SNS Target Post Irradiation Examination Program 2012-2013

SNS Accelerator Advisory Committee

May 8, 2013

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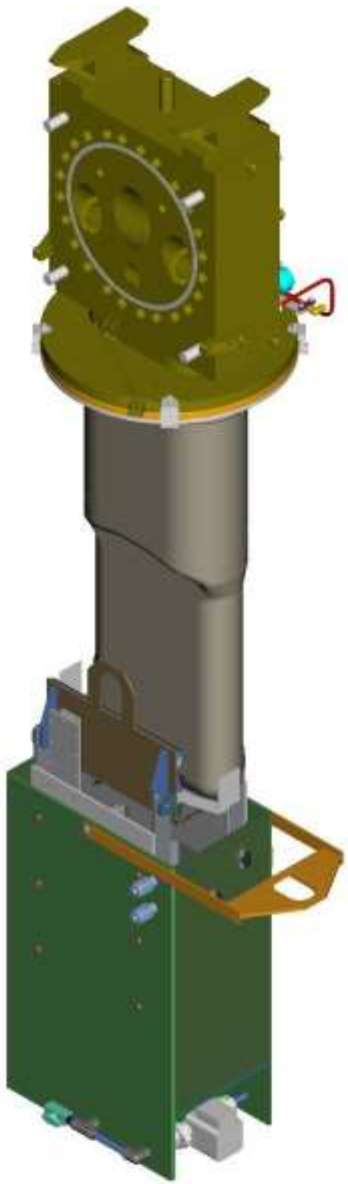
Outline

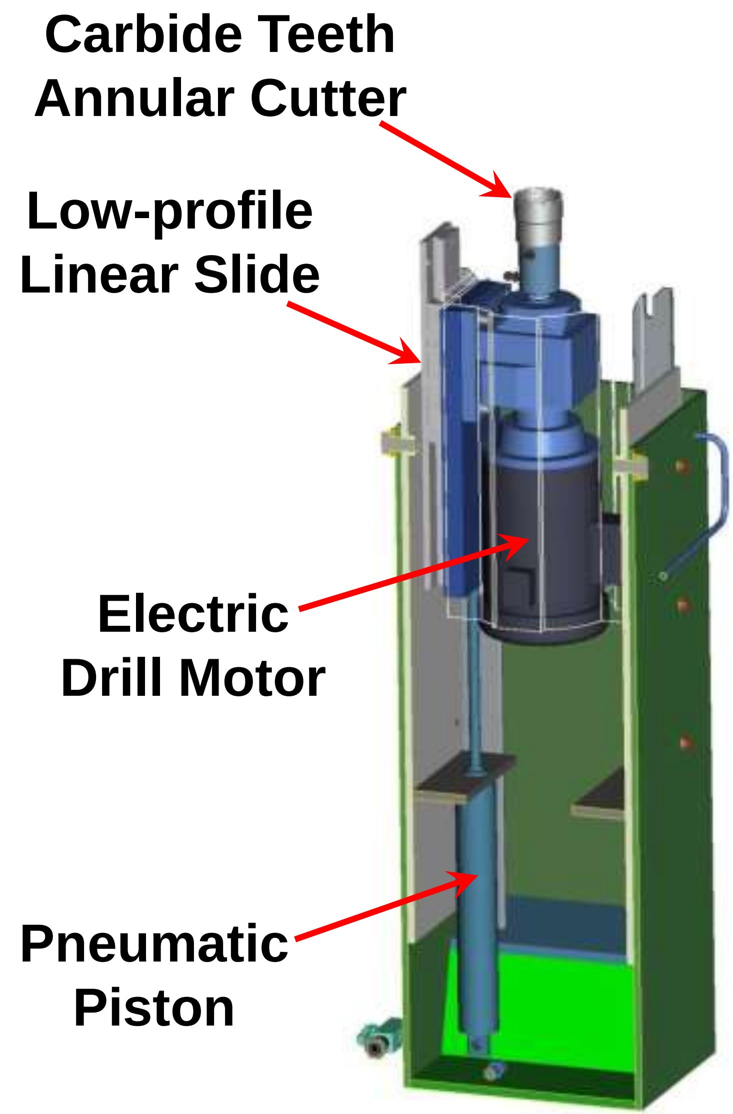
- Overview of PIE accomplishments 2012-2013
  - Results from characterizations performed by Babcock and Wilcox (B&W) on Targets 1 and 2
  - Erosion damage observations in Targets 4-7
  - Identification of leak locations in Targets 6 and 7
- Post Irradiation Examination (PIE) contributions to target development:
  - Identification of leak locations in Targets 6 and 7
  - Development of computer simulations modeling cavitation-induced erosion
  - Target design improvements
    - Purchase and utilization of “clean grade” 316L stainless steel for fabrication of target beam entrance windows
    - Development of bolt-on removable shroud
    - Refine/polished surface finish on mercury facing surfaces

PIE program was established to learn about degradative processes occurring in SNS target modules during operation

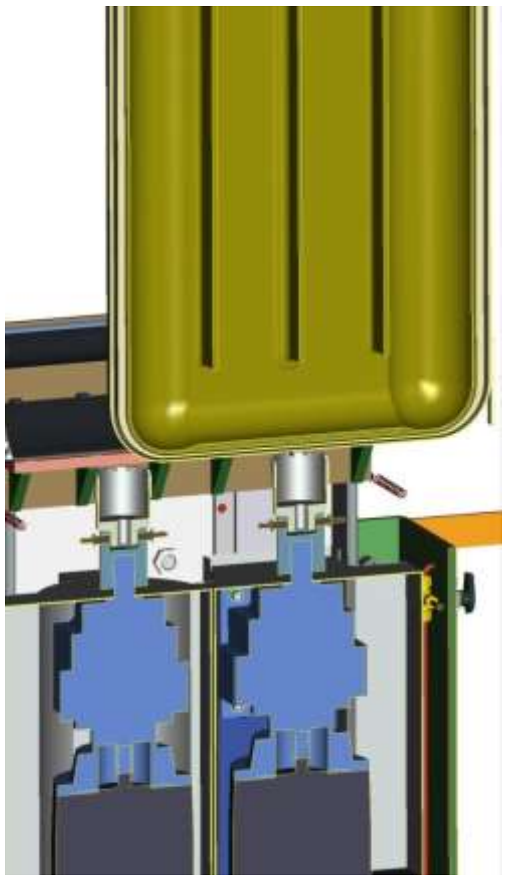
- During operation the inner surfaces of SNS target modules are damaged by cavitation-induced erosion
- Mechanical properties of the 316L vessel material are altered during operation from displacement damage
- Additionally, PIE has been shown to be critical in diagnosing problems with target modules after service
- Partial list of techniques utilized:
  - Inspection of target interiors using articulating videoprobes
  - High-resolution photography of target vessels and samples
  - Optical and electron microscopy of specimens removed from targets
  - Mechanical properties characterization of sample material removed from targets
  - Pressure-decay testing of target vessel interstitial region

Targets were sampled using annular cutters

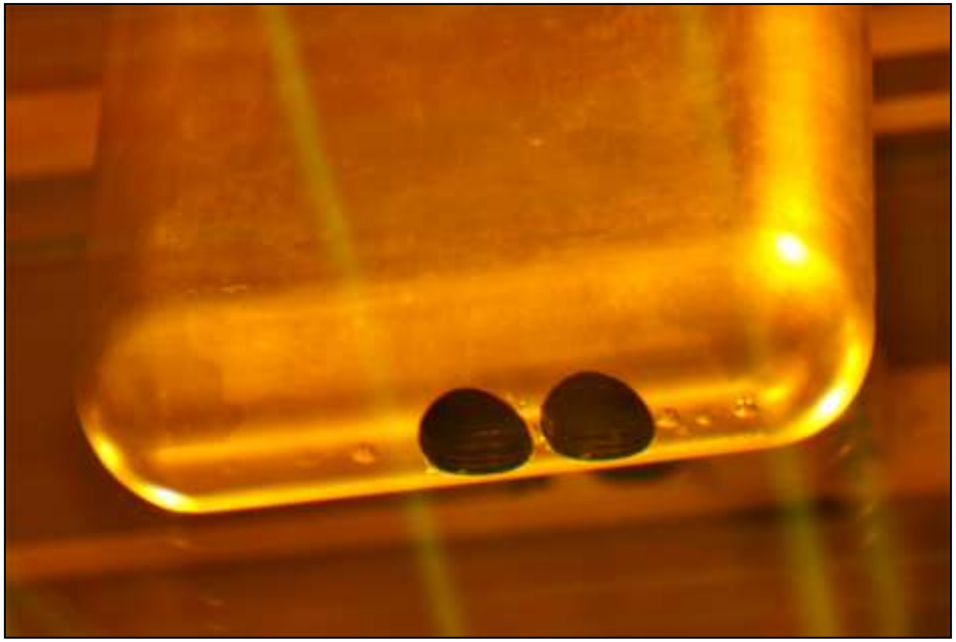


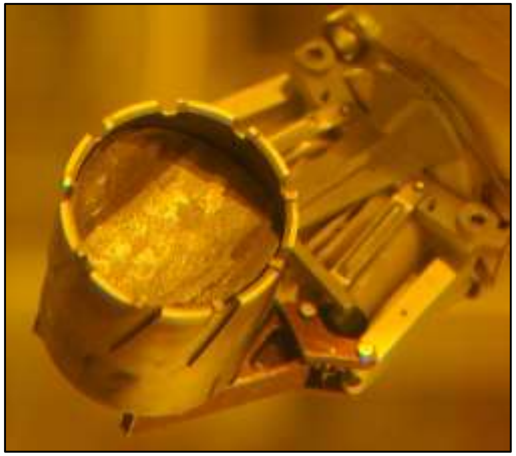


Center-cut Position



Disk-shaped specimens were removed from beam entrance region of targets after service





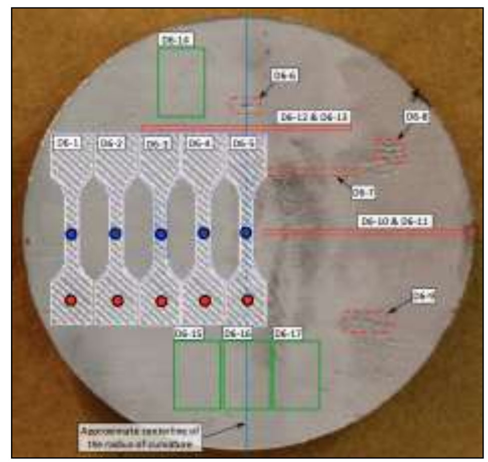
Sample disks were cleaned and machined using wire EDM

- Specimens were fabricated and tested by Babcock & Wilcox Technical Services Group (Lynchburg, VA, USA)
- The disks were cleaned in an ultrasonic bath and photographed; the images were used to produce specimen maps for each disk
- Specimen machining maps were produced for each disk and the specimens were machined via electrical-discharge machining (EDM)

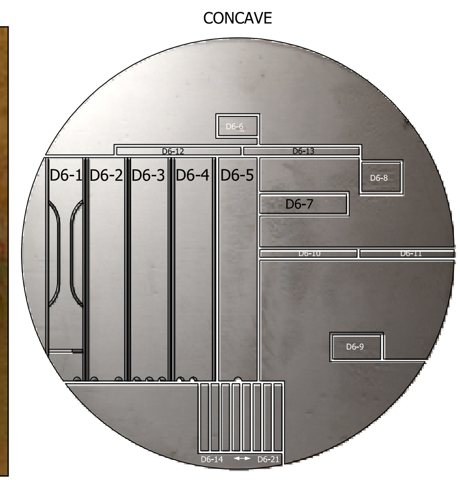
Example: Disk 6 from Target 2

Before Cleaning

After Cleaning

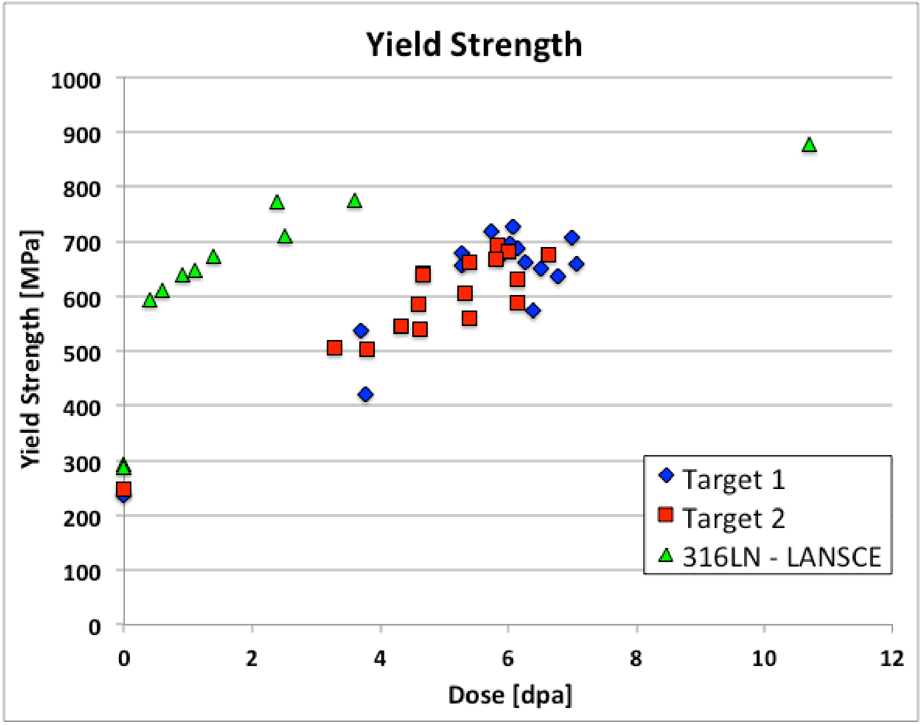


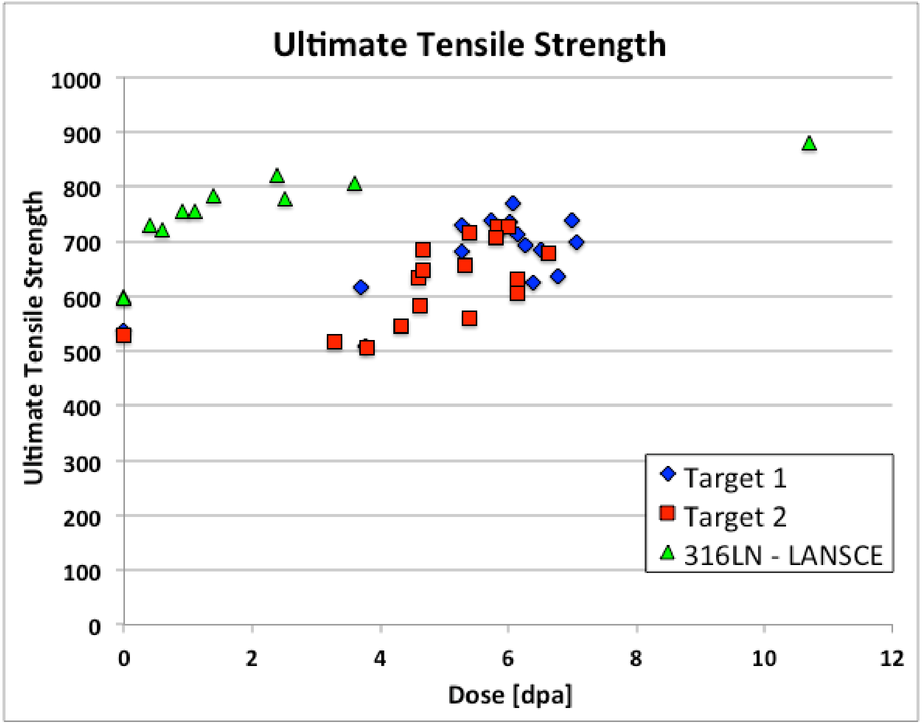
Specimen Map



EDM Machining Map

Tensile data show significant strengthening occurred during operation

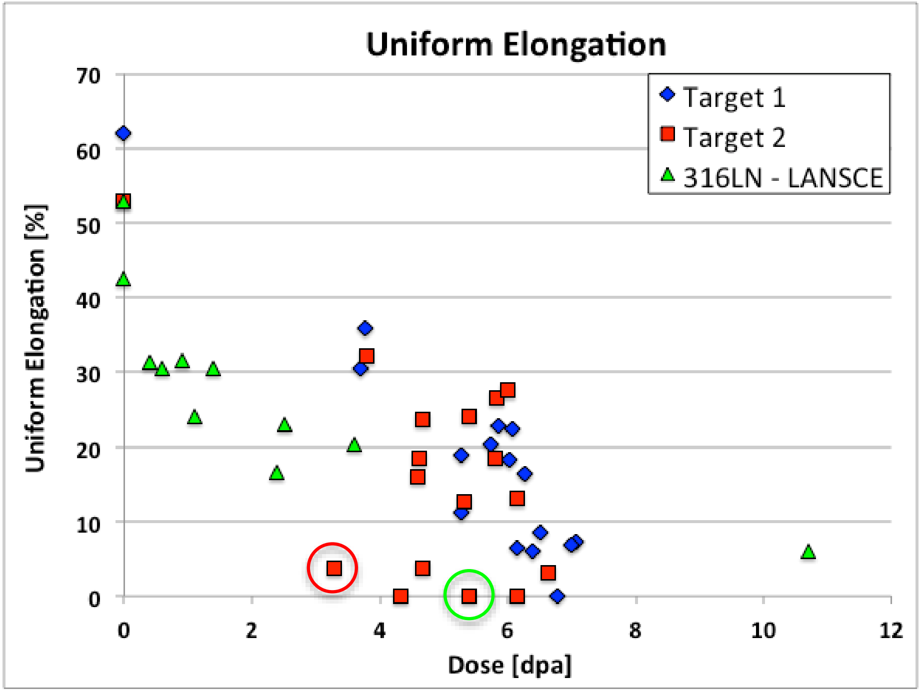


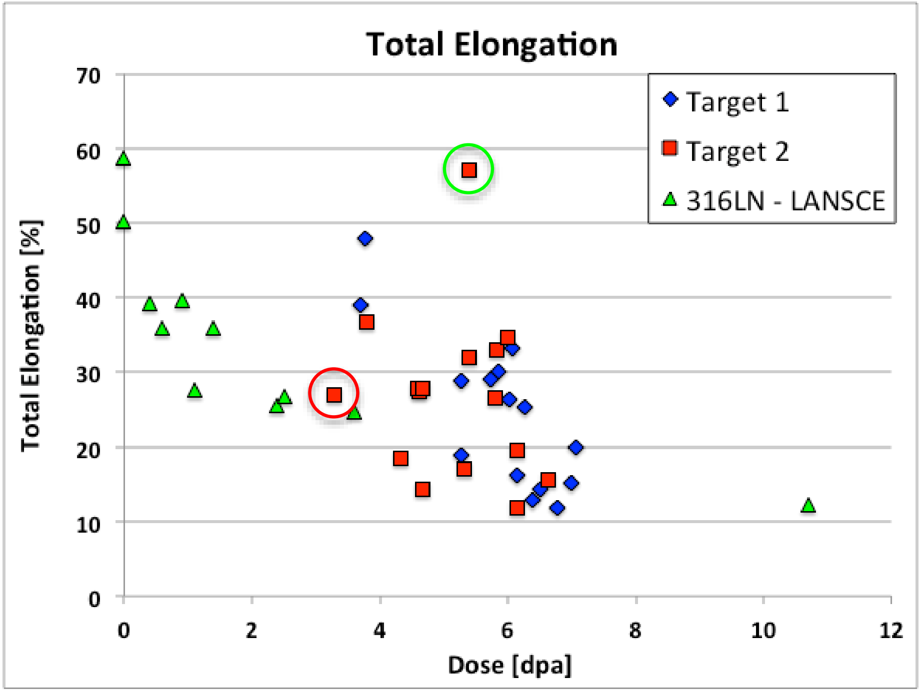


- LANSCE irradiation was 316LN – slight higher strength expected due to nitrogen addition
- General hardening trend of SNS tensile data is consistent with data in literature

