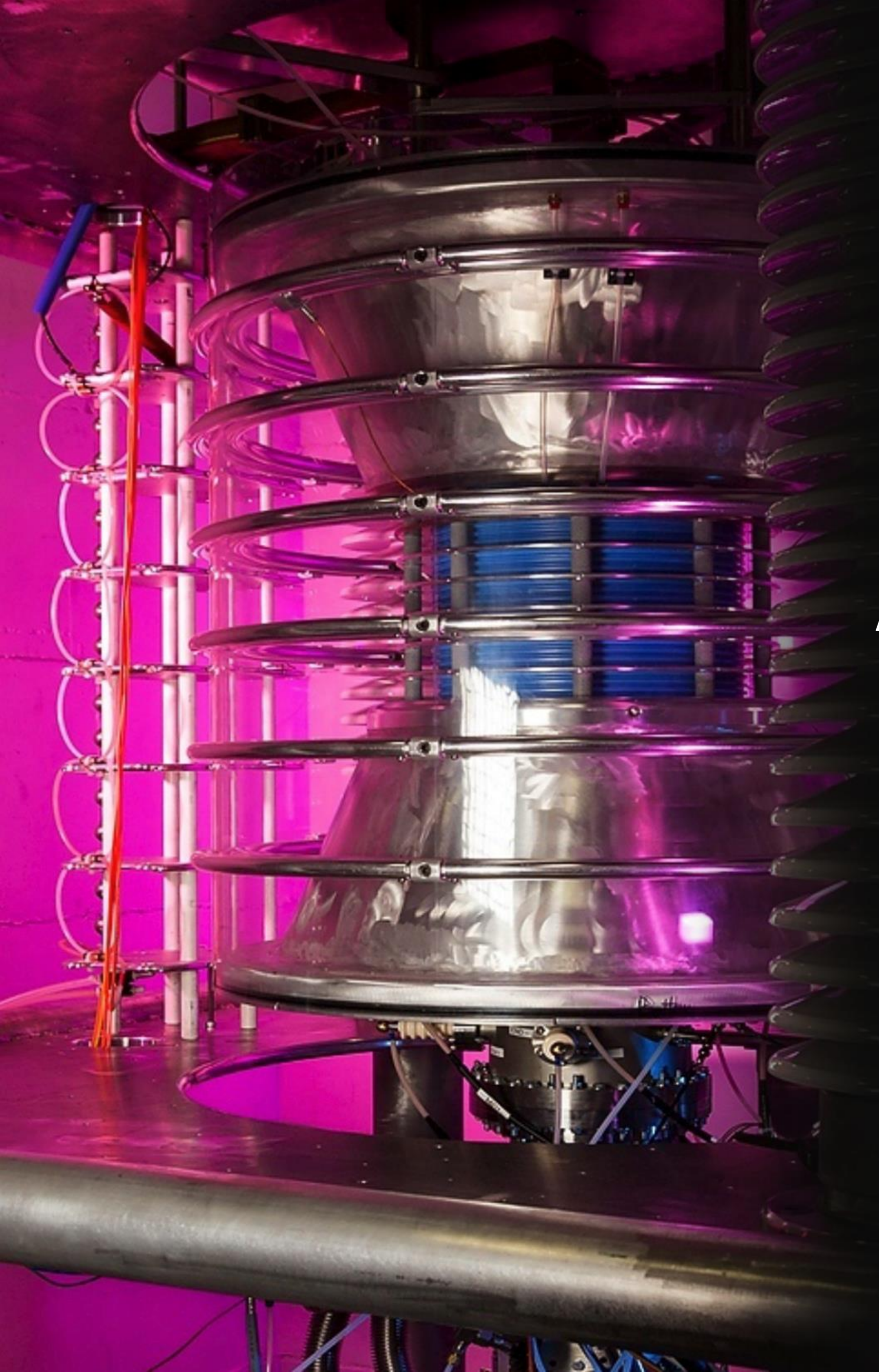

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PROVIDING NUCLEAR TECHNOLOGY FOR THE BETTERMENT OF HUMANITY

Accelerator-Based Neutron Generator to Drive Sub-Critical Isotope Production Systems

