High Power Target Design and Operational Considerations for Spallation Targets (SNS as an Example)

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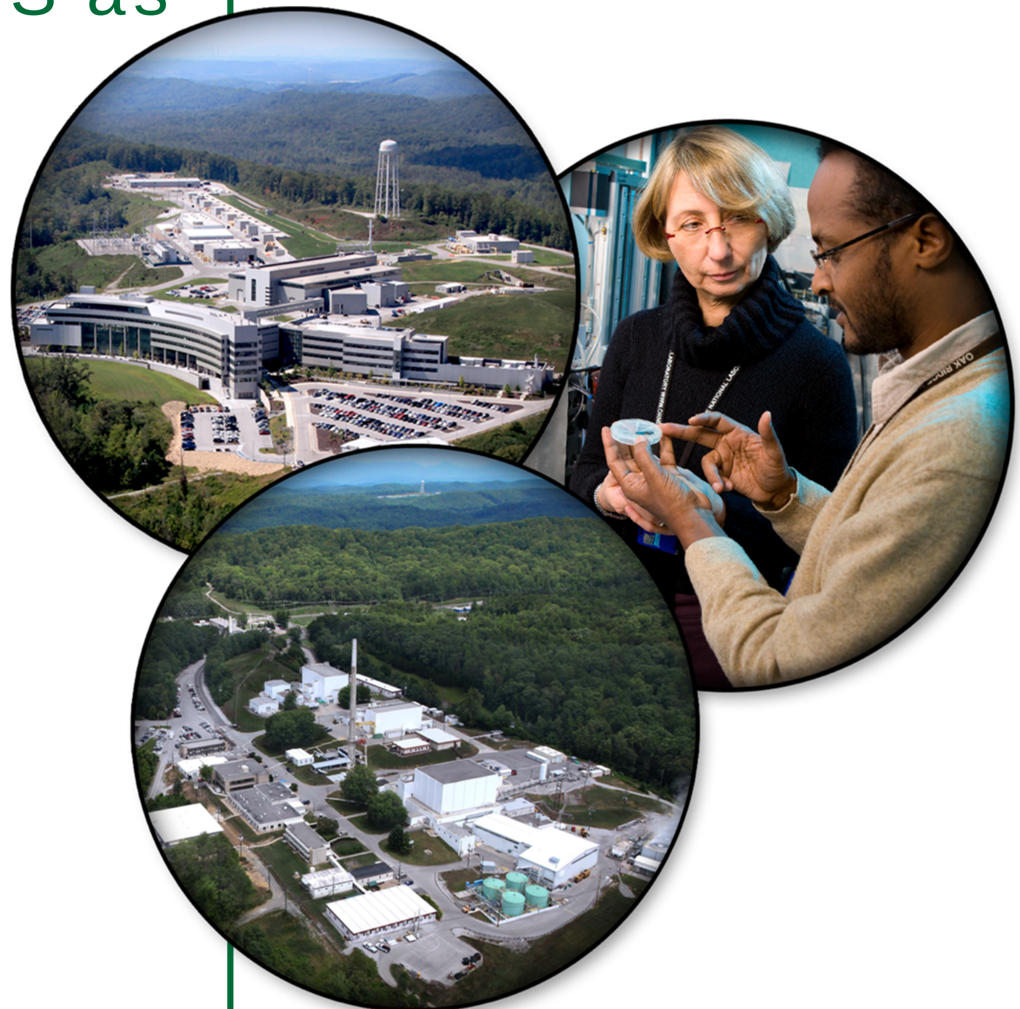

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U.S. DEPARTMENT OF ENERGY

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At the Start of the SNS Target Systems, The Team attacked 4 Major Design Goals

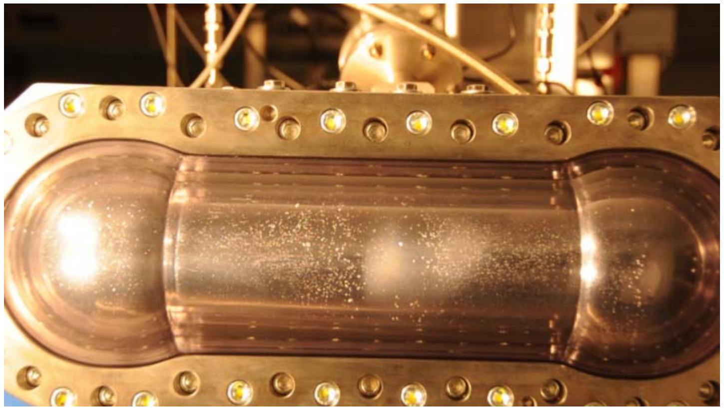
- Design a Hg target system to produce room temperature and cold neutrons at high intensity using a one MW proton beam that would satisfy the requirements of the scattering instruments. (60 pulses per sec of <1 micro-sec width, 18 Beam Lines (6 Split), and Linac/accumulator ring)
- Design a system that could be operated safely.
- Design a system that could be built within the cost and schedule limits. ($105M Construction, $35M R&D, 7yrs construction, 11 yrs total)
- Design a system that can be maintained (Efficient remote handling is a major driving requirement).

Target R&D Program Has Addressed Key Design and Operational Issues

- Steady state power handling.
  - Cooling of target/enclosure window – wettability.
  - Hot spots in Hg caused by recirculation around flow baffles.
- Thermal Shock.
  - Pressure pulse loads on structural material.
  - Cavitation induced erosion (so-called pitting issue, K).
- Materials issues.
  - Radiation damage to structural materials.
  - Compatibility between Hg and other target system materials.
- Demonstration of key systems:
  - Mercury loop operation.
  - Remote handling.
- Nuclear data.

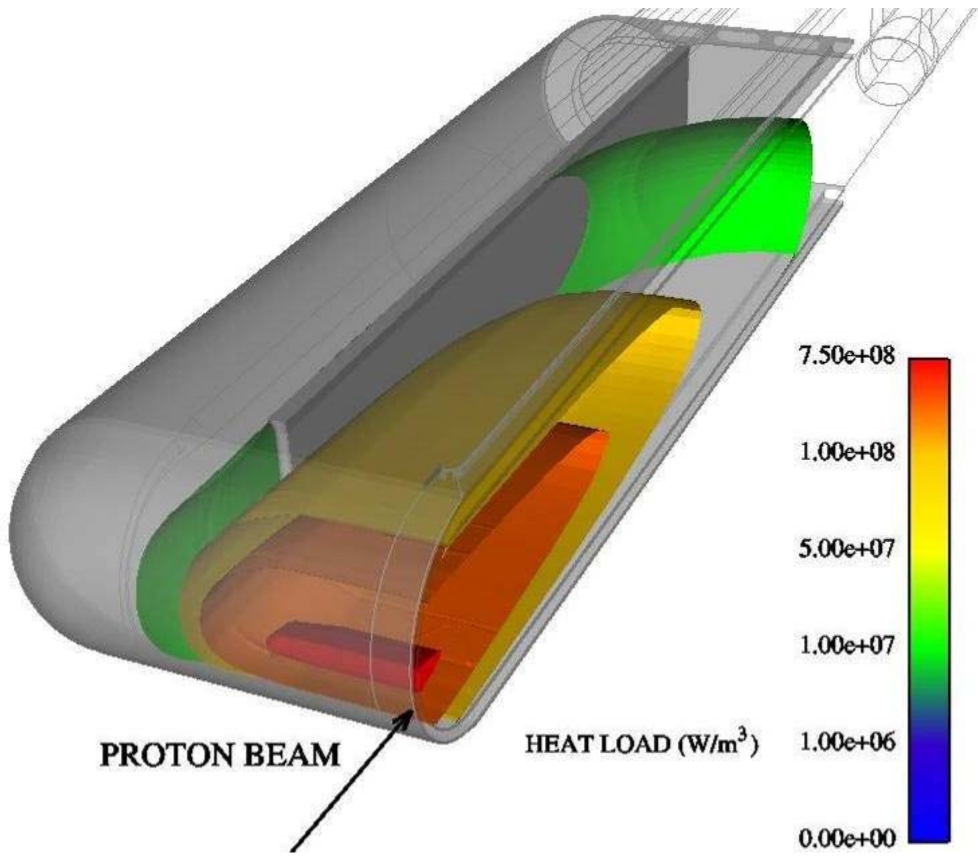
Mercury target development activities at the TTF are still going on.

