Project X efforts at PNNL

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Dave Senor, and Mary Peterson

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PNNL Involvement Relevant to Project X

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- Project X Nuclear Energy Station
  - Continue to Develop PNNL Concept - see Report PNNL-21134
  - Organize Project X Energy Station Workshop at Fermilab to bring HEP and DOE NE communities together - January 29, 30, 2013 https://indico.fnal.gov/conferenceDisplay.py?ovw=True&confId=5836
- High Power Beam Window Design
  - *Investigating with Internal Funds*
  - >750kW beam power
- Beneficial use of PXIE Beam Dump
  - *Investigating with Internal Funds*
  - Developing experimental concept to resolve reactor antineutrino anomaly
  - Beneficial Isotope Production
  - Nuclear Data
  - Materials Irradiation

Project X Nuclear Energy Station Workshop

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- Fermilab is funding PNNL to lead the organization of a workshop in late January on Nuclear Energy Applications of High Intensity Proton Accelerators

- Workshop Objective

  The Project X Energy Station Workshop objective is to identify and explore the nuclear energy relevant research and development that would be possible in a Nuclear Energy Station associated with the Project X Linac and identify the design requirements for conducting the research. The U. S. Nuclear Energy mission will always require the use of test reactors but one of the hypotheses is whether a Nuclear Energy Station associated with Project X could accelerate and enhance the ability to test and evaluate early research concepts. This workshop will identify the synergy and benefit that the Project X Linac could bring to the nuclear energy community. The workshop will also cover topics related to design requirements, challenges and trade-offs associated with optimizing a high-power continuous wave linear accelerator target station for nuclear energy research.

Project X Nuclear Energy Station Workshop

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- Test the hypothesis - *Could a Nuclear Energy Station associated with Project X accelerate and enhance the ability to test and evaluate early research concepts for nuclear energy applications?*

- Workshop will be organized into two working groups
  - WG1: Proton Beam and Target Design Requirements

    Conveners:
    - Patrick Hurh (FNAL)
    - Bernie Riemer (ORNL)
    - Mikey BradyRaap (PNNL)
  - WG 2: Science and Technology Applications

    Conveners:
    - David Senor (PNNL)
    - Eric Pitcher (LANL)
    - Yousry Gohar (ANL)

Project X Nuclear Energy Station Workshop

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- Keynote Speakers
  - Dr. Burton Richter (SLAC)
    - Technical Challenges in Nuclear Energy and Innovative Uses of Accelerators
  - Dr. Monica Regalbuto (DOE NE)
    - DOE NE R&D Challenges and Roadmap for Addressing
  - Dr. Stuart Henderson (FNAL) – Role of Accelerators
  - Dr. Todd Allen (INL) – Future Needs for Irradiation Testing
- Workshop Goals/Outcomes
  - DOE NE (HQ & community) participation in workshop
  - Identify and explore possible R&D program for a Nuclear Energy Station
  - Identify associated design requirements → Influence the Project X design
  - Participants from NE & HEP-accelerator communities with backgrounds in
    - Accelerator-based applications, Nuclear & material science, Isotope production
    - Applications of high intensity proton beams and targets
    - Advanced nuclear reactor concepts, advanced nuclear fuel cycles, light water reactor sustainability, enhanced and accident tolerant fuels

Project X Energy Station has the potential to benefit several areas (beyond HEP)

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- Could support much needed testing of materials for Nuclear Energy programs to:
  - Ensure the sustainability and safety of the current fleet of reactors as well as future extensions
  - Develop new higher performance and safer reactor fuels and materials
  - Enable the development of innovative economical small reactors
  - Enable the development of new advanced reactor concepts, such as those using liquid metal or molten salt coolants
- In addition, could support DOE Office of Science programs such as
  - Materials Program - Fusion Energy Sciences (FES)
  - Isotope Production Program – Nuclear Physics (NP)
  - (ultra/very) cold neutrons – Nuclear Physics (NP)