K. Farrell and T.S. Byun, *Journal of Nuclear Materials*, 296 (2001) 129-138

Tensile data show appreciable total elongation remained after ~7 dpa



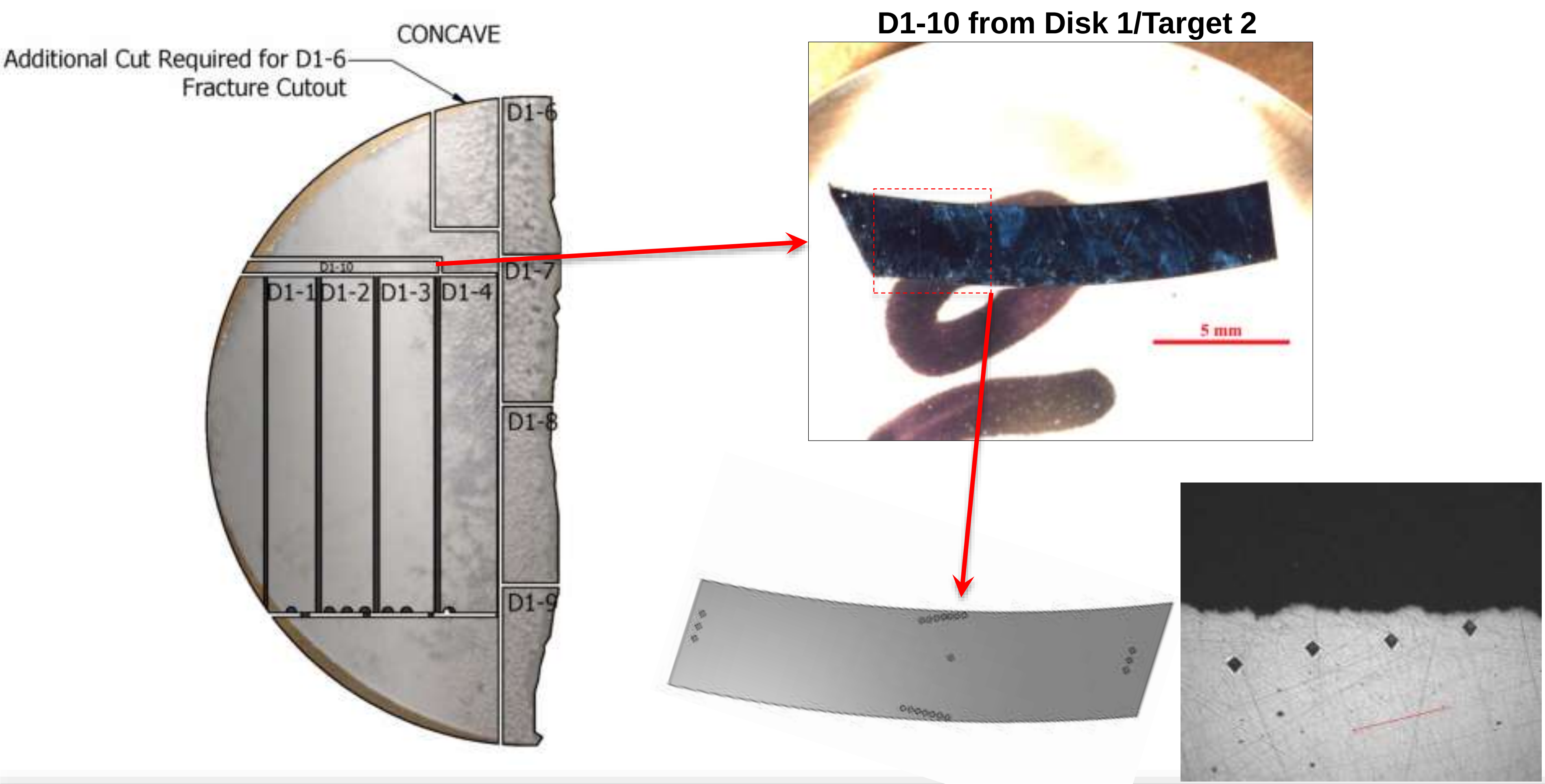


- Reduction in uniform elongation observed in Targets 1 and 2 are generally consistent with previous LANSCE data
- Prompt plastic instability in some SNS specimens were attributed to nonmetallic inclusions and specimen geometry/surface roughness

K. Farrell and T.S. Byun, *Journal of Nuclear Materials*, 296 (2001) 129-138

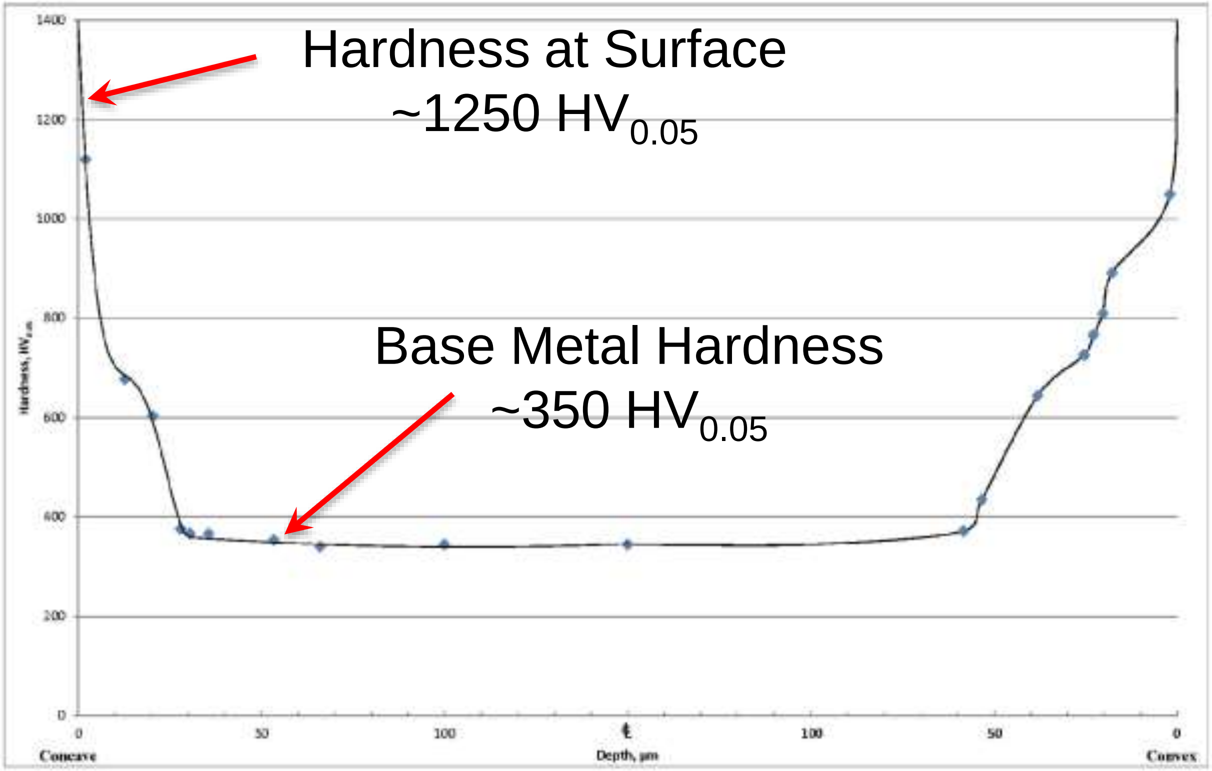
Specimens were removed from disks to characterize the Kolsterising® treated layer

- Specimens were machined from disks removed from Targets 1 and 2 via wire electrical discharge machining (EDM)



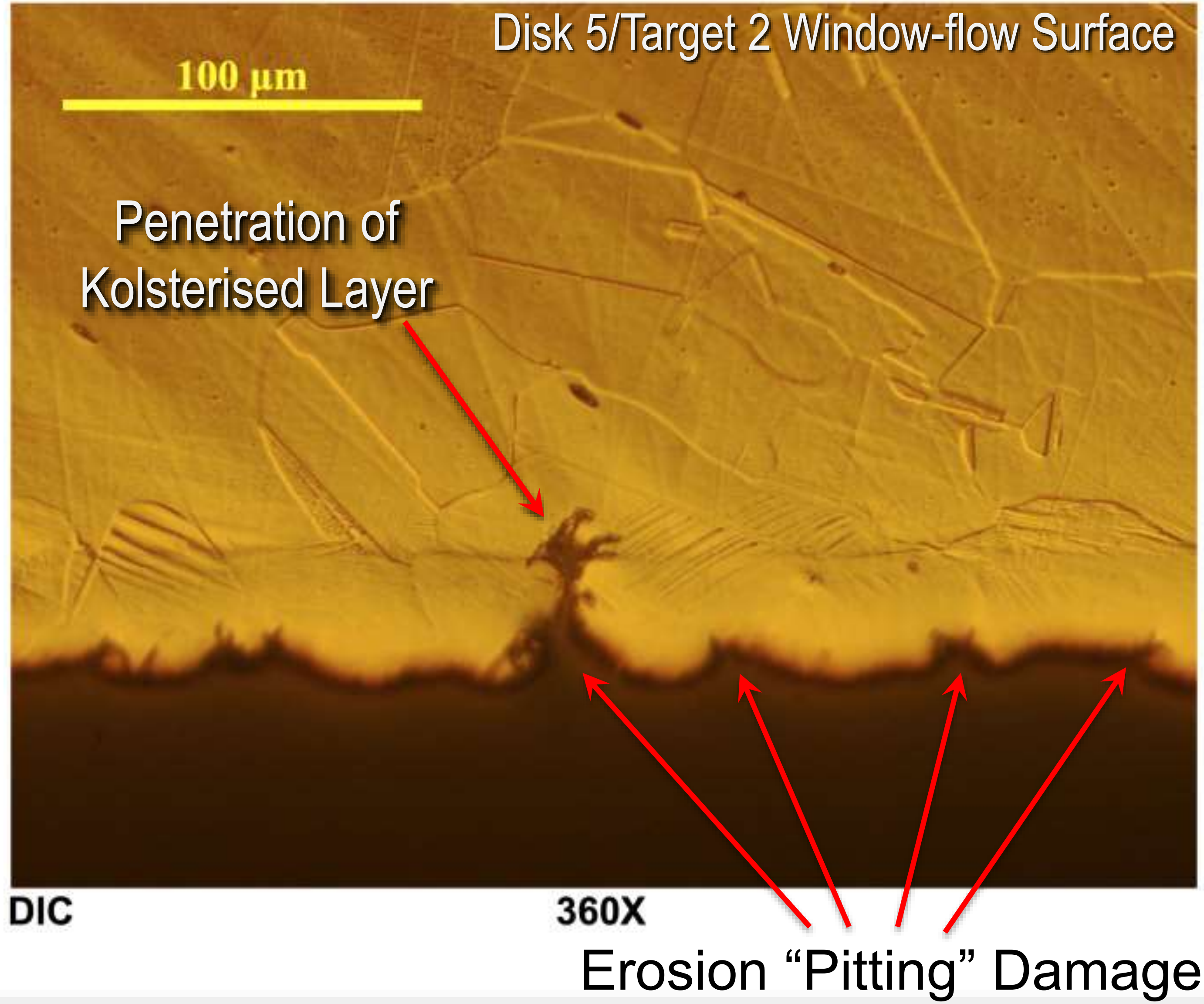
Hardness testing showed the Kolsterising® treated layer was present after irradiation

- Microhardness values from Target 1 indicate the high-initial hardness at surface was still present after irradiation
- Data suggest Kolsterised layer remains stable after irradiation to ~4-5 dpa, thereby maintaining protection throughout a typical target lifetime

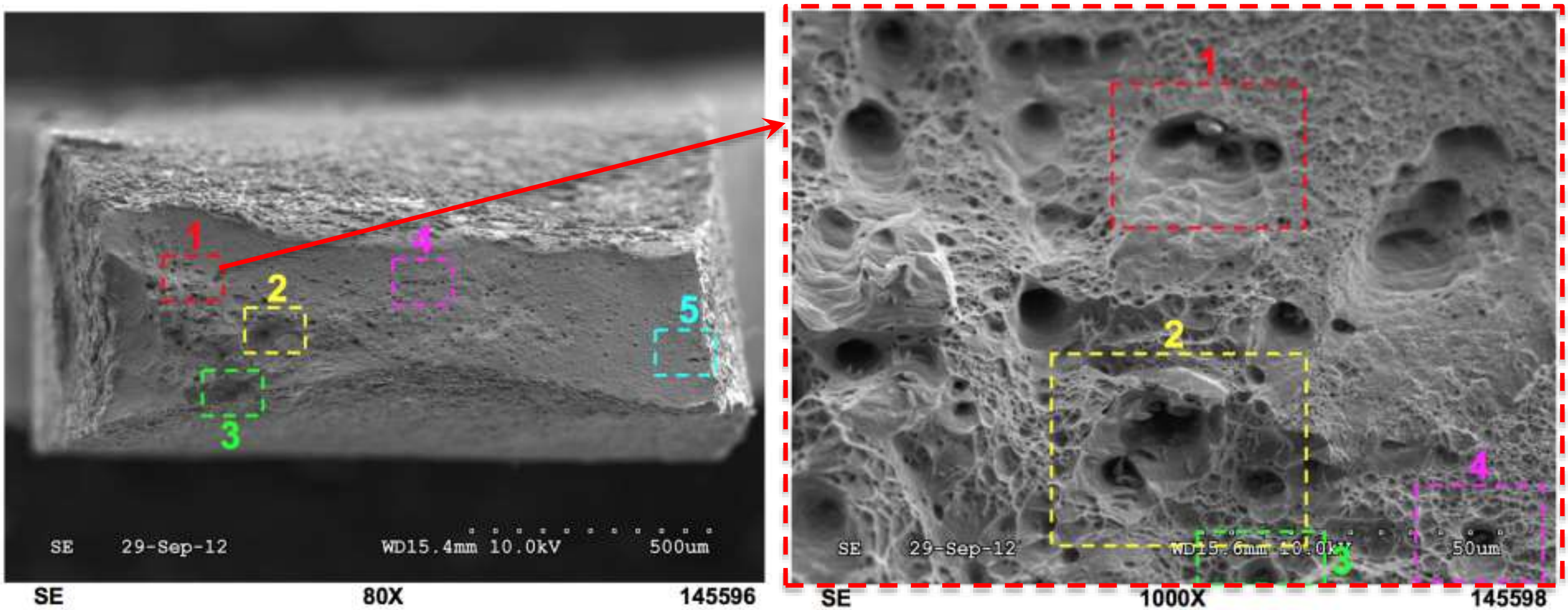


Disk 5/Target 1 Hardness Profile

Penetration of Kolsterised layer leads to accelerated erosion damage

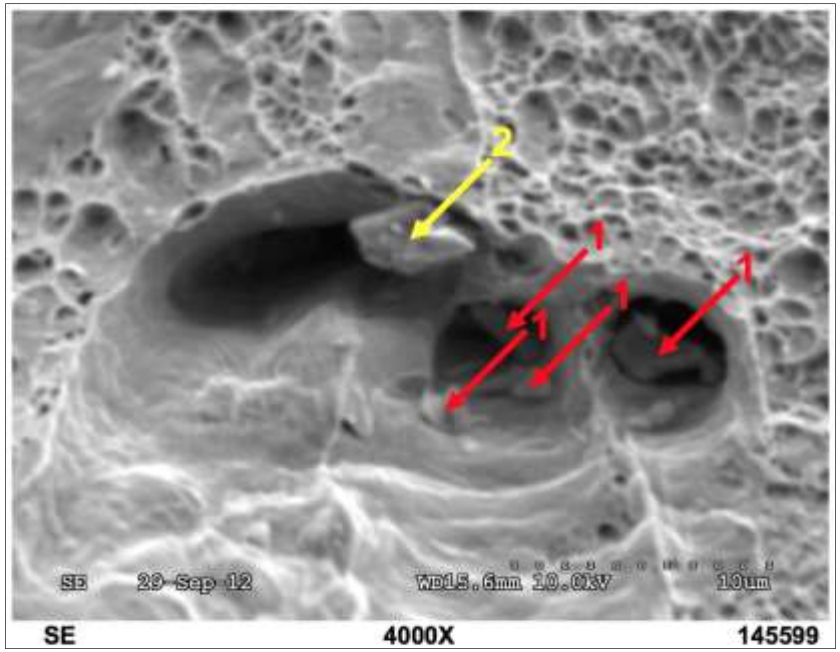


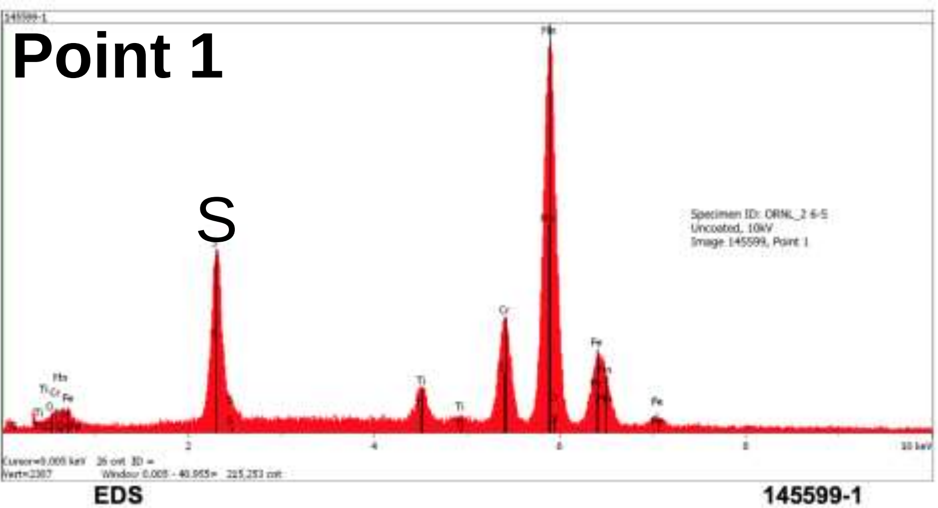
Nonmetallic Inclusions were found on fracture surface of tensile specimens

