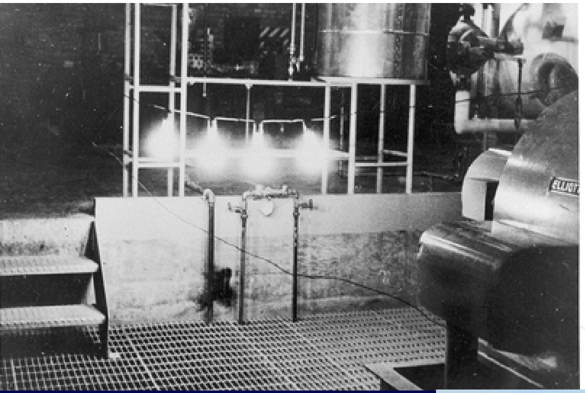
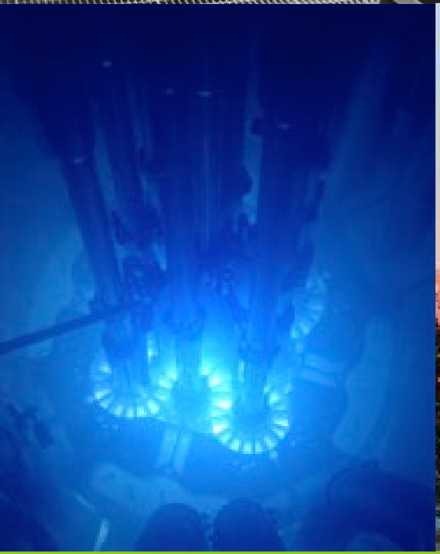
U.S. DEPARTMENT OF ENERGY
Office of Science

APS-DPP, Mini-Conference: Public-Private Partnerships for Fusion Energy III
October 19, 2022

U.S. DEPARTMENT OF ENERGY
Nuclear Energy



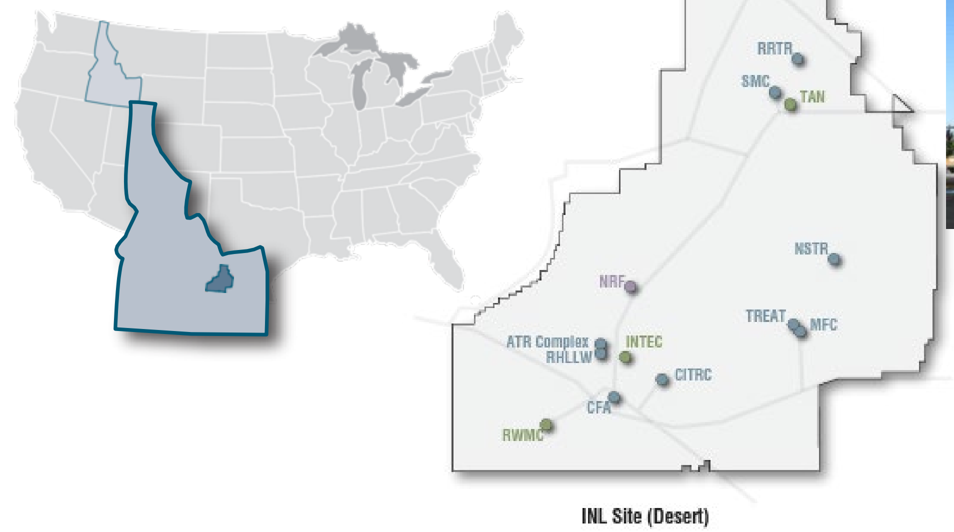
Idaho National Laboratory
Fusion Nuclear Science R&D Capabilities