Project X Nuclear Energy Station Concept

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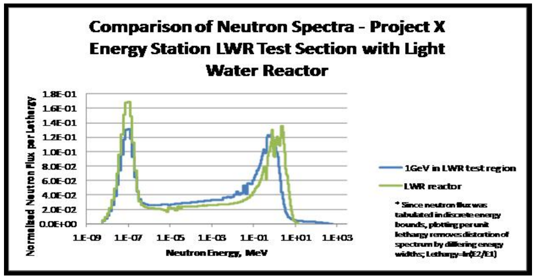
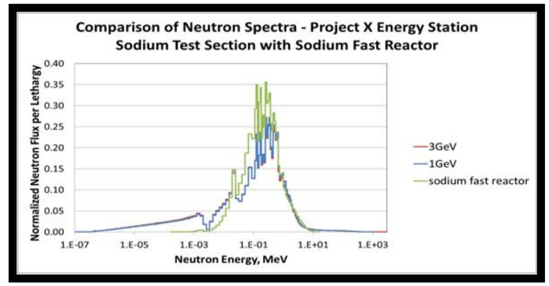
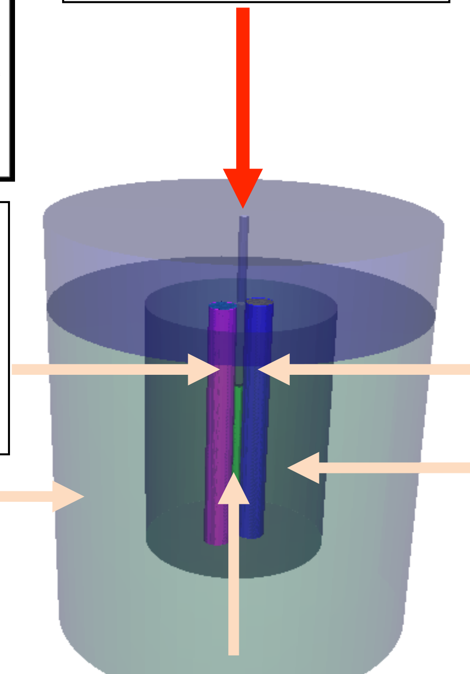
Nuclear Energy Station Concept to provide high flux irradiation at volumes comparable to reactors



Project X Proton Beam
- 1mA @ 1 GeV (1 MW)



Thermal Spectrum Closed Loop Test Module
- Removable/replaceable/customizable
- Independent cooling system
- N spectrum/material/temp/pressure tailored to match reactor conditions
- LWR, HTGR, MSR
- >1e14 n flux, accelerated dpa, He produced

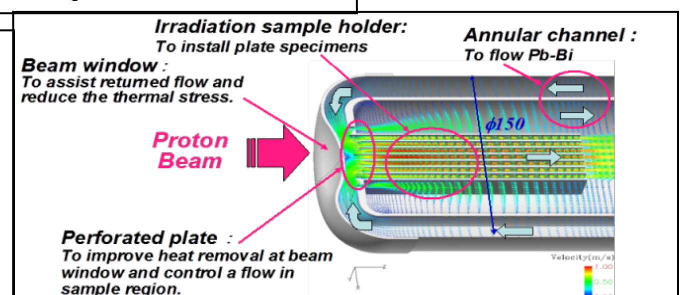


Fast Spectrum Closed Loop Test Module
- Removable/replaceable/customizable
- Independent cooling system
- N spectrum/material/temp/pressure tailored to match reactor conditions
- SFR, LFR, GFR
- >1e14 n flux, accelerated dpa, He produced

Reflector
- Steel/iron/nickel
- Could be D2O for thermal n beams
- High n scatter
- Flattens n flux distribution

Lead Matrix Test Region
- Lead with gas cooling
- ~ 2 m diameter, 3 m length
- Low n absorb/ High n scatter
- High n flux/ Fast n spectrum
- Acts as gamma shield

Spallation Target
- Liquid Pb-Bi
- >30 neutrons/proton
- 1 GeV protons penetrate ~50 cm in lead
- Isotropic n flux distribution
- Similar to fission spectrum
- Samples can be irradiated in proton beam
- Adding W or U can increase n flux level
- Small volume ~ 10 cm dia, 60 cm length
- Cleanup system for spallation products



JPARC Concept

High Power (>750kW) Beam Window Design PNNL facilities, capability & experience include

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- Radiochemical Processing Laboratory (RPL)
  - Category II Non-Reactor Nuclear Facility – rpl.pnnl.gov
- Reactor irradiation testing experience – such as Tritium Technology Program testing in Advanced Test Reactor (ATR); reactor and fusion materials testing in Fast Flux Test Facility
  - Radiation damage of materials, structural design
  - Thermal management
  - Designed and fabricated complex machined parts for use in reactors
  - Designed unique weld joints for nuclear applications and has experience in welding these joints
  - In addition to welding, PNNL has experience in joining ceramics, particularly SiC, but others as well
- Remote Material Testing/Design/Development/Examination capabilities involving hazardous, radioactive, & liquid metal materials
- Additional detail provided in backup slides

Exploring the potential beneficial use of the PXIE beam dump as an experiment station

