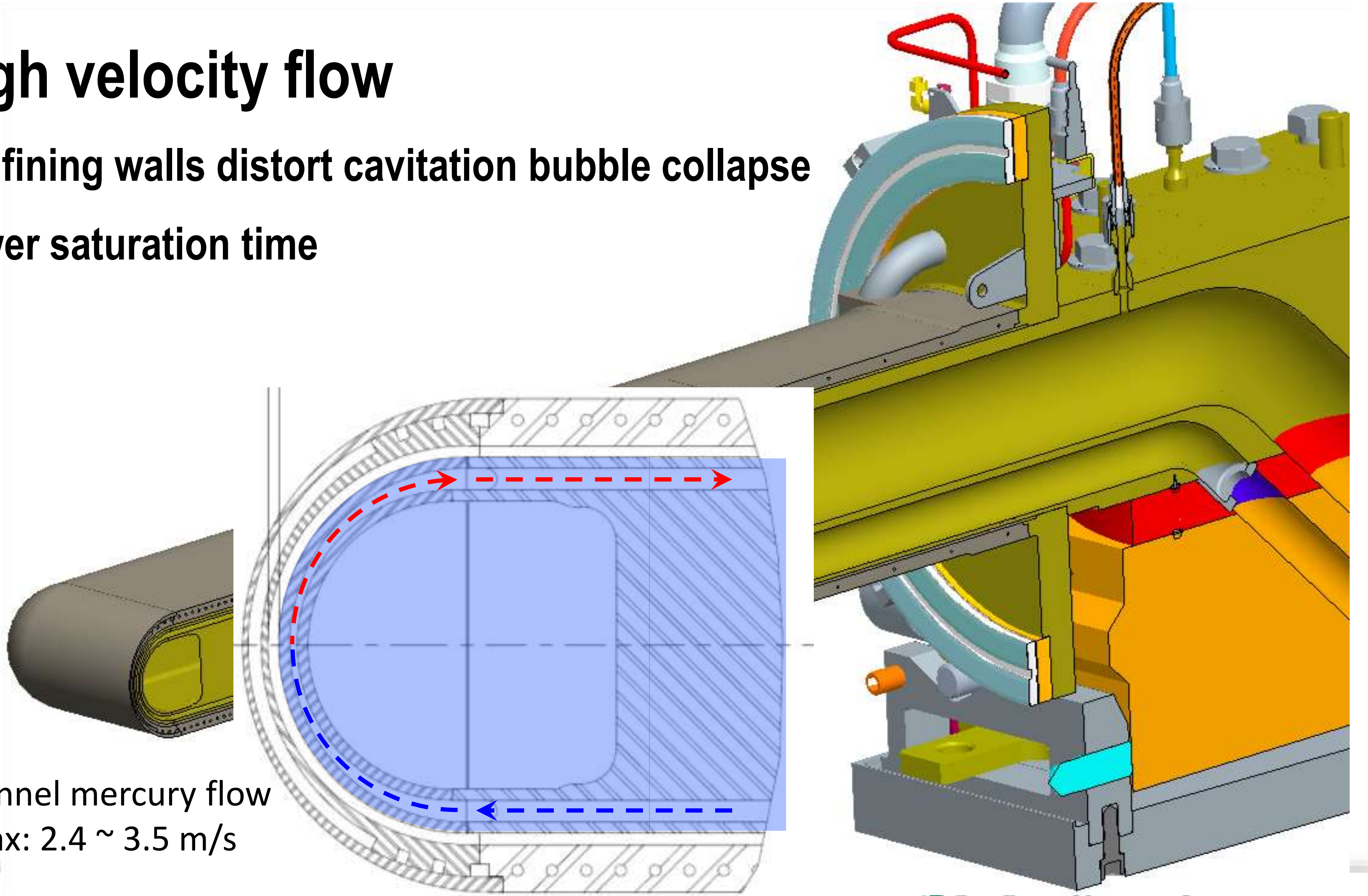
T3

Through holes

More erosion downstream of large through-holes

Beam window channel surfaces have much less cavitation damage – why?

- **High velocity flow**
- **Confining walls distort cavitation bubble collapse**
- **Lower saturation time**

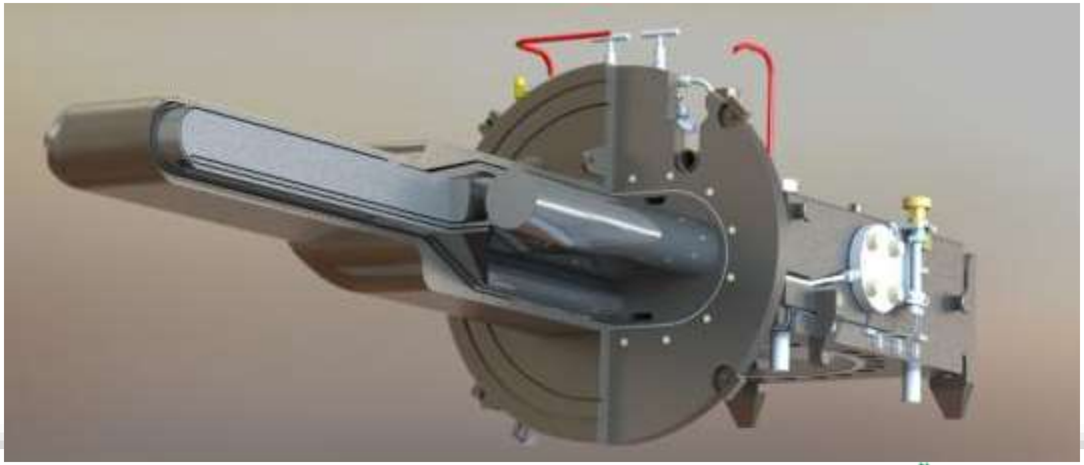


Topics

- Target Station Challenge – Robust Operation with Experimental Factors
- Capabilities and Limits of Present Target Design
- **Target Development – Jet Flow Target**
- Target Supply and Manufacturing
- Leak Detection
- Spare IRP Fabrication Update
- Aluminum Proton Beam Window (PBW) Update

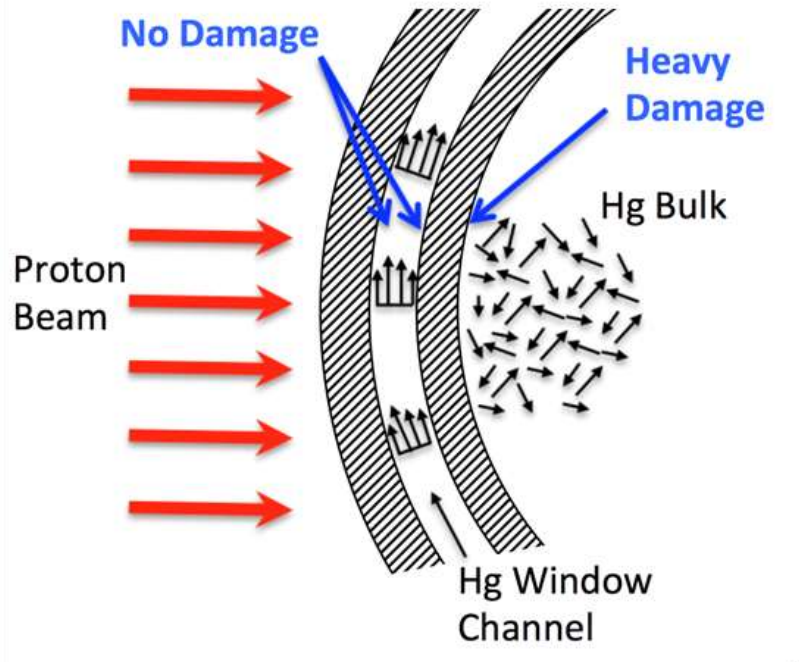
The jet-flow target design aims to extend target life at up to 1.4 MW

- Establishes 2 m/s flow over inner window surface where cavitation erosion has been most severe
- Mimics flow in beam window channel, where damage has been less than bulk side
- Experimental data also indicates flow provides some degree of damage mitigation
  - Not as much as gas mitigation technologies

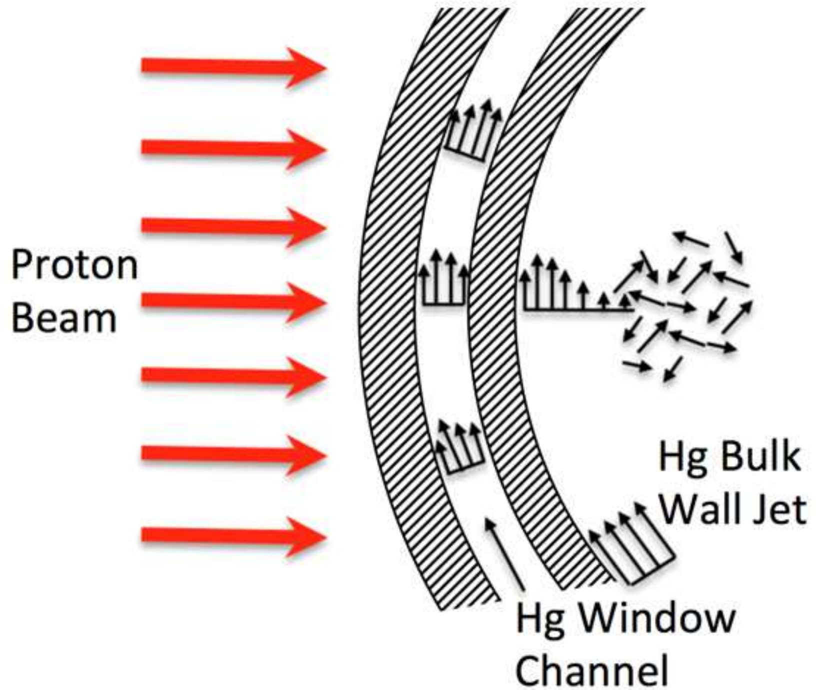


The jet flow design moves the quasi-stagnation zone (~0 m/s net flow) away from the inner window surface

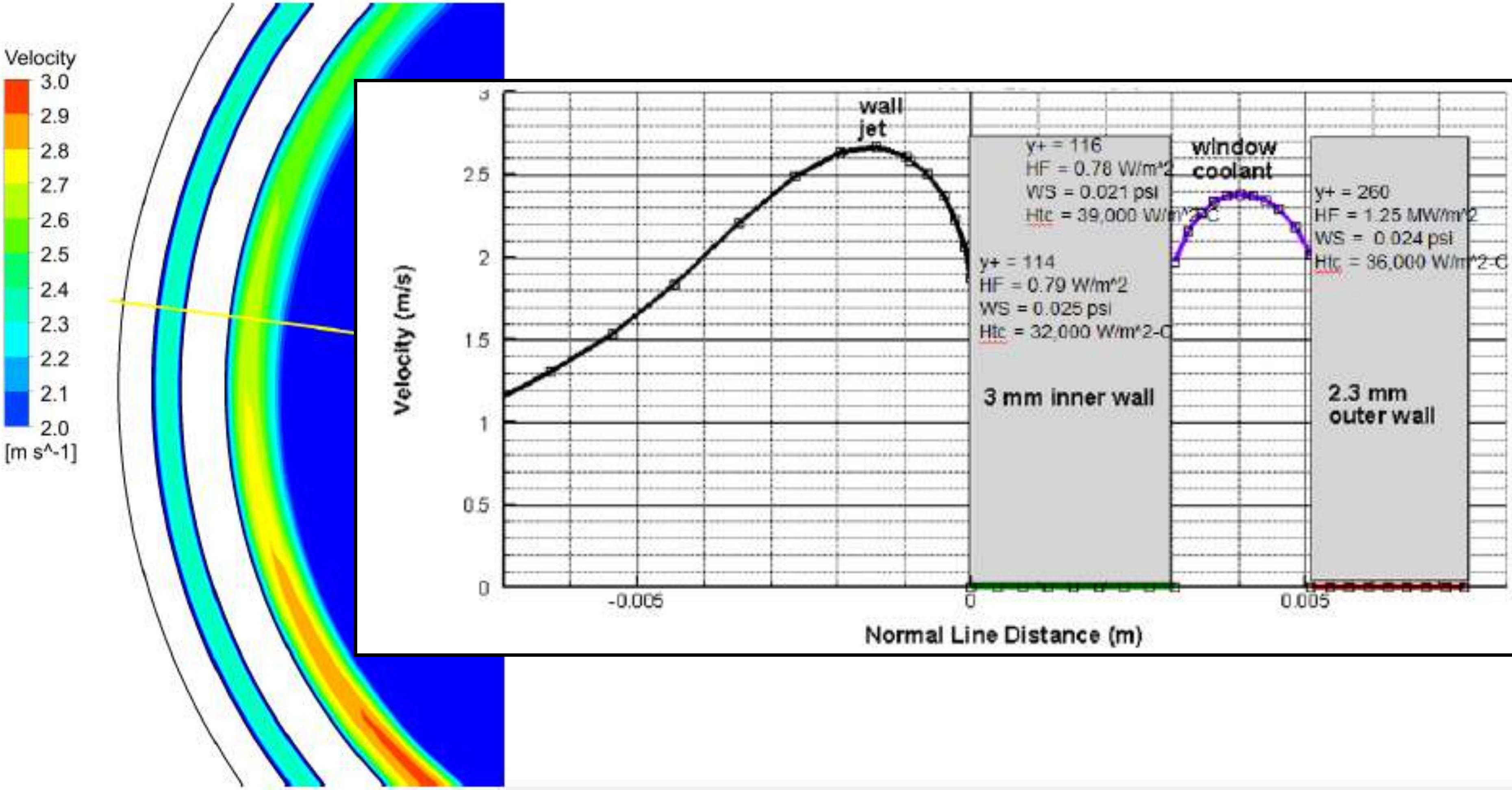
Original SNS Target



Desired Jet-flow Target



The jet flow design achieves 2+ m/s flow across the inner window bulk flow surface



