

Use of Fusion Neutron Sources for Near-Term Applications



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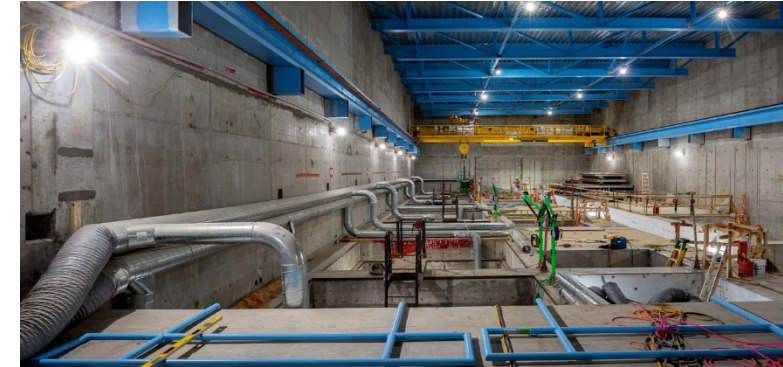
December 2025



SHINE's Sustainable Approach To Fusion

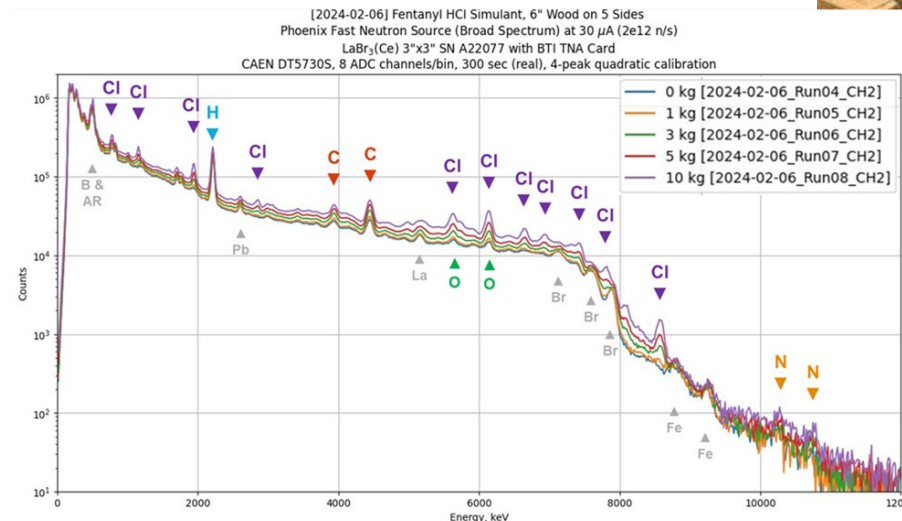
VISION: TRANSFORMING HUMANKIND THROUGH FUSION TECHNOLOGY

- Phase 1: Delivering low-yield fusion systems (DD & DT) for 10+ years
 - Years of licensing facilities with activation, tritium, rad waste disposal, etc.
 - Providing commercial neutron radiography and DT irradiation services
- Phase 2: Producing medical isotopes
 - Delivering Lu-177 for cancer treatment; scaling up volume quickly
 - Commissioning Mo-99 facility with 8 fusion systems, fission subcritical assemblies, and aqueous U/FP processing
 - Significant experience gained in nuclear construction, licensing, rad waste mitigation/handling, and decommissioning planning
- Phase 3: Applying lessons learned towards aqueous UNF recycling pilot facility and investigating fusion-enabled transmutation
- Phase 4: Looking for opportunities to apply our hard-gained experience and expertise to support the broader fusion community



Neutron System Delivery

- Several delivered neutron generators with satisfied customers
 - GE-Hitachi, Ultra NCS (UK), German MoD, US Army
 - First deployed commercial system in 2015
 - Experienced maintenance/service team providing exceptional service to customers
- Recently awarded the DT neutron source delivery for the UKAEA LIBRTI project
- Continued application development ongoing
 - Example: DHS cargo inspection project



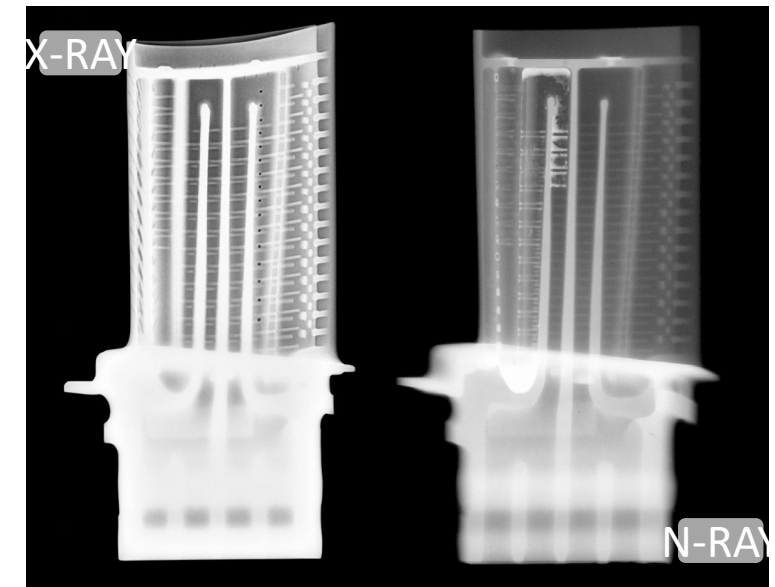
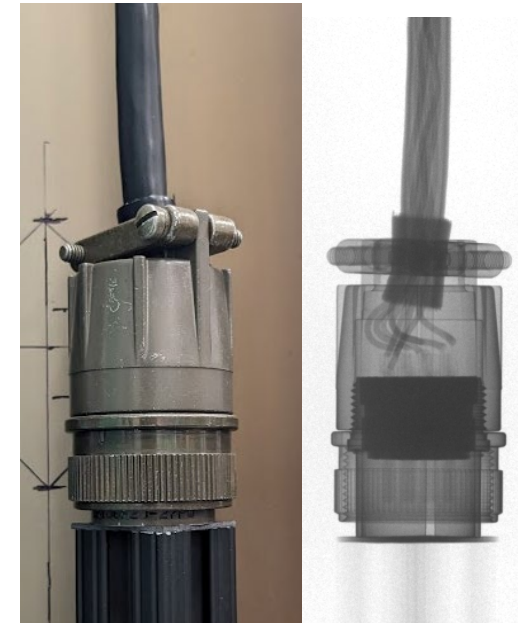
Current Use Case: Nuclear Fuel Rod Scanner

