



#### **Outline**

What is the SNS?

Other spallation neutron sources

- Our neutron source and a few target design details
  - Plus a little bit of development history

- SNS operating experience
  - Target experience, remote handling
- Future prospects

### What is the Spallation Neutron Source?

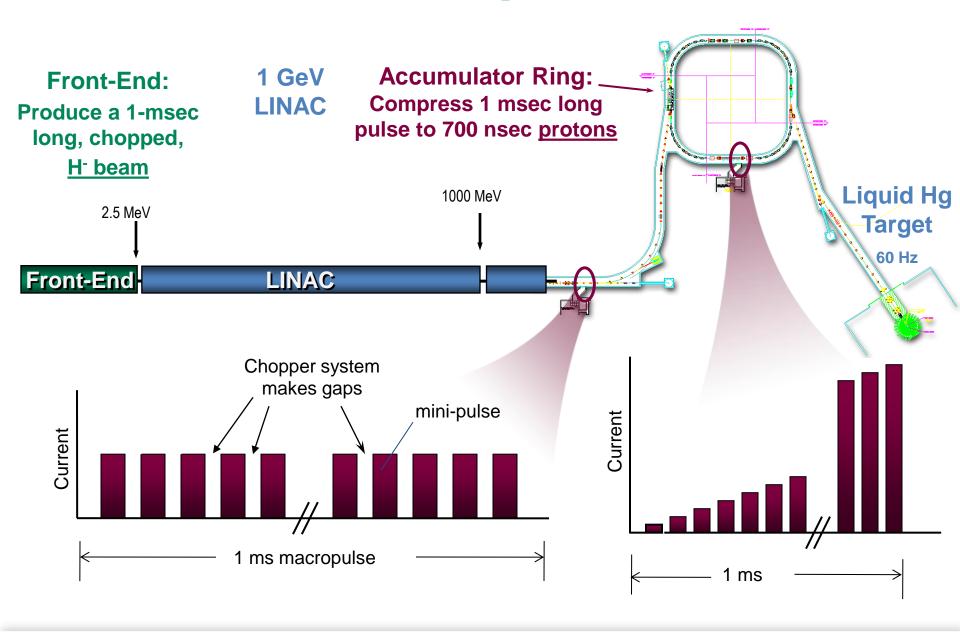
- SNS is <u>one of two U.S.</u> Dept. of Energy Office of Science user facilities for neutron science at Oak Ridge National Laboratory (ORNL) in Tennessee
- The SNS provides intense <u>pulsed</u> neutron beams for scientific research and industrial development
- SNS produces neutrons with an accelerator-based system that delivers short (microsecond) proton pulses to a targetmoderator system, where neutrons are produced by a process called spallation
- State-of-the-art neutron instruments provide a variety of capabilities for researchers across a broad range of disciplines, such as physics, chemistry, materials science, and biology

## The SNS was constructed under a partnership of several U.S. laboratories

Construction cost: \$1.4B

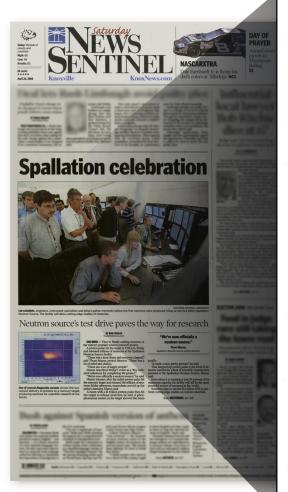


### **SNS Accelerator Complex**

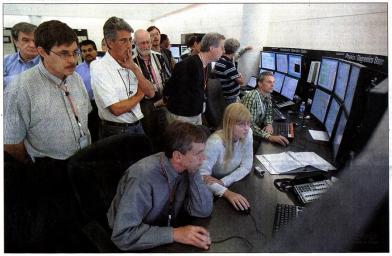




#### First beam on target, first neutrons and Technical **Project Completion goals were met in April, 2006**

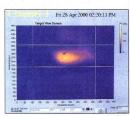


### **Spallation celebration**



Lab scientists, engineers, instrument specialists and others gather moments before the first neutrons were produced Friday at the \$1.4 billion Spallation

#### Neutron source's test drive paves the way for research



One of several diagnostic screens shows the successful delivery of protons to a mercury target, producing neutrons for scientific research of ma-

OAK RIDGE - They're finally making neutrons at the nation's premier science research project.

A proton pulse hit the target at 2:04 p.m. Friday and released trillions of neutrons at the Spallation

Neutron Source facility. There was a loud cheer, and everyone clapped," aid Thom Mason, project director. "There was a lot of relief and elation.

of or rener and enauth.
"There are a lot of happy people."
Mason described Friday's event as a "key technical milestone for completing the project."

"We're now officially a neutron source," he said. Ninety minutes after the initial proton pulse hit the mercury target and released the trillions of neutrons Friday afternoon, researchers revved up the pulse's intensity, Mason said.

A beam with a 10 trillion proton pulse then hit the target to release neutrons, he said. A phosphorescent screen on the target showed the beam

#### "We're now officially a neutron source."

Thom Mason,

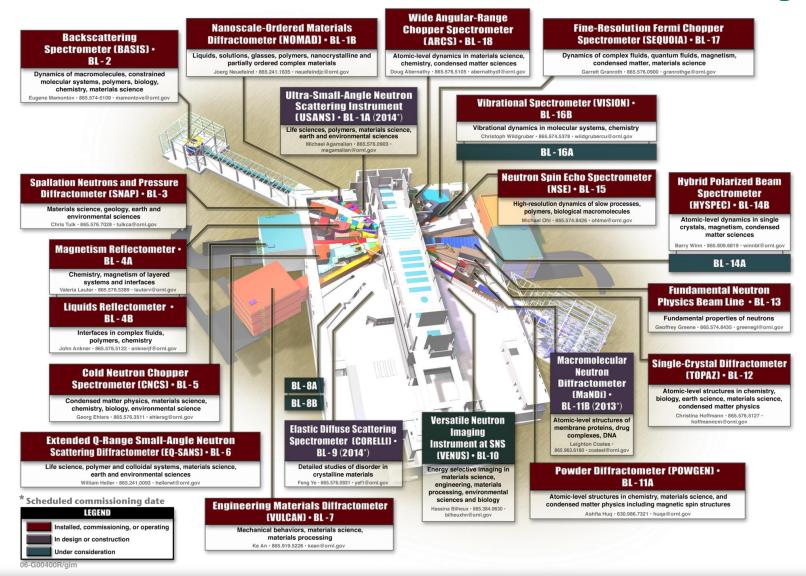
n Neutron Source project dir

"It made a nice, pretty picture," he said. That stepped-up proton pulse is the level of in-tensity needed for a host of scientific experiments planned at the Spallation Neutron Source, Mason

Even when it is running at just 20 percent of its maximum capacity, the facility will still be the most powerful source of neutrons in the world. Scientists plan to use the \$1.4 billion SNS to perform cutting-edge studies on various materials.



