INL's experimental and computational capabilities for fusion technology development

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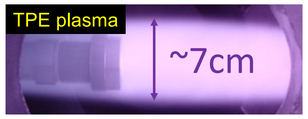
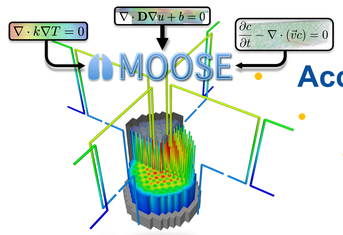
Experimental

- **The Safety and Tritium Applied Research (STAR) facility:**
  - DOE less than Hazard Category 3 radiological facility that handles:
    - **Tritium** (licensed for up to 1.6 gram)
    - **Beryllium** containing compounds (e.g. FLiBe)
    - **Radioactive** materials (< 1 mSv/hr = 100 mrem/hr at 30 cm)
- **Experimental capabilities (see the fact sheet below)**
  1. ***Linear plasma device for FW and divertor material testing***
     - **Tritium Plasma Experiment (TPE)**
       - Provides T retention and trapping, plasma-material interaction
       - Key experimental capabilities:
         - Tritium plasma (< 500 Ci / shot),
         - High-flux plasma (>10^{22} $m^{-2}s^{-1}$) ,
         - Mixed (D-T-He) plasma



Material size: (6-25) mm OD & (0.25 – 2.0) mm thickness

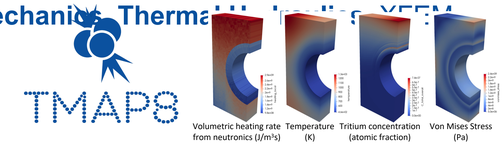
  2. ***Permeation systems to measure H/D/T mass transport properties***
     - **Tritium Gas Absorption Permeation (TGAP)**
       - Provides diffusivity, solubility, and permeability of tritium (T)
       - Key experimental capabilities:
         - Tritium (T_2) gas (< 25 Ci per campaign)
         - Independent control of H_2 and T_2 partial pressures
         - Low tritium partial pressure (10^{-12} < p_{T2} [Pa] < 10^{2})
         - Low temperature (RT to 700 °C)
     - **Static Gas Absorption Permeation (SGAP)**
       - Provides diffusivity, solubility, and permeability of H & D
       - Key experimental capabilities:
         - H_2 and D_2 gas pressure (10^{3}< p_{D2}[Pa] < 10^{5}), high temperature (RT to 950 °C)
  3. ***Forced-convection loops to advance tritium extraction efficiency***
     - **Tritium Extraction eXperiment (TEX)**
       - Lead lithium (PbLi) loop to improve efficiency of T extraction
       - Test tubular membranes (Fe, V, Nb, coated tubes, etc.) of vacuum permeator
       - Additional test section configurations possible.
     - **Molten Salt Tritium Transport Experiment (MSTTE)**
       - Molten salt (FLiNaK, FLiBe) loop to study T extraction methods
  4. ***Exhaust pumping technology development for compact T fuel cycle***
     - **Permeation Experiment for Asymmetric Surfaces (PEAS)**
       - Advances material sciences (e.g. surface condition, material interdiffusion, coating material) required to maintain H isotopes (H,D) super-permeation for metal foil pump development
       - Gas-, Atomic-, and plasma-driven H/D permeation system with in-vacuo surface cleaning (with Ar ion sputter guns) and Auger surface characterization on both front/back surfaces



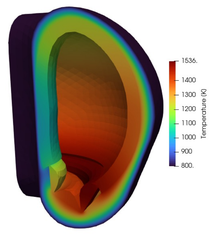
- **Material irradiation capabilities for solid breeder materials**
  - **Neutron RADiography (NRAD) reactor -** 300 kW TRIGA research reactor
    - Provides cost-effective neutron irradiation option with low neutron flux

Computational

- **System-level T & safety analysis for paths to commercialization**
  - **Fusion safety analysis by MELCOR-TMAP**
    - MELCOR is a US NRC computer code developed by SNL to analyze a wide range of accidents and transients that may occur in a nuclear power plant to model and analyze the safety and performance of nuclear system.
    - MELCOR-fusion (developed by INL) was used for many fusion systems:
      - ITER's safety analysis; V&Vd for ITER Non-Site Specific Safety Report (NSSR) 1&2 in 1997, Generic Site Safety Report (GSSR) in 2001, and the Report Preliminary on Safety (RPrS) in 2011, IFMIF-DOMES etc.
      - Many of US design studies including, ARIES, FNSF, FESS studies in the US, and DEMO safety analysis in Europe and Japan,
    - MELCOR-TMAP added Tritium Migration Analysis Program into MELCOR
      - Trace element tracking for H, D, T, Surface reactions, vapor-liquid-solid equilibrium model, Composite interface model for solid structures implemented (coated surfaces), Non-condensable gas modeling improved, HTO modeling
  - **Reliability, Risk, and Optimization by RAVEN, EMRALD, and SAPHIRE**
    - INL can provide the following safety, optimization, and regulatory supports:
      - Hazard analysis, Risk-informed design and system analysis, Uncertainty analysis for multi-physics modeling and simulation, Gather and analyze reliability database for fusion systems, Preliminary PRA and risk metric development, Dynamic risk/reliability assessments, Physics-based risk/reliability assessments, Probabilistic physics-of-failure modeling, Availability and design optimization, Regulatory analysis
- **Accelerating nuclear innovation through advanced ModSim**
  - **MOOSE (Multiphysics Object-Oriented Simulation Environment)**
    - Is a modular and complete platform for fission and fusion multiphysics
      - **Multiphysics, open-source, massively parallel, NQA-1 Software Quality Assurance**
      - MOOSE applications covers wide range of physics:, https://mooseframework.inl.gov/
        - Chemical Reactions, Contact, **Electromagnetics**, Fluid Properties, Fluid Structure Interaction, Function Expansion Tools, Geochemistry, **Heat Conduction**, Level Set, **Navier Stokes**, Peridynamics, **Phase Field**, **Porous Flow**, **Ray Tracing/Particle Tracking**, rDG,, Stochastic Tools, **Tensor Mechanics**, **Thermal Hydraulics**, XFEM
  - **MOOSE-based fusion applications:**
    - **Tritium Migration Analysis Program – TMAP8,** https://mooseframework.inl.gov/TMAP8/
      - Performs multiscale tritium transport and thermal analysis fusion systems



    - **SALAMANDER (Software for Advanced Large-scale Analysis of MAgnetic confinement for Numerical Design, Engineering & Research)** brings together different MOOSE-based physics module, including TMAP8 and Cardinal. https://mooseframework.inl.gov/salamander/
      - Performs multiphysics analysis of FW & blanket systems
    - **Cardinal: MOOSE+OpenMC+NekRS,** https://cardinal.cels.anl.gov/
      - Exascale simulation tool showcase for coupling non-MOOSE-based applications and uses MOOSE physics "glue", and has simulated:
        - Gas-cooled microreactors, sodium fast reactors, molten salt reactors, high-temperature gas reactors, and tritium breeder blankets
    - **MOOSE-based fusion applications developed by UKAEA**
      - Aurora, Apollo, Proteus, Phaethon, etc..
- **Other ModSim development under DOE NE for advanced reactors**
  - **Virtual Test Bed**, https://mooseframework.inl.gov/virtual_test_bed/
  - **Digital Innovation Center of Excellence (DICE),** https://dice.inl.gov/



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