PITTING ISSUE/TARGET DECISION

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November 13–15, 2002

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Criteria and Deadlines for Examining the Pitting Problem Were Established Last April

- Testing of a target geometry and material combination at WNR that has pitting damage that can be scaled from 100-200 test pulses to at least 14 days of operation in SNS at 1 MW proton beam power.

- Demonstration of high cycle scaling behavior of "high pressure pulse" pitting damage up to at least one million cycles for materials similar to those successfully tested at WNR.

- No obvious fabricability, radiation damage, engineering, etc. showstoppers with the selected material or geometry.

- October 15, 2002 - Go/No-go decision on mercury based on the three criteria listed above.

Pitting Studies Conducted Since Last DOE Review

- WNR tests successfully completed in June/July 2002.
  - Decontamination and SEM inspections complete.
  - Image processing to determine pitting statistics 75% complete.
- Four off-line pitting simulation devices are being used to facilitate extrapolation to high cycles.
- Status report on Pitting Issue submitted to DOE on July 31.
- Held two meetings with cavitation damage experts to confirm approach and seek guidance.

Cavitation Damage Experts Were First Consulted in May 2002

- Formed a Cavitation Damage Experts Committee and held meetings on May 9–10, 2002 and October 8, 2002.
  – Roger E. A. Arndt (University of Minnesota), Steven L. Ceccio (University of Michigan), Robert J. Etter (Naval Surface Warfare Center, Carderock Division), Arthur E. Ruggles (University of Tennessee), David L. Stinebring (Applied Research Laboratory/Penn State).
- Outcome from May 2002 meeting:
  – Consensus that the pitting of the WNR mercury target containers was due to cavitation.
  – SNS project assessment, approach, and near-term plans were reasonable.
  – Recommendations on additional tests for June 2002 WNR tests were incorporated and tests conducted.
  – High pressure, high cycle tests should be the highest near-term priority.

21 Targets Were Tested in the June–July 2002 Campaign at the WNR Facility

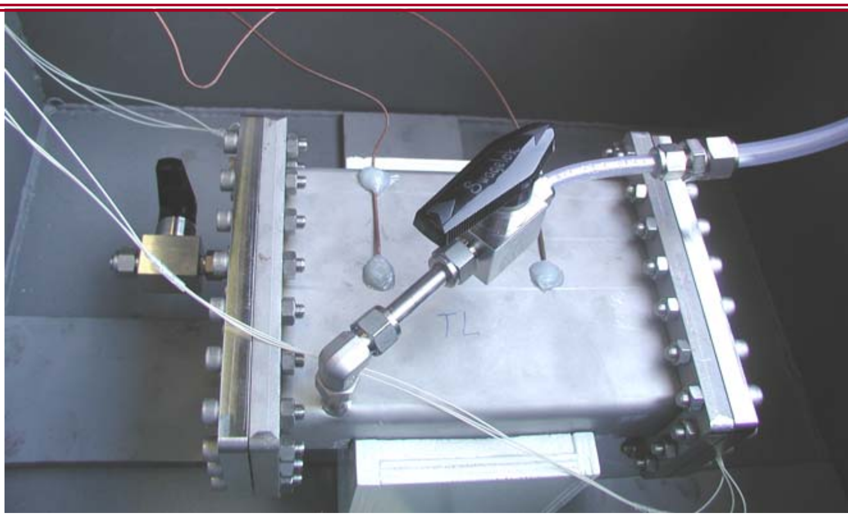
- Most targets have rectangular cross-section.
- Many have plates at top or bottom to simulate slot in duplex structure.
- Base case uses CW 316SS test surfaces and 100 pulses.

- Power dependence
  - High-Power (Base Case).
  - Medium Power.
  - Low Power.
- Bubble/gas layer mitigation tests
  - Three thin targets in series (study effect of length and bubbles).
  - Protective gas layer flowing along the beam window.
  - Small, stagnant gas layer at top of target.
- Geometry effects
  - Double-wall: “Water-Cooled” Container.
  - Double wall: “Hg Cooled” Container.
  - Curved nose effect.
  - “L” shape with 45° reflection on rear and free surface on top to simulate long target.
- Material variations
  - Kolsterized, CW 316SS test surfaces.
  - Electro-polished surface.
  - Nitronic-60 instead of 316SS.
- Bubble diagnostic target
- Effect of number of cycles
  - 1,000 pulses instead of 100.
- Three Cylindrical targets fabricated by FzJ (material/coating variations)
  - Martensitic steel from ESS.
  - CrN coating from JAERI.
  - Annealed 316LN .
- PbBi filled cylindrical target
  - Repeat of previous test, but with target completely filled.

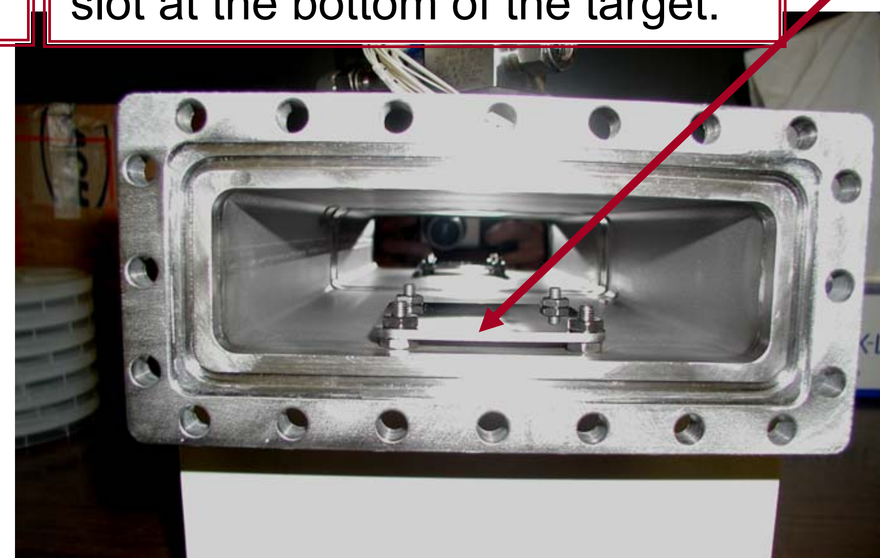
Most of the Targets Used in June 2002 WNR Tests Had a Rectangular Cross-Section

- Front and rear cover plates were test specimens.
  - 8,000 SEM images gathered during pre- and post-test inspections of these and other specimens.
- Insert plate used to simulate small Hg flow passage used to cool the Hg container.

Interior: 41 x 143 mm rect, 215 mm length
Cover plates: 2 mm thick.