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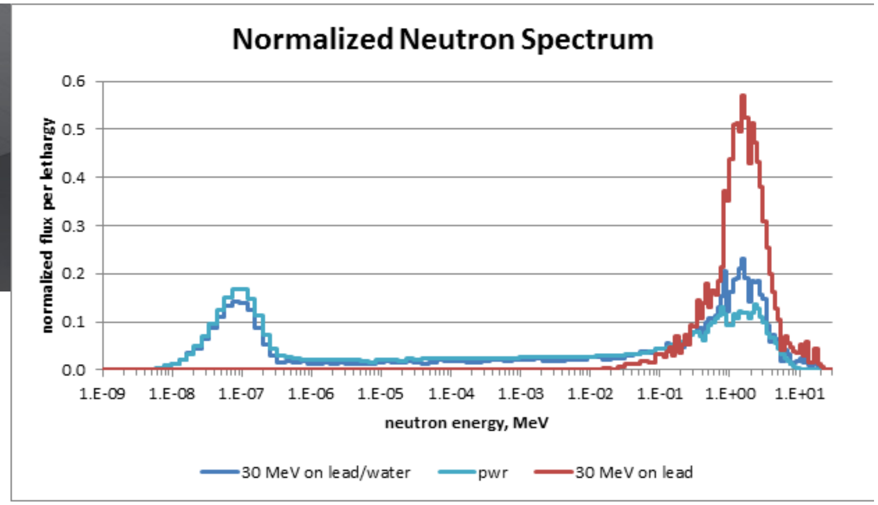
- The possibility of a broad scientific program at an experimental station deployed in the PXIE beam dump is under study at PNNL
  - Isotope production
    - Proton, neutron reactions
    - Rabbit system for retrieval of short-lived isotopes
    - Use PNNL sealed target (including U, Pu) design for isotope production
  - Nuclear data
    - Proton, neutron, gamma ray reaction integral cross sections
    - Unique/exotic/short-lived isotope production
  - Supporting neutrino science
    - Precision prompt beta spectrometry
  - Material irradiation damage testing
    - To benefit fission, fusion and spallation R&D

PNNL Project: Resolving the Reactor Neutrino Anomaly by Precision Beta Spectrometry



Goal

- Develop an improved experimental approach to resolve the "reactor neutrino anomaly" by reducing uncertainties in the associated measured fission product beta spectrum

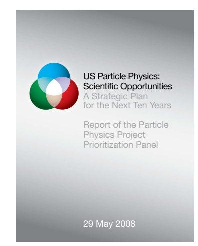
Rationale

- Analyses to explain the "reactor neutrino anomaly" are based on 30 year old set of fission product beta spectra at ILL
- New data can reduce uncertainties and chance of systematic bias
- Accelerator neutron source offers advantages over reactor source in terms of testing sensitivities
- PNNL has the expertise in all of the areas needed to design/deploy experiment

Proposed Approach

- A new approach utilizing the flexibility of an accelerator neutron source with spectral tailoring coupled with a careful design of an isotopic fission target and beta spectrometer will allow further reduction in the uncertainties associated with prediction of the reactor neutrino spectrum and ultimately allow resolution of the reactor neutrino anomaly

Why It Matters



- DOE-HEP 10-year plan includes "a world-class neutrino program as a core component of the US program"
- Future reactor-based neutrino physics experiments will require improved (sub 1%) neutrino spectra to resolve fundamental questions on the nature of neutrinos

PNNL Capabilities Can Provide Relevant Support to Project X

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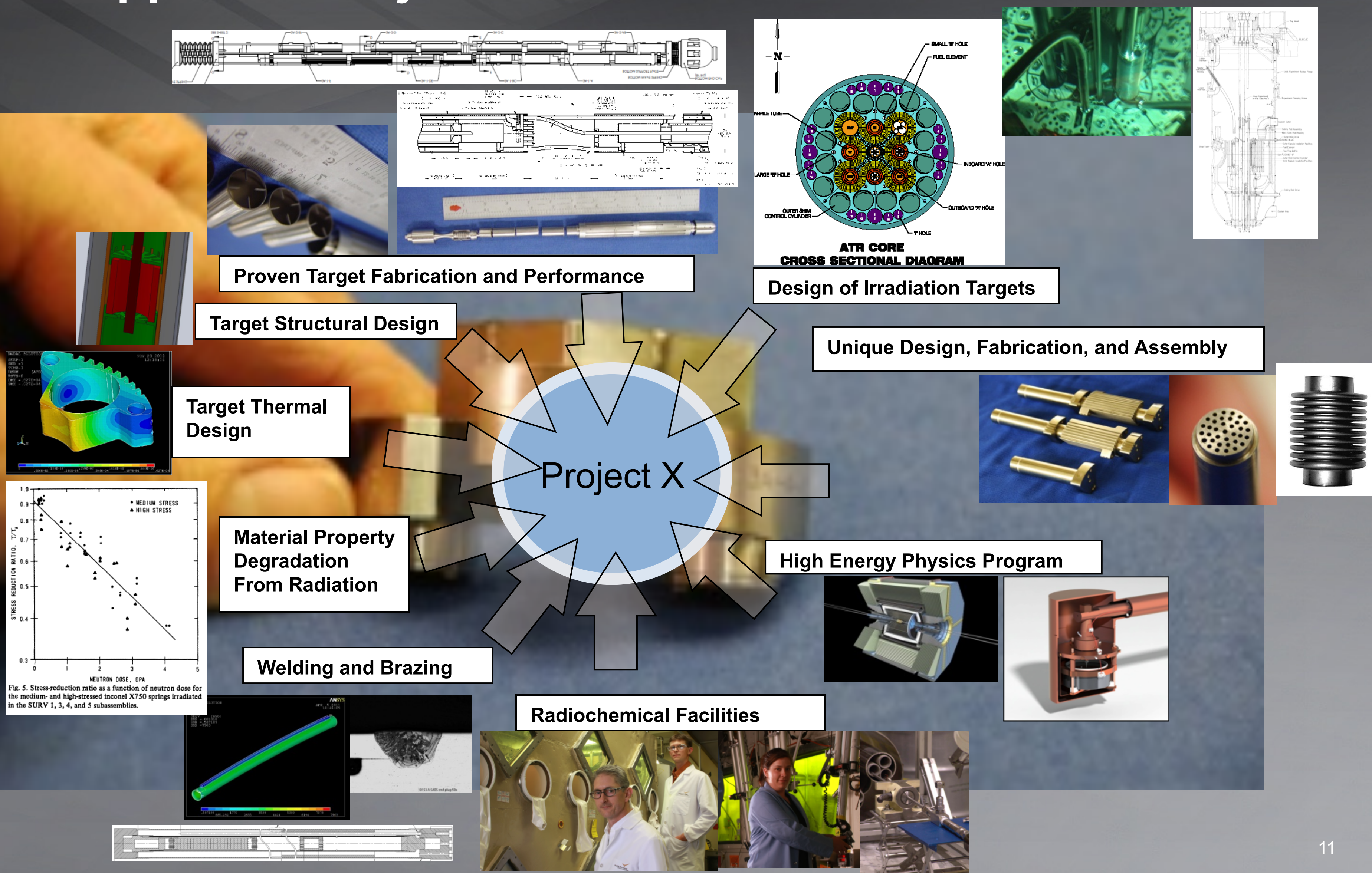