Oak Ridge National Laboratory
MANAGED BY UT-BATTELLE FOR THE U.S. DEPARTMENT OF ENERGY

Most recent in-beam mercury target experiment re-confirmed benefit of flow

- Key results from 2011 WNR small gas bubble experiment showed:
  - Flow w/o bubbles reduced damage to ~1/2 of stagnant mercury at pulse intensity equivalent to SNS at 1.3 MW
    - But - only reduced damage by 15% at the 2.5 MW level
  - Small gas bubble injection reduced damage to ~ 1/3rd that of stagnant no-bubble mercury, even at high power
- Experience of JSNS target with an operating bubbler is being carefully watched
  - On-line vibration measurement shows effective *pressure wave* attenuation

Steps to achieve higher power targets

- Increasing mercury pump speed & total flow
  - Currently running at 280 rpm; nominal is 400 rpm
- Thinning the beam entrance window
- Use SS316LN (20% higher allowable stress than SS316L)

- However …

The center baffle is more difficult

- Baffle's function is to suppress dilatational modes of the vessel with resonance close to 60 Hz
- Modal analysis has unresolvable uncertainties for coupled fluid-structure vessel system
- Target design without a center baffle should be possible
  - Narrowing of front body should help
  - Consistent changes to IRP might be necessary
- PIE: If center baffle is truly cracked through its wall thickness, it is not functioning as intended
  - Maybe we can safely get rid of it

Risk of cavitation failure at higher power grows

- We will see how effective the jet-flow approach is at 1.4 MW for mitigating damage through experience and PIE
  - Damage erosion rate dependency is certainly non-linear with power
- Gas mitigation of some kind may be necessary at higher powers to have acceptable target life
  - Small gas bubbles and / or protective gas wall

Target cavitation lifetime at high power is difficult to accurately predict

- Running targets to failure provides real information on true weakness of the design
- Credible simulation tools incorporating all relevant physics do not exist – complex problem
  - Fluid-structure interaction, shock, cavitation, multi-phase flow
- Knowledge gained from PIE and analysis of failed targets should drive effective changes in next generation targets
- We cannot rely on incomplete data, inference, and assumption

Target R&D work for cavitation damage mitigation has been suspended

- Difficult funding conditions and other division priorities
- TTF is operational and ready for prototypic development of small gas bubble injection and protective gas walls

Engineering target design for 2+ MW target needs to get started

- It will take years to develop
- Next generation target design should be done consistently with next generation IRP work
- We need a plan consistent with other facility objectives

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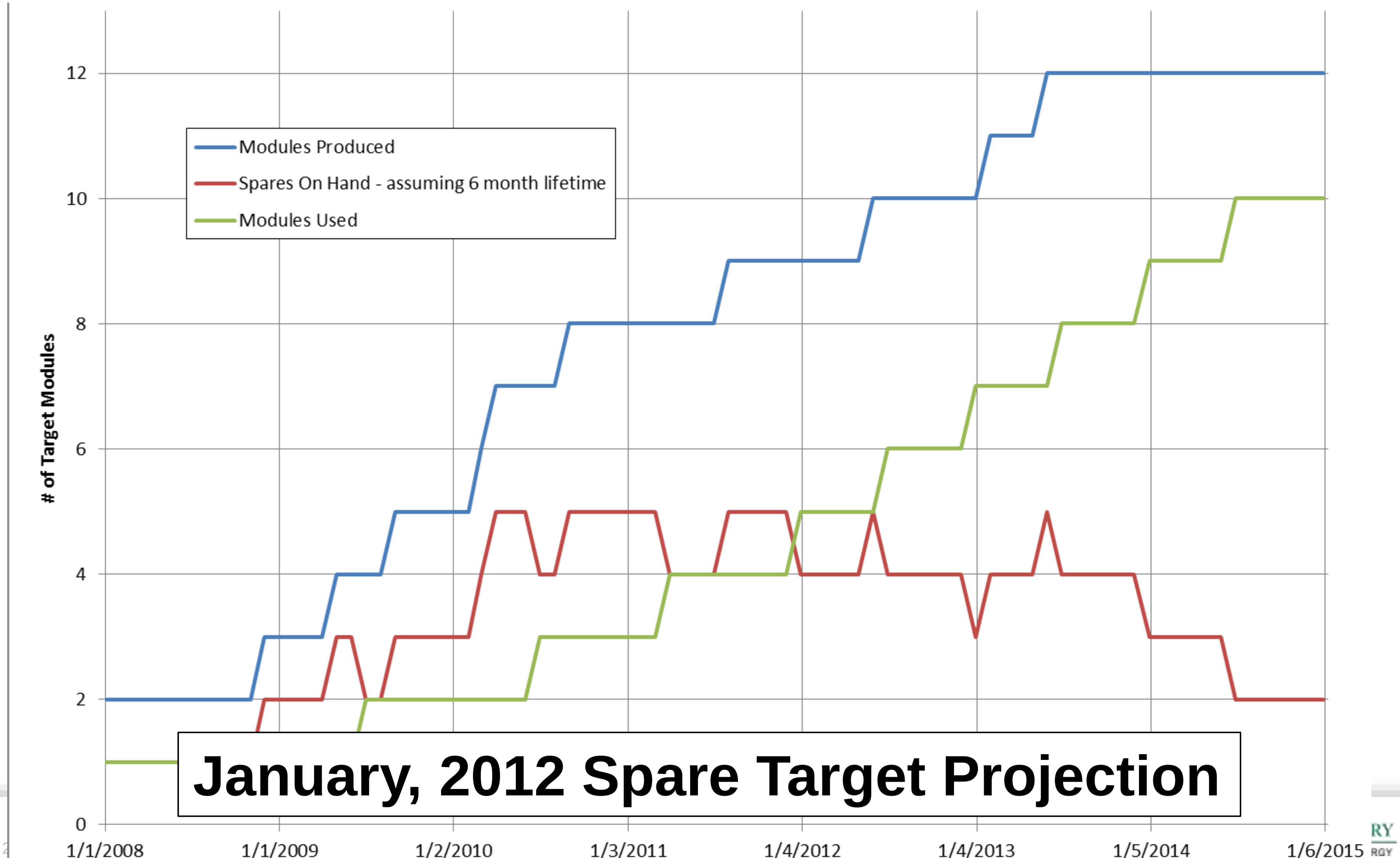
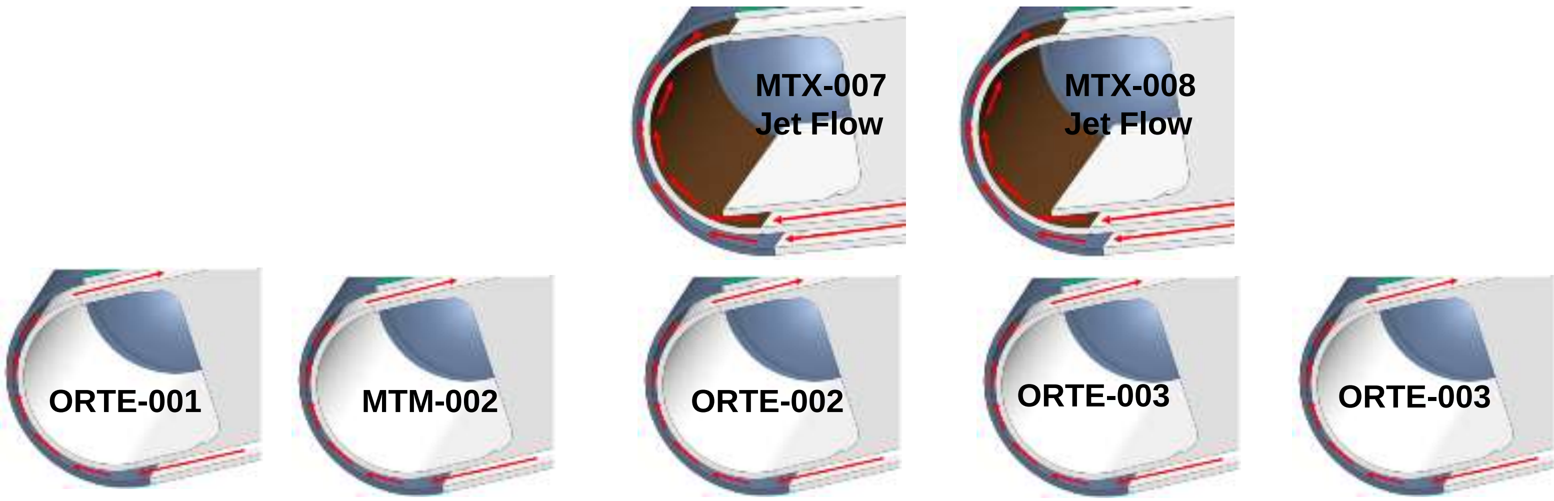
In January 2012, we predicted a healthy supply of target modules and we planned for 2 spares at steady state



The present spare target status is less flattering. Goal is now 4-6 spare targets at all times.



?

Now -------- 8/13 -------- 2/14 -------- 8/14 -------- 2/15 -------- 8/15

MTM-003 installed	ORTE-001 installed??	MTM-002 installed??	MTX-007 (Jet Flow) installed	MTX-008 (Jet Flow) installed?	?

- Above timeline shows projected spare targets on hand, below timeline show projected installed targets
- Inventories are based on current orders, additional orders are obviously necessary

We must design and manufacture components to eliminate "avoidable failures"

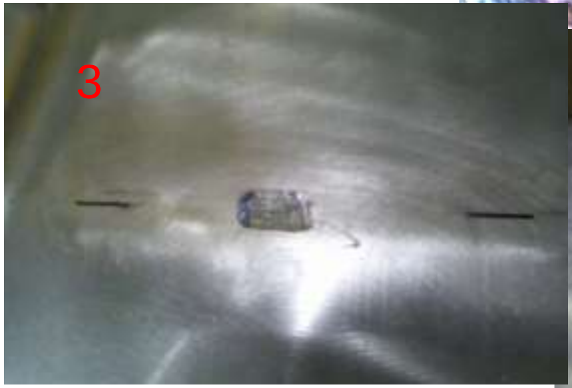
- The Target 6 and Target 7 failures were clearly the result of non-compliant welds…however:
  - As designed, the joint was difficult to align and weld
  - Specified inspection was insufficient
  - Analysis in this specific area was not detailed enough to highlight low design margin at the weld joint.
- Actions Taken:
  - Multiple internal/external reviews of target QA and manufacturing processes
  - Audits of fabrication packages for all spares and in process targets
  - Internal/external Failure Modes and Effects (FMEA) analysis
  - SNS has employed additional QA staff to monitor manufacturing of Target Modules and other target station components (Inner Reflector Plug [IRP] and Proton Beam Window [PBW])

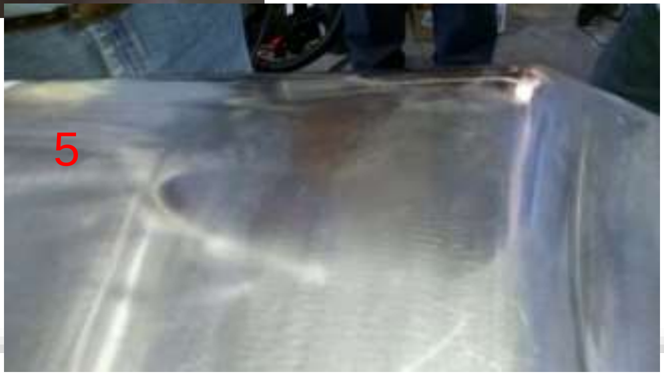
Specific actions have been taken to verify the quality of on the shelf spare targets

- Spare target internal (root) welds were visually inspected to the extent possible via borescope
  - Lack of weld penetration found on a transition cover plate weld of MTM-002 – this target is currently being repaired by supplier
- All available x-ray film was reviewed by a certified weld inspector
  - All comments were further addressed or inspected via visual or ultra-sonic examination
  - In one case, an unacceptable weld defect was found on the water shroud of a spare target (MTM-003). This defect was repaired onsite prior to installation in November, 2012.