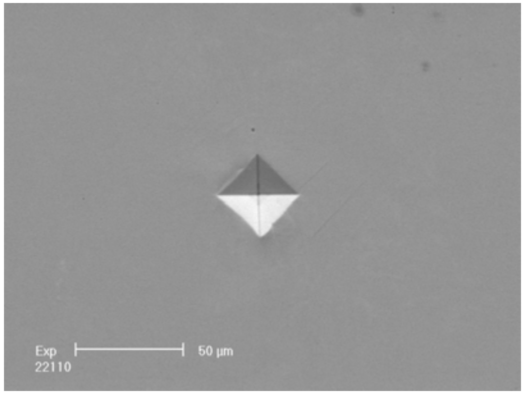


Insert plate forms a small Hg slot at the bottom of the target.



Methodology Used to Characterize Pitting

- Pitting was characterized in regions centered at micro-indentation marks placed near the center of each highly polished plate.
  - Marks, which form a 5 x 5 array spaced 5 mm apart, serve as fiducial points.
  - 100x and 400x SEM images taken at each location.



- Key pitting parameters:
  - Fraction of area covered with pits.
  - Mean depth of erosion (e_o).
    - For high cycle, significant mass loss tests:

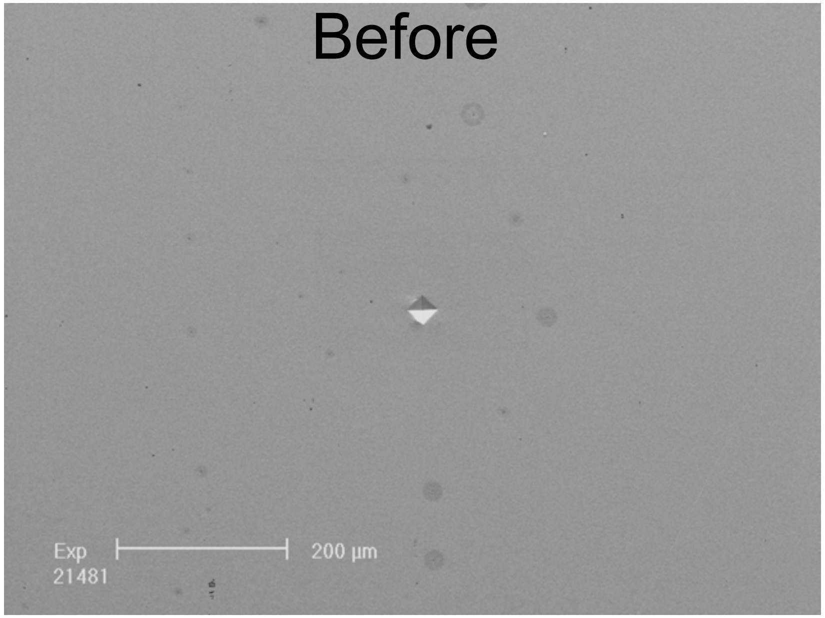
      e_o = mass loss/density/area.
    - For low number of cycles volume loss was estimated using microscopy results:

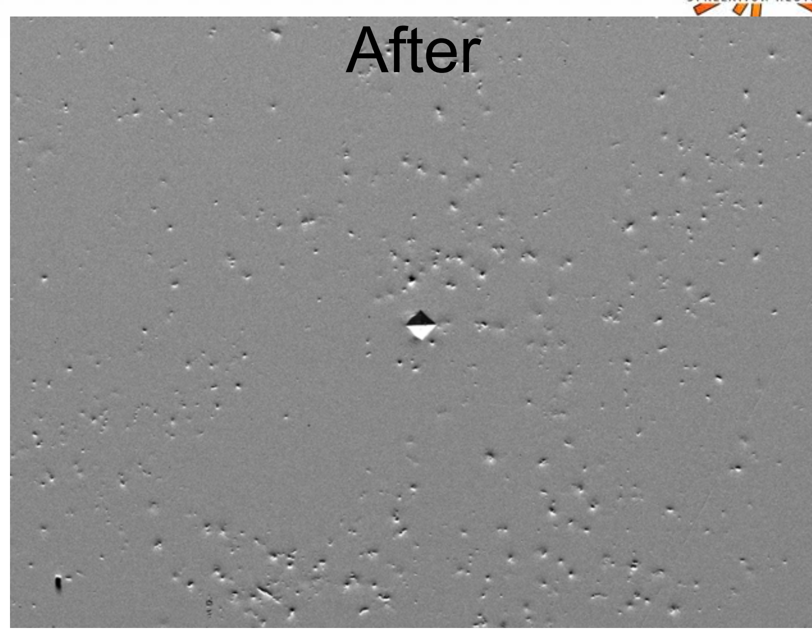
      e_o = (Vol removed by pits)/(Surf area in μ–scope image).

Methodology Used to Characterize Pitting (cont'd)

- For the WNR results, volume removed by pits estimated by summing over the volume for every pit.
  - We assume that the depth of each pit = the radius of the pit.
    - This appears to be an over-estimate.
- "Equivalent SNS Power Level" is scaled by the peak energy density in the test compared to the SNS value.

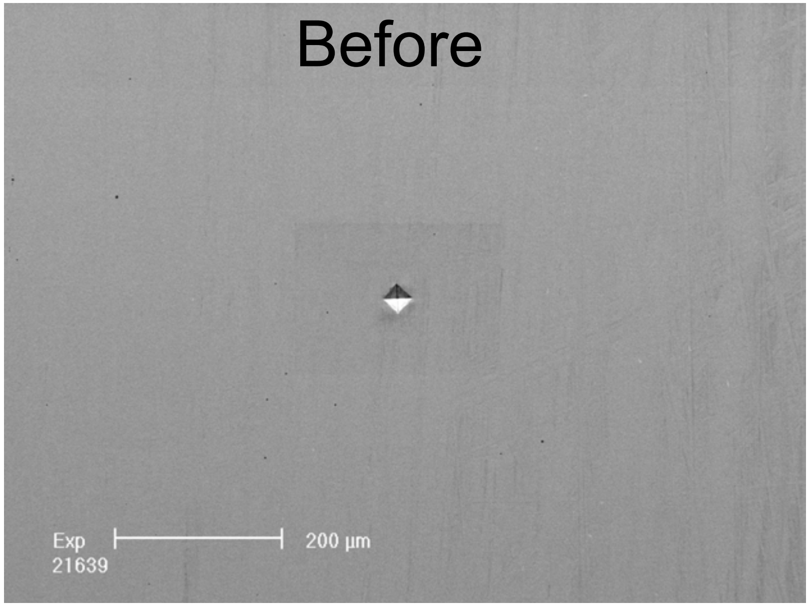
High Power Target (Reference Case)

