Driven Subcritical Systems: SHINE's Experience and Lessons Learned

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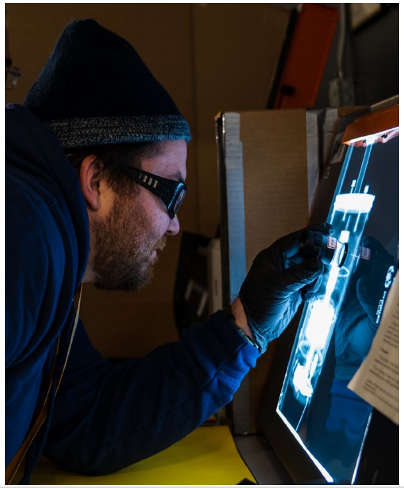
SHINE's Market-Driven Approach

VISON: TRANSFORMING HUMANKIND THROUGH FUSION TECHNOLOGY



1 Inspect Industrial Components

Fusion 1.0
(solid target)

COMMERCIAL, PROFITABLE

2 Produce Medical Isotopes

Fusion 2.0
(gas target)
+
Radiochemical & Uranium Processing 1.0

COMMERCIAL, SCALING

3 Recycle Nuclear Waste

Fusion 3.0
(warm / hot plasma)
+
Radiochemical & Uranium Processing 2.0

DEVELOPING

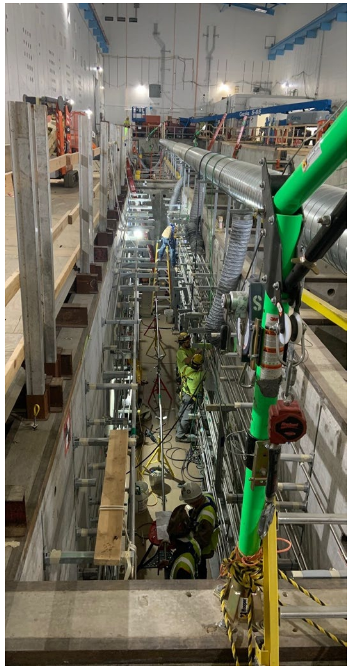
4 Generate Fusion Power

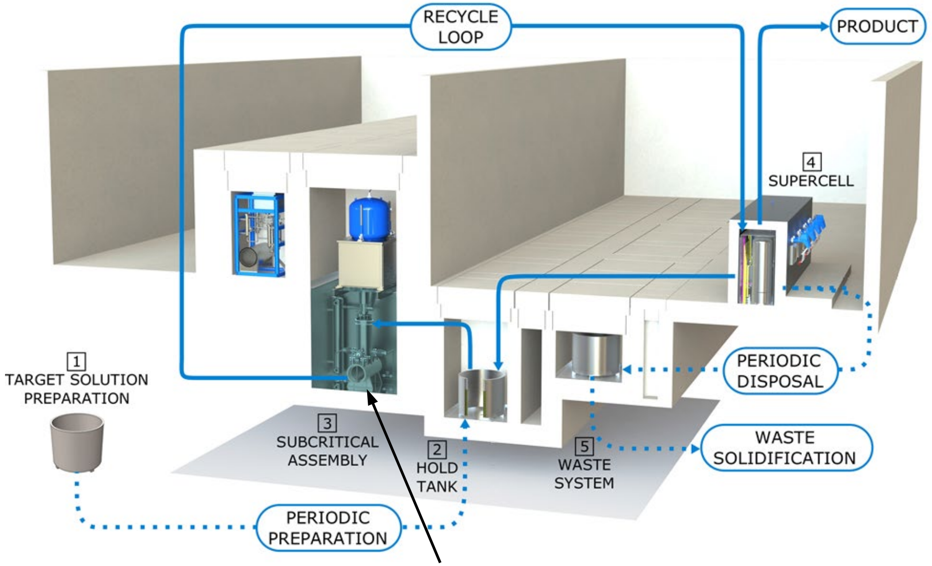
Fusion 4.0
(hot plasma)

EARLY R&D

Phase 2: Isotope 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
- Financing Pathway
  - Early R&D funding on underlying tech (e.g. SBIR)
  - NNSA cooperative agreement for foundational work (50% match)
  - Continued support from NNSA at much lower matching, but primarily privately financed