MTM-003 water shroud weld defect was successfully repaired

- The weld defect identified by our re-examination of the X-Ray film was successfully located and repaired – this target is currently installed in operation

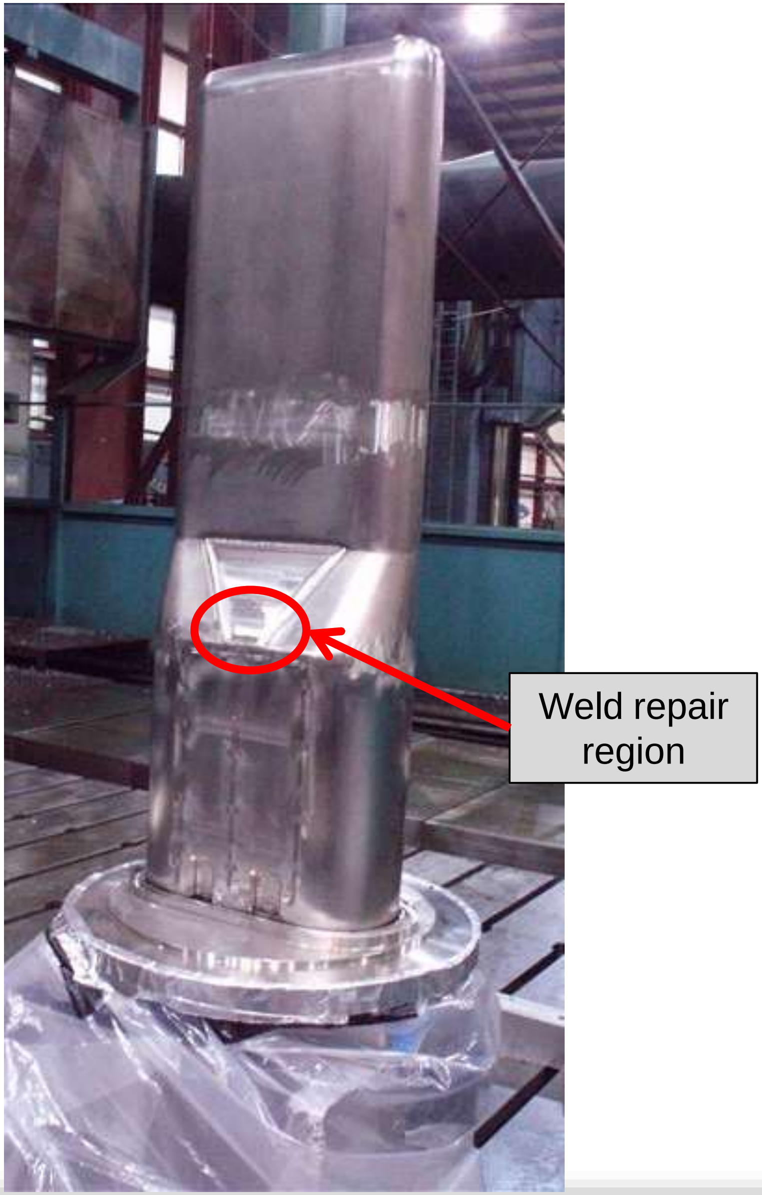




MTM-002 is currently being repaired at the supplier's facility

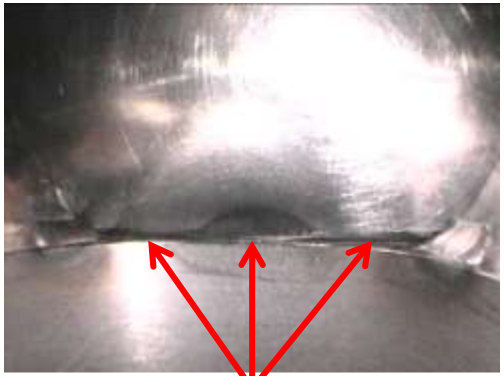
- The water shroud has been removed in order to repair the weld defect

In process water cooled shroud removal



Hg Vessel with shroud removed

The weld defect on MTM-002 has been repaired



Lack of penetration

External excavation

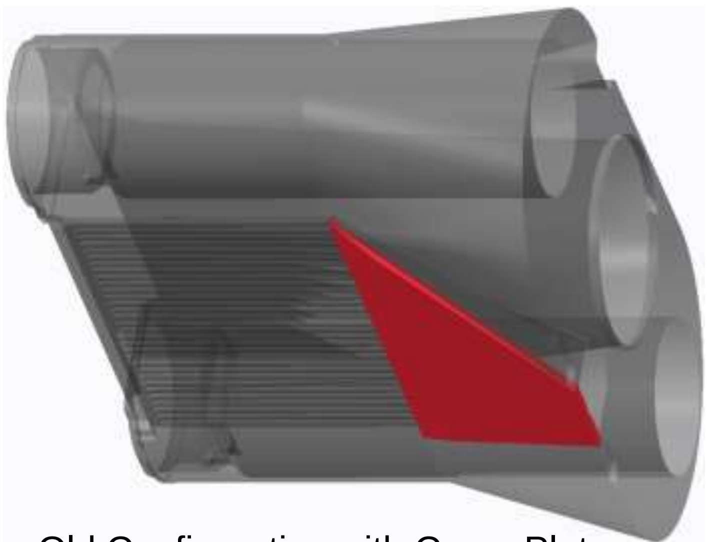
Internal excavation

External repair complete

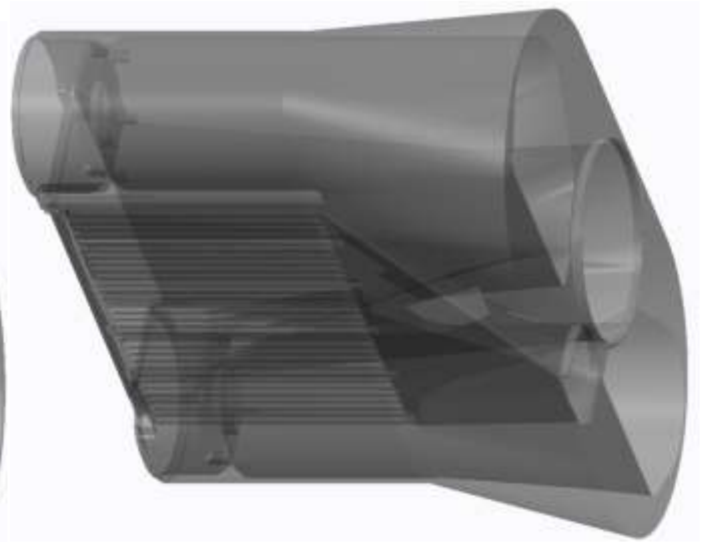
Internal repair complete

- **Water Shroud must now be replaced, we expect delivery in July, 2013**

For future targets, the cover plate has been redesigned so that the failed weld joint is eliminated:



Old Configuration with Cover Plate

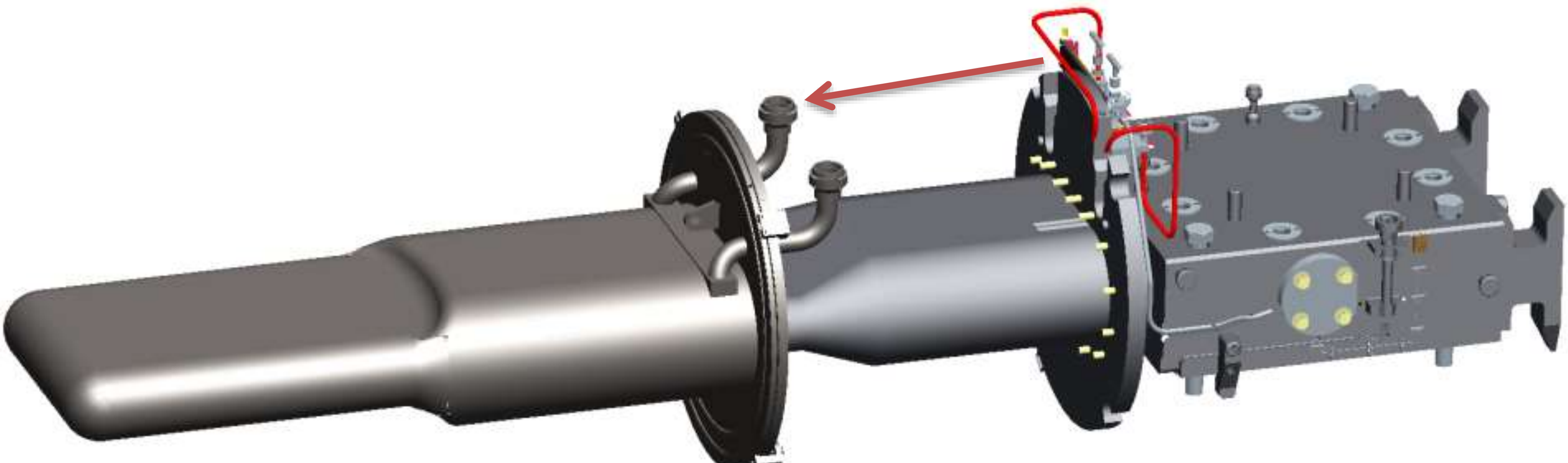


New Configuration without Separate Cover Plate

- **The cavity beneath the cover plate is now formed via plunge electrical discharge machining (EDM).**

Bolt on water shroud

- PIE options do not currently allow cutting away of water shroud to facilitate visual inspection of the Hg vessel outer surface
- Bolted joint would replace so called “closure weld” to seal the interstitial space between Hg vessel and water cooled shroud
- Sealing is via an aluminum coated all metal seal - has been tested in mercury
- Extensive manufacturing simplifications included



Fabrication process for future targets has been made more robust.

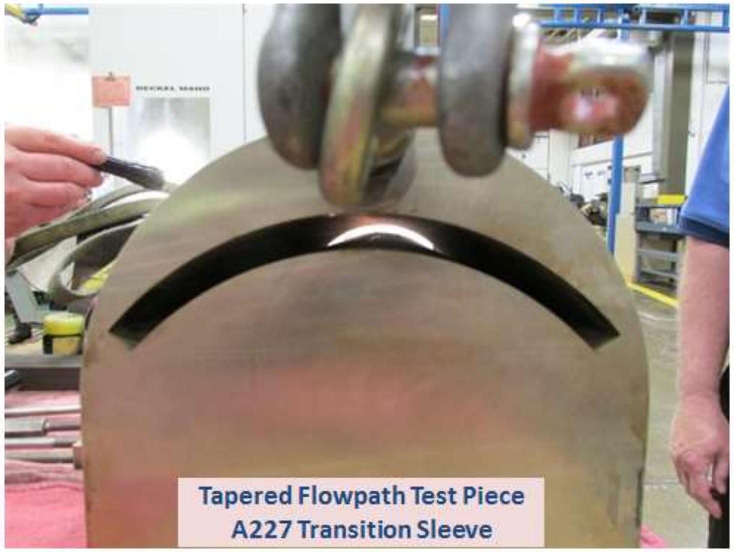
- Weld inspection and reporting is enhanced
  - All welds require internal visual inspection as possible.
  - Ultra-sonic examination is required when x-ray is not feasible
- Improved specification and control of weld filler material
- ORNL will supply specially processed (electro slag re-melt) stock material for beam entrance windows to reduce inclusion population
- Finished beam entrance windows and front portion of Hg vessel front body will be radiographed for parent material porosity and defects
- On-site source surveillance and inspection has been increased.