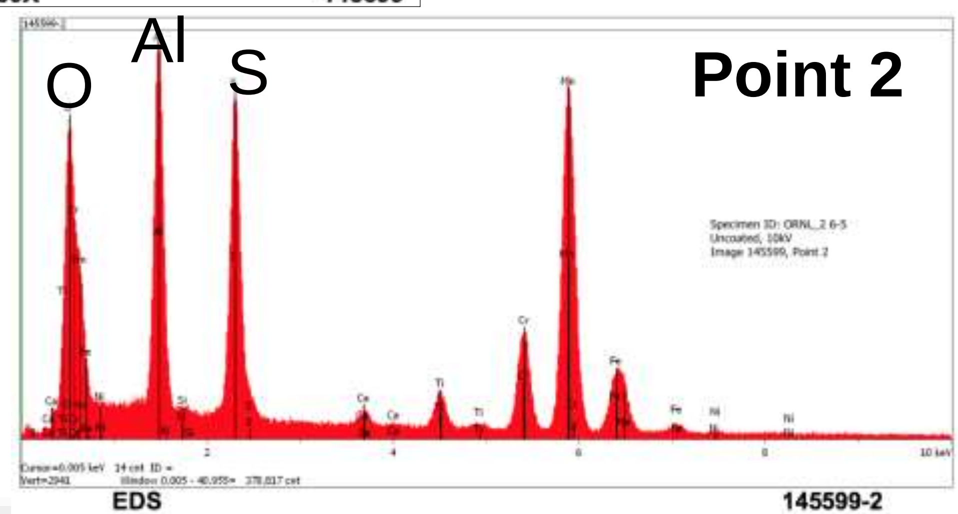


- Significant amounts of nonmetallic inclusions were found on <u>all fracture surfaces examined</u>
- Inclusions with several different compositions were found including Ca, Al, S, O, Mg

Nonmetallic inclusions were comprised of several different chemical compositions





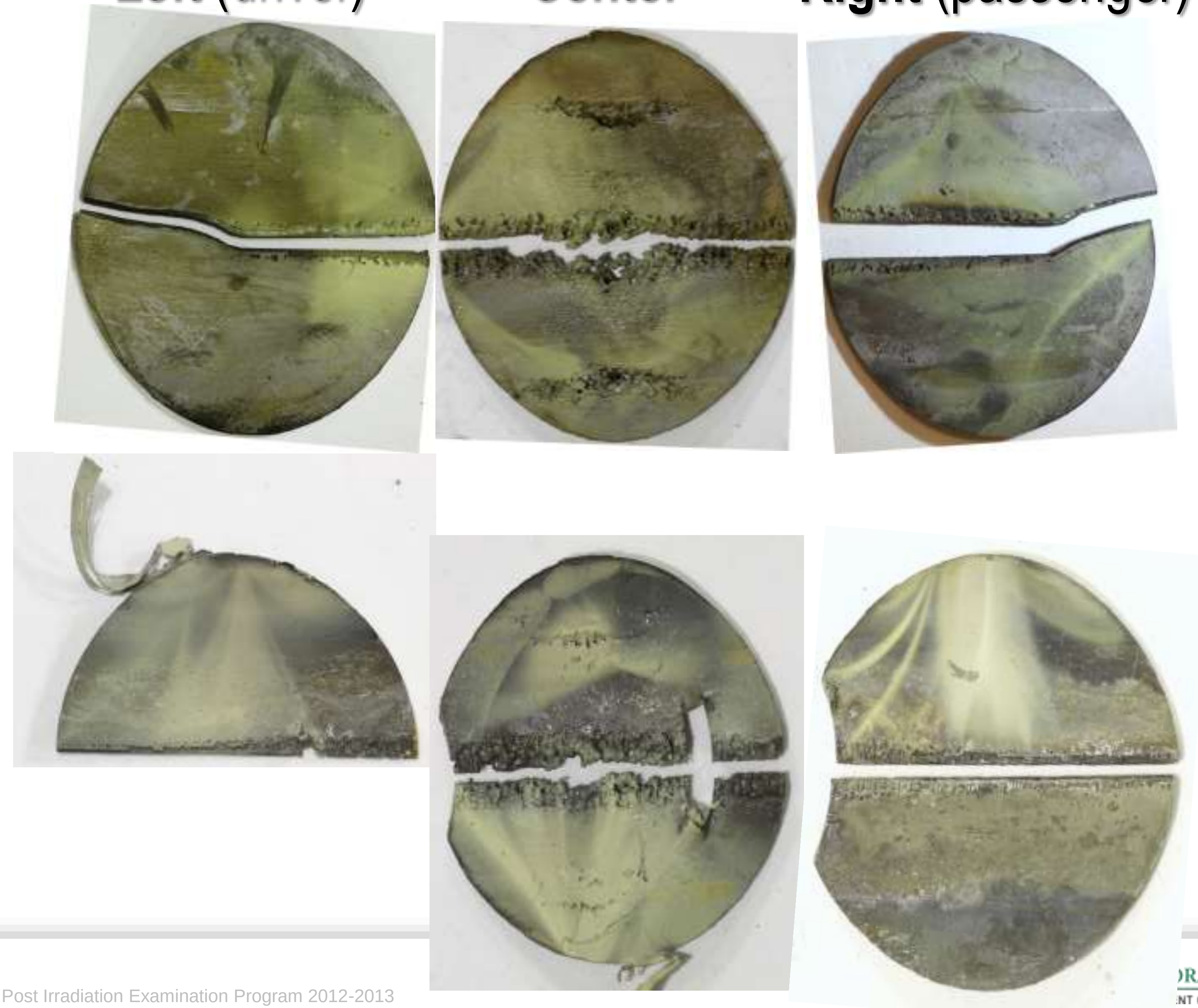


Significant cavitation-induced erosion was observed on inner wall of Targets 4 and 5

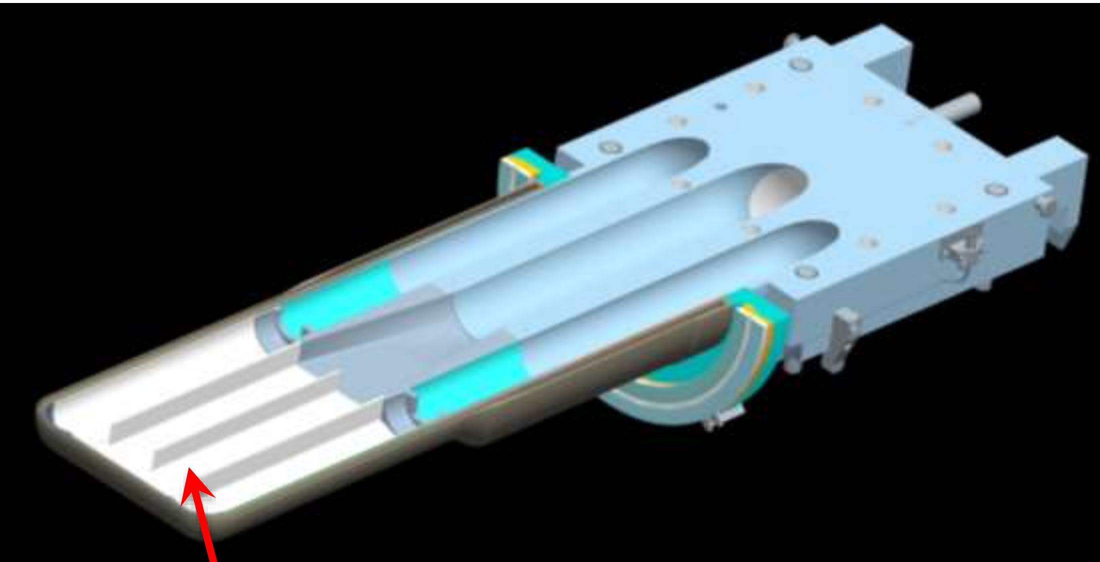
Left (driver) **Center** **Right** (passenger)

Target 4

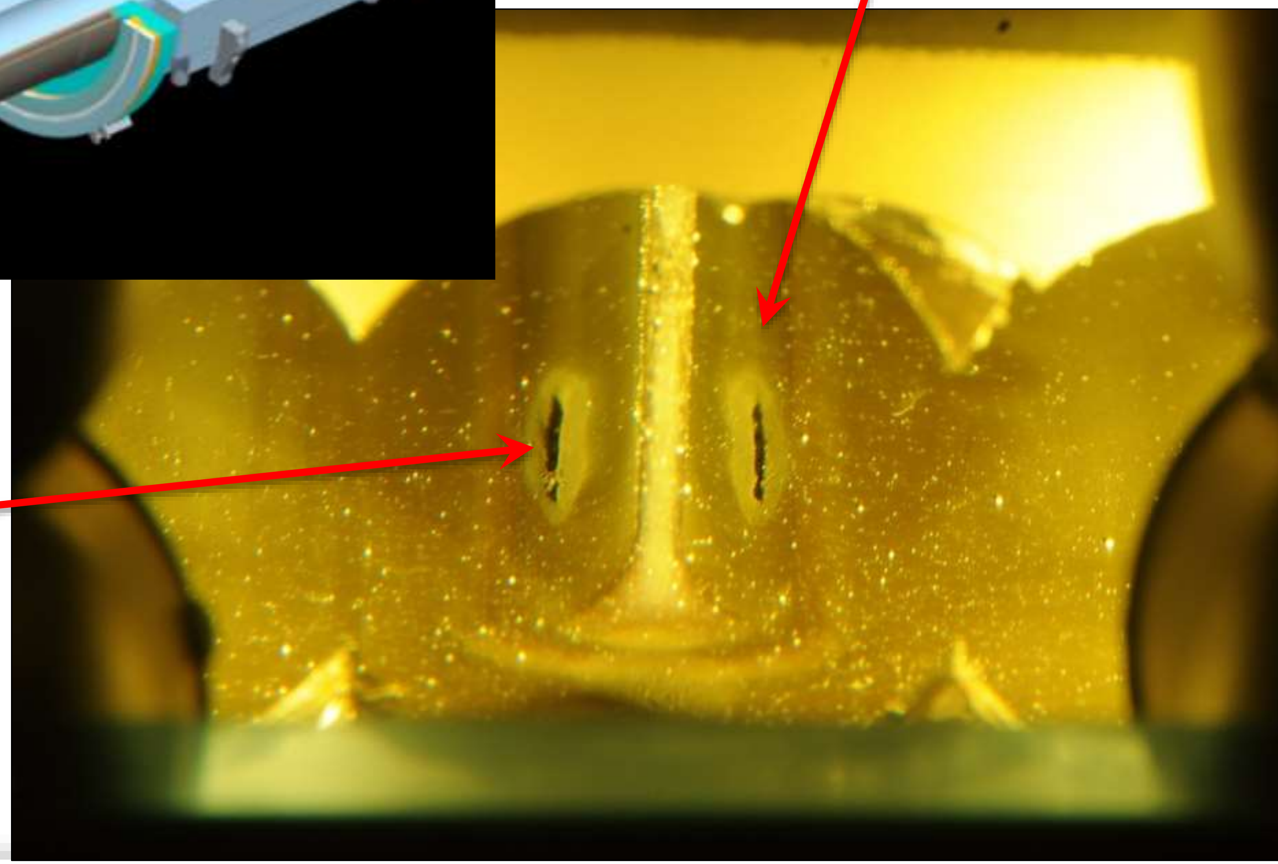
Target 5



Slit-shaped erosion “Hot Spots” were observed on either side of center baffle



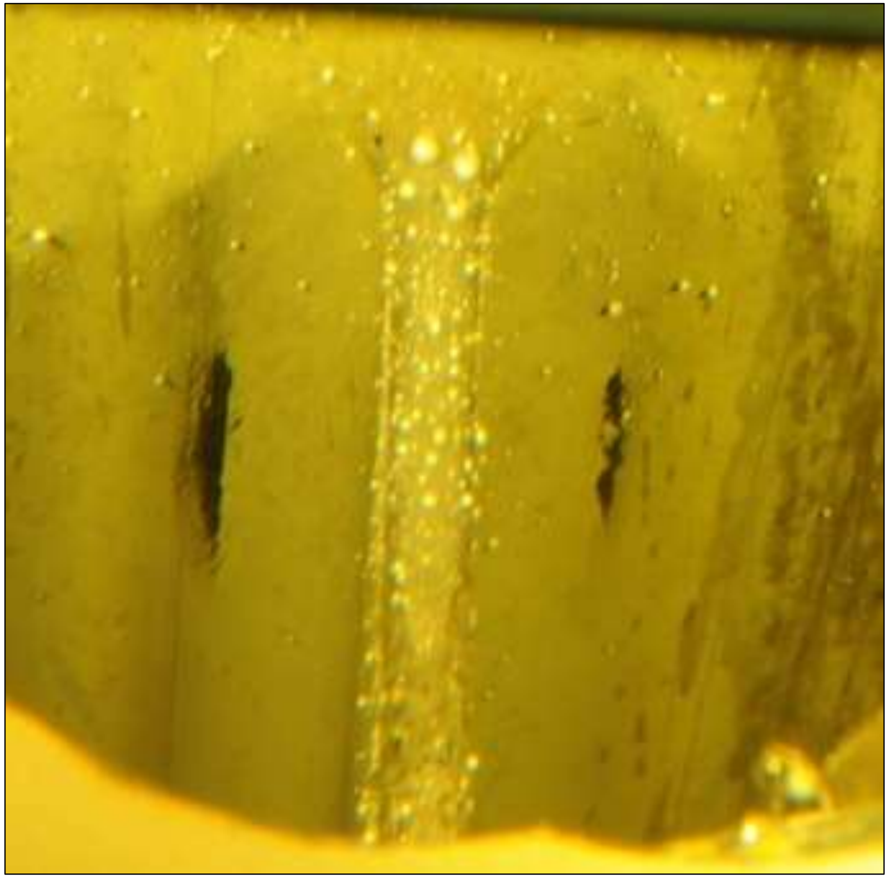
Top Interior Surface of Target 5



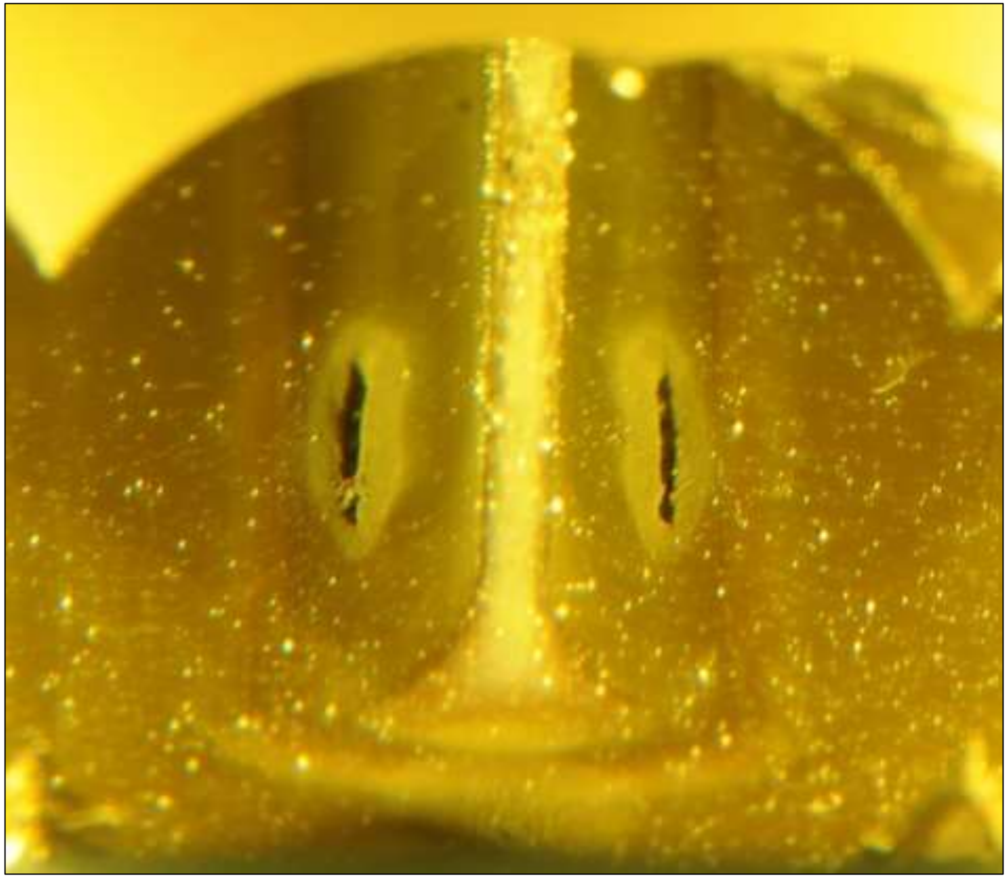
Slit-shaped Cavitation-Induced Erosion Patterns

Slit-shaped erosion "hot spots" were observed on top and bottom inner surface of Targets 4 and 5

Bottom of Target 5



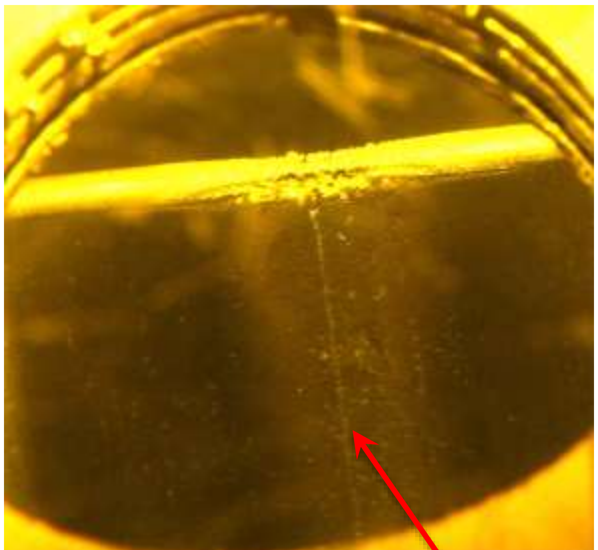
Top of Target 5



A crack-like feature was observed on the center flow baffles of Targets 4 and 5

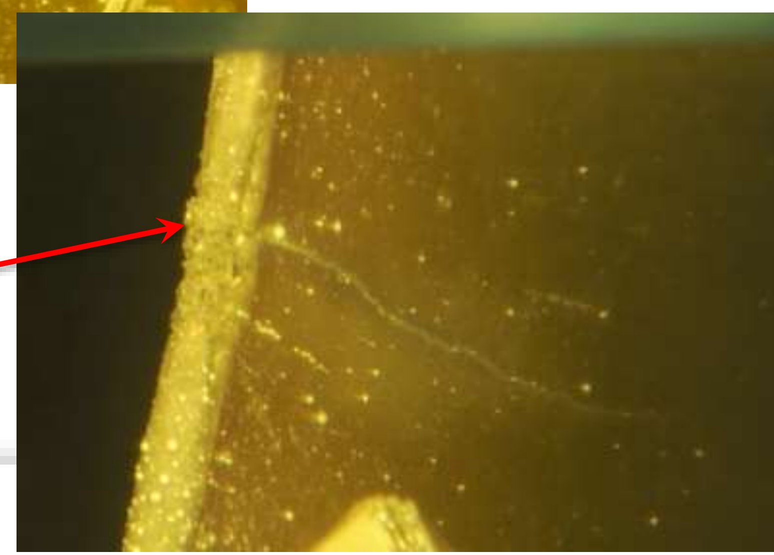
- Current PIE capabilities **do not** allow sampling of the center flow baffle

