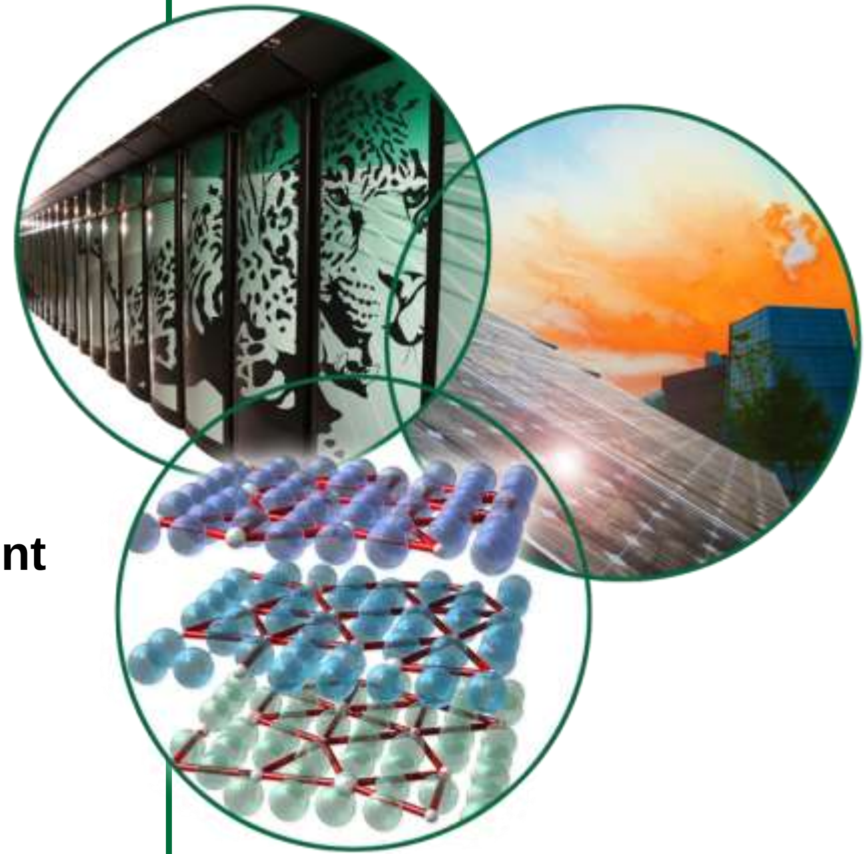
SNS Accelerator Advisory Committee
Oak Ridge, TN
January 10-11, 2012

Target Development

Bernie Riemer



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U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

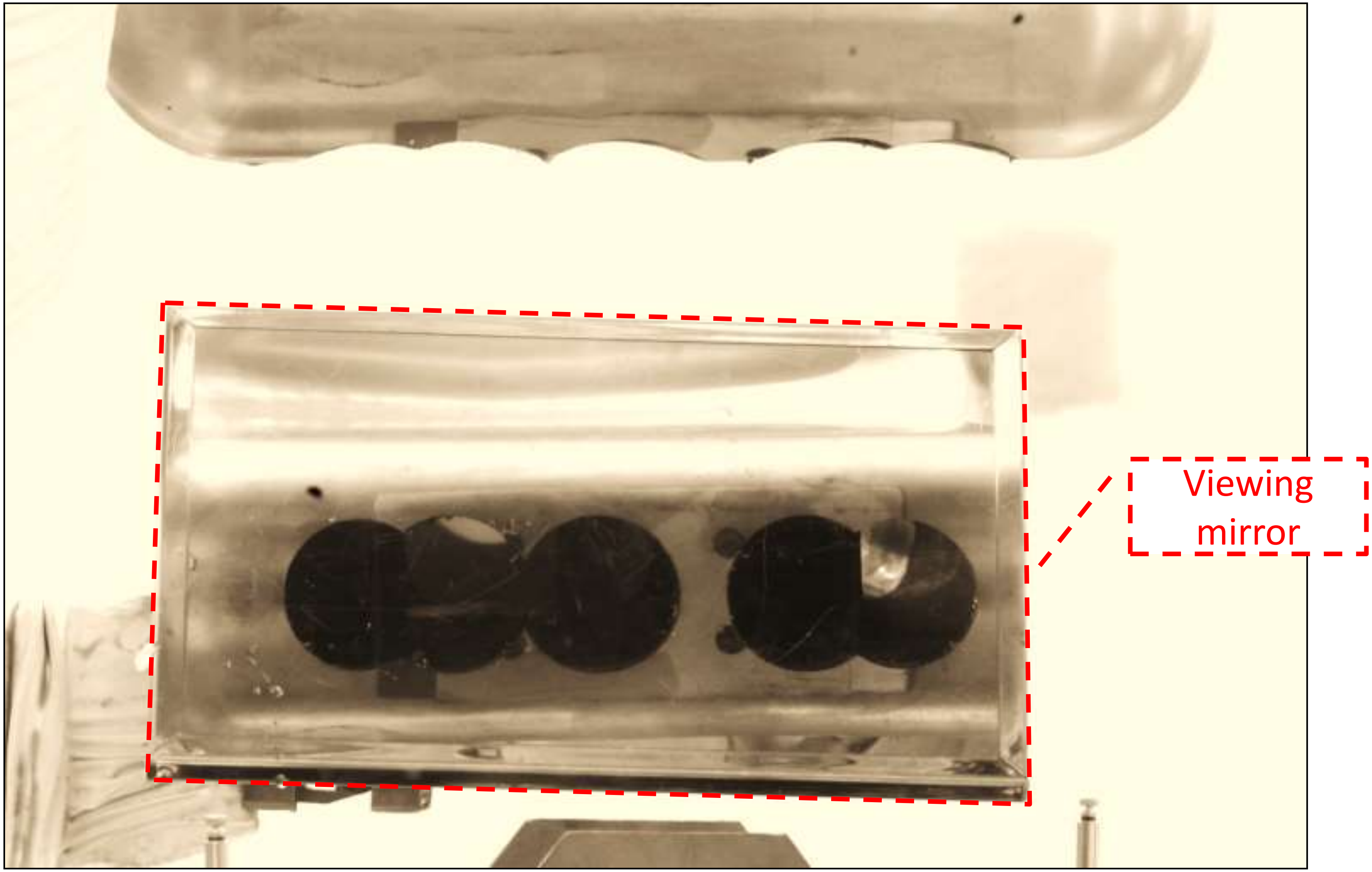
Target cavitation damage mitigation R&D efforts have been suspended

- New management priorities leave target R&D unfunded
- Target development team will analyze data from WNR experiment and document results
- No further mitigation studies or experiments to be conducted, aside from “Jet-flow” target concept engineering work … possibly prototype testing
- PIE work remains funded in FY12

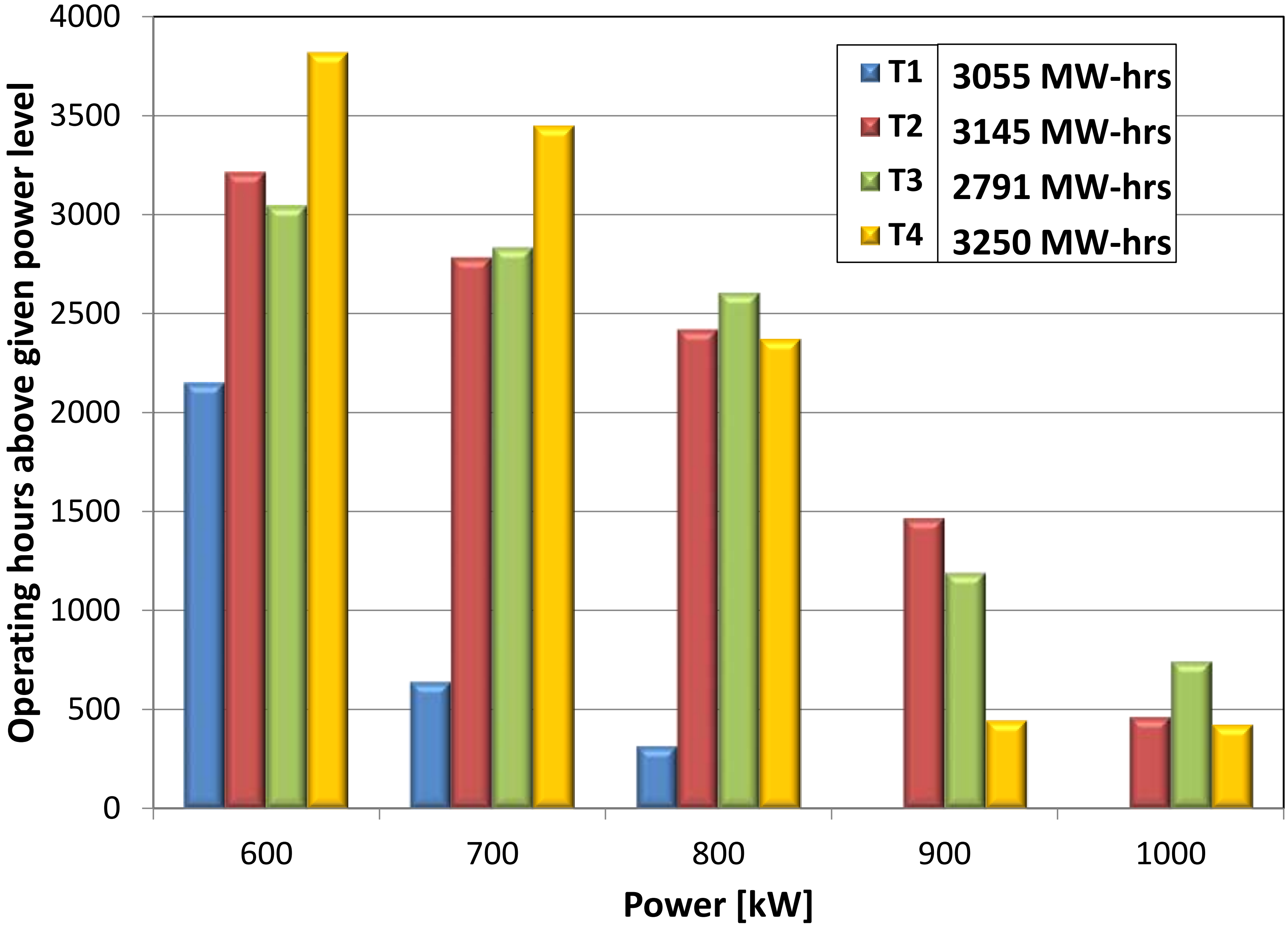
Outline

- PIE
  - Leak in Target #3 (T3)
    - Where is it? What was the mechanism? Why this target?
  - Damage observations in T1, T2 and T3
  - Correlation of saturation time & flow with damage patterns
  - Detailed PIE work done on T1 specimens completed
- Progress in R&D for damage mitigation
  - WNR experiment for small gas bubble mitigation
  - Modifications to TTF for prototypic testing of gas walls and small gas bubble injection
- Jet-flow target design introduction

Five hole cuts were made in T3 beam entrance window – Where's the leak?