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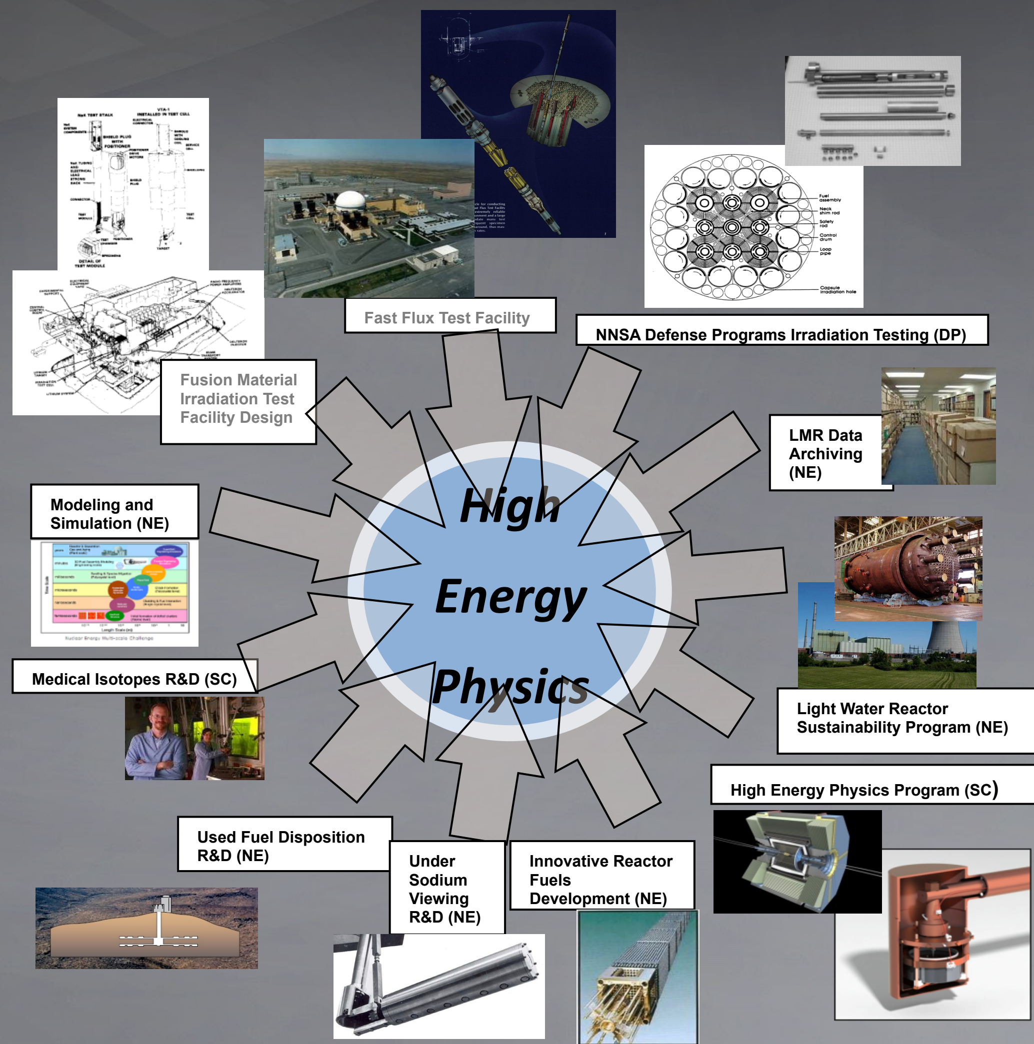
Backup