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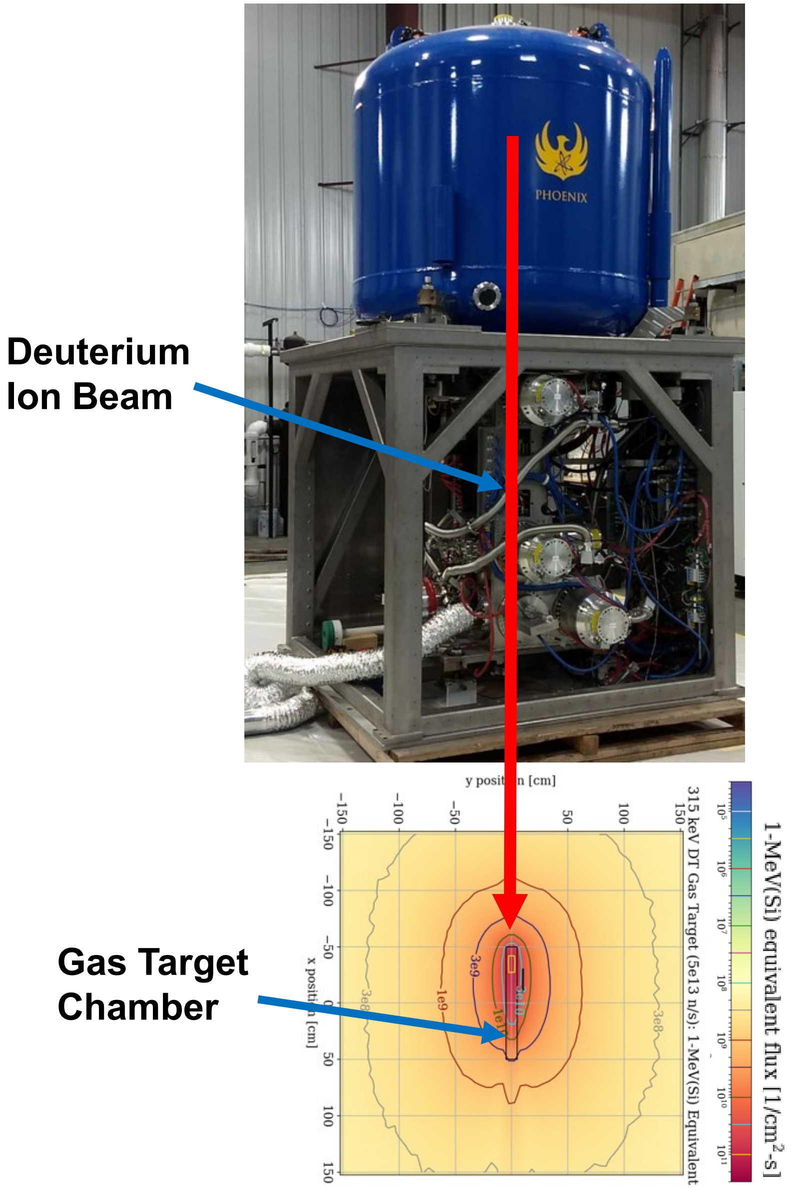
Fusion Neutron Drivers

FLEXIBLE PLATFORM DEVELOPED FOR MULTIPLE APPLICATIONS

- Received R&D funding (SBIR, Army) in 2009
- First commercial sale of lower yield variation in 2013
- Tech development “valley of death” covered in large part by NNSA cooperative agreement
- Two units operating today with additional being constructed



<u>Theory of Operation</u>

1. Microwave ion source creates dense deuteron plasma
2. DC accelerator extracts ion beam (300kV)
3. Magnetic field focuses ion beam
4. Differential pumping system maintains target pressure while keeping accelerator pressure low
5. Beam strikes tritium (or deuterium) gas and generates neutrons
6. $5x10^{13}$ n/s measured output