Operating hours above power level



Damage on target inner vessel wall specimens cut from center of beam window surface facing bulk mercury

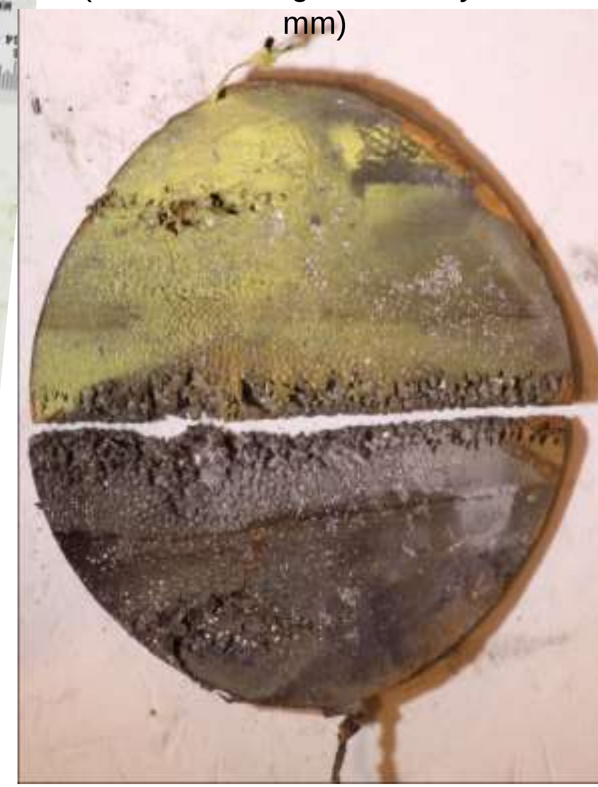
T1

Cleaned at B&W

T2

T3

Fractured across full width of inner window
(cut missed target center by ~ 13 mm)



(Views oriented as during operation)

Damage to inner vessel wall at center
surface facing mercury channel

T1

Cleaned at B&W

T2

T3

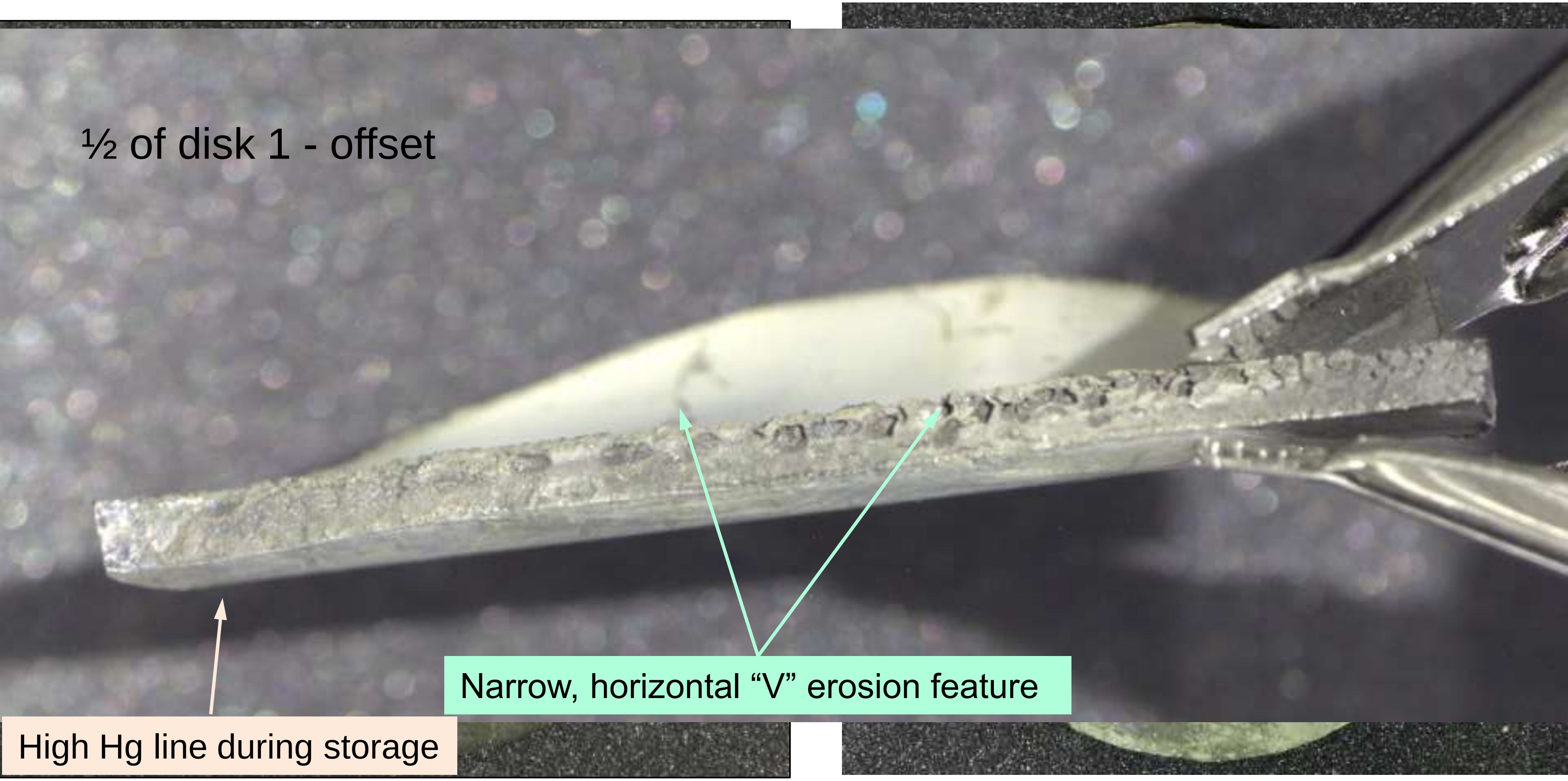
Other differences between T2 and T3

- T3 material for mercury vessel front body and outer beam window underwent hot isostatic press (HIP)
  - Process adopted to reduce porosities that were observed in T1 and T2 which required numerous TIG weld repairs
  - HIP has consequence of fully annealing the material, which has less cavitation damage resistance vs. cold-worked mat'l
  - *HIP used with all targets after T2*
- Window mercury flow orifice was removed beginning with T3 operation
  - Increased window channel flow velocity to compensate for reduced mercury pump speed

Target 2 inner wall – disks 1 & 5

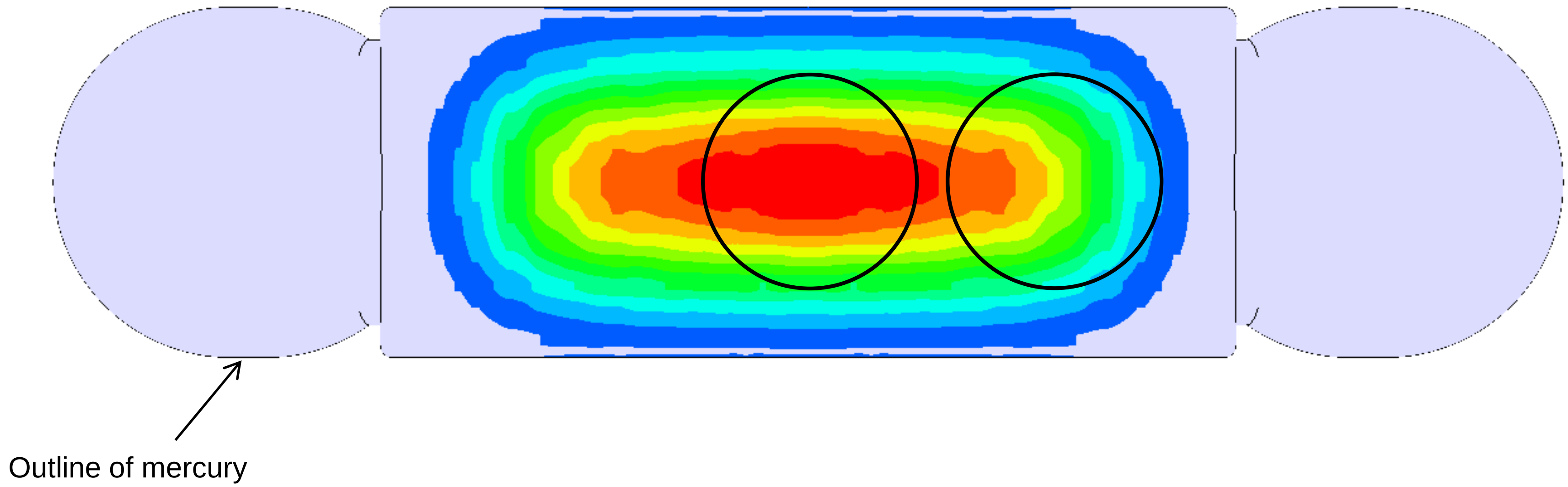
Disk 1 – offset cut

Disk 5 –center cut



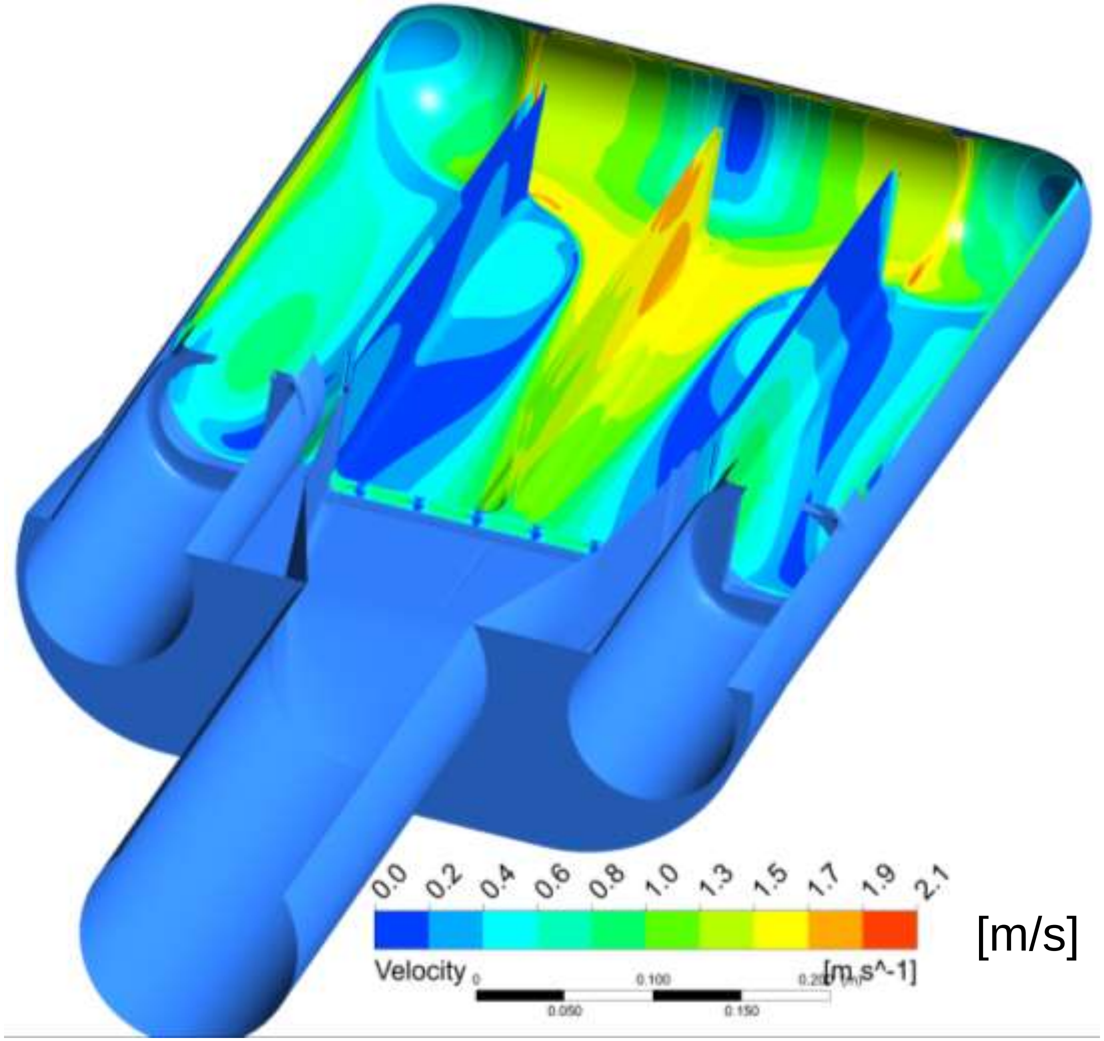
Relative deposited beam energy density at center and off-center specimen locations

- Based on “nominal” proton beam incident profile on target



Mercury flow near the wall is a likely mitigating mechanism

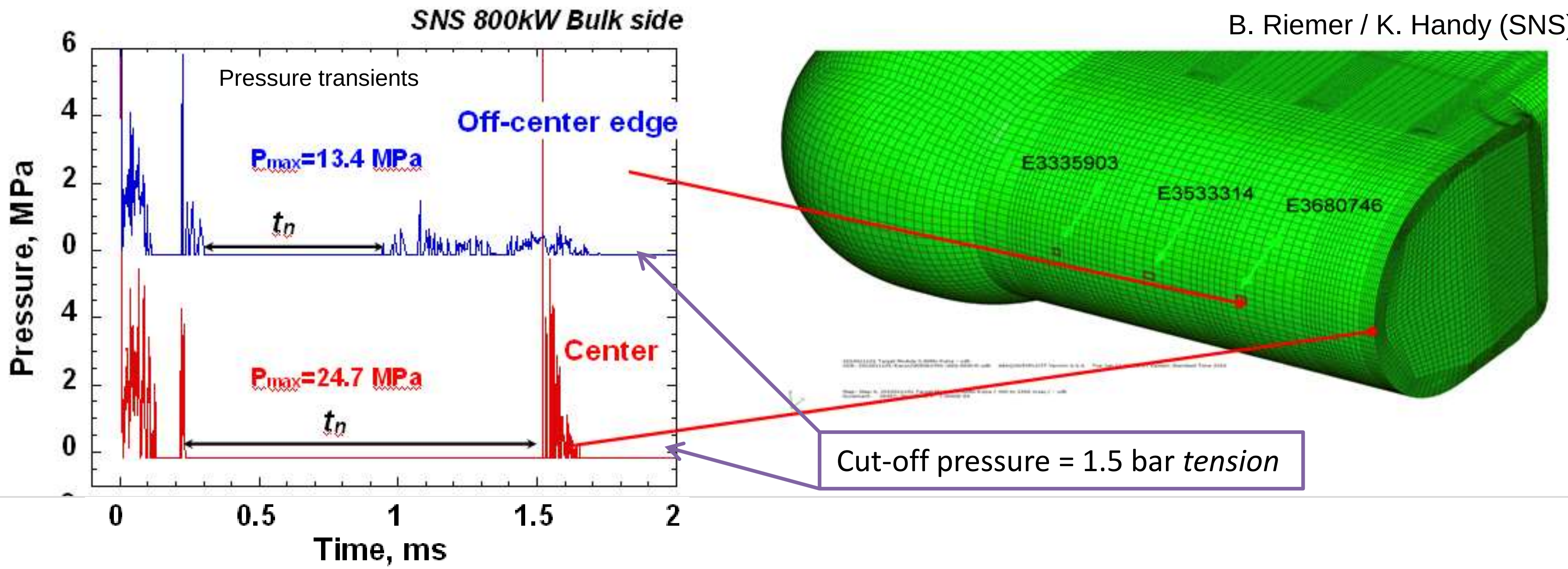
- **Higher velocity at the wall → greater damage *mitigation***