PNNL Capabilities Can Provide Relevant Support to High Energy Physics



Radiochemical Processing Laboratory (RPL)

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- **Analytical Support Operations**
  - ID/quantification of radioactive isotopes & organic/inorganic radiological compounds.
- **Analytical Transmission Electron Microscope**
  - radionuclide materials analysis at the nanometer scale
- **Helium Gas Measurements**
  - gas mass spectrometer for measurement of extremely low concentrations of helium in very small samples of radioactive and non-radioactive materials, & in selected gases.
- **Hydrogen Gas Measurements**
  - a unique quadrupole mass spectrometry system that provides sensitive measurements of hydrogen in very small samples of radioactive and non-radioactive materials.
- **Medical Isotopes**
- **Radiochemical Process Engineering**
- **Quantitative Gas Mass Spectrometer**
  - rapid sample turnaround, with typical detection limits
- **Radiochemical Separation**
  - Unique facilities and broad-based staff allow for separations research to span the spectrum from the molecular level up to testing of flowsheets for industrial application.

Radiochemical Processing Laboratory (RPL)

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- **Radiological Dispersion and Interfacial Chemistry**
  - Capability to study and control properties (composition, particle size distribution, surface charge, viscosity, and density) in radioactive and non-radioactive systems using equipment on bench tops, radiological fume hoods, glove boxes and hot cells.
- **Radiological Nuclear Magnetic Resonance Laboratory**
- **Radiological Surface Science Laboratory**
  - multi-instrument facility that combines powerful surface analytical capability with the ability to examine radioactive samples,
- **Reactor Dosimetry**
  - Techniques & monitors to make measurements in complex reactor environments and computer programs to determine fundamental neutron exposure & radiation damage.
- **Shielded Facilities Operations**
  - Hot cell complexes & stand alone mini-cells provide unique, complimentary capabilities for bench-scale to pilot-scale work with wide varieties/forms of radioactive materials.
- **Spectroscopic Capabilities**
  - For studies of highly radioactive materials (tank waste, spent fuel)
- **Thermoanalytical Capabilities**
  - Provides real-time and correlated information on reaction products, reaction enthalpies, mass changes, reaction kinetics, and heat transfer.

PNNL Experience: Irradiation Target Design

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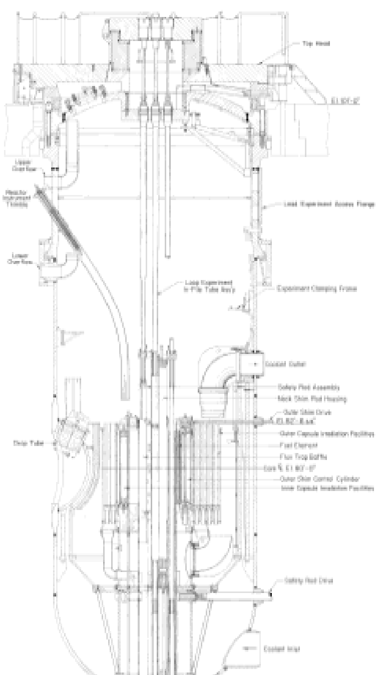
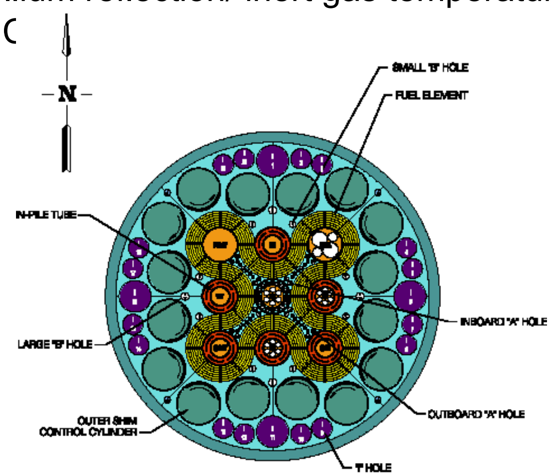
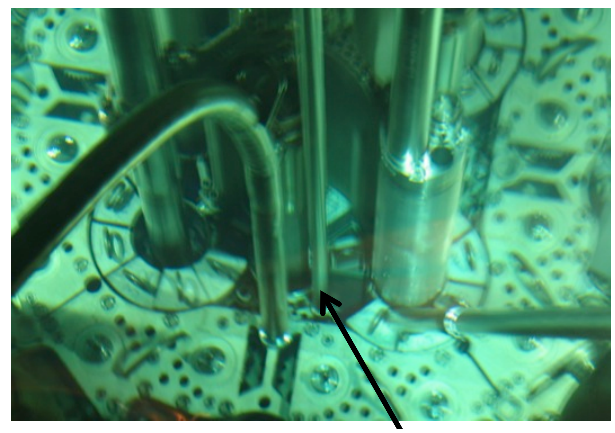
- Extensive Capabilities with Proven Performance of Target Designs in Challenging Complex Nuclear/Thermal Environments
  - Advanced Test Reactor (ATR) Irradiation Targets
    - Max thermal power = 110MWt (22 MWt per lobe)
    - Max thermal neutron flux=1E15 n/cm^2/s in flux trap
    - Water cooling/ beryllium reflection/ inert gas temperature control systems, typical test temperatures from 50°C to 1000°C