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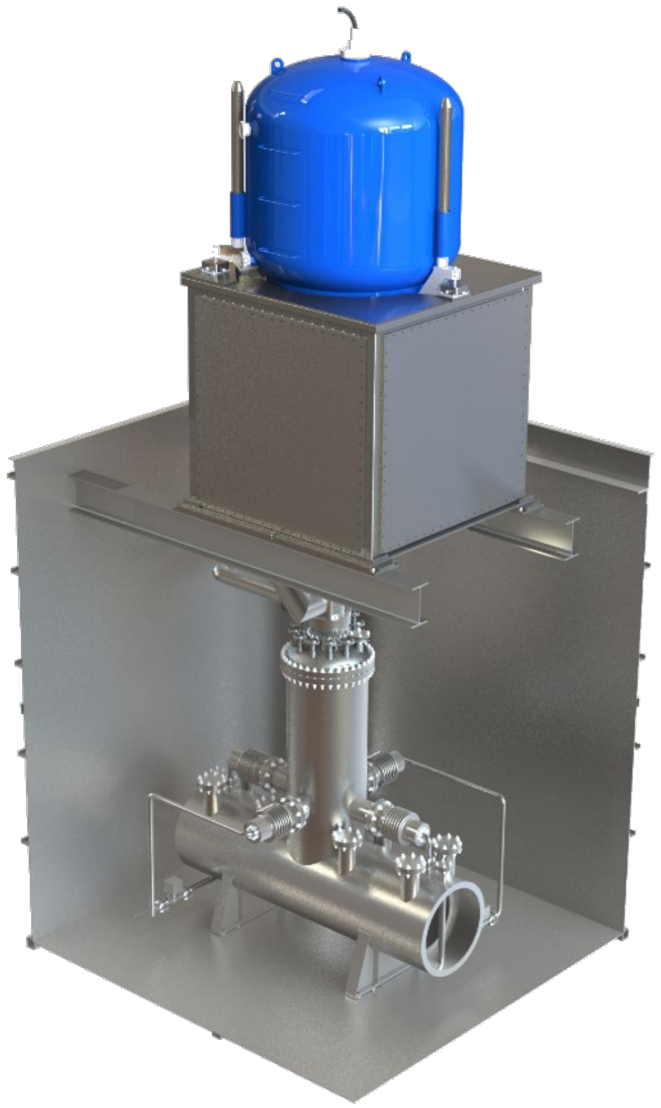
Subcritical Assembly Approach

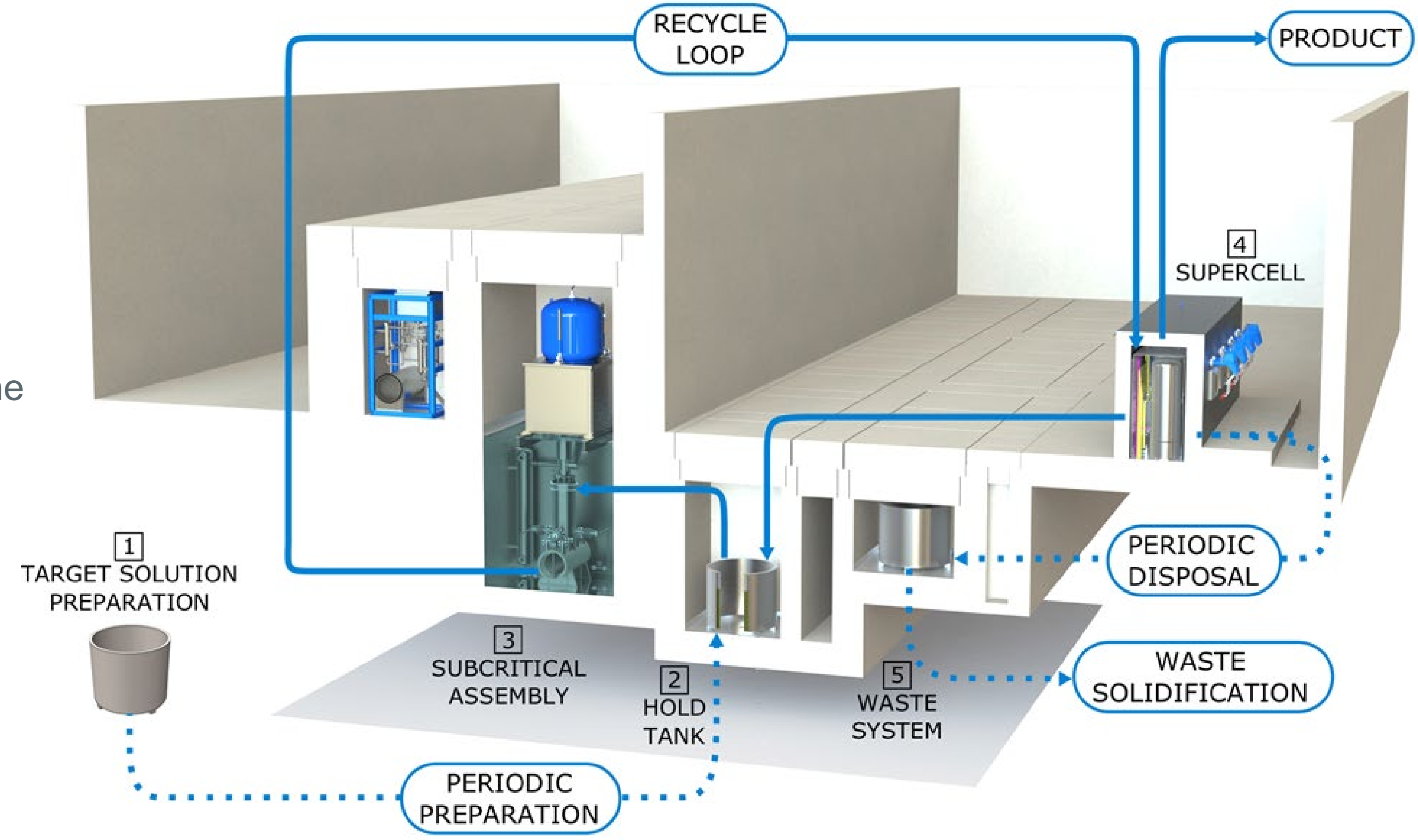
- Driven by 14 MeV neutron source
  - Aqueous, annular subcritical configuration (thermal spectrum)
- Small SCA systems: Licensed to 125 kW each
  - Low source term—helps ensure safety of public and workforce
  - Low decay heat per system < 1 kW within 5 hours
- Low enriched uranium (LEU) reusable target
  - Product compatible with current supply chain
  - Eliminates need for HEU
  - Reduces waste
- Multiple units and trains provide operational scalability and flexibility