- Target Test Facility is now operable with an experimental target that can support small gas bubble and gas wall testing
  - Bulk mercury flow is exactly prototypic to SNS
  - Two orifice bubblers are currently installed
- Some measurements have been made with optical system and the Acoustic Bubble Spectrometer
- Some success has been obtained



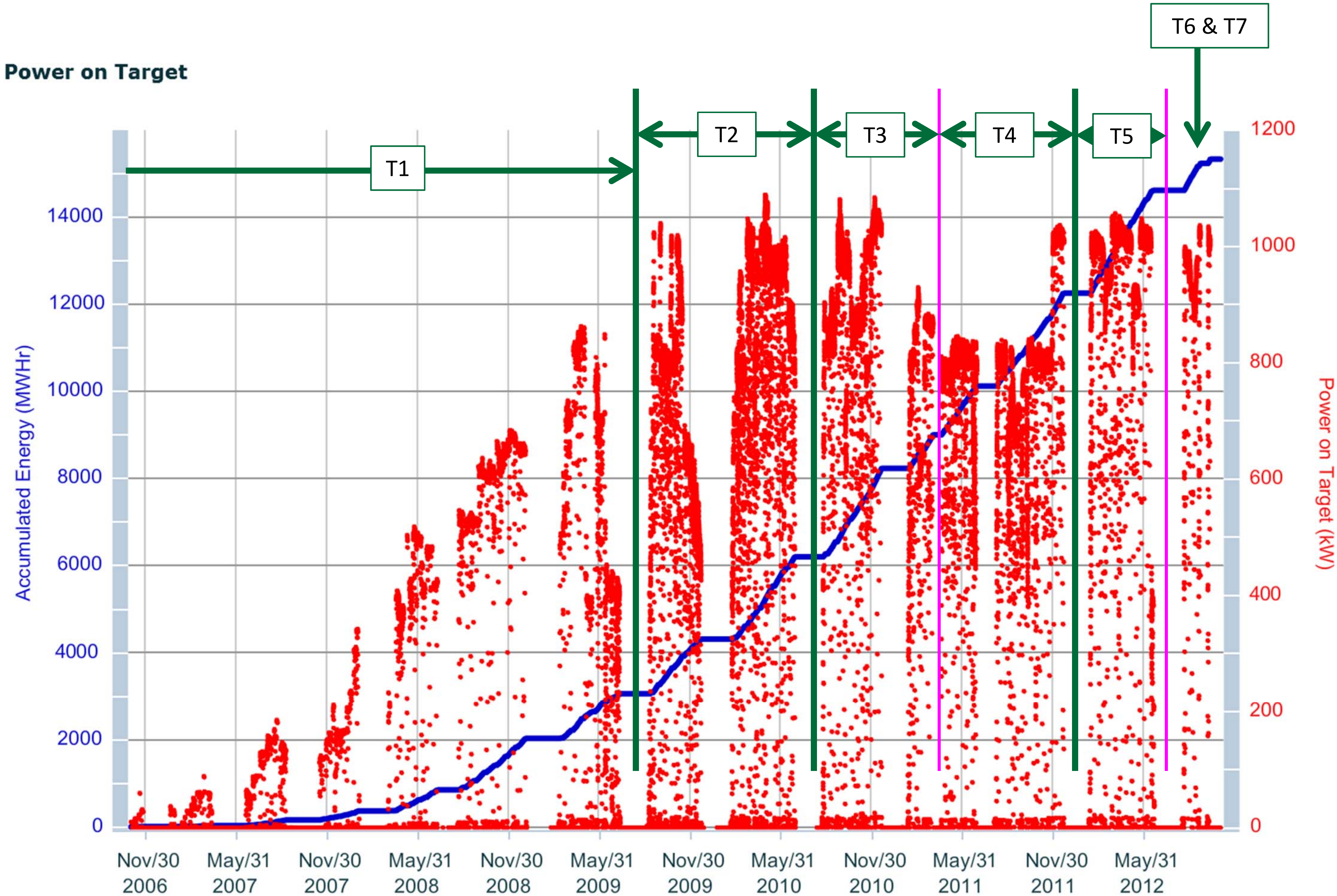
The constant-volume heating process for each beam pulse leads to a large pressure pulse in the mercury

- Peak energy deposition in Hg for a single pulse = 13 MJ/m^3 *
  - Peak temperature rise is only ~ 7 K for a single pulse, but rate of rise is 10^7 K/s!
- This is an isochoric (constant volume) process because beam deposition time (0.7 μs) << time required for mercury to expand
  - Beam size / sound speed ~ 30 μs
- Local pressure rise is 38 MPa (380 atm compared to static pressure of 3 atm!)*
- Mercury expansion and wave reflection at the vessel interface lead to tension and cavitation of the mercury