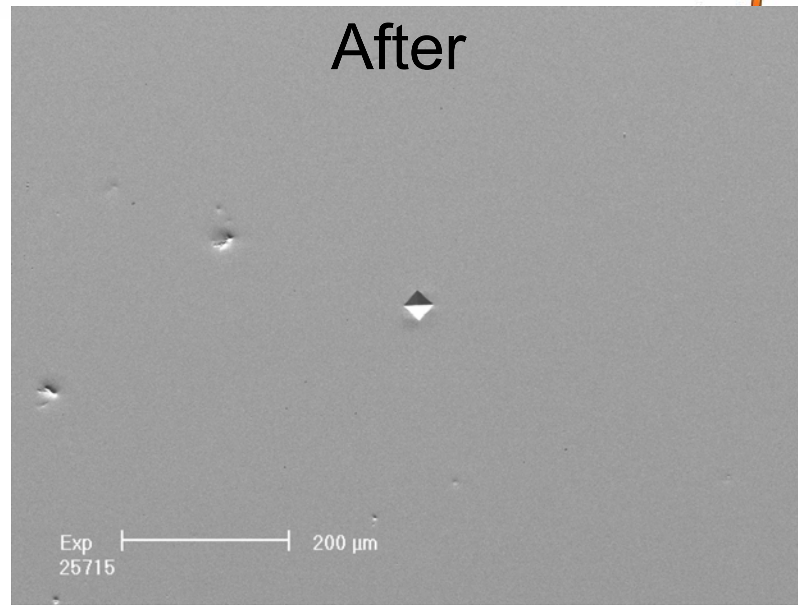




TL - High Power Target			
Specimen # 29754			
Equivalent SNS Power Level = 2.5			
		Summary for Worst* Image	
Summary for All Images		Image # 25665	
Frac Pit Area	**0.0143**	**Frac Pit Area**	**0.0464**
Average Pit Area (μm^2)	11.4	Average Pit Area (μm^2)	30.2
Diam of Ave Area Pit (μm)	3.8	Diam of Ave Area Pit (μm)	6.2
Max Area of Pit (μm^2)	1597.9	Max Area of Pit (μm^2)	1597.9
Diam of Max Pit (μm)	45.1	Diam of Max Pit (μm)	45.1
Mean Erosion Depth (nm)	**27.3**	**Mean Erosion Depth (nm)**	**131.9**

Medium Power Target (1.1 MW Equiv.)





TM - Medium Power Target				
Specimen # 29756				
Equivalent SNS Power Level = 1.1				
			Summary for Worst* Image	
Summary for All Images			Image # 25665	
Frac Pit Area	**0.0012**		**Frac Pit Area**	**0.0025**
Average Pit Area (μm^2)	10.3		Average Pit Area (μm^2)	21.7
Diam of Ave Area Pit (μm)	3.6		Diam of Ave Area Pit (μm)	5.3
Max Area of Pit (μm^2)	1597.9		Max Area of Pit (μm^2)	1597.9
Diam of Max Pit (μm)	45.1		Diam of Max Pit (μm)	45.1
Mean Erosion Depth (nm)	**2.5**		**Mean Erosion Depth (nm)**	**11.6**

Pitting Statistics for June 2002
WNR Test Specimens

Statistics for Worst Regions of Front Plate

Target	Equivalent SNS Power Level (MW)	Fraction of Area with Pits (%)	Mean Depth of Erosion (nm)
TL - High Power Target	2.5	4.6	132
TM - Medium Power Target	1.1	0.3	12
TH - Low Power Target	0.4	0.2	4
KILO - 1,000 Pulse	2.9	3.6	101
BL - Bubble Layer	2.7	0.3	8
EP - Electro-Polished	2.8	0.4	4
K - Kolsterized	3.1	0.03	0.1
L - L-Shaped	2.5	2.5	45
Nitronic 60	2.8	1.4	23
DW1 - H2O Double Wall - Front Surface 2	2.2	0.1	5
DW1 - H2O Double Wall - Front Surface 3	2.2	2.2	55
DW1 - H2O Double Wall - Top Surface 3	2.2	2.0	51
DW2 - Hg Double Wall - Front Surface 1	2.9	2.9	118
DW2 - Hg Double Wall - Front Surface 2	2.9	2.0	36
DW2 - Hg Double Wall - Front Surface 3	2.9	0.6	13
B1 - Bubble Injection Target	3.4	2.9	65
B2 - Tall Target	3.4	7.7	123
B3 - Short Target	3.4	0.5	7

All targets, except KILO, exposed to 100 WNR beam pulses

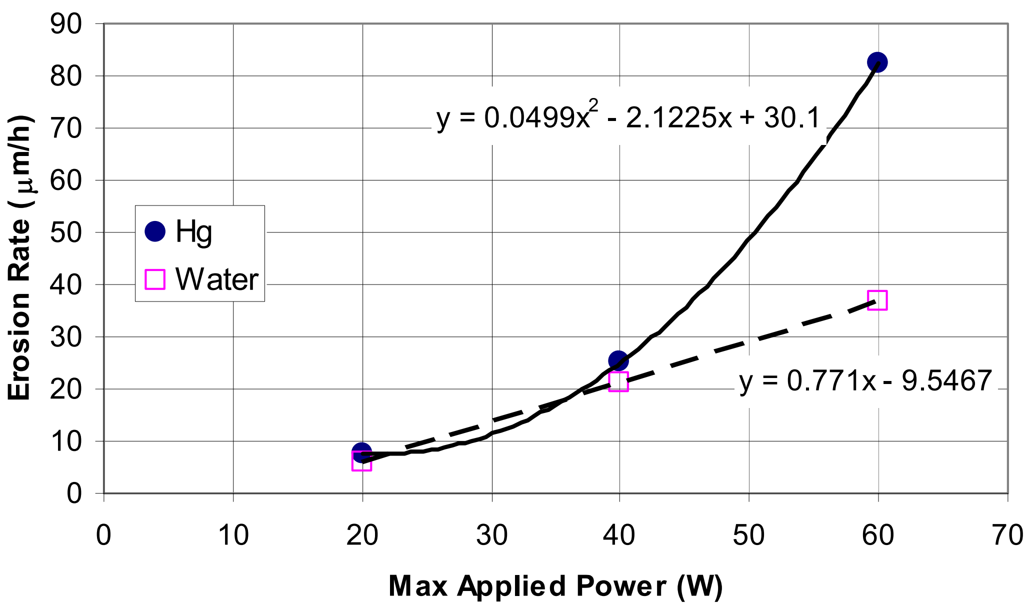
Erosion Rate May Have (Beam Power)^4 Dependence

- As pointed out by Carpenter and Ruggles

  Mechanical Power in Pressure Pulse $\propto$ (Beam Power)^2
- From ultrasonic horn tests

  Erosion $\propto$ (Mechanical Power)^2
- Combining these results yields

  Erosion $\propto$ (Beam Power)^4
- Roughly consistent with WNR test data
  - Will verify second item above with more off-line tests