The first Jet flow target is expected to arrive in January, 2014

4/22/13

A226 WCS Rear Sleeve
Ready for .125" Cooling Holes

A234 Transition Body
Gundrilling Completed



Tapered Flowpath Test Piece
A227 Transition Sleeve

WEDM Drops from
Tapered Flowpath
Test Piece

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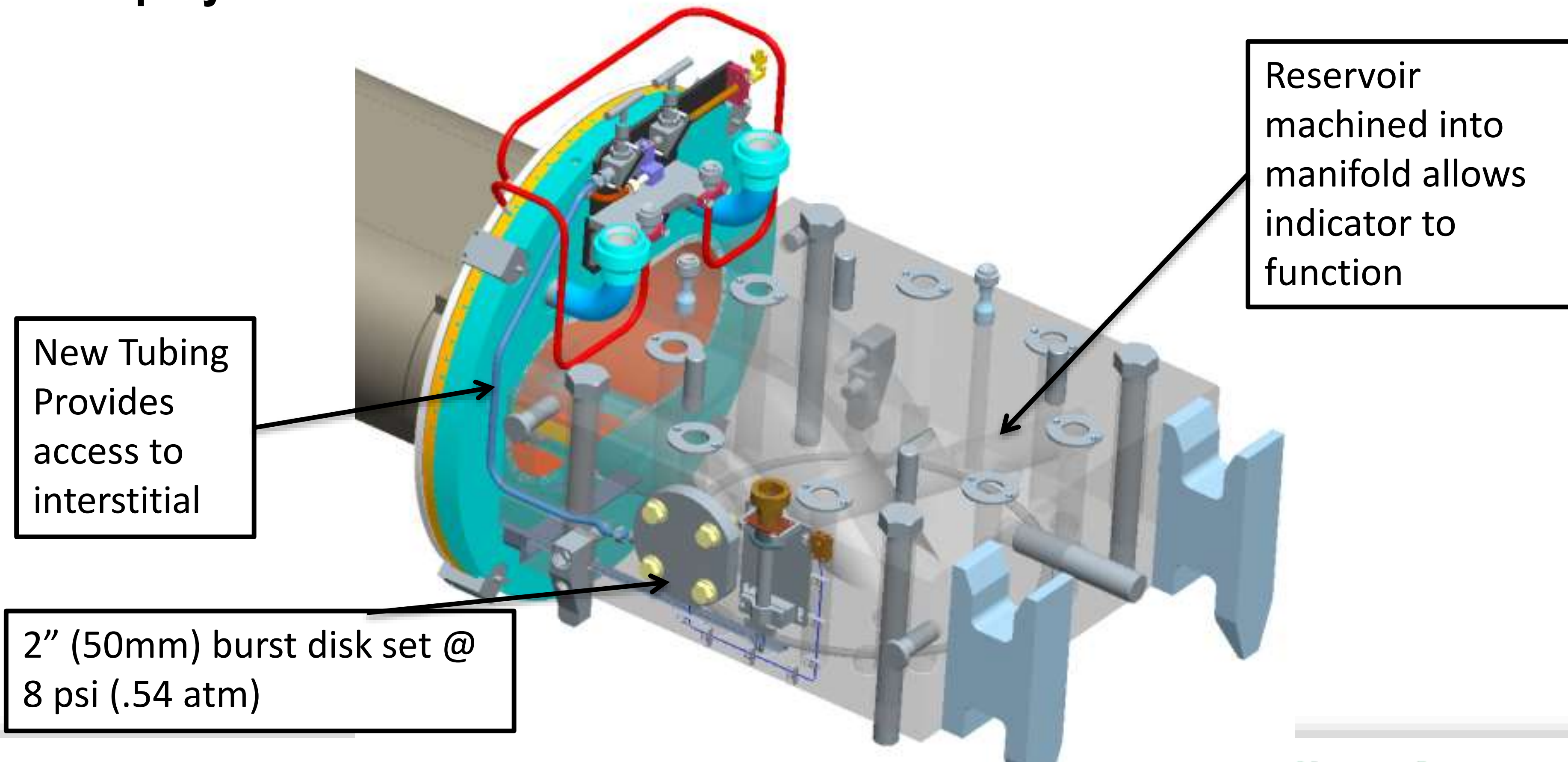
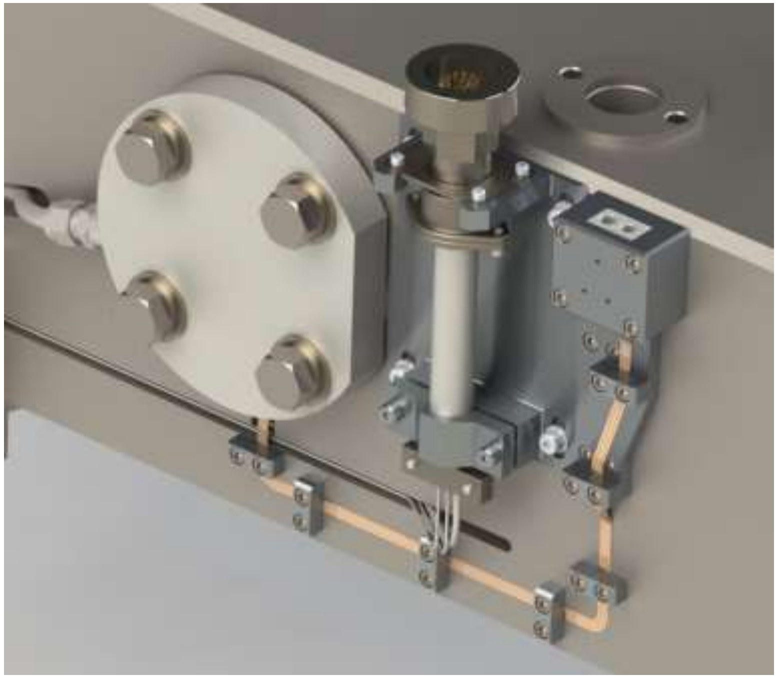
Burst Disk Leak Detection will be deployed on the next target to be installed

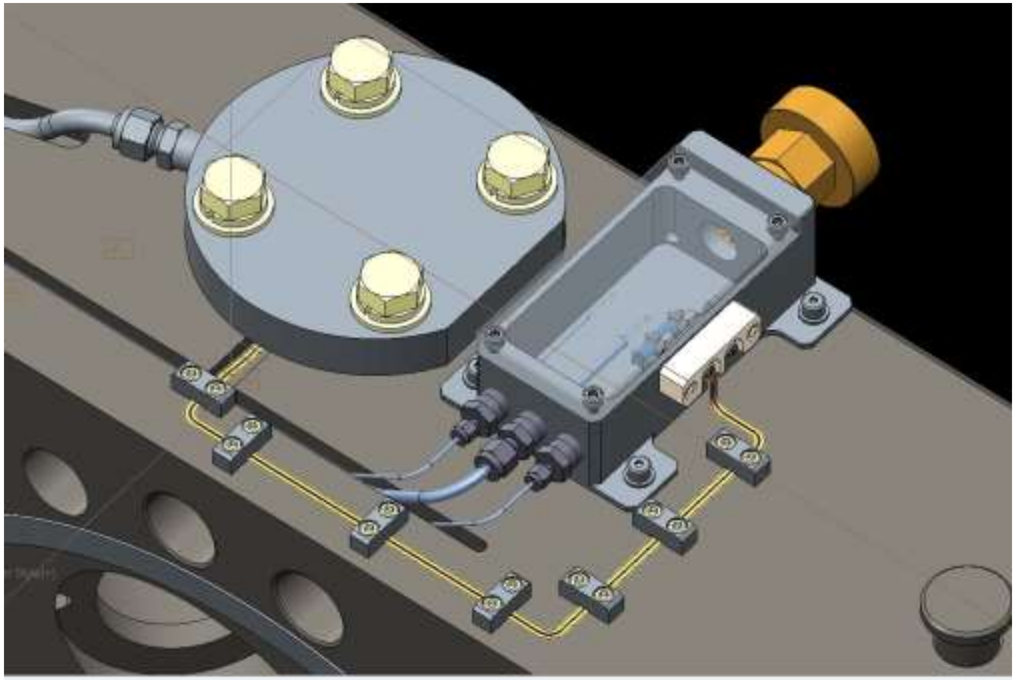
- Burst disk leak detection method has been mocked up and tested successfully
- Employs off-the-shelf burst disk with custom holder and indicator



Connector arrangement will be independent on initial targets, and integrated with existing leak detector leads on future targets



Independent arrangement for initial targets



Integrated arrangement for future targets

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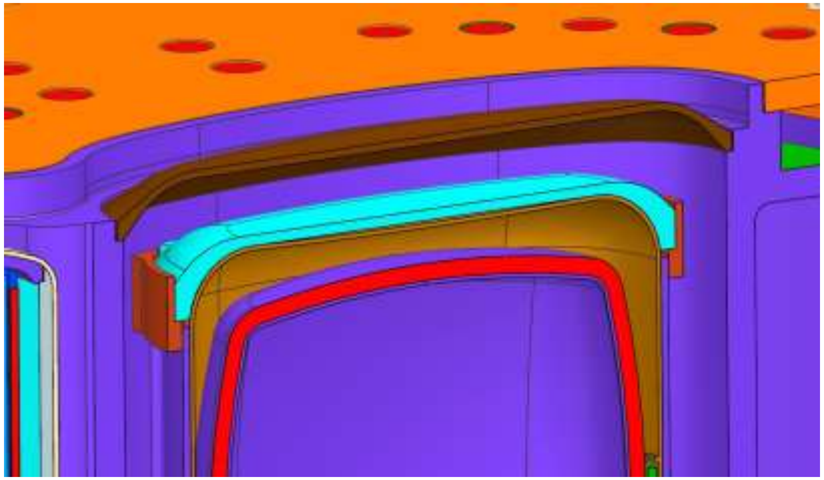
- **Spare IRP Fabrication Update**
- Aluminum Proton Beam Window (PBW) Update

The Spare Inner Reflector Plug (IRP) is not complete

- Cracks have been identified in two of the three completed cryogenic moderator vacuum vessels, requiring that the vessels be replaced.
- One of the vessels is currently installed within the Lower IRP. Therefore, other finished parts will have to be cut and repaired in order to recover.
- Delivery date is uncertain, but likely ~ December, 2013

Internal Weld Cracks



Potential Repair Configuration

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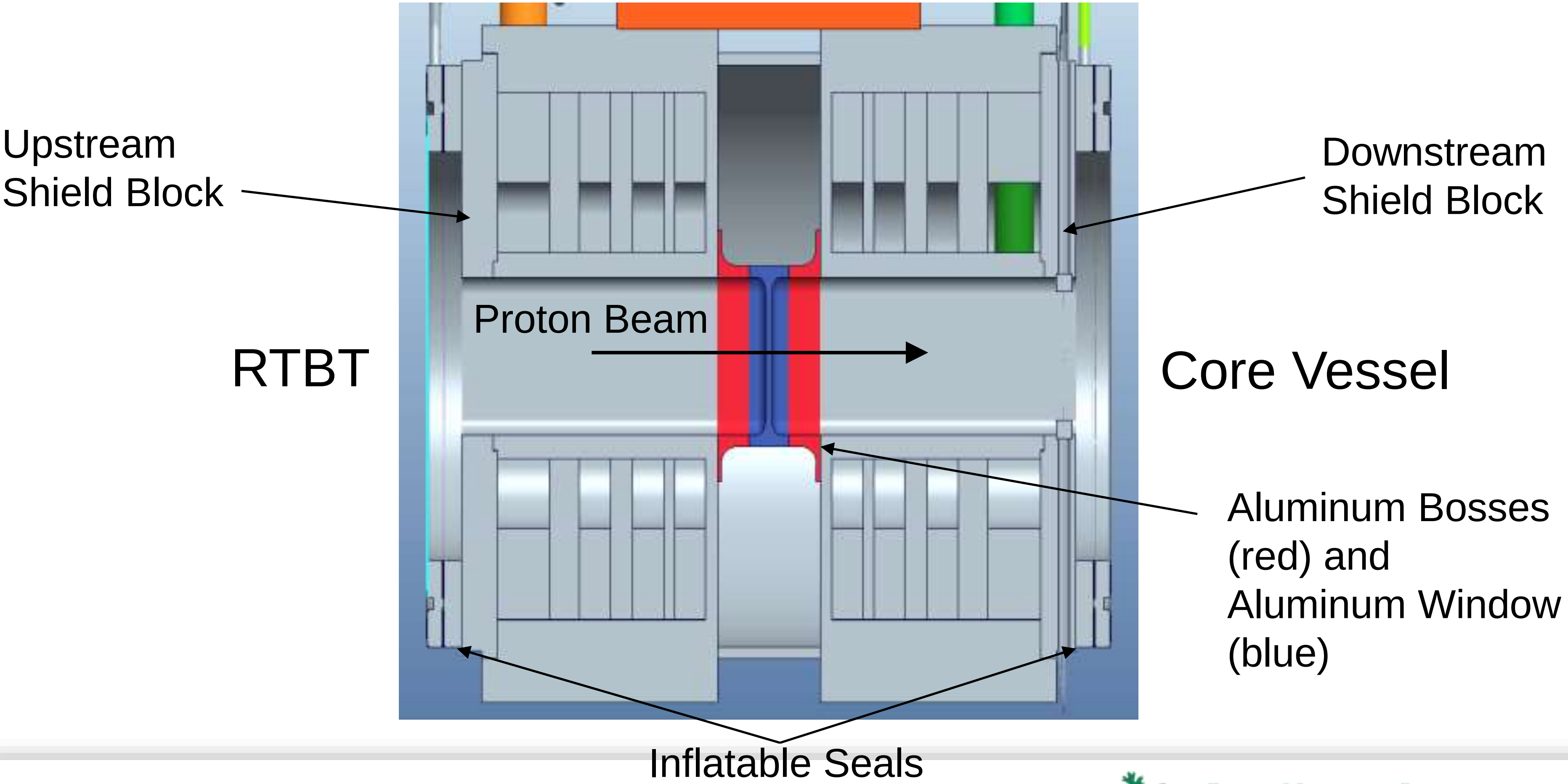
- Spare IRP Fabrication Update
- **Aluminum Proton Beam Window (PBW) Update**