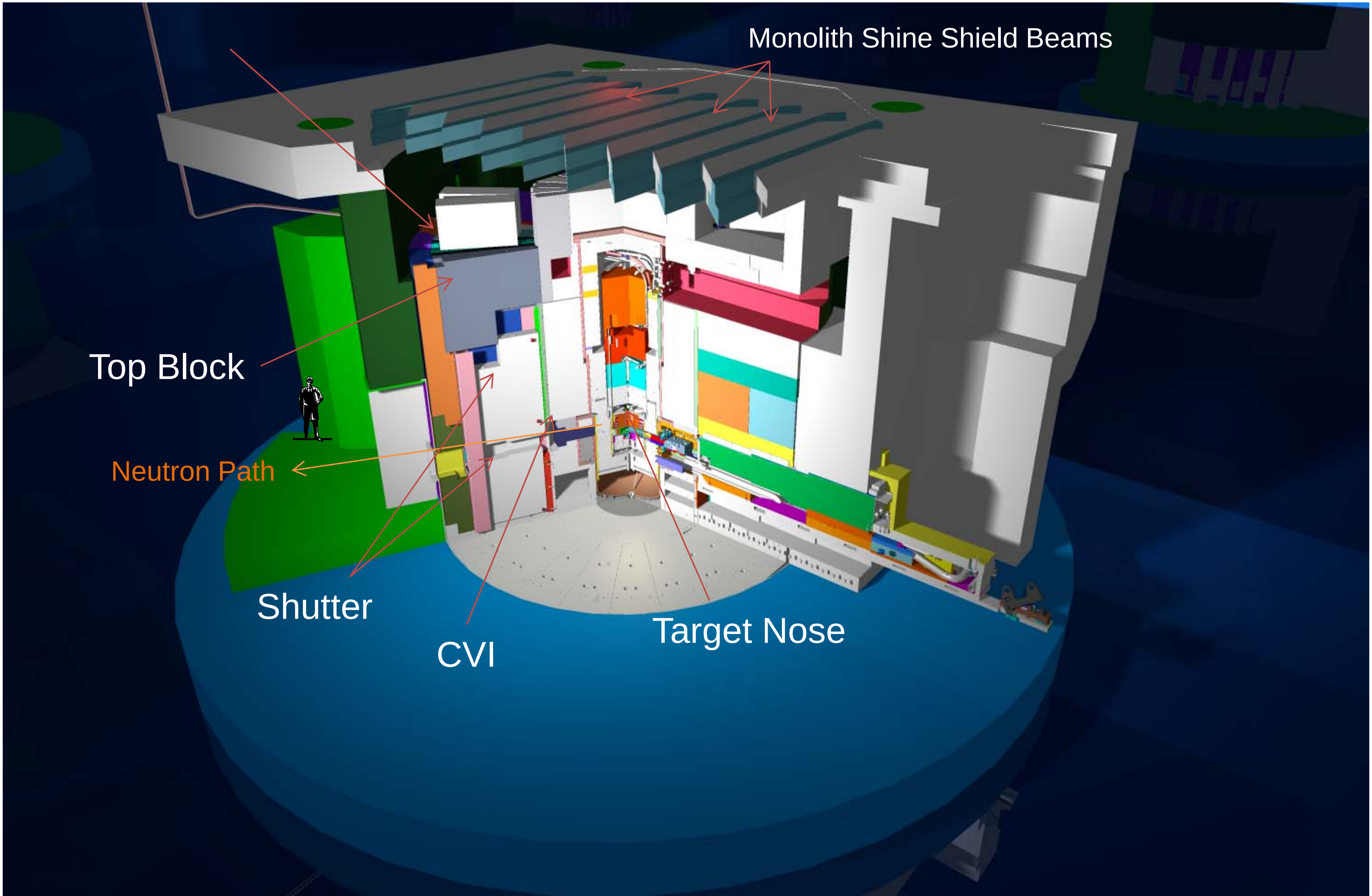


* SNS @ 2 MW

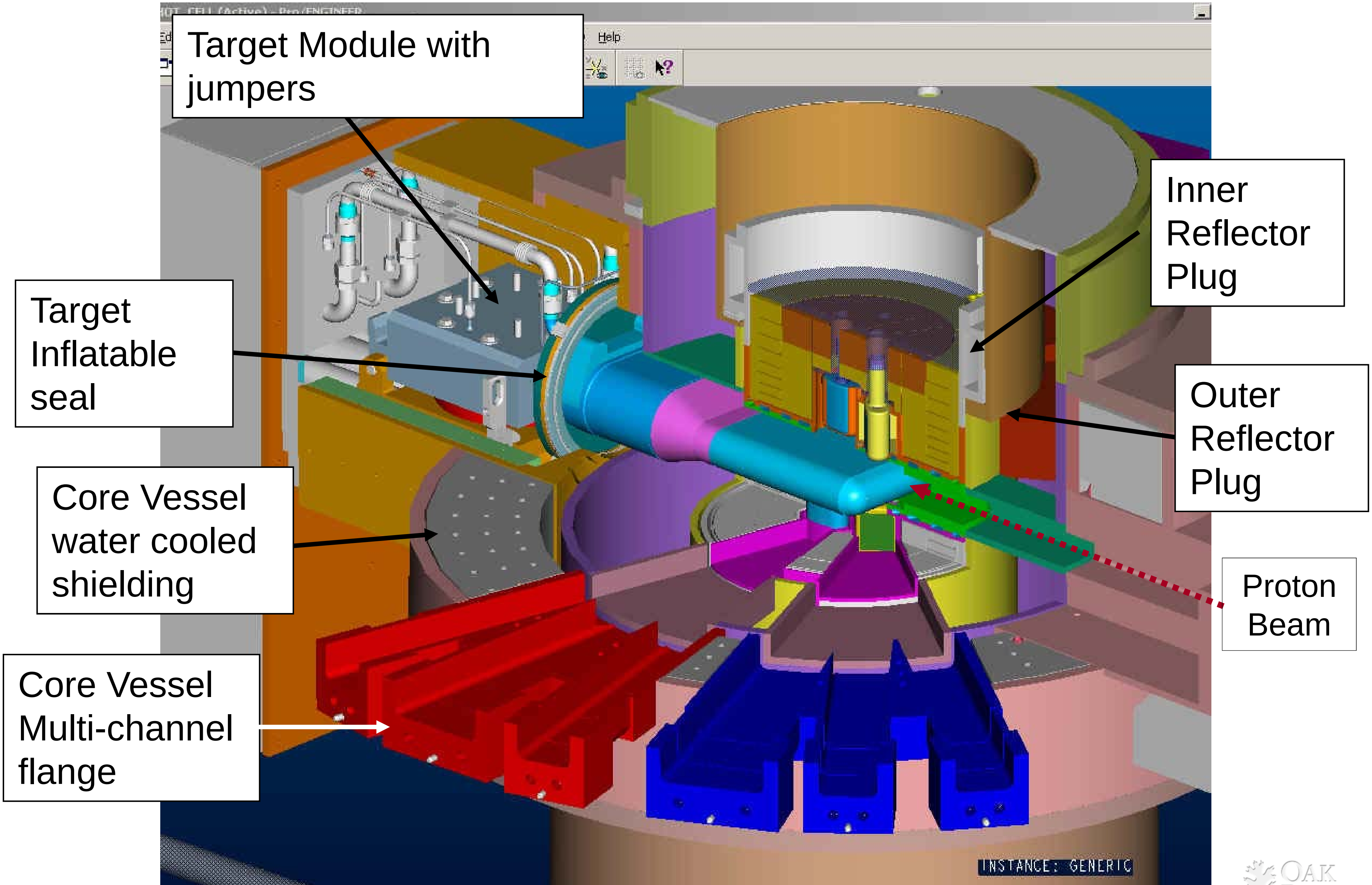
Energy and power on target from October 2006



Spallation Neutron Source Target Station at ORNL



The mercury volume of the SNS target module fits within the upper and lower portions of the Inner Reflector Plug



Why was mercury chosen for the SNS target?

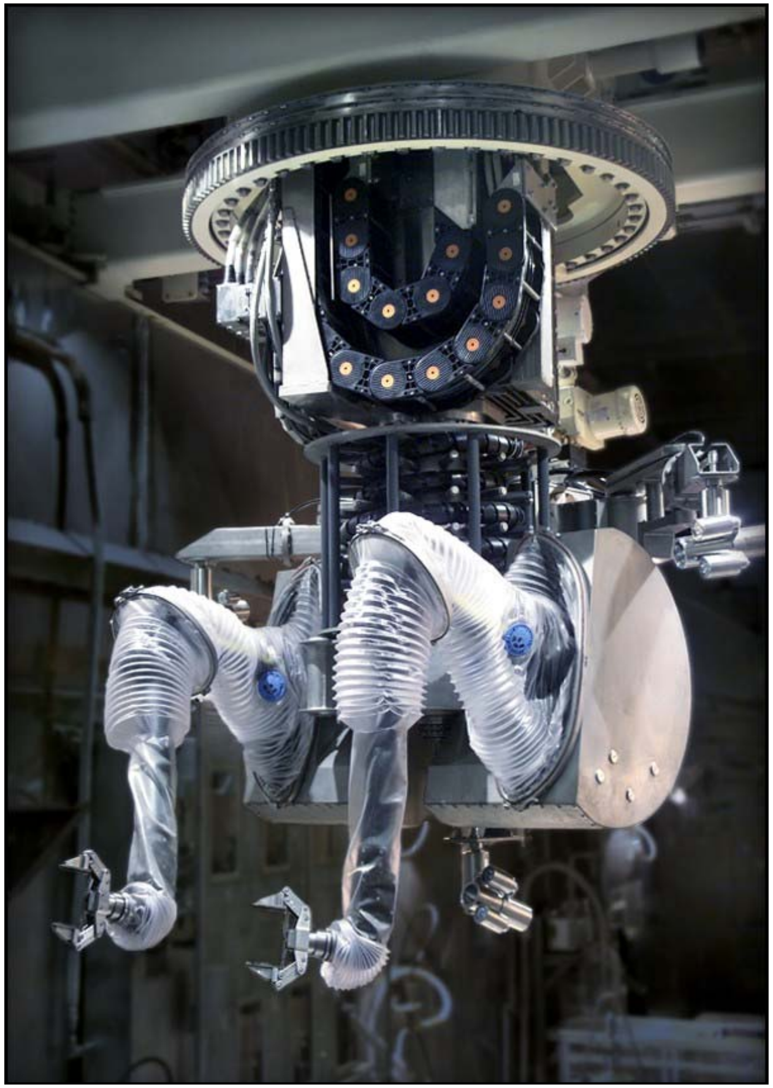
- The SNS provides world-leading *intense* neutron beams (current) by exploiting higher accelerator power
- High-power operation increases the heat removal demand in stationary, *solid targets* (e.g., tungsten or tantalum) necessitating greater volume fractions of coolant
  - Neutron intensity suffers as spallation zone becomes more spread out
  - At ~1.5 MW, further gains in intensity with higher power has diminishing return
- Liquid metals (LM) can serve as both spallation target and coolant
- LM can serve the purpose for the life of the facility, reducing waste impact
- Mercury is liquid at room temperature and has good nuclear properties for a pulsed source
  - No heating systems needed to maintain liquid state
  - Minimal decay heat

Remote Handling System from SNS

- **SNS system**
  - **Robotic bridge crane – 20 ton capacity for FRIB**
  - **Robotic bridge servomanipulator transporter**
    - **Equipped with 500 lb aux hoist**
  - **Window workstations for specific maintenance & waste handling operations**
  - **All RH systems hands-on maintained**

RH Upgrade Option
Servomanipulator Bridge & Manipulator

- **SNS Servomanipulator Bridge & Manipulator**
  - **Telerob EMSM 2B**
  - **Dual-arm, high performance servo-manipulator (SM) provides full cell coverage**
  - **Master arm position control with force feedback**
  - **Digital control**
  - **Three on-board CCTV cameras**
  - **500 lbf capacity auxiliary hoist**
  - **Force Ratio Control 2:1 up to 20:1**
  - **55 lbf (25 kg) continuous /100 lbf (45 kg) peak capacity**



Master Slave Manipulators (MSM)

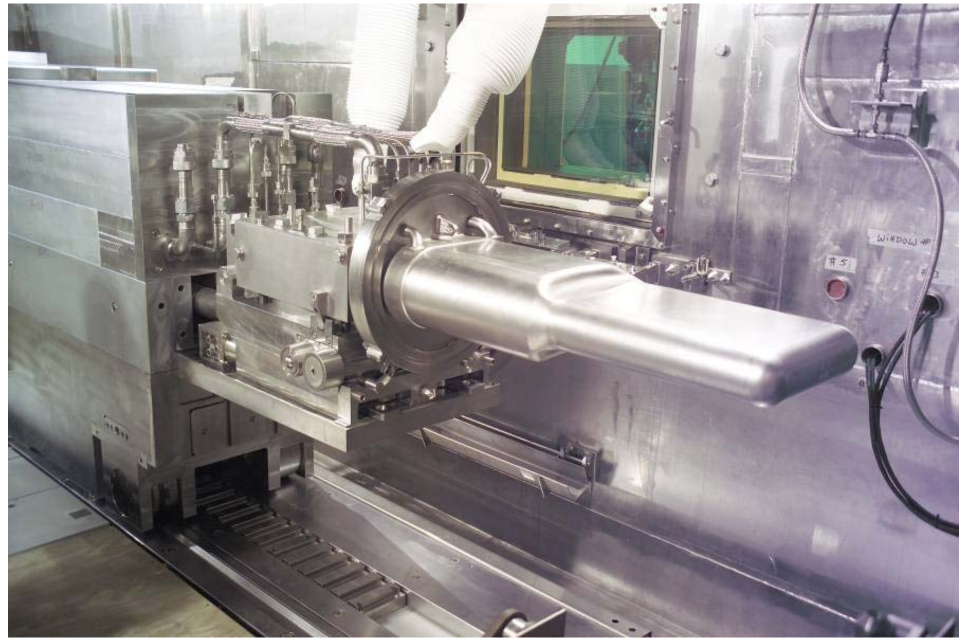
- **SNS CRL Model F example**
  - **100 lbf (45 kg) peak capacity**
- **Excellent for repetitive tasks in limited volume location (limited reach)**
- **Relatively low cost**
- **Can be coordinated with RH control room, video system and mobile systems control**
- **Provides many remote tool service interfaces**