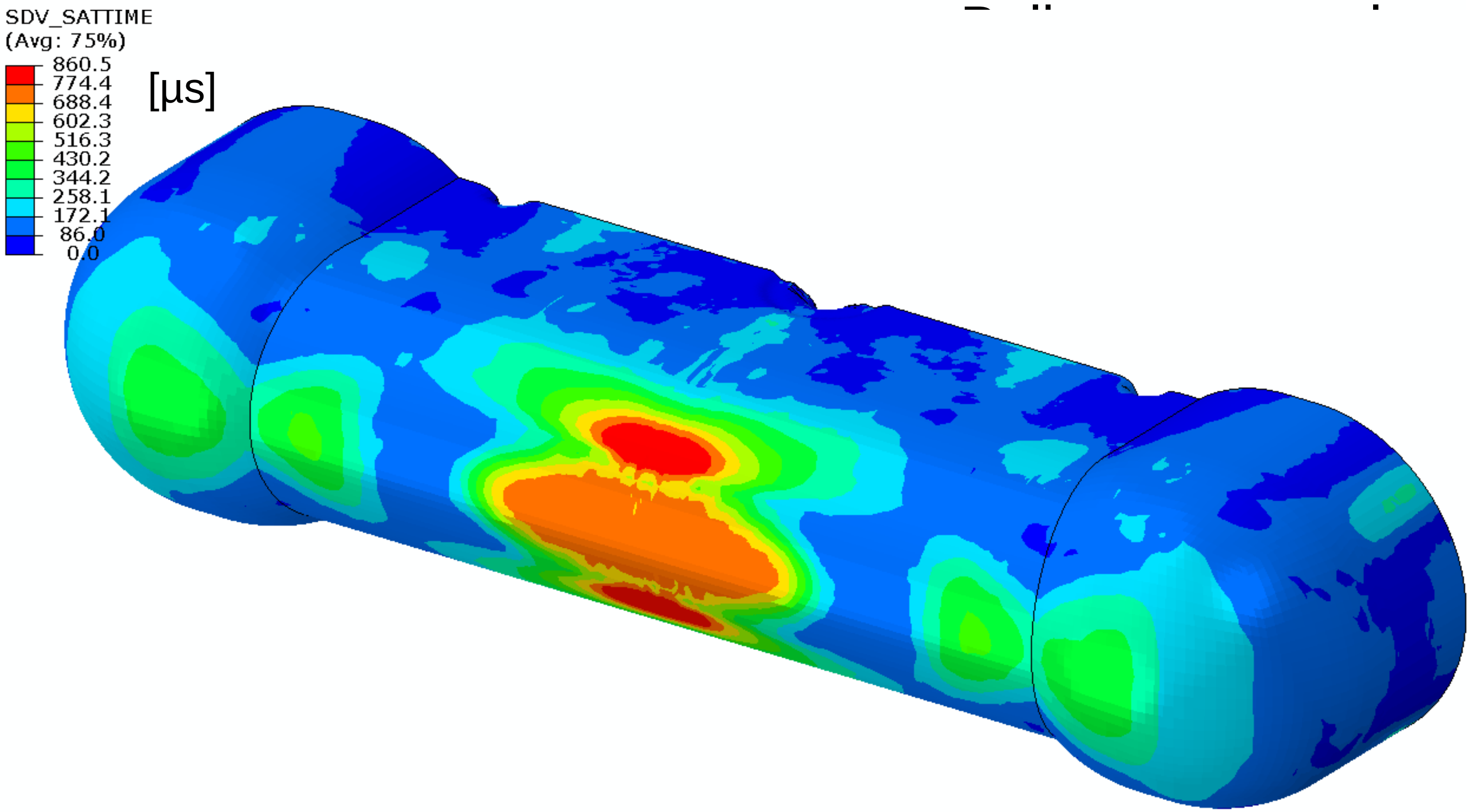
[m/s]

Cavitation bubble growth due to pressure history

- **Concept of saturation time for damage potential estimation**



Saturation time on bulk mercury at 1 ms from pressure pulse simulation



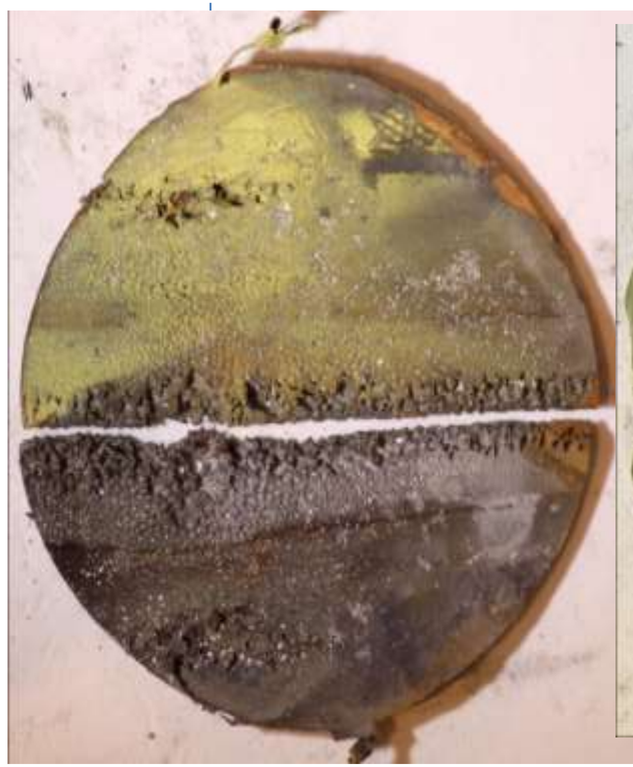
Higher saturation time at the wall → increased damage *potential*

S. Kaminskas / B. Riemer

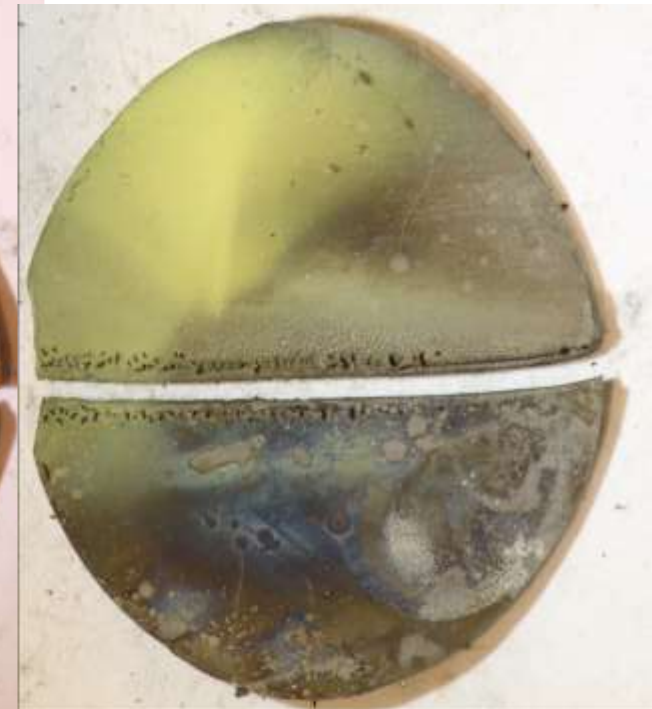
T3 inner wall surface facing bulk Hg

Disk 1
(driver side)

Disk 5
(center)



Disk 9
(passenger side)