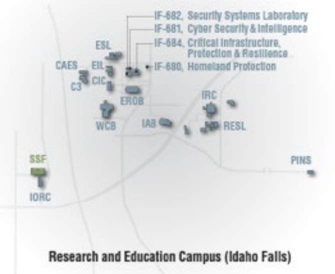


Masashi Shimada, and Chase N. Taylor
Fusion Safety Program

INL Idaho National Laboratory

INL/MIS-21-65450



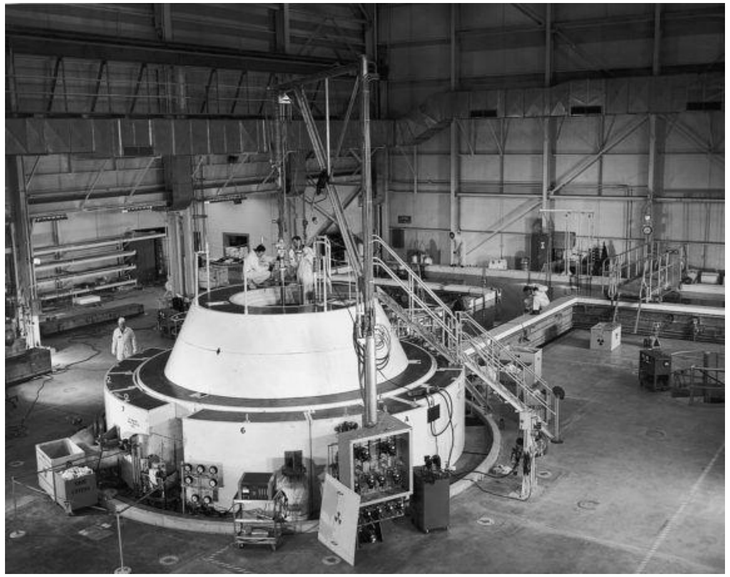


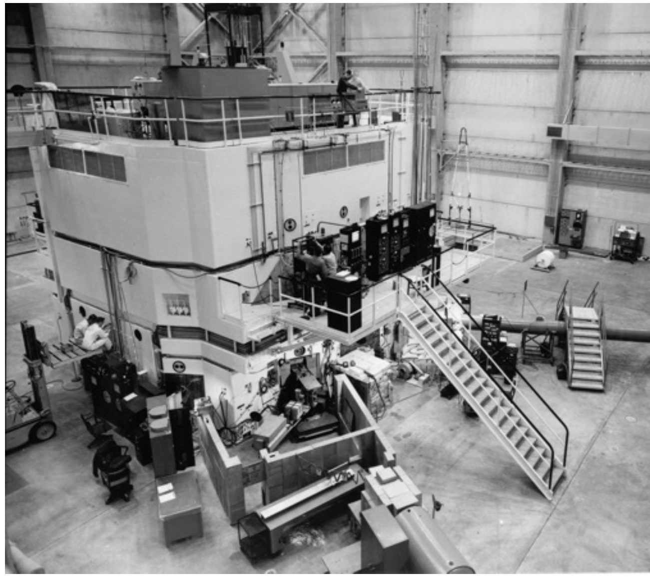
890 square-miles

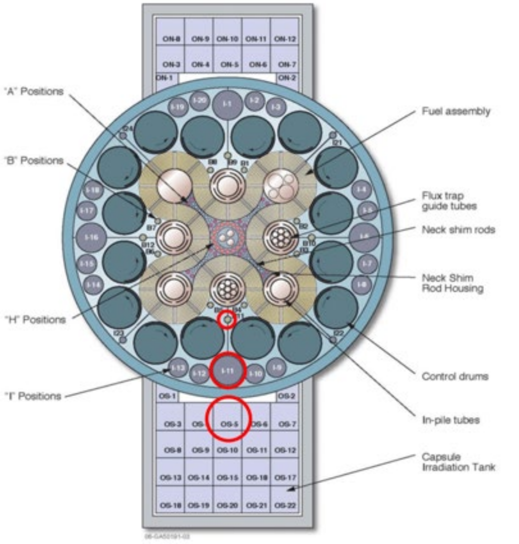
https://factsheets.inl.gov/SitePages/Home.aspx