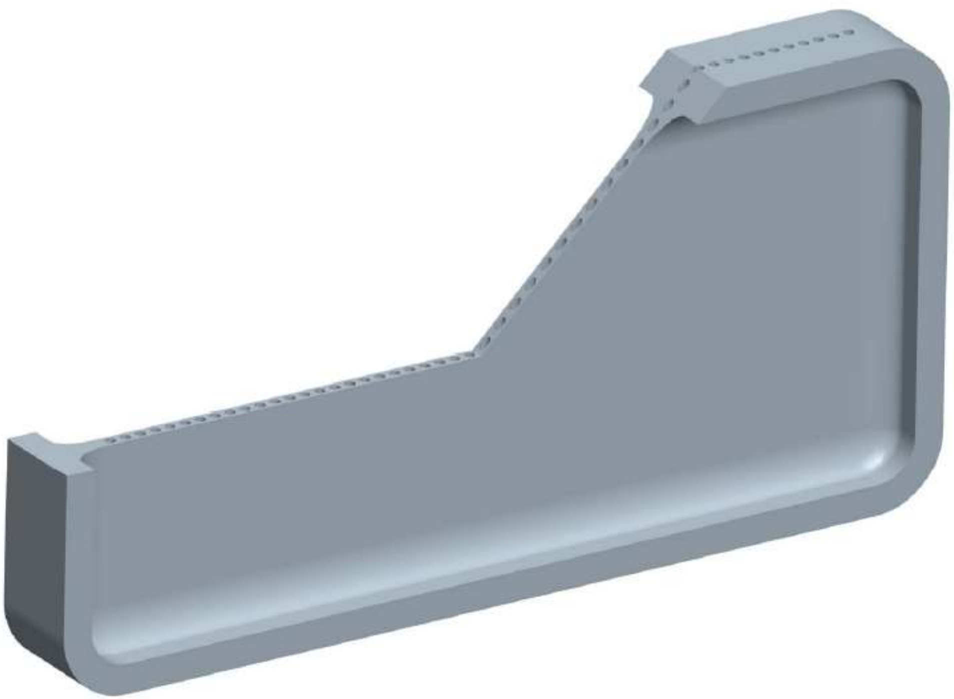
The Aluminum Proton Beam Window Design is in fabrication

- **Internal design of shield blocks remains unchanged**
- **Minor changes to shield blocks for aluminum to steel interface**

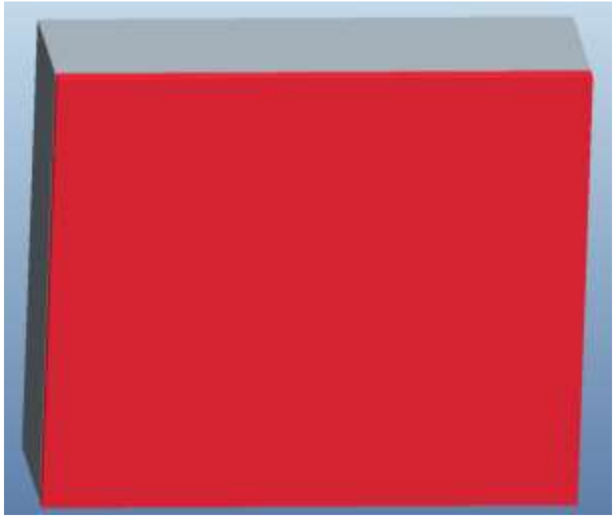


Design Description

- Flat plate with closely spaced parallel holes from single piece of aluminum
- 0.200” thick plate with 50 vertical .125” diameter holes spaced uniformly 0.200” apart center to center
- 1.25” welding boss all around exterior