### **Neutron production serving a growing instrument suite is our mission: ~5000 h/y**



- ISIS TS-1 at RAL
  - 40 / 50 Hz, short-pulse (SP)
  - 800 MeV H<sup>+</sup>
  - 160 kW
  - W plates target with Ta cladding



T. Broome, ISIS

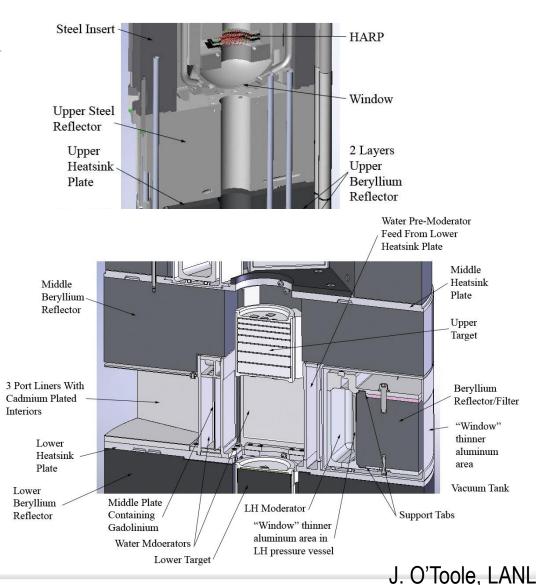


- ISIS TS-1 at RAL
  - 40 / 50 Hz, SP 800 MeV H<sup>+</sup>
  - 160 kW
  - W target with Ta cladding
- ISIS TS-2 at RAL
  - 10 Hz, SP 800 MeV H<sup>+</sup>
  - -32 kW
  - Monolithic W rod target
    - with Ta cladding

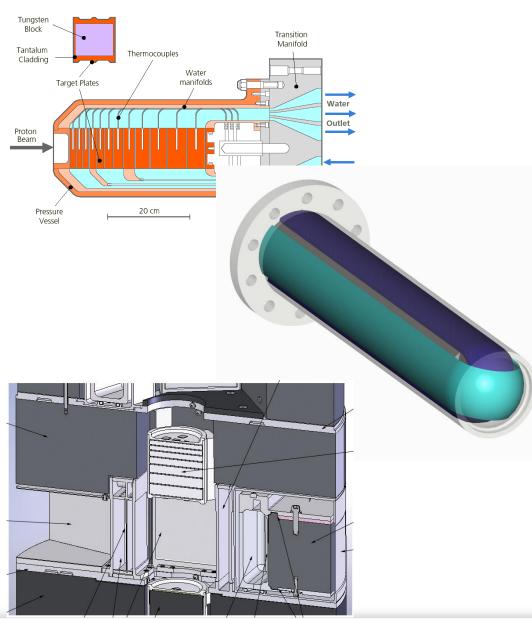


L. Jones, ISIS

- ISIS TS-1 at RAL
  - 40 / 50 Hz, SP 800 MeV H<sup>+</sup>
  - 160 kW
  - W target with Ta cladding
- ISIS TS-2 at RAL
  - 10 Hz, SP 800 MeV H<sup>+</sup>
  - 32 kW
  - W target with Ta cladding
- LANSCE at LANL,
  - 20 Hz, SP 800 MeV H<sup>+</sup>
  - -100 kW
  - W disks target with Ta clad



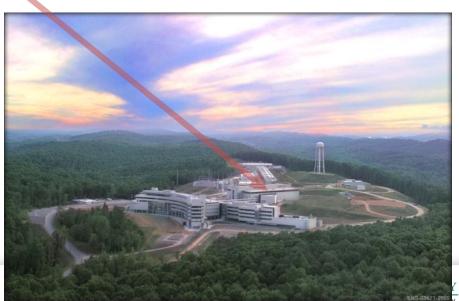
- ISIS TS-1 at RAL
  - 40 / 50 Hz, SP 800 MeV H<sup>+</sup>
  - -160 kW
  - W target with Ta cladding
- ISIS TS-2 at RAL
  - 10 Hz, SP 800 MeV H<sup>+</sup>
  - -32 kW
  - W target with Ta cladding
- Lujan LANSCE at LANL,
  - 20 Hz, SP 800 MeV H<sup>+</sup>
  - $-100 \, kW$
  - W target with Ta cladding



- SINQ at PSI
  - Continuous beam, 570 MeV H<sup>+</sup>
- SNS at the ORNL
  - 60 Hz, short-pulse, 1 GeV H<sup>+</sup>
- JSNS at the JPARC
  - 25 Hz, short-pulse, 3 GeV H<sup>+</sup>







### **PSI: Swiss Spallation Neutron Source SINQ**

- Solid lead in Zircaloy tube array target
- Water-cooled, stationary SS316L vessel, AlMg3 safety hull
- MEGAPIE experiment: molten lead-bismuth



Pb / Zircaloy target



Target bulk shielding



SINQ - Target

Target-01.jpg GK87 / 12.05.99

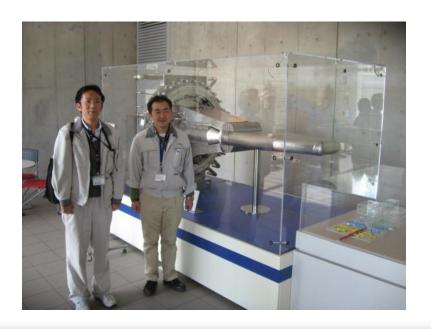
W. Wagner, PSI



### **Neutron Source Target at J-PARC**

- Mercury, stationary, SS316L vessel
- Ca. 20 tons of mercury, circulates at 11 liters/sec
- Magnetic pump, HX, storage tank all on target trolley





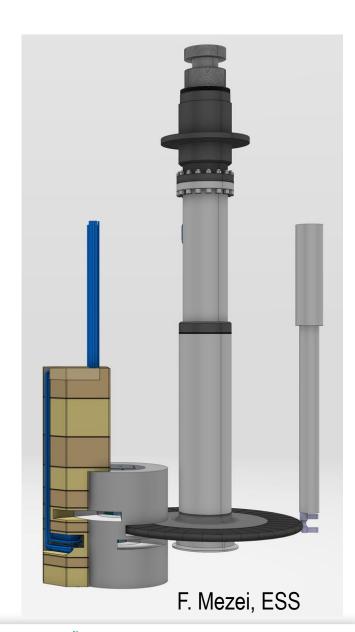
### On the horizon ...

#### CSNS

- 25 Hz, SP, 100–200–500 kW, 1.6 GeV H+
- Ta clad W plates target (ISIS TS-1 type)

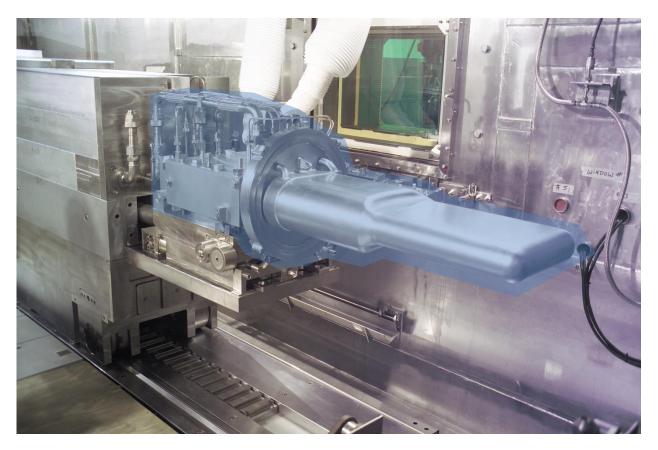
#### ESS

- 14 Hz, <u>long-pulse</u> (2.86 ms)
- 5 MW 2.5 GeV H+
- Helium gas-cooled, rotating target of tungsten blocks