Ross Radel, PhD
President, Phoenix Nuclear Labs

PNL Introduction

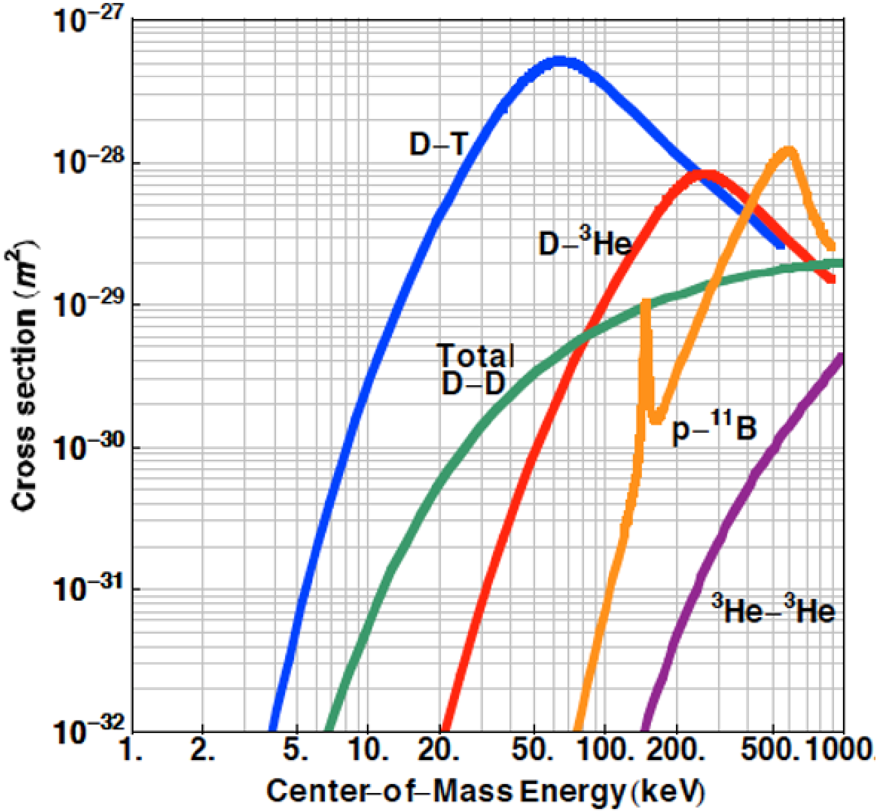
- Development stage company in Madison, WI with ~35 employees
- PNL has developed high yield, gas target neutron generator
- Measured neutron yield of 3×10^{11} DD n/s
- Fundamental technology combines very high current DC ion source, high voltage electrostatic accelerator, and gaseous deuterium or tritium target
- Multiple fielded systems

Theory of Neutron Production

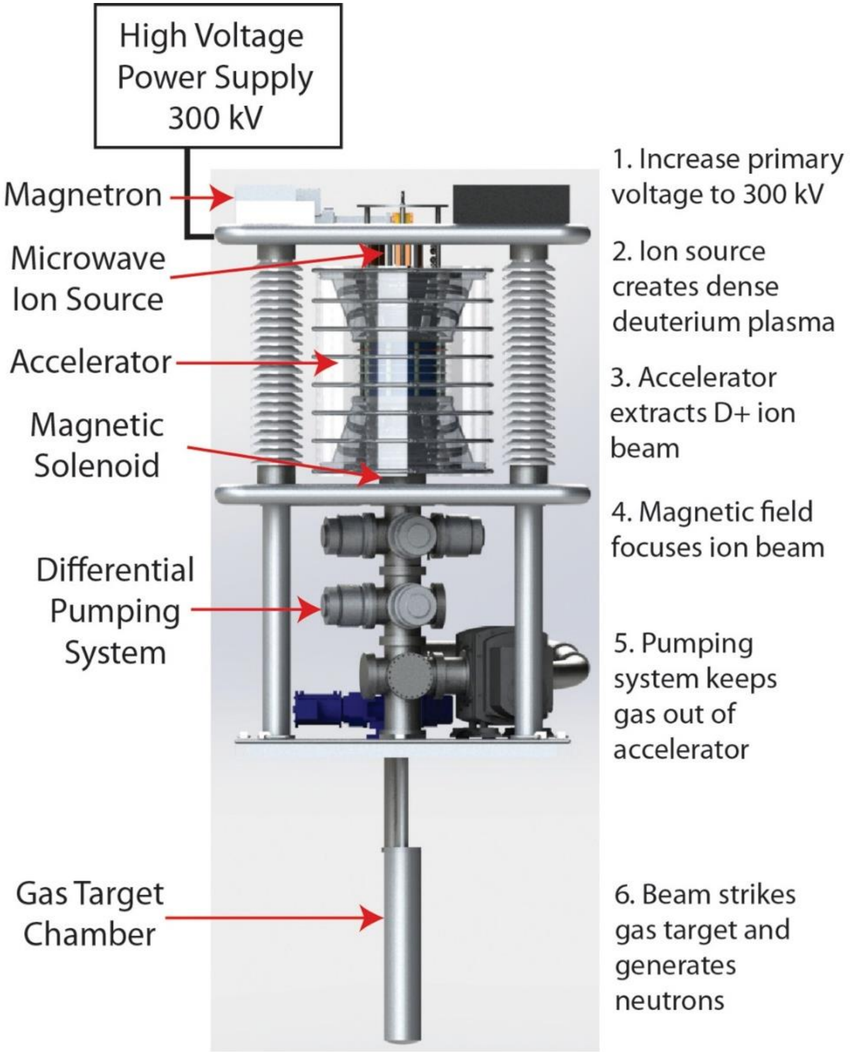
- Neutrons produced via nuclear fusion reaction
  - D + D → He-3 + n (2.5 MeV)
  - D + T → He-4 + n (14.1 MeV)