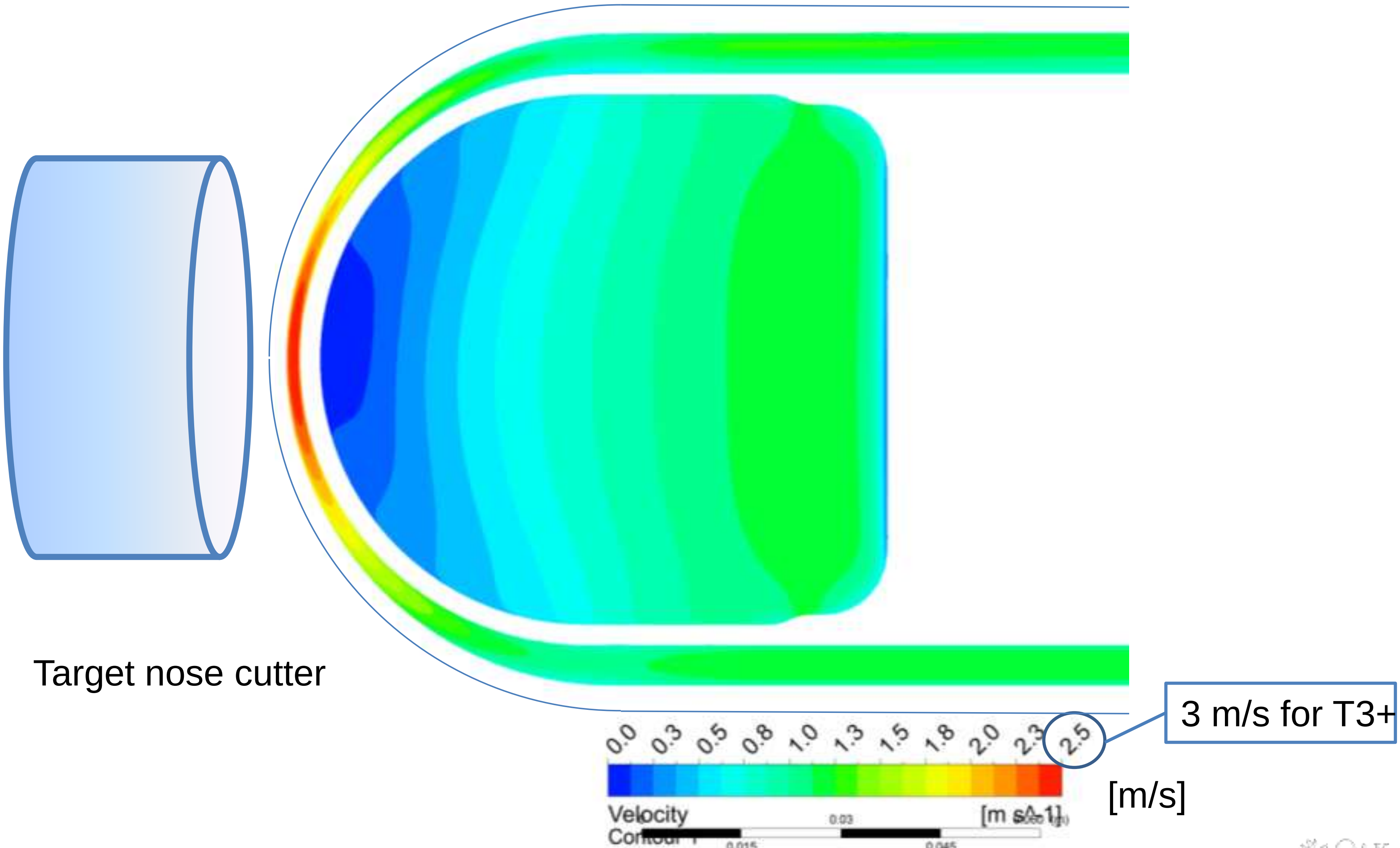
Missed center by ~ 13 mm

T3 far outside cuts

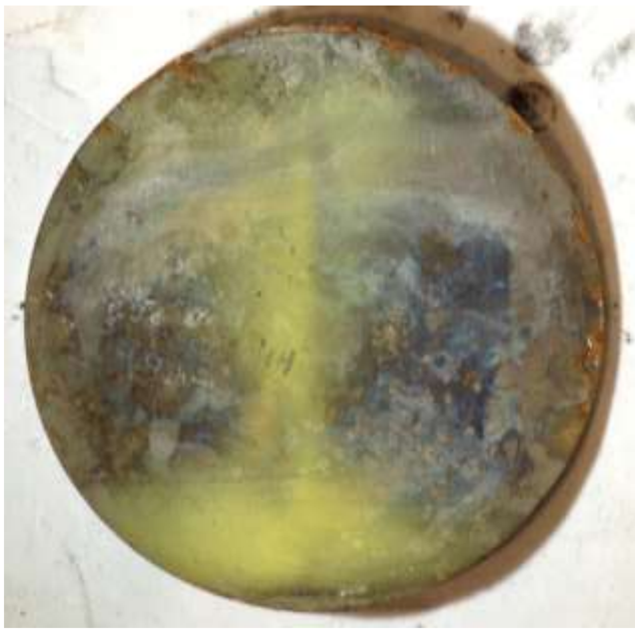
Disk 14 – driver side supply

Disk 18 – passenger side supply

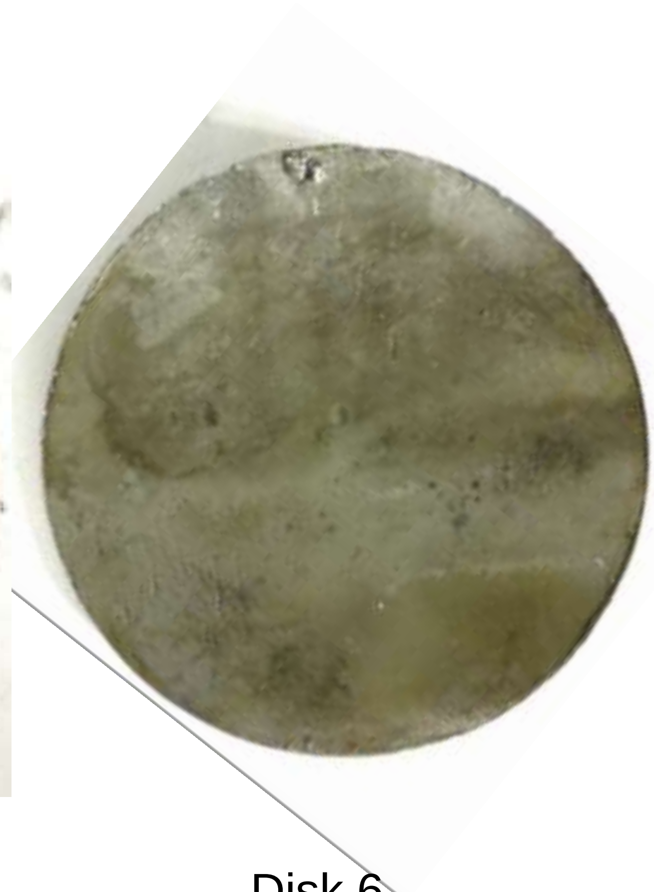
Mercury velocity – vertical section at mid-width



T3 outer window channel surface



Disk 2
(driver side)



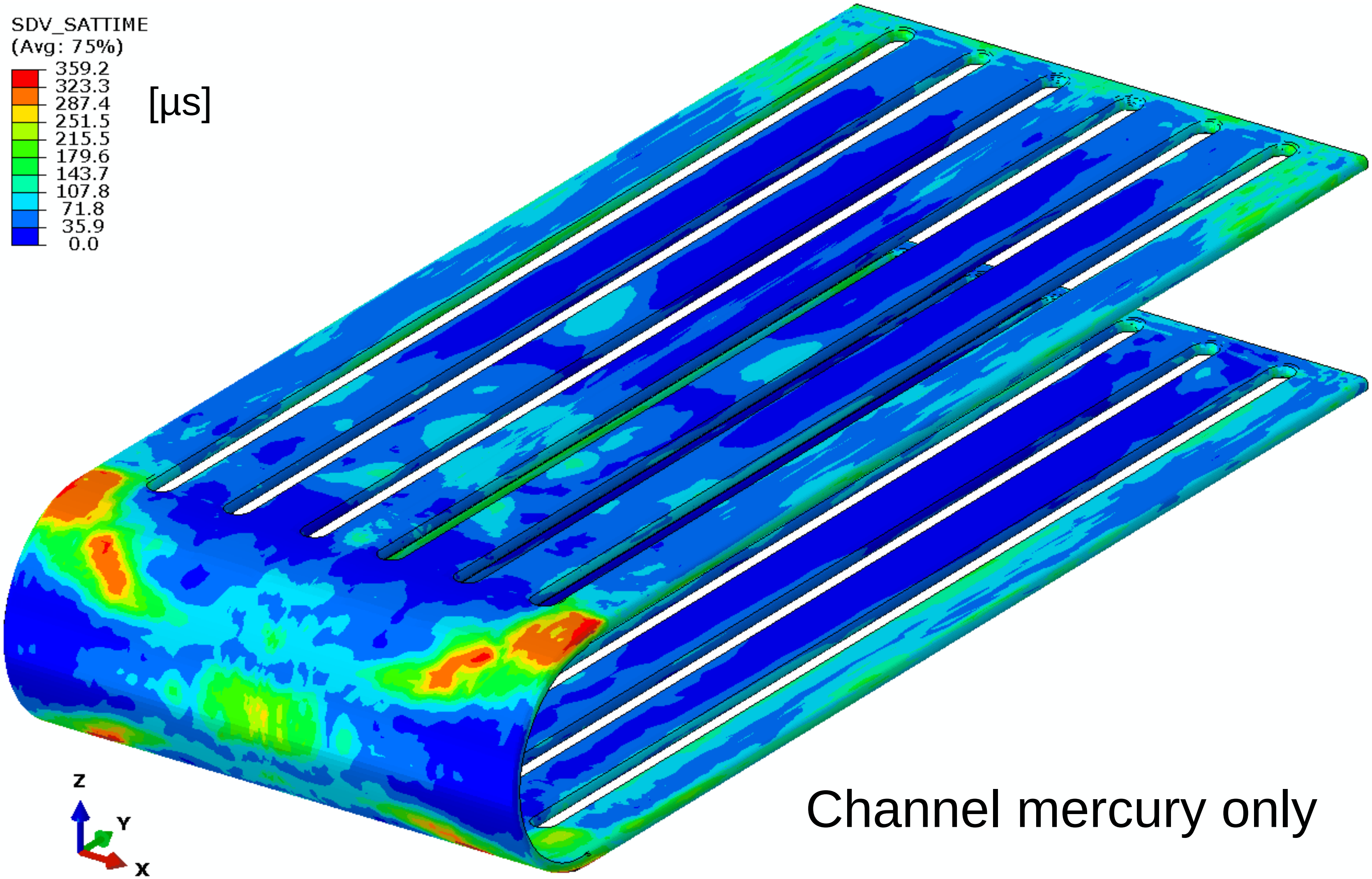
Disk 6
(center)

Disk 10
(passenger side)

