Energy Station Concept

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Rationale

- DOE-NE needs continued irradiation testing to support programs: SMR, LWR sustainability, Fuel Cycle R&D, Advanced Concepts, Gen-IV
- Limited availability and irradiation space in existing DOE reactors (HFIR and ATR)
- Project X provides opportunity for neutron source for irradiation testing without reactor or subcritical multiplier
- Project X accelerator will be built whether DOE-NE participates or not

Why It Matters

- The DOE Nuclear Energy mission will always require the use of test reactors but a Nuclear Energy Station associated with Project X could accelerate and enhance the ability to test and evaluate early research concepts.

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**
  - Materials Program - Fusion Energy Sciences (FES)
  - Isotope Production Program – Nuclear Physics (NP)
  - ultra cold neutrons – Nuclear Physics (NP)

PNNL Energy Station Concept

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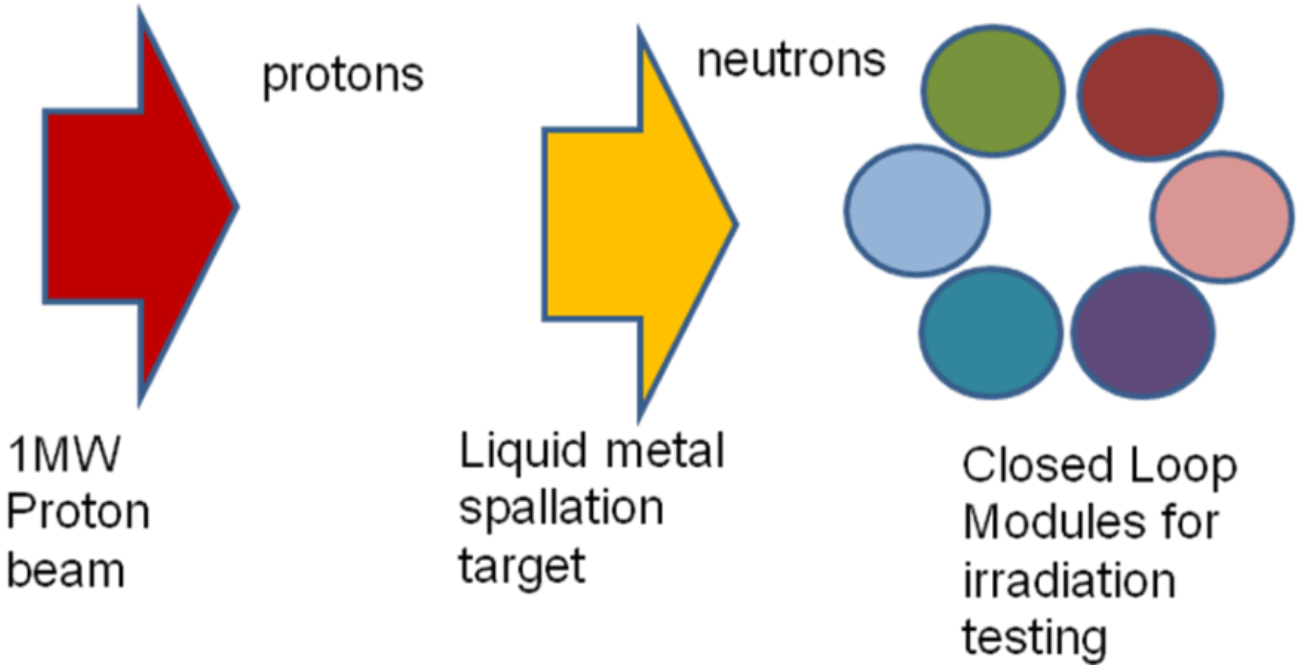
- A new approach utilizing the flexibility of an accelerator neutron source with spectral tailoring coupled with a careful design of a set of independent test loops can provide a flexible neutron test station for DOE NE applications



Project X Energy Station Concept

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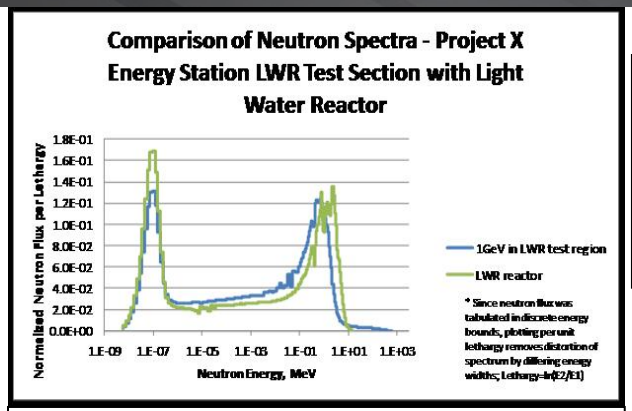
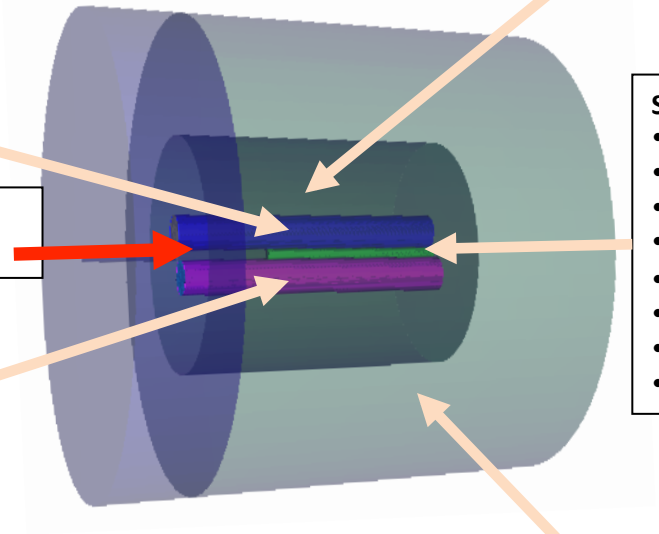


Thermal Spectrum Test Module: LWR, HTGR, MSR

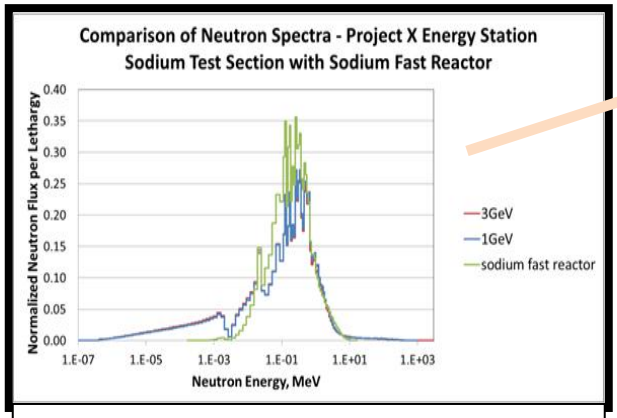
Closed Loop Test Modules
- Removable/replaceable/customizable
- Independent cooling system
- n spectrum/material/temp/pressure to match reactor conditions
- ~30 cm dia

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



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

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



Fast Spectrum Test Module: SFR, LFR, GFR

Reflector
- Steel/iron/nickel
- High n scatter
- Flattens n flux distribution

Energy Station is Unique Combination of Existing Technologies

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- Proton beam CW - 1 GeV - 1 mA - 1 MW
- Spallation Target:
  - Liquid lead or lead-bismuth release ~30 neutrons/proton
  - Neutron spectrum similar to fission spectrum but with high energy tail
  - Technology has been demonstrate at MEGAPIE
- Test Matrix
  - Solid lead or other (zircalloy) – high scatter, low absorption
  - Maximizes neutron flux, provides space for array of test modules
  - Simple solid block with cooling, holes for test modules
- Closed Loop Test Modules
  - Independently tailored irradiation environments (LWR, HTGR,SFR,LFR)
  - Independent heating/cooling system for each to control temperatures
  - Concept utilized in FFTF (sodium), BOR-60 (sodium, lead), ATR (press. Water)
- Reflector to minimize leakage neutrons

Energy Station Components – Spallation Target

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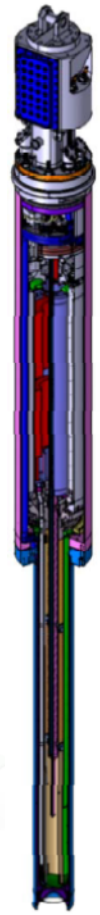
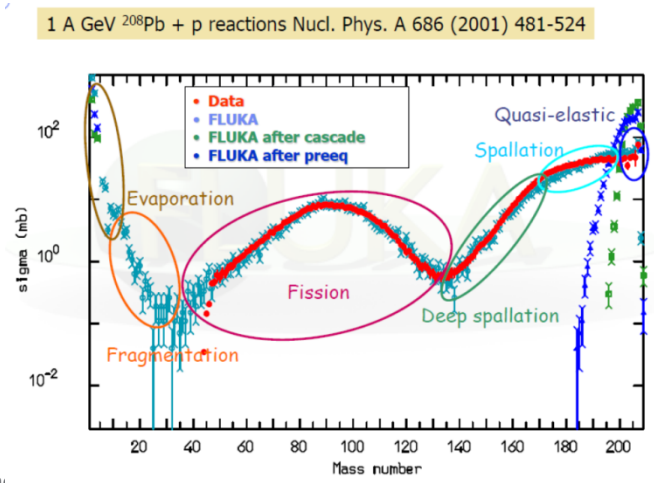
- Spallation Target:
  - 6.24e15 p/s proton beam
  - Nominal 10 cm diameter
  - High neutron yield Pb or LBE ~30 neutrons/proton
  - 1 GeV protons penetrate ~50 cm in lead
  - Neutron spectrum similar to fission but with high energy tail
  - Coolant is target material, no stress issues in target
  - Beam window may be life limiting
    - Experience base from ISIS, SINQ, MEGAPIE, SNS, is ~7-22 dpa/yr on front window for SS316, T91, Inconel
    - For our 10 cm diameter ES window, ~8 dpa/yr
  - Need careful oxidation control, on-line cleanup
  - Spallation products like fission products
  - >400 KW energy deposited
  - Potential for in-beam materials testing

MEGAPIE (0.8 MW) LBE target has been demonstrated





Energy Station Components – Test Matrix

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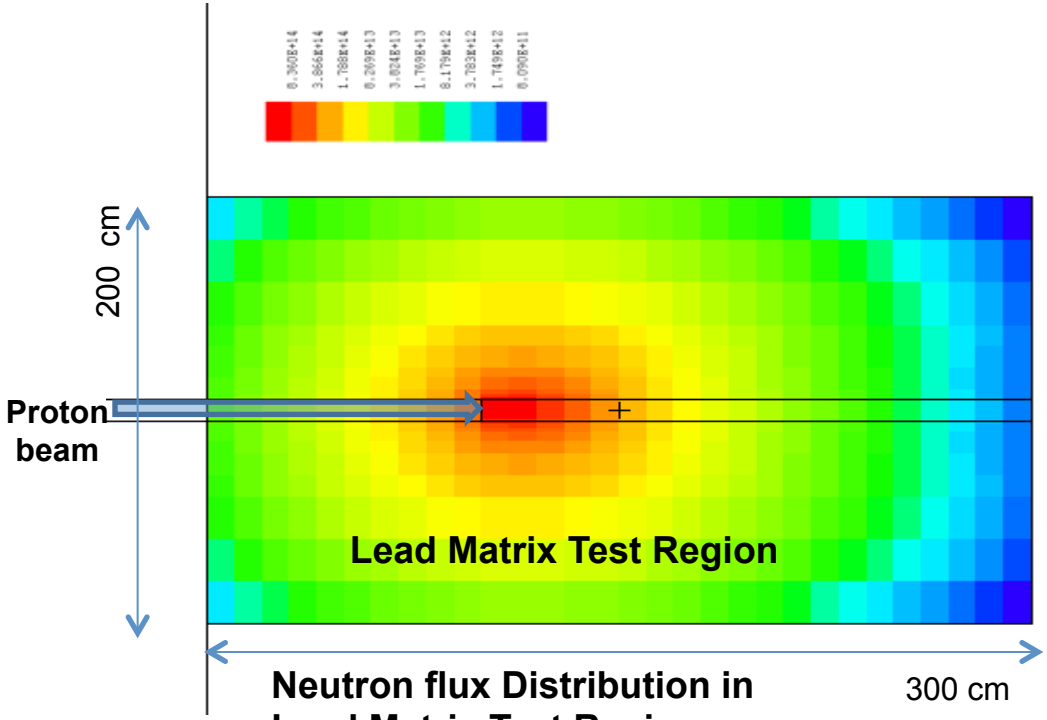
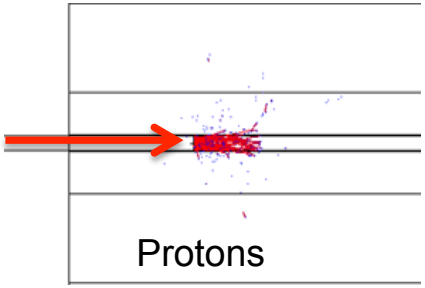
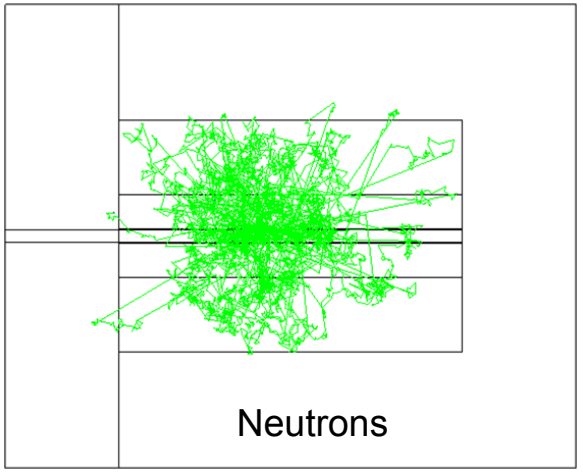
- Test Matrix
  - Solid lead or other (zircalloy) – high scatter, low absorption
  - Maximizes neutron flux, provides space for array of test modules
  - Simple thermal analysis indicates heating may allow solid lead matrix
  - Beam tubes could provide additional testing flexibility