SNS Remote Handling Control Room

- **The servo master station and attendant video systems are co-located with the bridge and cell utility control systems to unify operations.**
- **Interconnected bridge, video and audio controls at each window workstation are also required to facilitate efficient operator interface**

Target Module Replacement

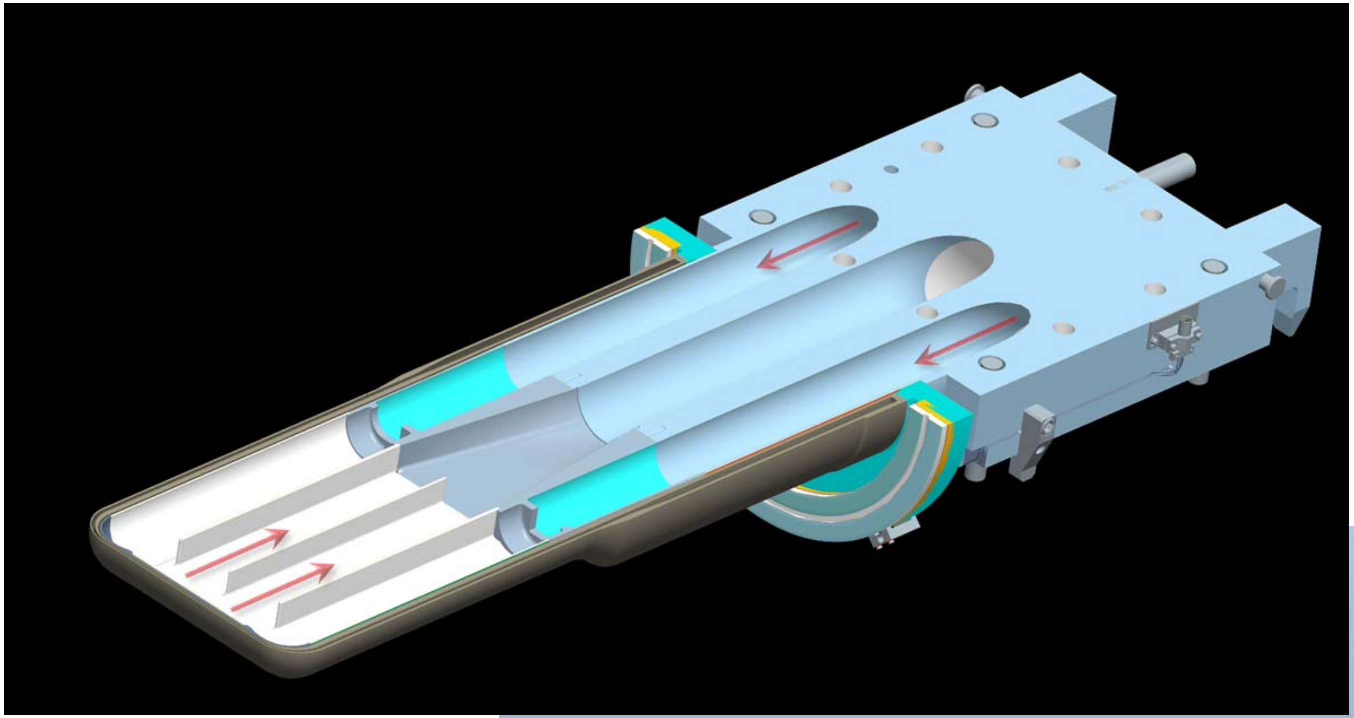
- Target Replacement
  - Target Maintenance Environment
    - Target Service Bay
    - Maintenance Equipment
    - Radiation and Contamination
  - Target Replacement Operations
  - Target Replacement Lessons Learned

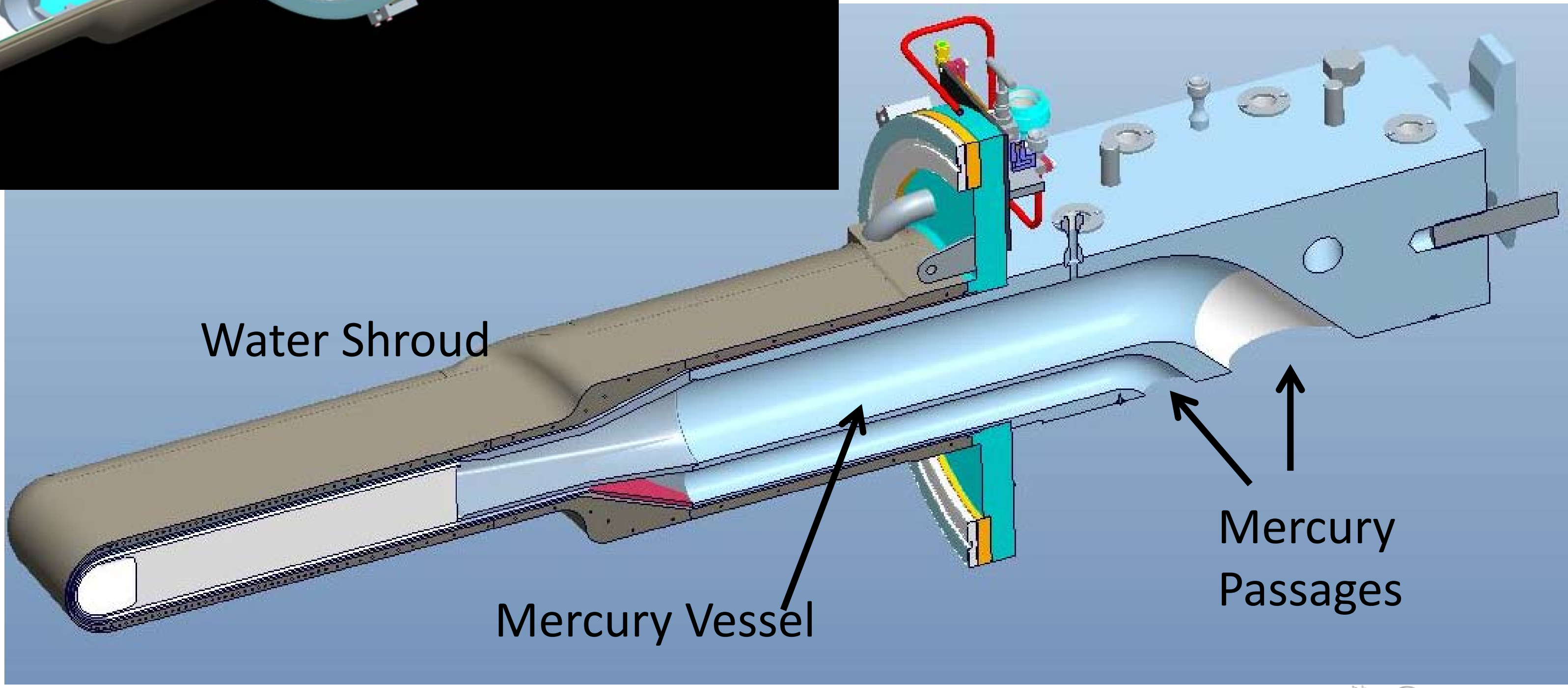


SNS Target Module

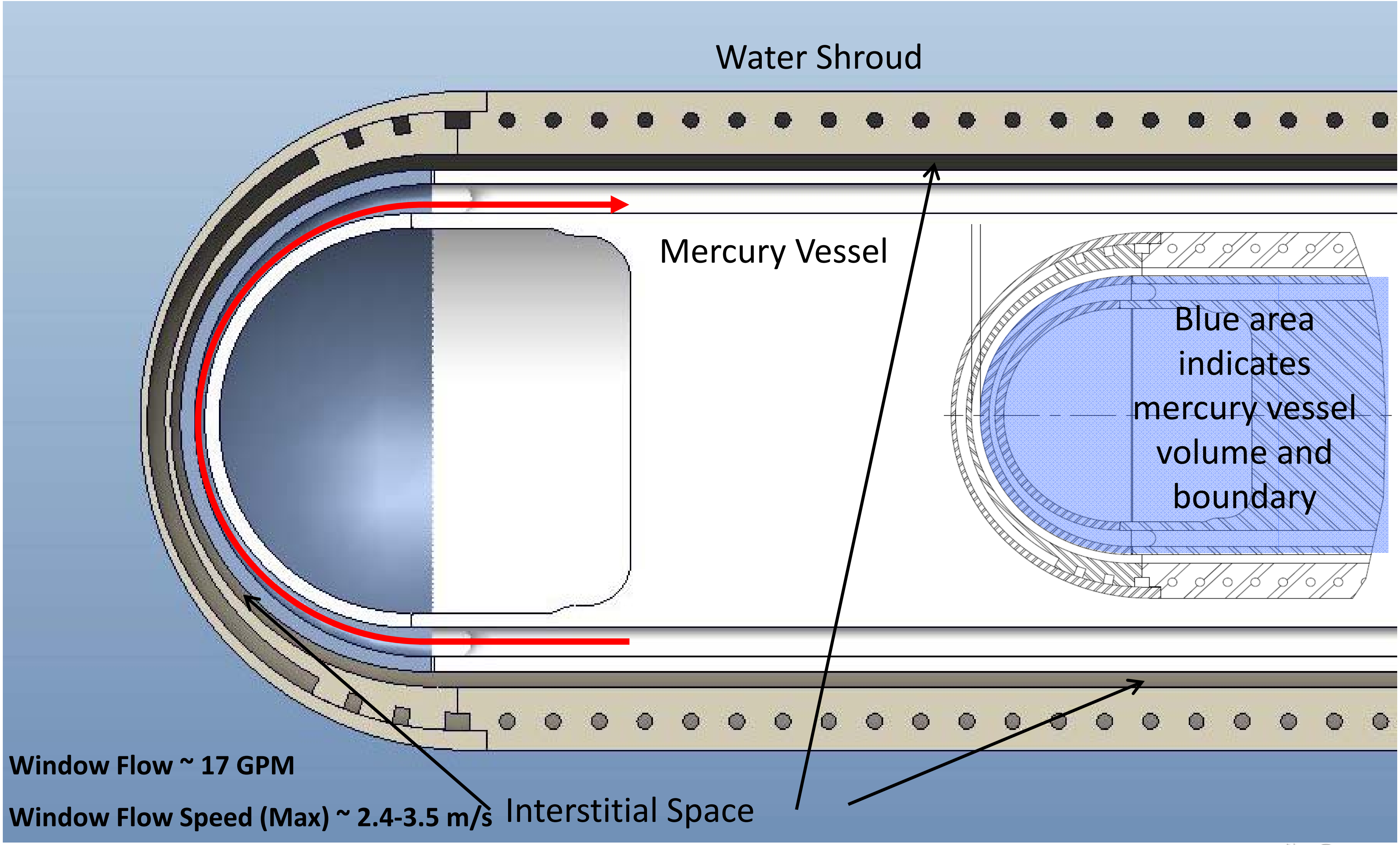
- Replacement of the target modules is accomplished using only remote handling tooling and procedures (hands-on operations are not possible)
- While the tooling and procedures utilized enable successful replacement of the targets, continuous process improvement is employed to ensure successful replacements