T3 disk 10 eroded region at top edge

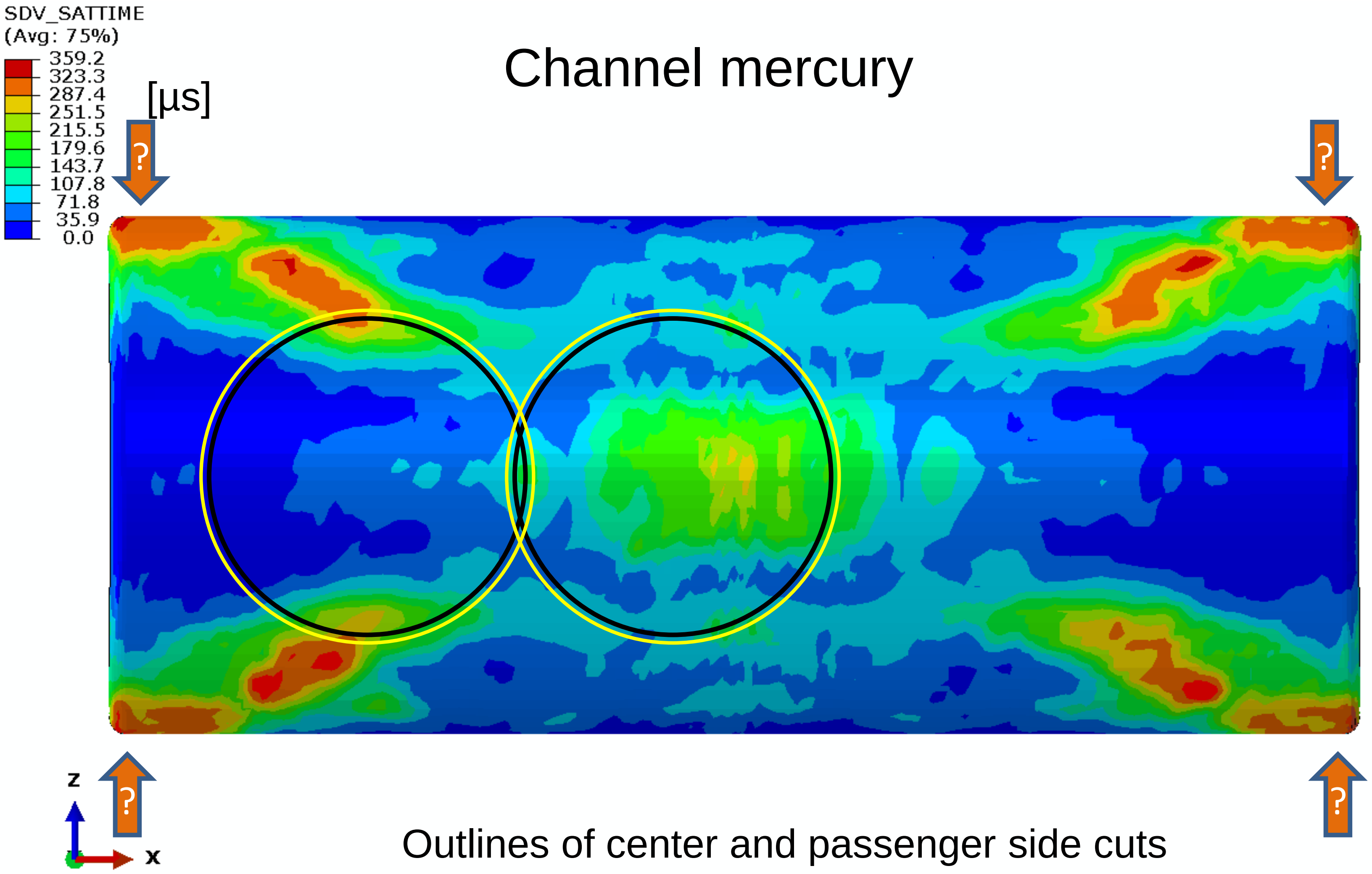
Partial through-wall hole in disk 10

Saturation time on <u>channel</u> mercury at 1 ms from pressure pulse simulation



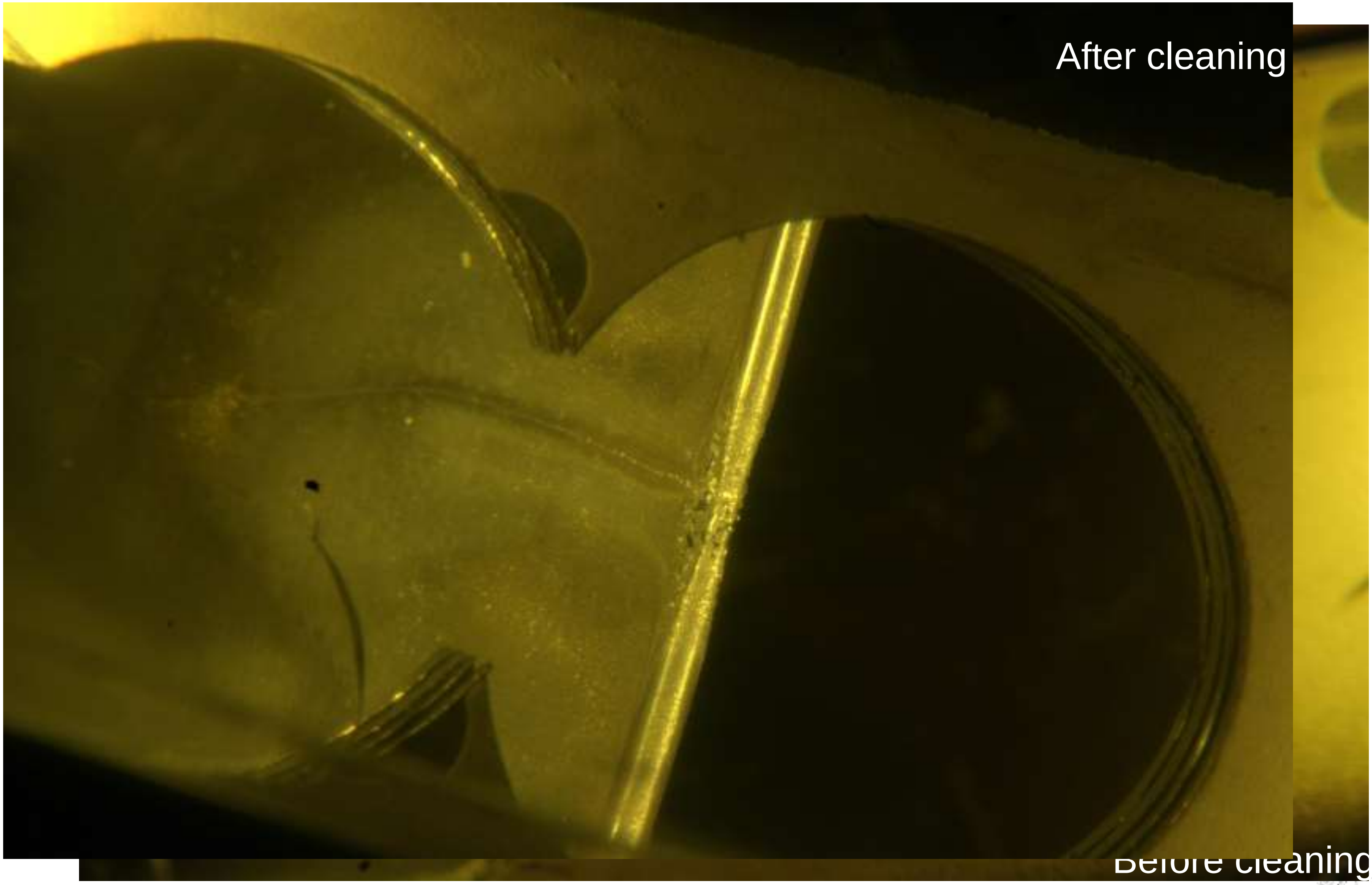
Channel mercury only

Saturation time on channel mercury at 1 ms from pressure pulse simulation

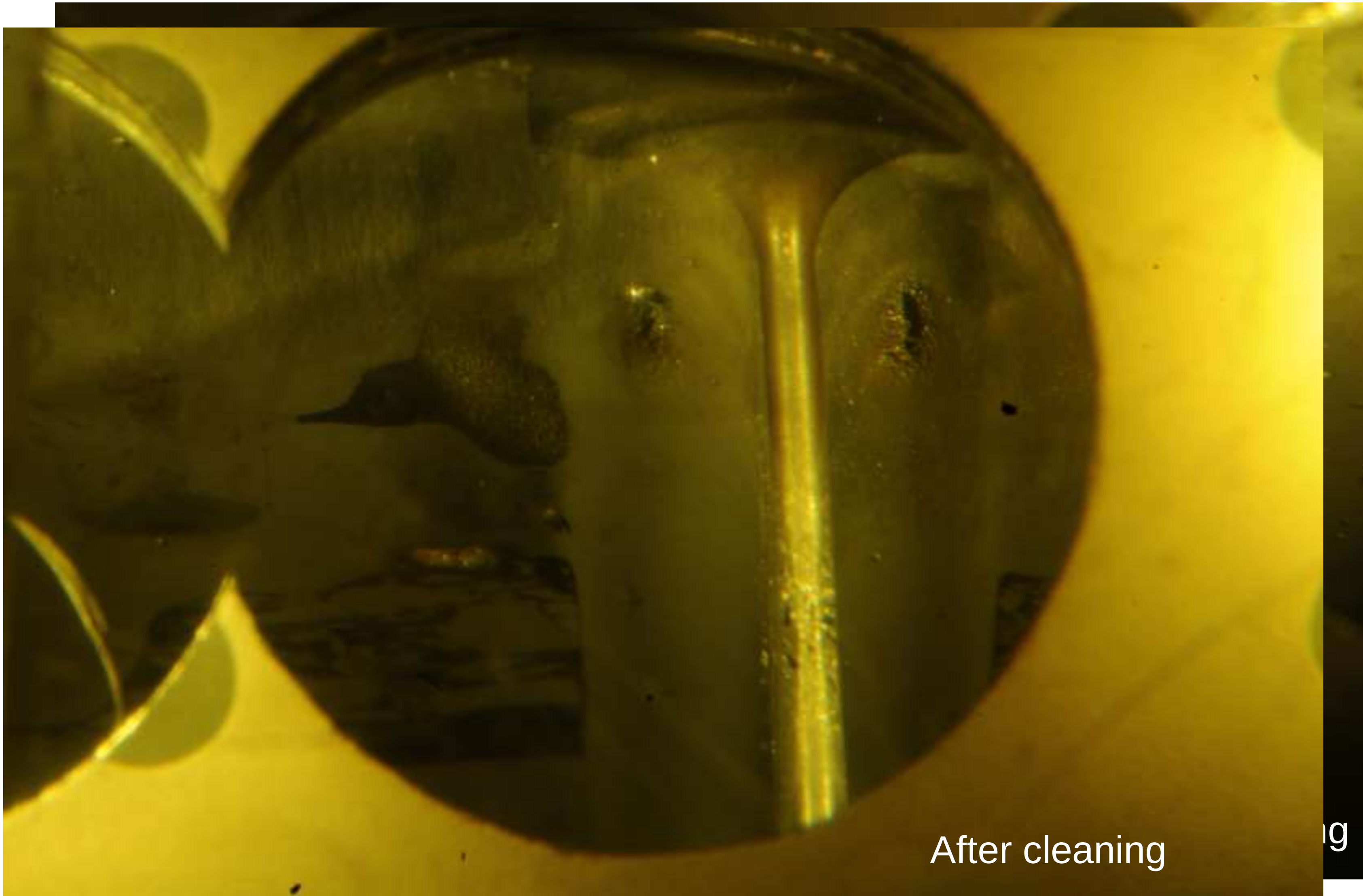


Outlines of center and passenger side cuts

Erosion on center flow baffle Sharp line (both sides) – suggest a crack



T3: Severe erosion at base and top of center flow baffle



B&W Technical Services Group has performed well on Target 1 PIE

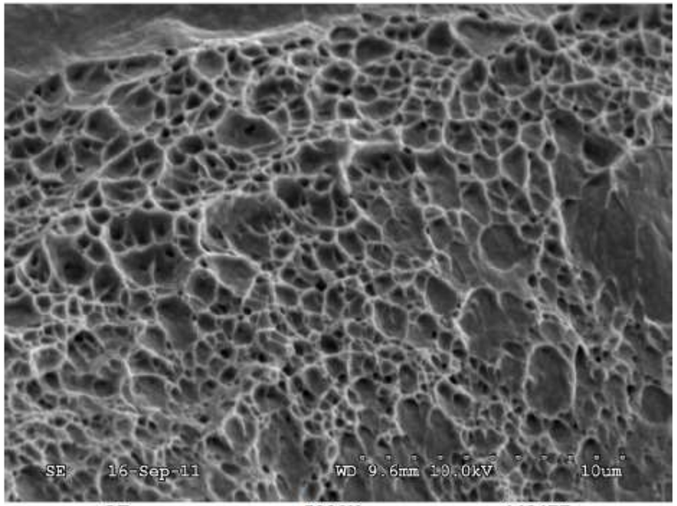
- Four of eight disk specimens were sent to B&W for a range of tasks
  - Cleaning, photography
  - Detailed pitting / erosion characterization
  - Hot machining of test specimens
  - Irradiated mechanical property testing
  - Microscopy
- Findings of material inclusions
- Phase-2 subcontract awarded for similar work on T2
  - T2 disk specimens delivered to B&W in December

Tensile specimens were machined from sample disks and pulled to failure

Specimen ID	Test Temperature (°C)	Strength (MPa) Yield	Strength (MPa) Ultimate	Fracture Load (N)	Fracture Stress (MPa)	Fracture Strength (MPa)	Elongation (%) Uniform	Elongation (%) Total	Reduction in area (%)
D1-1	21.7	416.4	508.9	164.6	264.3	136.4	38.7	48.8	48.4
D1-2	21.7	537.1	616.6	520.4	881.9	432.4	32.4	40.0	51.0
D1-3	22.2	574.1	623.5	533.8	864.0	444.5	8.9	14.8	48.5
D1-4	21.7	664.2	692.2	645.0	1131.0	536.3	19.5	27.8	52.6
D6-1	22.8	657.5	697.9	640.5	1285.6	515.6	10.19	20.22	59.9
D6-2	22.8	706.4	738.9	133.4	217.0	106.9	9.9	15.66	50.7
D6-3*	22.8	632.7	637.1	102.3	141.9	81.3	10.06	12.19	42.7
D6-4	22.8	654.4	685.2	671.6	1258.3	541.7	11.49	16.73	57
D7-1	20.6	655.4	681.4	498.2	671.6	407.8	14.56	19.54	39.3
D7-2	20.6	668.2	717.6	671.6	1096.5	543.7	24.73	31.29	49.8
D7-3	21.1	696.1	734.6	560.4	877.6	458.5	20.55	27.47	47.8
D7-4	20.6	685.3	712.9	53.4	83.3	43.2	8.62	16.31	48.1
D7-5	20.6	733.2	769.6	774.0	1308.2	635.9	24.73	34.75	51.4
D7-6	20.6	717.0	737.7	676.1	1298.6	553.1	22.47	30.29	57.4
D7-7	20.6	679.1	728.5	573.8	1054.4	472.0	21.71	30.78	55.2

Table 8.5.1: ORNL SNS Irradiated Tensile Testing Results Summary.

Example SEM images of tensile specimens



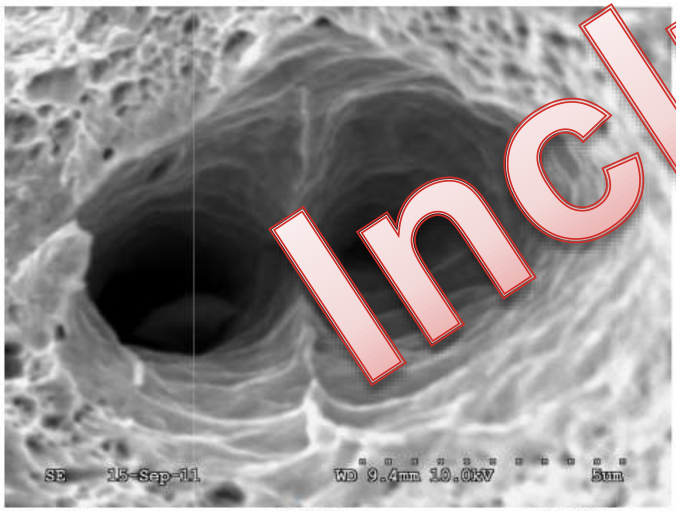
SE 5000X 142177

Figure 9.4.1.3: Higher magnification micrograph of lower right area of Figure 9.4.1.2. Fracture morphology is ductile microvoid coalescence.

1000X 142149

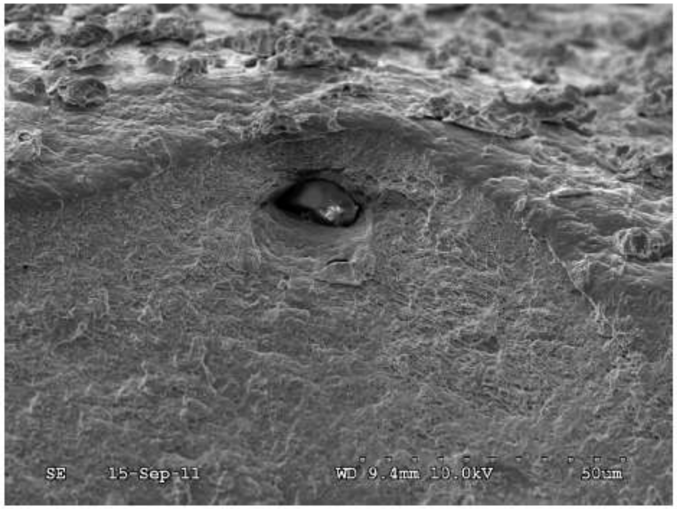
Figur[illegible]3.8[illegible] magnification micrograph showing area 4 in Figure 9.1.3.1. The lower h[illegible]f the image contains ductile microvoids; the upper half exhibits evidence of [illegible] fra[illegible]e.

Inclusions!