Neutron flux Distribution in Lead Matrix Test Region





High Flux Volumes Available in Test Matrix Region

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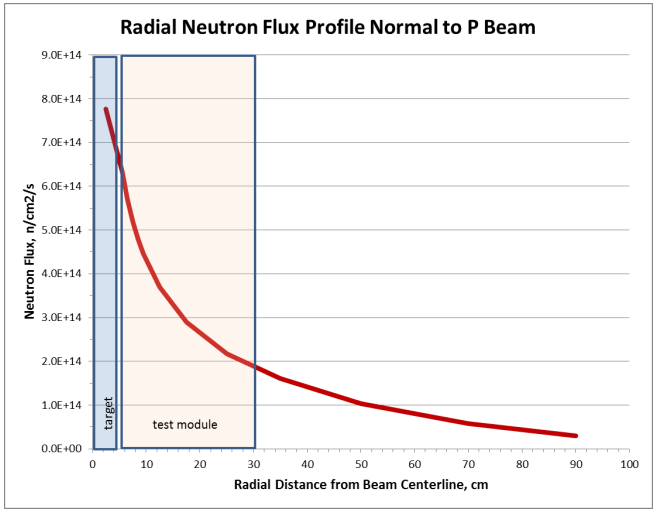
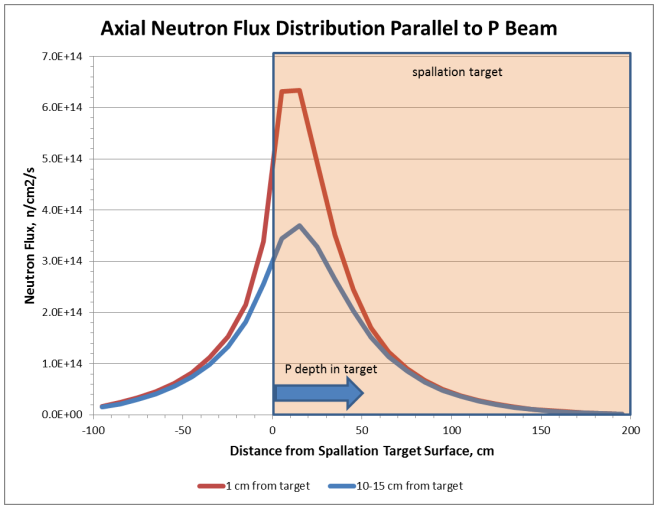
Neutron Flux Range (n/cm2/s)	Axial Extent (cm)	Outer Extent (cm)	Volume (liters)
>5e14	30	8	~2.8
>3e14	50	15	~23
>1e14	110	60	~600
>5e13	160	80	~2000
>1e13	250	100	~9000





- 1 GeV protons penetrate ~ 50 cm in lead or LBE target, generate ~30 neutrons/proton
- Neutron flux falls off radially but lead matrix helps
- Axial profile peaks ~20 cm below target surface, provides ~100 cm >1e14 n/cm2/s

Energy Station Components – Closed Loop Test Modules

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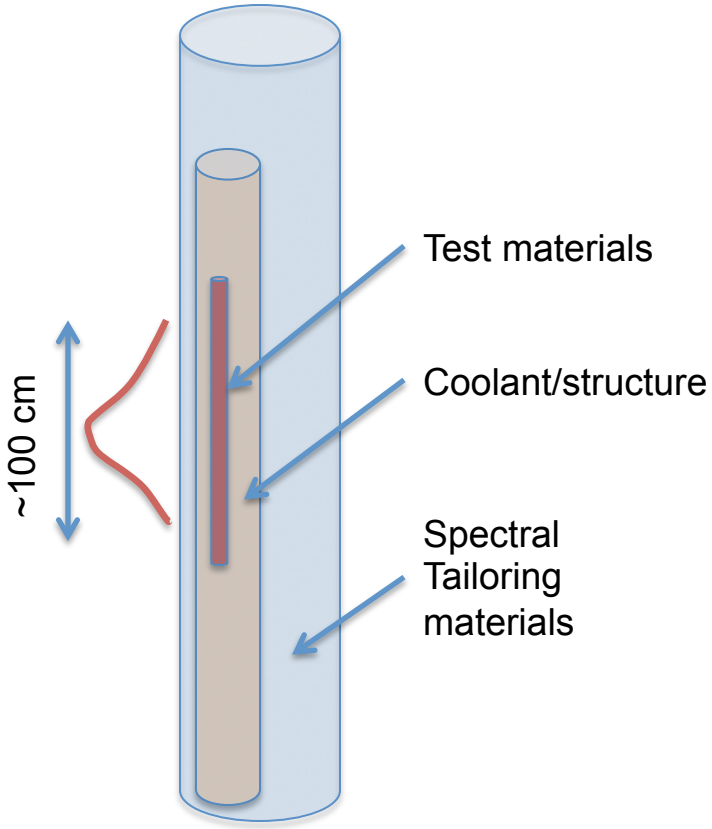
- Number of modules can be varied
- Each module can have unique independent coolant and materials and operate at independent temperatures (sodium, lead, molten salt, water, helium)
- Neutron spectrum can be tailored from fast to thermal to match reactor conditions (the gamma to neutron ratio can also be tailored)
- Miniaturized test specimens can maximize testing in high flux region
- Modules are Removable, Replaceable, shipped offsite for post irradiation examination (PIE)



Spectrum Tailoring Can Simulate A Different Reactor in Each Module

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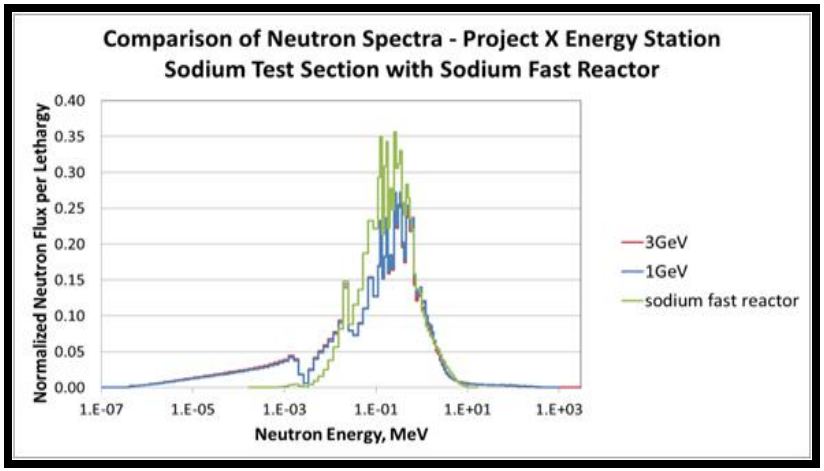
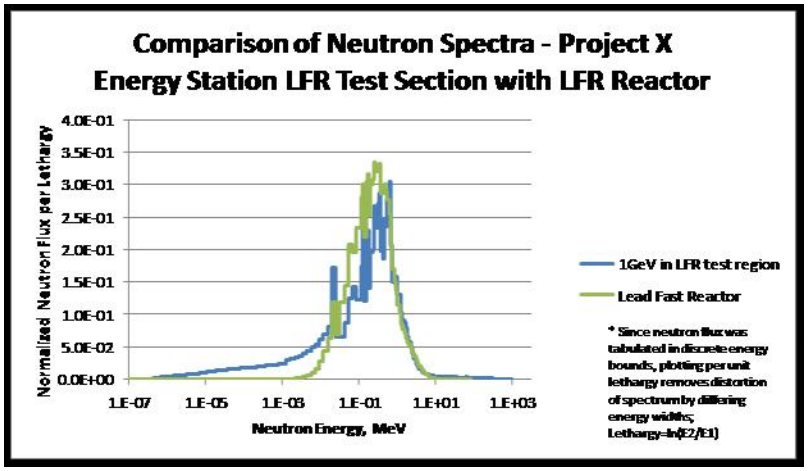
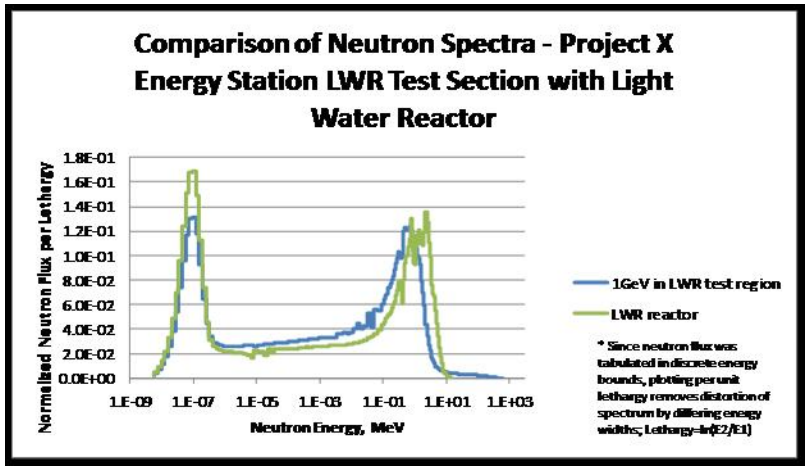


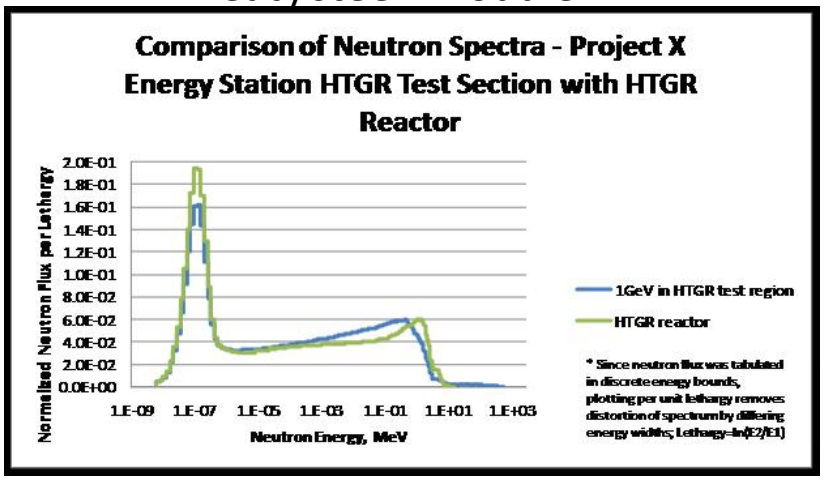
Sodium/steel Module



Lead/steel Module



Water/Zr Light Water Module



Graphite/He Module

How Does Energy Station Compare?

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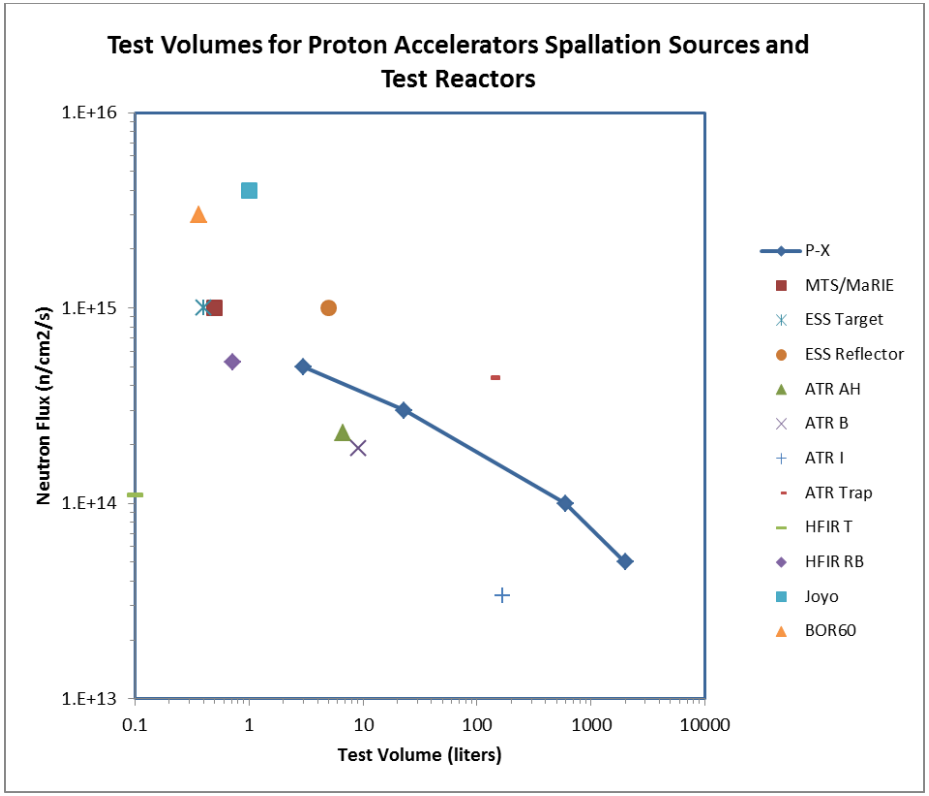