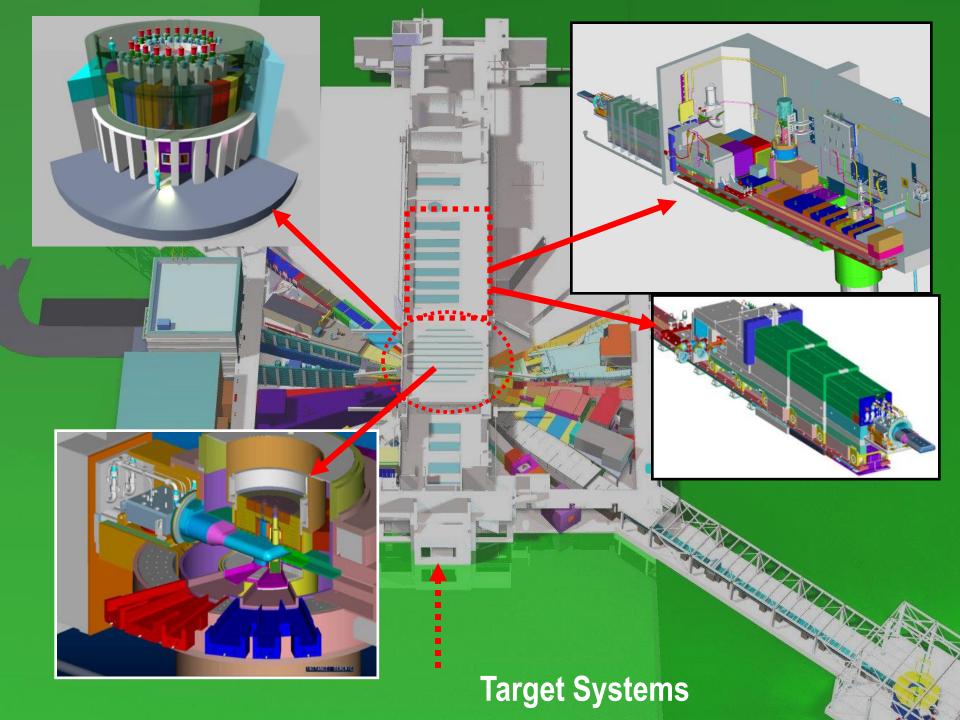


## The SNS uses mercury as the spallation target

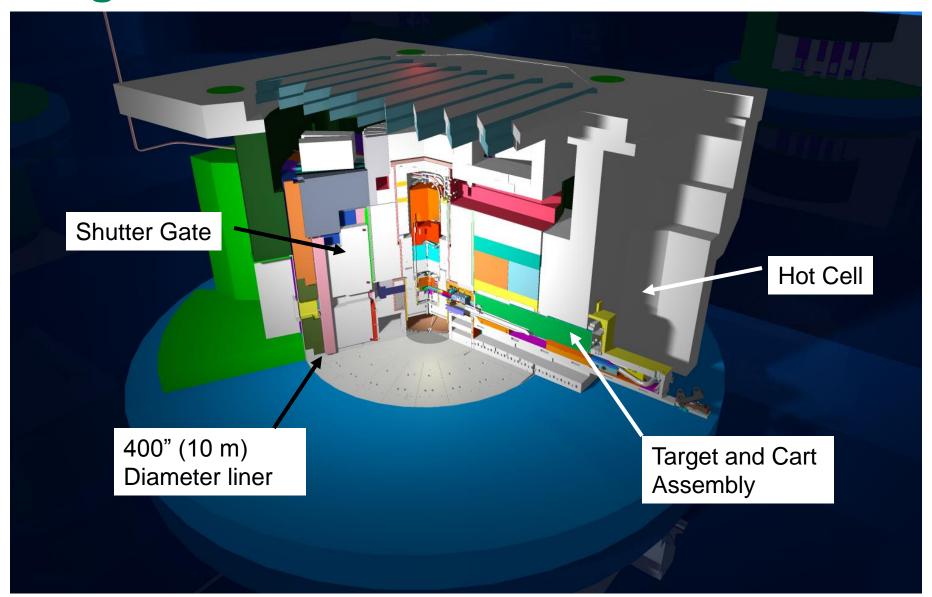
More than 20 tons of it — circulating through a target module



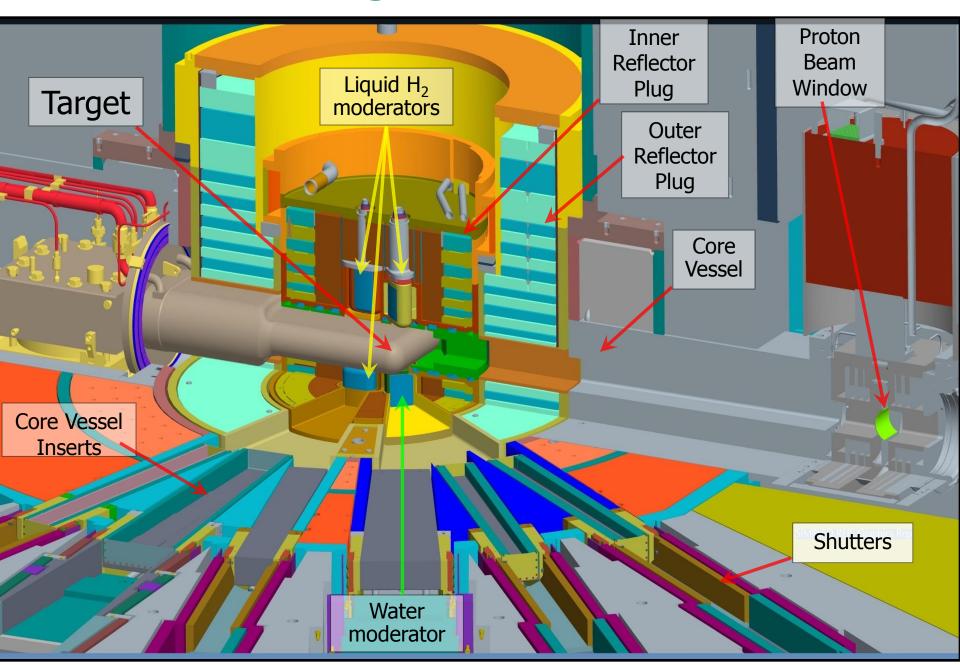
• The target module is a *replaceable* component