ATR CORE CROSS SECTIONAL DIAGRAM



TMIST-1 leadout in the ATR B-2 position

- PNNL Tritium Technology Program supports design, development, demonstration, testing, analysis, and post irradiation characterization of Tritium-Producing-Burnable-Absorber-Rods (TPBAR) for NNSA
- TMIST (TPBAR Materials Irradiation Separate-Effects Test) is a series of irradiation tests in ATR designed, developed, and executed by PNNL for the Tritium Technology Program
- PNNL is Design Agency for Program
- Issues: Thermal management, active temperature control, activation, tritium containment

Target Thermal Design

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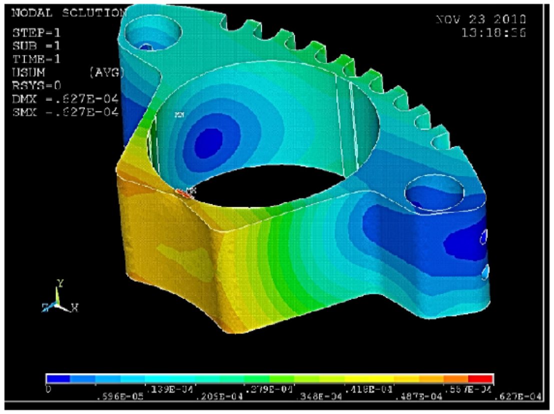
- PNNL has extensive thermal modeling capabilities needed to design a target that will perform under demanding and complex heat deposition conditions



  - ANSYS and multi-physics experience
  - Irradiation Energy Deposition
  - Conduction, Convection, Radiation
  - Thermal Gradients
  - Gas Mixtures and Control
  - Full 3-dimensional modeling

- These modeling capabilities have been proven through years of successful in-reactor irradiation testing

Material Property Degradation from Radiation Damage

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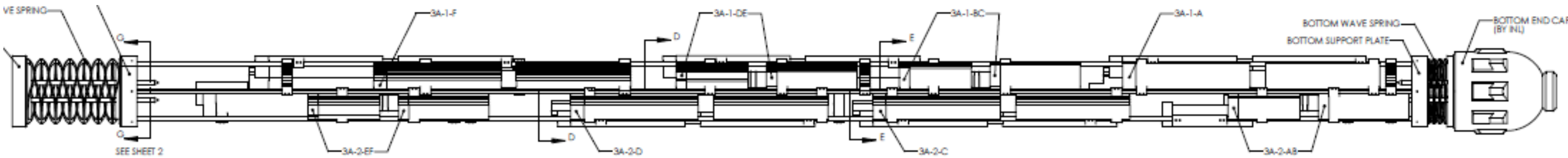
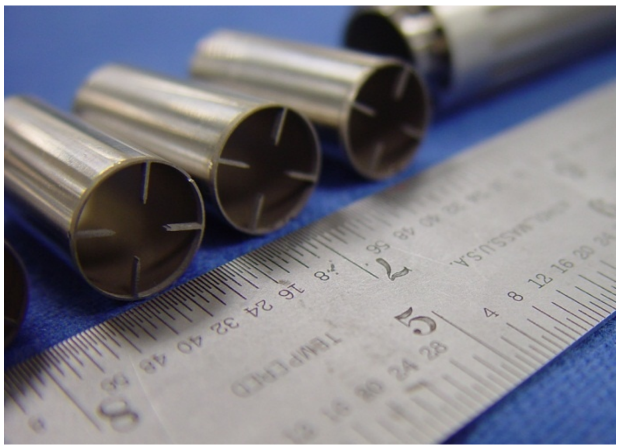
- Changes in material properties from radiation effects in accelerator target materials and beam windows can be life limiting
- For example, the buildup of helium from nuclear reactions can be life limiting for some materials
- PNNL has developed the capability to measure He in very low concentrations in steels
- PNNL has experience in relating high fluence effects to material property degradation
- PNNL has developed molecular dynamics methods for modeling displacement cascades at atomistic levels
- PNNL has established dosimetry capabilities that might be useful in benchmarking actual conditions against predictive design codes