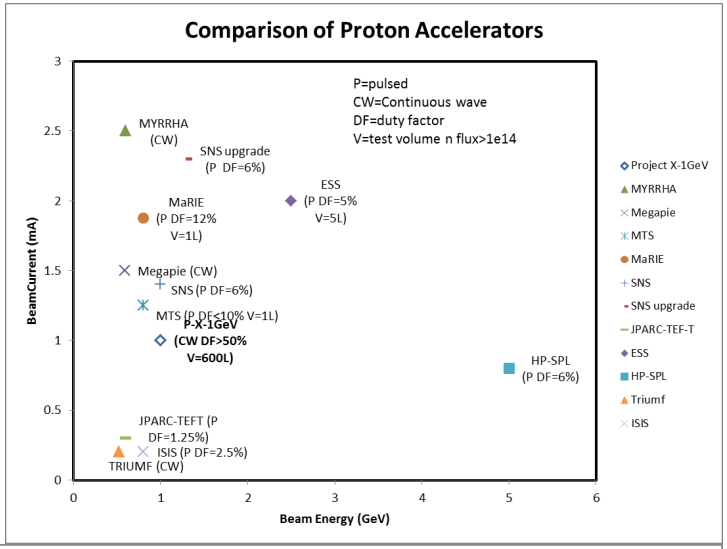

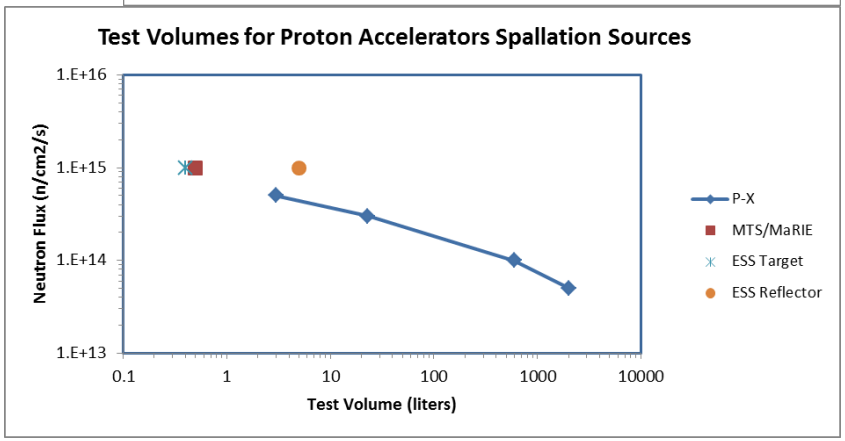

- Irradiation volumes at high flux comparable to reactors
- Accelerator parameters are in range of other proposed systems

Energy Station Capabilities

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- Flexible design allows support to multiple missions for DOE-NE, SC-FES, SC-NP
- Benefits of test reactor volumes and neutron fluxes without reactor issues – licensing, fuel supply, safety, waste
- Robust technology allows it to be designed and constructed with today's technology in order to fill gaps in tomorrow's technology
- Continuous wave, high availability, high beam current provides potential for irradiation tests to high fluence
- Energy distribution of spallation neutrons similar to fast reactor fission spectrum but with high energy tail up to proton energy
- Ability to tailor neutron spectrum from fast to thermal as well as the gamma to neutron flux ratio
- H and He generation in materials higher than in reactor allowing accelerated aging testing
- Potential for beneficial isotope production and/or neutron beams simultaneous with irradiation testing

Programs Energy Station Could Support

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	Material (Temp Cont.)	ADS/ LFR (lead)	HTGR (Helium)	SFR (sodium)	LWR (water)	MSR (Fl salt)	Fusion (Lithium)	Other - Nuclear Data Isotope Prod.
Fuel Cycle R&D (NE)	X	X	X	X	X	X		X
Used Nuclear Fuel Disposition R&D (NE)		X						X
Advanced Modeling & Simulation (NE)		X	X	X	X	X		X
LWR Technologies (NE) (Industry)	X				X			
Gas Reactor Technologies (NE)	X		X					
Advanced Reactor Concepts (NE)	X	X	X	X	X	X		X
Small Modular Reactors (NE) (Industry)	X		X	X	X	X		
Space & Defense Power (NE)	X		X	X	X			X
Fusion (SC)	X						X	
Isotopes (SC)	X							X

DOE Office of Nuclear Energy

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- DOE NE R&D Roadmap (2010) listed four objectives:
  - Develop technologies to improve reliability, sustain safety, and extend life of current fleet of reactors
  - Develop innovations that improve affordability of new reactors
  - Develop and test sustainable fuel cycles
  - Minimize risks of nuclear proliferation and terrorism
- Roadmap Focus Areas:
  - Aging phenomenon and degradation of system structures and components, develop and test advanced monitoring and NDE technologies, improve materials data such as composite cladding;
  - Fundamental nuclear phenomena and advanced fuels and materials to improve the economic and safety of advanced reactors such as corrosion resistant materials, radiation resistant alloys
  - Development of a suite of sustainable fuel cycle options that improve uranium resource utilization, maximize energy generation, minimize waste generation, improve safety, and limit proliferation risk
  - Development of the tools and approaches for understanding, limiting, and managing proliferation risks, such as options that enable decreasing the attractiveness and accessibility of used fuel and intermediate materials, and transmuting materials of potential concern.

LWR Technologies

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R&D Scope	Environment	Testing Needs
• Sustainability of current fleet of reactors • Aging and reparability • Material damage such as pressure vessel embrittlement • Reparability such as knowing when helium accumulation prevents weld repairs to structures • Safety, performance during potential accident conditions • Monitoring	• Thermal Spectrum • Light water moderator and coolant • Zr cladding • Temperature range ~300 C	• Structural material properties as a function of dpa and temperature • Effect of irradiation temperature on fracture toughness • Cumulative 50-100 dpa • Applicability of fast reactor data to LWRs

Energy Station Can Help LWR Technologies

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- Thermal spectrum test environment at relevant temperatures
- Metal hydride such as zirconium hydride can provide higher hydrogen density than water at LWR temperatures without high pressures (has been demonstrated in sodium fast reactors such as FFTF, Phenix)
- Water loop can be used to test materials interactions
- Higher H and He generation rates for corresponding damage accumulation could allow accelerated testing of materials
- Potential test volumes in Energy Station could be 100's of liters

Fuel Cycle R&D
Advanced Reactor Technologies

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R&D Scope	Environment	Testing Needs
Advanced Reactor Technologies • Gen-IV, aSMR • Basic physics • Material research and testing • Modeling and simulation of reactor systems and components • Probabilistic risk analysis of innovative safety designs and features • Development activities to establish concept feasibility for future deployment **Fuel Cycle R&D** • Material testing • Structural materials • Advanced nuclear fuels • Reactor systems • Instrumentation and controls • Power conversion systems • Process heat transport systems • Dry heat rejection • Separations processes • Waste forms • Modeling and simulation • Small scale tests to validate system elements	**Sodium cooled fast reactor (SFR)** • Sodium coolant Steel cladding • Temperature range ~550 C **Lead cooled fast reactor (LFR)** • Fast spectrum • Pb or LBE coolant Steel cladding • Temperature range 500-800 C **Gas cooled fast reactors (GFR)** • Fast spectrum • Temperature range ~600-850 C • Helium coolant Steel cladding **Very High Temperature Reactor (VHTR)** • Thermal spectrum Graphite moderated • TRISO fuel Helium cooled • Temperature range ~1000 C **Supercritical water cooled reactor (SCWR)** • Thermal spectrum • Light water coolant Steel cladding • Temperature range ~550 C **Molten Salt Reactor (MSR)** • Thermal spectrum • Sodium fluoride salt coolant • Fuel dissolved in coolant • Temperature range ~700-800 C	• Structural material properties as a function of dpa and temperature • Material compatibility at operating conditions • Integral tests of fuel, structural materials • Feature tests of components • Fuel performance with minor actinides • Cumulative ~200 dpa • Long life fuel concepts ~300-500 dpa

Energy Station Can Help Fuel Cycle R&D and Advanced Reactor Technologies

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- All of the advanced concepts can be tested in appropriately designed test loops
- Neutron flux tailoring can create fast or thermal spectrum test environments that match very different reactor environments at relevant temperatures
- Room for separate sodium, lead, LBE, helium, molten salt, water loops that can be used to simultaneously test materials interactions
- Candidate materials such as fuel and cladding can be irradiated in a prototypic coolant, temperature, and neutron spectrum
- Temperature is a critical parameter in materials irradiation and precise temperature control will be a key aspect of the Energy Station Test Module design
- Higher H and He generation rates for corresponding damage accumulation could allow accelerated testing of materials
- Potential test volumes in Energy Station could be 100's of liters

DOE Office of Science – Fusion Energy Science

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R&D Scope	Environment	Testing Needs

Technology gaps requiring materials qualification
• Plasma facing components
• Low activation structural materials
• Solid breeder materials
• Safety
	• 14 MeV neutrons
	• Materials surrounding fusion ignition region
	• Tritium producing lithium blanket region
	  • He cooled Li-lead
	  • Lead cooled
	  • He cooled ceramic/ Be
	  • Water cooled ceramic/Be
		• Structural material properties as a function of dpa and temperature
		• 20-30 dpa/yr
		• Cumulative 150-200 dpa
		• Temperature range of 550-1000 C
		• He and H concentrations up to 1500 appm and 6750 appm

Energy Station Can Help Fusion Energy Science Technologies

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- Dedicated fusion loop for materials testing with high energy neutron spectrum test environment at relevant temperatures
- Room for separate lead, helium, water loops that can be used to simultaneously test materials interactions
- The dpa accumulation and high energy neutron spectrum component can simulate fusion environments better than reactors
- Testing in the proton beam can provide high dpa and high neutron energies
- H and He generation rates for corresponding damage accumulation could allow testing of fusion materials
- Candidate fusion blanket materials can be irradiated in a prototypic coolant, temperature, and high neutron flux
- Temperature is a critical parameter in materials irradiation and precise temperature control will be a key aspect of the Energy Station Test Module design

Beneficial Use of Project X Injector Experiment (PXIE) Fusion Energy Science

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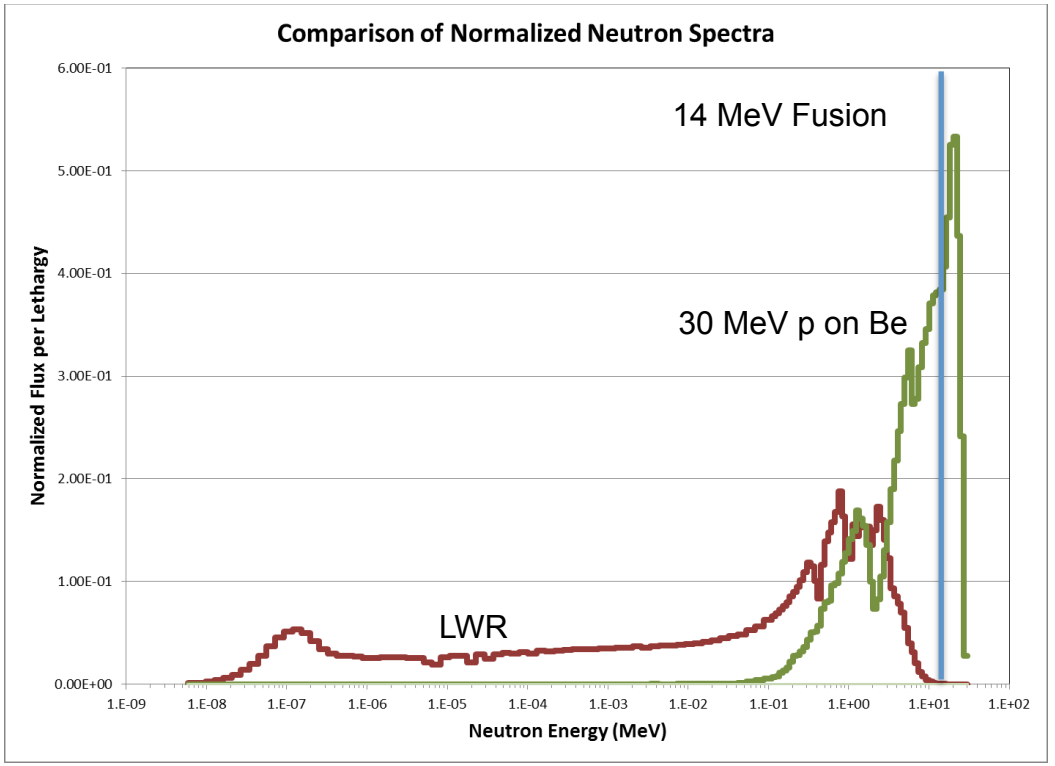
- The 30 MeV proton beam at PXIE directed on a beryllium target can produce a high energy neutron spectrum useful for fusion studies

Energy Range	Neutron Flux (n/cm2/s)	Fraction
<1 MeV	2.1e13	0.12
1-5 MeV	4.3e13	0.25
5-10 MeV	3.2e13	0.18
>10 MeV	7.8e13	0.45
Total	1.7e14	1.00



DOE Office of Science – Isotope Production

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R&D Scope	Environment	Testing Needs
Radioisotope Production methodology	• Neutron spectrum tailored for specific isotopes • Easy access and retrievability • Minimize contamination • Short-lived isotopes may need rabbit system	• Low activation target and structural materials • Target/capsule compatibility