The target has three mercury supply channels and one common return channel





The beam passes into the bulk mercury through four stainless steel shells



Waste Shipment Operations

- SNS is design to utilize an over-the-road waste shipment cask known as the TN-RAM for disposal operations
  - To date, three waste shipments have been completed:
    - Target #1 shipped in May 2010
    - PBW #1 shipped in December 2010
    - Target #2 shipped in May 2011
  - Cask loading occurs via the Service Bay and involves significant remote handling
    - Handling of activated components
    - Loading of the cask liner
    - Cask liner bolt torquing

Waste Shipment Operations

PBW Waste Preparation

PBW Cask Liner is Loaded into the Service Bay

PBW Cask is positioned over Top Loading Port

PBW is lowered into Service Bay for loading Into Liner

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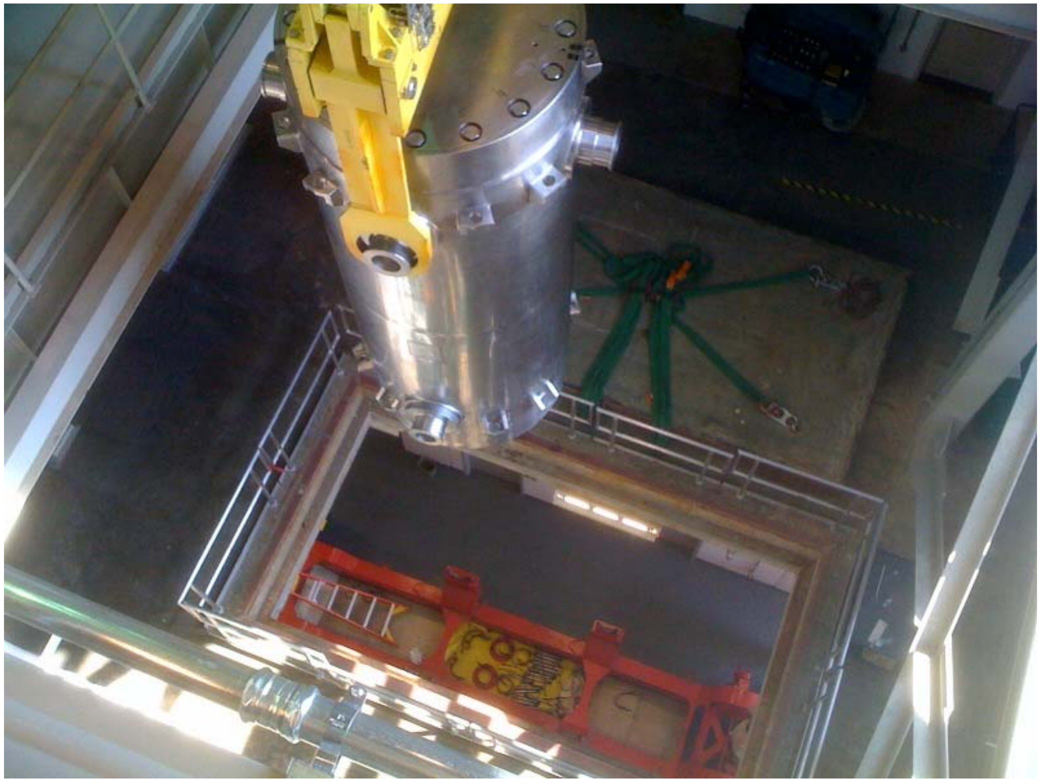
Waste Shipment Operations