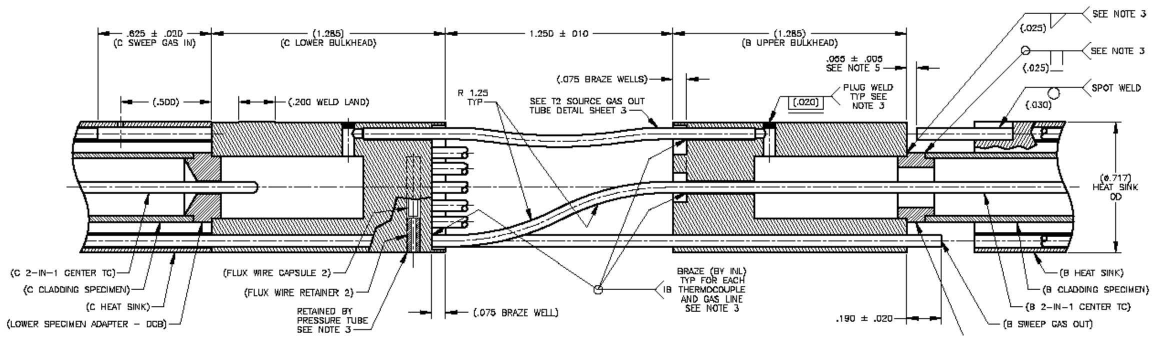
Proven Target Fabrication and Performance

In many respects, design of in-reactor targets can be more demanding than accelerator targets



TMIST-3 In-Reactor Test Cage Assembly

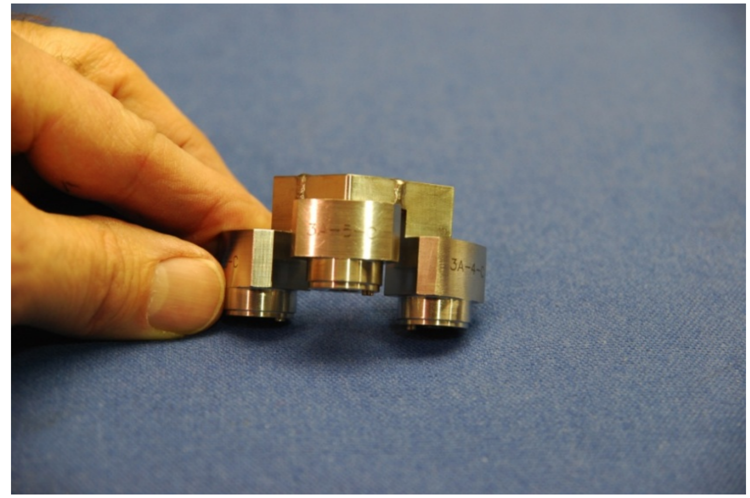




TMIST-2 In-Reactor Tritium Permeation Test Assembly with Real-Time Instrumentation and Control

Unique Design, Fabrication, and Assembly

- PNNL has designed and fabricated complex machined parts for use in reactors
- PNNL has designed unique weld joints for nuclear applications and has experience in welding these joints
- In addition to welding, PNNL has experience in joining ceramics, particularly SiC, but others as well
- Various approaches used for differential strain relief



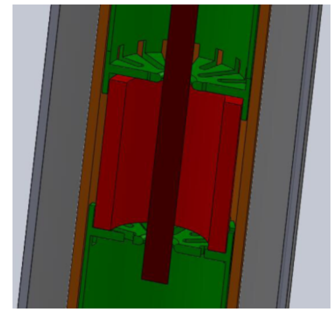
TMIST-3 Upper End Plug, illustrating unique fabrication and joining solutions for in-reactor tests

The holes shown in the end cap photo are 0.020 inches in diameter

Mini-Flex Hydroformed Bellows

Target Structural Design

- Extensive Structural Mechanics Modeling Capabilities
  - ANSYS Structural Code Modeling
    - Mechanical, Thermal, and Multi-physics
  - Solid Works 3D Modeling
  - Linear / Nonlinear Stress Analysis
  - Dynamic Transient Analysis
  - Modal Analyses / Natural Frequencies



- Irradiated Material Properties
  - High Strength Alloys, Stainless Steel, Zirco ,
    and Aluminum Alloys
  - Damage, DPA, Growth, Swelling
  - Thermal Effects
  - Transmutation, Hydrogen Embrittlement
  - Fatigue
  - Stress Relaxation