SE 10,000X 142148

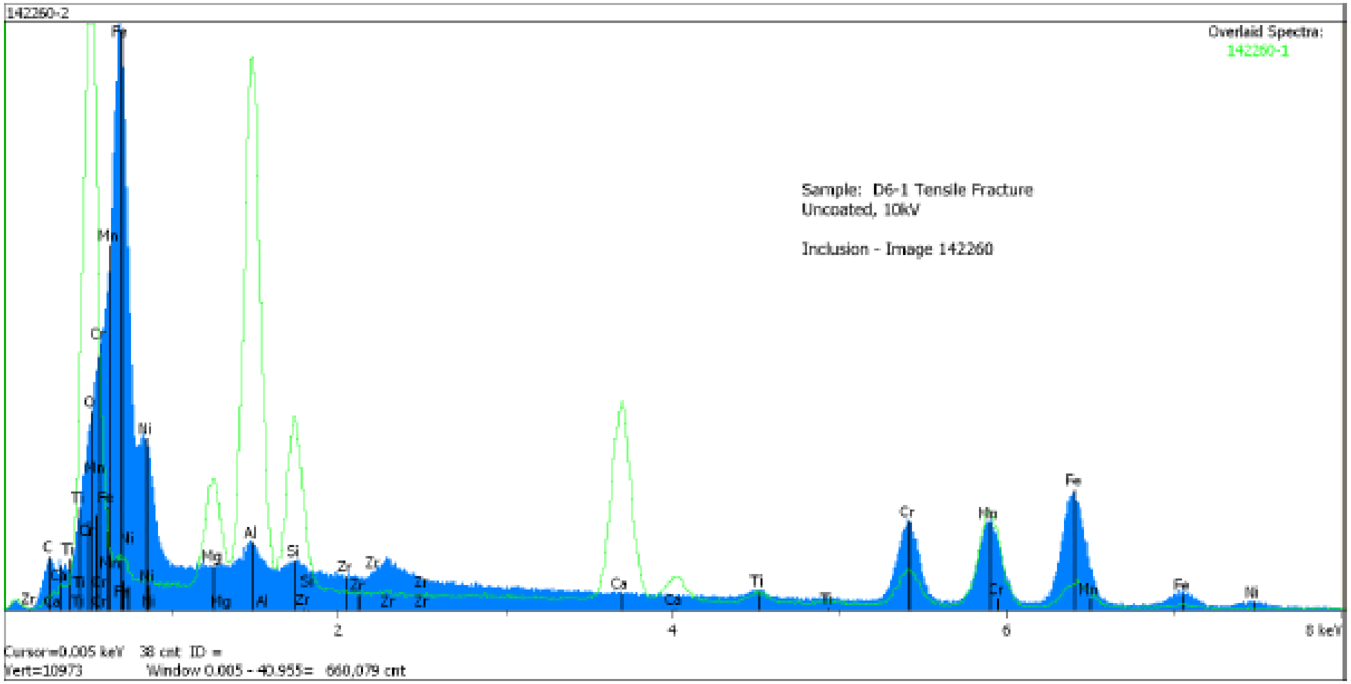
Figure 9.1.3.7: Very high magnification SE micrograph showing two closely spaced microvoids located at point 3 in Figure 9.1.3.1. The initiating inclusion is visible inside the left microvoid.



SE 80X 142175_A

Figure 9.1.4.7: Higher magnification SE micrograph taken of area 4 in Figure 9.1.4.1. Ductile shear fracture is evident, along with an inclusion within a void.

EDS results on inclusion indicate aluminum, calcium, oxygen, …



Comparative EDS spectrum results.

Figure 9.3.2.4: EDS spectrum results comparing inclusion (green line) to base material (solid blue). The inclusion contained higher concentrations of magnesium, aluminum, silicon, calcium, and oxygen compared to the base material.

- Calcium Aluminate treatment is a method for reducing alumina inclusions
- Are the sizes and distribution density typical for these forms of stainless steel??
- How can we improve on this?

PIE summary

- Observations from PIE set the directions for next generation targets
  - Inner wall is getting severely damaged – was completely fractured in T3
  - Channel surface damage less prominent – from what can be seen
  - Central baffle appears to be cracking; erosion at tip
  - Spots of through-wall erosion on front body seen in T3
- We have not found the leak in T3 yet
  - Power history / total energy on T3 do not look causal
  - It is likely from the channel, but we are unable to confirm this
- Maps of saturation time at 1 ms are showing good correlation with damage observations
  - Cross correlation with flow at wall to be considered (stress perhaps too)
  - A useful tool for where to look for problems, and future designs
- T1 PIE: Lots of ductility left in T1 material (up to ~ 7 dpa)
  - Longer target life possible (higher rad damage possible)
  - Inclusions in T1 material a worry, need study

Target #3 is slated for waste shipment this February

- Opportunity to find and characterize leak will be lost
- Should we try to keep and store T3 with hope to study it further a later time?
  - Outlook for a suitably equipped facility & additional funding to do more PIE on T3 is not good
  - No other options besides service bay
  - PIE operations in service bay will remain challenging
- Tools for PIE in the service bay remain limited
  - A concept for a remotely operated reciprocating saw was estimated at $235k – no funding

Plans for PIE

- Continue nose hole cutting on targets and inspections for cavitation damage, analysis for irradiated properties to establish data for increasing dpa limit
  - Procure new video-probe
- Follow through with B&W subcontract on T2 specimens, and prepare subcontract for T3
- Investigate inclusions in target materials, and find ways to get better material
  - We have archive material from T3 and beyond
- Requests for next generation targets
  - Removable shroud – finding mercury vessel leaks EZ
  - Improve surface finish, especially in beam windows and front body
    - Electro-polish can additionally help improve damage resistance
  - Burst disk for added leak detection

Small gas bubble mitigation experiment at LANSCE – WNR

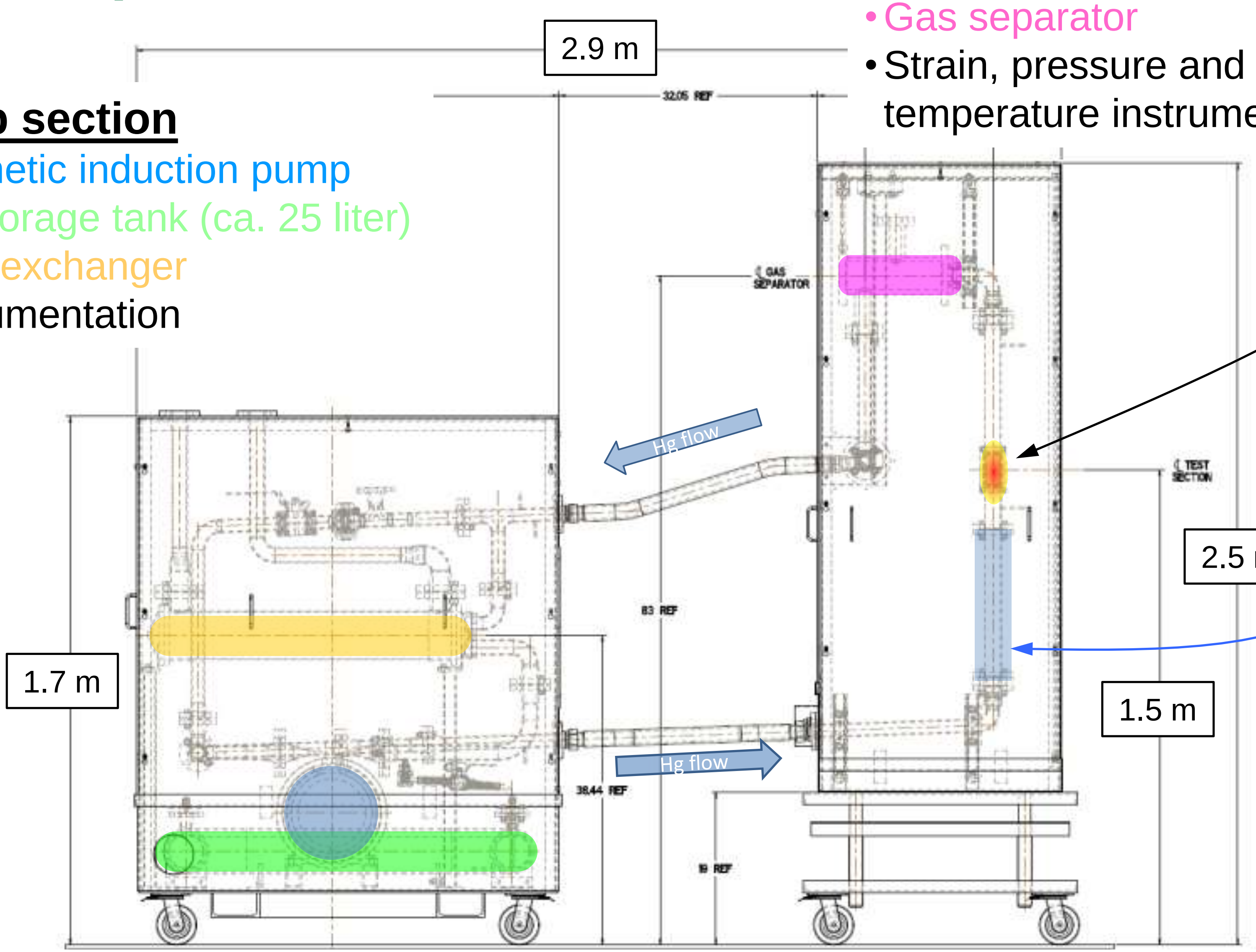
Nearly 3 years invested in this

- Evaluation of cavitation damage mitigation efficacy by the introduction of dispersed small gas bubble populations
  – Approximate population range of interest:
    - Bubble radii: 10 – 150 μm
    - Gas void fractions $10^{-5} – 10^{-4}$
- Pressure wave mitigation was also assessed
- Irradiations of 19 test conditions, including control cases, were completed in July
  – 100 pulses per test condition
- Pitting damage is now under assessment

Multi Bubbler Test Loop (MBTL)

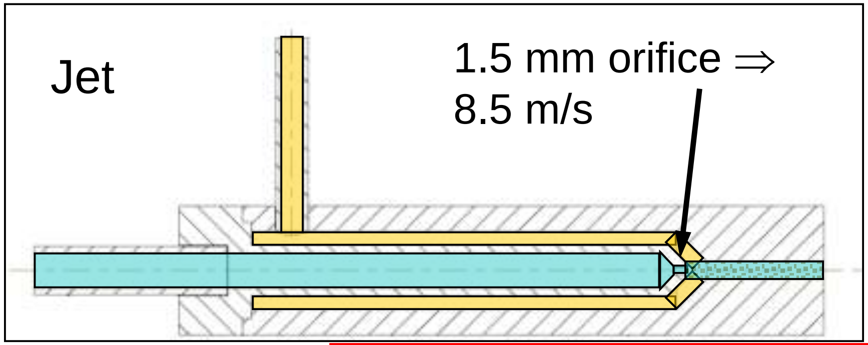
Bubbler / test section
- Damage test plates
- Bubbler section
- Gas separator
- Strain, pressure and temperature instrumentation

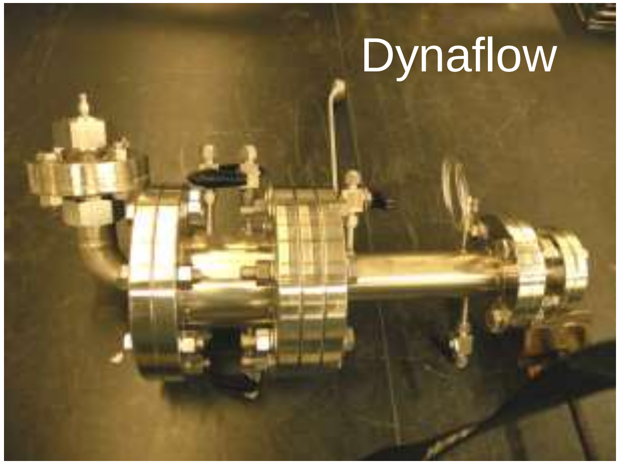
Pump section
- Magnetic induction pump
- Hg storage tank (ca. 25 liter)
- Heat exchanger
- Instrumentation

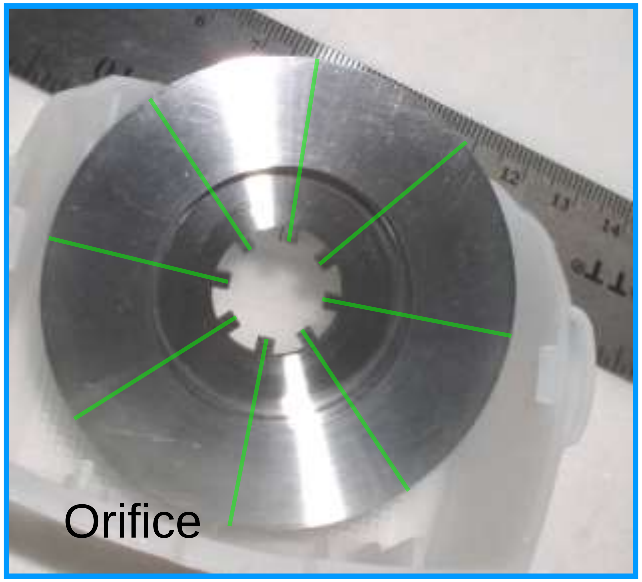


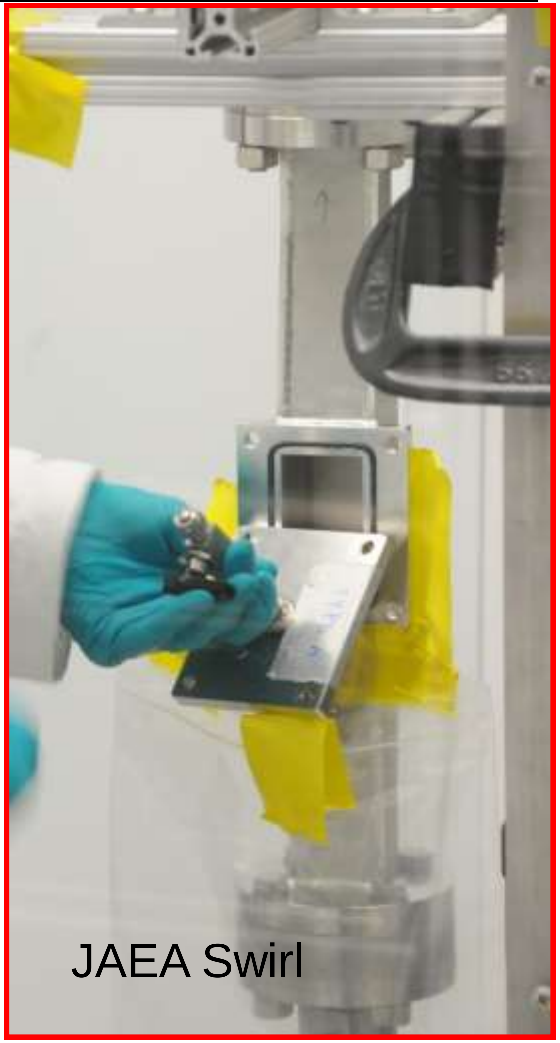
Many bubble generators considered, tested