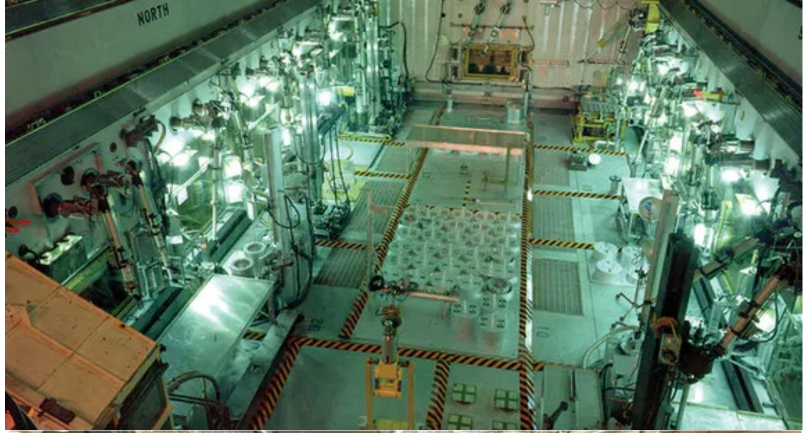
52 nuclear reactors

https://factsheets.inl.gov/SitePages/Home.aspx



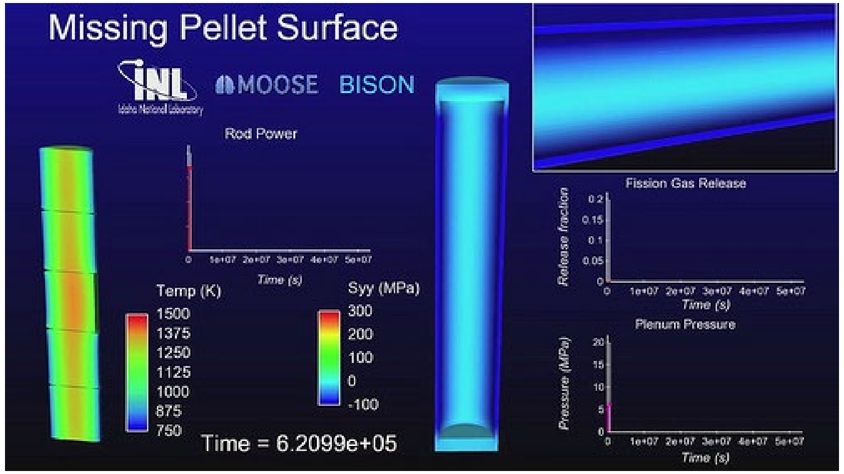


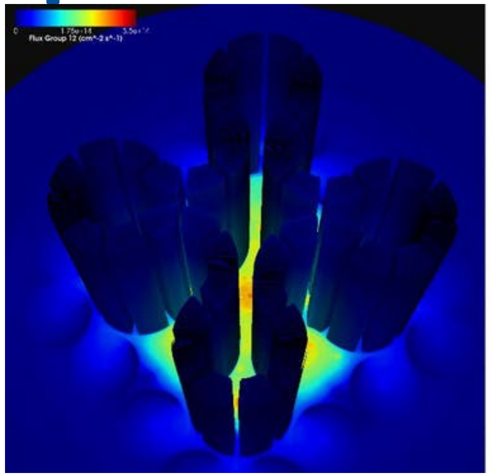


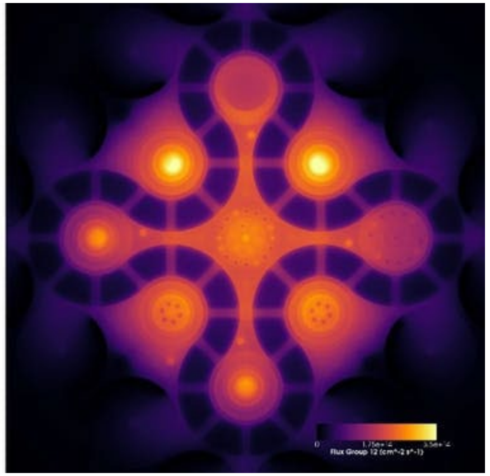


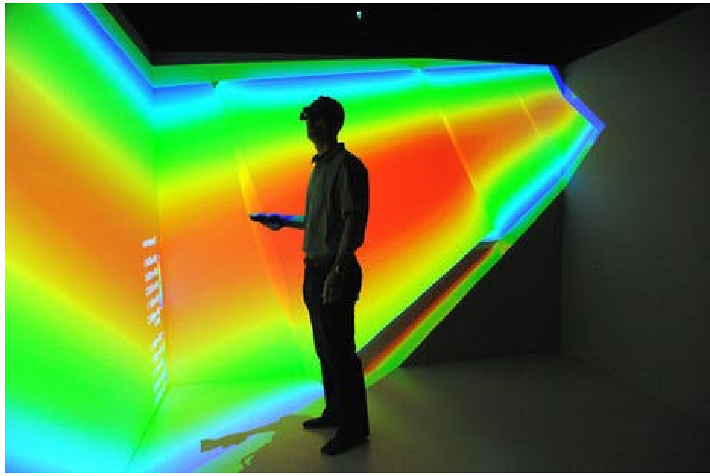
Experimental & Computational capabilities