### **Target Monolith 3-D model**

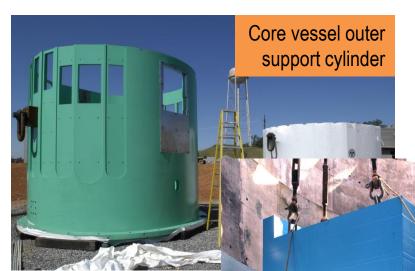


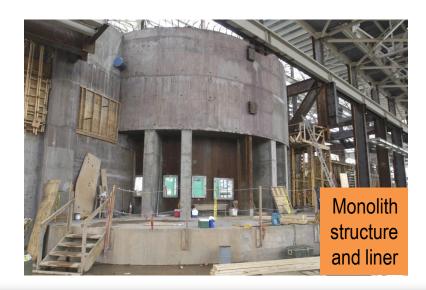
### **Core of SNS target monolith**



### From CAD to hardware ....

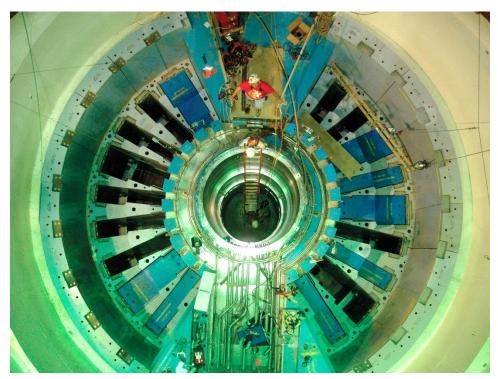






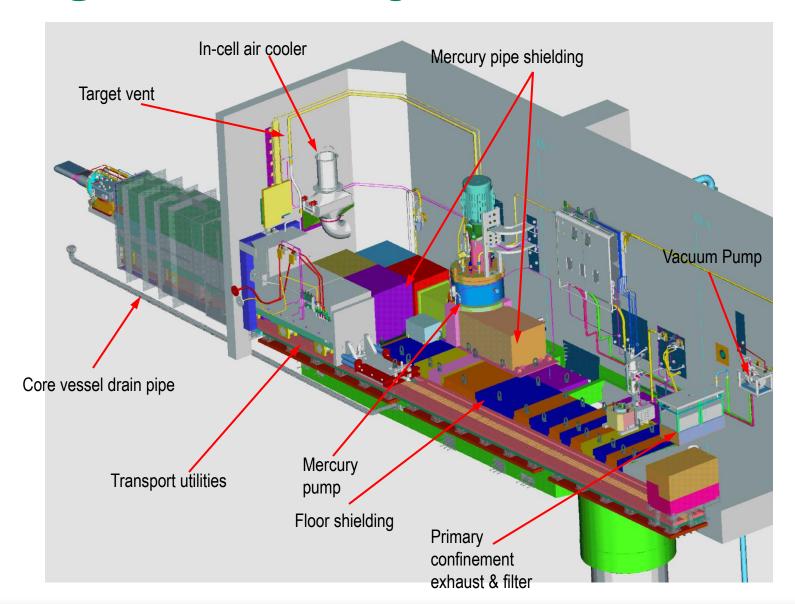


# Top of monolith Inner reflector plug installation

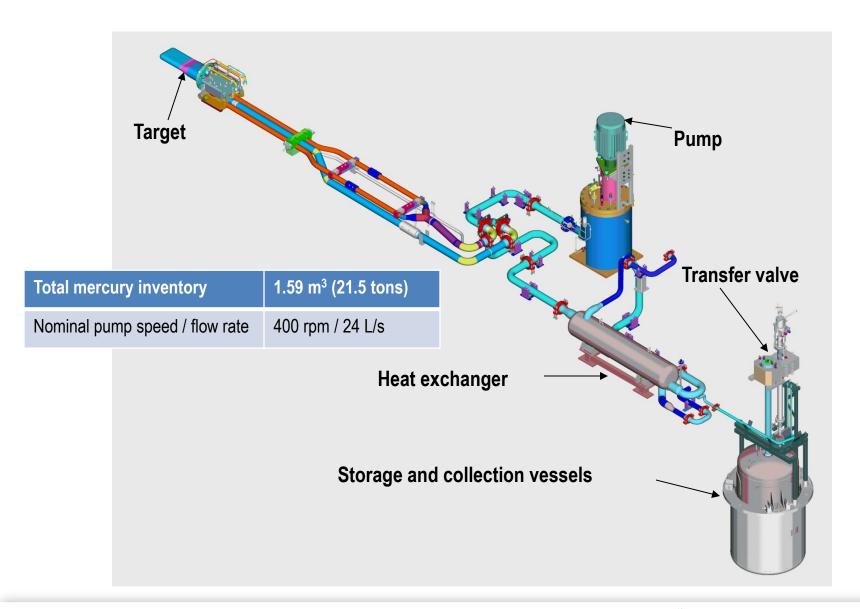




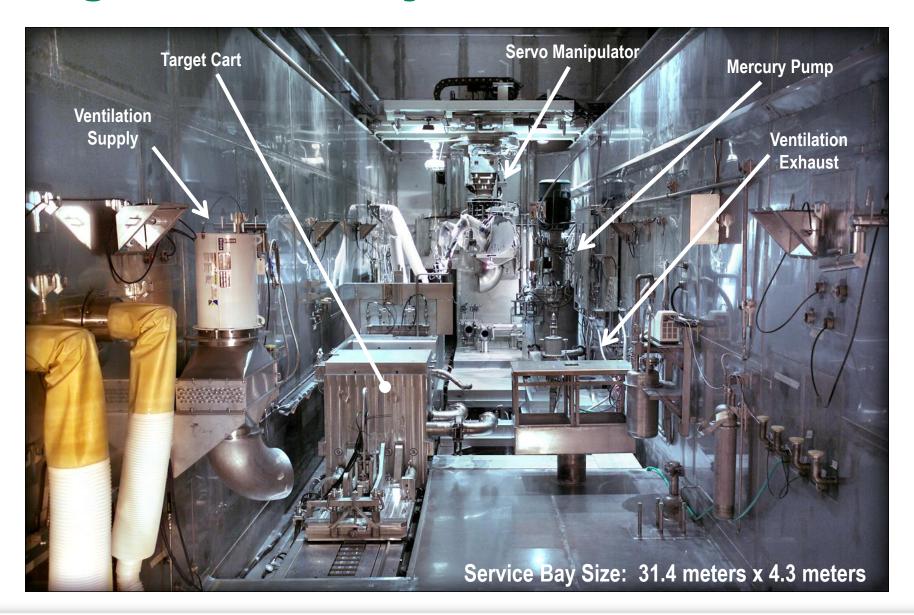
### **Target Process System**



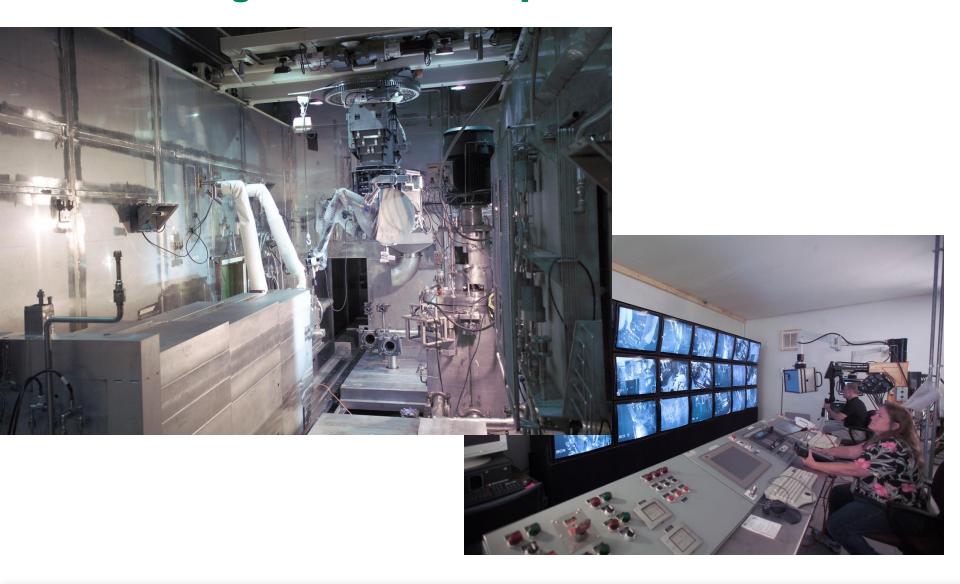
### **Mercury Process Loop**



### **Target Service Bay**



### Remote handling is done via a servo-manipulator and 4 through-the-wall manipulators



### SNS mercury target was a first of a kind design: MW class, liquid metal and short-pulse

Not a safety credited component!