- SHINE has developed a system for the active measurement of nuclear fuel enrichment and density with DD neutrons
- Major subcomponents
 - Automated fuel rod handling
 - Steady-state DD fusion source
 - 3×10^{10} n/s
 - Delayed neutron and gamma detection
 - Densitometer
 - Data analysis software
- SHINE customers have used this system to test OVER 1 MILLION fuel rods



Neutron Imaging Center

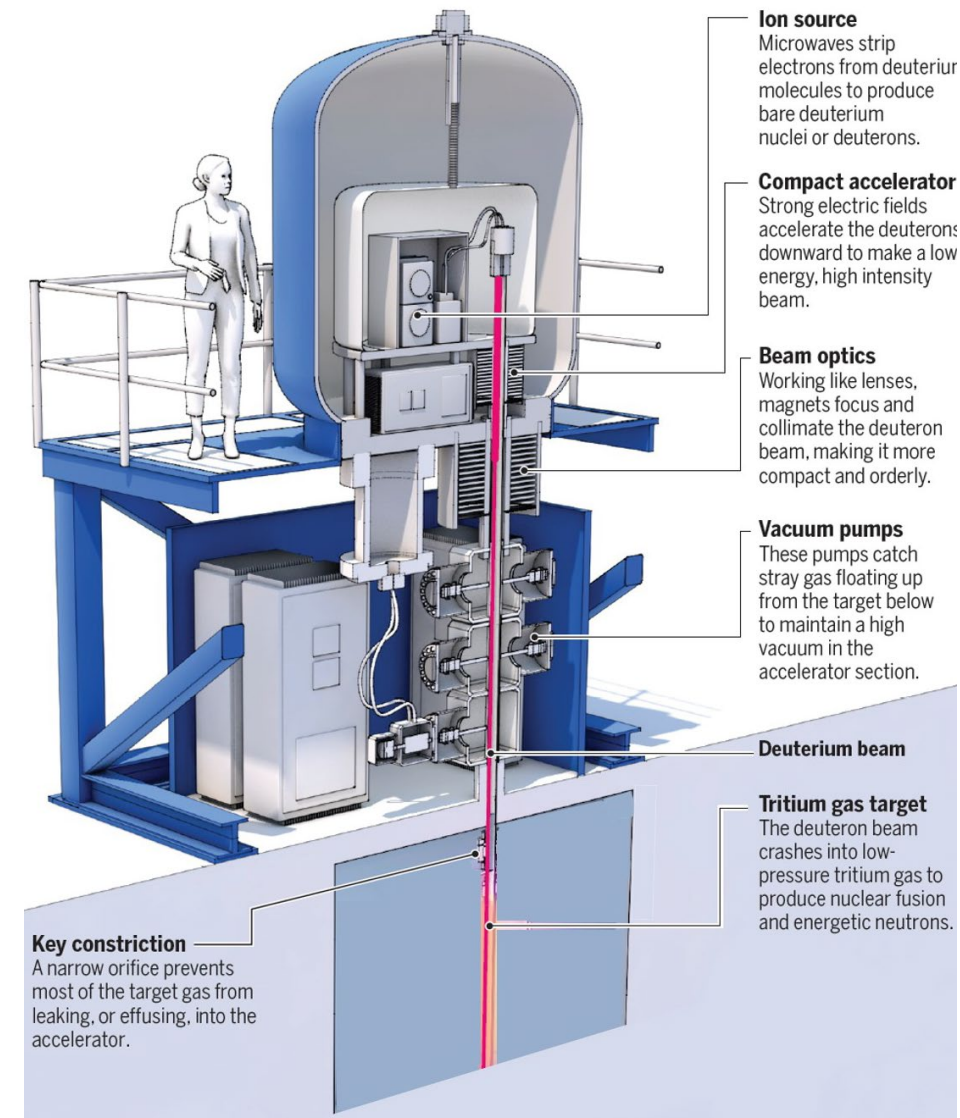
- Accelerator-based neutron source removing the reliance on aging reactor sources for neutron imaging and neutron radiation testing
 - 10,000 square foot (929 m²) facility in Fitchburg, Wisconsin, USA
- The neutron source has been in commercial operation since 2020 and has been reliably operated with >99% uptime during this period
- Built from the ground up as a neutron radiography facility
 - Thermal and fast neutron beamlines for 2D imaging, 3D CT imaging, & radiation effects testing
 - ASTM Category I Image Quality
- The facility maintains active compliance/permits with:
 - ATF, ITAR, and DoD explosives safety and security regulations
 - Aerospace & defense quality programs (ISO9001, AS9100, NAS410, etc.)



High-Yield DT Neutron Source Overview

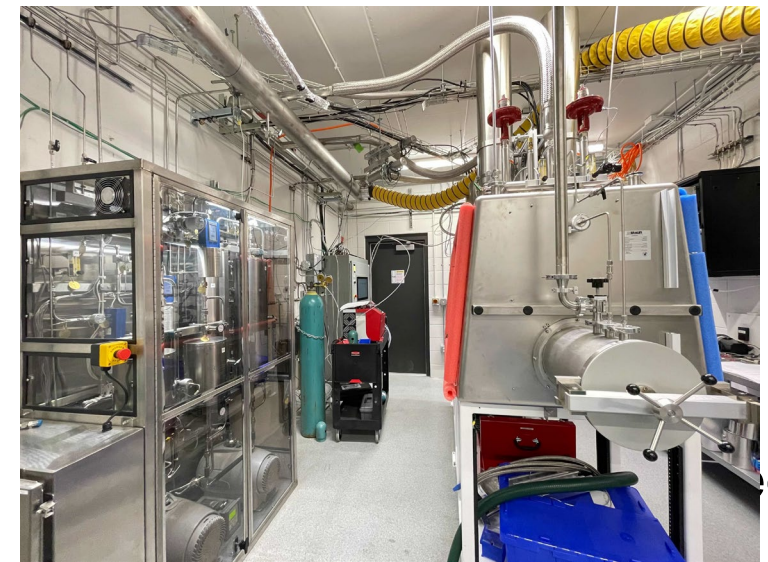
Sequence of Operation

1. Microwave ion source creates dense deutron plasma
2. Up to 80 mA of deutron current extracted ($\sim 90\%$ D^+)
3. DC accelerator extracts ion beam (up to 315k V)
4. Magnetic solenoid focus and x-y steering of ion beam
5. Differential pumping system maintains target pressure at ~ 40 Torr while keeping accelerator pressure under 40 mTorr
6. Beam strikes tritium (or deuterium) gas target and generates neutrons in a line source as the beam slows in the gas
7. Up to 4.6×10^{13} n/s measured output