Target 4



Target 5 “Passenger Side”

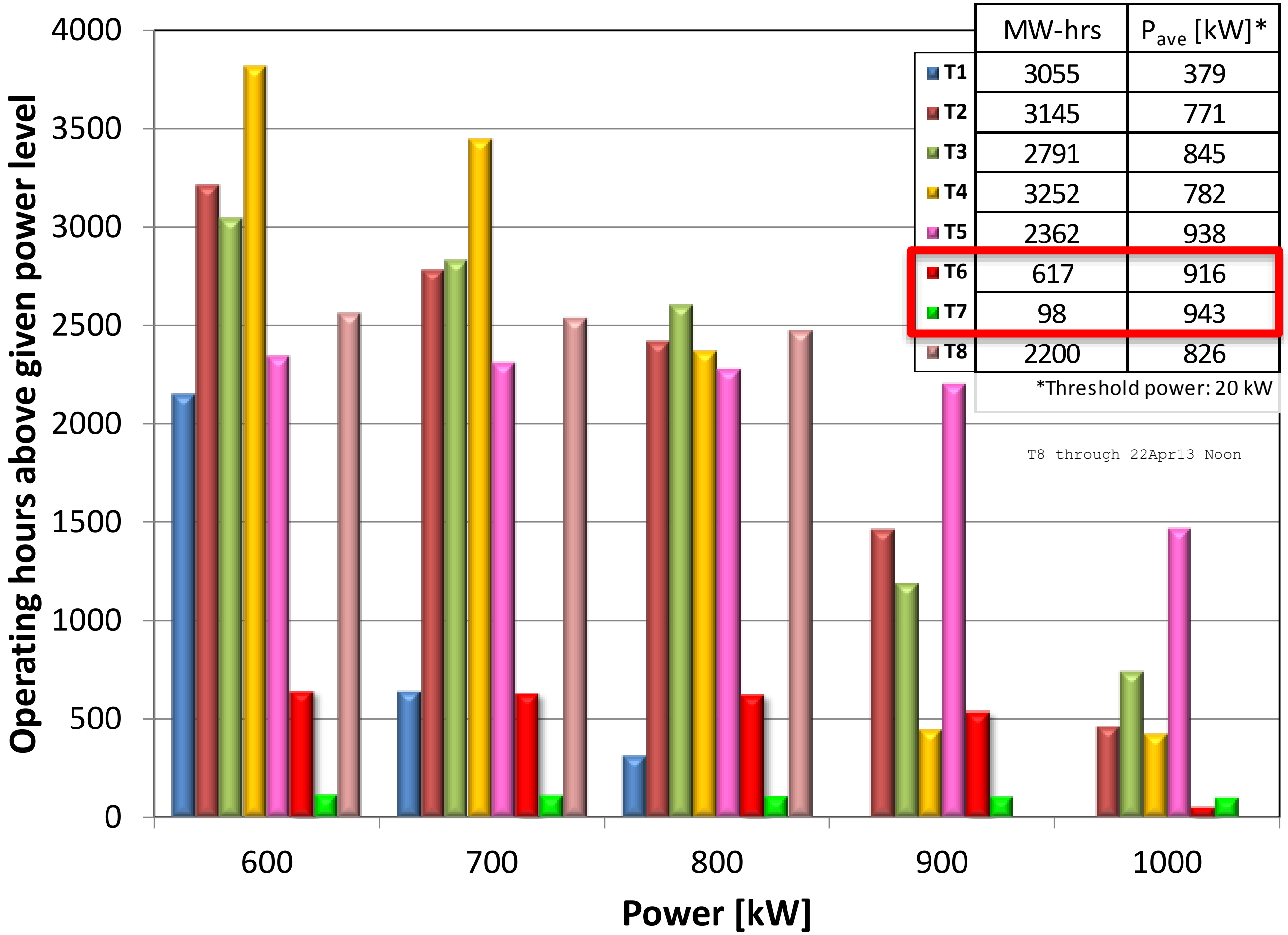
Target 5 “Driver Side”



Crack-like feature observed on center baffles of Targets 2-5

Targets 6 and 7 provided a glimpse at the early stages of erosion damage

- Early expirations of Targets 6 and 7 provided unique observations of the early stages of cavitation-induced erosion damage



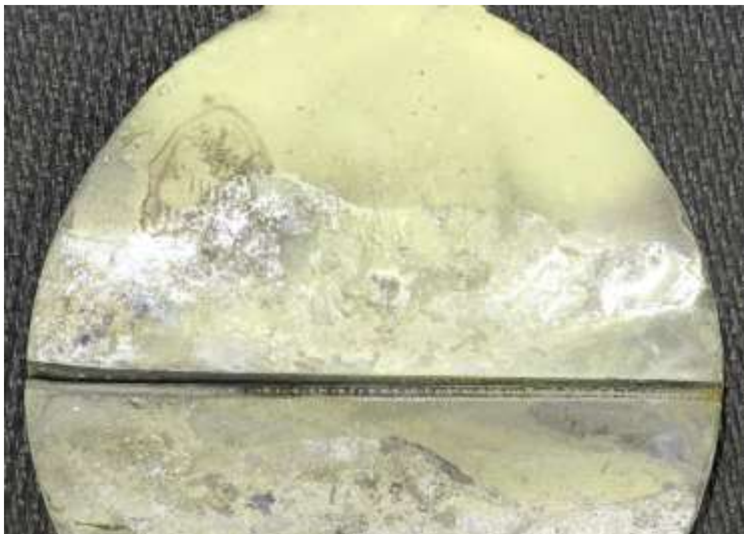
	MW-hrs	P_{ave} [kW]*
T1	3055	379
T2	3145	771
T3	2791	845
T4	3252	782
T5	2362	938
T6	617	916
T7	98	943
T8	2200	826

*Threshold power: 20 kW

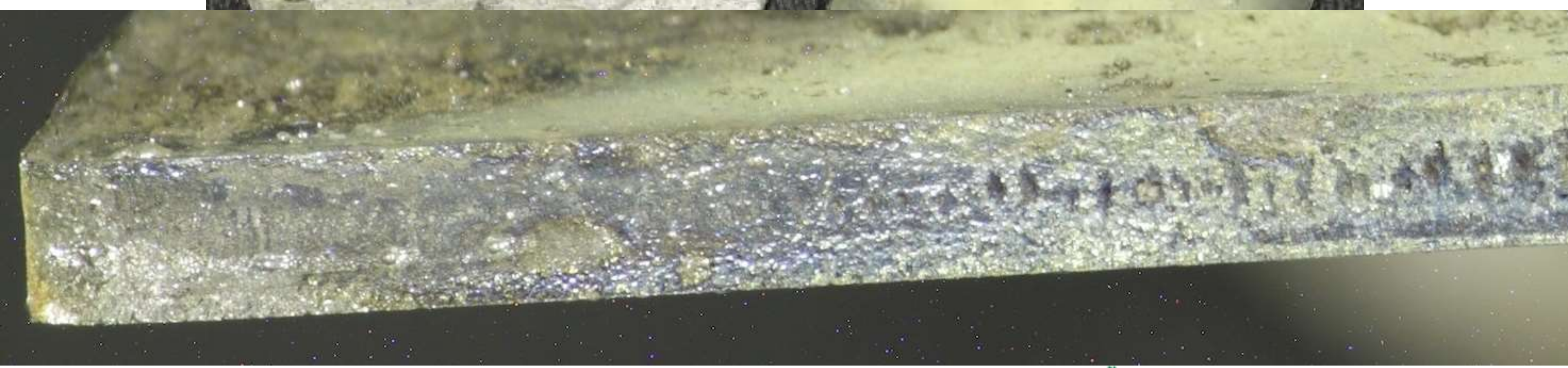
Significant cavitation-induced erosion observed on Target 6 vessel inner surface

- Significant erosion was observed on the bulk flow facing surface of Target 6 and inner wall was segmented in two pieces after 617 MW-hr

Left Off-center

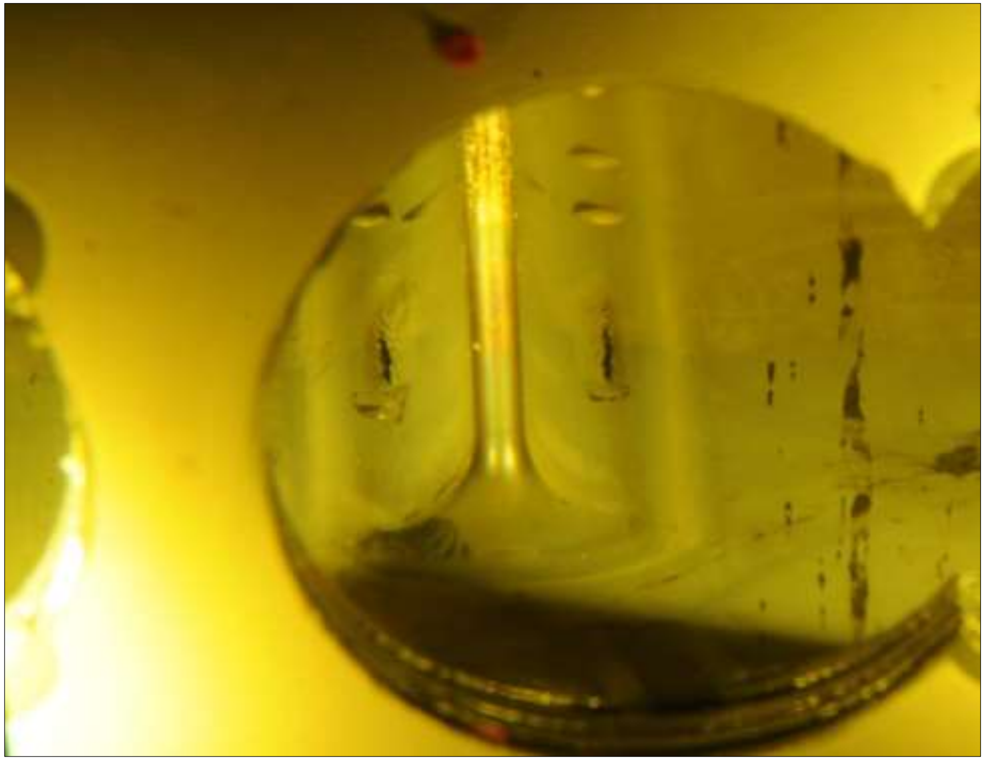


Center

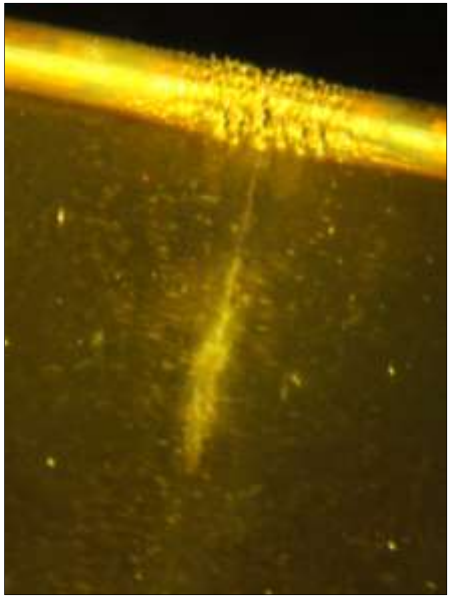


Erosion "hot spots" and crack-like feature on center baffle were observed on Target 6 after 617 MW-hr

Erosion Hot Spots on Target 6



Center Baffle (before cleaning)



Center Baffle (after cleaning)

Small amount of cavitation-induced erosion observed on Target 7 vessel inner surface

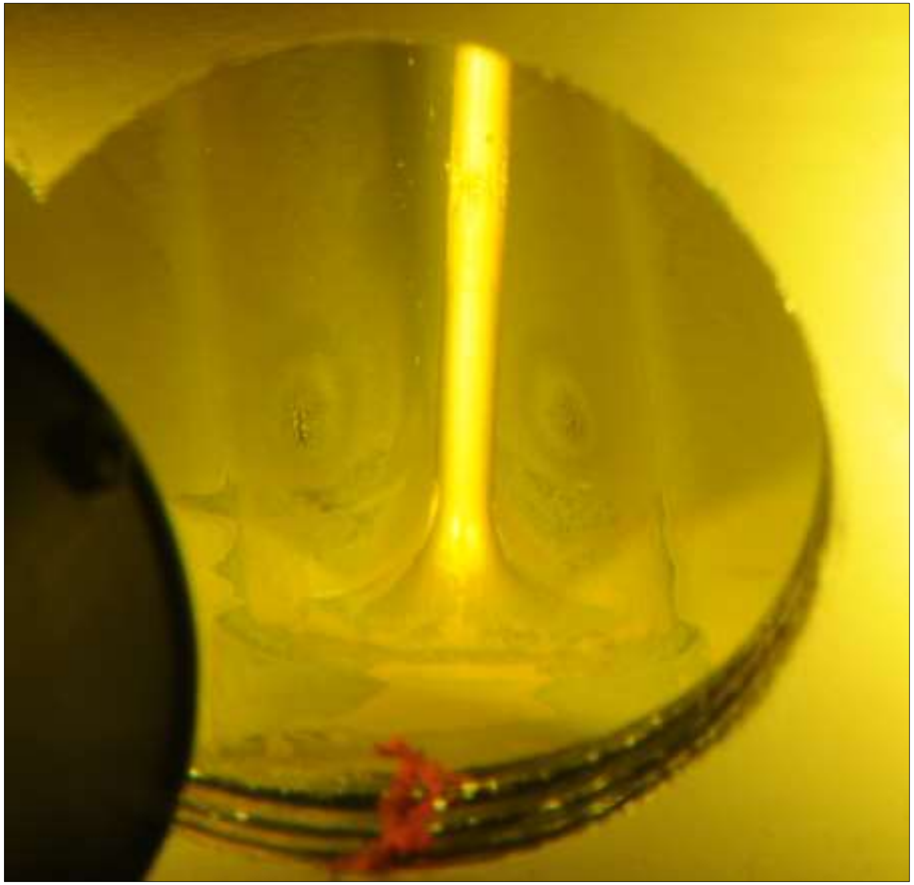
- Erosion was observed on the bulk flow facing surface of Target 7; a small patch of erosion was observed along the vertical beam center after 98 MW-hr

Left Off-center

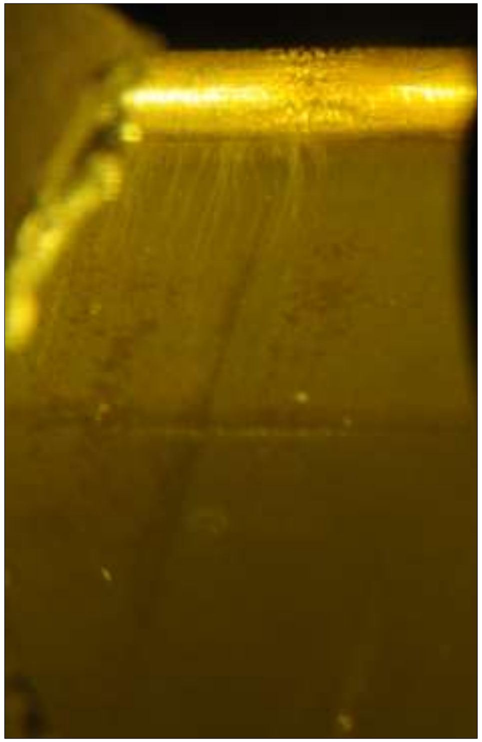
Center

Erosion "hot spots" were observed on Target 7 – but no crack-like feature was apparent

Erosion Hot Spots on Target 7



Center Baffle (before cleaning)



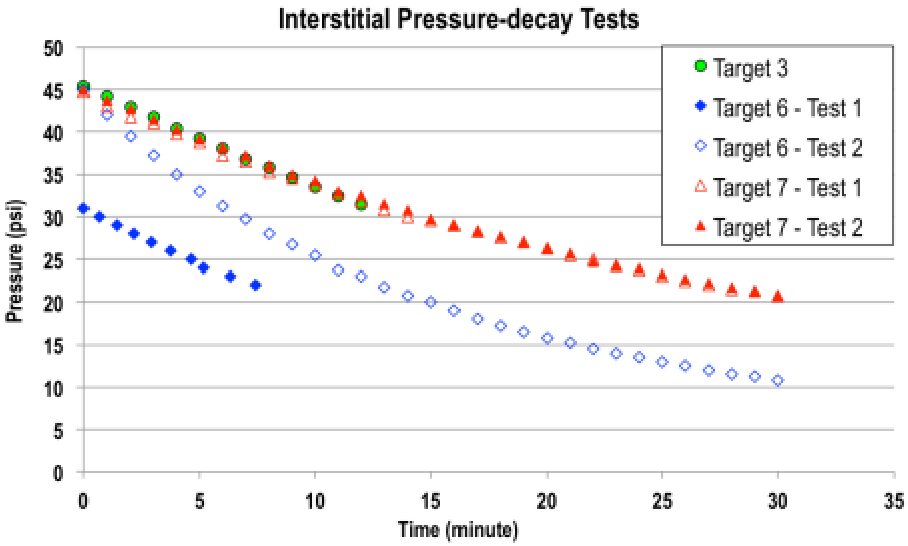
Center Baffle (after cleaning)

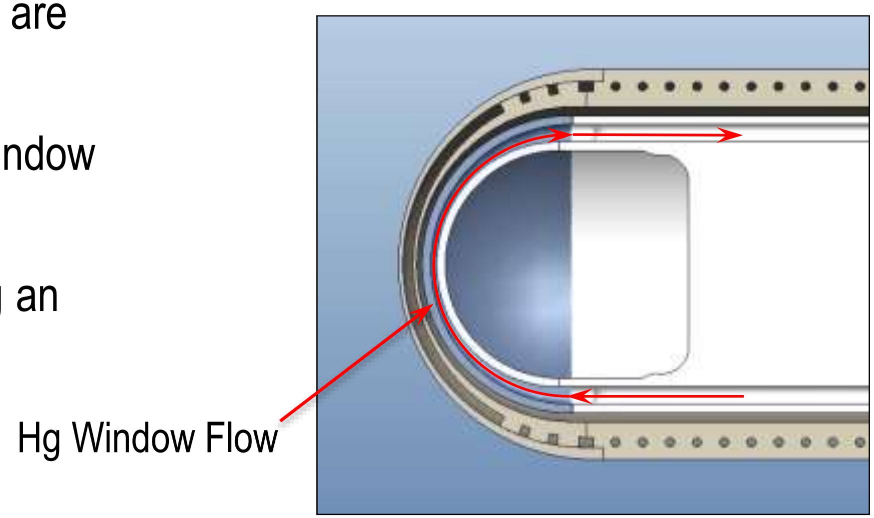
PIE Contributions to 2012-2013 Target Development