https://factsheets.inl.gov/SitePages/Home.aspx



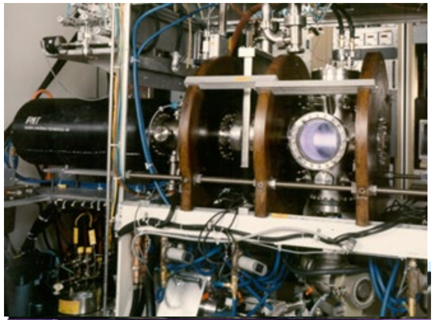


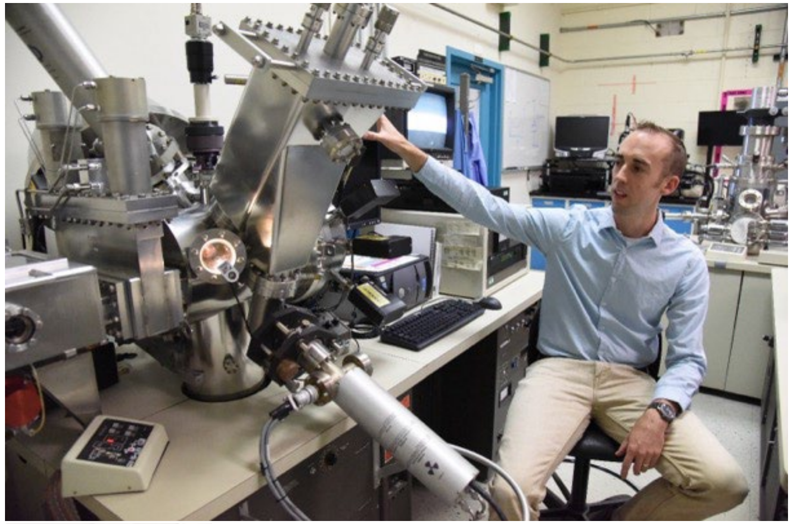




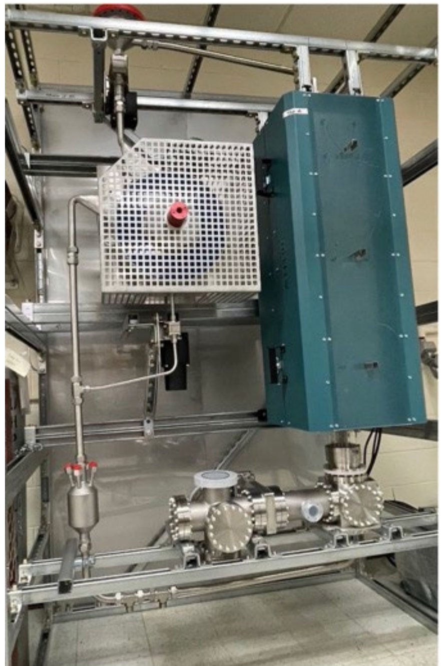
890 square-miles, 52 nuclear reactors, and INL capabilities

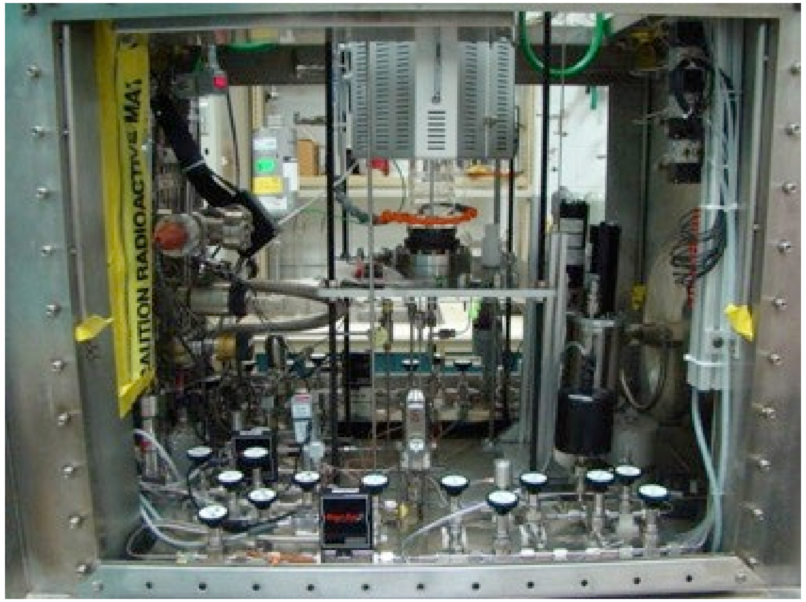
- **Idaho National Laboratory (INL) is the nation's lead laboratory for nuclear energy R&D.**
  - INL is the (geographically) largest national laboratory with 890 square-miles DOE Idaho site.
  - DOE Idaho site is the birthplace of nuclear energy, and 52 nuclear reactors were built in DOE Idaho site.
  - The world's first usable electricity from nuclear energy was generated in EBR-I in 1951.
- **Industry support**
  - Through Gateway for Accelerated Innovation in Nuclear (GAIN), DOE is making the state-of-the-art and continuously improving RD&D infrastructure available to nuclear industrial community for faster and cost-effective development of innovative nuclear energy technologies toward commercialization.
    - **Experimental capabilities with primary emphasis on nuclear and radiological facilities**, examples are:
      - **Advanced test reactor (ATR),** the world's premier nuclear test reactor and the only U.S. research reactor capable of providing large-volume, high-flux thermal neutron irradiation in a prototype environment.
      - **Hot Fuel Examination Facility (HFEF),** one of the largest hot cell in the U.S. for post-irradiation examination of highly radioactive nuclear fuels and materials.
      - **Irradiated Materials Characterization Laboratory (IMCL),** Haz. Cat. 2 nuclear facility for microstructural, thermal, and mechanical characterization of irradiated nuclear fuels and materials.
      - **High Temperature Test Laboratory (HTTL)** for development of advanced sensor and instrumentation, etc.
    - **Computational capabilities along with state-of-the-art modeling and simulation tools (e.g. MOOSE, BISON etc.)**
    - **Information and data through knowledge and validation center**
    - **Land use and site information for demonstration facilities**





Tritium and beryllium





Tritium and beryllium

- **Safety and Tritium Applied Research (STAR) facility is DOE less than Hazard Category 3 radiological facility**
  - To advance fusion nuclear sciences (especially, tritium retention and permeation in fusion materials, and tritium extraction from plasma exhaust and liquid breeding materials) for DOE FES and INFUSE
  - Is conveniently located close to the Advanced Test Reactor, the largest fission test reactor in the U.S.
- **Unique capabilities at STAR facility includes:**
  - Tritium handling (maximum allowable tritium inventory to 1.6 gram ~ 15,390 Ci)
  - Radioactive material handling (typically < 1 mSv/hr = 100 mrem/hr at 30 cm)
  - Use of inert-gas gloveboxes and/or ventilated enclosures for the containment of tritium, beryllium, & lead
    - Tritium: Fusion fuel for deuterium-tritium (D-T) fusion system
    - Beryllium: Molten salt (e.g. FLiBe) breeding materials and Be as PFC
    - Lead: Liquid (e.g. PbLi) breeding materials (e.g. PbLi)
- **What we can provide at STAR facility includes:**
  - Tritium retention in fusion material (plasma facing and blanket breeding materials)
  - Tritium transport properties (diffusivity, solubility, and permeability) in fusion materials (solid and liquid)
  - Tritium testing of T-compatible pumps, tritium extraction system, and novel plasma exhaust technologies
  - Diagnostics and sensor testing with tritium and toxic materials (e.g. FLiBe and PbLi)
  - Bulk defect and surface chemistry characterization in fusion materials