Energy Station Can Help Isotope Production Technologies

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- Dedicated isotope production loop with capability to vary neutron spectrum test environment and temperatures to optimize for isotopes of interest
- Room for separate loops that can be used to simultaneously produce and test a variety of isotopes
- Testing in the proton beam can provide accelerator produced isotopes
- Higher neutron energies than reactors can enhance production of isotopes only produced by fast neutrons
- Temperature is a critical parameter in some isotope target irradiations and precise temperature control will be a key aspect
- A rabbit system can be integrated into the test module for rapid insertion and retrieval of short lived radioisotopes
- Reflector region can utilize “waste” neutrons for beneficial isotope production such as ^{60}Co
- Spallation reactions produce broad range of reaction products and the target cleanup system could be designed to separate particular isotopes of interest

Other Nuclear Physics

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- Nuclear Physics
  - Simulated reactor neutron source
  - Isotopes, neutron beams
  - Access to irradiation volume
- Nuclear Data
  - Integral cross sections for proton, neutron, and gamma ray reactions
  - Differential energy dependent nuclear data
  - Unique/exotic/short lived radioisotopes

Energy Station Could Benefit Design of Other Accelerator Targets

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- Test Bed for Accelerator physics and technology
- Materials selection for targets, diagnostics, structures, mechanical systems typically based on limited data from fission reactor and fusion community
- Potential for much different response in high power accelerator due to high flux of high energy particles
- Materials irradiation in Energy Station can address target issues
  - Beam-Target Interface
  - Radiation damage/transmutation reaction impurities
  - Remote Handling
  - Liquid metal target components

Conclusions

- The Nuclear Energy Station, based on using Project X high energy protons impinging on a heavy metal target to produce spallation neutrons, could provide a new continuous neutron source to complement materials testing at aging US research reactors
- No major technical challenges to designing and building such a facility (continuous spallation source operating in Switzerland for years)
- The Energy Station is well suited for fission/fusion materials studies, as well as isotope production, transmutation studies, and cross section measurements
- The CW beam from the Project-X linac will be a unique facility in the United States to address key physics and technology demonstration
  - Nuclear Energy
  - Fusion Energy Science
  - Nuclear Physics
  - Accelerator physics and technology

Charge to Working Group 1
Proton Beam & Target Design

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- Review target technology options for the Project X Energy Station concept and explore the interplay with the scientific requirements developed in WG2.
- Evaluate the proposed PNNL conceptual facility design in regards to reliability, ease of operations, radiological protection, flexibility, and scientific capability (along with WG2).
- Identify Fermilab site-specific regulatory and internal policy limitations to the Energy Station science scope and conceptual facility design.
- Develop, to the extent possible, the target facility design requirements for a Project X Energy Station (in concert with WG2).
- Identify areas for R&D to validate and/or develop the required technologies for a Project X Energy Station.

Charge to Working Group 2
Science and Technology Applications

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- Review existing and proposed accelerator based nuclear materials science facilities and available test reactors with an eye to opportunities for exploiting the Project X proton beam.
- Identify the role(s) that a PX ES could play to fill the immediate and future needs for the nuclear fission and fusion research communities and define the path forward for identifying and creating a viable user base.
- Evaluate the proposed PNNL conceptual facility design in regards to meeting the identified scientific and technological needs (with WG1).
- Work with WG1 to understand how a PX ES scientific program might be bounded by Fermilab site-specific regulatory & internal policy directives.
- Develop, to the extent possible, the target facility scientific requirements for a Project X Energy Station (in concert with WG1).
- Identify knowledge or data gaps that R&D could address in the near term to validate the proposed science program, refine the target facility scientific requirements, and/or develop the required technologies for a Project X Energy Station.

Applications for Material Science

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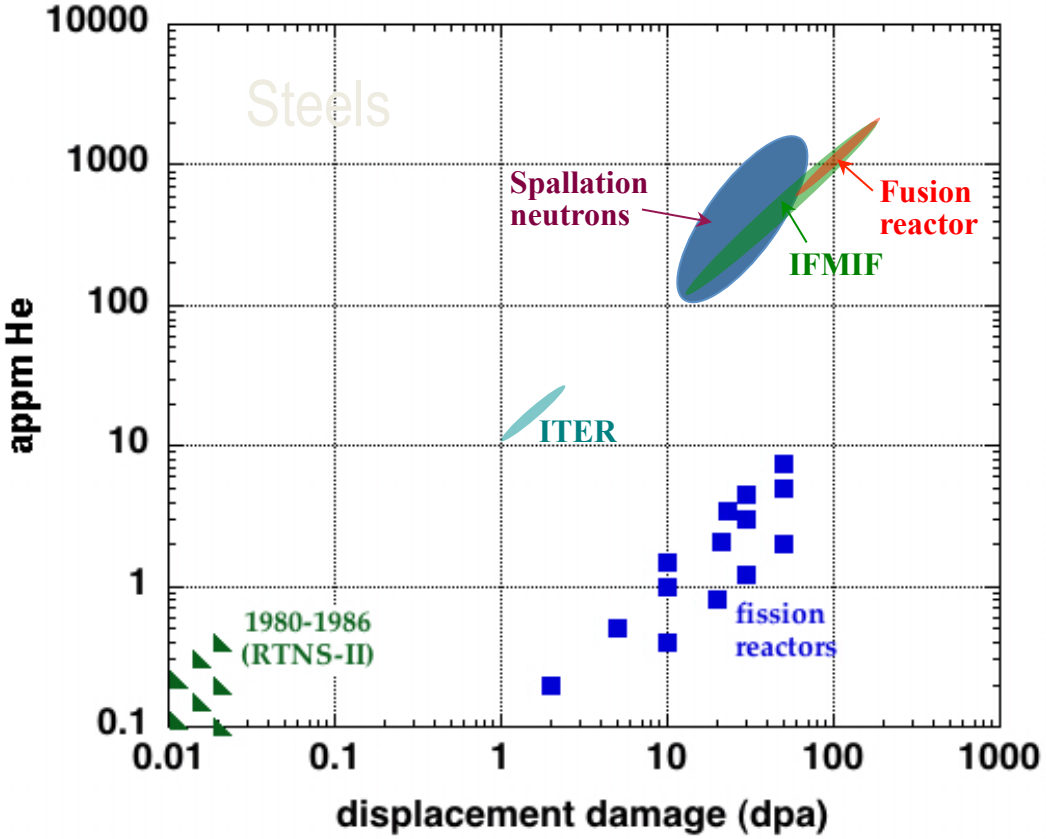
January 2013

Materials Irradiation

- Suitable irradiation sources are a critical need for future fission/fusion materials development
- A MW-class proton beam driving a target designed for high neutron flux can meet this need



Mission Areas

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- Material Science
  - Test bed for structural and target material for accelerated radiation damage and liquid metal effects
  - Neutron spectra and temperatures typical of reactor concepts for materials testing without building a reactor or requiring reactor fuel
  - Radiation environments may throw light on new materials or physics
- Chemistry/Performance of Targets
  - Study the chemistry/irradiation-induced changes of LBE or solid spallation target concepts in a prototypic high radiation environment
- Physics
  - Investigate life-limiting phenomena (transmutation impurities, radiation damage)
  - The rate of incineration very long lived minor actinides or fission products in a given neutron spectrum
  - Neutron/photon/electron heat generation and deposition

Materials Irradiation Damage Testing

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- Correlating charged particle damage with existing reactor neutron damage data
- Proton, neutron and gamma induced reactions
- Gas generation
  - Hydrogen implantation, migration, blistering
  - Helium generation from alpha production reactions
- Reactor materials testing
  - Cladding and structural materials
  - Control rod absorber materials
  - Reactor vessel and internal component materials
  - Pre-screening tests for reactor irradiation testing
- Accelerator materials testing
  - Chopper, scraper, absorber, dump materials
  - Beam window materials
  - Low activation materials
  - Radiation resistant materials (effects of impurities, heat treatment, temperatures)
  - Can reach 20-40 dpa/yr

Courtesy R. Kurtz, PNNL

Materials Issues Common to Fission, Fusion, Accelerators in Energy Station

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Materials Compatibility Issues	Materials properties issues	Integrated performance issues
• Coolant • Cladding • Target • Moderator • Transmutation products • Decomposition products • Thermal and Irradiation Stability Issues • Target material swelling • Cladding swelling • Moderator swelling • Target spalling • Irradiation damage effects • Chemical stability • Phase stability	• Thermal conductivity • Heat capacity • Melting point • Emissivity • High temperature strength • Creep behavior • Thermal expansion • Vapor pressure	• Effects of fission or transmutation product buildup • Stoichiometry changes during irradiation • Gas release • Thermal performance • Target material restructuring • Power-to-Melt behavior • Changes in properties with burnup • Fabricability • Target burn efficiency

Spallation Targets

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High Power Spallation Neutron Sources

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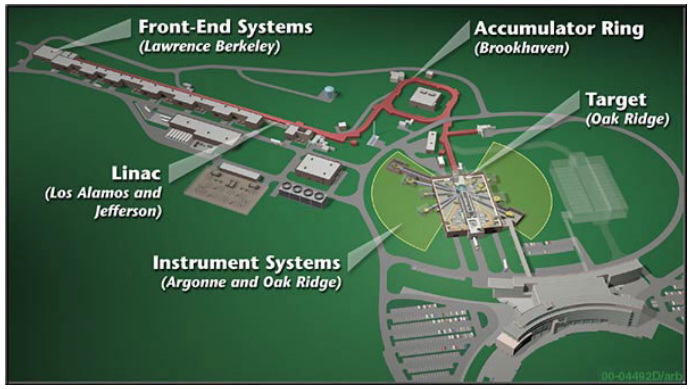
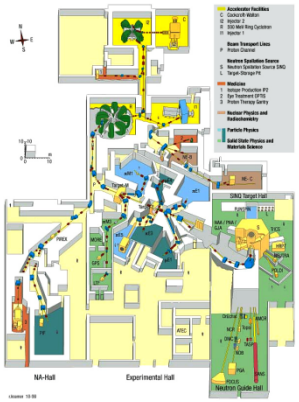


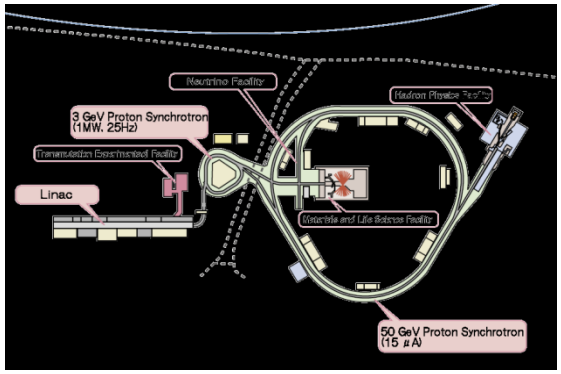
SNS – ORNL

Hg target



SINQ – PSI

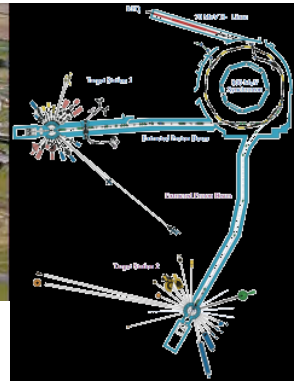
LBE target



JPARC – JAEA/KEK

Hg target

LANSCE - LANL



ISIS – RAL UK

Solid W target

Comparison of Energy Station with Other Accelerators

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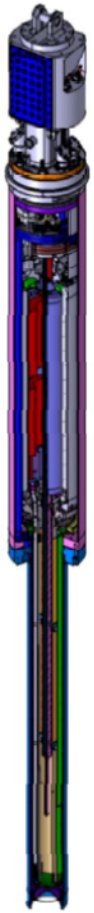
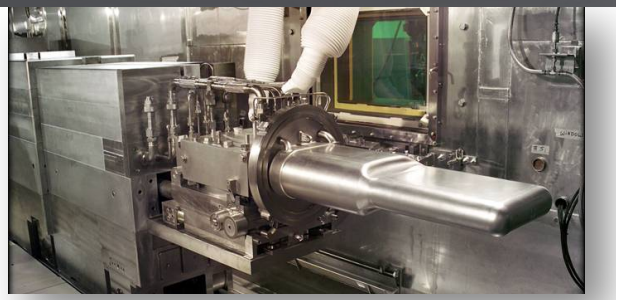
Facility	Initial Operation	Current	Energy	Beam Power	Mode	Peak n flux n/cm2/s	High flux volume
Project X Energy Station	**2021**	**1 mA**	**1 GeV**	**1 MW**	**CW>50%DF**	**6e14**	**3L >3e14 600L >1e14**
MYRRHA 85MWt (ADS) Pb-Bi spallation	2023	2.5 mA	600 MeV	1.5 MW	CW linac		
MEGAPIE – PSI Pb-Bi spallation target	2006	1.25 mA	590 MeV	0.8 MW	CW		
SINQ – PSI lead target, D2O moderator	1996	2.3 mA	590 MeV	1.2 MW	CW	1e14	
MTS – LANL Tungsten target (dual) with Ta front face, Pb-Bi or D_2O coolant	2015	1.25 mA	800 MeV	1 MW	Pulsed <10%DF	1.6e15	0.2 L 0.45 L
SNS – ORNL Liquid mercury spallation target	2006	1.4 mA	1 GeV	1.4 MW	Pulsed 6% DF		
SNS upgrade – ORNL		2.3 mA	1.3 GeV	3 MW	pulsed		
JPARC TEF-T – JAEA Liquid Pb-Bi spallation target	~2015	0.3 mA	600 MeV	0.2 MW	Pulsed 1.25%DF		
ESS – Sweden Rotating Tungsten or Liquid mercury spallation target	2018	50 mA	2.5 GeV	5 MW	Pulsed 5%DF	6.5e14 2.2e15 T 1.2e15 R	0.4 L target 5 L reflector
India – ADS-Pb, Pb-Bi, W		10-30 mA	1 GeV	10-30 MW	CW SRF		
ISIS – UK Synchrotron	1984	0.2 mA	800 MeV	0.16 MW	Pulsed 2.5%DF		
Triumf	1969	0.2 mA	520 MeV	0.10 MW	CW		