Tritium Safety and Licensing

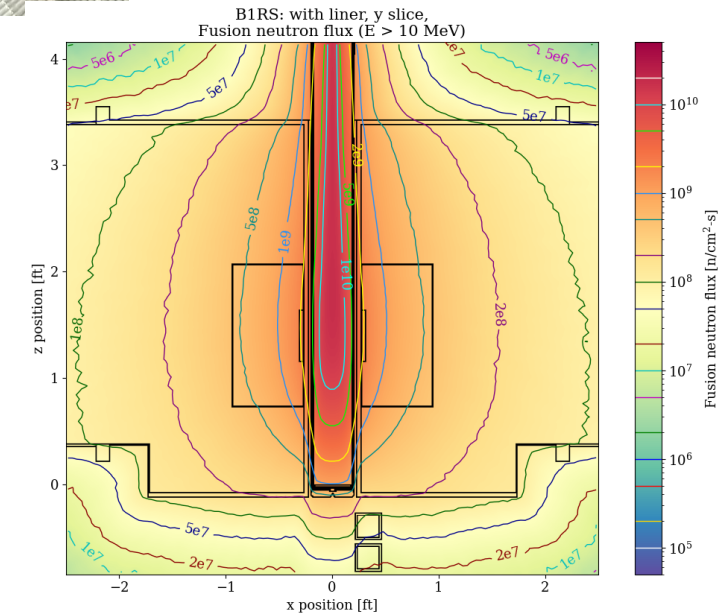
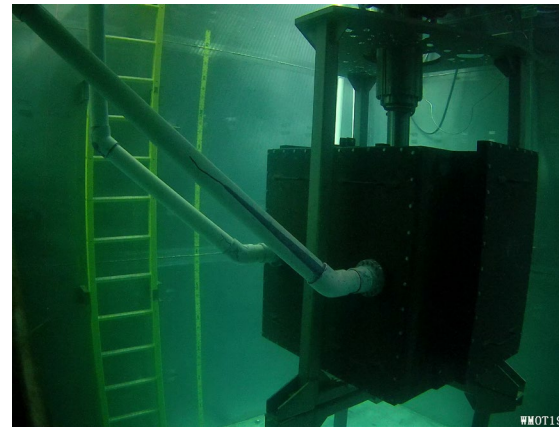
- SHINE License Basis (US – NRC Agreement State)
 - First of a kind for this license type – 17,000 Ci (~1.7 gram) limit
 - Relatively small lot (~2 acres)
 - Required a 40' stack and 2500 cfm airflow
 - Processes for cleanup of tritium from neutron generator wall multiple iterations
- Equipment housed in a 400 ft² (37 m²) isolated room
 - Glovebox for loading and tritium cleanup
 - Glovebox for tritium separation (TCAP system from SRNL)
 - Glovebox and stack cleanup and monitoring
- Partnerships have been a crucial success factor
 - Savannah River National Laboratory
 - Torion Plasma Corporation
- Experience gained in licensing/operation has been invaluable preparation for new facilities



FLARE™ by SHINE – Rad Hard Testing

FUSION LINEAR ACCELERATOR FOR RADIATION EFFECTS

- SHINE launched a high flux 14 MeV neutron irradiation service in 2023
 - $>1.3 \times 10^{13}$ n/s DT steady-state source
 - 4.1×10^9 n/cm²/s for small irradiation volumes
- Supports multiple test protocols including single event effects, displacement damage, and total ionizing dose
- Very large irradiation cavity supports testing of multiple parts and conditions simultaneously
- Fully licensed facility for tritium handling and DT neutron operations



Available fast flux with 1.3×10^{13} n/s source

*Service commercially available to fusion system developers,
defense microelectronics survivability community, and others*

FIRE Collaboration Test Plans – PbLi and FLiBe

PARTNERED WITH MIT ON THE UW-MADISON PROGRAM

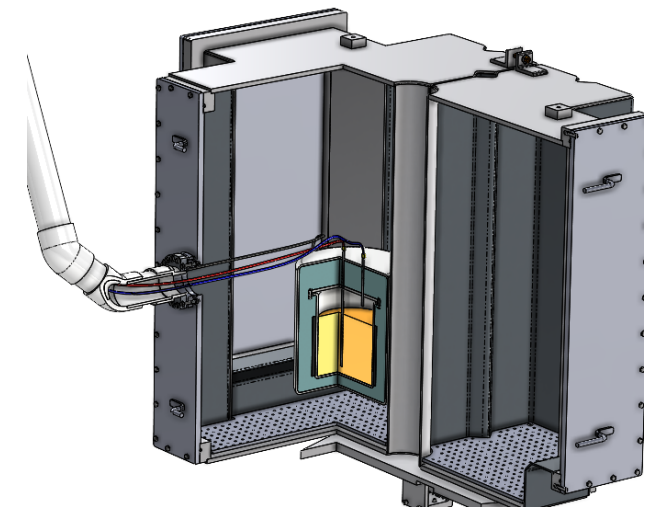
- Key goals include:

- Utilize FLARE facility for mid-scale tritium breeding demonstrations in liquid breeders
- Demonstrate tritium accountancy and understand behavior in FLiBe and PbLi at small fluences
- Provide critical validation data for tritium transport

Name	BABY	BABY	FIRE	FIRE	FIRE
Breeder	CLiF	FLiBe	PbLi	PbLi	FLiBe
Volume (L)	0.1	1	1 (x2)	1	1
Fusion n/s	10^8	10^8	$10^8, 10^{13}$	10^{13}	10^{13}
Approx TBR	10^{-4}	10^{-3}	10^{-3}	10^{-3}	10^{-3}
T production [T/s]	10^4	10^5	10^4 - 10^5	10^{11}	10^{11}
Location	MIT PSFC Vault lab		MIT + SHINE	SHINE facility	