Summary

- **INL is excited to discuss the collaboration opportunities in all the following general topic areas:**
  - Enabling technologies (e.g. T testing of T-compatible pumps and T extraction system)
  - Materials science (e.g. Bulk defect and surface chemistry characterization in irradiated materials)
  - Diagnostic development (e.g. sensor testing for PbLi and FLiBe and under extreme irradiation conditions)
  - Modeling and simulation (e.g. Tritium safety analysis with MELCOR-Fusion, MELCOR-TMAP, and MOOSE-TMAP)
  - Unique fusion experimental capabilities (e.g. D-T testing)

- **Please check the following links for more information:**
  - INL fact sheets: https://factsheets.inl.gov/SitePages/Home.aspx
  - INL fusion program: https://fusionsafety.inl.gov/SitePages/Home.aspx

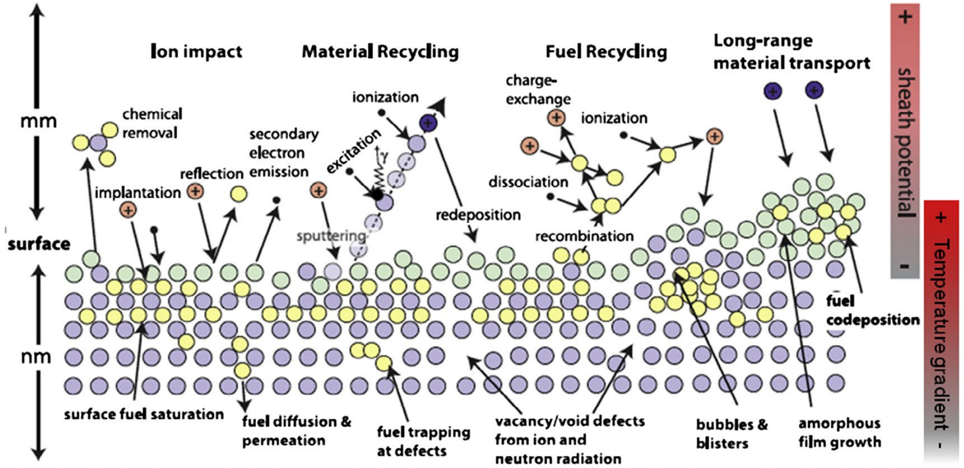
- **INL Point of Contact for INFUSE**
  - Masashi Shimada, 208-533-4472, Masashi.Shimada@inl.gov

Supporting slides

Capabilities and objectives of STAR R&D

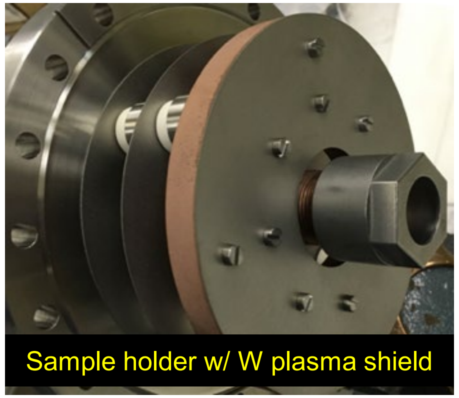
- **Hazard category**
  - STAR facility is DOE less than Hazard Category 3 nuclear facility
- **Unique capabilities**
  - Tritium handling
    - Total tritium inventory restricted to less than 1.6 gram (15,390 Ci)
    - Current tritium inventory is 3000 (± 50) Ci as of July 2021
    - Use of a inert-gas glovebox and/or ventilated enclosure for T containment
  - Radioactive material handling
    - Dose rate limit: Radiological work permits set < 1 mSv/hr (100 mrem/hr) at 30 cm
    - Dose limit: 7 mSv (700 mrem) as INL administrative limit for annual dose
  - Chemically toxic (e.g. Be, FLiBe) and liquid materials (e.g. PbLi)
    - Use of a inert-gas glovebox for Be containment