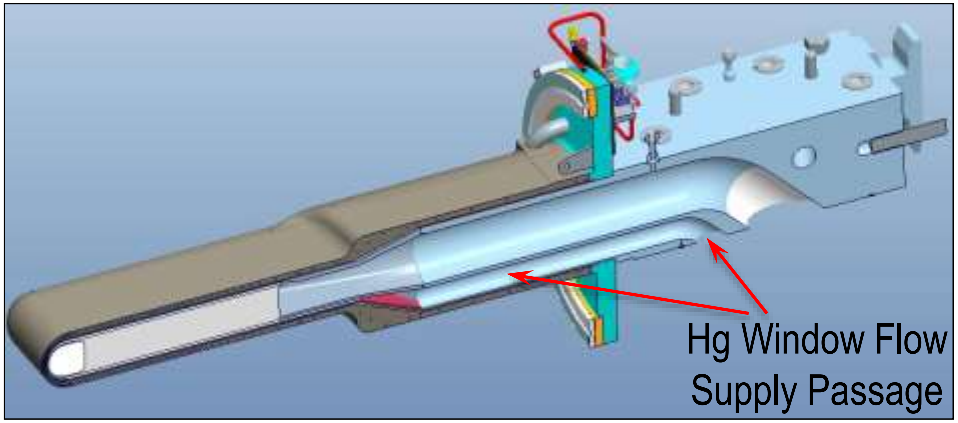
- Identification of leak locations in Targets 6 and 7
- Development of computer simulation techniques for modeling of cavitation-induced erosion
- Purchase and utilization of “clean grade” 316L stainless steel material for fabrication of target beam entrance windows
- Specification of a low-roughness/polished surface finish for mercury facing surfaces
- *Development and implementation of bolt-on/removable shroud*

Leaks from the target vessel were confirmed for Targets 6 and 7 by leak-down testing

- Leaks were confirmed in Targets 6 and 7 using pressure decay testing
- Debris from cavitation erosion and spallation products are *somewhere* in the mercury loop
- It was initially thought a partial blockage of mercury window flow may have occurred
- The window flow supply passage was inspected using an <u>articulating videoprobe</u>

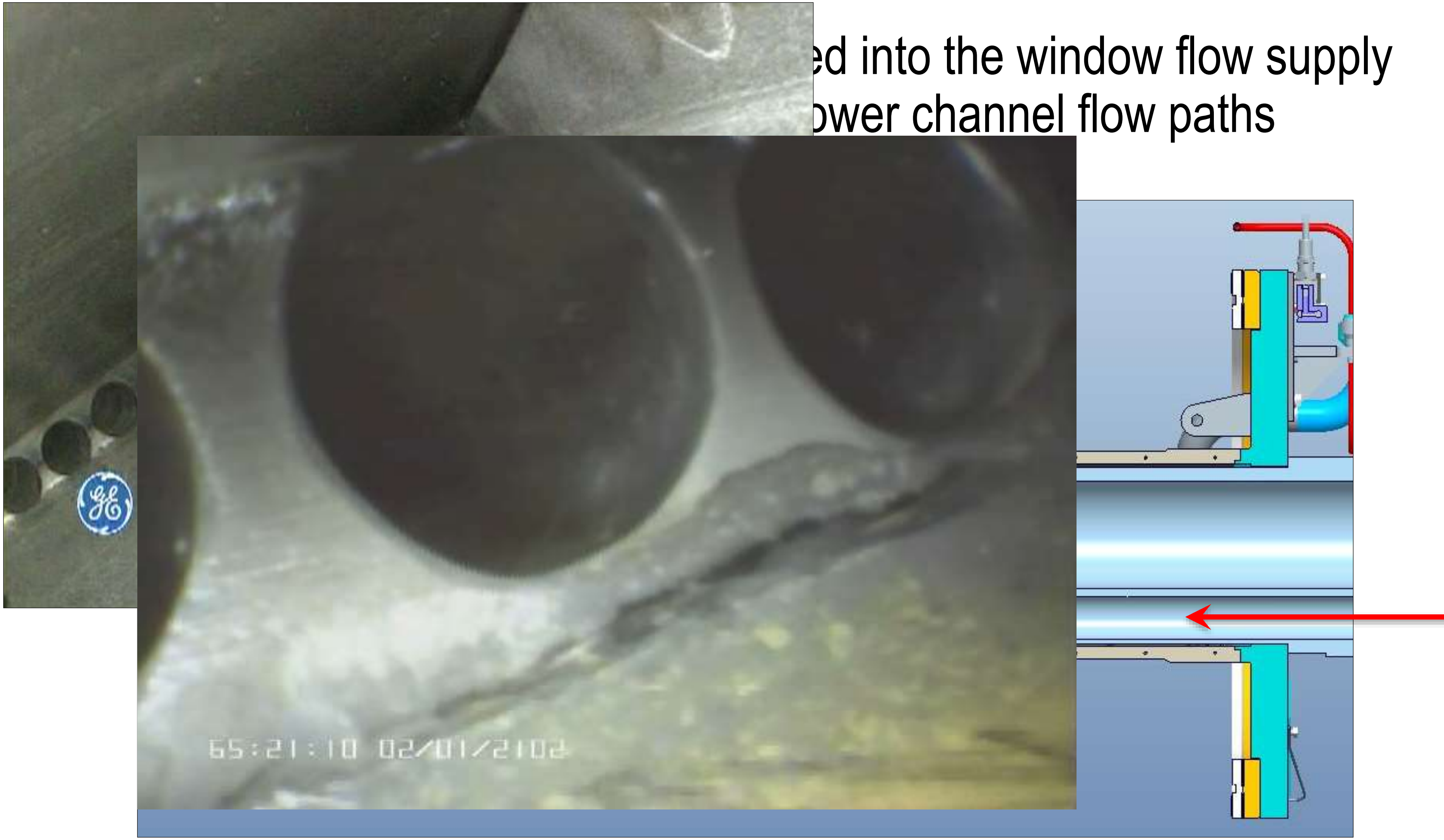






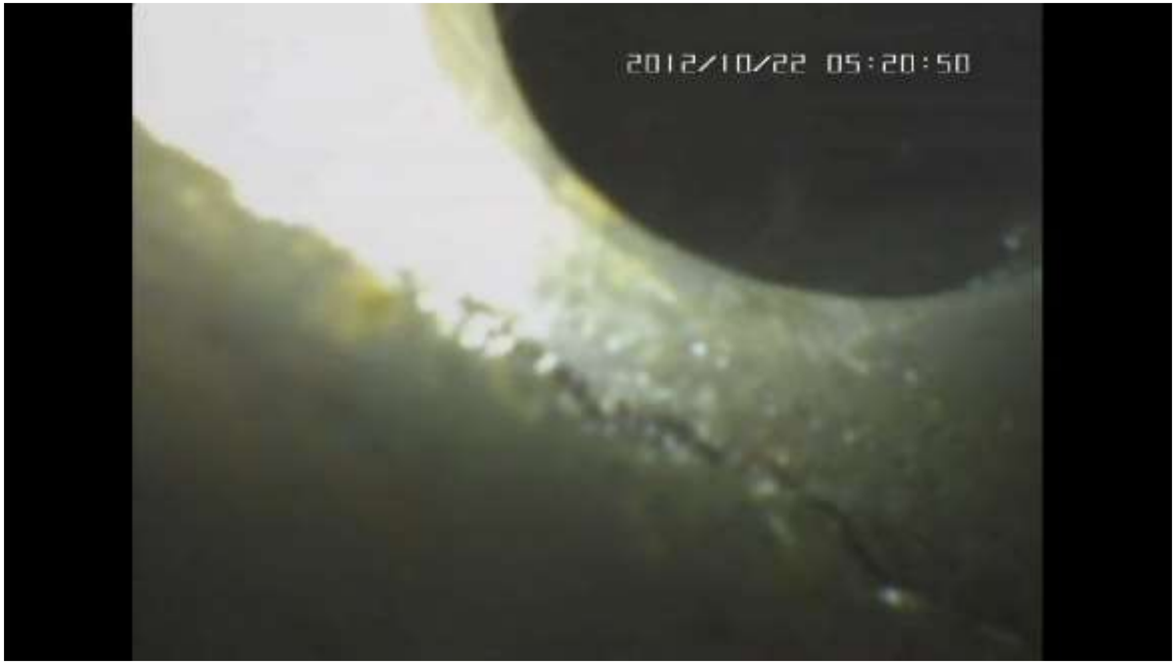
Articulating videoprobe examination found a crack like feature on a weld joint

…ed into the window flow supply
…ower channel flow paths



Target leaks were located using bubble solution and videoprobe inspection

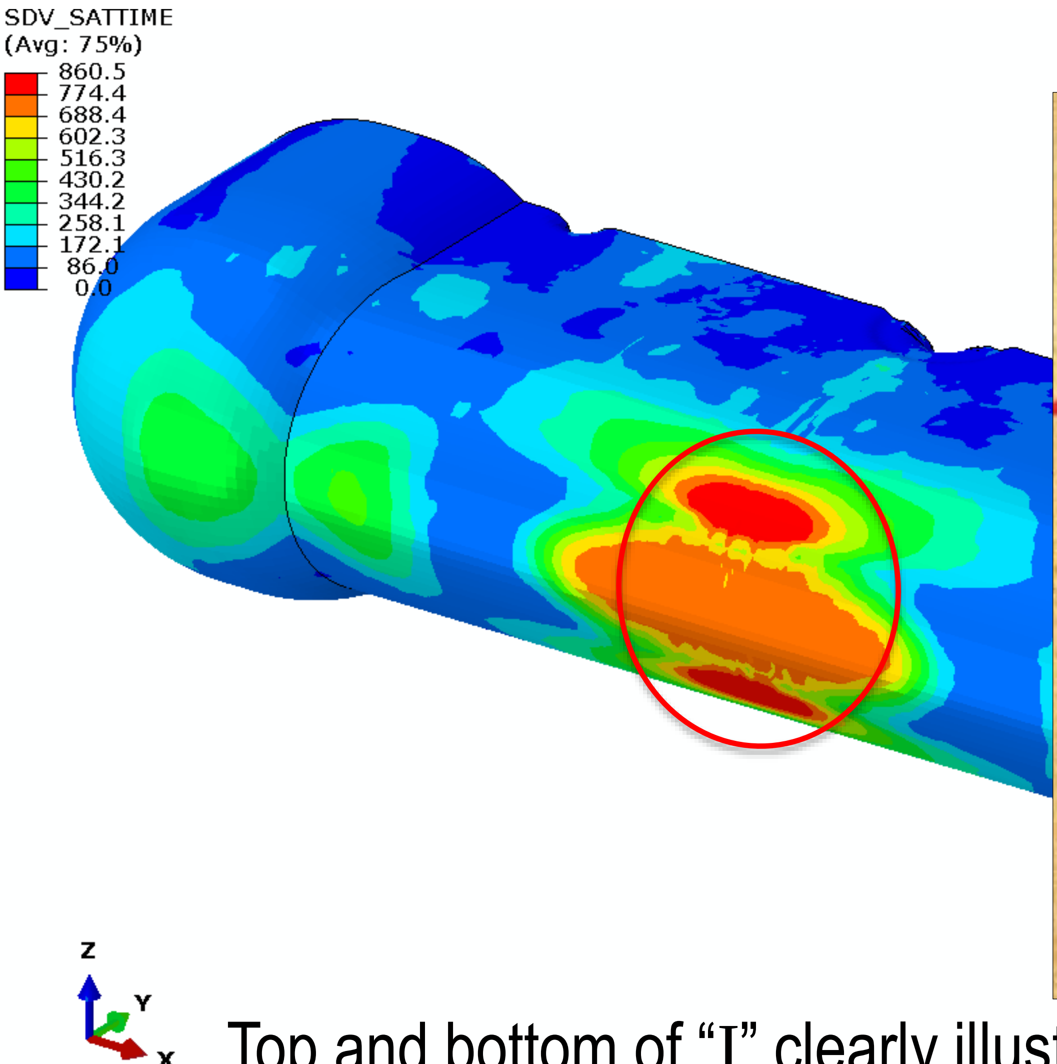
- On Oct. 22, 2012 the videoprobe was reinserted into the window-flow supply passage and the interstitial volume was pressurized to ~30 psi
- “Snoop” was poured down the videoprobe cable and made its way to the “area-of-interest”:



Patterns of erosion in SNS targets stimulated efforts for better understanding of mechanisms governing cavitation erosion

- Observed erosion patterns do not appear to directly correlate with incident beam or deposited energy density
- Concept of "saturation time" was result of work done by J-PARC collaborators
  - Proposed as a measure of *damage potential* for cavitation-induced erosion
- Building on a finite element analyses technique developed for SNS target vessel structural dynamic response to beam pulse, subroutines have been developed to provide the saturation time pattern throughout the target mercury

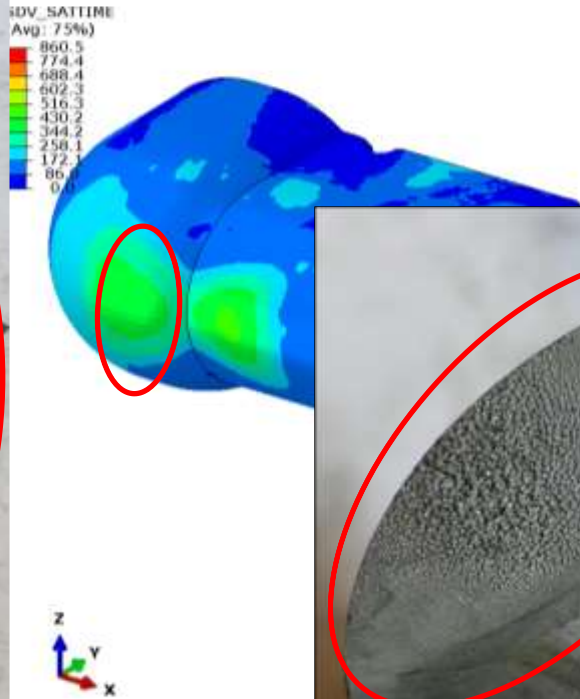
Saturation Time maps correlate with erosion patterns observed on bulk flow-facing surface of Target 1



Top and bottom of "I" clearly illustrated in saturation time map of bulk flow facing surface

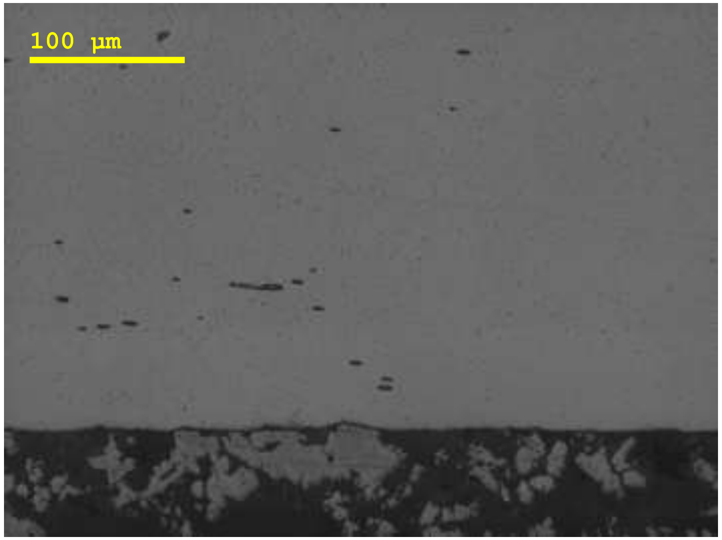
T3 Outer Wall – Ends of Bulk Supply Lines

Damage outside of beam path is indicated by saturation time



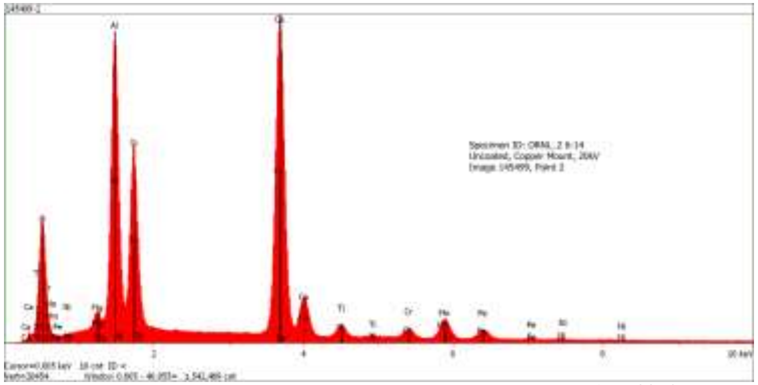
Presence of nonmetallic inclusions prompted purchase of "clean-grade" ESR processed 316L

- Nonmetallic inclusions were observed in material of the Targets 1 and 2 beam-entrance region, or "windows"
- Inclusions were characterized for Target 2 material according to ASTM E45
- After consultation with steel manufactures a "clean grade" plate of electro slag remelt (ESR) processed 316L was purchased
- The ESR processed 316L plate will be used to fabricate future target beam entrance windows



OM 360X

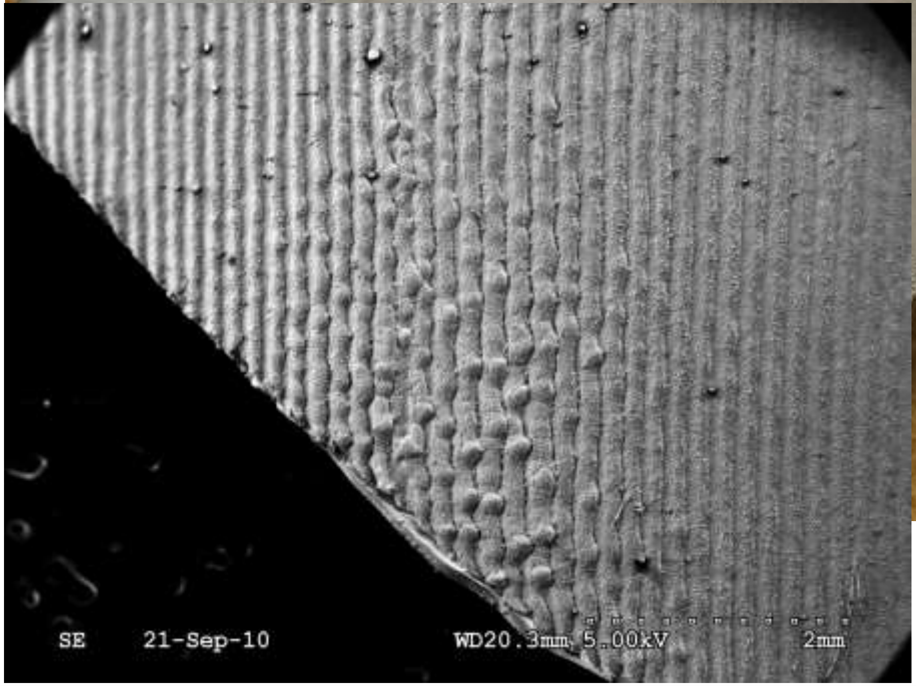
Figure 8.18: Disk 6, Section 6-16. Convex side.