Spallation Targets

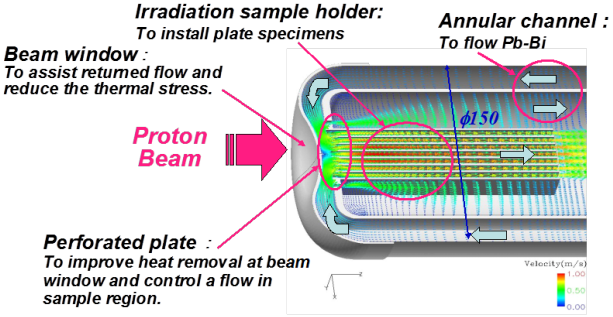
- Solid-target
  - SINQ at PSI (~1.2 MW “DC” beam)
- Liquid Hg
  - Spallation Neutron Source (1.1 MW pulsed)
  - Japan Proton Accelerator Research Complex (0.3 MW pulsed)
- Pb-Bi Eutectic (LBE) liquid target
  - MEGAPIE at PSI (0.8 MW)
  - JPARC TEF-T
- ESS has selected rotating solid tungsten target as baseline but is also evaluating LBE

MEGAPIE LBE target





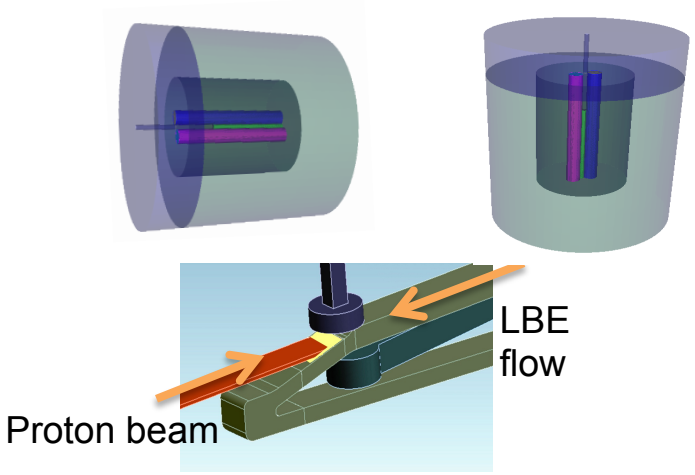
SNS Hg target



JPARC TEF-T: 600 MeV-200kW proton beam facility target concept

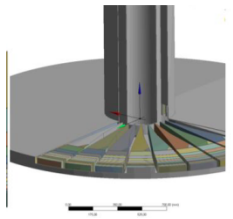
Options

- Vertical versus horizontal proton beam alignment on spallation target
- Beam window or windowless spallation target design
- Solid rotating spallation target versus liquid heavy metal target
- Proton beam size
  - Beam power density can be varied by selecting beam diameter or beam rastering over larger surface
  - Smaller beam diameter -> higher n flux but also higher heating density and higher dpa on window



ESS windowless LBE target concept

U. Fischer et al, Displacement Damage and Gas Production Data, 4th HPTW, Malmö, Sweden, May 2-6, 2011



ESS He cooled concept, 7 t, 5 year life

Prototype water cooled, Jülich, ~1984

Liquid or Solid Spallation Targets

- Solid rotating target
  - Rotating wheel, 1-2 m diameter with proton beam incident on rim
  - Speed of rotation depends on cooling
  - Mechanically very complex with rotating seals
  - Remote handling equipment for servicing
  - Water, helium, or liquid metal cooling
  - Mean density of target is diluted by coolant
  - Lifetime limited by radiation damage
- Liquid lead or LBE
  - Do not suffer from radiation damage
  - Lifetime may be limited by beam window radiation damage
  - Containment in event of pressure vessel failure
  - Heating system to keep liquid is needed
  - Corrosion of container materials

Comparison with Solid Tungsten Target

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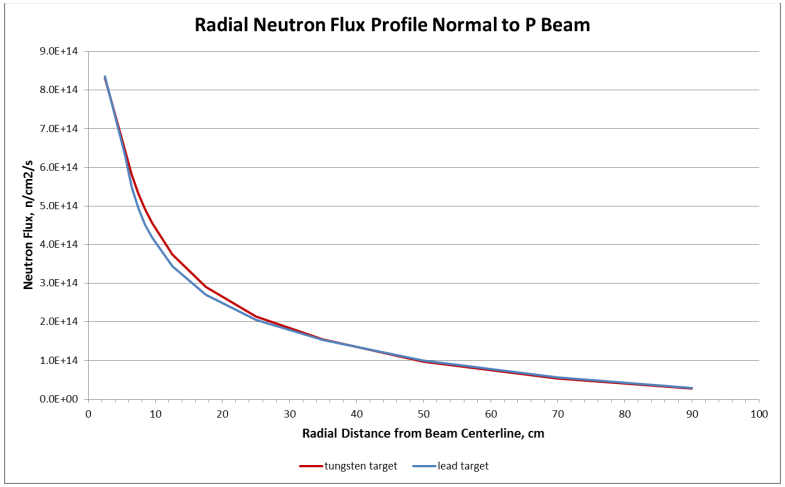
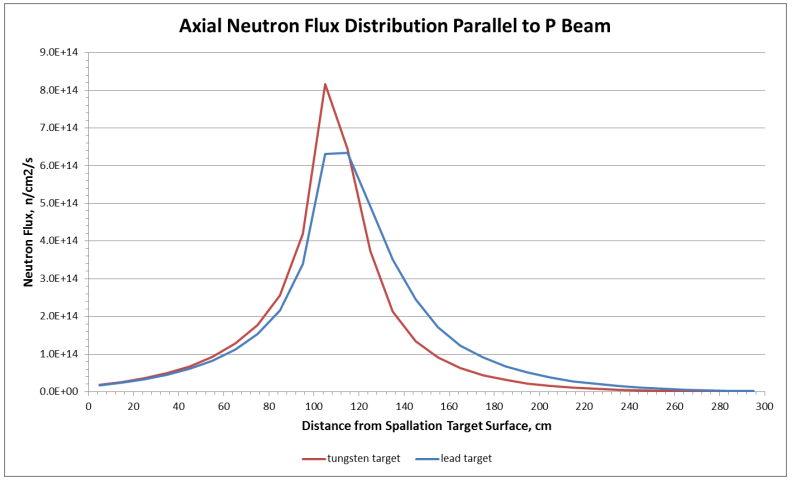
Neutron Flux Range (n/cm2/s)	Axial Extent (cm)	Outer Extent (cm)	Volume (liters)
>5e14	30	8	~4
>3e14	50	15	~32
>1e14	110	60	~600
>5e13	160	80	~1700
>1e13	250	100	~6200

- 1 GeV protons penetrate ~ 30 cm in full density Tungsten targets
- Increases neutron flux levels radially, axially, but decreases axial extent
- ~30 neutrons/proton





Thermal Considerations

- LBE Spallation Target
  - Melting point of LBE is ~126 C
  - Inlet temperature of 200 C
  - Maximum flow velocity of 2 m/s based on erosion and corrosion concern
  - For 1 MW deposited, the target diameter would need to be ~6.5 cm
  - Outlet temperature would be 300 C
- Lead Matrix
  - Melting point of pure lead is ~327 C
  - Could be thermally isolated from target or test module loops using narrow gas gap to reduce heat transfer
  - For peak heating in lead matrix of ~46 W/cc in first cm next to target, temperature rise through 1 cm of lead could exceed 250 C
  - Hottest areas of matrix could use different material (such as Zircalloy)

Other PNNL Involvement Relevant to Project X

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Other PNNL Involvement Relevant to Project X

- High Power Beam Window Design
  - *Investigating with Internal Funds*
  - Beam window that will handle radiation damage and thermal stresses >750kW beam power
  - ESS plans to replace window every 6 months

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

Other PNNL Involvement Relevant to Project X

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- 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

Primary Technical Risks of Project X mitigated by the Project X Front End R&D Program - PXIE

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- Integrated systems testing, known as the Project X Injector Experiment (PXIE), will be completed over the period FY12-16.
- PXIE is a program of research and development aimed at integrated systems testing of critical components comprising the front end of the Project X linac
- This program is a key component of the larger Project X R&D program.
- Successful completion of PXIE will validate the concept for the Project X front end, thereby minimizing the primary technical risk element within Project X.
- Successful systems testing will also demonstrate the viability of novel front end technologies that will find applications beyond Project X.
- PXIE parameters
  - 30 MeV, 1.6 mA (upgrade to 5mA), continous wave (cw) proton accelerator
  - See http://www-bdnew.fnal.gov/pxie/

What is PXIE?

- Integral systems test of fron tend of Project X proton linear accelerator
- Goal is to validate Project X technologies at full design parameters

CW DC H- ion source delivering 5 mA (nominal) at 30 keV
Low Energy Beam Transport (LEBT) section with beam pre-chopping
Continuous Wave (CW) Radio Frequency Quadrupole (RFQ) operating at 162.5 MHz and delivering 5 mA at 2.1 MeV
Medium Energy Bea m Transport (MEBT) section with beam chopper and 20 kW maximum beam absorber
Two low-beta superconducting cryomodules for accelerating 1mA of beam to 30 MeV
Beam diagnostic section capable of measuring particle distribution
Beam dump capable of accommodating 1.6 mA at 30 MeV (50 kW) for extended periods

PXIE Beam Dump

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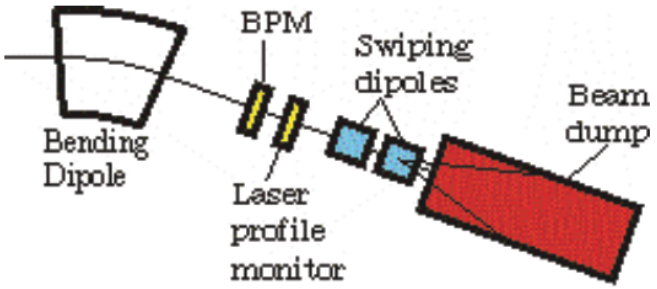
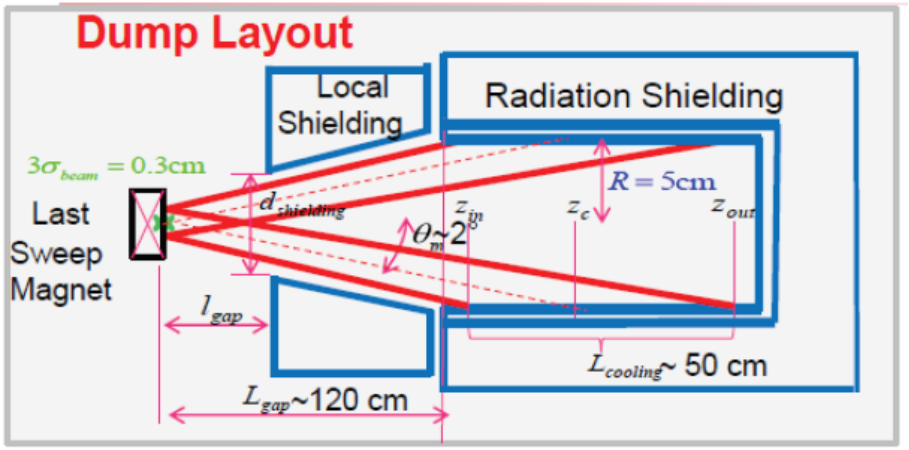
- Power rating – 50 kW at beam energy of 25 MeV
- Local radiation shielding required
- X&Y swiping magnets (2°angle)
- Issues include
  - high power density
  - Sputtering
  - High gas load





Conventional Beam Dump

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
    - PNNL sealed target design could be used for isotope production
    - Infrastructure needed for retrieval/processing/shipping
  - 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
    - Proton beam target – Be, W, Mo, Zr, Pb, Be can generate neutrons
    - Spectral tailoring can reproduce reactor spectrum
    - To benefit fission, fusion and spallation R&D

Materials Irradiation Damage Testing

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- Correlating charged particle damage with existing reactor neutron damage data
- Proton, neutron and gamma induced reactions
- Gas generation
  - Hydrogen implantation, migration, blistering
  - Helium generation from alpha production reactions
- Reactor materials testing
  - Cladding and structural materials
  - Control rod absorber materials
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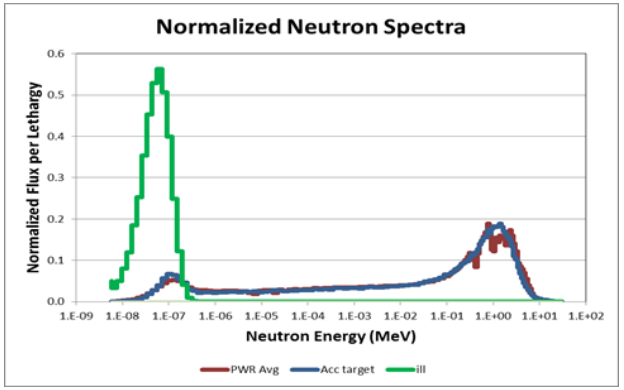
  - Pre-screening tests for reactor irradiation testing
- Accelerator materials testing
  - Chopper, scraper, absorber, dump materials
  - Beam window materials
  - Low activation materials
  - Radiation resistant materials (effects of impurities, heat treatment, temperatures)
  - Can reach 20-40 dpa/yr