- FIRE project will provide first-of-its-kind information regarding:

- Global TBR measurements in FLiBe and PbLi at a high fusion neutron rate ($>10^{13}$ n/s)
- Tritium permeation through conventional and advanced, fusion-relevant materials
- Ease of tritium extraction as a function of temperature and system
- Expected tritium losses from a system / overall tritium accountancy
- Chemistry of extracted tritium
- Material compatibility with high-temperature liquid breeders



Larger-scale potential for tritium breeding testing at FLARE

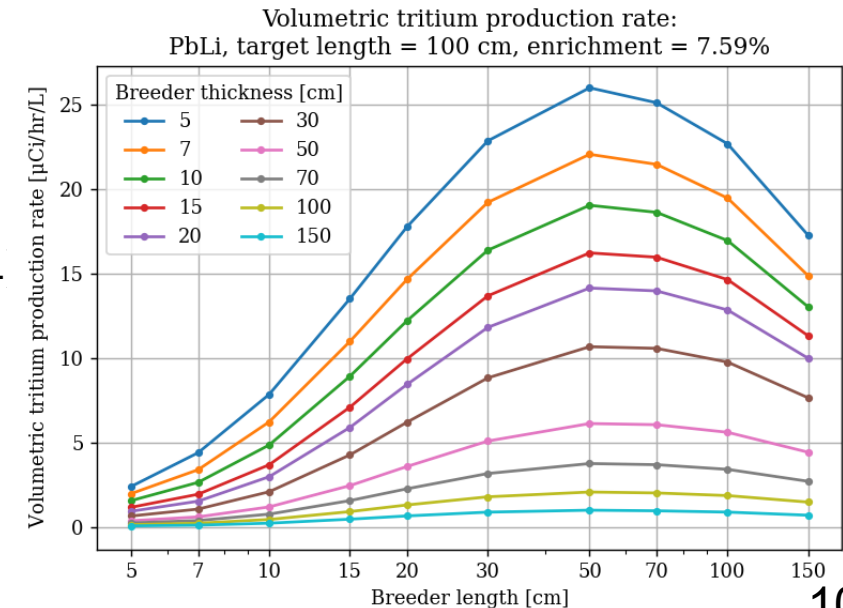
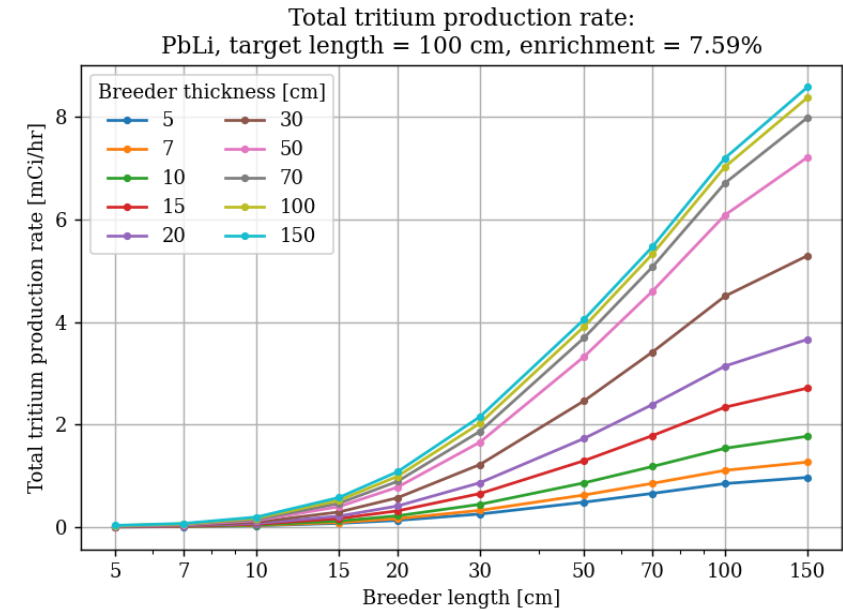
■ SHINE is well-positioned to perform intermediate-scale breeding tests

- Intense DT neutron source
- Air cavity provides natural secondary safety barrier
- License amendment in process to grow to 3.5g of tritium
- Currently seeking license amendment that will allow for deliberate tritium production

■ MCNP modeling shows that experimentally useful quantities of tritium can be produced at FLARE

○ Assumptions:

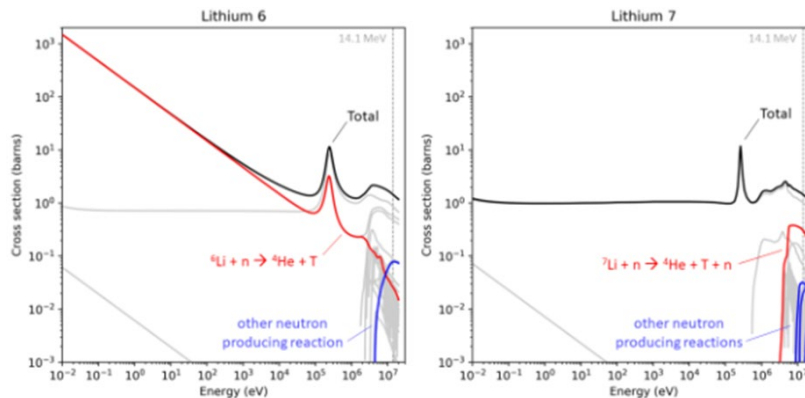
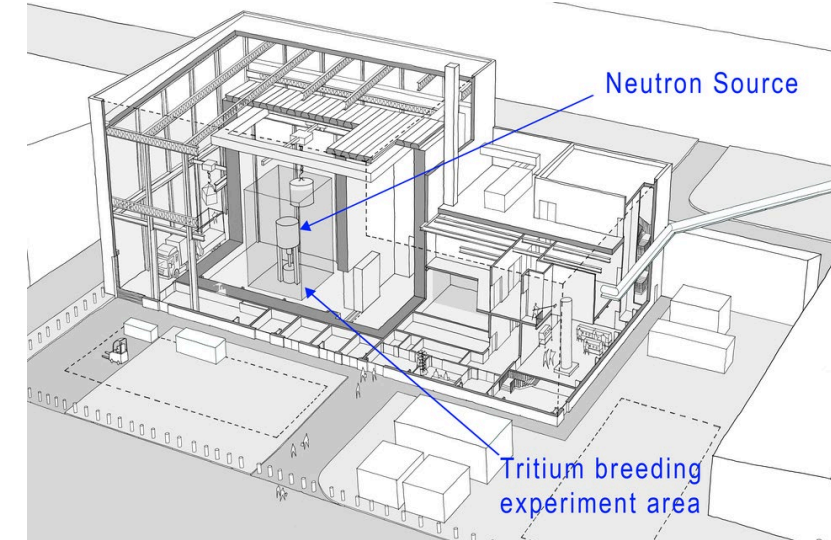
- Neutron source strength = 2×10^{13} n/s
- Annular configuration with W/SS first wall, interstitial SS/H₂O cooling channels in tritium breeding zone, and SS back supporting structure (BSS) and vacuum vessel
- Tritium breeding material is PbLi with natural lithium (not enriched) at 600 K
- Annular tritium breeding zone thickness = 50 cm and height = 50 cm (volume = 541 L)
- Run time = 50 hours
- Tritium production = 166 mCi (total) or 307 μ Ci/L (volumetric)
 - 6.14 GBq (total) or 11.4 MBq (volumetric)