EDS 145499-2

Machining marks from wire EDM act as nucleation sites for cavitation erosion

- Machining "line" marks left by wire EDM has been shown to act as nucleation sites for erosion
- To increase incubation period, the nucleation sites will be eliminated by polishing the vessel inner surface



Target design changes have been implemented from lessons learned during PIE

- Target design and manufacturing specifications have been guided by lessons learned during the PIE program:
  - Utilization of "clean grade" 316L material
  - Improvement of surface finish quality
  - Implementation of a bolt-on water-cooled shroud
  - Jet Flow Target: Alteration of bulk flow pathway (damage mitigation through flow)

Summary of SNS PIE Program 2012-2013

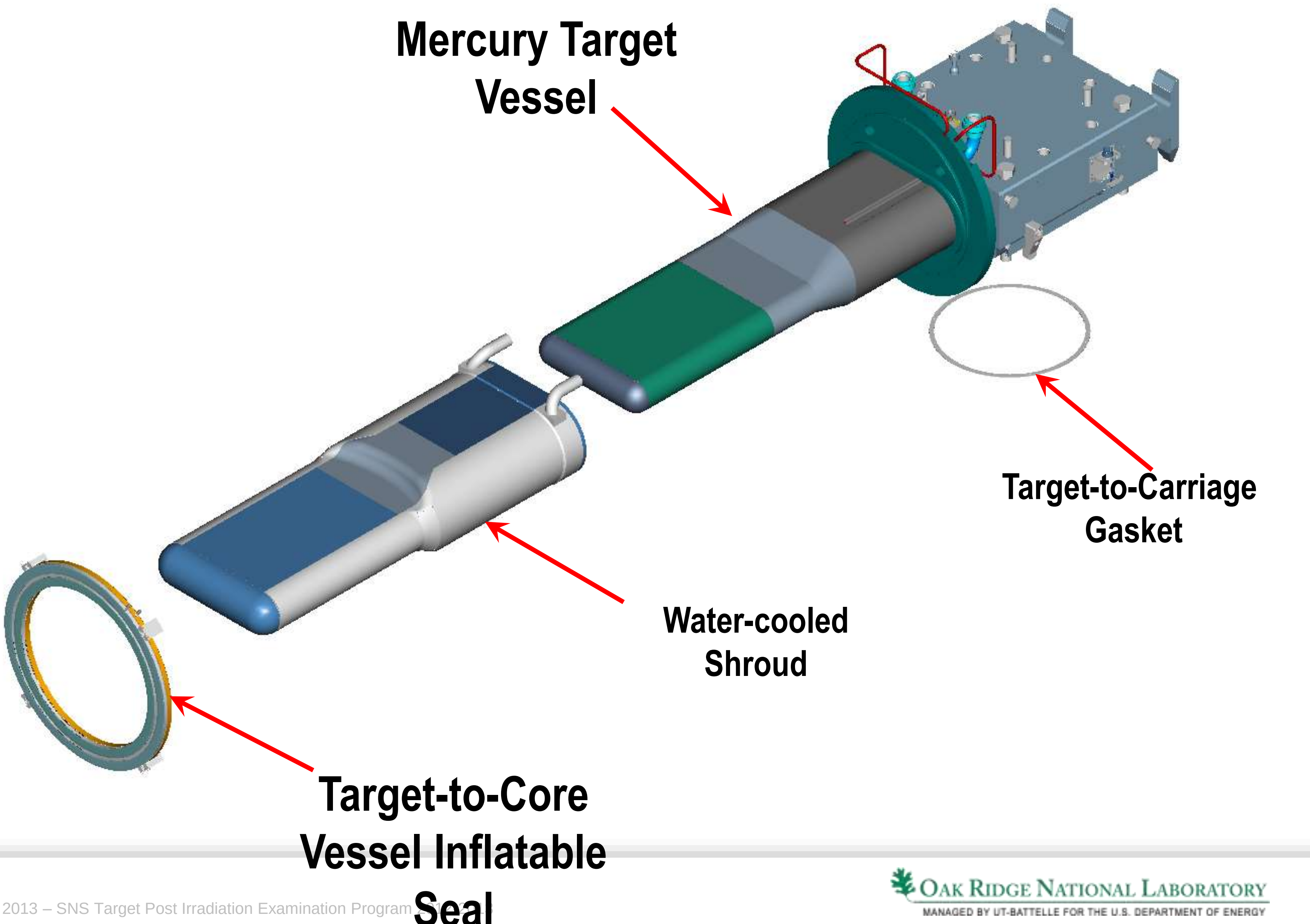
- Mechanical properties including microhardness and tensile properties were measured and reported for Target 2
  - Tensile properties indicate sufficient ductility remains at 10 dpa
  - Microhardness testing and optical microscopy revealed Kolsterising treated surface layer still present after irradiation
  - Nonmetallic inclusions were characterized using SEM and ASTM E45 testing
- Significant cavitation induced erosion was observed in Targets 4-5
- Leak locations were identified in Targets 6 and 7 using articulating videoprobe inspections
- Computer modeling simulations have been developed that closely match erosion patterns observed in SNS Targets
- Identification and characterization of nonmetallic inclusions prompted the purchase of clean-grade ESR processed 316L for fabrication of future target beam entrance windows

PIE will be critical for understanding target performance at higher operating power

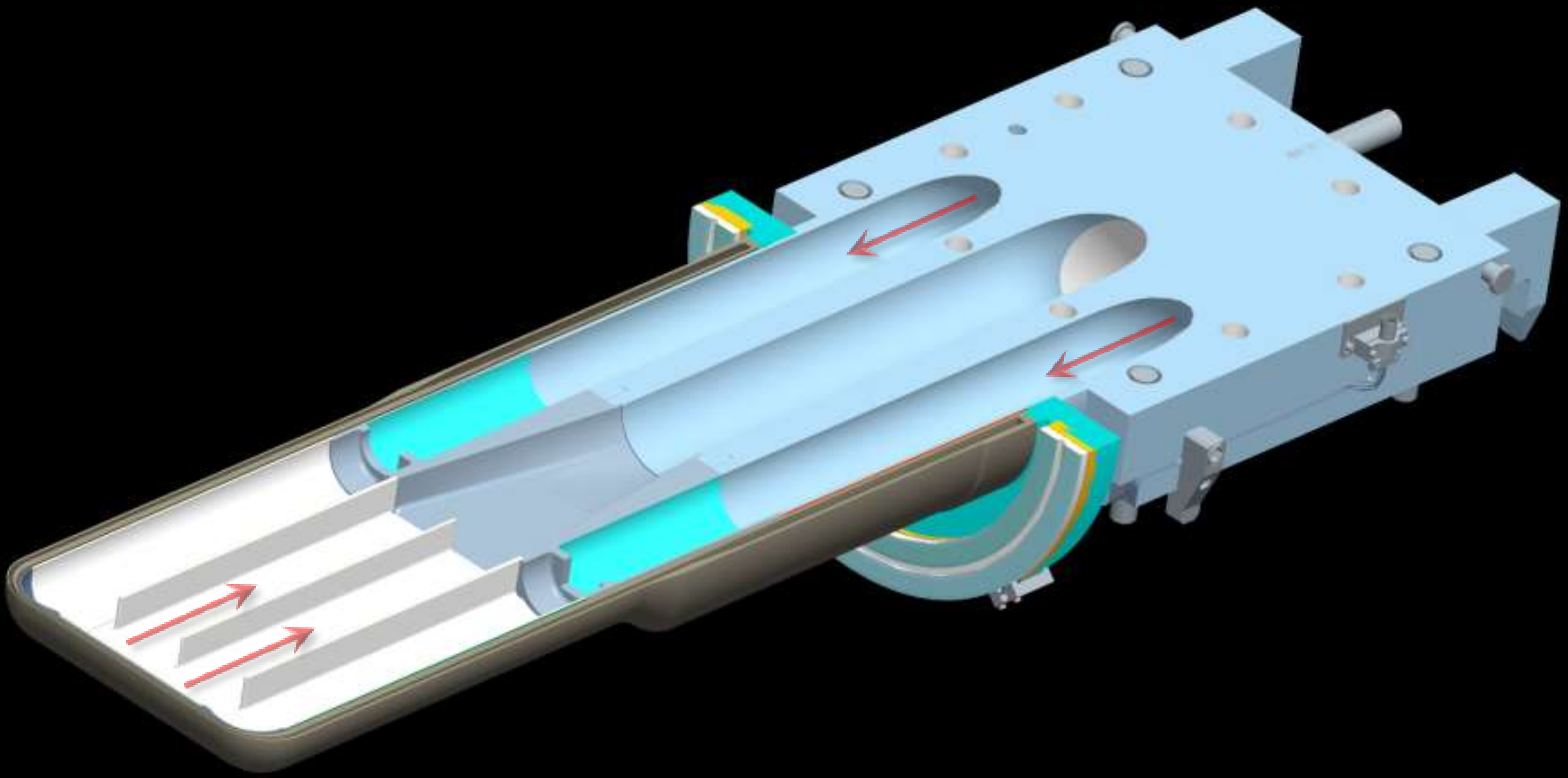
- Future PIE Work
  - Determine fracture mode for inner wall specimens
    - Sample fracture surfaces from inner wall disk specimens
    - Analyze fracture surfaces using scanning electron microscope
  - Inspect center baffle to determine nature of crack-like feature
    - Pry open center baffle using specialized remote tooling (Exp. “Jaws of Life”)
    - Inspect baffle during opening using an articulating videoprobe
  - Characterize mechanical properties of higher dose (>10 dpa) targets
- PIE will be critical to understanding target design weaknesses as operating power increases
  - Susceptibility of vessel material to liquid metal embrittlement?
  - Mechanical properties at higher dpa dose levels?
  - Does high power operation (>1 MW) initiate additional cavitation-induced erosion hotspots?