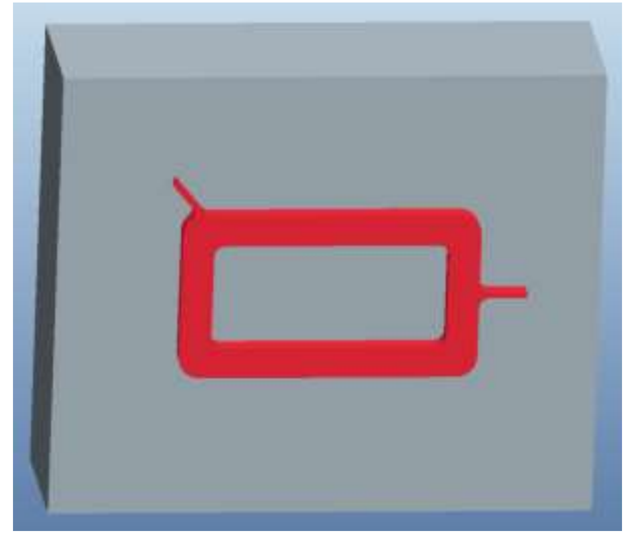


Manufacturing – Explosion Bonding



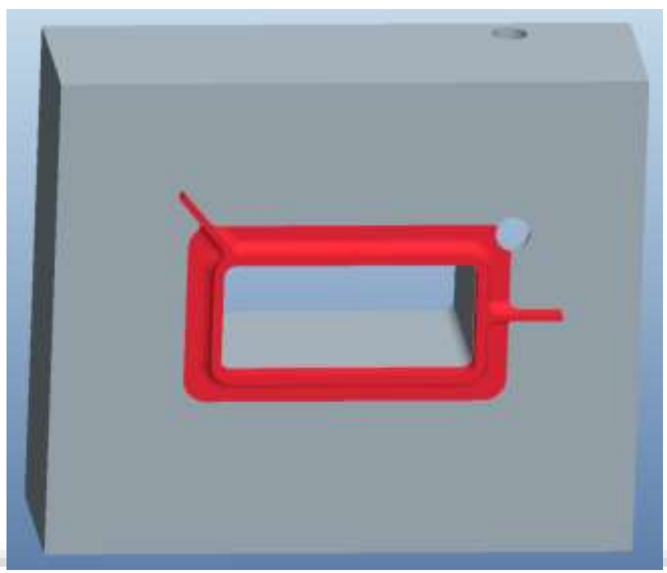
Explosion Bond Al to SS

Ultrasonic Inspection



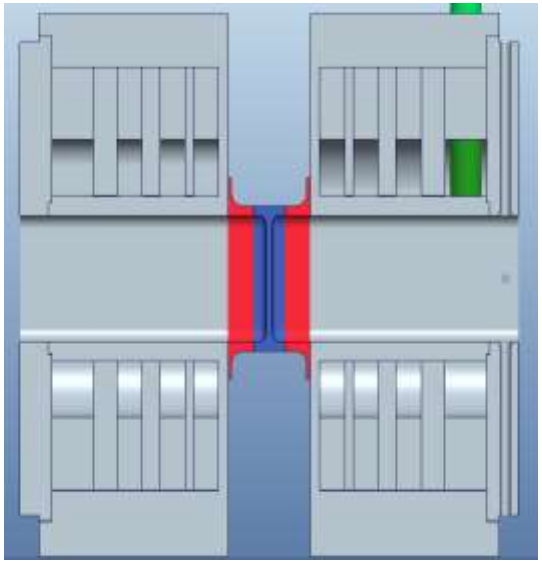
Machine to Final Interface

Helium Leak
Test Bond



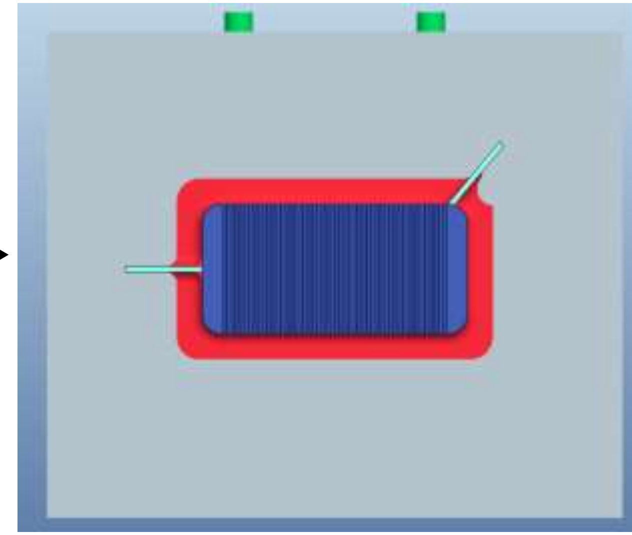
Final Machine Weld Boss

Manufacturing – EB Welding

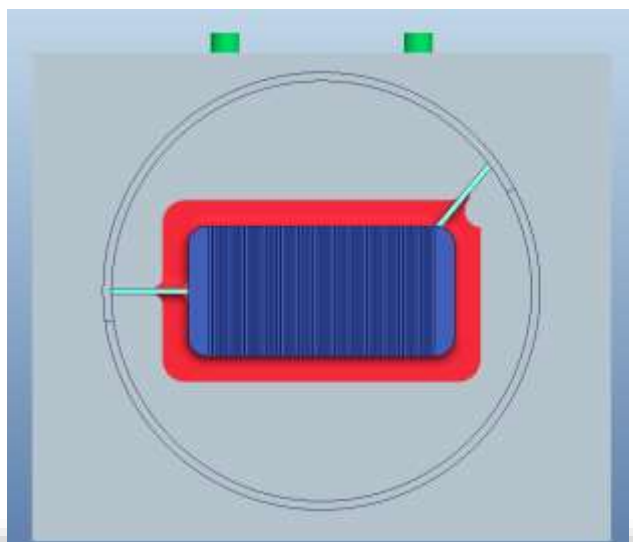


EB Welding

Remove Weld Crown
and Helium Leak Test



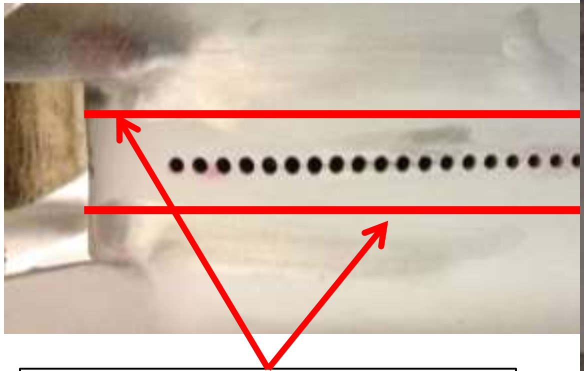
Weld Baffles



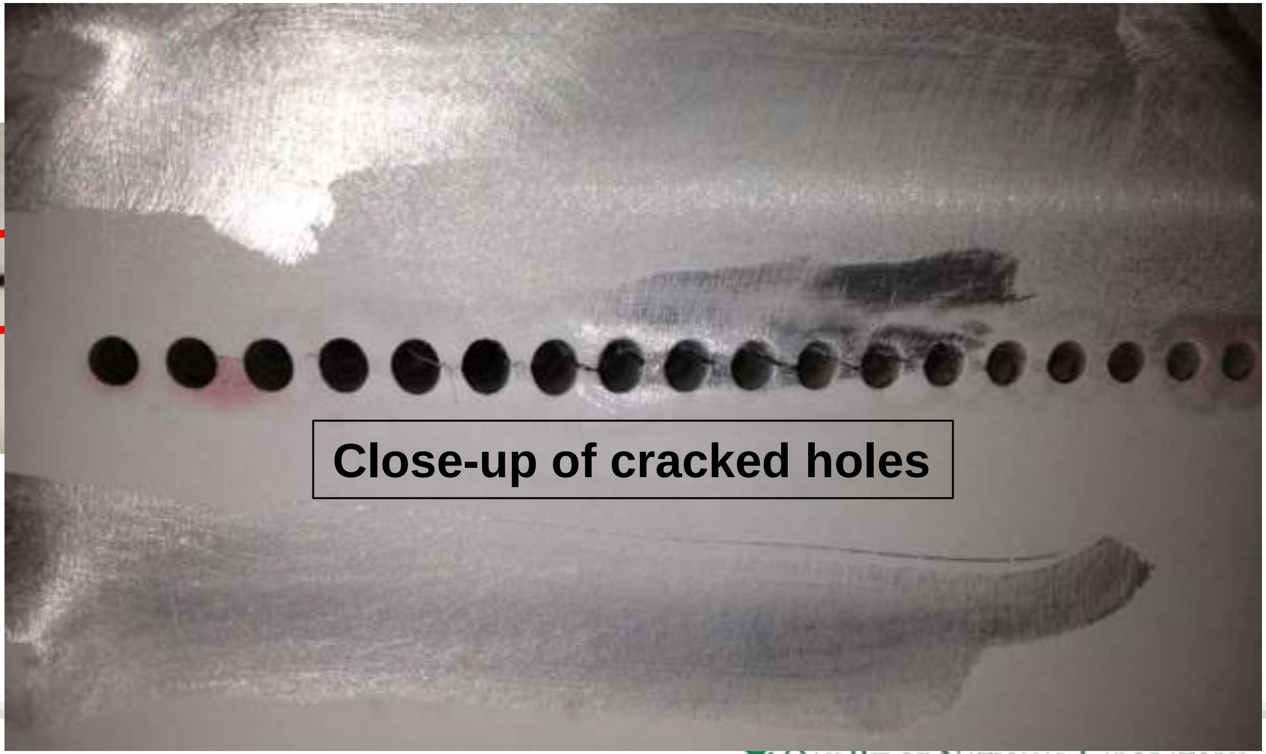
Weld Outer Ring

Aluminum EB welding of PBW has caused delays

- The initial EB weld resulted in a small surface porosity and one small lack of fusion, which required repair.
- The TIG weld repair attempt fatally damaged the window section, which will be removed and replaced
- Repair schedule is uncertain, but we expect the window to arrive safely in time for January 2014 installation



Weld joint locations



Close-up of cracked holes

Proton Beam Window Manufacturing

- **PBW #4 (Inconel) is currently installed**
- **PBW #5 (Inconel) has been delivered**
- **PBW #6 (Aluminum) is in fabrication**
- **Tentative plan is to install PBW #6 (Aluminum) in January, 2014 so that we have an Inconel window on hand as a spare**

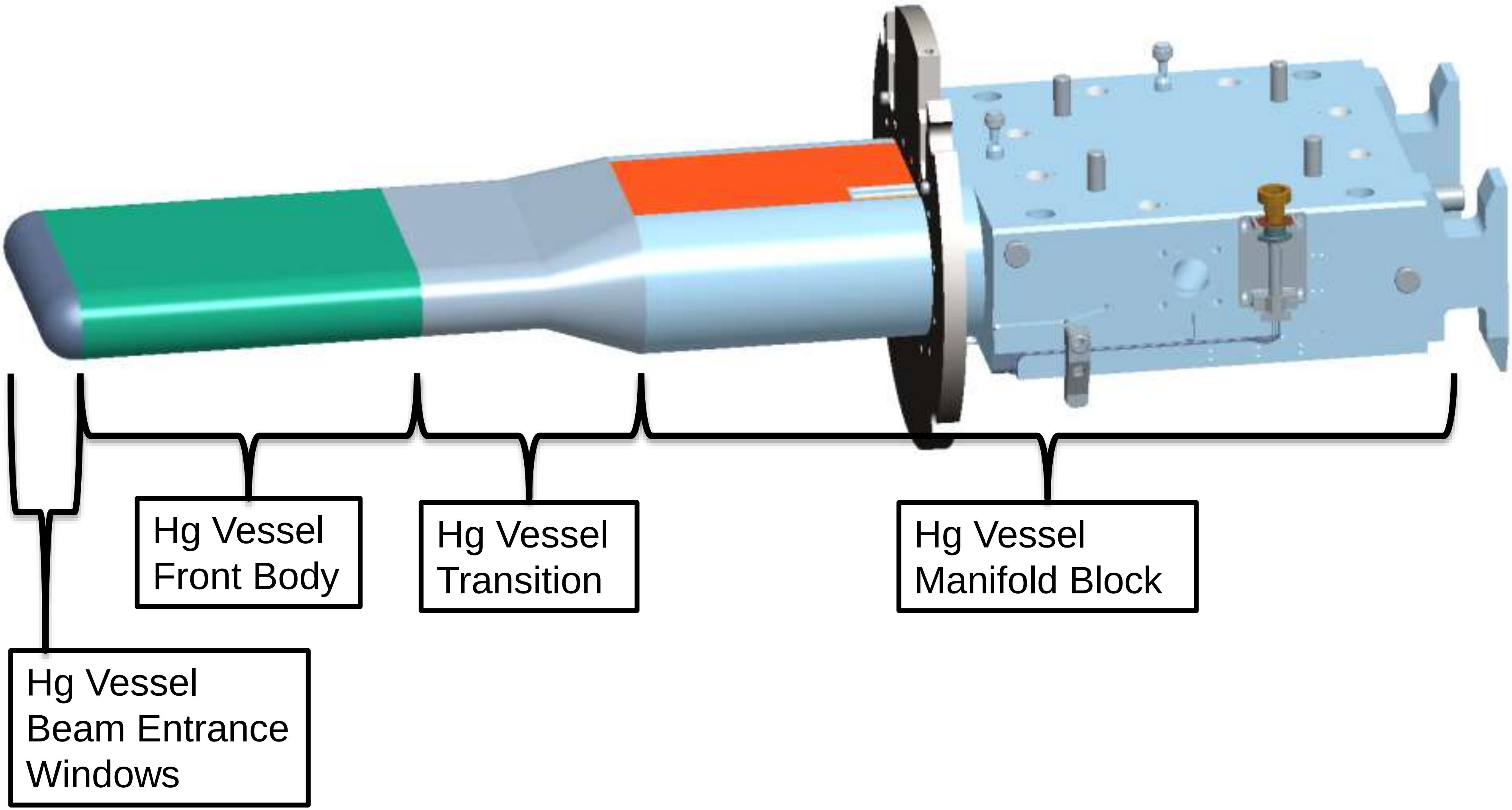
Questions and Comments Please

Supporting / extra slides

Jet Flow Design Goals

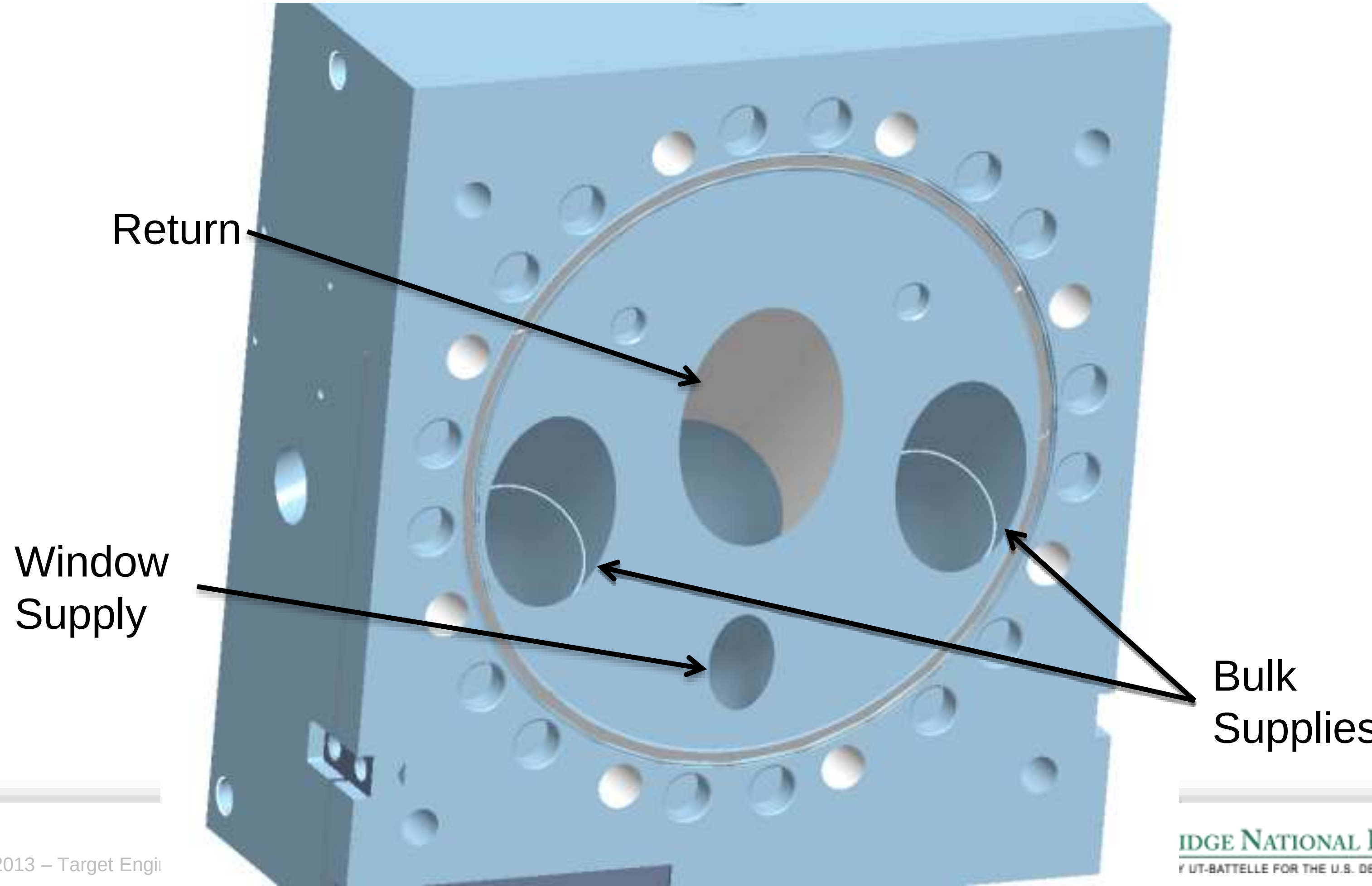
- Extend Target Module Lifetime
- Reduce cavitation damage to inner wall of Hg vessel
  - Potentially lengthen target module lifetime under the assumption that the primary failure mechanism is a domino effect initiated by damage to the inner wall
  - Better understand mitigating and compounding effects / factors for cavitation damage
- Enhance window flow resistance to cavitation damage
  - Maximum window flow velocity is maintained over a longer length by changing the profile of the outer window
- Address potential structural vulnerabilities
- Improve / simplify manufacturing
- Improve options for Post Irradiation Examination