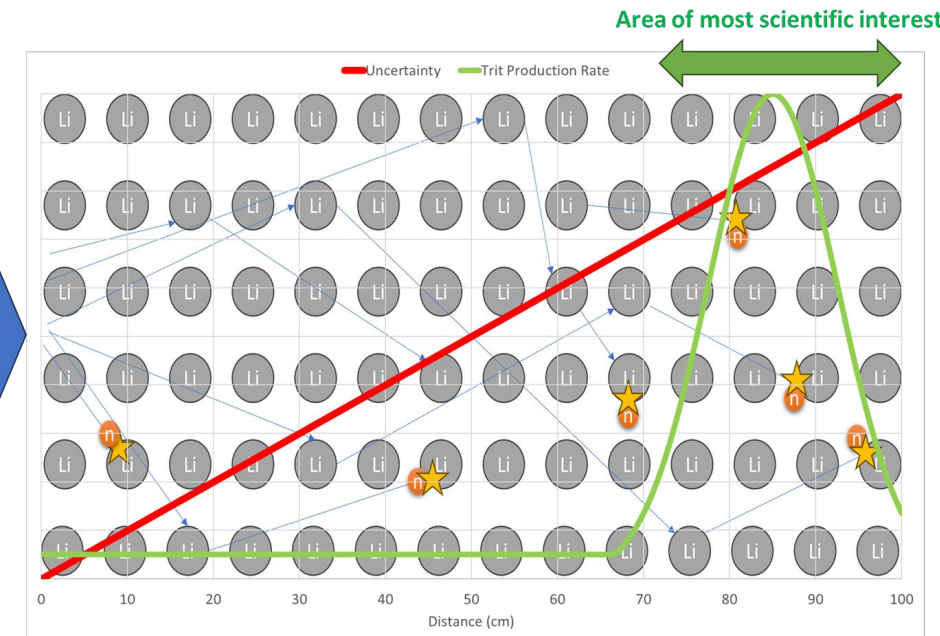
Lithium Breeding Tritium Innovation (LIBRTI)

UKAEA PROGRAM FOR ENGINEERING-SCALE BREEDING BLANKET TESTING

- Tritium breeding is needed for a sustainable fusion fuel cycle
- SHINE was selected to provide a FLARE-like DT neutron source to support the UKAEA LIBRTI project
- Breeder blanket efficacy is critically dependent upon both neutron and tritium transport
 - Most tritium is created ~1m from the source as neutrons need to be moderated to where the X-section is more potent
 - Uncertainty increases as you move through the blanket
 - High starting flux needed for neutrons to reach that deep
- LIBRTI is the first facility to construct a breeder test on this scale and with **sufficient neutron flux / T₂ production**



Neutron Source



Plasma Window will Allow for Increased Flux

Concept: Expand on SHINE's gas target technology with a plasma window - higher localized flux and higher neutron output potential