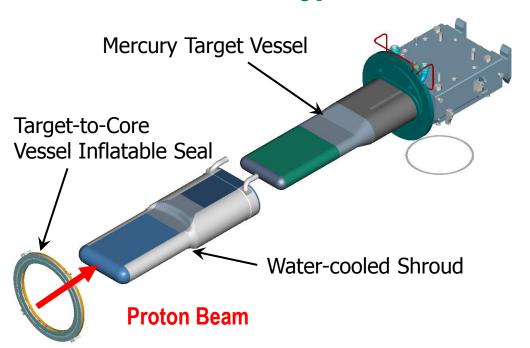
Neutronics performance

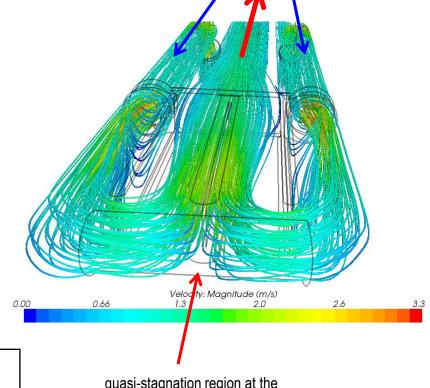
- Coupling with moderators and reflector
- Power deposition
- Radiation damage
- Afterheat, waste radionuclides
- Thermal hydraulics / CFD
  - Process loop and target module
  - Steady state and transient flow and temperature

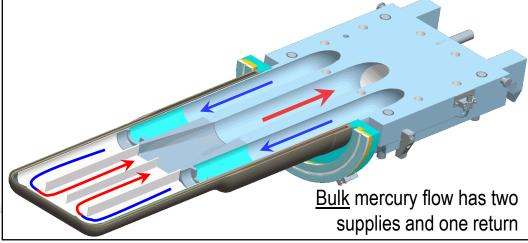
- Stress analysis and evaluation to structural design criteria for service load conditions
  - Normal operating conditions
  - Off-normal events
    - Beam misalignment
    - Over-focused beam profile
  - Vacuum leak tests
  - Manufacturing acceptance tests
  - Shroud integrity after mercury vessel leak

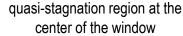
### **SNS Mercury Target Module**

Mercury vessel surrounded by a water-cooled shroud Both are made from type 316L stainless steel











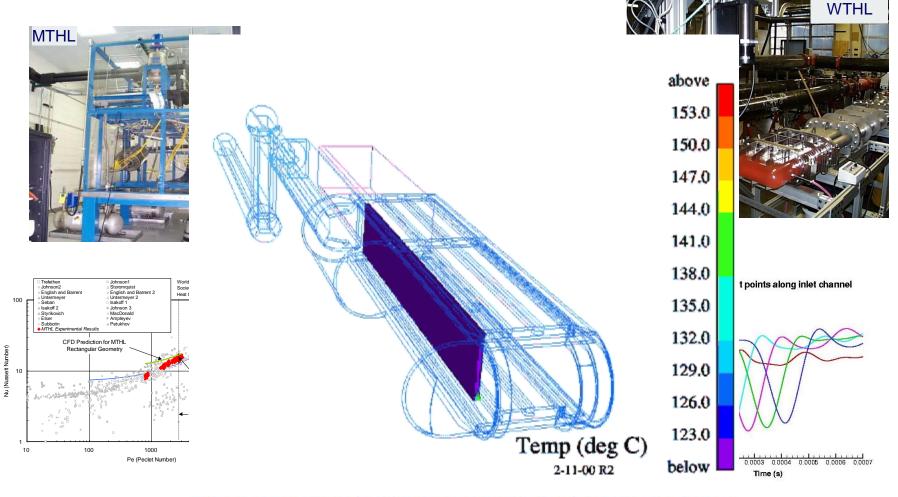
### **SNS Target Module Design Mercury flow is comprised of bulk and channel regions**

 Bulk flow is nearly stagnant where the two bulk mercury supplies meet at beam entrance window Window channel mercury flow is uniform and high speed Channel mercury flow  $V_{max}$ : 2.4 ~ 3.5 m/s OAK RIDGE NATIONAL LABORATORY

# Early project phase: A focused R&D program addressed identified technical risks early in the project

- Steady state power handling
  - Cooling of target vessel window wettability of mercury on stainless steel
  - Hot spots in mercury caused by recirculation around flow baffles
- Thermal Shock
  - Effects of pressure pulse due to short-pulse beam interaction on mercury vessel
- Materials issues
  - Radiation damage to structural materials
  - Compatibility between mercury and other target system materials
- Demonstration of key systems:
  - Large mercury loop operation
  - Remote handling

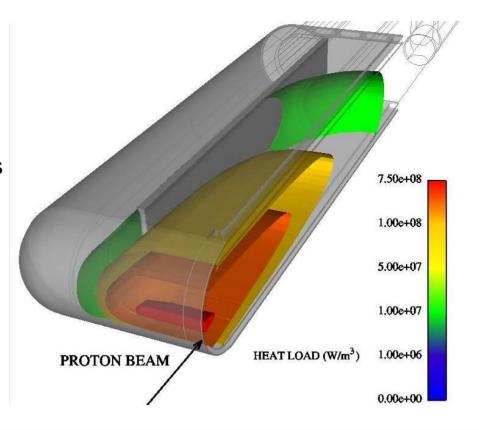
An aggressive R&D Program sufficiently resolved all *known* issues by 2002





### Constant volume heating process leads to large pressure pulse in mercury

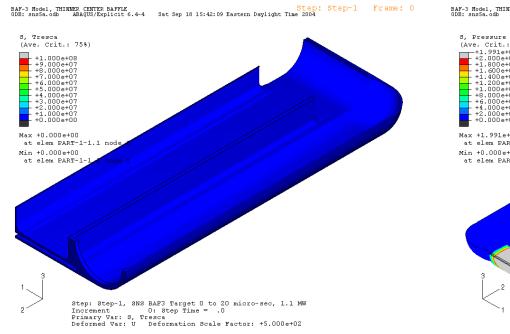
- Peak energy deposition in Hg for a single pulse = 13 MJ/m<sup>3</sup>\*
  - Peak temperature rise is only  $\sim 7$  K for a single pulse, but rate of rise is  $10^7$  K/s!
- This is an constant volume process because beam deposition time (0.7 µs) << time required for mercury to expand
  - Beam size / sound speed  $\sim 30 \mu s$
- 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 in the mercury and cavitation