Hg Vessel Design - Jet Flow



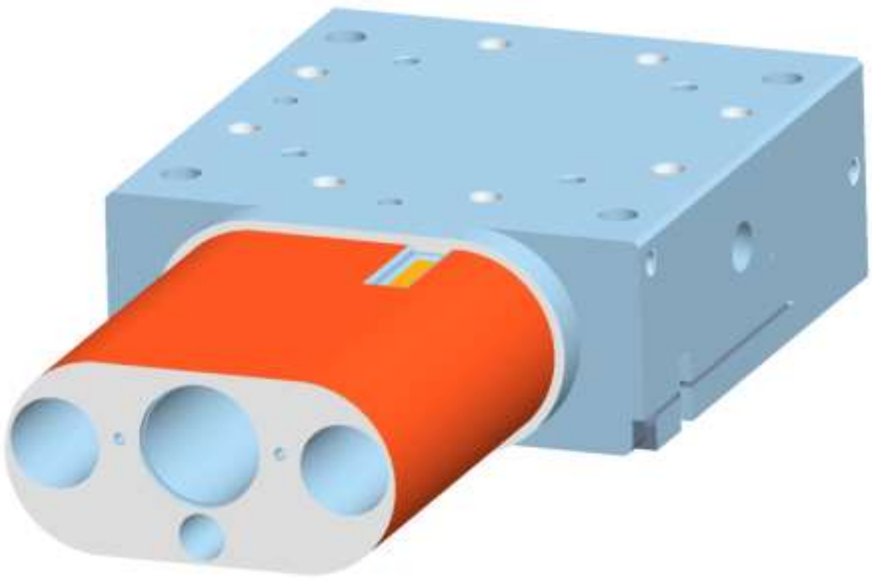
Hg Vessel Design - Jet Flow

Mercury supply and return locations are a fixed boundary condition

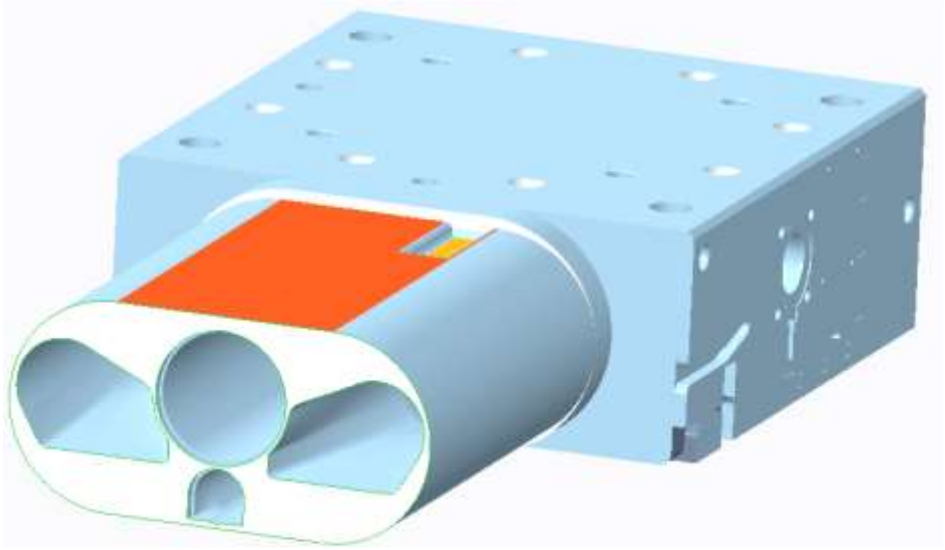


Hg Vessel Design - Jet Flow

- **Interface to front of target carriage is the same as the existing design (2 bulk supplies, 1 window flow supply, 1 return)**
- **Jet flow is "stolen" from the two bulk supplies, beginning at front end of the manifold block**
- **Window flow supply is modified to improve weld joint geometry**



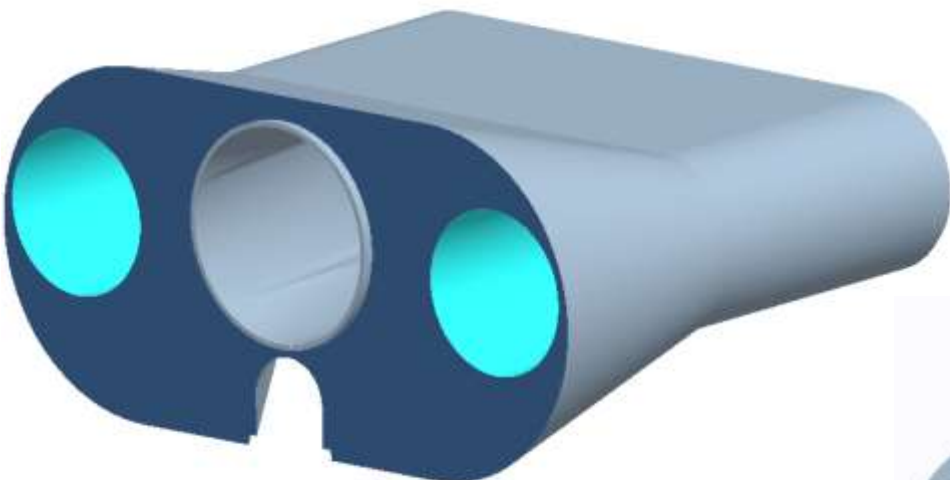
Existing Configuration



Jet Flow Design

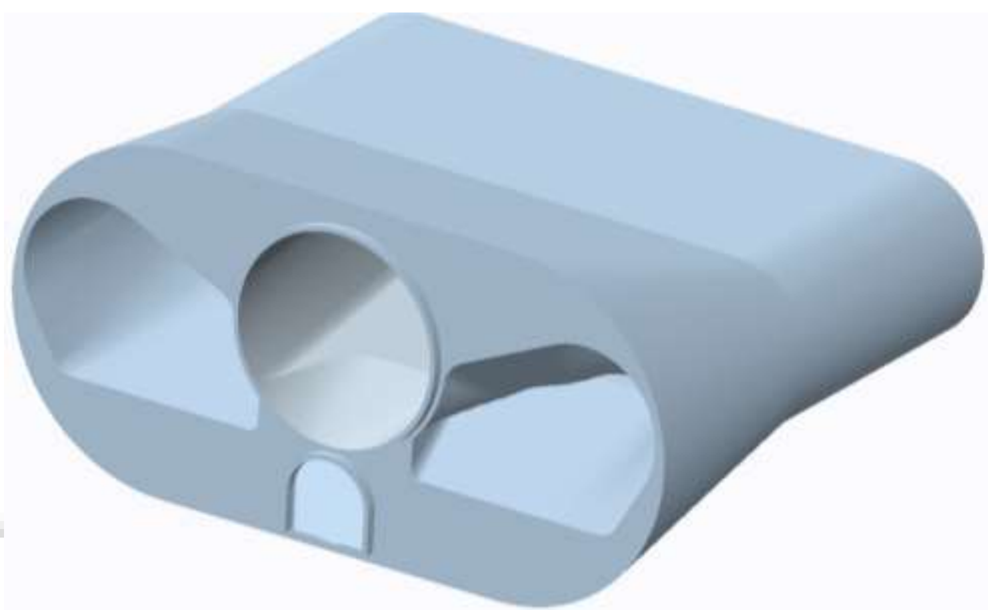
Hg Vessel Design - Jet Flow

- **Jet flow is separated from the bulk flow at the Hg vessel transition**
- **Bulk flow orifices are modified to push more flow to the jet flow**
- **Trapezoidal cover plate is integrated to eliminate difficult weld joints**