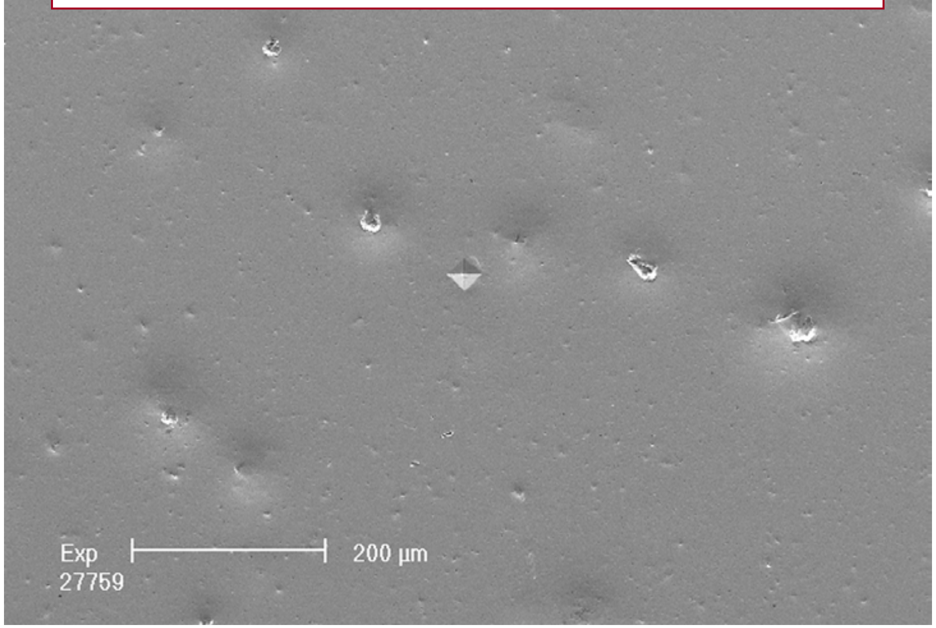


From ultrasonic cavitation erosion studies by Kass et al. , Tribology Letters 5 (1998) 231-234

Small Hg Slots in Targets Have Severe Pitting

- Bottom surface of inserts and slot in the front of the double wall Hg target are badly damaged.
- Narrow channel of mercury appears to be especially vulnerable.
- Re-design of SNS target to use water cooling for beam window is underway.

KILO target - bottom of insert plate



TL target - bottom of insert plate

Nov. 13-15, 2002

Summary of WNR Pitting Tests

- Several test cases showed significantly reduced erosion on the front wall specimen.

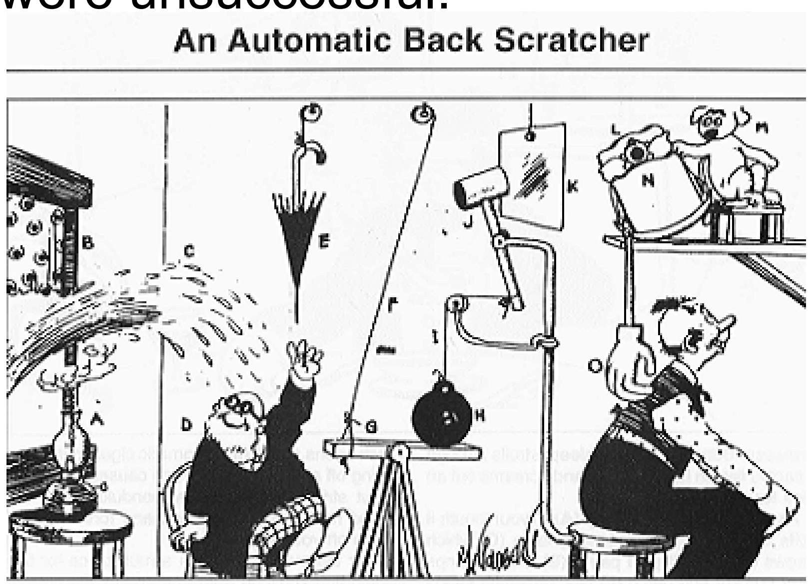
Feature	Normalized Erosion*
Bubble Layer	0.06
Electro-polished	0.03
Kolsterized surface	0.0008
1/2 Reference Power	0.09

* Erosion relative to reference (2.5 MW) case

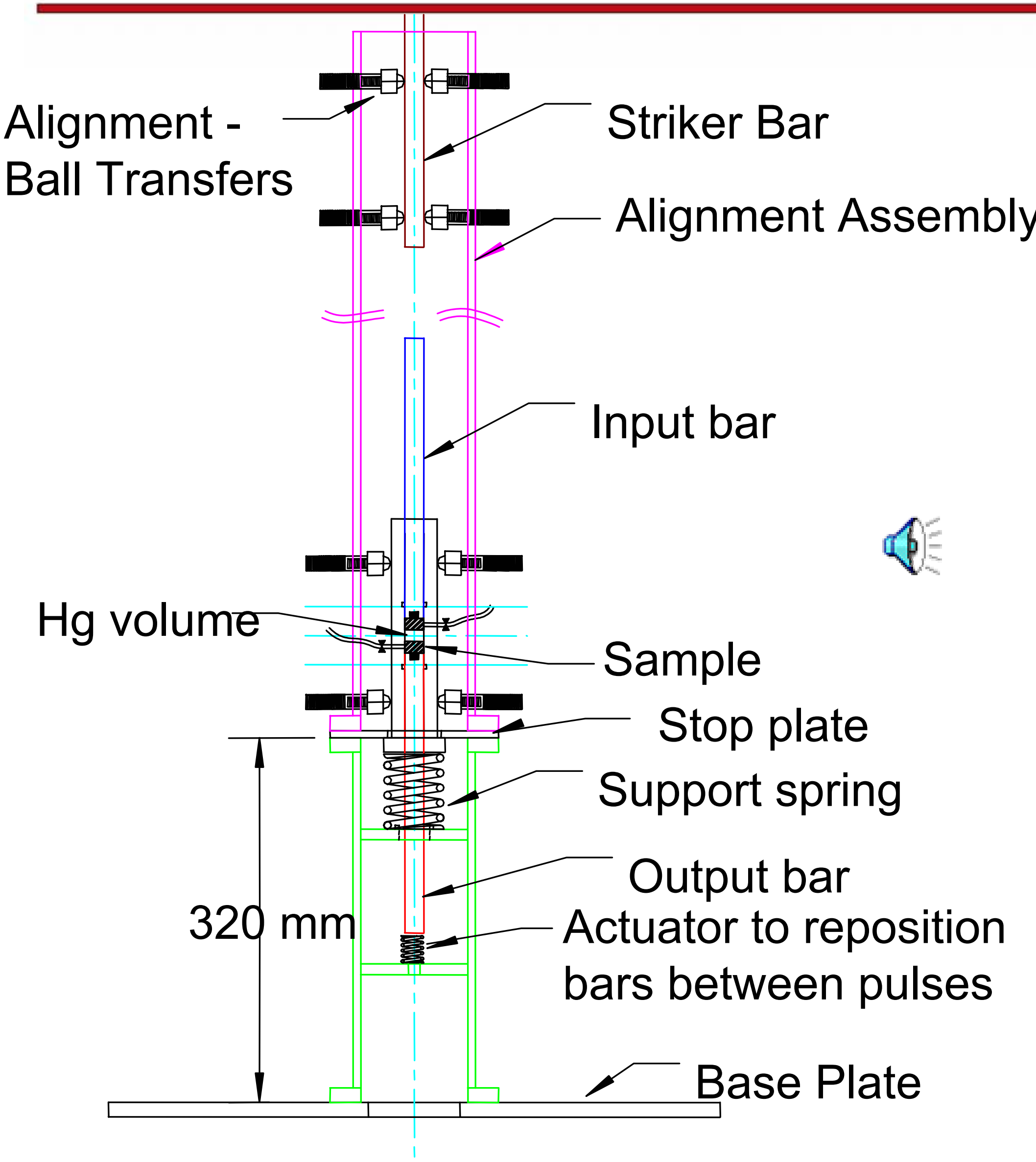
- Erosion was less sensitive to several other features.
  – Gas void, L-shaped target, Nitronic-60 instead of 316SS, curved nose.
- Bubble injection reduced the erosion by at least a factor of 2 compared to a similar target without bubble injection.
  – Effect may be significantly larger due to higher intensity in bubble target.