- Higher accelerator energy and beam current result in higher neutron yield

- D-T reaction provides more neutrons but requires tritium



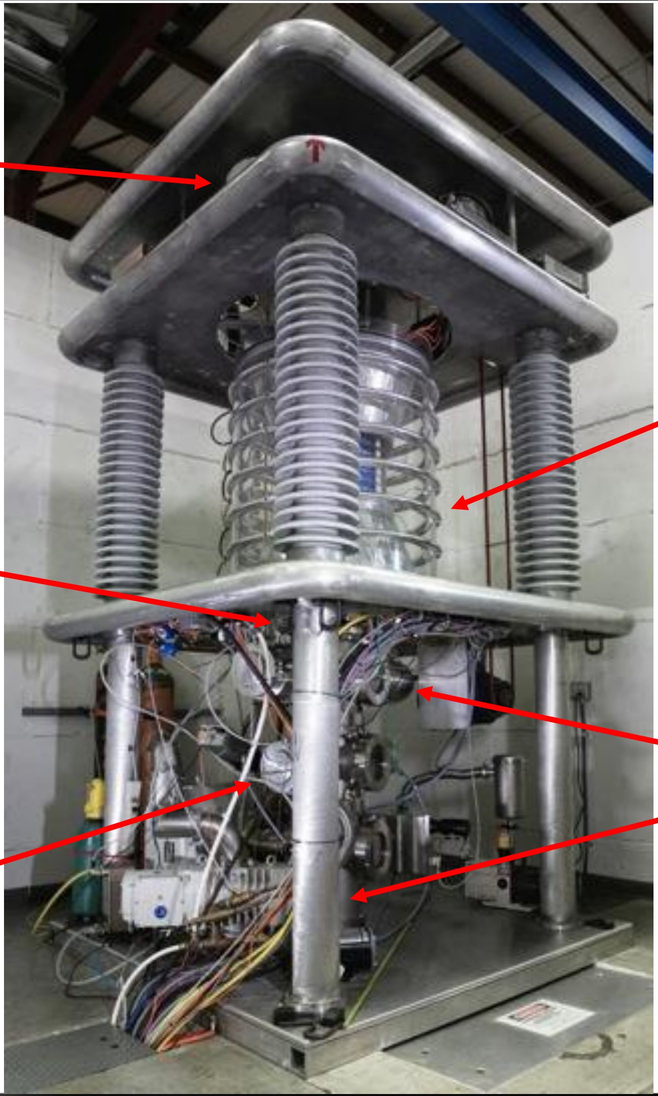
Neutron Source Overview



Generation 1 (Army)

- Built on shoestring budget through SBIR program
- Development completed in late 2012
- Used by Army R&D lab to take neutron radiographs of munitions

Generation 2: SHINE



Generation III: Ultra-NCS

Ultra System Operation

- Measured neutron yields up to $6x10^{10}$ DD n/s
  - 300kV, 50 mA on target
  - Equivalent to $4x10^{11}$ n/s with gas target
- Reliable operation for hundreds of hours
  - Most time spent at 275kV, 30mA
  - <u>Extremely</u> stable operation; shutdowns rare