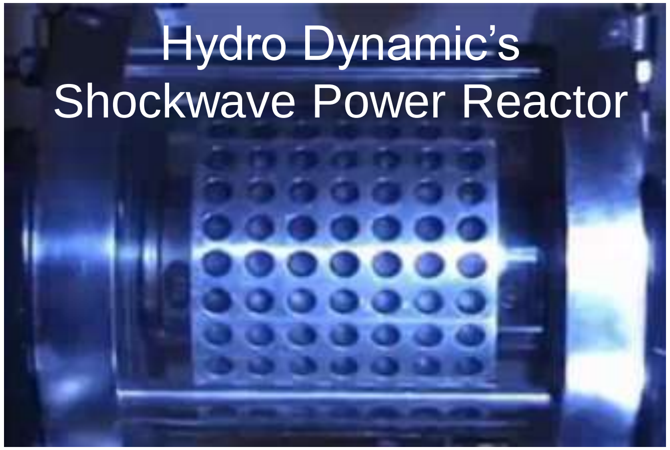
- **Flow channel miter bends**
- **Univ. of Tennessee swirl bubblers**







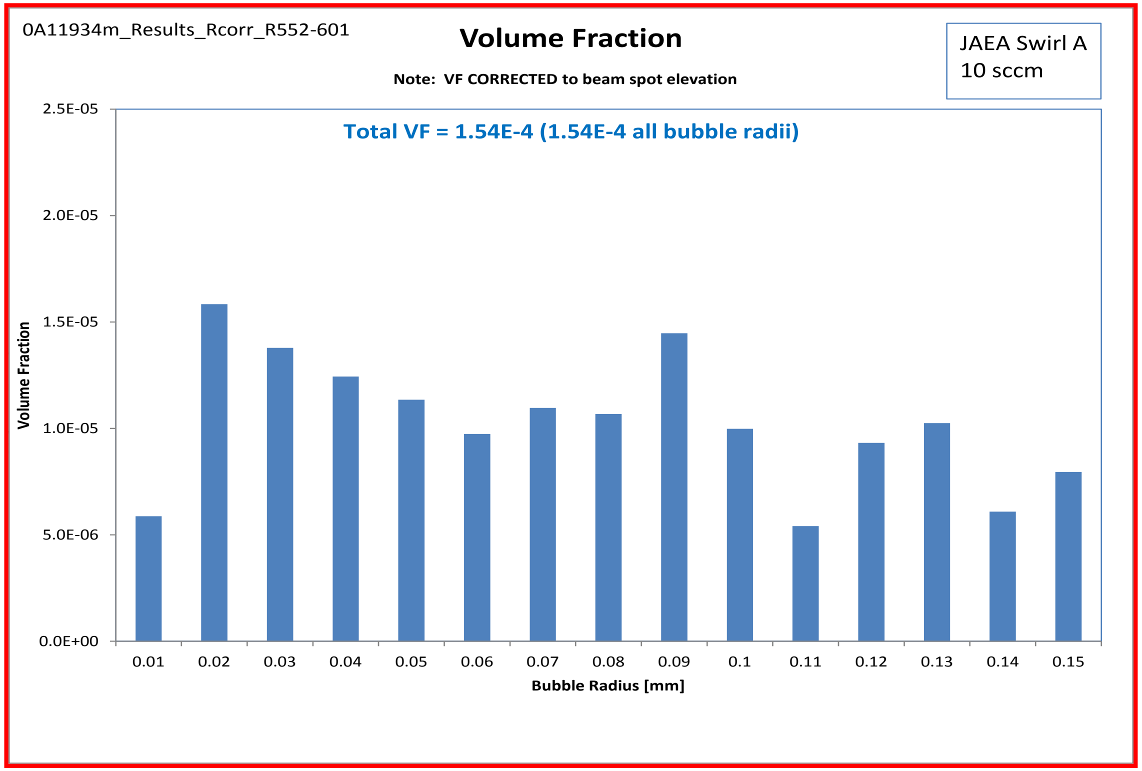




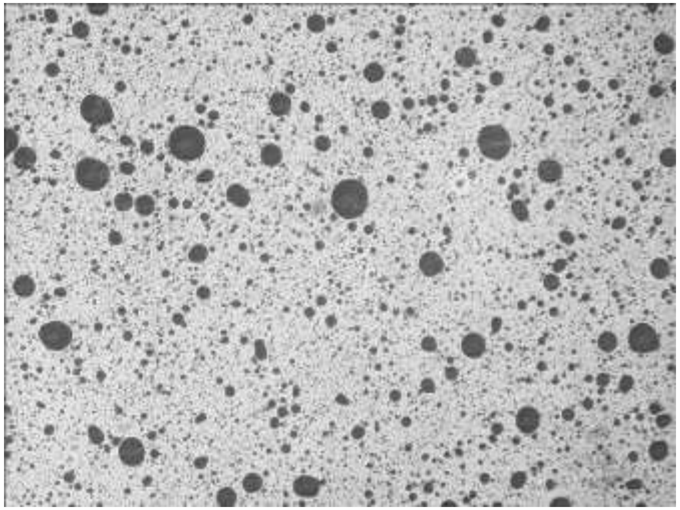
MBTL in vapor controlled lab space
early pre-irradiation testing

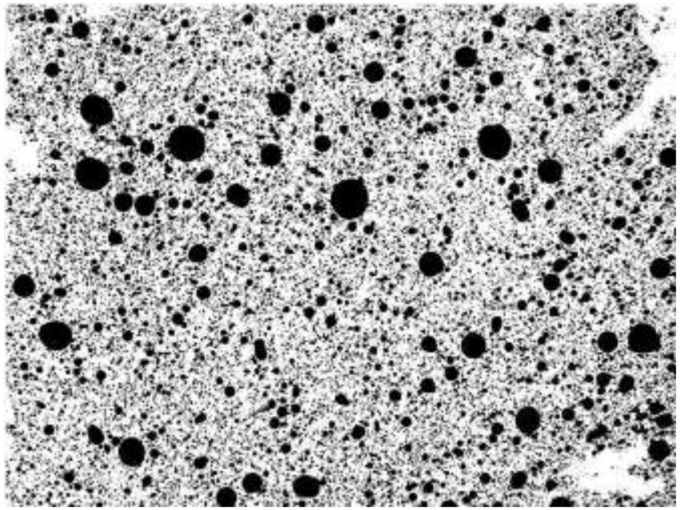
JAEA's swirl bubbler

- **Several versions were tested**
- **Hydraulic losses were high (Swirl "A")**
  - **Scaling to SNS or JSNS indicates excessive pressure drop**



Bright field image of bubbles that rise up to horizontal view port (FOV: 10 x 7.5 mm)





Analyzed image provides bubble size distribution data (ImageJ)

MBTL in WNR Blue Room

Damage assessment

- Test plates were made from annealed 316L stainless steel
- Polished surfaces were pre-inspected with an optical scanning microscope
- Decontamination of the test plates commenced in mid October and was completed mid November
- Damage assessment is being done by optical scanning and laser profiling microscopes
- Damage parameters:
  - Fraction of area damaged
  - Pit depth
  - Eroded volume

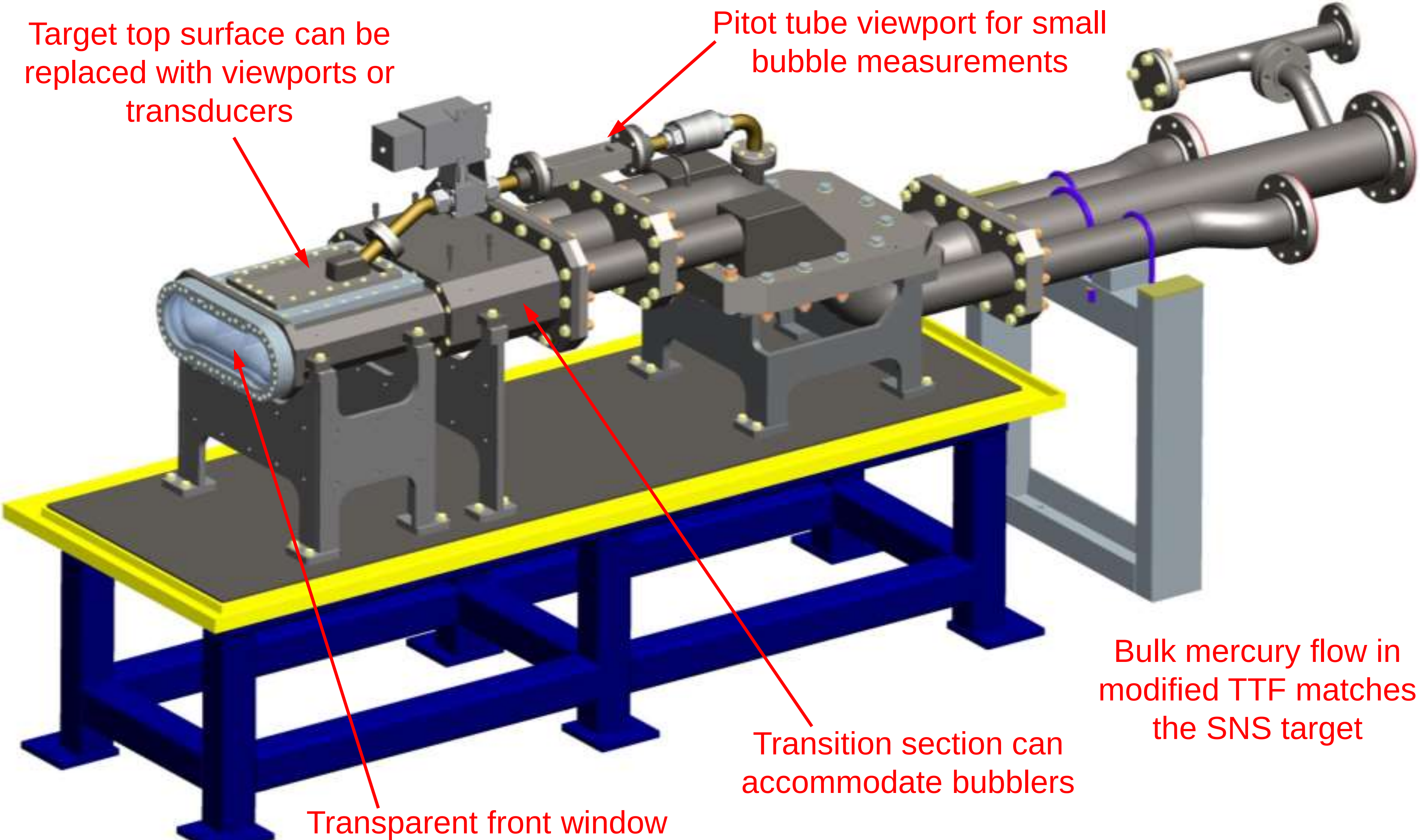
Remaining tasks to complete WNR experiment

- Complete optical microscopy of 38 test plates
  - Multiple imaging sets needed per plate
  - Process images to obtain damaged area fraction data and identify regions for detailed inspection
- Laser profiling microscopy
  - Focus on selected areas of worst pitting on each plate
  - Compile data on pit depth and eroded volume
- Rank damage parameters between test conditions
- Complete analysis of other test data
  - Bubble populations, LDV, strain, acoustics
- Judge mitigation efficacy for bubblers, recommend bubblers for TTF testing and SNS deployment
- Document
- Dispose of test apparatus when appropriate

Prototypic testing of small gas bubble and gas wall mitigation in TTF was under preparation