Off-Line Pitting Simulation Devices Are Being Used to Help Extrapolate to High Cycles

- Four off-line devices have demonstrated pitting damage similar to in-beam tests for a small number of pulses.
  - ORNL - simple mechanical device (drop test).
  - JAERI - Electromagnetically driven mechanical impact test device.
  - Lithotripter (kidney stone blaster) experiment at Boston University.
  - Ultrasonic horn used mainly for materials screening studies.
- Attempts to modify a servo-hydraulic impact test machine to simulate pitting damage were unsuccessful.



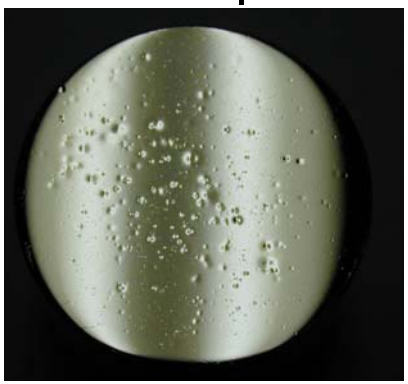
A Simple Drop Test Apparatus Is Being Used at ORNL to Perform Pitting Damage Tests



ORNL Drop Test Has Provided Data Up to One Million Cycles

- Upper specimen from ORNL drop test device (316SS).
- Specimen diameter = 16 mm.

100 drops



6.8 x 10^4 drops

1.0 x 10^5 drops

3.7 x 10^5 drops

7.4 x 10^5 drops

9.2 x 10^5 drops

Comparison of Pitting Damage in Drop Tests to WNR Tests

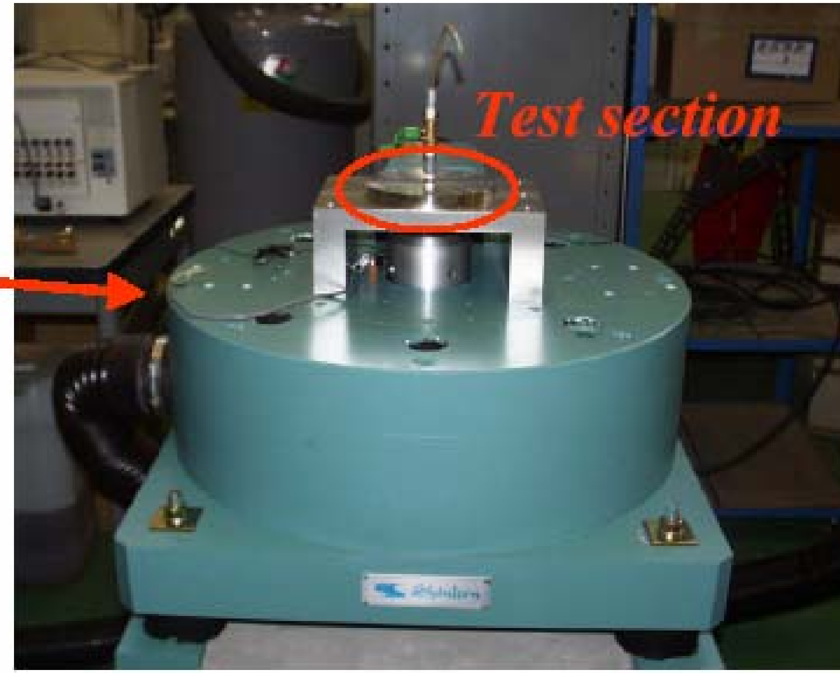
Test Specimen	Fraction of Area with Pits (%)	Diam of Ave Area Pit (μm)
250 mm Drop	6.1	15
WNR - 2.5 MW Equiv	4.6	6
125 mm Drop	1.8	12
WNR 1.1 MW Equiv	0.25	5

← Most of the data taken so far at this drop height (250 mm Drop)

Statistics shown for 100 pulses in all cases

JAERI Has Developed an Electromagnetically Driven Impact Test Device to Simulate Pitting

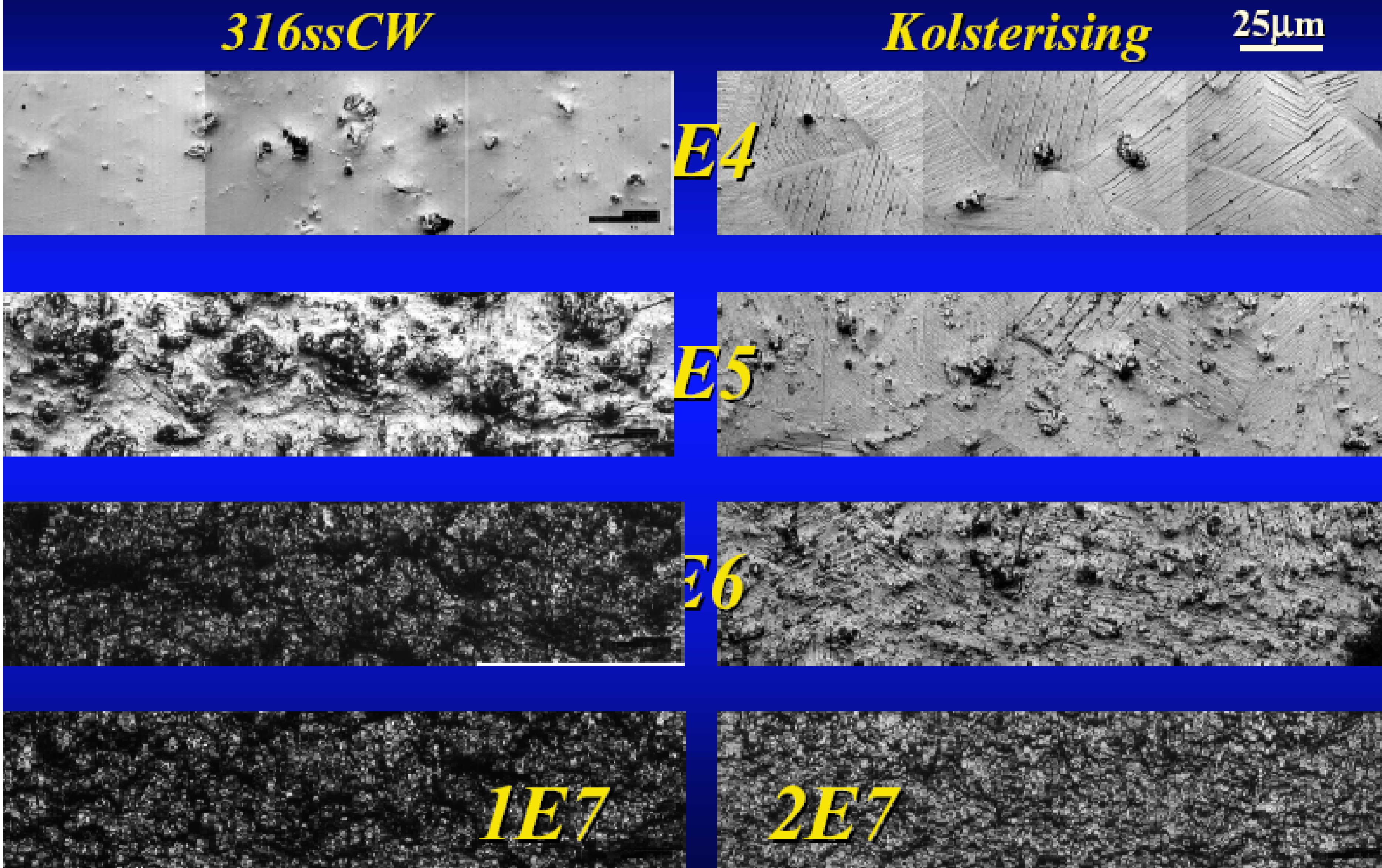
was installed in JAERI on 1st July !