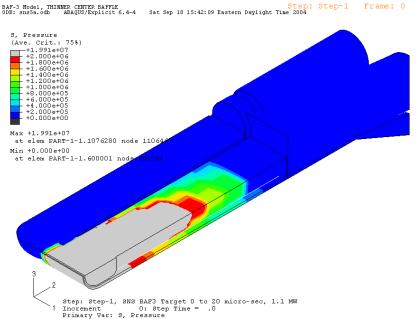




#### Pressure pulse effects on vessel structural response are simulated with an explicit finite element technique B.W. Riemer / Jnl. of Nuclear Mater. 343 (2005) 81-91

- Includes an empirical model for cavitation in mercury
- Benchmarked with Hg target test data obtain at LANSCE WNR
- Needed for estimating the fatigue life of the vessel



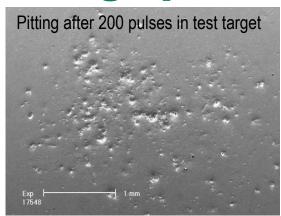


Mercury pressure evolution

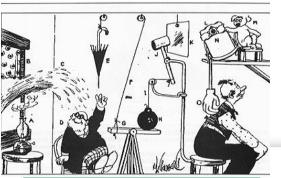
Vessel dynamic stress

### Cavitation Damage was identified as a concern late in the SNS project design phase

- Confirmed in late 2001 that beam-pulse-induced cavitation could severely damage SNS target
- Revisited liquid vs. solid target decision
  - Too late and too expensive to build a facility capable of handling both types
  - Well-defined decision criteria and time frame (~ one year) established
    - Formed advisory team with world-wide leaders in cavitation
    - Negotiated access to LANSCE for two sets of in-beam tests with dedicated beam
    - Strengthened collaboration with J-PARC: coordinated R&D plans;
       access to an important off-line test apparatus and academic resources
    - Established several other off-line test capabilities at ORNL
    - Re-constituted a solid target design team to prepare fallback design





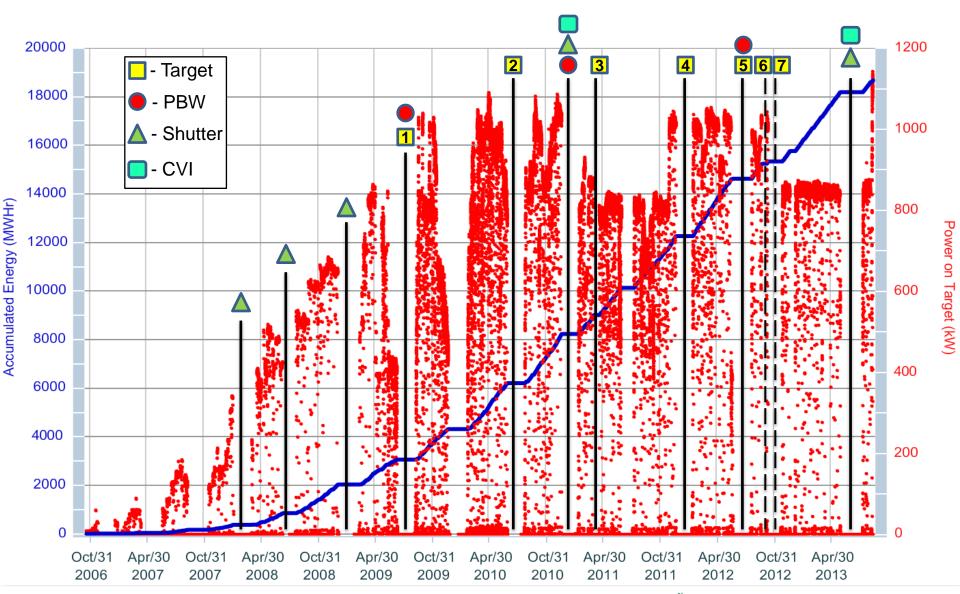


# ISOLDE molten lead target cavitation erosion predated SNS experience, but this was unknown to us

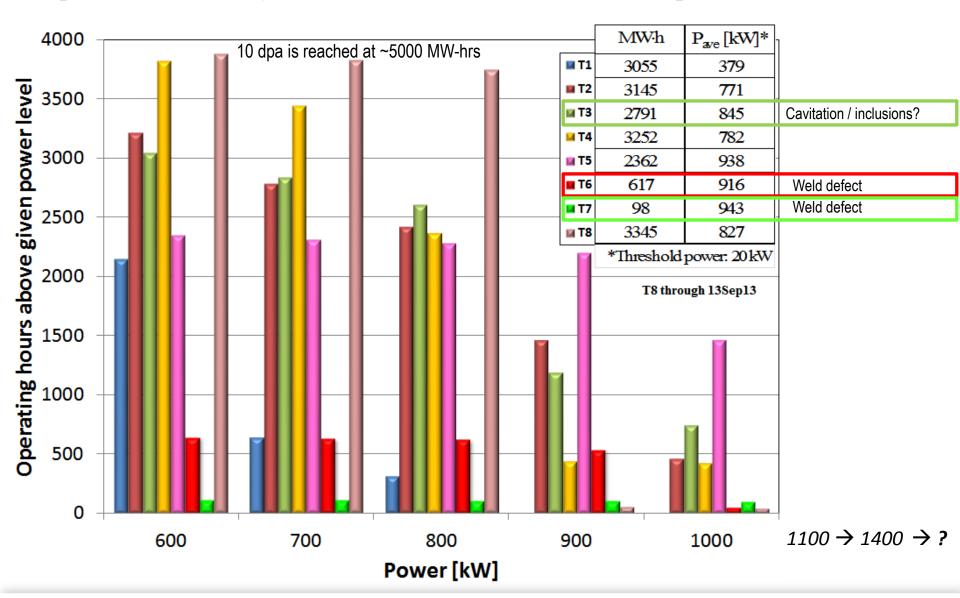


J. Lettry et al. / Nucl. Instr. and Meth. in Phys. Res. B 204 (2003) 251–256

## Power on target & accumulated energy Major Remote Handling Component Replacements



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



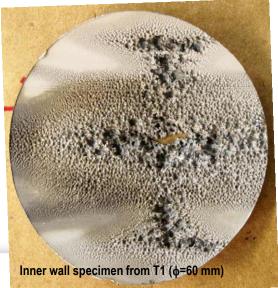
Targets are examined using a variety

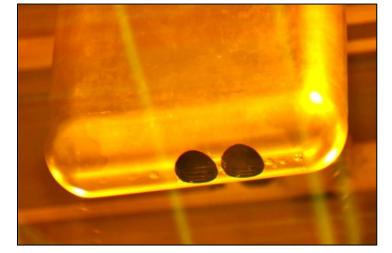
of techniques for PIE

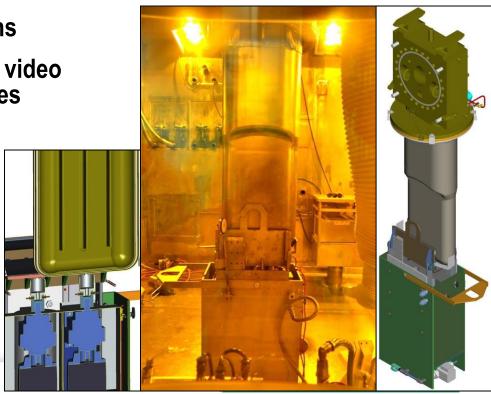
 Two to five cuts have been made in Targets 1-7