- Development funding provided by NNSA through cooperative agreement funding (50% matching)
  - Additional funding provided directly to national laboratories was also important to early technology development



Isotope Separation Process Overview

1. Periodic solution preparation from LEU
2. Solution chemistry check and staging
3. Irradiation for 5.5 days
4. Extraction, purification, QC & packaging
   - Mo captured on column (3 trains)
   - Purified via LEU-modified Cintichem process
     - Consists of precipitation of contaminants, chelation of the Moly, and filtering of the product solution
5. Waste solidification



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Commercialization Best Practices and Lessons Learned

- Use government funding from federal agencies relevant to long term commercialization efforts to fund the earliest stage, highest risk R&D.
    - SHINE received $25M in initial funding from the DOE for its isotope production facility,
    - Signal to industry and private investors – essential in getting the project off the ground.
    - SHINE has raised over $700M in additional private capital

- Engage customers early to influence facility capabilities and requirements and sign contracts well in advance of bringing a commercial facility online.
    - Multiple customer commitments to purchase isotopes secured as early as 2014
    - Commitments were critical in securing additional private capital

- Engage with key regulators early and often.
    - SHINE began robust engagement with the NRC over a decade in advance of the anticipated commercialization date, and years before it formally entered the regulatory process.
    - Allowed SHINE to develop a regulatory strategy in collaboration with its key regulator
        - First-of-a-kind facility with an unclear regulatory pathway was issued SER "at light speed," as former NRC chairperson Allison M. Macfarlane described it.

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Regulatory Best Practices and Lessons Learned

PRE-APPLICATION MEETINGS SUPPORTING A FIRST-OF-ITS-KIND FACILITY

- Short-term acceptance of a burdensome regulation might shorten a licensing review cycle, but can have long-term consequences to project cost and schedule
  - NRC staff is willing to listen to fact-based arguments on safe alternative approaches and work to find a pathway to approval
- Use pre-application meetings to gain momentum
  - Focus on topics which support NRC acceptance of the application for review (i.e., ensuring a complete, high-quality application is tendered by the applicant)
- Utilize regulatory audits to minimize the number and scope of formal RAIs
  - Preparing for pre-application meetings are resource-intensive, but worth the effort
  - Where formal RAIs are needed, use audit to gain clarity on the request and discuss draft responses and supplements to assess whether it will meet the need
- Challenge the NRC Staff/NRC Management to ensure any formal request for information to be docketed has a sound regulatory basis
  - Doing so reduces the number of curiosity based RAIs and ensures requests are directly related to the reasonable assurance determinations that the NRC Staff need to make

Construction Permit (CP) Application	
Cons. Permit App (Part 1) Submitted	Mar 2013
Cons. Permit App (Part 2) Submitted	May 2013
Issuance of EIS	Oct 2015
Issuance of Safety Eval Report	Oct 2015
Mandatory Hearing	Dec 2015
Issuance of Construction Permit	Feb 2016

Operating License (OL) Application	
Operating License Application Submitted	July 2019
Application Acceptance for Docketing	Oct 2019
Issuance of Environmental Impact Statement (EIS) Supplement	Jan 2023
Issuance of Safety Eval Report	Feb 2023