Driving force : Electric magnet force
Max. force : ca 400 kgf
Max. acc. : ca 200 G

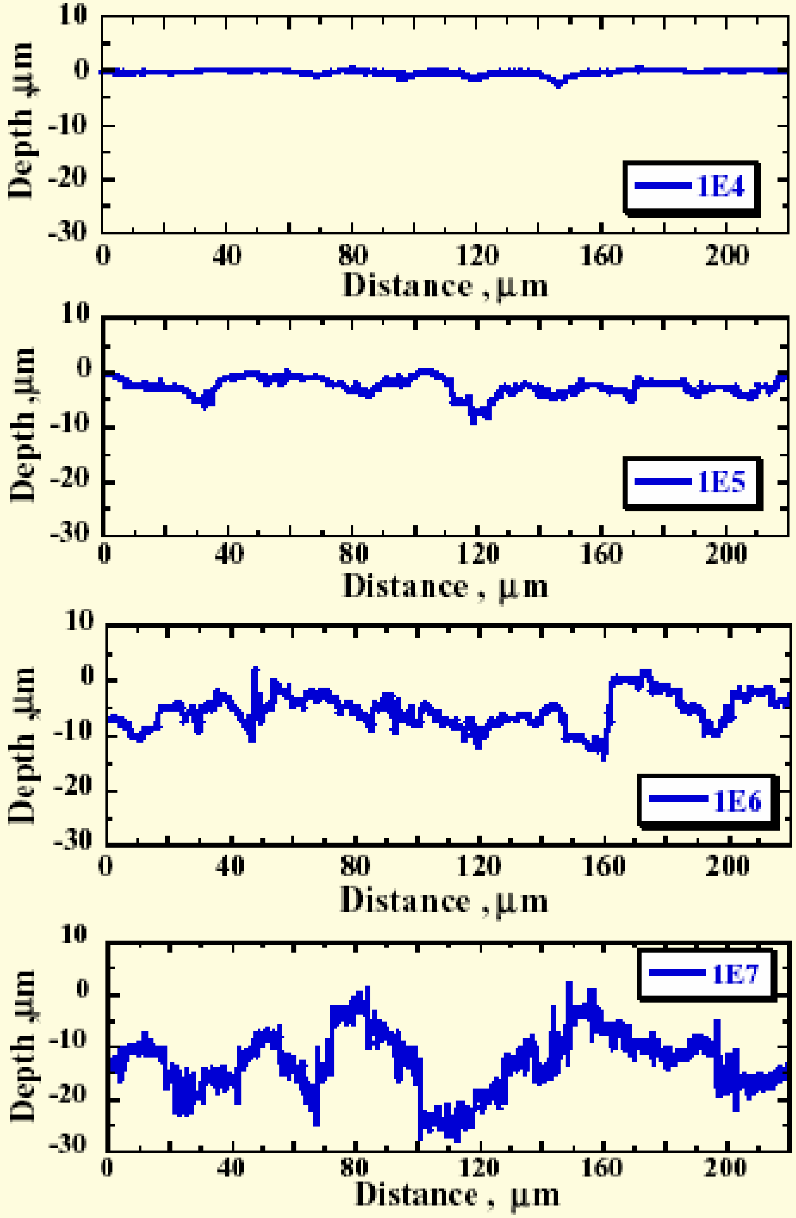
Rising rate : ca 1G/μs
Frequency of cycles : max. 20 Hz

Pitting damage in 316ssCW & Kolst.