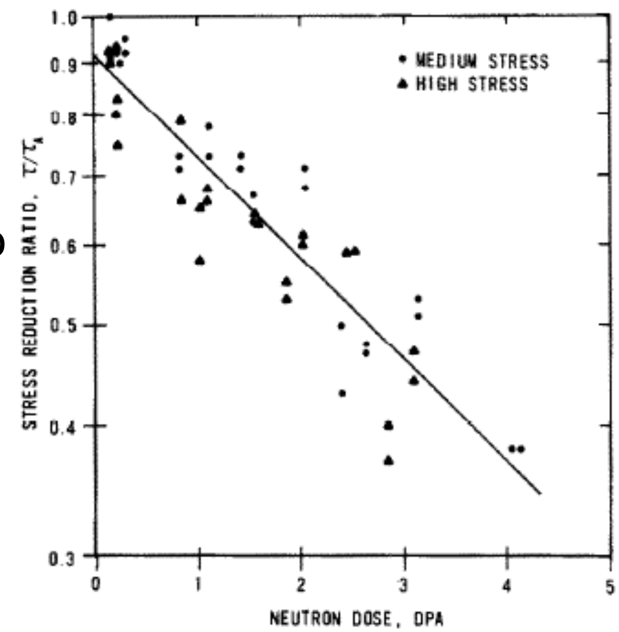
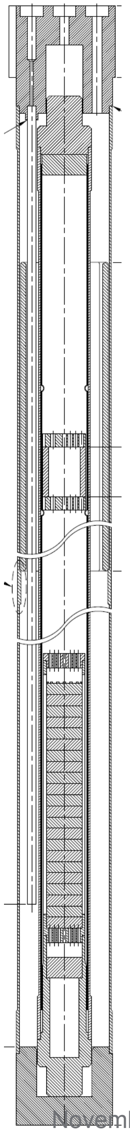
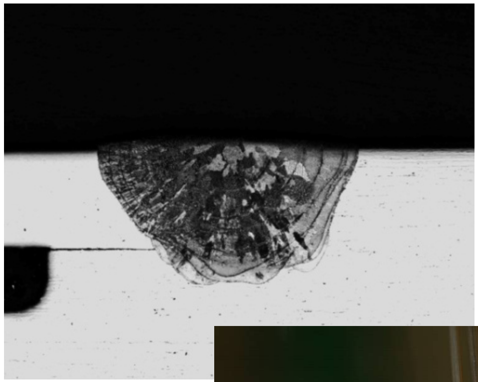


Fig. 5. Stress-reduction ratio as a function of neutron dose for the medium- and high-stressed inconel X750 springs irradiated in the SURV 1, 3, 4, and 5 subassemblies.

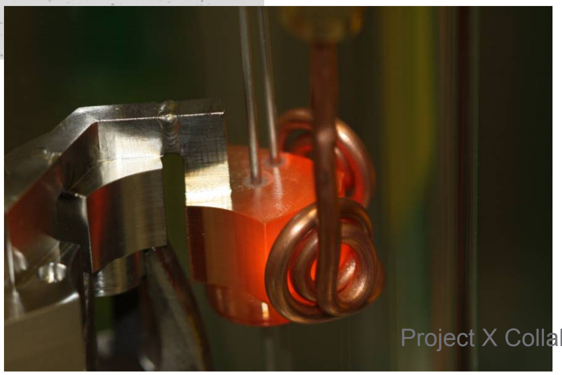
Welding and Brazing

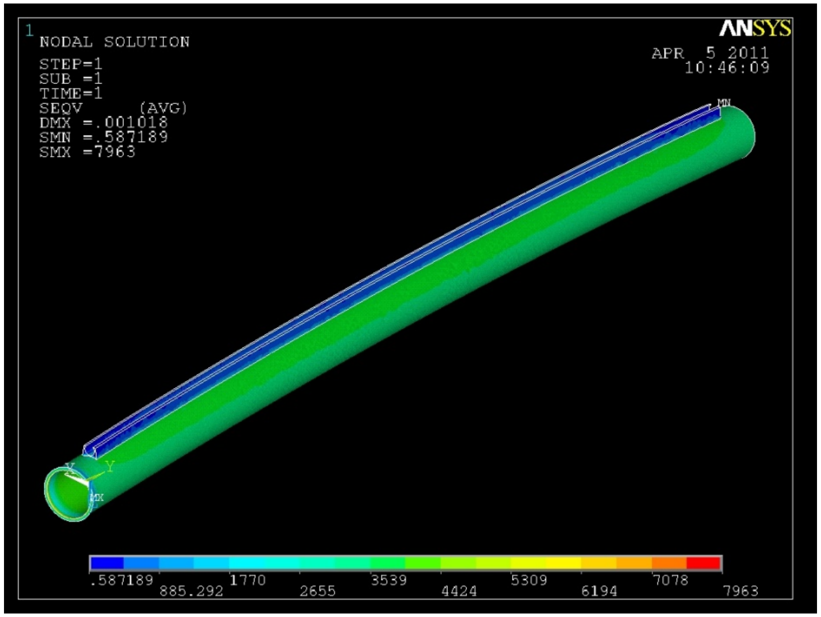
- Weld Joint and Braze Design, Specification and Qualification
- E-Beam, TIG and Laser Welding Capabilities
- American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code Compliance and Analyses
- Commercial ASME NQA-1 Quality Assurance Program required by US Nuclear Regulatory Commission (USNRC) for reactor applications





TMIST-3 Test Fabrication Analysis





PNNL Capabilities Relevant to Project X

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- Hanford Engineering Development Laboratory heritage
- Facility design experience
- Nuclear Quality Assurance Program (NQA-1), required for Nuclear Facility Applications
- Reactor irradiation testing experience – such as Tritium Technology Program testing in ATR; reactor and fusion materials testing in Fast Flux Test Facility
  - Radiation damage of materials, structural design
  - Thermal management
  - Weld development, unique weld joint design
  - Fabrication and assembly
  - Quality assurance inspections, documentation
  - Remote handling, post irradiation examination
- Remote Material Testing/Design/Development/Examination capabilities involving hazardous, radioactive, and liquid metal materials
- Path for waste disposal
- Environmental Assessments for NRC
- Licensing support