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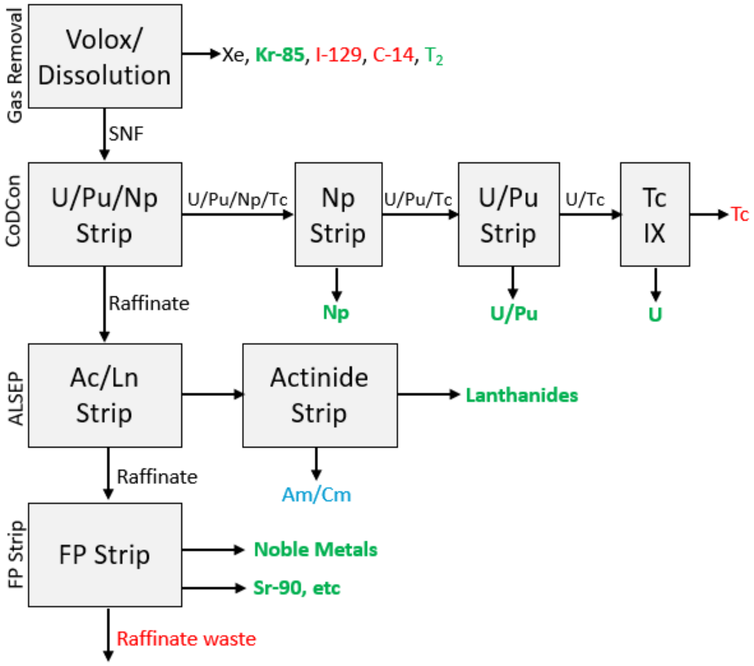
Technical Best Practices and Lessons Learned

- Safety and quality lessons
  - Define a graded approach to nuclear quality
  - Minimize active safety controls and operator actions, aim for passive safety
  - Minimize footprint of safety-related equipment to minimize seismic II/I considerations
  - Use risk-based approach to define seismic design requirements (i.e., ANS 2.26 methodology)
- General design lessons
  - Where it makes sense, design for replacement rather than designing for the life of the facility
  - Add more space, penetrations, conduits than anticipated, for design flexibility
  - Develop early guidance on requirements and design bases for the project (e.g., codes and standards, seismic, ITPs, EMI/RFI)
  - Mock-up equipment and run processes as close to scale as possible to identify scale-up issues
  - Develop and maintain 3D model to determine space requirements and assess conflicts
  - Starting construction before 100% design completion (to save schedule) is a large risk
- Knowledge and data management lessons
  - Be explicit about and track margins (i.e., normal operating, operating limit, safety limit)
  - Develop and maintain databases early (e.g., MEL, margin management, safety functions)
  - Prioritize mentorship and knowledge transfer to avoid challenges caused by attrition or movement within the organization

Next Phase: Used Nuclear Fuel (UNF) Recycling

ENABLING THE NEXT 100 YEARS OF CLEAN NUCLEAR ENERGY

- SHINE developing a UNF recycling solution to:
  - Provide domestic RepU, MOX, and (perhaps) HALEU alternative
  - Reduce UNF volume and help answer, “what about the waste?”
  - Isolate MA and select FP for further transmutation
- Leveraging unique capabilities
  - Licensing, construction, and commissioning of 10 CFR Part 50 facility
  - Radionuclide separation and handling
- Starting with high-TRL technologies to de-risk project
  - Partnering with leaders in this space
  - R&D for US regulatory compliance and improved economics
- Driving transmutation concepts forward
  - Lower TRL, but high impact



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Applying Lessons: UNF Recycling Commercialization Risk

- Technical Risk
  - Identifying where direct National Lab support and funding R&D opportunities exist
- Government/Public Perception Risk
  - Proliferation concerns must be mitigated (Sandia supporting)
  - Directional alignment needed – but there is a tailwind due to climate change and Russian invasion of Ukraine
    - NE-43 and those in this room can all support here
- Economic Risk
  - Revenue
    - Working to understand DOE/Federal appetite for recycling UNF stockpile
      - SHINE willing to provide significant private funding; then collect fees based on processed volume
      - Discussing long-term economic paradigm with Utility partners
    - Performing market validation of output products
      - Commercial Utilities (fuel disposition; MOX and RepU sales) and radio/stable isotope customers (public and private)
  - Construction/Operation Cost
    - Moly-99 facility costs much lower than conventional FOAK nuclear construction project
      - Graded approach to quality; In-house commercial grade dedication
    - Leveraging lessons learned, especially on seismic matters
    - Utilizing existing project controls, safety analysis, and licensing infrastructure (built over past 10+ years)
    - Government can help by providing loan guarantee programs (like new nuclear power)

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