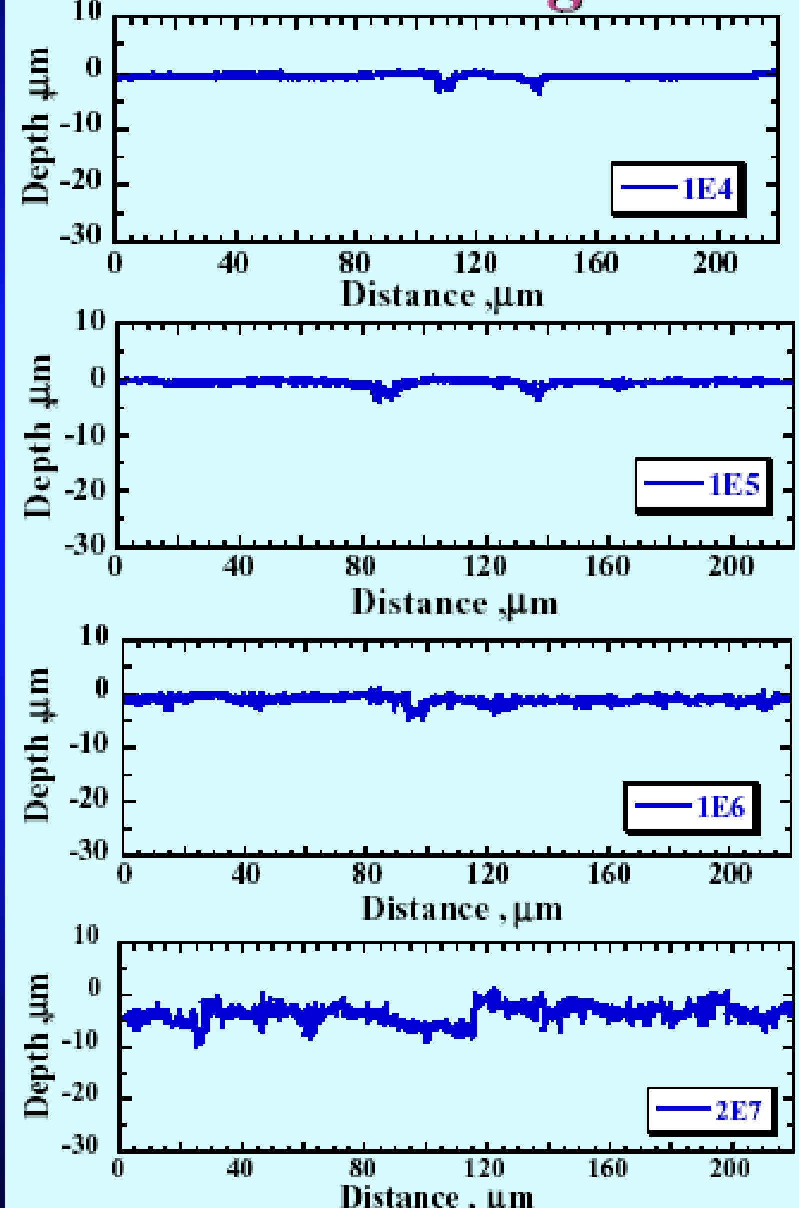


Roughness measurement

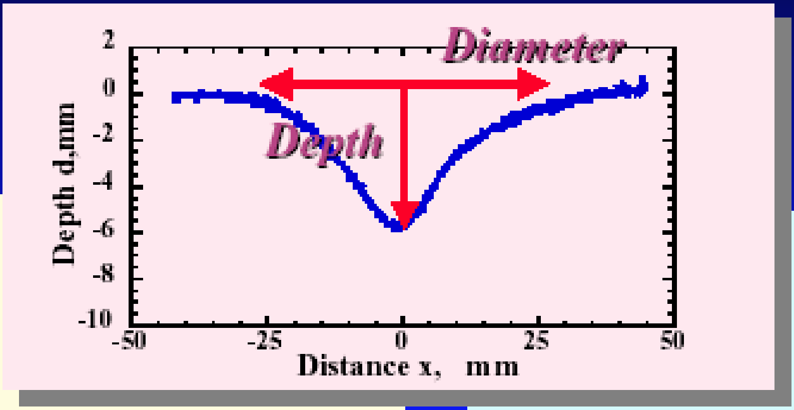
316ssCW

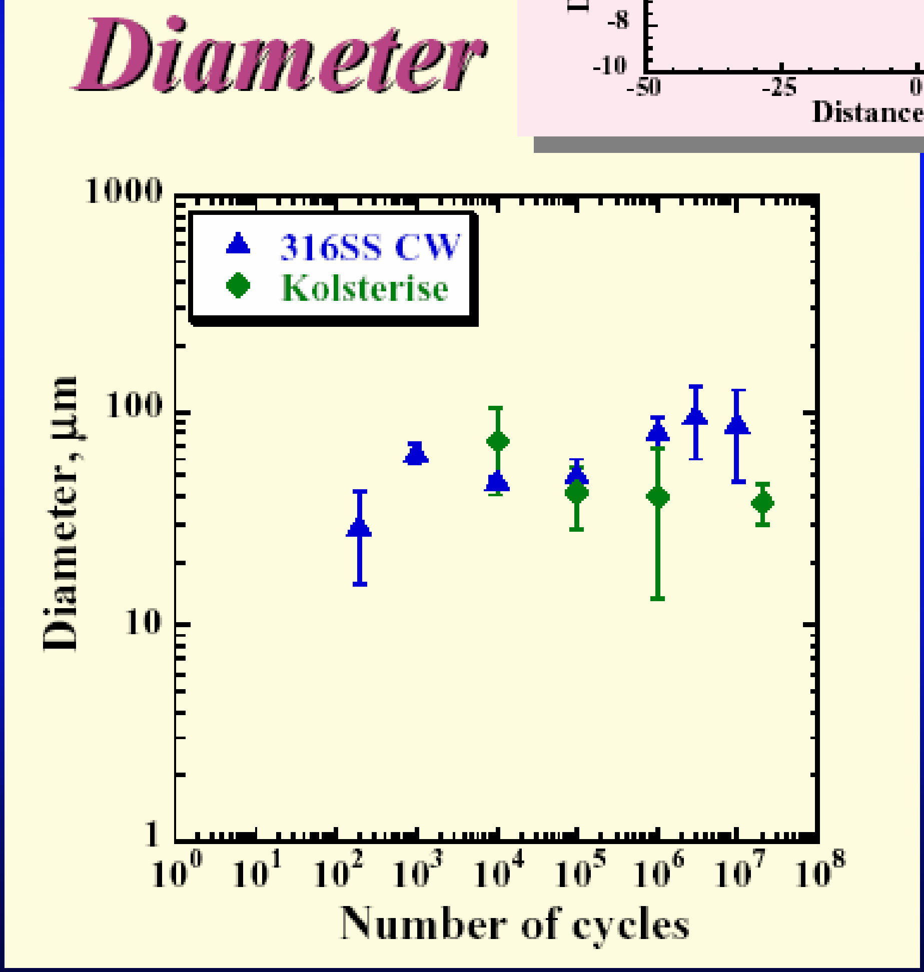


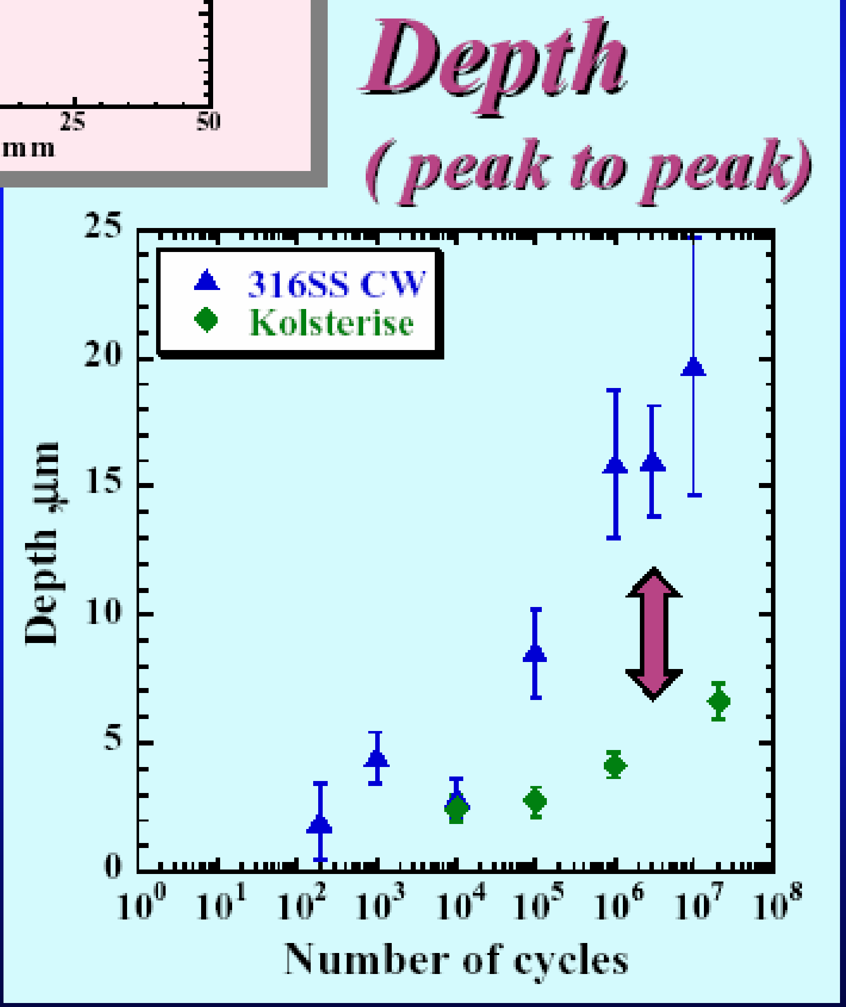
Kolsterising



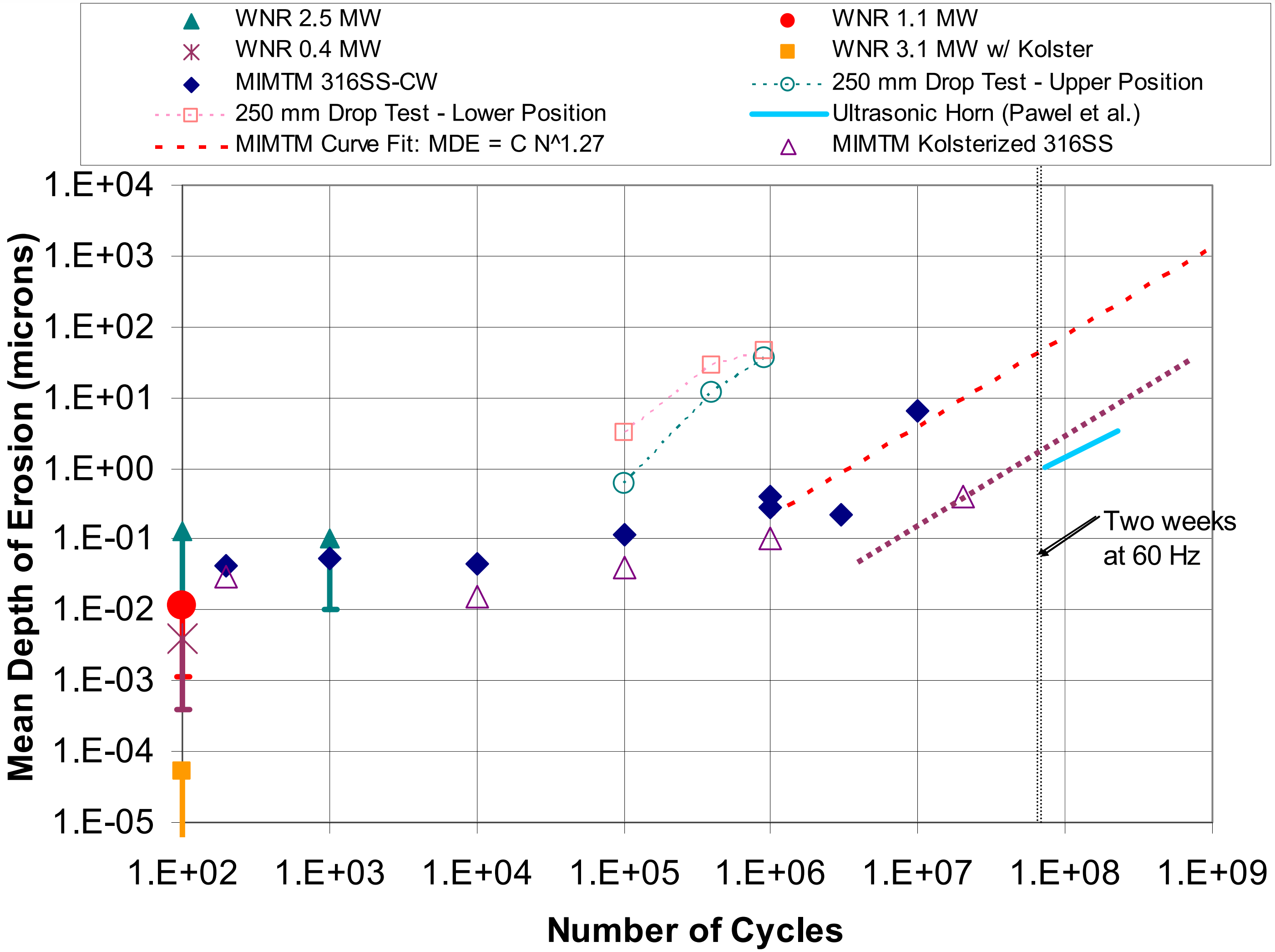
Characterization of pit morphology







Summary of Pitting Erosion Tests



Using this data, the estimated Mean Depth of Erosion at 1 MW for 2 weeks < 50 μm

Large Uncertainties Remain in Extrapolating Results to 100 Million SNS Pulses

- Energy deposition profile is much different in the WNR tests than in SNS.
  - Peak value and shape matched, but size is smaller (~ 1/3 scale).
- Frequency in off-line tests is not matched to 60 Hz on SNS.
  - WNR tests run at 0.03 Hz.
  - Drop tests run at 1 Hz.
  - MIMTM tests run at 1-15 Hz.
  - Ultrasonic horn tests run at 20 kHz.
- Radiation effects (especially uncertain for Kolsterizing treatment).
- Pits in off-line tests do not exactly match beam tests.
- Beam tests performed on small-scale, “closed” targets with stagnant Hg.
- Lifetime limiting mechanism, and therefore erosion thickness limits, not understood.
  - Erosion may form cracks that grow with load cycles, i.e., fatigue, until a leak occurs.

Outcome from October 2002 Meeting with EFAC and Cavitation Experts

- Both committees endorsed decision to maintain mercury as the target material.

- Recommended further R&D efforts

  – Improve understanding of cavitation erosion and failure mechanisms.

  – Develop mitigation schemes.

Concluding Remarks

- Significant progress has been made on the pitting issue since the last DOE-SC Review.
  - Pitting damage from in-beam tests with a more realistic target geometry has been quantified.
  - Effects of varying peak energy density, materials/treatments, target geometry, and a few mitigation schemes were also examined.
    - Energy density, surface treatment (Kolsterizing), and gas injection appear to be especially high-leverage items.
- Off-line tests have provided some understanding of how damage scales with cycles.
- The data indicates that we have met the criteria for maintaining Hg as the target material.
  - Significant uncertainties and associated risks remain.
  - Further R&D efforts are required.