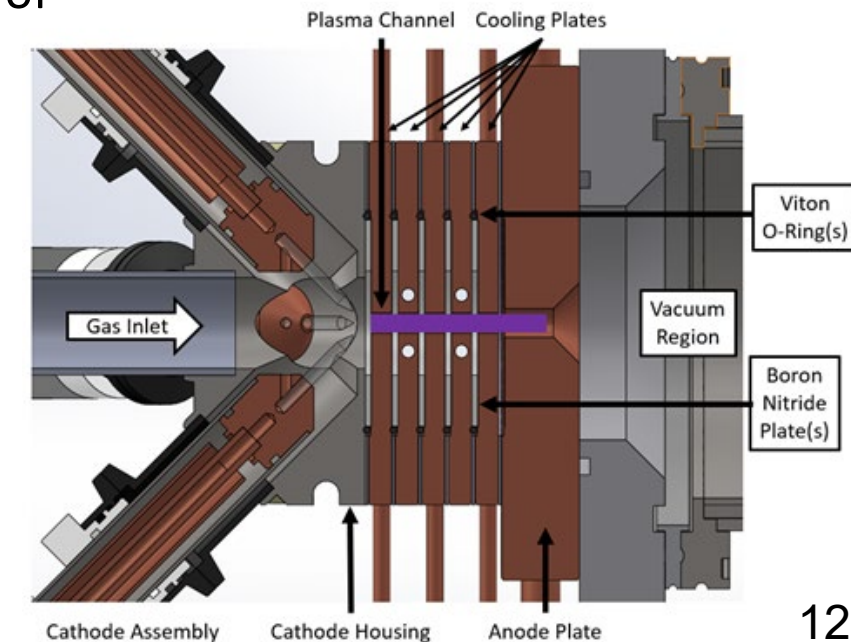
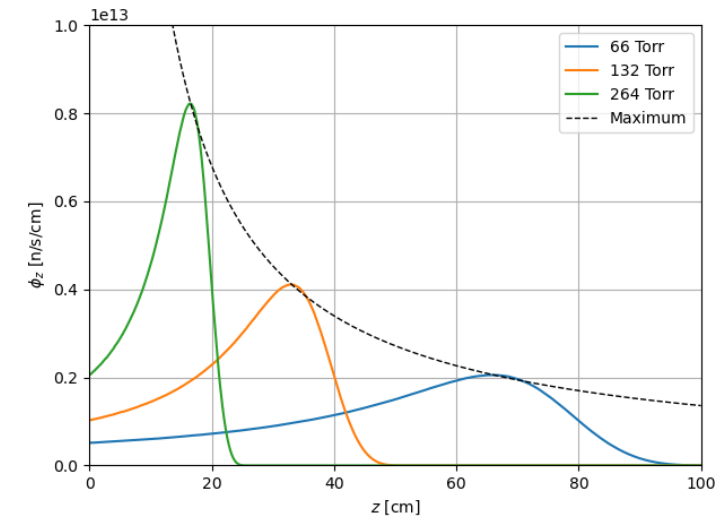
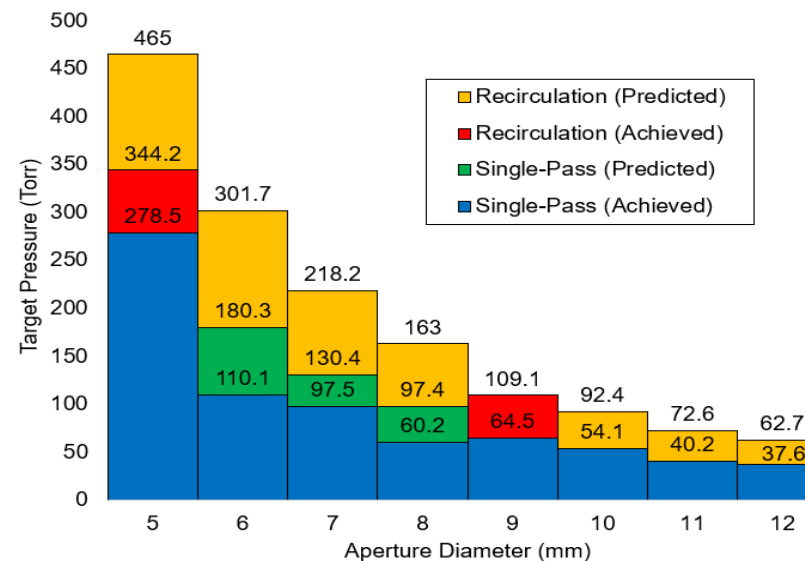
➤ **Plasma window:** Strike a plasma in the final aperture, creating a viscous boundary between the gas target and the vacuum region of beam transport

Demonstrated Results

- Increased target pressure by **10X**: stops beam in shorter distance & increases local neutron flux
- Increased final aperture area by **5X**: allows higher beam current & neutron yield

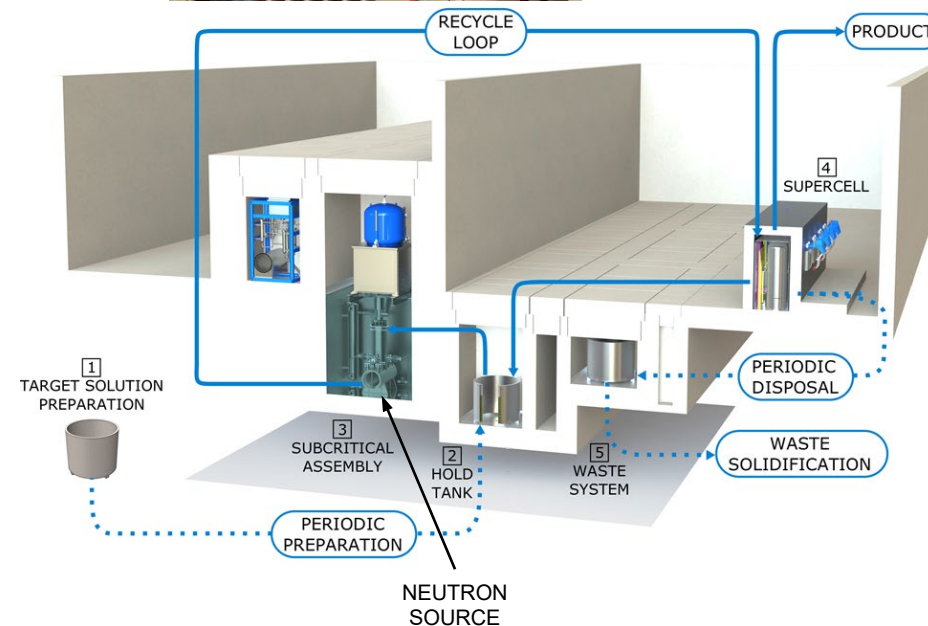
Next Steps: Test plasma window with beam present, then find optimal ratio of increased pressure and aperture size to maximize tritium yield.