Courtesy R. Kurtz, PNNL

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 (and bias?) in the associated measured fission product beta spectrum



Rationale

- Previous measurements in 1980s in thermal beam of ILL reactor contained no fission contribution above ~ 1 eV, not representative of reactor spectrum
- Accelerator neutron source offers advantages over reactor source in terms of testing sensitivities

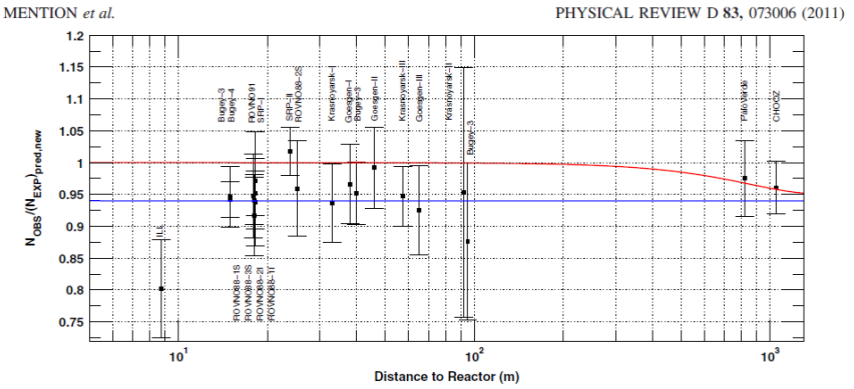
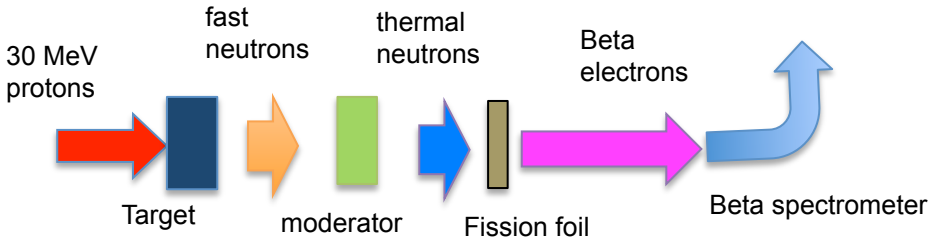


FIG. 5 (color online). Illustration of the short baseline reactor antineutrino anomaly. The experimental results are compared to the prediction without oscillation, taking into account the new antineutrino spectra, the corrections of the neutron mean lifetime, and the off-equilibrium effects. Published experimental errors and antineutrino spectra errors are added in quadrature. The mean averaged ratio including possible correlations is 0.943 ± 0.023. The red line shows a possible three-active neutrino mixing solution, with $\sin^2(2\theta_{13}) = 0.06$. The blue line displays a solution including a new neutrino mass state, such as $|\Delta m^2_{\text{new,R}}| \gg 1\ \text{eV}^2$ and $\sin^2(2\theta_{\text{new,R}}) = 0.12$ (for illustration purpose only).

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.



- PNNL has the expertise in all of the areas needed to design/deploy experiment

Beneficial Use of PXIE Fusion Energy Science

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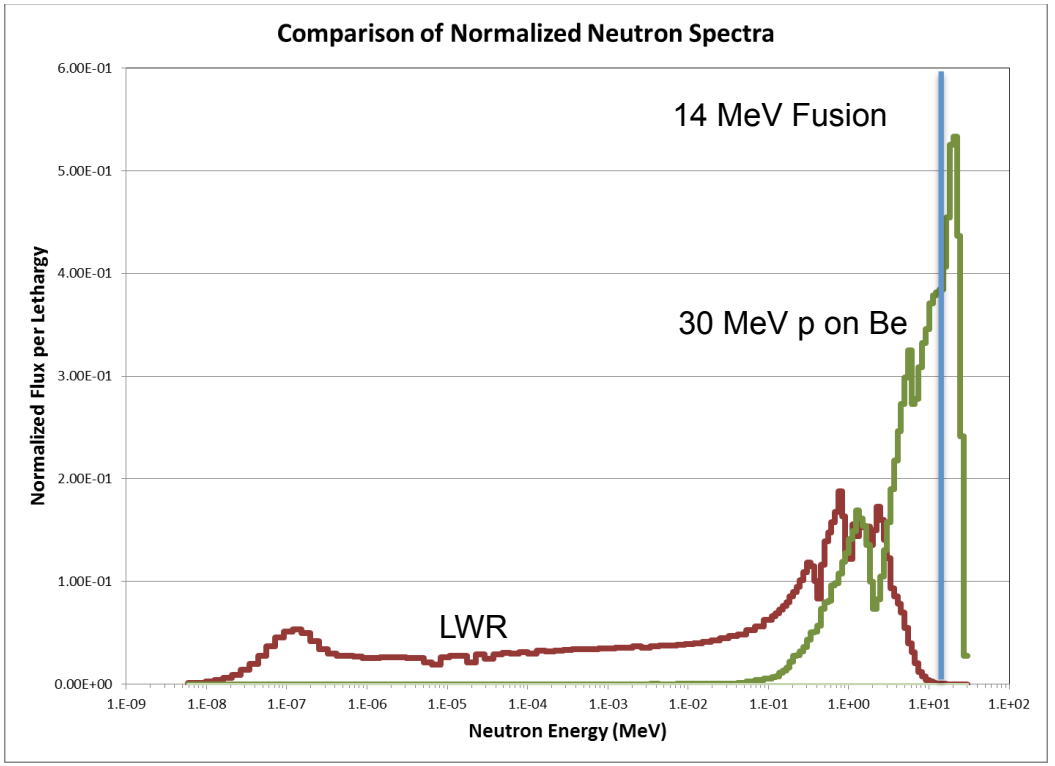
- The 30 MeV proton beam at PXIE directed on a beryllium target can produce a high energy neutron spectrum useful for fusion studies

Energy Range	Neutron Flux (n/cm2/s)	Fraction
<1 MeV	2.1e13	0.12
1-5 MeV	4.3e13	0.25
5-10 MeV	3.2e13	0.18
>10 MeV	7.8e13	0.45
Total	1.7e14	1.00



PNNL Capabilities

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PNNL Capabilities Can Provide Relevant Support to Project X

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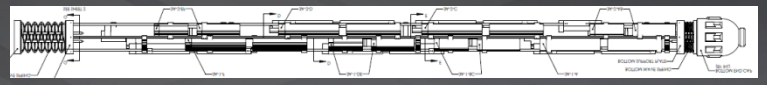
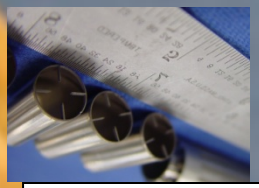
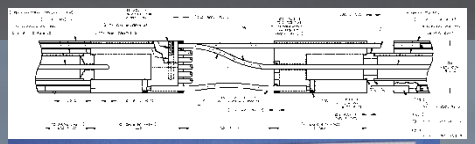
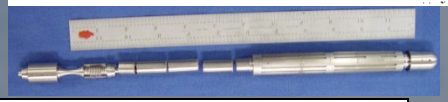
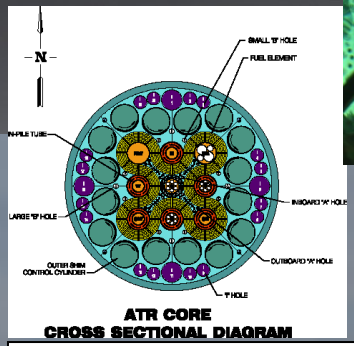
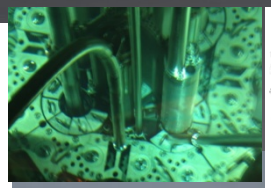


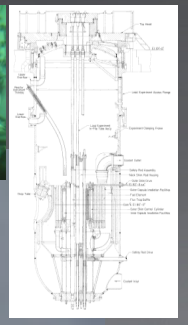


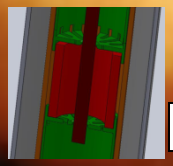








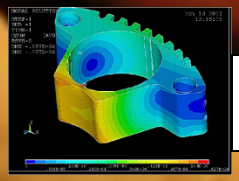




Proven Target Fabrication and Performance

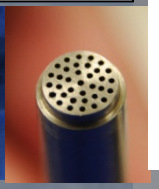
Design of Irradiation Targets

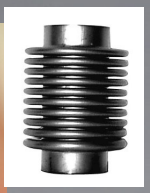
Target Structural Design



Target Thermal Design

Unique Design, Fabrication, and Assembly





Project X

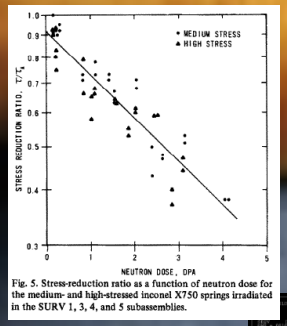
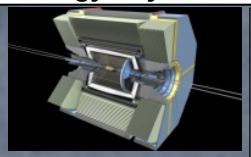
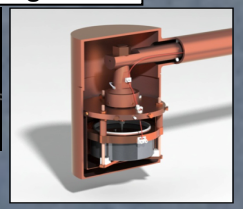


Fig. 5. Stress-reduction ratio as a function of neutron dose for the medium- and high-stressed inconel X750 springs irradiated in the SURV 1, 3, 4, and 5 subassemblies.

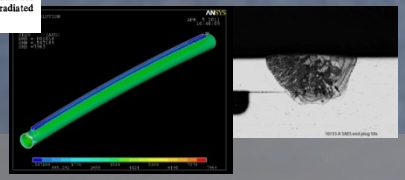
Material Property Degradation From Radiation

High Energy Physics Program





Welding and Brazing



Radiochemical Facilities

PNNL Capabilities Can Provide Relevant Support to Project X Energy Station

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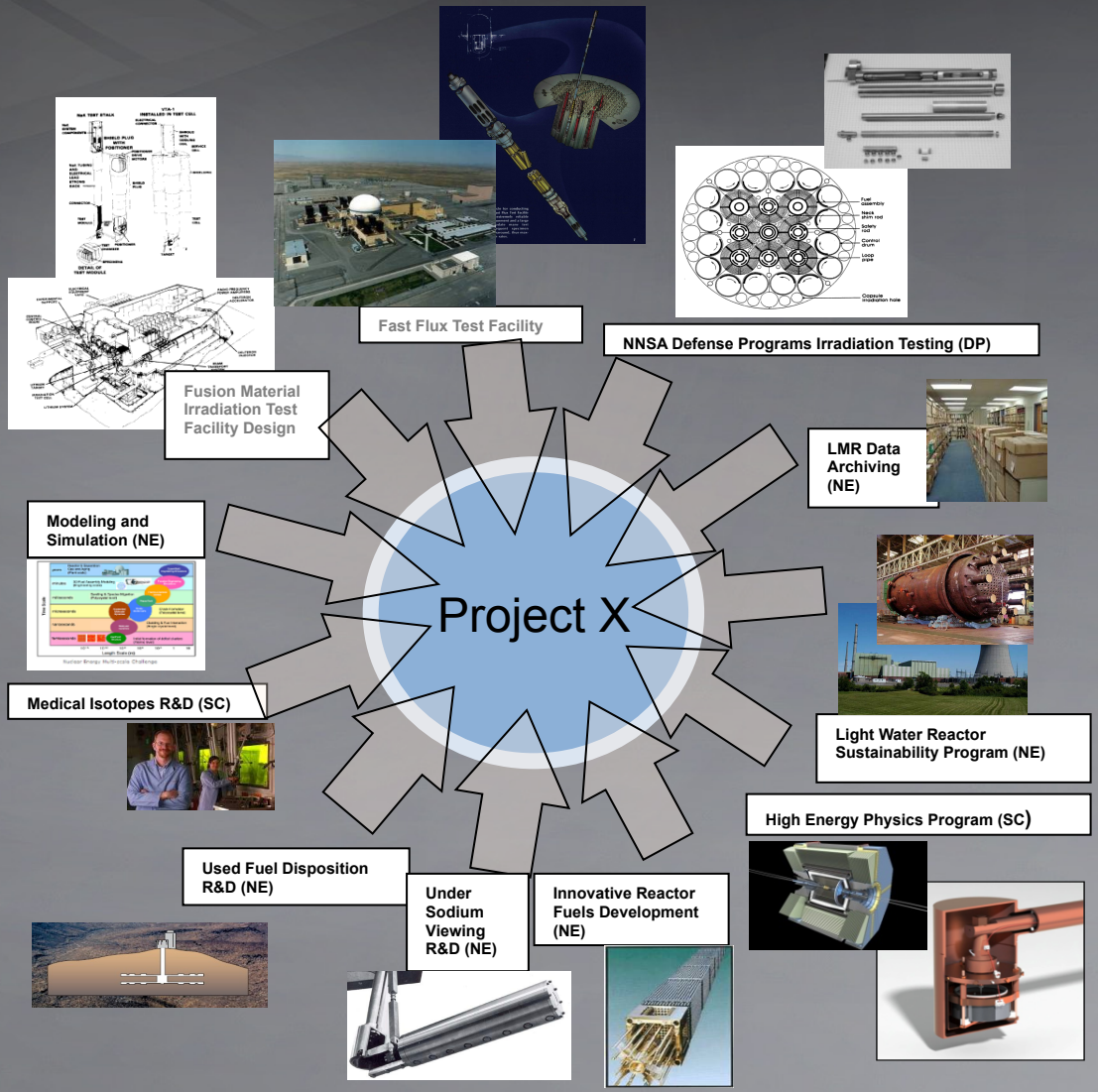