Backup Slides…

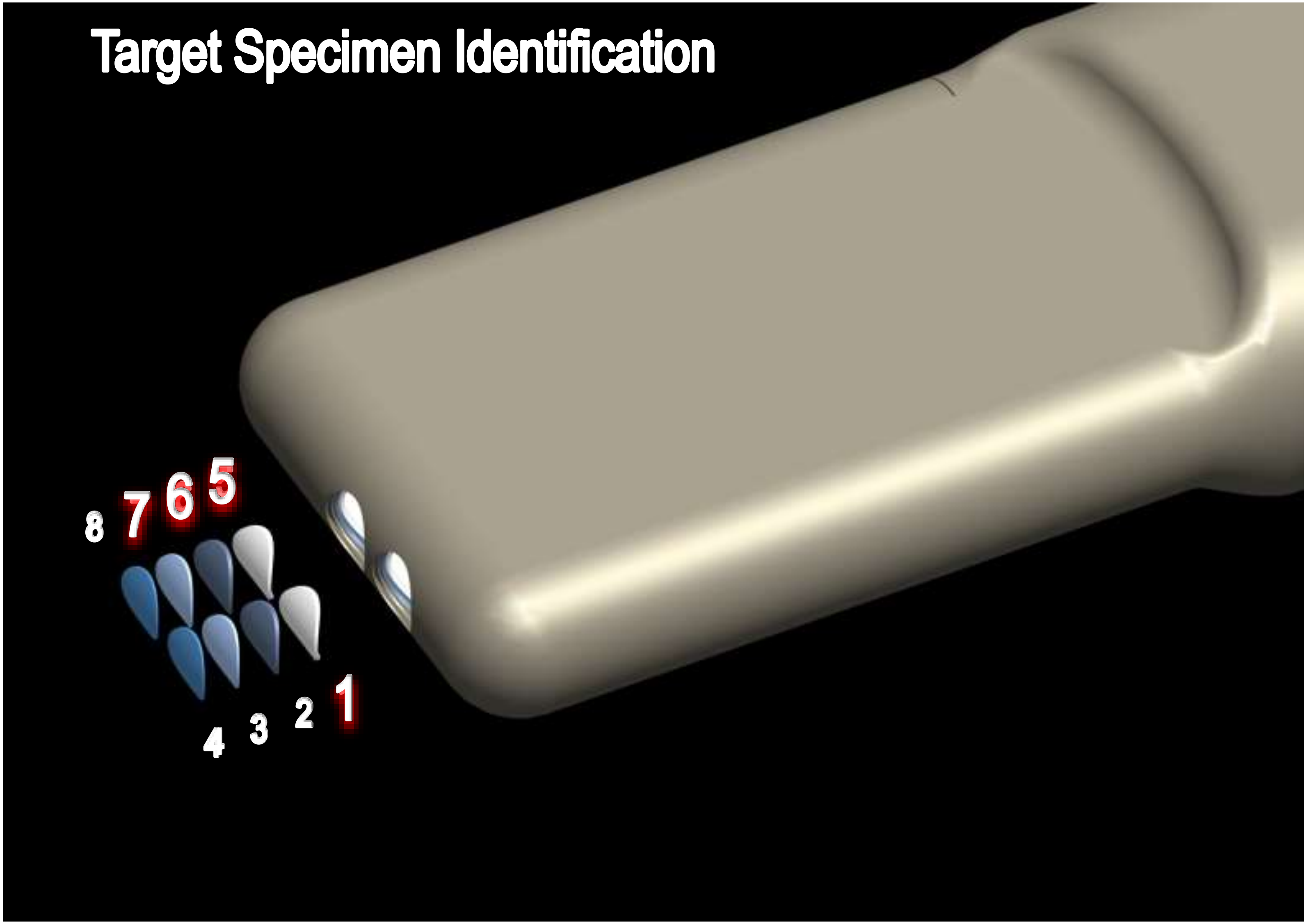
SNS Target Design



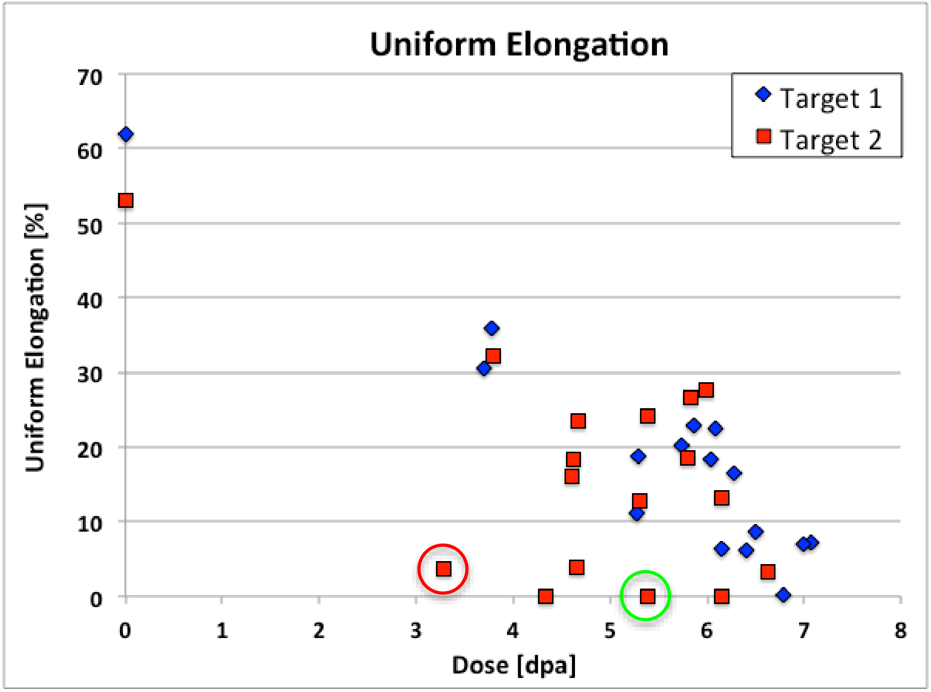
SNS Target Bulk Mercury Flow

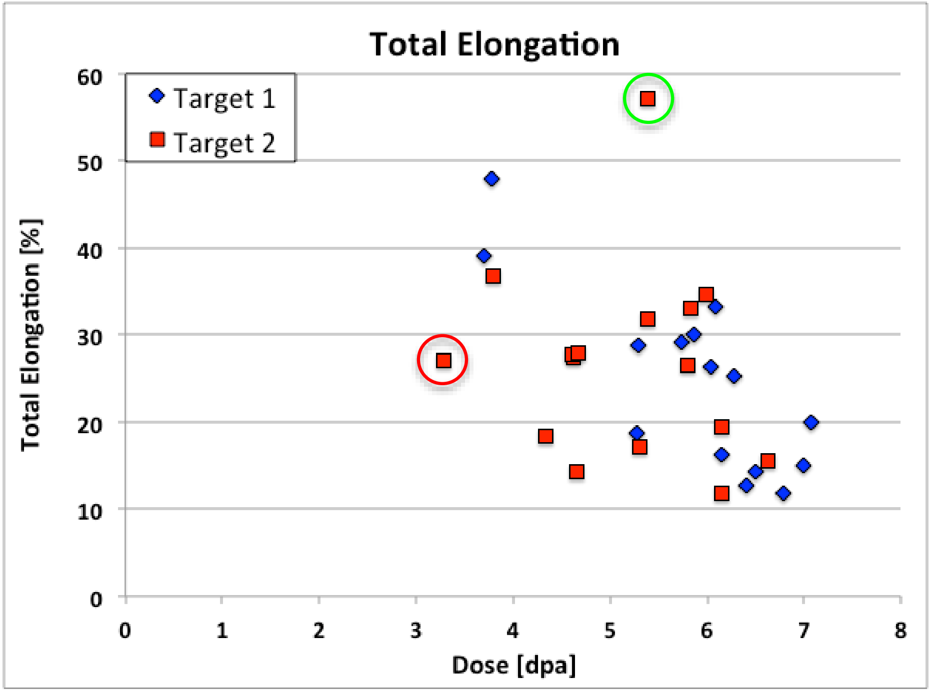


Target Sampling



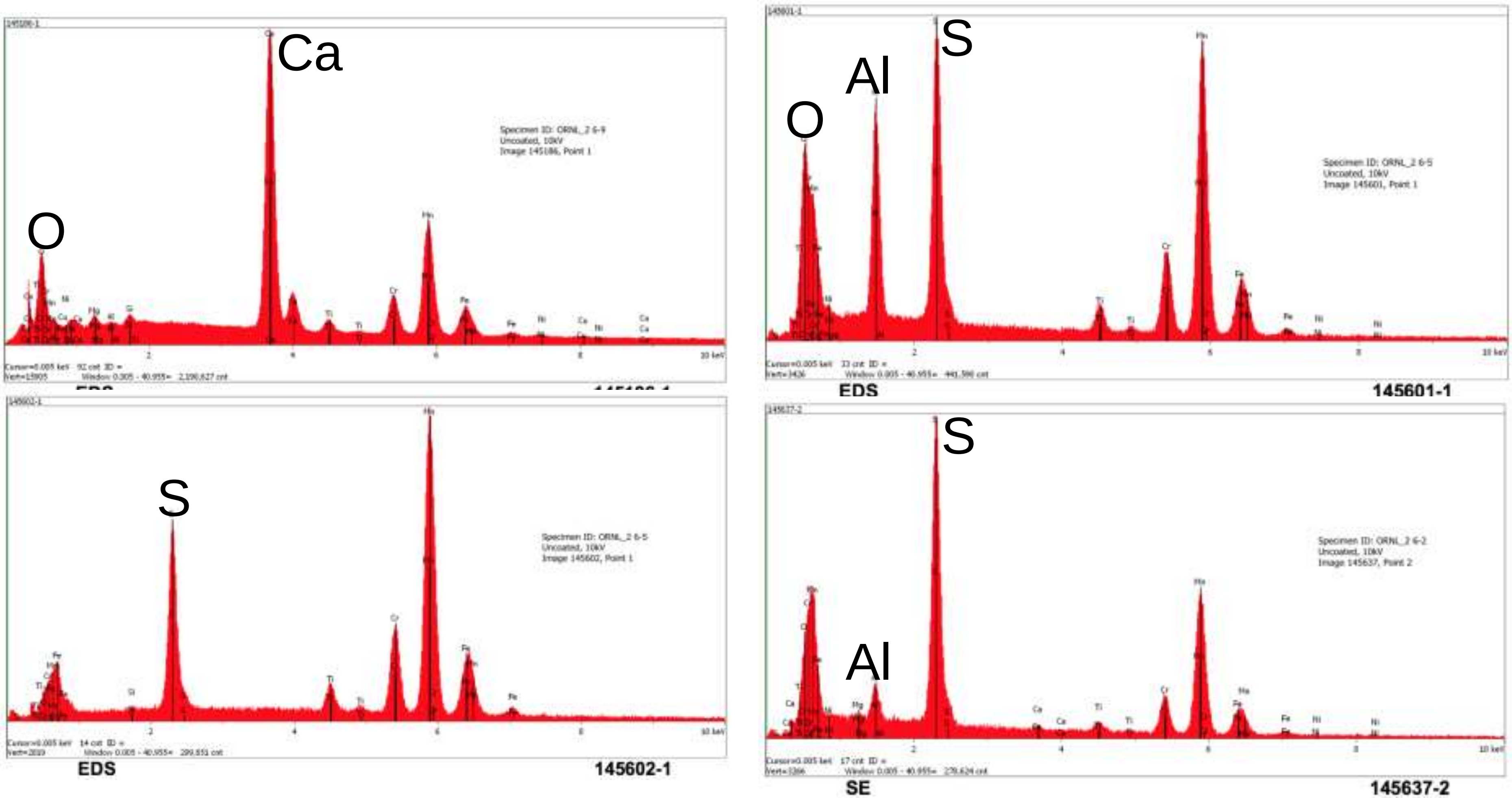
Tensile Data – Targets 1 and 2





- Steady decrease in uniform and total elongation with dose
- Scatter is attributed to the de-cohesion of nonmetallic inclusions and small specimen size effect (roughness)

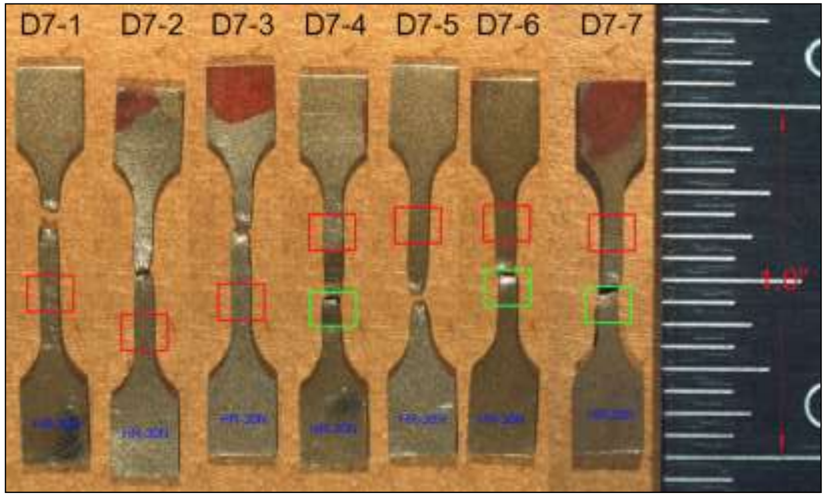
EDS Spectrums of Non-metallic

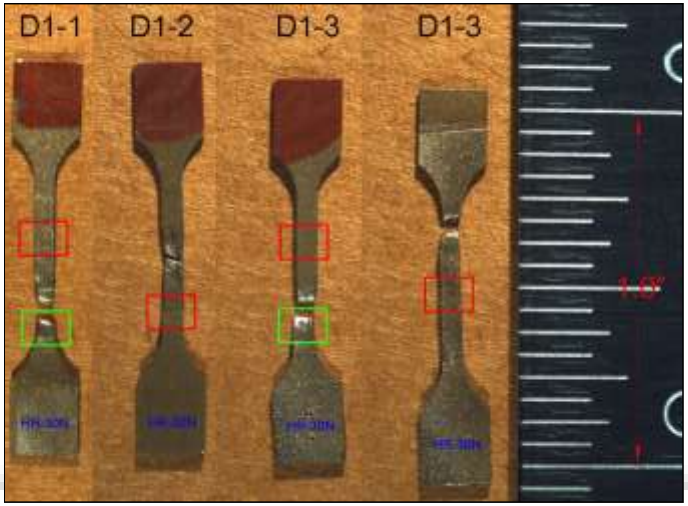


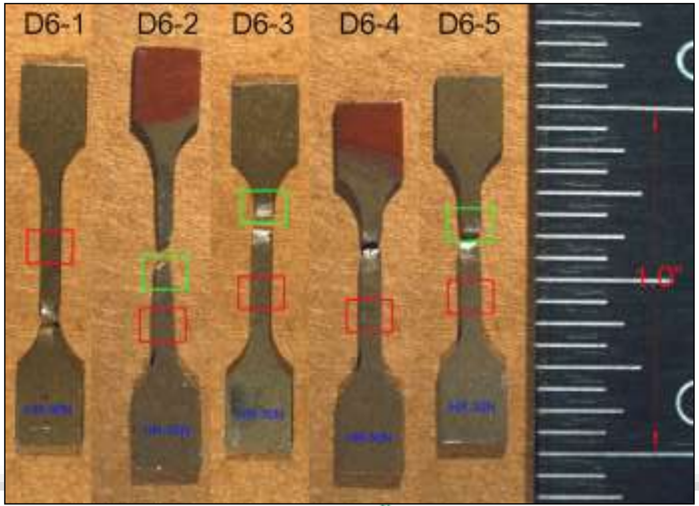
- Several different inclusion compositions were observed
  - Ca-rich
  - Al-rich
  - S-rich

Tensile Testing Results

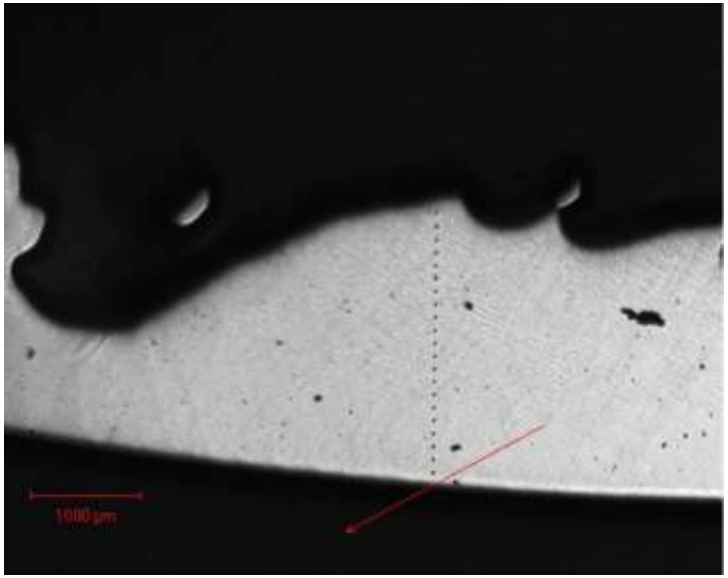
- Most specimens fractured in center of gauge section
  - Target 2 Tensile Specimens:

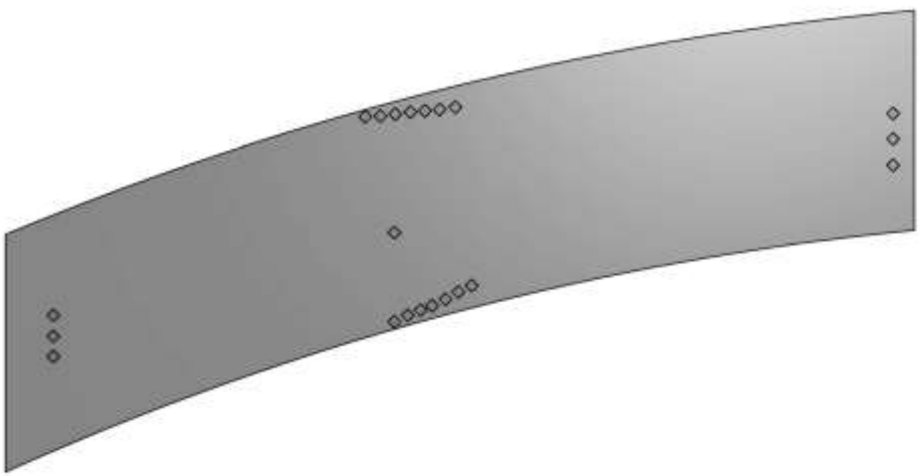


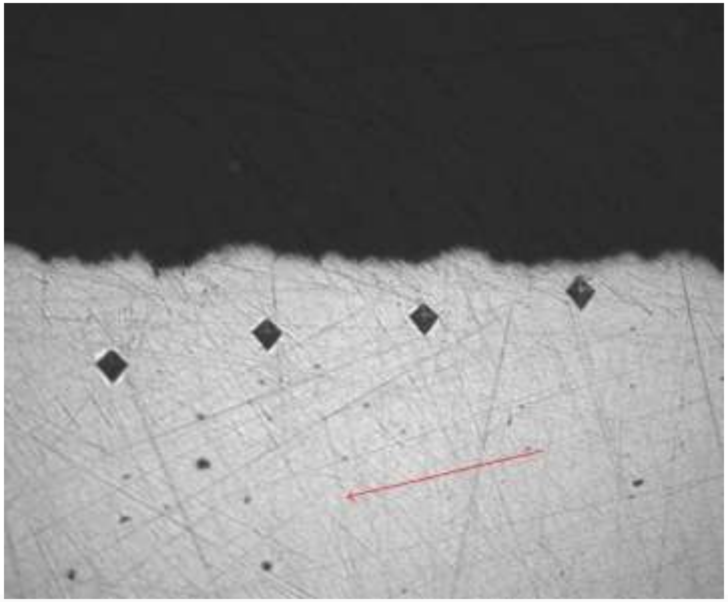




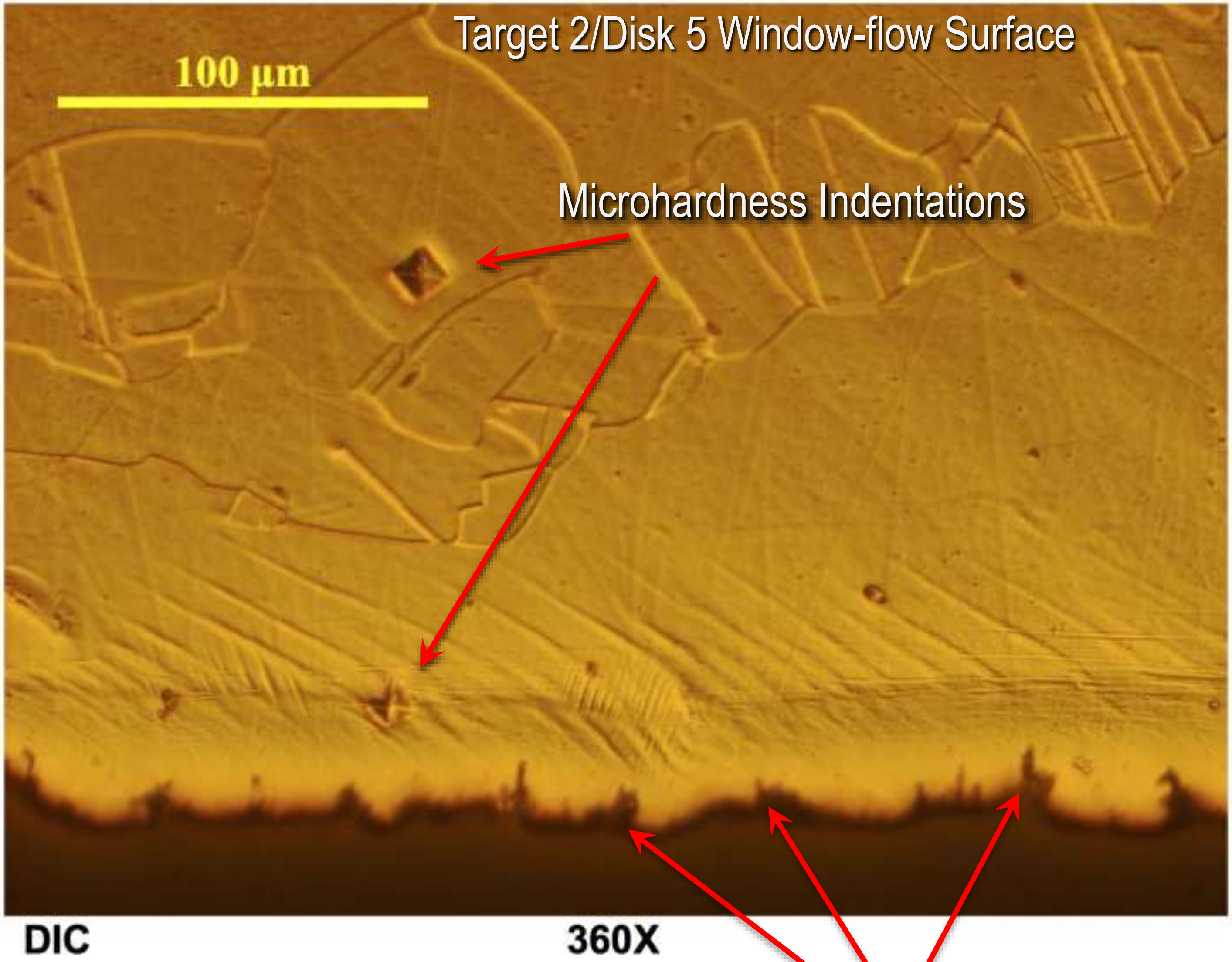
Various Hardness Indentation Patterns Were Used