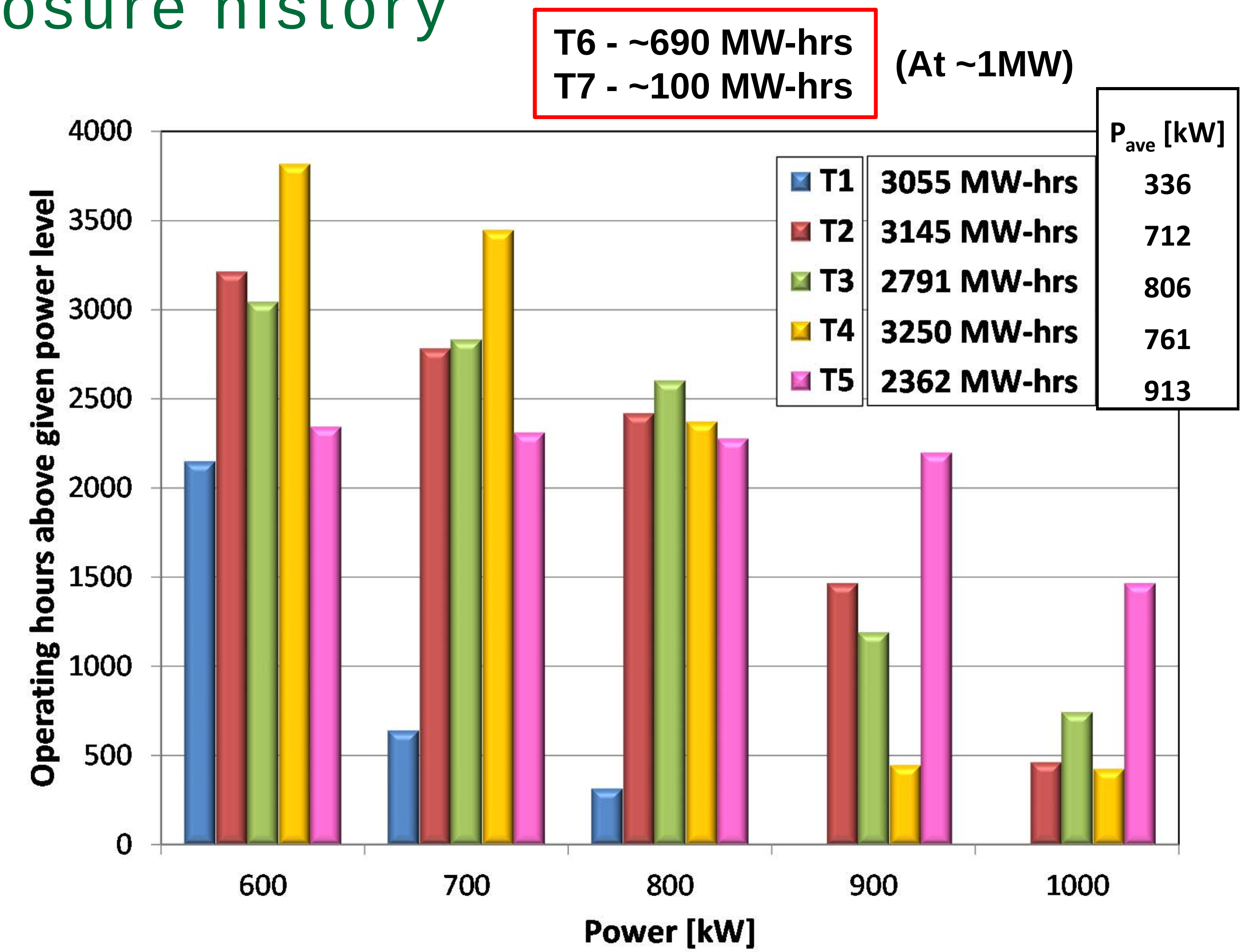


Cask Lifting from Truck

Translating Cask over for Lowering into Cask Cart

Each of the seven SNS targets used to date has a different exposure history

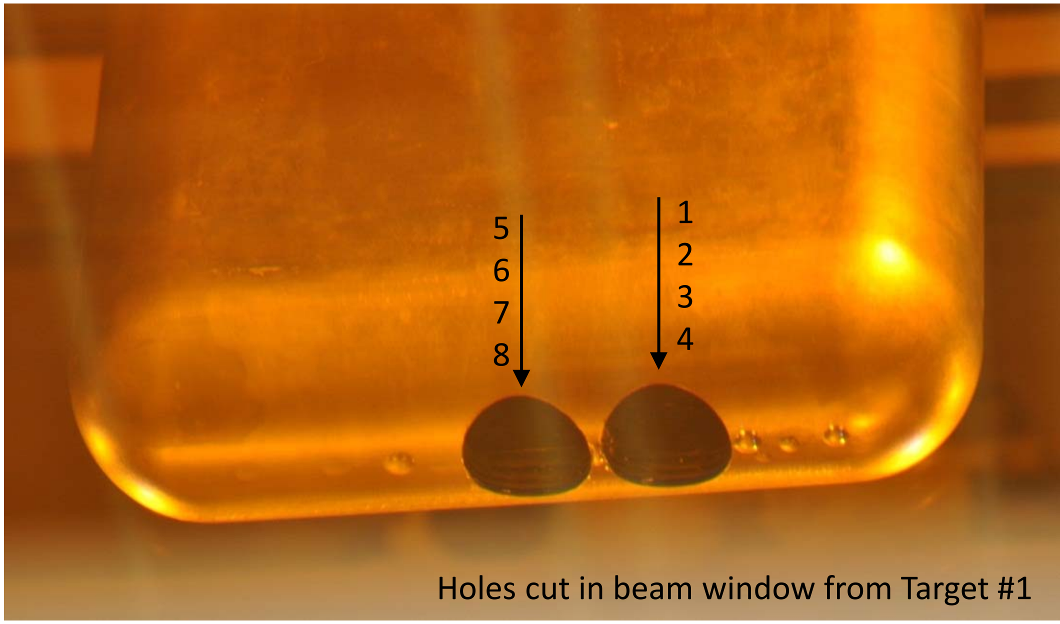
Manufacturer / Serial No.	SNS Installation Number
MTX-001	T1
MTX-002	T2
MTX-005	T3
MTX-006	T4
MTM-001	T5
MTX-004	T6
MTX-003	T7



- T3 (the one that leaked) had a similar "high-power" operating life compared to T2
- T4 received the largest total energy
- T5 had the highest average power, but lowest total energy & radiation damage
- 10 dpa limit is reached at ca. 5000 MW-hrs

Substantial effort has been expended to understand cavitation damage through Post-Irradiation Examination (PIE)

- Two to five hole cuts have been made in T1-T4
  - Three were done on T5
- We have performed
  - Through shield-wall photography
  - Direct photography of disk specimens
  - Internal examinations by video scope and compact cameras

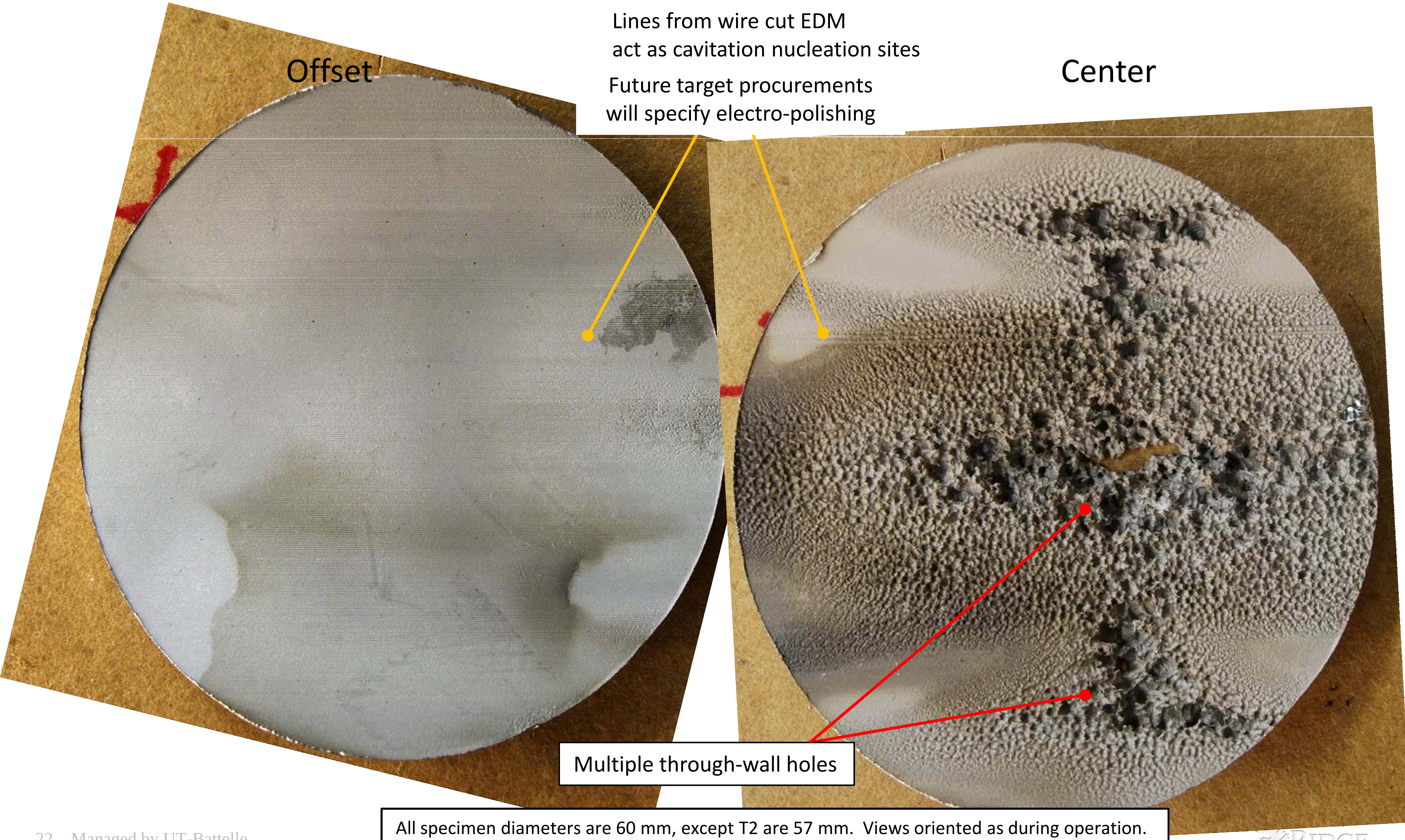


Holes cut in beam window from Target #1

- Specimens from T1 & T2 were selected for detailed examination and analysis by B&W Technical Services Group