- Remotely operated annular cutter
- Targets have been inspected using:
  - Through shield-window high-resolution photography
  - Direct photography of disk specimens

Internal examinations using security video cameras and articulating video-probes







## Significant cavitation-induced erosion on

inner wall

Target 4



Left offset

Center



Right offset



Target 5



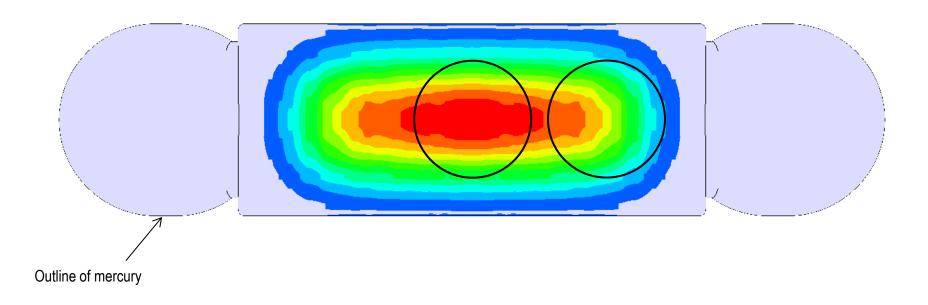




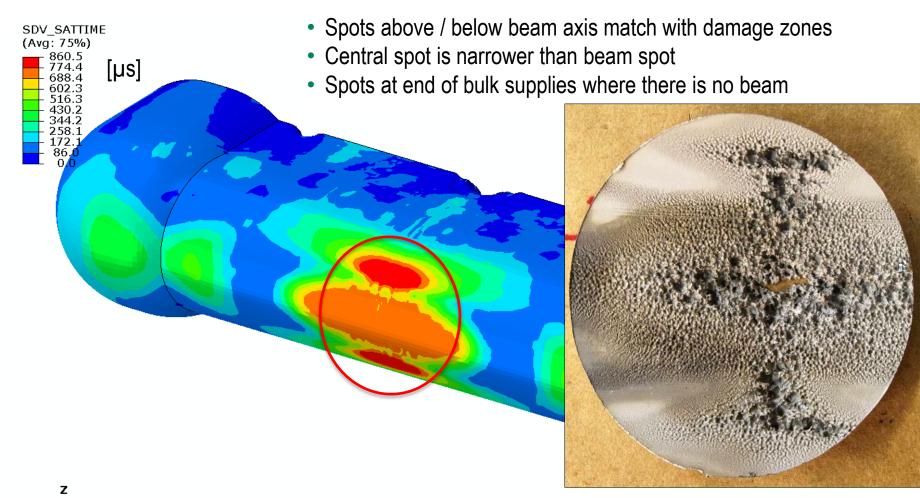
View from inside target looking into the beam

## Relative deposited beam energy density at specimen locations does not correlate well with observed damage

- From design basis beam profile on target
- Damage pattern is more narrow than beam horizontal width
- Why the " $\Phi$ " pattern of erosion?



# Saturation time on bulk mercury correlates well with damage pattern



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

# Outer wall at beam entrance has much less damage

- T3 <u>outer</u> window channel surface
  - Where was the leak?



View from inside target looking into the beam

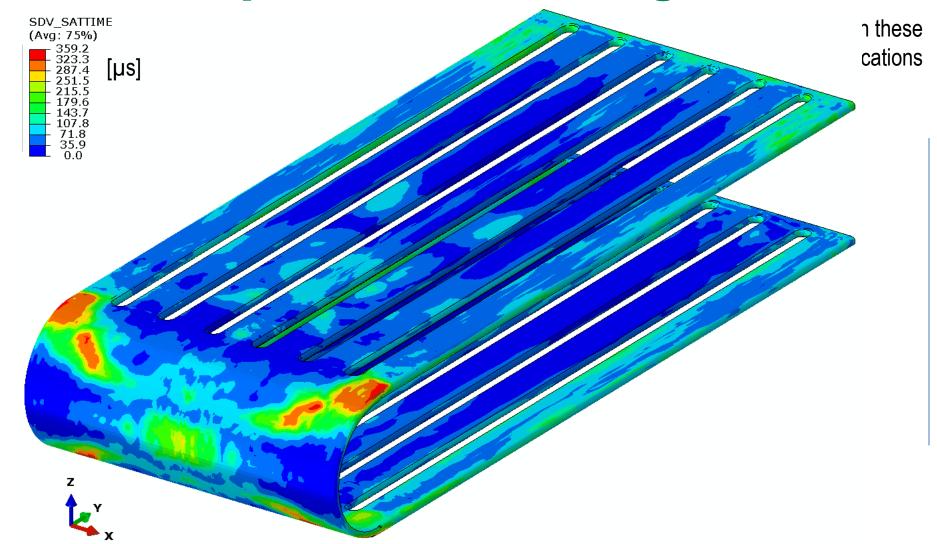
# T3 offset outer specimen eroded region at top edge had a deep pit

- Partial through-wall hole suggests actual leak might be nearby
- We went to the limit of our abilities to cut and examine the target
  - Improved capabilities continue to be sought

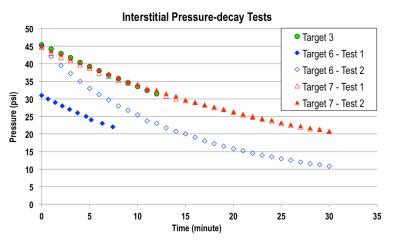




# Saturation time on channel Hg has high value near point of near through-hole

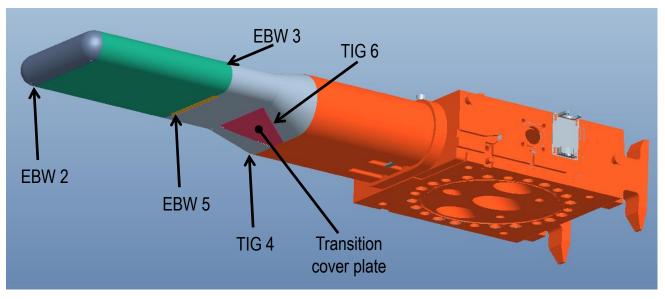


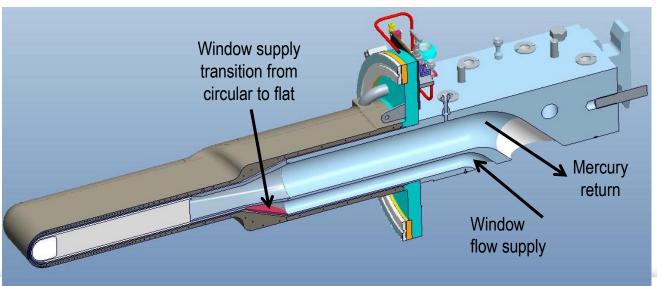
## Leaks from the target vessel were confirmed for Targets 3, 6 and 7 by pressure decay testing



- In the cases of T6 and T7, erosion failures seemed unlikely based on beam delivered to target and average power
  - T6: 617 MW-h, Pave = 916 kW
  - T7: 98 MW-h, Pave = 943 kW
- A facility stand-down was imposed to investigate and understand T6 and T7 leaks before operations could resume
- It was speculated that mercury window flow passages might have become blocked, thus leading to overheating and failure of beam windows
- The window flow supply passage was inspected using an articulating videoprobe