Plasma window upgrade can raise flux from 2×10^{10} n/cm²s to 1×10^{12} n/cm²s



Fission Product Production/Separation

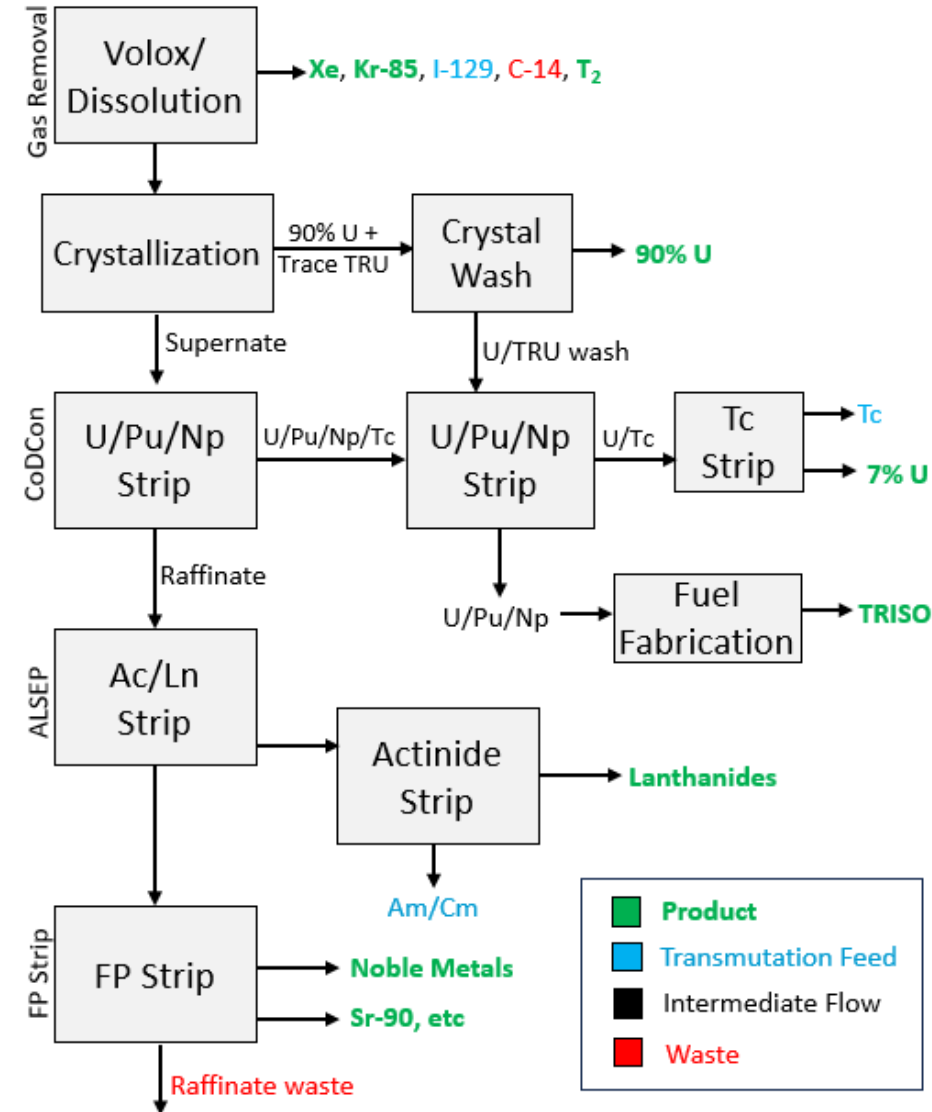
- Licensed and constructed. Installing process equipment.
- Facility will produce >50% of US **Mo-99** demand
 - 10 CFR Part 50 SER issued in early 2023
 - 2nd site in Netherlands; site eval and licensing underway
- Production Process
 1. Irradiate aqueous LEU subcritical assembly with DT neutrons
 2. Up to 1 MW of fissions produced
 - a. Mo-99 has a ~6% cumulative yield
 3. Transfer UO_2SO_4 to hold tanks and then the “super cell”
 - a. Mo-99 extraction, purification, QC & packaging
 4. Final products ship to customers



UNF Recycling and Isotope Recovery

NEWLY DEVELOPED TECHNOLOGIES PRESENT UNIQUE OPPORTUNITIES

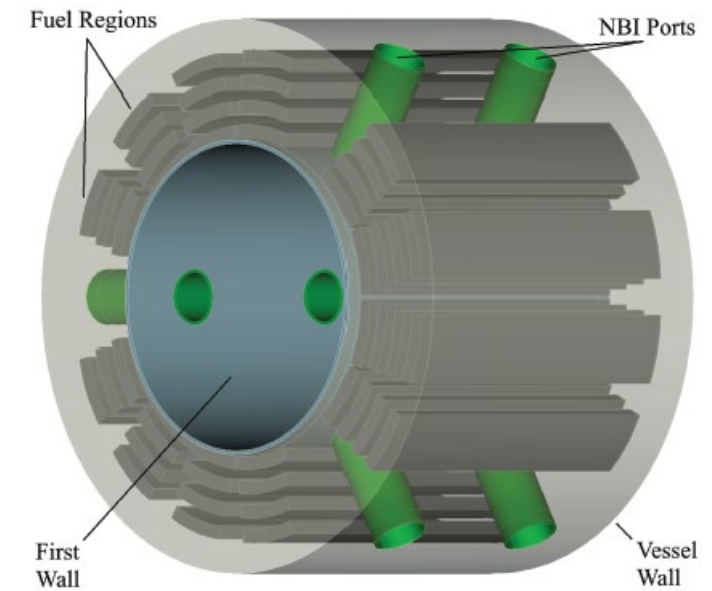
- Evaluating technology improvements for regulatory compliance and improved economics
 1. Voloxidation for pre-processing fuel assemblies allows isolation of iodine/tritium to avoid liquid contamination
 2. CoDCon extraction to create a **blended U/Pu** stream
 3. Removal of minor actinides (via ALSEP) from the waste stream; future transmutation
 4. Harvest platinum group metals and rare earth elements for sale
 - a. Am-241, Kr-85, and Sr-90 are commercial targets as well
 5. >95% of waste volume expected to be suitable for near-surface disposal
 - a. Assessing deep bore disposal with Deep Isolation
- Approach combines proven and novel technologies and implements SHINE's improved safety and regulatory approach to greatly reduce the lifecycle cost of a recycling facility