T1 inner wall center and offset specimens surface facing bulk mercury volume

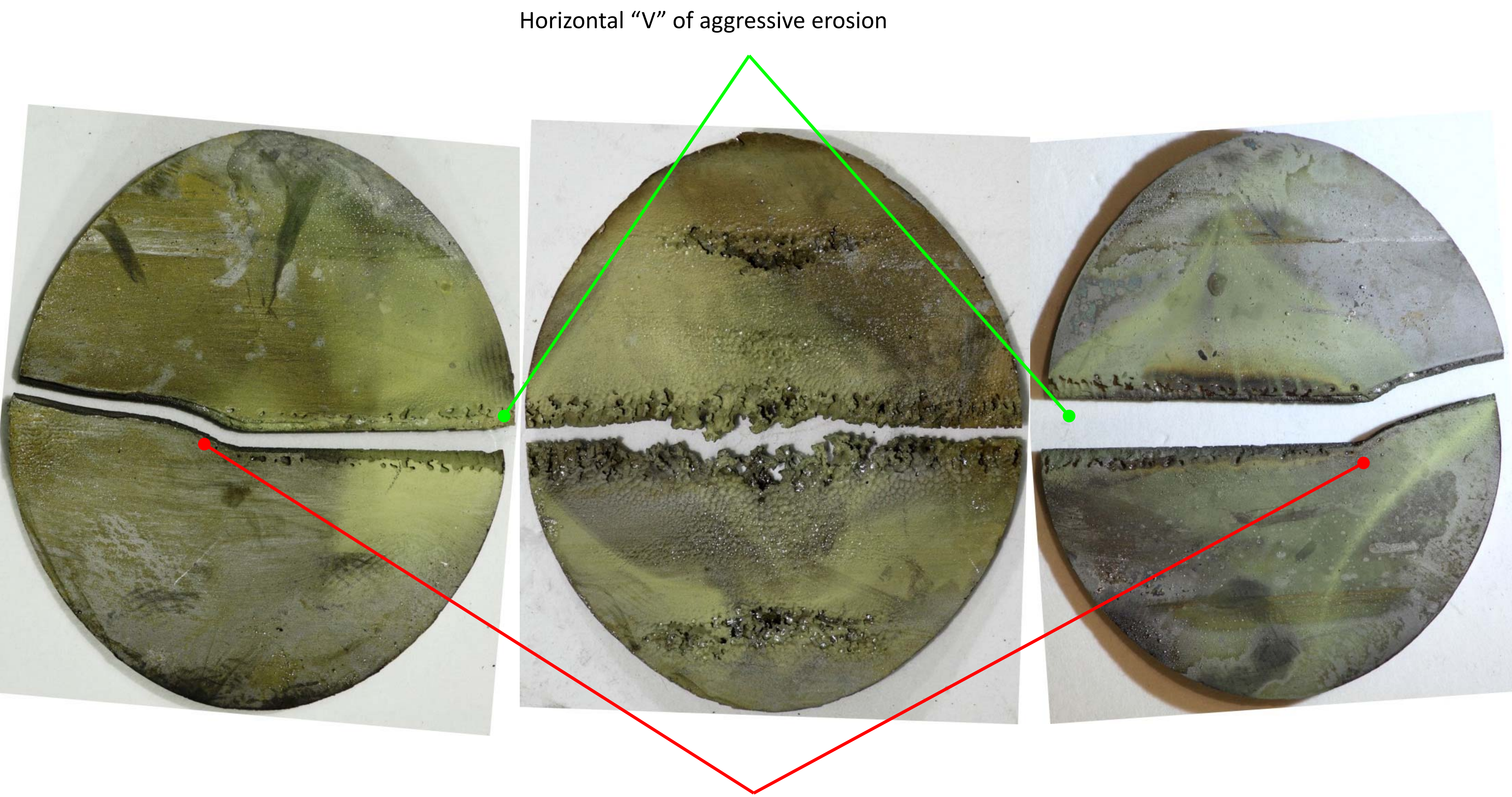
T1: 3055 MW-hrs; P_{ave} = 336 kW



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

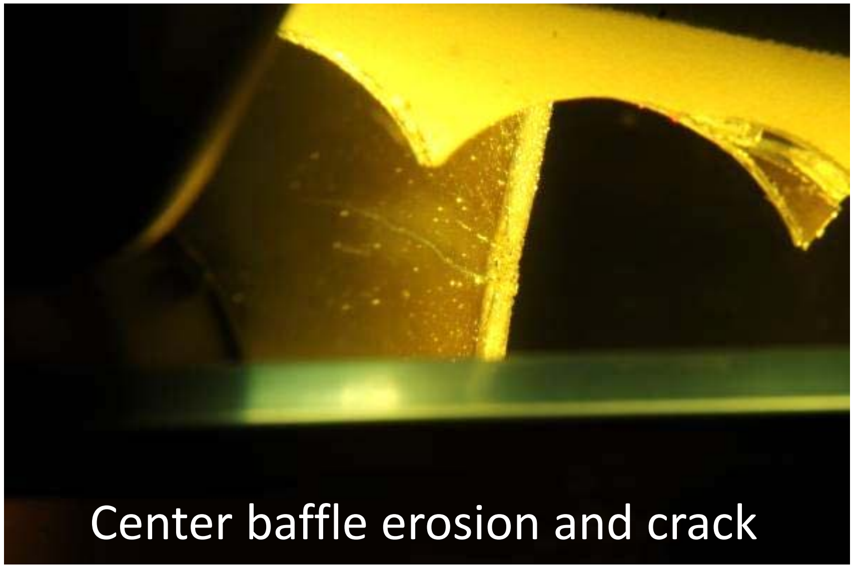
T4 inner wall surface facing bulk Hg damage is generally similar to T2 and T3

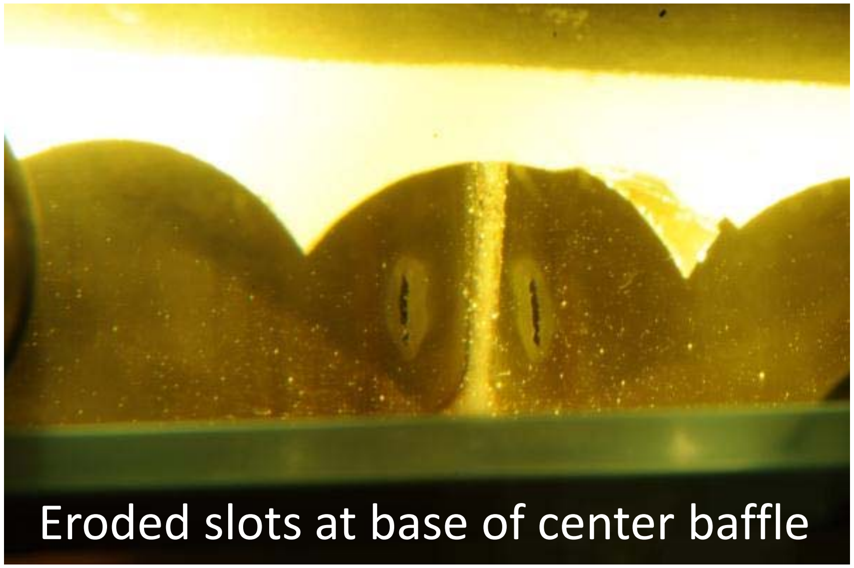
T4: 3250 MW-hrs; P_{ave} = 761 kW
Highest total energy on target



Target Post Irradiation Examinations

- Detailed PIE analysis of Target #2 specimens was completed by B&W Technical Services subcontractor
  - Report is under review
- Three circular cuts were made in Targets #4 and #5 beam windows
  - T4 photography – body and disks – completed
  - Photography of T5 body completed before it was placed in shipping cask liner
    - T5 is due for waste shipment soon


Center baffle erosion and crack

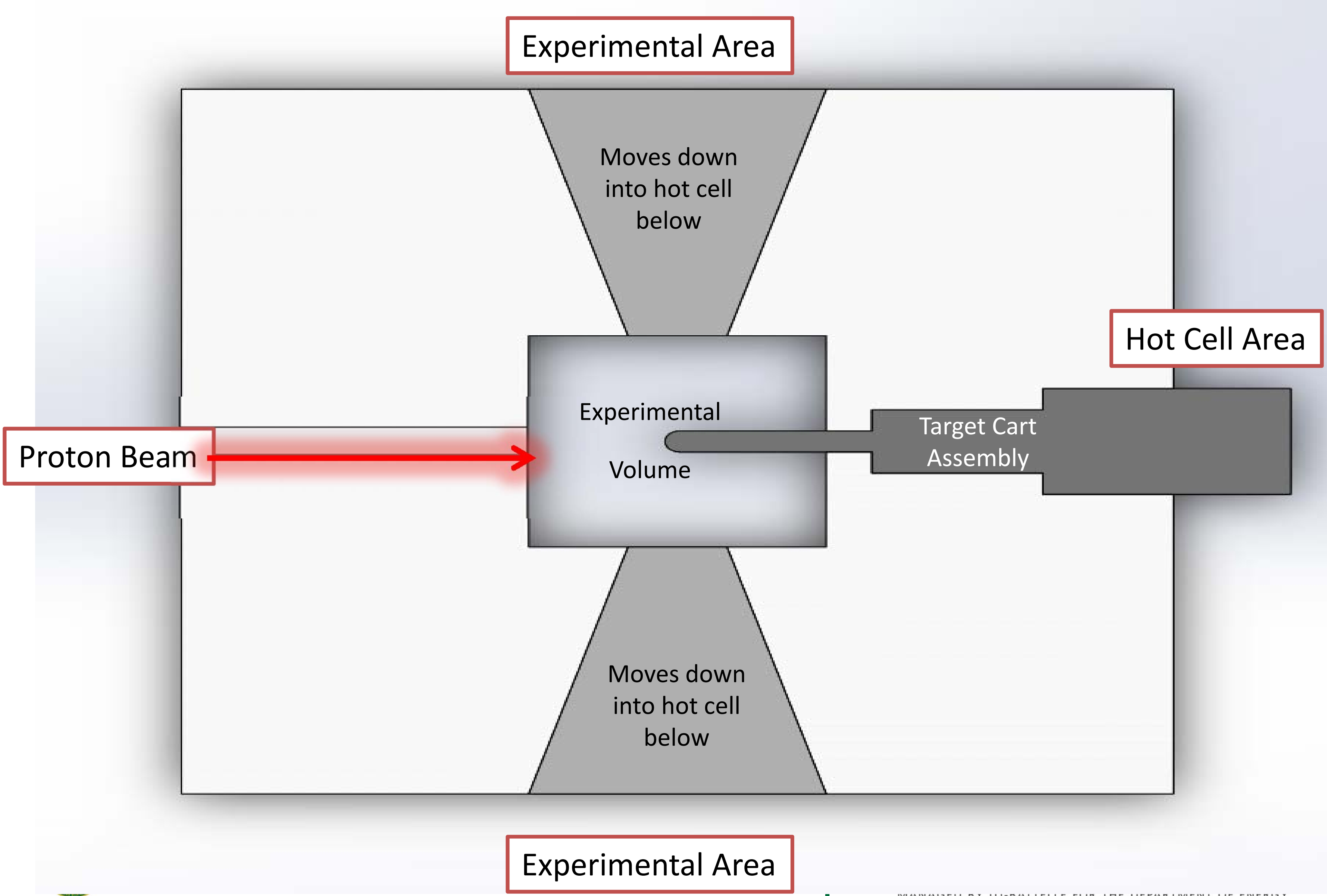

Eroded slots at base of center baffle

- Targets #6 and #7 provide an opportunity
  - Shorter operating time at 1 MW operation will show damage at earlier phases

Why have the last two mercury target modules indicated premature end-of-life?