Radiochemical Processing Laboratory (RPL)

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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)

Pacific Northwest NATIONAL LABORATORY
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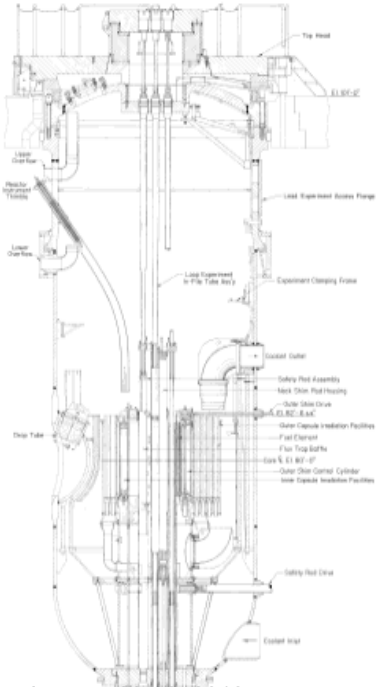
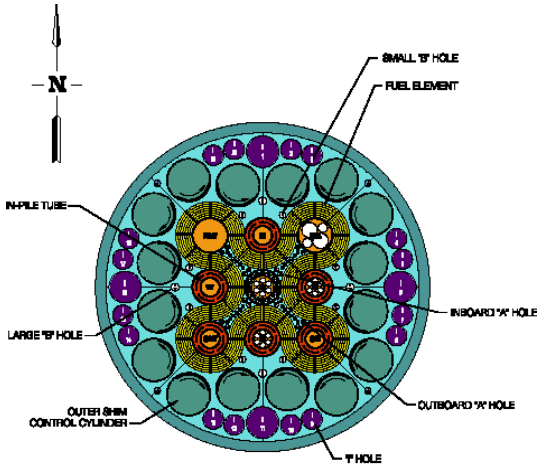
- **Radiological Dispersion and Interfacial Chemistry**
  - Capability to study and control properties (composition, particle size distribution, surface charge, viscosity, and density) in radioactive and non-radioactive systems using equipment on bench tops, radiological fume hoods, glove boxes and hot 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

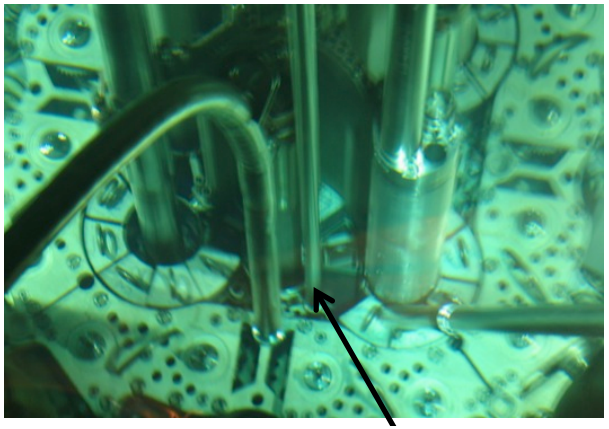
Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- 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

Pacific Northwest NATIONAL LABORATORY
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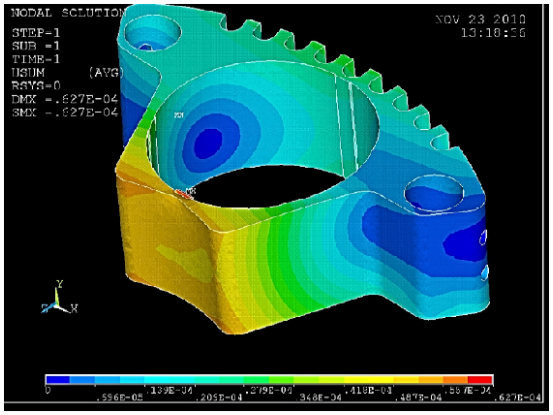
- PNNL has extensive thermal modeling capabilities needed to design a target that will perform under demanding and complex heat deposition conditions
  - ANSYS and multi-physics experience
  - Irradiation Energy Deposition
  - Conduction, Convection, Radiation
  - Thermal Gradients
  - Gas Mixtures and 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

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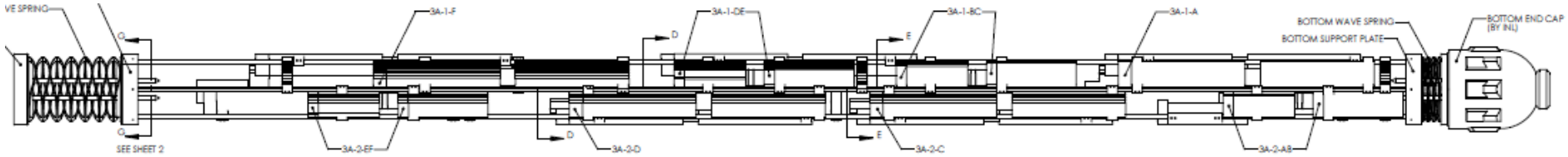
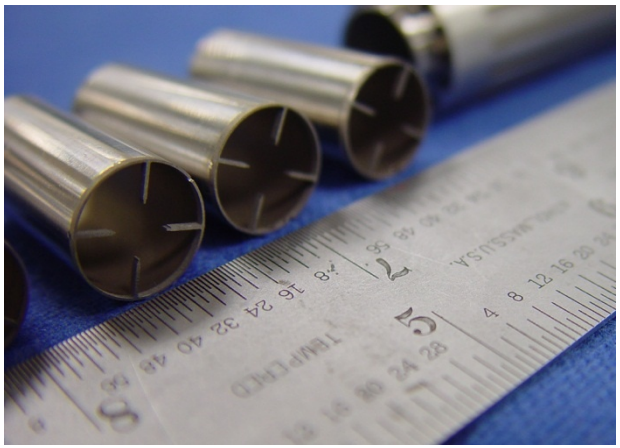
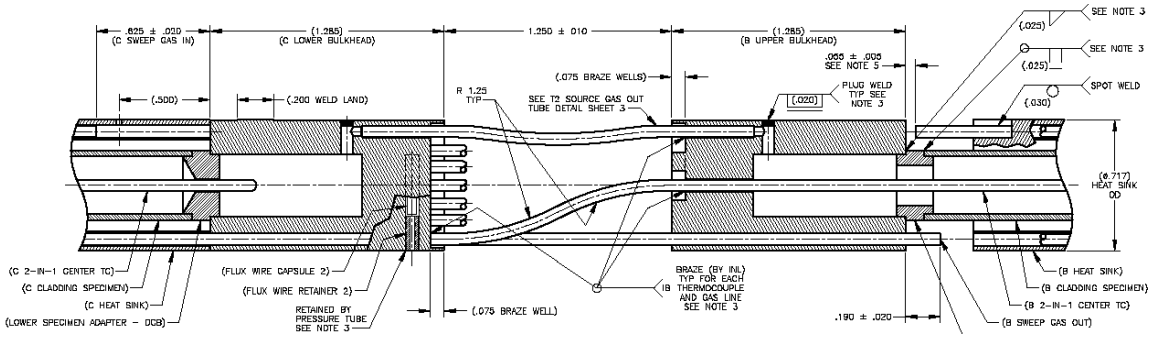
In many respects, design of in-reactor targets can be more demanding than accelerator targets



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

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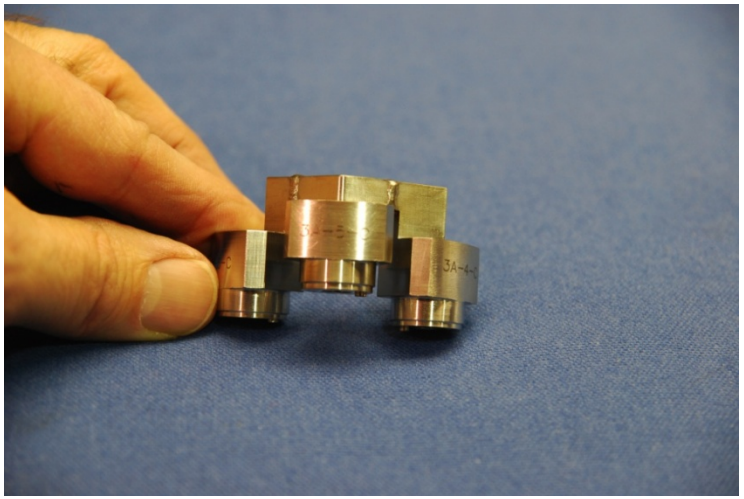
- PNNL has designed and fabricated complex machined parts for use in reactors
- PNNL has designed unique weld joints for nuclear applications and has experience in welding these joints
- In addition to welding, PNNL has experience in joining ceramics, particularly SiC, but others as well
- Various approaches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

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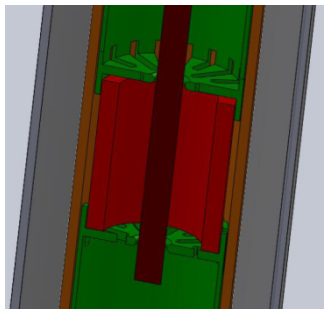
- Extensive Structural Mechanics Modeling Capabilities
  - ANSYS Structural Code Modeling
    - Mechanical, Thermal, and Multi-physics
  - Solid Works 3D Modeling
  - Linear / Nonlinear Stress Analysis
  - Dynamic Transient Analysis
  - Modal Analyses / Natural Frequencies



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

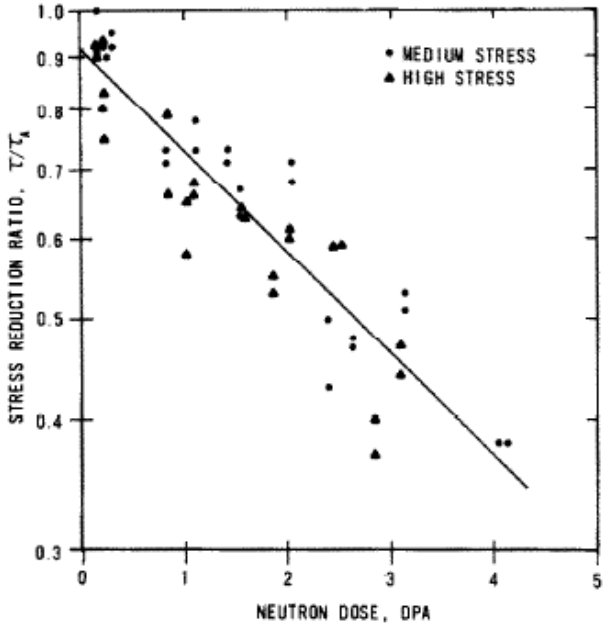
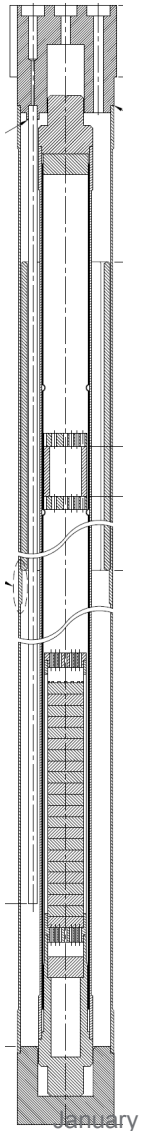
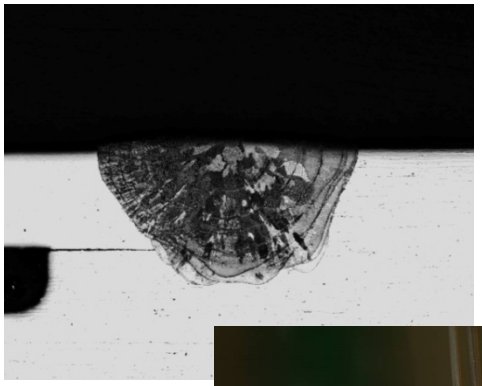


Fig. 5. Stress-reduction ratio as a function of neutron dose for the medium- and high-stressed inconel X750 springs irradiated in the SURV 1, 3, 4, and 5 subassemblies.