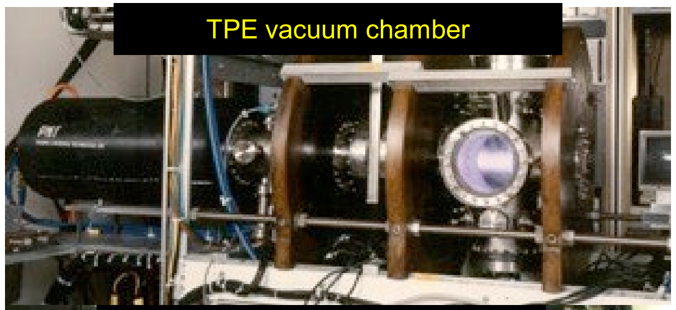
- **Objective** is to investigate experimental <u>safety</u> R&D for DOE SC Fusion Energy Sciences and Nuclear Energy
  1. In-vessel tritium source term:
     - Tritium retention in plasma facing components (PFCs)
  2. Ex-vessel tritium release term:
     - Tritium permeation in PFCs and structural materials
     - Tritium absorption, desorption, and extraction from blanket materials
     - Tritium permeation in fission structural materials
  3. In-vessel dust source term:
     - Evaluation of dust production rate and explosivity determination
- NOTE: STAR facility is temporally shutdown from April – Oct. 2021 for HVAC upgrade

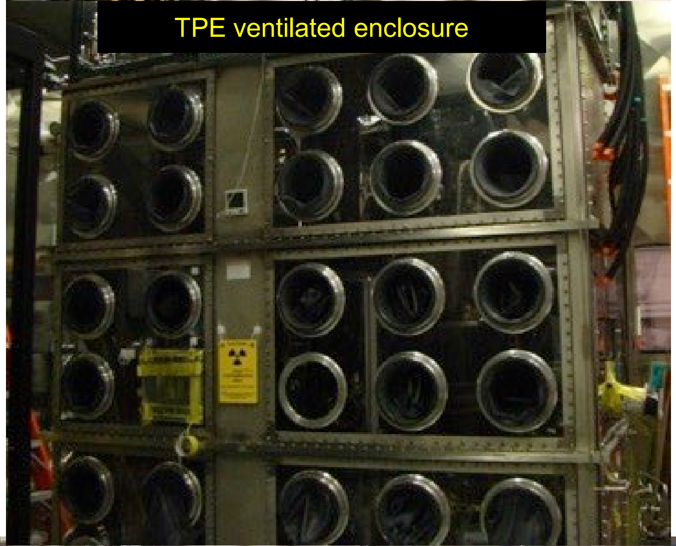


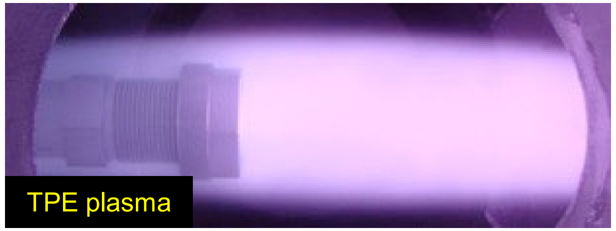
TPE - Tritium Plasma Experiment

- **TPE is a unique linear plasma device in four elements:**
  - **Tritium plasma (< 500 Ci per discharge),**
  - **Divertor-relevant high-flux plasma (>10^{22} $m^{-2}s^{-1}$) ,**
  - **Moderately radioactive (< 1 mSr/hr @ 30 cm) materials**
  - **Mixed (D-T-He) plasma**
- **Utilizes two containments other than its SS vacuum vessel**
  - **Ventilated enclosure (as a high contamination area/HCA boundary)**
  - **Ventilated room (as a contamination area/CA boundary for T)**
- **Installation of new plasma source**
  - **Design based on UCSD PISCES-A source**
  - **Increased plasma performance and availability**
  - **Minimized impurities (e.g. C)**
    - **Impurity level in plasma decreased significantly**
- **Test material size**
  - **6mm – 25 mm OD discs**
  - **0.25 – 2.0 mm in thickness**
- **Post-exposure examination capabilities**
  - **D/He//T retention measurement by thermal desorption spectroscopy**
  - **D/He depth profile by glow-discharge optical emission spectroscopy**
  - **Surface chemistry analysis by X-ray photoelectron spectroscopy and scanning Auger spectroscopy**
  - **D depth profile by nuclear reaction analysis (collaboration w/ SNL-NM)**