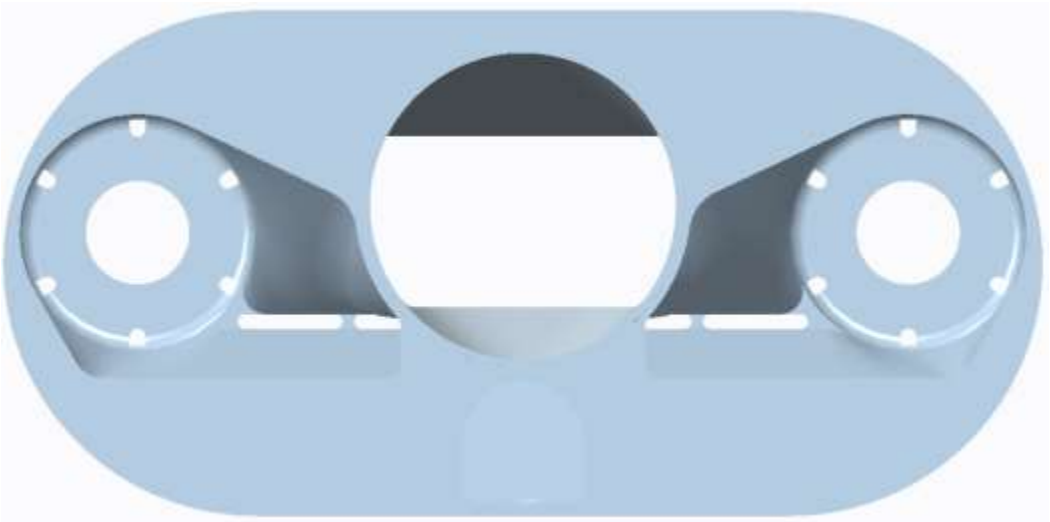


Existing Configuration

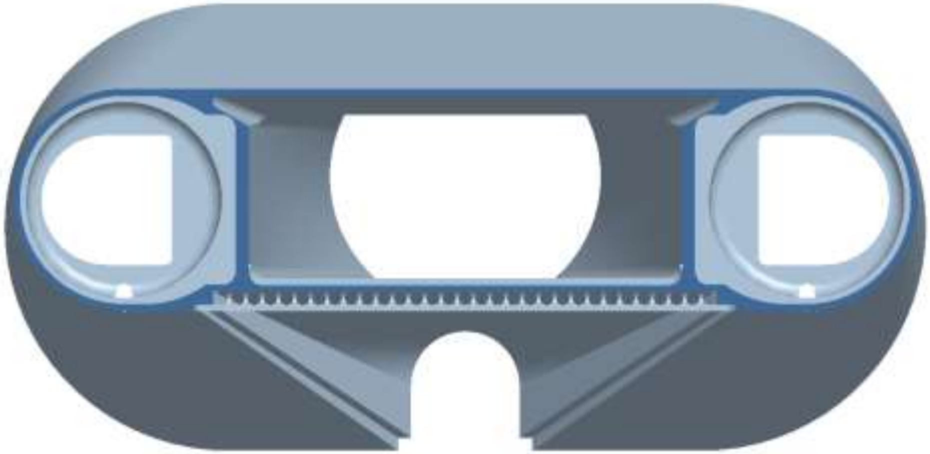
Jet Flow Design



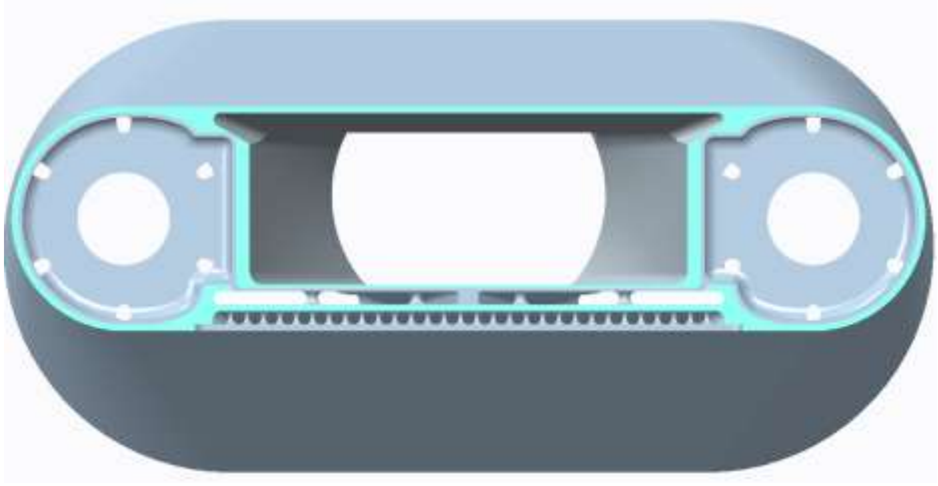
Hg Vessel Design - Jet Flow



Jet Flow Design



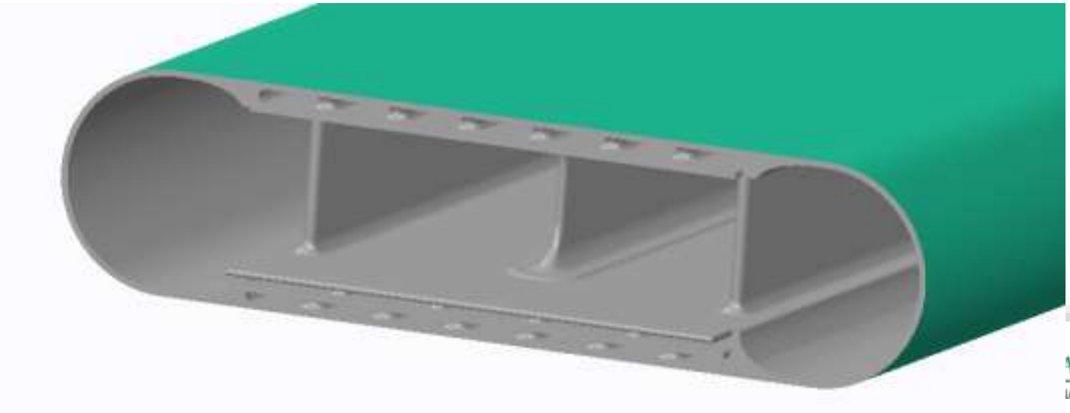
Existing Configuration



Jet Flow Design

Hg Vessel Design - Jet Flow – Center Baffle

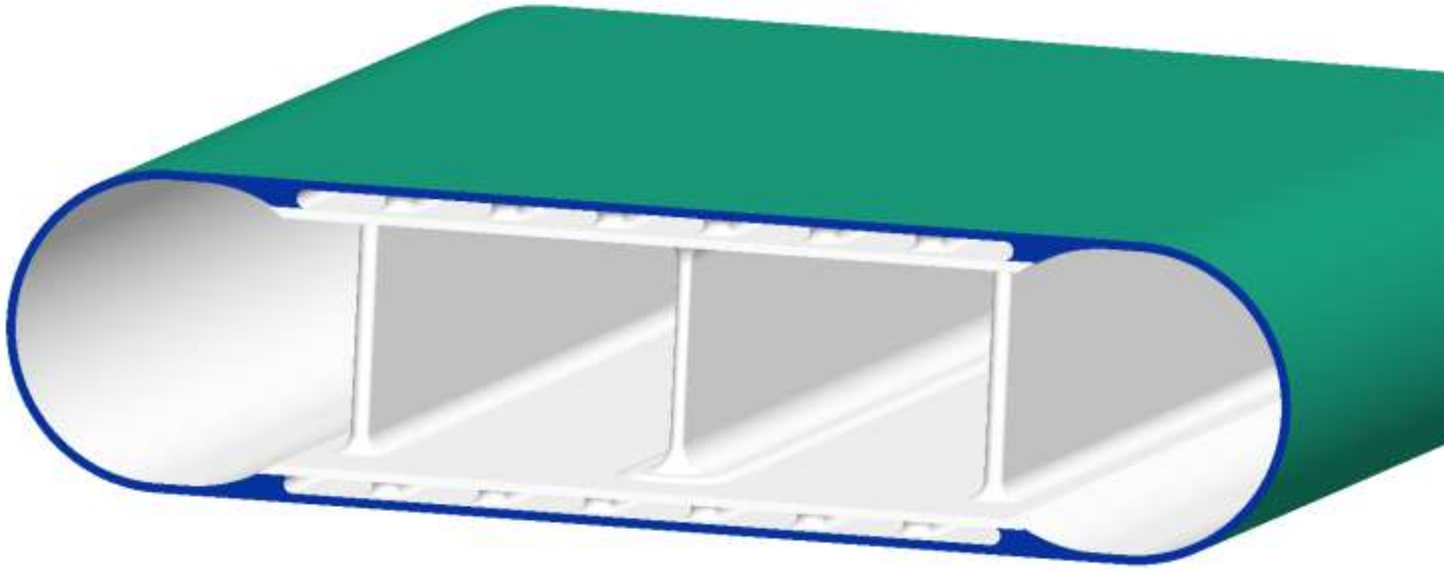
- Center Baffle is required by modal analysis, but is a source of design consternation
  - Increases thermal stresses
  - Increases pressure pulse stresses
  - Combined with reduced pump speed the baffle affects transient flow behavior, which may lead to thermal striping / fatigue issues.
- These issues are not unique to the Jet Flow Target Design
- Center baffle has been moved back ~1.6 inches. This is a compromise which attempts to keep natural frequencies away from 60 hz, while reducing thermal stress at the center of the baffle.



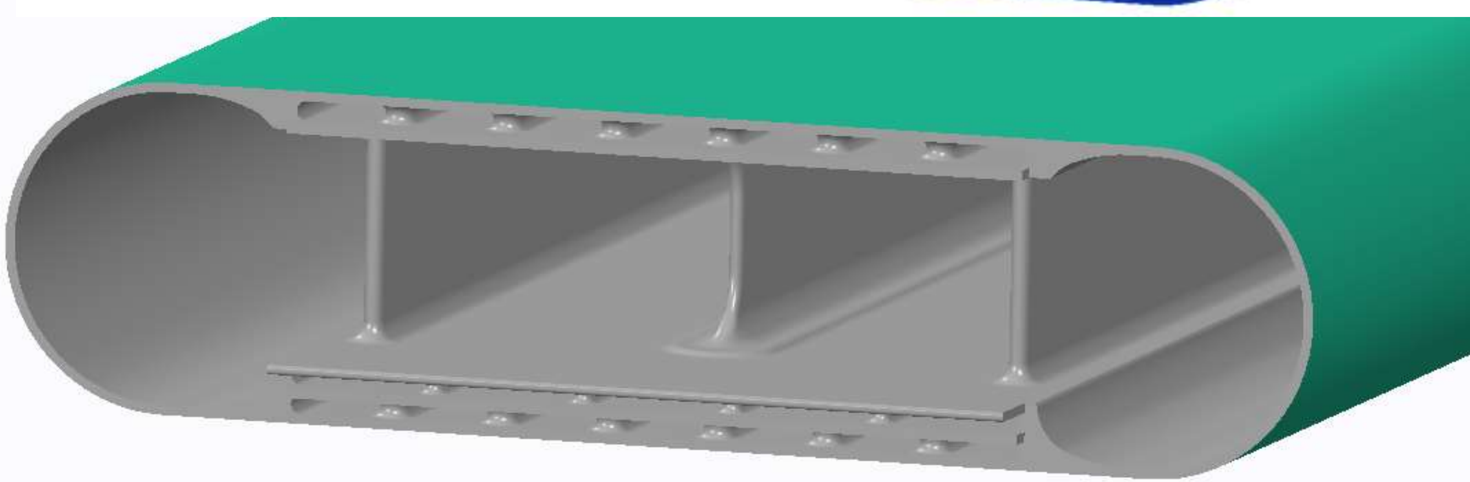
Hg Vessel Design - Jet Flow

- 2nd layer of flow slots is added to bottom of Hg vessel front body to allow the jet flow to release at the base of the inner window

Existing Configuration

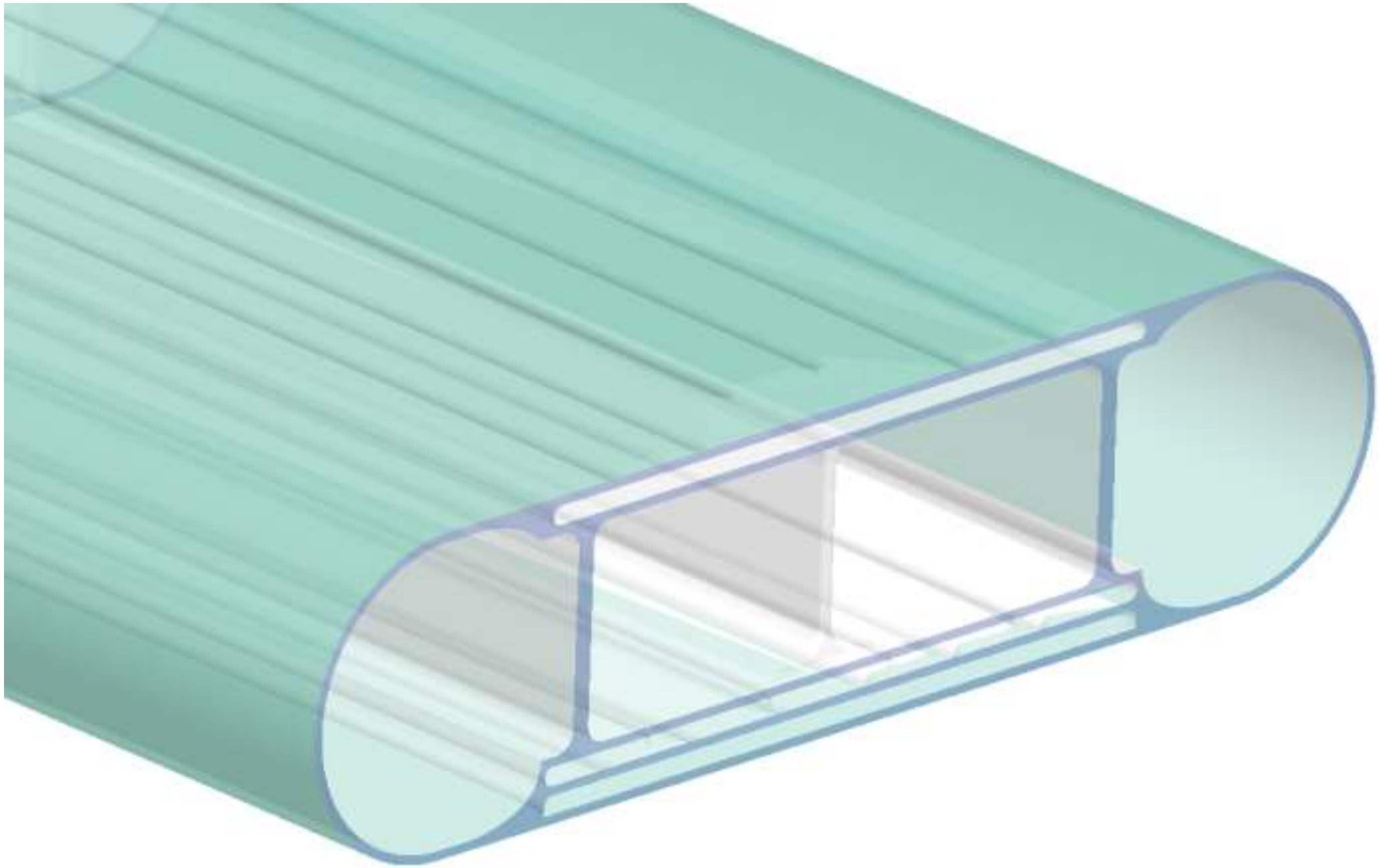


Jet Flow Design



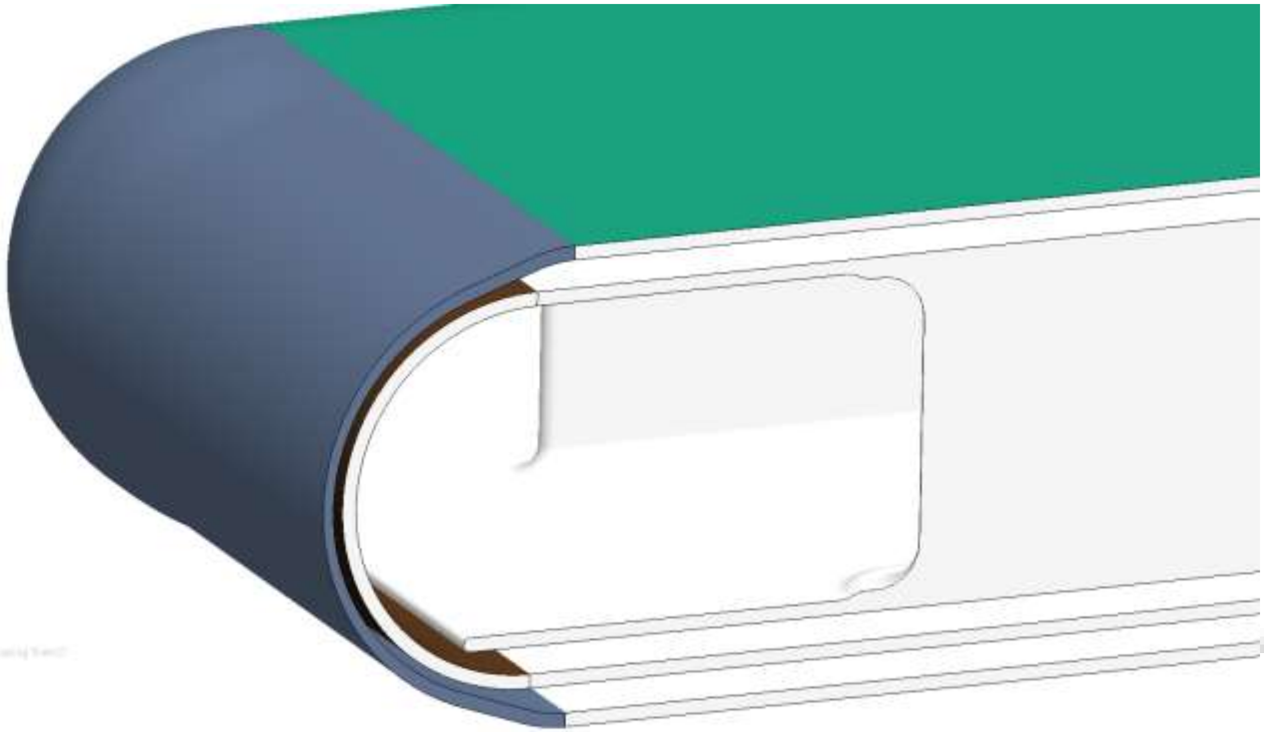
Hg Vessel Design - Jet Flow

- The central ribs which form the window flow return slots have been shortened in order to lower the thermal stress between the rear of the front body and the transition.



Hg Vessel Design - Jet Flow

- The inner window is identical to the existing design
- The outer window has been modified
  - Thickness reduced from .120” to .090” to increase power handling (reduce thermal stress)
  - Profile has been adjusted so that the minimum thickness between the inner and outer windows is maintained for a longer flow path



Hg Vessel Design – Jet Flow

- Other jet flow physical parameters:
  - Length of “diving board”
  - Height of “dam”