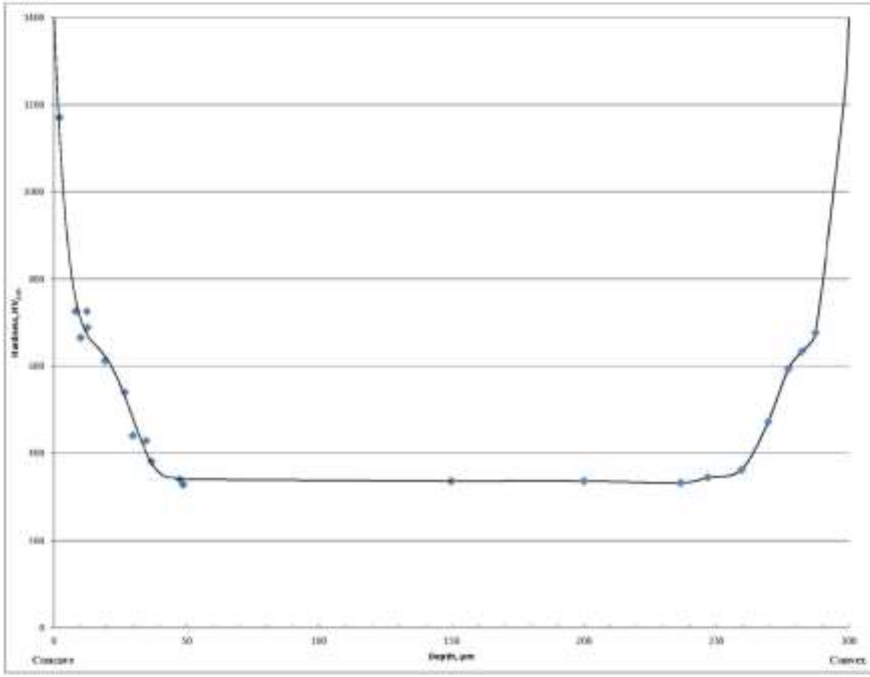


Kolsterised Layer on Disk 5/Target 2

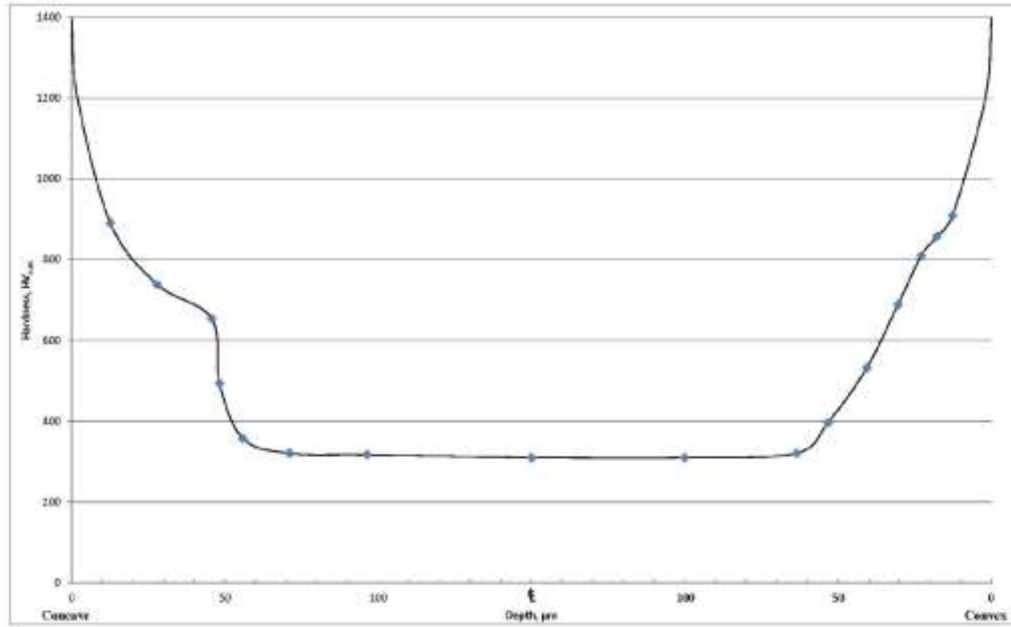


Erosion “Pitting” Damage

Hardness of Irradiated Kolsterised Surface

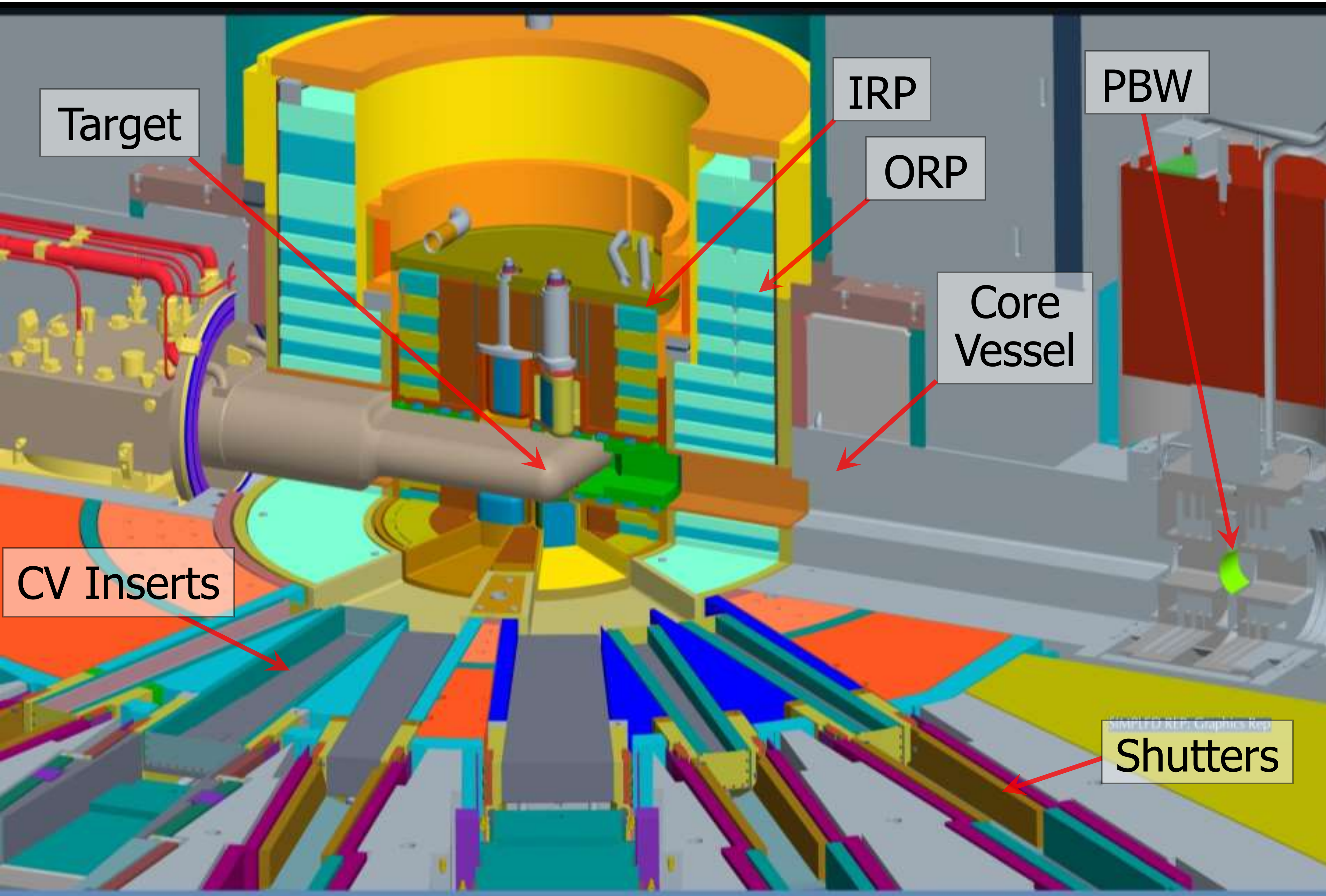


Disk 6/Target 1
Hardness Profile



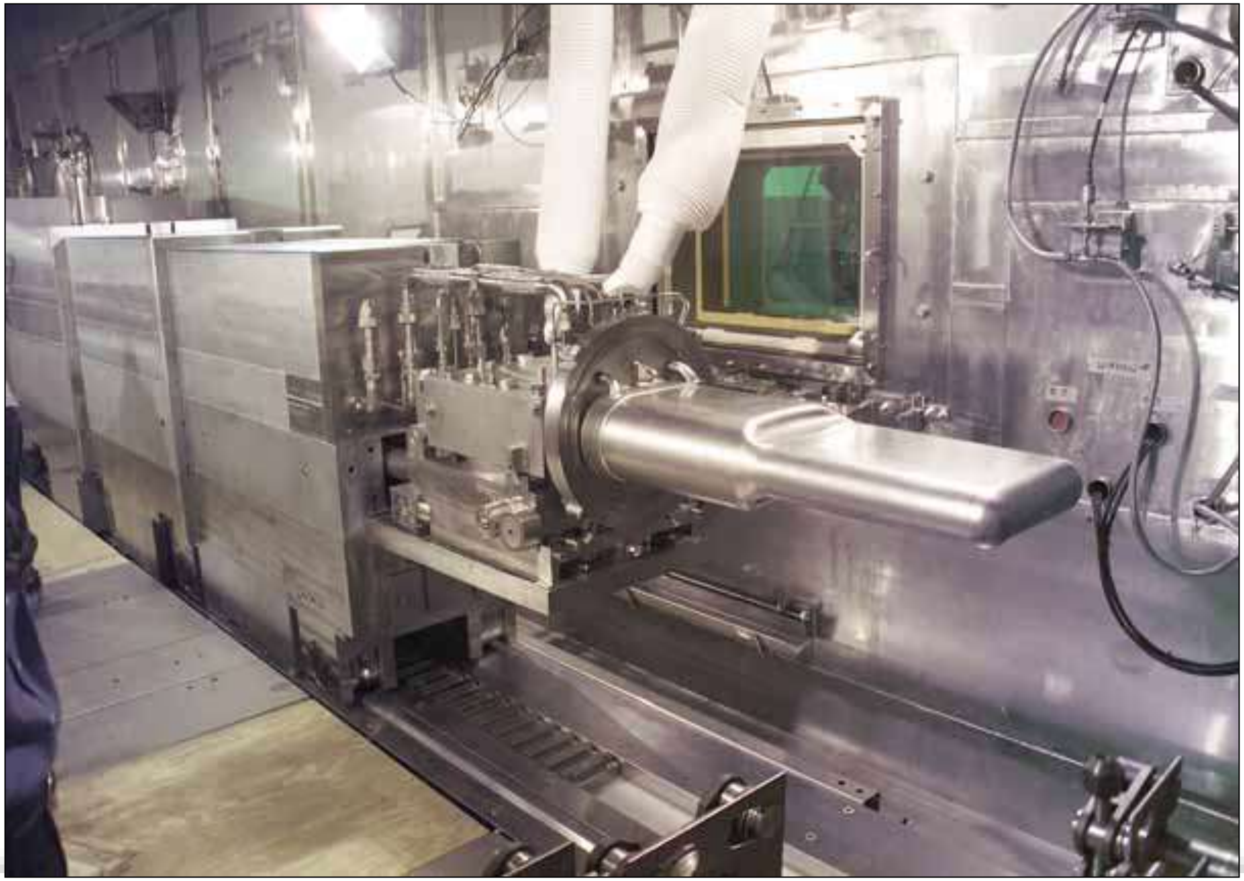
Disk 1/Target 1
Hardness Profile

SNS Target Design



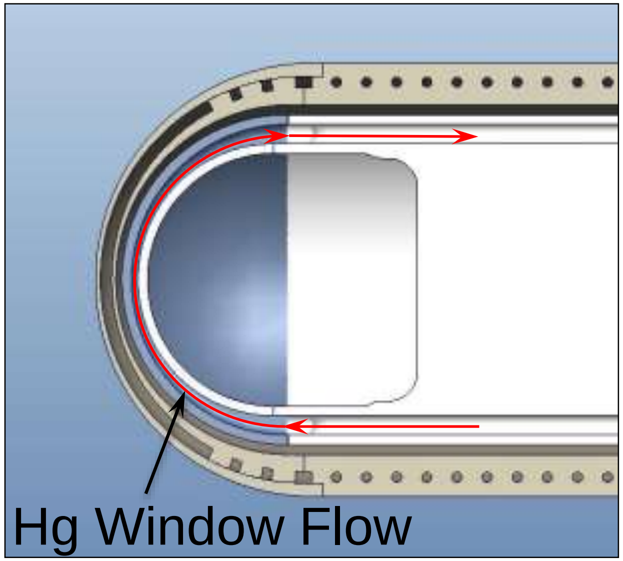
SNS Target Design

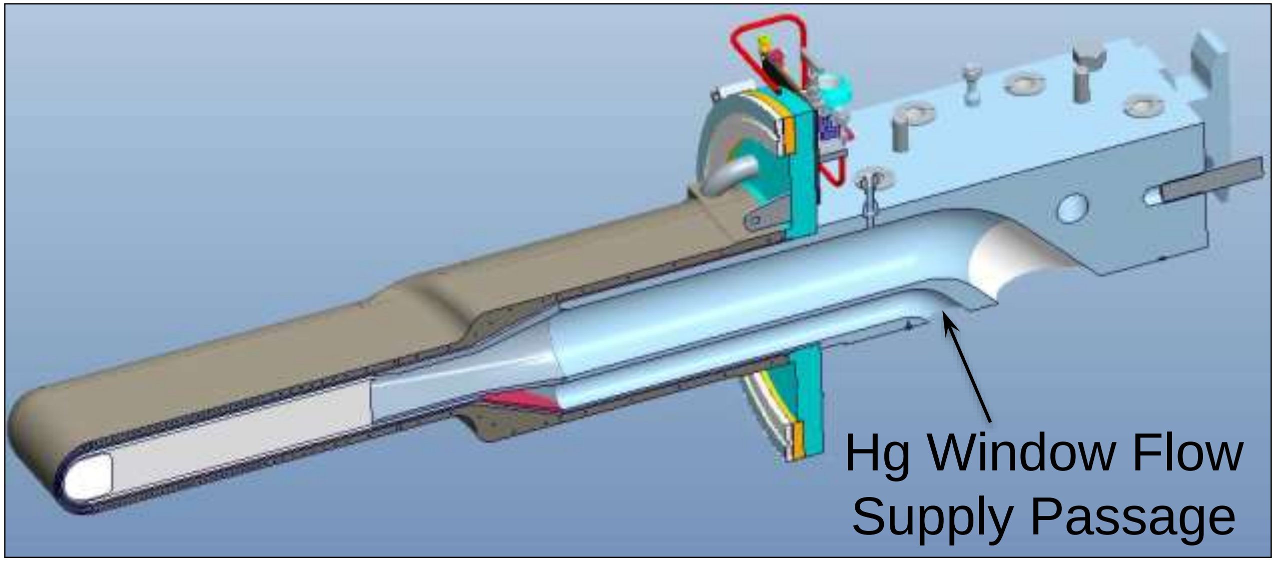
- The SNS Target is a liquid metal design, utilizing flowing mercury (23 L/sec) as the neutron producing material
- Target vessel and water-cooled shroud are composed of AISI 316L austenitic stainless steel



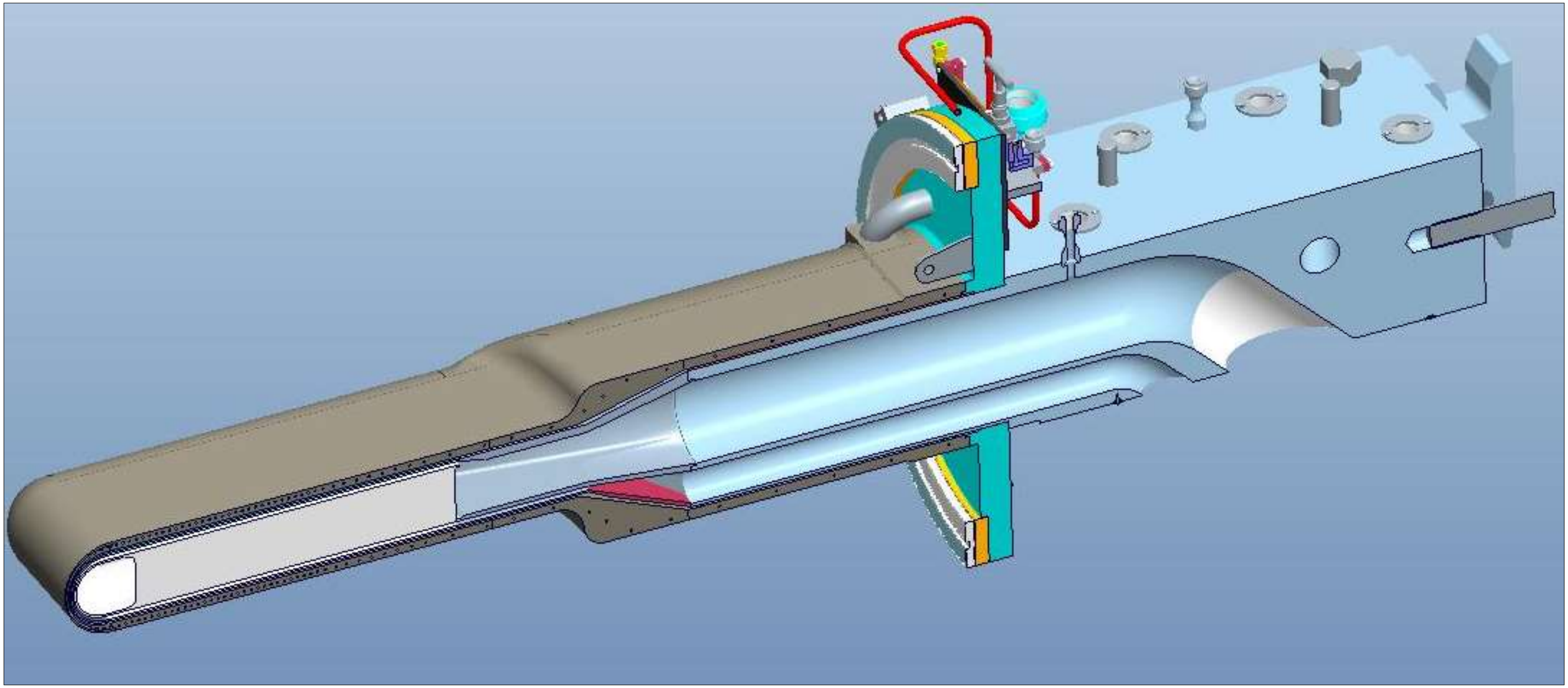
Target 6 – Mercury Window Flow

- Beam entrance region of the mercury target vessel is cooled by a uniform high-velocity (2.5 – 3.0 m/s) "window-flow" of mercury
- The high velocity mercury and narrow channel appear to mitigate cavitation-induced erosion

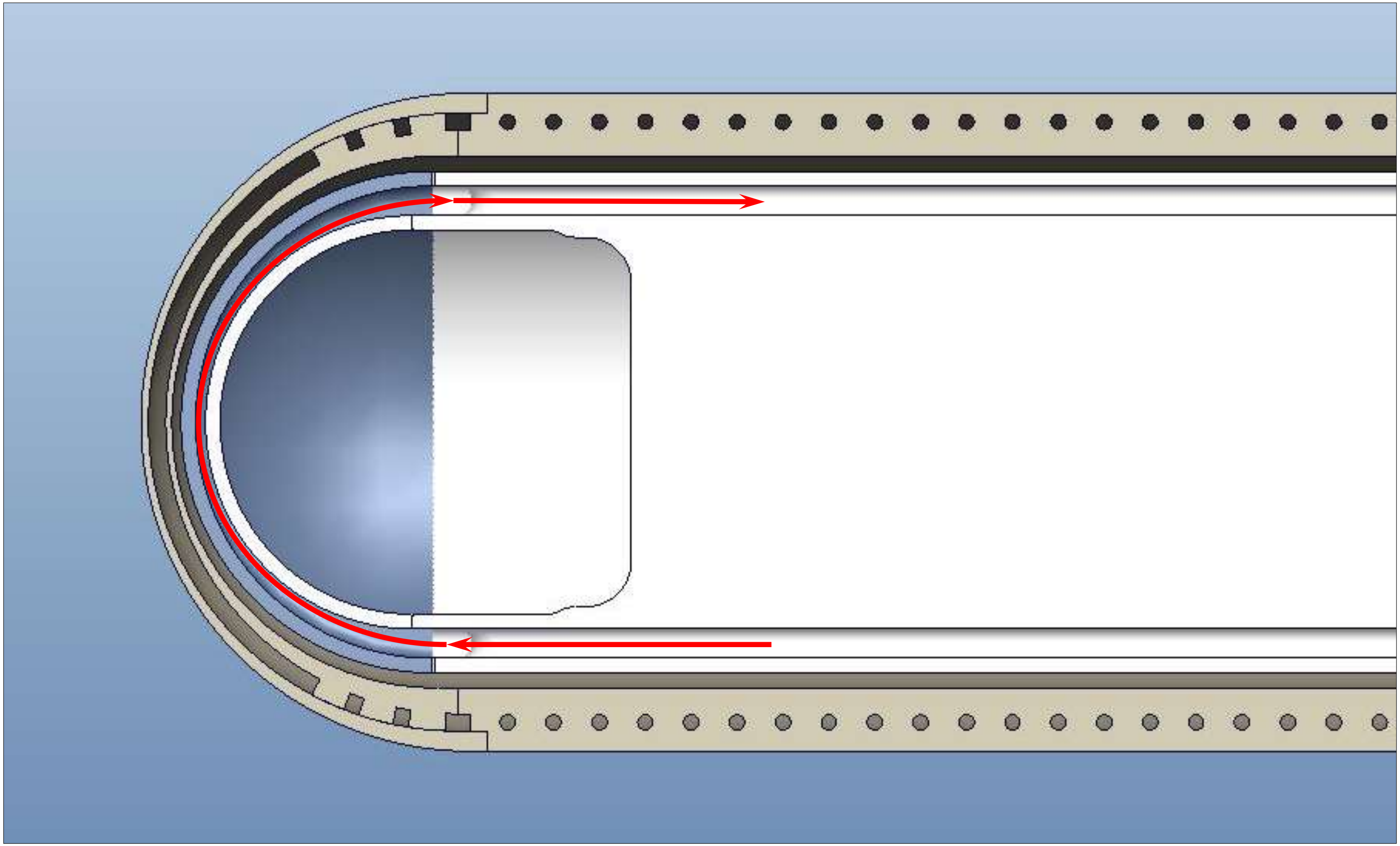




Target Assembly



Target Assembly



Target Module – Water Shroud Flow