Sample holder w/ W plasma shield

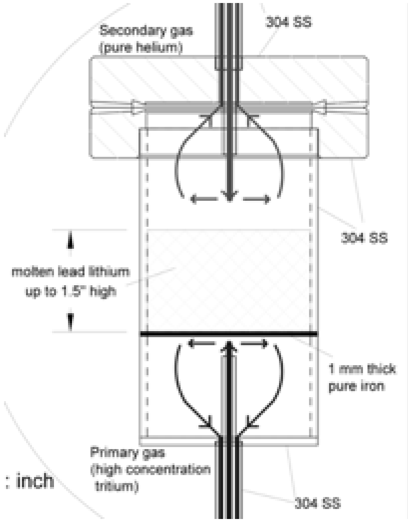

TPE vacuum chamber


TPE ventilated enclosure

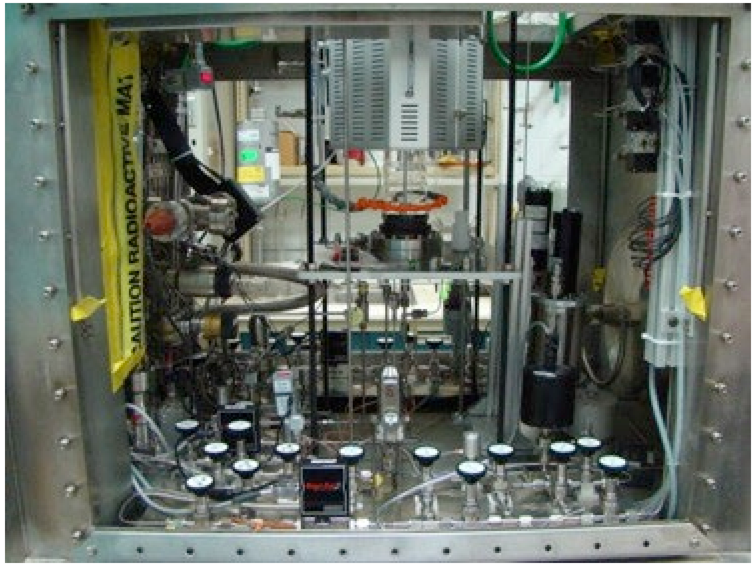

TPE plasma

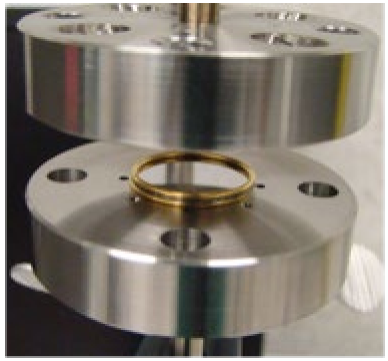
TGAP - Tritium gas absorption and permeation

- **TGAP is a unique tritium permeation experiment in five elements:**
  - **Tritium (T_2) gas (< 25 Ci per campaign)**
  - **Independent control of H_2 and T_2 partial pressures**
  - **Low tritium partial pressure ($10^{-12} < p_{T2}$ [Pa] $< 10^0$)**
  - **Moderately radioactive (< 1 mSr/hr @ 30 cm) materials handling**
  - **Liquid (e.g., PbLi, FLiBe) and disc shaped metal specimens**
- Utilizes a Ventilated Enclosure for tritium containment
- Utilizes solid Au O-rings or Inconel C-rings for sealing
- Tritium permeability was measured in RAFM and polycrystalline W.



Test section for T solubility in PbLi





20mm OD specimen and Au wire O-rings (left) and C-rings (right)

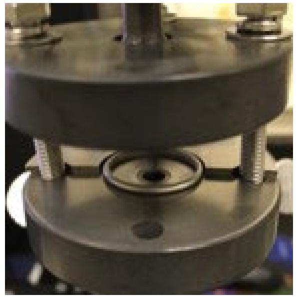
SGAP - Static gas absorption and permeation

- SGAP is a unique combined absorption and permeation experiment:
  - Hydrogen and deuterium gas pressure ($10^3 < p_{D2}[Pa] < 10^5$)
  - High temperature (up to 950 °C)
  - Lliquid or ceramic breeder materials (PbLi, FLiBe, Li_2ZrO_3, etc.) and PFC/structural material (W, RAFM steels, etc.)
  - Moderately radioactive (< 1 mSr/hr @ 30 cm) materials handling
- Utilizes a Laboratory Hood for hydrogen/deuterium containment

Absorption section

Static Gas Absorption Permeation (SGAP) system

Permeation section



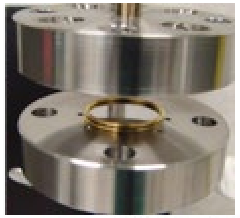
Gas-phase H/D/T permeation systems at INL

Static Gas Absorption Permeation

- is a combined H/D absorption & permeation system
  - **Hydrogen and deuterium partial pressure**
    - $10^3 < p_{Q2}$[Pa] $< 10^5$ (where Q=H or D)
  - **High temperature**
    - Absorption: up to 950 C (1223K)
    - Permeation: up to 900 C (1173K)
  - **Vertically standing furnace capable of testing**
    - Liquid (e.g. PbLi and FLiBe)
    - Disc specimen from 6 mm to 25 mm OD
  - **Moderately radioactive materials handling**
    - Dose rate limit< 1 mSr/hr @ 30 cm