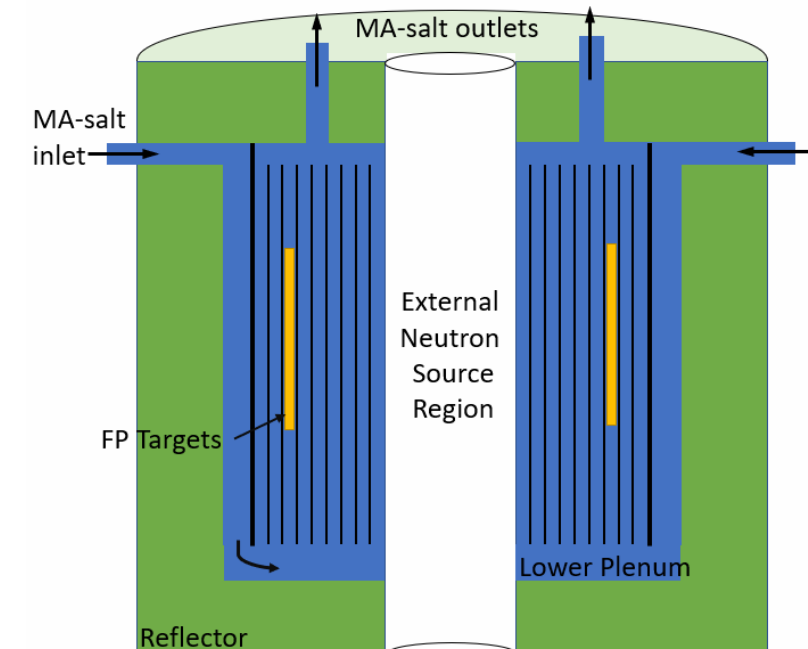
Longer Term: Transmutation

MAXIMIZING BENEFITS OF A CLOSED FUEL CYCLE

- Goal: Eliminate minor actinides (Np, Am, Cm) via fast fission
 - Assessing liquid (molten salt) core options
 - Evaluating fusion-driven subcritical systems and critical systems
 - Additionally, fission products (e.g. I-129 and Tc-99) can be converted to shorter lived or stable isotopes via neutron capture
- Benefits:
 - Molten cores: Minor actinides don't enter fuel rod supply chain
 - Systems can operate nearer to (or at) critical levels due to increased negative reactivity
 - Molten salt core allows for rapid capture of short-lived fission products for secondary sale
 - Significant separation development to be performed
- SHINE has been awarded an ARPA-E NEWTON grant to investigate/test blanket technologies over the next 3 years



Courtesy of UW-Madison*





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Therapeutic Isotopes

- SHINE has established the largest source of GMP Lu-177 currently produced in North America
 - Emergent cancer treatment isotope – rapidly growing usage
- Vertical integration & technology are our key differentiators
 - Yb Enrichment: We produce our own Yb-176 via in-house electromagnetic separation
 - Irradiation: Research reactors today; moving to in-house irradiation
 - Lu-177 Processing: Our technology provides significant scaling advantage
- Producing GMP Lu-177 from our Wisconsin, USA facility
 - 200,000 doses per year capability

Lu-177 Product Spec Sheet

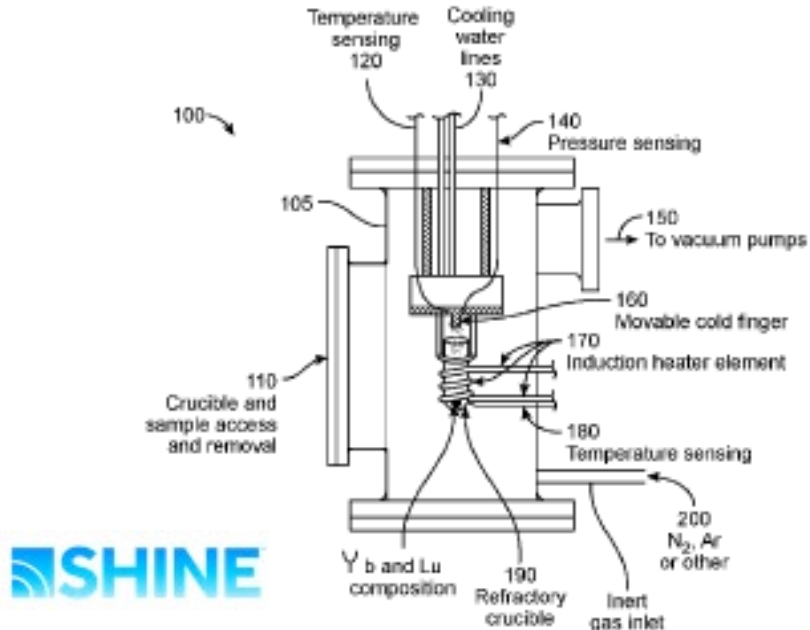
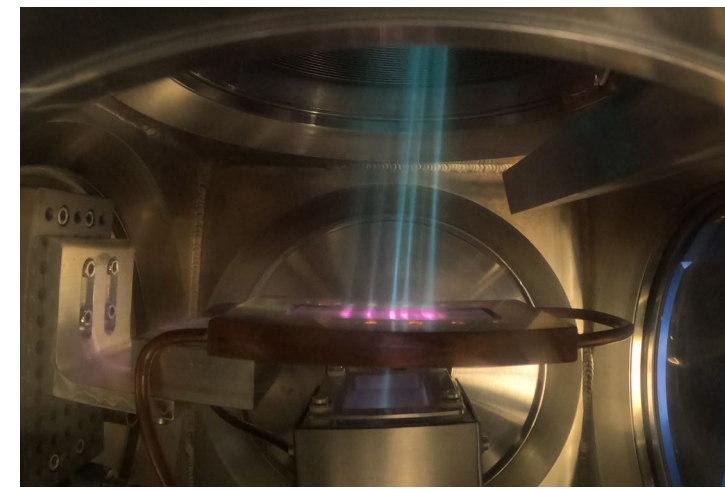
PACKAGING OPTIONS	10 mL flat bottom vial 2mL conical glass vial
CHEMICAL FORM	n.c.a. $^{177}\text{LuCl}_3$ in 0.04M HCl solution
SPECIFIC ACTIVITY	$\geq 3,000$ GBq/mg at SHINE calibration time
RADIOCHEMICAL PURITY	$\geq 99\%$ as $^{177}\text{LuCl}_3$
RADIONUCLIDIC PURITY	$\geq 99.9\%$ ^{177}Lu
RADIOACTIVITY CONCENTRATION AT SHINE CALIBRATION TIME	1.0Ci/mL (37GBq/mL) +/-10%
EXPIRY	10 days from the end of synthesis
STANDARD CALIBRATION TIME	Tuesdays 1200 central time (U.S) at 1.00 Ci/mL
CGMP	Meets ICH-Q7 and FDA-21CFR
RADIOLABELING YIELD	$\geq 99\%$

Lu-177 Production Process



Enrichment, Separation, and Purification

- Built/operating enrichment system with improved yield/purity
 - 50 g/year Yb-176 production per machine; >99.7% isotopic purity
 - Producing more Yb-176 than is being consumed today
- Thermal distillation separation relies on the wide variation of boiling points (Lu: 3,402 °C, Yb: 1196 °C)
 - Irradiated metal target is heated under vacuum
 - Yb sublimates and is captured on a cold trap; Lu concentrates
- Material dissolved in HCl and purified via HPLC process
- Testing these processes for Tb-161 production today



Typical HPLC Output