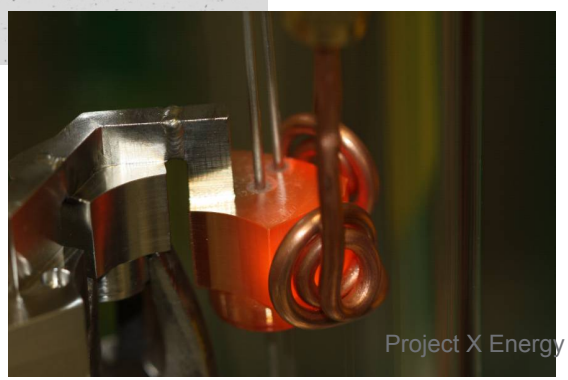
Welding and Brazing

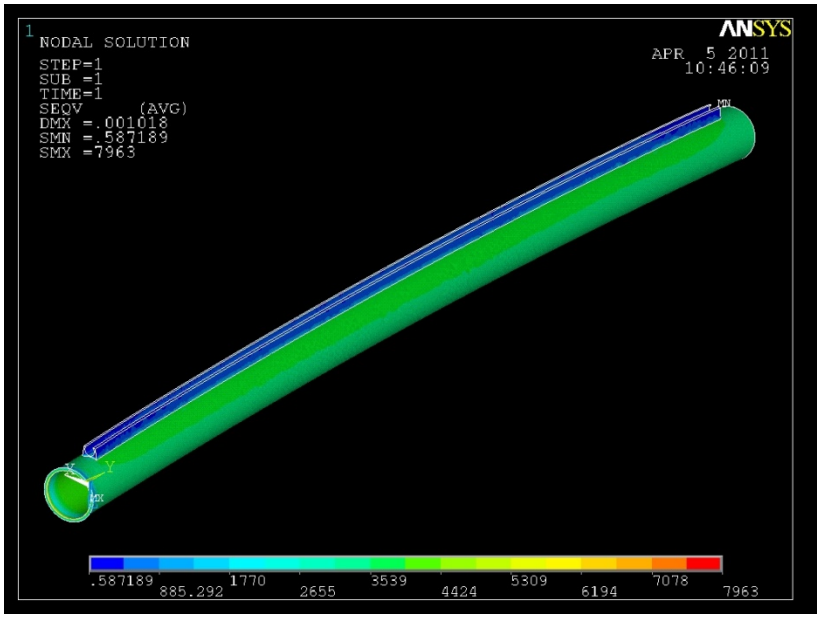


- Weld Joint and Braze Design, Specification and Qualification
- E-Beam, TIG and Laser Welding Capabilities
- American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code Compliance and Analyses
- Commercial ASME NQA-1 Quality Assurance Program required by US Nuclear Regulatory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

Relevant Experience
FFTF Technology

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- Instrumented, temperature controlled testing capability similar to FFTF Materials Open Test Assembly (MOTA).
  - The liquid sodium coolant, temperatures, and neutron flux environment in the FFTF provided irradiation test conditions similar to those expected for the Project X energy station.
    - High temperature thermocouples,
    - online test capsule temperature control through cooling gas mixtures,
    - monitoring, control, and reuse of the test assemblies
- FFTF Closed Loops
  - Two sodium closed loops were designed, fabricated, and installed at FFTF. Each had a 2.3MW power capability independent of the primary reactor coolant system.

Relevant Experience:
FFTF Sodium Fast Reactor Closed Loops

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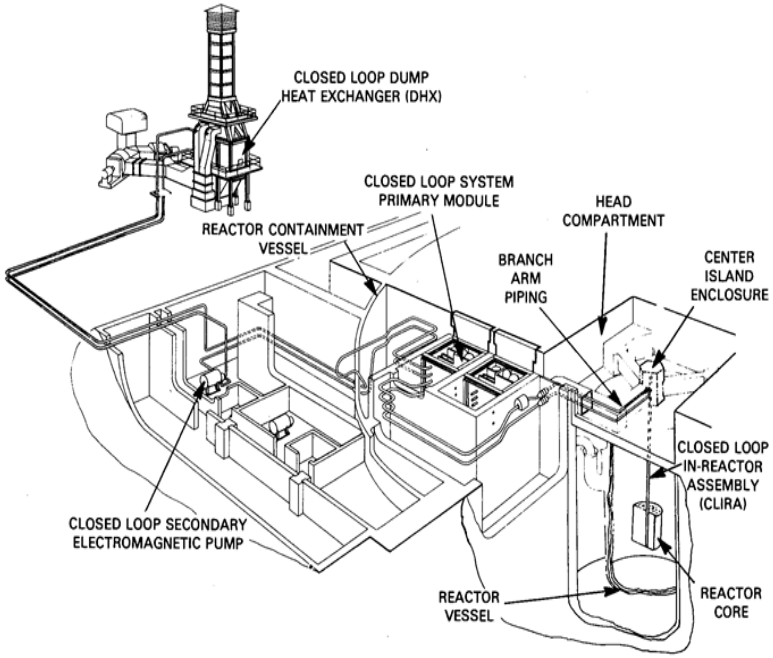

FIGURE 9-2. Closed Loop System Schematic.

Closed Loop Plant Layout

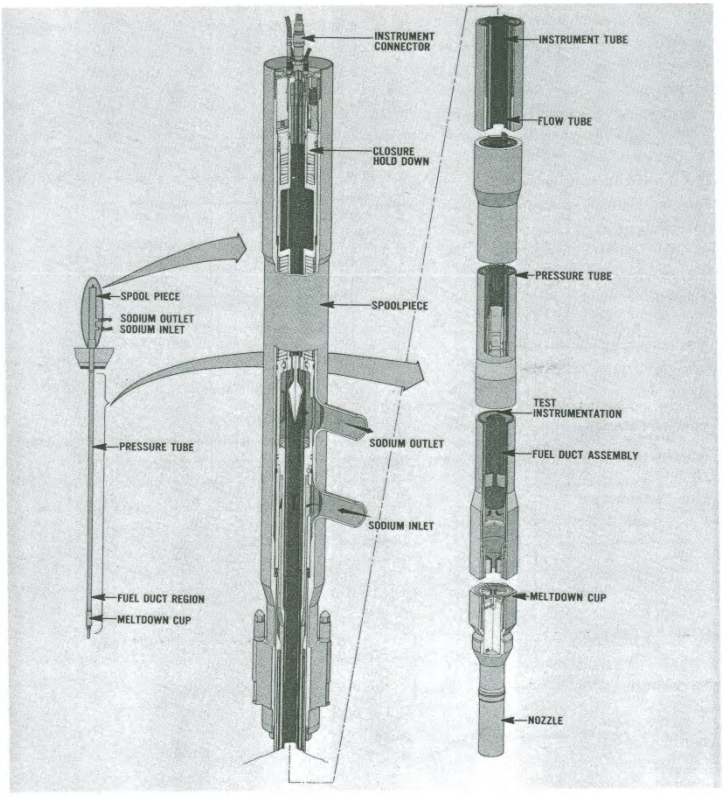

FIGURE 9-4. Closed Loop In-Reactor Assembly (CLIRA).

Closed Loop In-Reactor Assembly

Relevant Experience
FFTF Materials Irradiation

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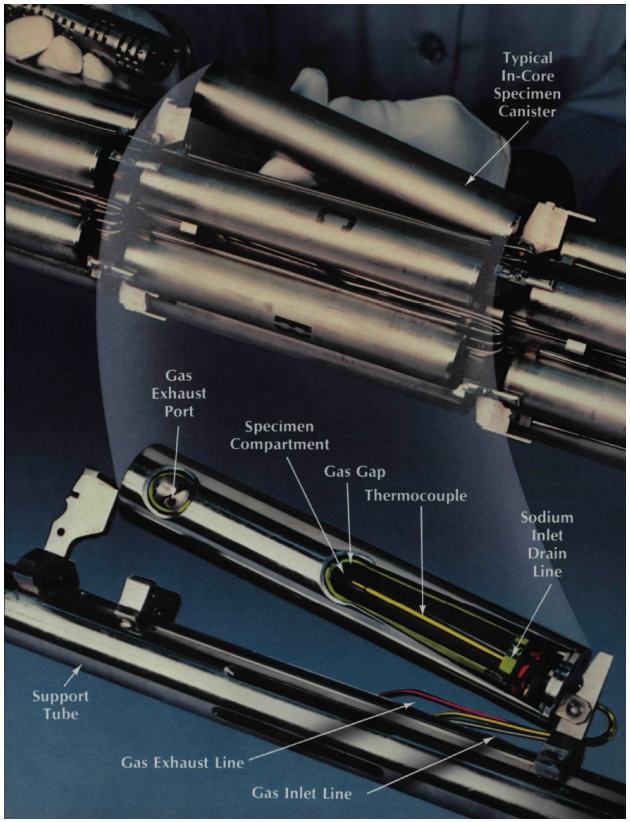
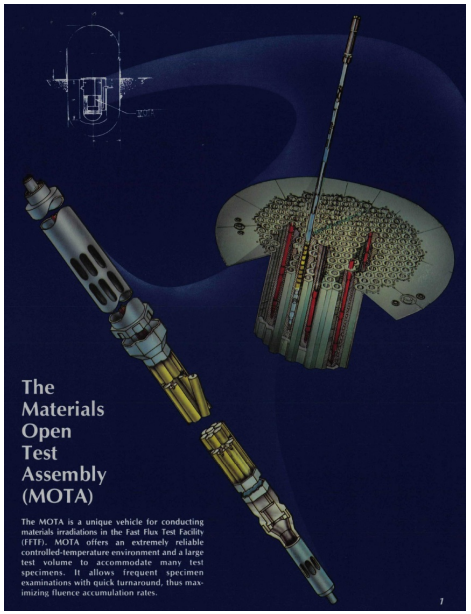
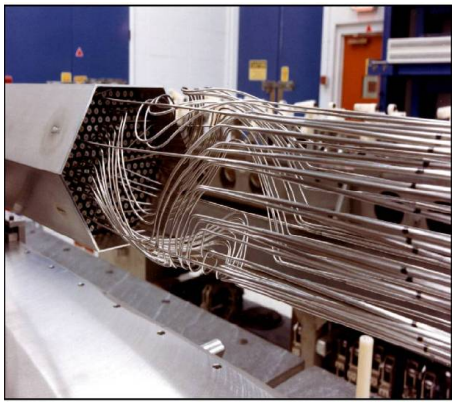
- Instrumented, controlled temperature MOTA capsules







Relevant PNNL Experience
Fusion Material Irradiation Test (FMIT)

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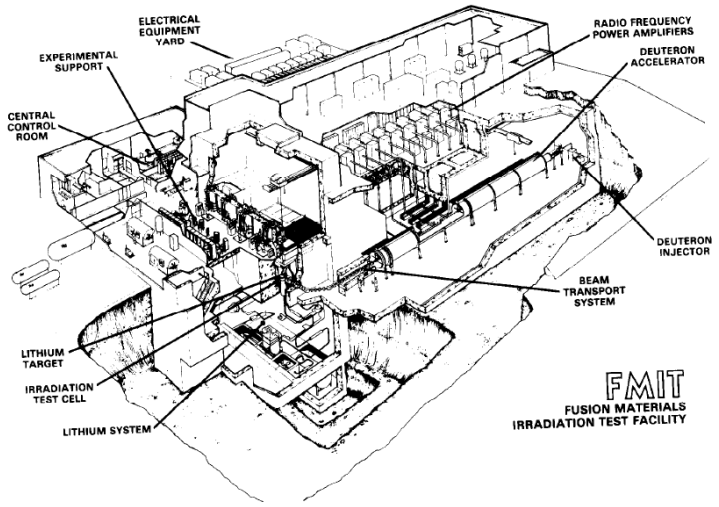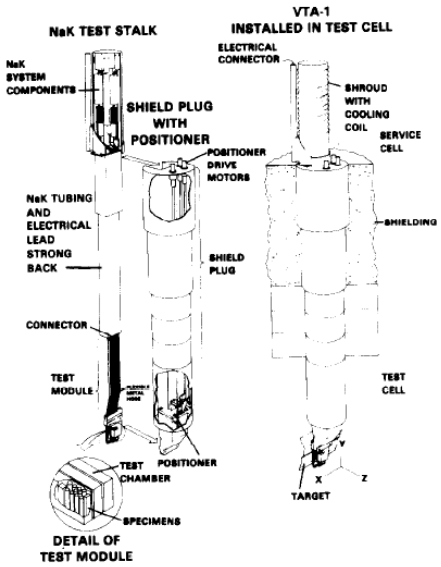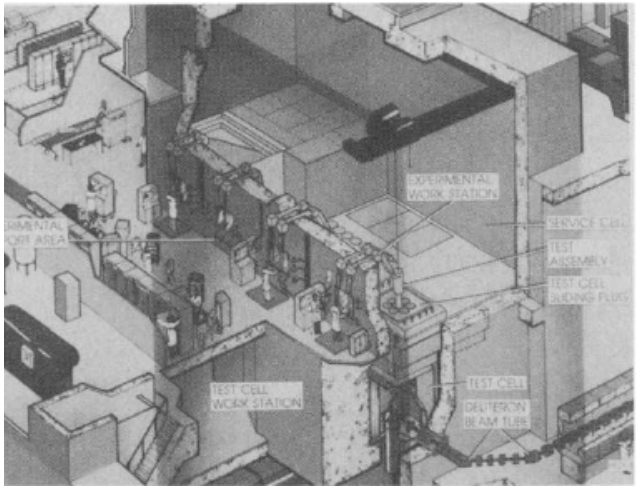
- 35 MeV, 100 mA Deuteron accelerator on windowless flowing lithium metal target
- US facility designed in 1980's for fusion material irradiation tests.
- Detail design and supporting tests completed and ready for construction when funding cut
- Test assembly region designed for thousands of miniature material test specimens in one test
- 3.5 MW beam energy deposited in target (2 MW/cm^3) 740 C peak lithium temperature, 33 liters/ second flow rate
- The independently cooled, reconstitutable test assemblies used a separate NaK cooling system to remove the heat deposited in the test region. Each test module could be lifted with an overhead crane for removal and insertion.