20mm OD specimen and C-rings

20mm OD specimen & Au O-rings



Absorption section

Static Gas Absorption Permeation (SGAP) system

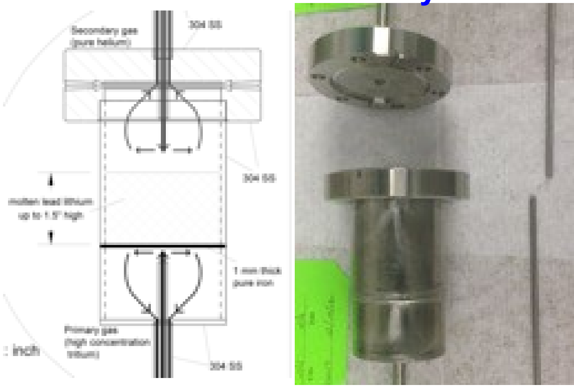
Permeation section

Tritium Gas Absorption Permeation

- is a combined T absorption & permeation system
  - **Use of tritium gas (HT, T_2)**
    - Tritium limit: 25 Ci per campaign
  - **Low tritium partial pressure**
    - $10^{-12} < p_{T2}$ [Pa] $< 10^0$
  - **Independent control of H_2 & T_2 partial pressure**
    - Enables accurate measurement of T permeability
  - **High temperature**
    - Absorption & Permeation: up to 700 C (973K)
  - **Vertically standing furnace capable of testing**
    - Liquid (e.g. PbLi and FLiBe)
    - Disc specimen from 6 mm to 25 mm OD
  - **Moderately radioactive materials handling**
    - Dose rate limit< 1 mSr/hr @ 30 cm

Tritium Gas Absorption Permeation (TGAP)

Test section for T solubility in PbLi



Surface/bulk characterization for tritium-exposed and low activation materials

for tritium-exposed and low activation materials at STAR

Online Dec 2016

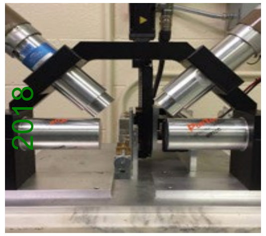
Glow discharge optical emission spectrometry (GD-OES)

Horiba Profiler 2

Specifications
- Depth profile 10-100s μm in minutes.
- Analyze 10s of elements simultaneously.
- Nanometer depth resolution.
- Directly measure H and D.

Impact
- Deuterium depth profiles >> 10 μm.

Online Jan 2018



Positron Annihilation Spectroscopy (PAS)

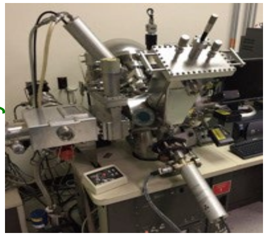
Coincidence Doppler broadening (CDB-PAS)

Lifetime (PALS)

Specifications
- Only technique sensitive to monovacancies.
- Measure defect size.
- Measure relative defect concentration.
- Ultra-low background.

Impact
- Correlate neutron damage to retention.

Online July 2017



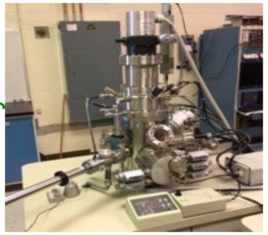
X-ray photoelectron spectroscopy (XPS)

Perkin-Elmer PHI 5100

Specifications
- Quantify surface chemistry (0.1 at %).
- Sensitive to top 1-10 nm.
- High resolution X-ray monochromator.

Impact
- Correlate surface condition with tritium permeation.

Online July 2017



Scanning Auger microprobe (SAM)

Perkin-Elmer PHI 660

Specifications
- Elemental surface composition of materials (Auger emission spectroscopy, AES).
- Scanning mode enables microscopy (scanning electron microscopy, SEM).

Impact
- Correlate morphology with chemical state.

Online Sept 2017

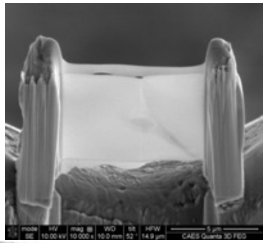
Digital microscope
Keyence VHX-5000

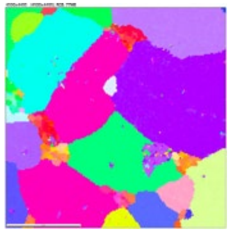
Confocal laser scanning microscope (CLSM)
Keyence VK-X250

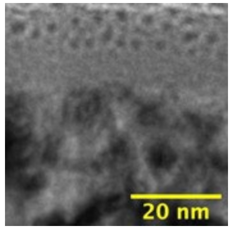
Specifications
- Large area image stitching.
- Profiliometry and roughness measurements.
- Particle, volume, size measurements.
- No sample preparation required.

Impact
- Quantify 3D surface morphology, **surface roughness**

for low activation materials at CAES







Focused ion beam (FIB)

FEI Quanta 3D FEG

Specifications
- High-resolution, high-vacuum dual-beam SEM/FIB for 2-D and 3-D material characterization and analysis.
- Equipped with EDS, EBSD and STEM detector.

Impact
- Cross-sectional analysis & TEM lamella

Scanning electron microscope (SEM)

JEOL JSM-6610LV

Specifications
- Images material surfaces ranging from micrometer to nanometer scale under high-vacuum and low-vacuum environment.
- Equipped with EDS, EBSD and CL.

Impact
- High resolution images,
- Crystal orientation

Scanning transmission electron microscope (STEM)

Tecnai TF30- FEG

Specifications
- Images materials structurally and chemically down to atomic scale.
- Equipped with HAADF, EDS, EELS, EFTEM, Electron Tomography, ASTAR/ TopSpin, PicoIndenter, Heating Stage.

Impact
- Quantify He bubble formation