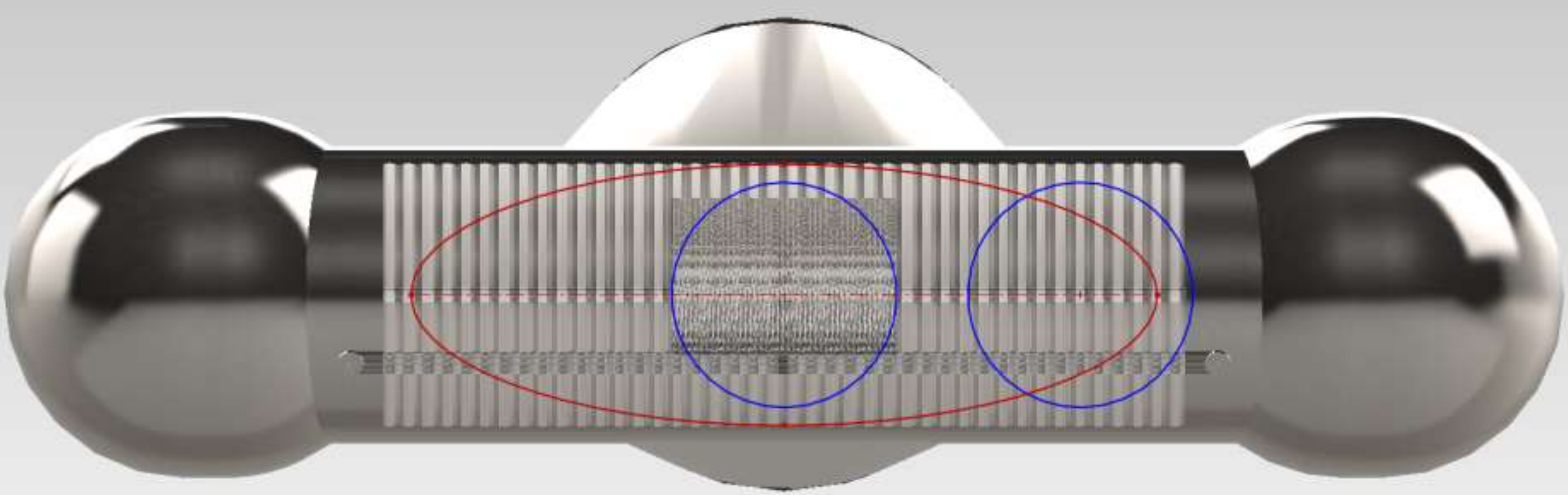
- Target development was proceeding with full scale, 2-phase tests under the SNS flow configuration
- Modifications to the TTF were started in FY11 to
  - Make the target bulk mercury flow identical to the SNS
  - Support small gas bubbler testing
  - Support tests of improved gas-wall configurations
- Modular target hardware was designed and ordered in FY11
  - Reconfigurable depending on test objective
  - About 90% of necessary parts obtained
- Work suspended

Target hardware for TTF testing of small gas bubbles and gas walls



Advances in 2-phase CFD modeling capabilities were guiding gas-wall design

- Goal of wide area coverage with good gas retention at wall
- Surface texturing needed with SNS bulk flow configuration
- Gas port locations, flow rates, and surface texture patterns studied

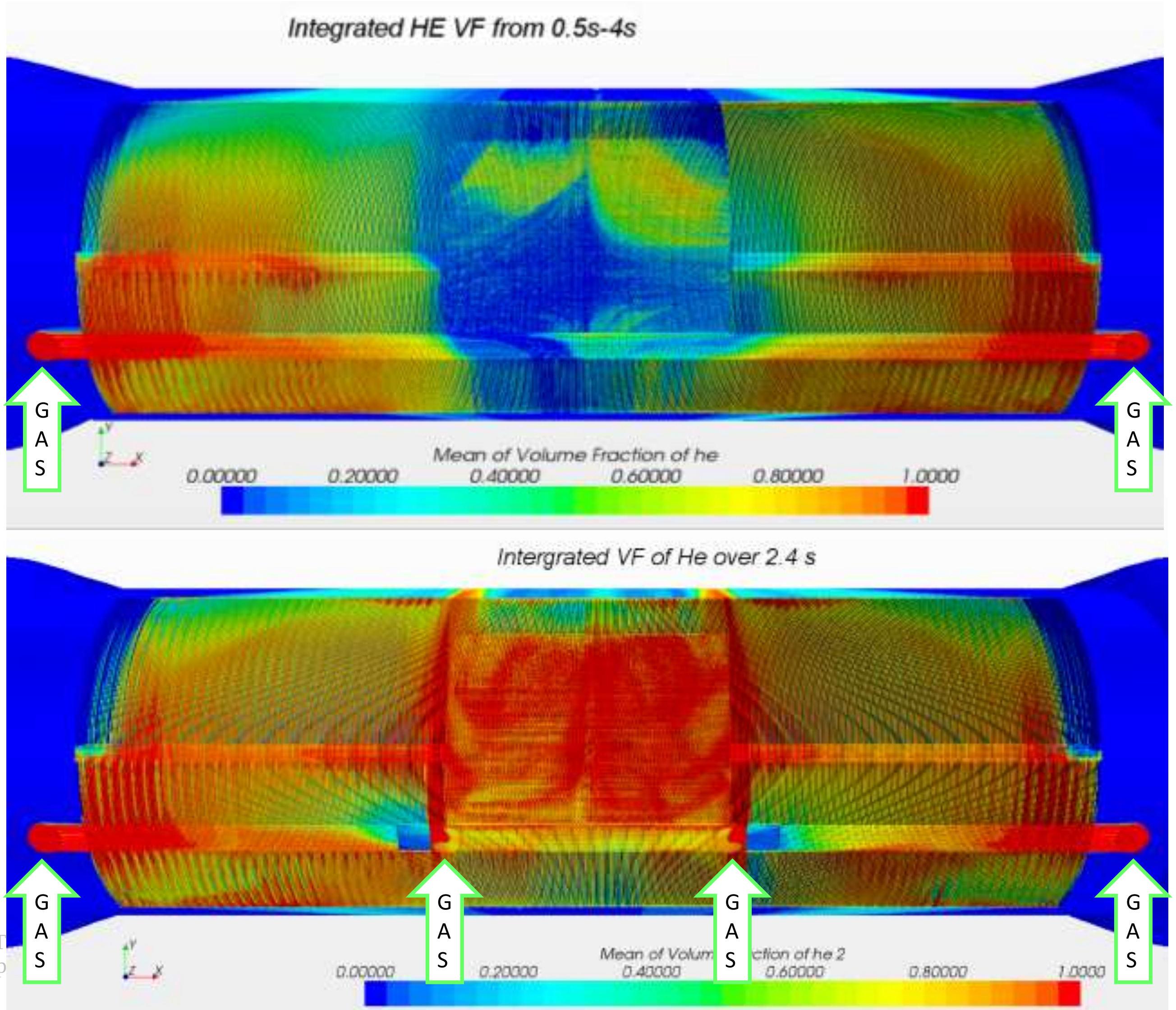


- Beam outline and PIE disks approximated
- Grooves with cones around beam axis

Time averaged gas fraction at surface

- Two vs. four gas ports
- 500 sccm each port

Nominal SNS flow
(pump at 380 rpm)

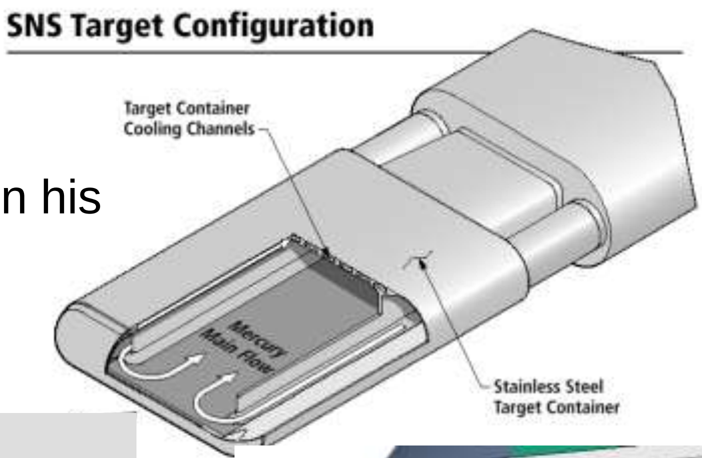


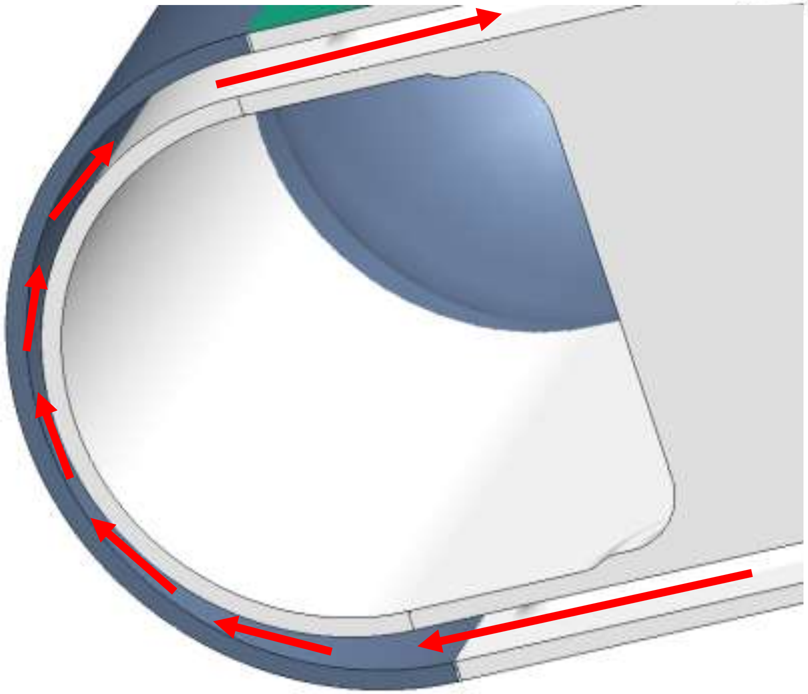
"Jet-Flow" target uses only mercury flow to mitigate damage – no gas

- Premise:
  - Protect inner wall bulk surface (most damage seen here)
  - Establish 2 m/s flow over inner wall (similar to channel flow)
  - By doing so, the outer wall / channel is protected
- Efficacy risk:
  - Leak of T3 is likely from a channel surface away from beam; jet-flow may do no good
- Advantages:
  - No gas injection →no gas system required
  - Modest change to existing target design
  - Low engineering risk, easier installation requirements

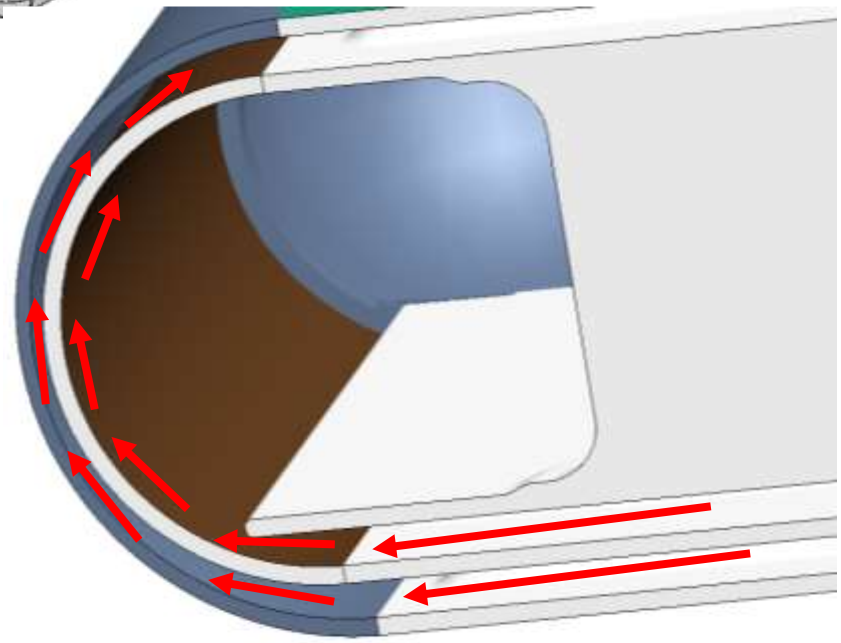
Mitigate Damage Via Flowing Hg

Peter Rosenblad will cover this in his Target Engineering presentation





Existing Configuration



Proposed Configuration

We are ready with good prospects for effective damage mitigation

- Target development personnel are still here
  - Reorganization has core team members in Neutron Source Design Group - Engineering Analysis Team
- If called upon, we can resume work on gas mitigation development
  - Based on what we’ve learned, both small gas bubbles (adopted by J-PARC) and gas-walls are promising
  - Parts for prototypic testing in TTF are mostly on-hand
- In the mean time, we will try the Jet-flow approach
- Much depends on our ambitions to improve neutron performance by increasing beam power on target, and how badly higher power reduces target life