## Mercury vessel assembly welds Path for video-probe access



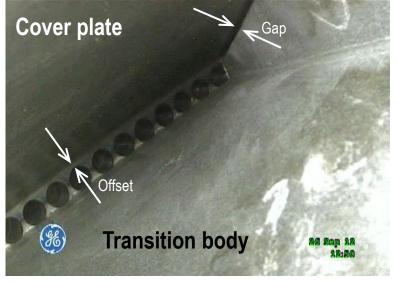


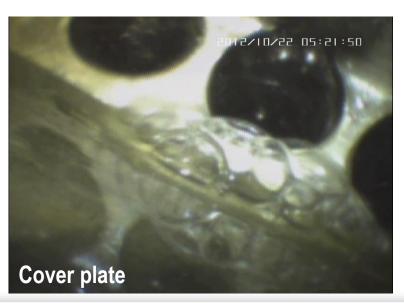
Video-probe inspections found leak at transition cover weld joint Pre-installation

- Pre-installation inspection was done to look for foreign objects
  - All clear, but clues to a problem were missed
- Use of leak detection fluid with external air pressure revealed leak at mid-span of weld





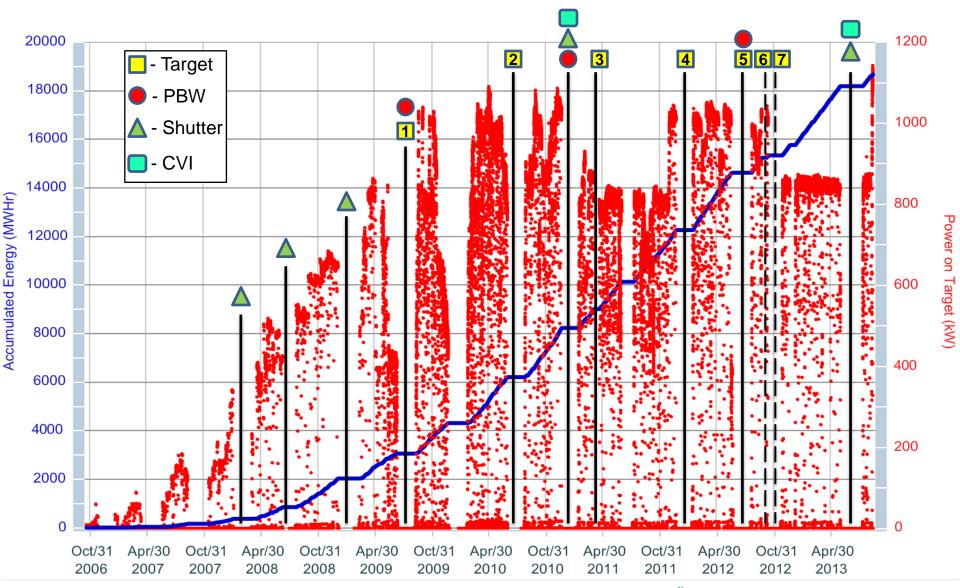




#### Remote Handling is critical to SNS operations

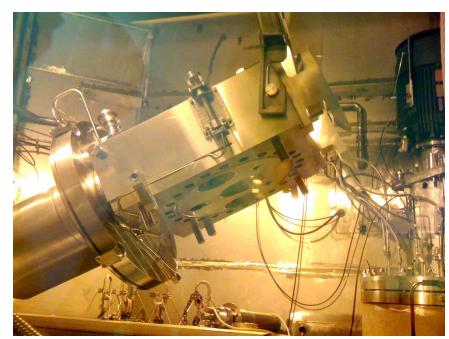
- Since SNS operation began in 2006, a significant amount of remote handling operations have occurred
- Remote handling at SNS encompasses:
  - Major component replacement & operational planning for
    - Targets
    - Proton Beam Windows (PBW)
    - Shutter and Core Vessel Inserts (CVIs)
    - Ring Injection Dump
    - Inner Reflector Plug
  - Target module Post Irradiation Examination (PIE) operations
  - Major component waste shipment operations
    - Shipments for target and PBW modules
    - Shutter Plug segment shipments

## Power on target & accumulated energy Major Remote Handling Component Replacements



### **Target Replacement Operation**

- Removal and reinstallation of the following components take place during each target replacement:
  - Four pieces of in-cell shielding (14 tons of steel)
  - Nine process and utility jumpers at the back of the target cart (1/2" fittings in addition to instrumentation connectors)
  - Two 2" and two 6" water coolant and mercury process lines
  - Seven process and utility jumpers at the target (1/2" to 2")



Lifting Sport Target off of Target Carriage

11 – 14 days to replace a target Goal is <= 7 days

- Other
- \_ M
  - Handling of multiple pieces of tooling
  - Capture and return of released liquid mercury from open pipes
  - Requires five person crew / one shift operation



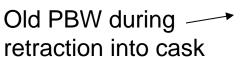
#### **Proton Beam Window Replacement**

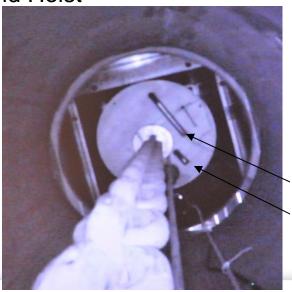




Shielded Cask and Hoist

New PBW with guide can and counterweight being installed





Cooling lines cut prior to removal with long handle tools

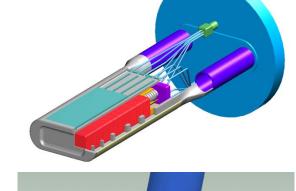
### **SNS Second Target Station (STS)**

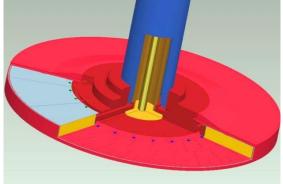


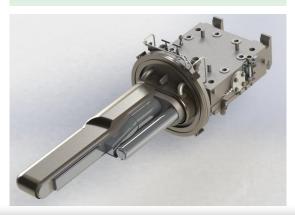
- Scope of STS includes design, build, install, test, and commission a second target station at SNS consisting of:
  - New spallation neutron source and supporting systems
  - Extension of SNS accelerator systems to as much as 3 MW (energy, current, duty factor)
  - Conventional support buildings
  - Initial neutron beam instruments

Concepts for STS is a short-pulse, 300 – 500 kW beam at 10 Hz

- Three credible target options under consideration:
  - Stationary tungsten plate target
    - Water-cooled
    - Good radiation lifetime
  - Rotating tungsten target
    - Water-cooled, minimal in spallation zone gives brightness advantage
    - 20+ year radiation lifetime
    - Waste shipping and handling tbd.
  - Mercury target
    - Established technology
    - Good radiation lifetime
    - Pulse issues (cavitation)







### **Summary**

- The SNS has gone from forest to neutron production in 7 years and was completed on schedule and within budget
- Presently there are 16 instruments available in the user program

   ultimately 25 will be operating
- Overall neutron production availability has exceeded 90%
  - Except for FY13 ⊗
- The mercury target has exceeded some early estimates for lifetime and power, but there have been premature failures
  - Cavitation damage is expected to become worse as power is increased
  - We are learning more about the unique mercury target and working to extend its lifetime as power is increased
- Plans for a second target station are underway