- The first five devices lived for an average exposure of ~2900 MW-hrs with only one end-of-life condition (T3 at 2791 MW-hrs)
- T6 indicated failure at ~690 MW-hrs and T7 indicated failure at ~100 MW-hrs
- Possible causes:
  - Sensor malfunction (common mode)
  - Operational issue (beam density, beam position, energy, etc.)
  - Installation issue (bolt torques, seal integrity, etc.)
  - Manufacturing issue (weld integrity, tolerances, etc.)
  - Material issue (material specification, material processing, etc.)

Top View: Reconfigurable Target Station



Upgrades at SNS and Other Physics Research

\+ Beam Energy Increase to 1.3 GeV?

\+ Second Target Station?
(10 Hz, 400KW, Rotating Pb Target)?

\+ Additional Target Stations?

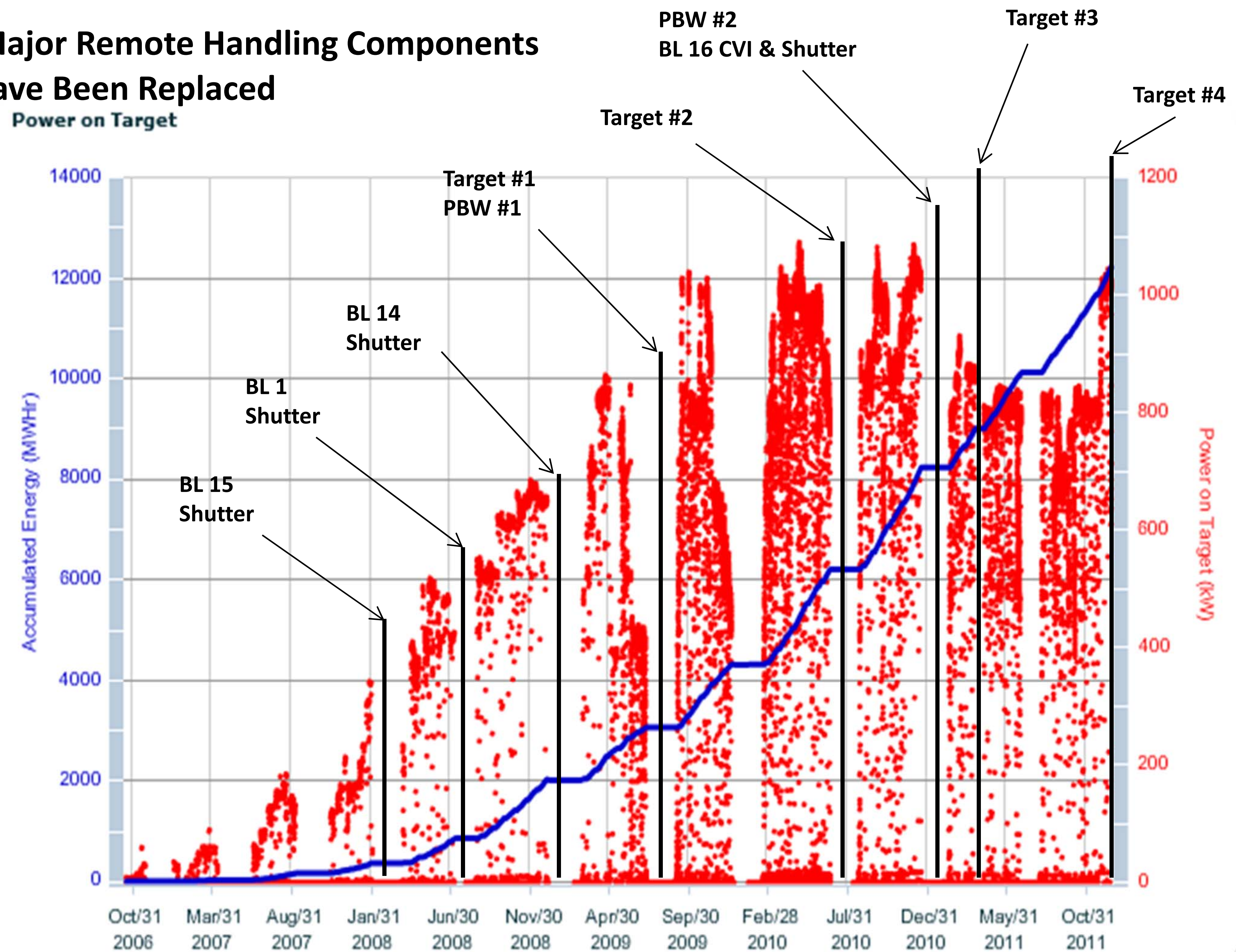
\+ Additional Physics and Materials Research?
(nEDM experiment -- Potential neutrino physics at SNS goes back to 1994 {later referred to as ORLAND} -- Coupons at the target location for radiation damage studies)

\+ Beam pulses – 1 msec or 690 ns

\+ Beam dumps

The SNS Target Team Delivered

- **Major Remote Handling Components Have Been Replaced**



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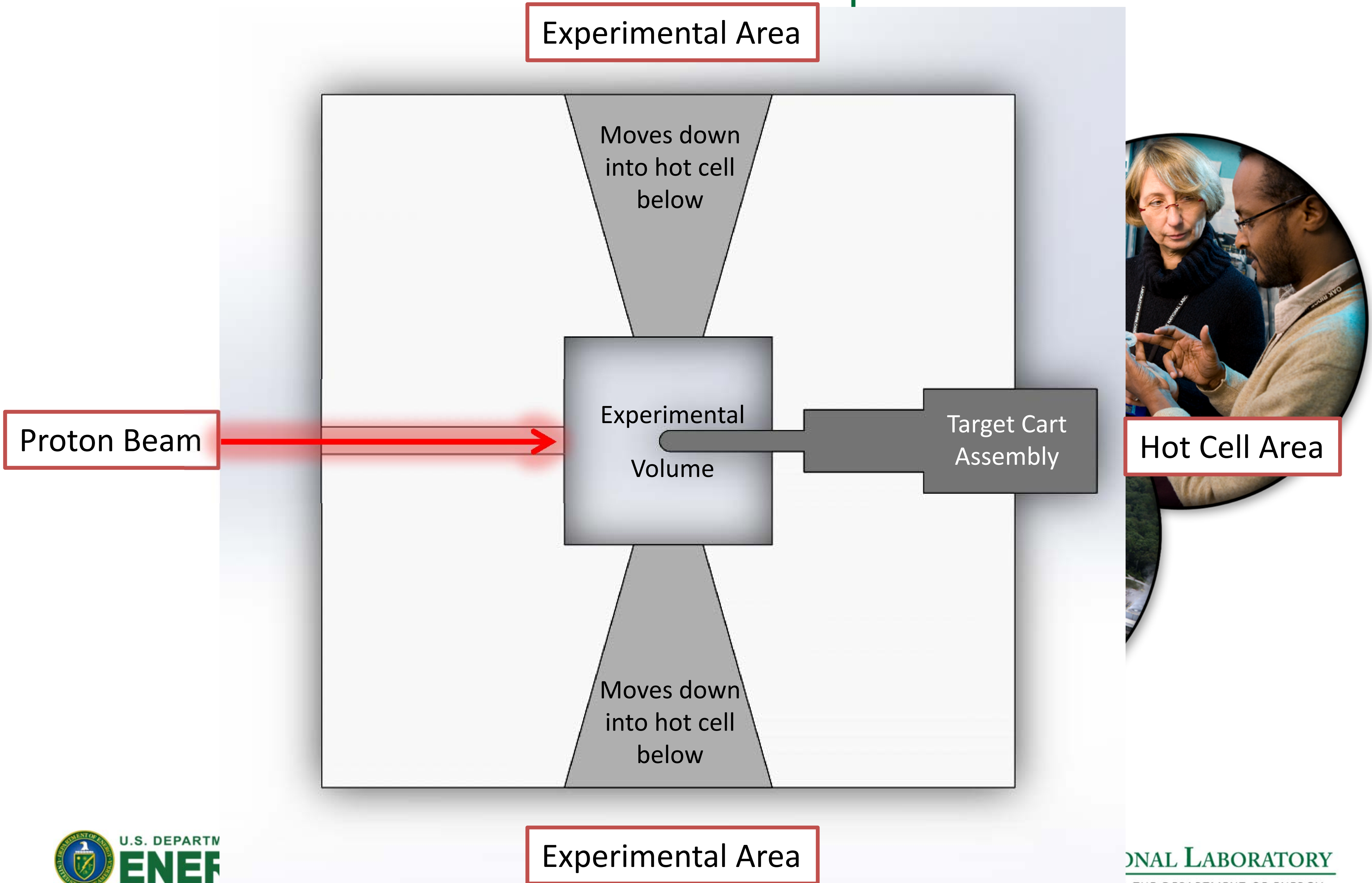

Top View: Reconfigurable Target Station