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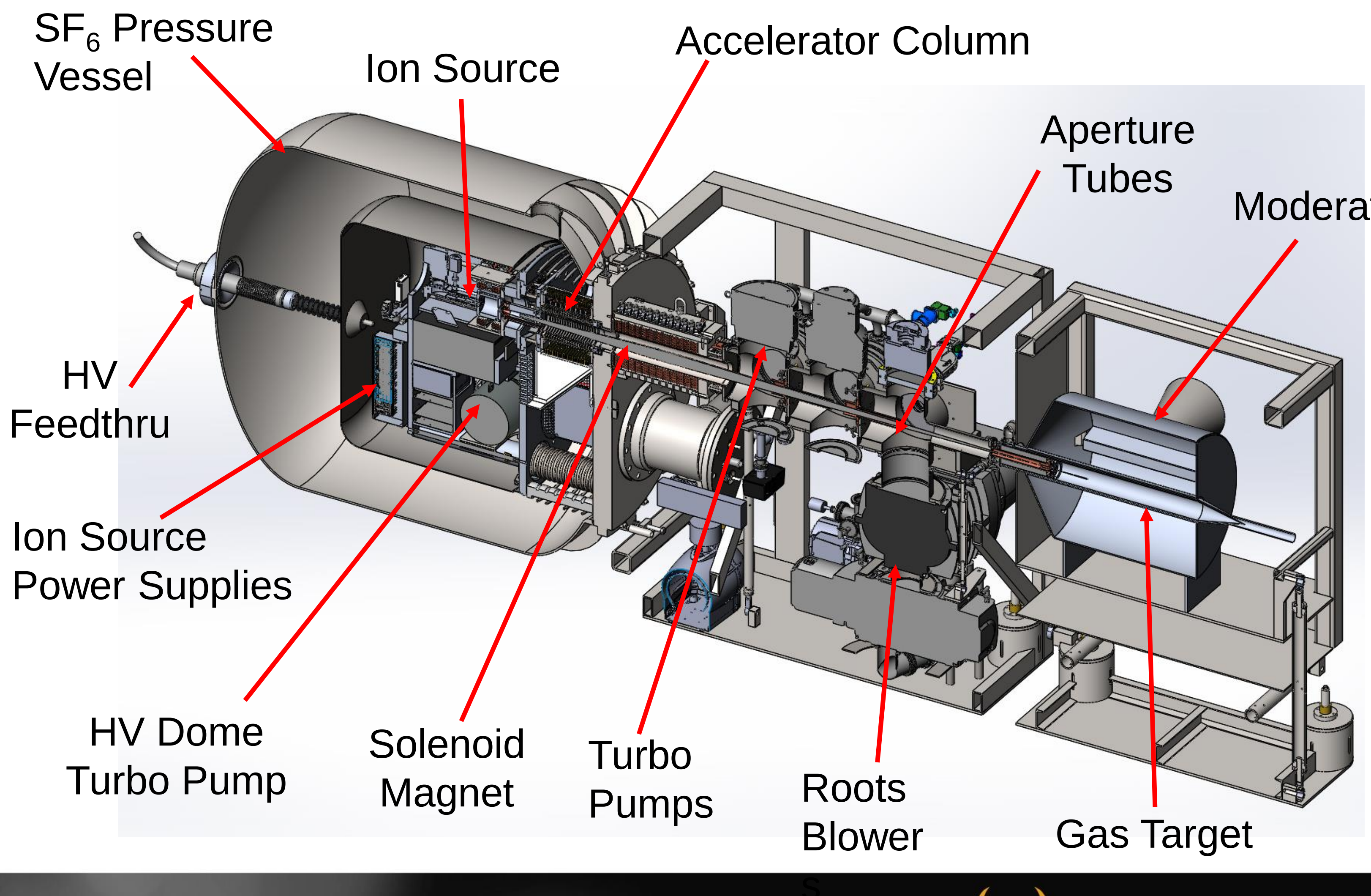
Next Generation – Army Gas Target



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Neutron Applications

← Neutron Tubes →

$100K-$500K per system

$1M-$3M per system

← Research Reactors/Spallation →

$50M-$1B+ per system

10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{16} 10^{17}

Neutrons/second

- Oil Well Logging
- Coal/Cement Analysis
- Scientific Research

Limited Strength

- Radiography
- Detection
- Isotope Production
- Replace Cf-252

- Neutron Diffraction
- Neutron Tomography
- Electricity Production

Limited Access

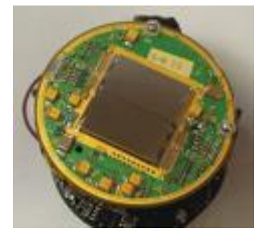
Technology Overlap

Ion Source

80%+

Accelerator

Detection



Imaging

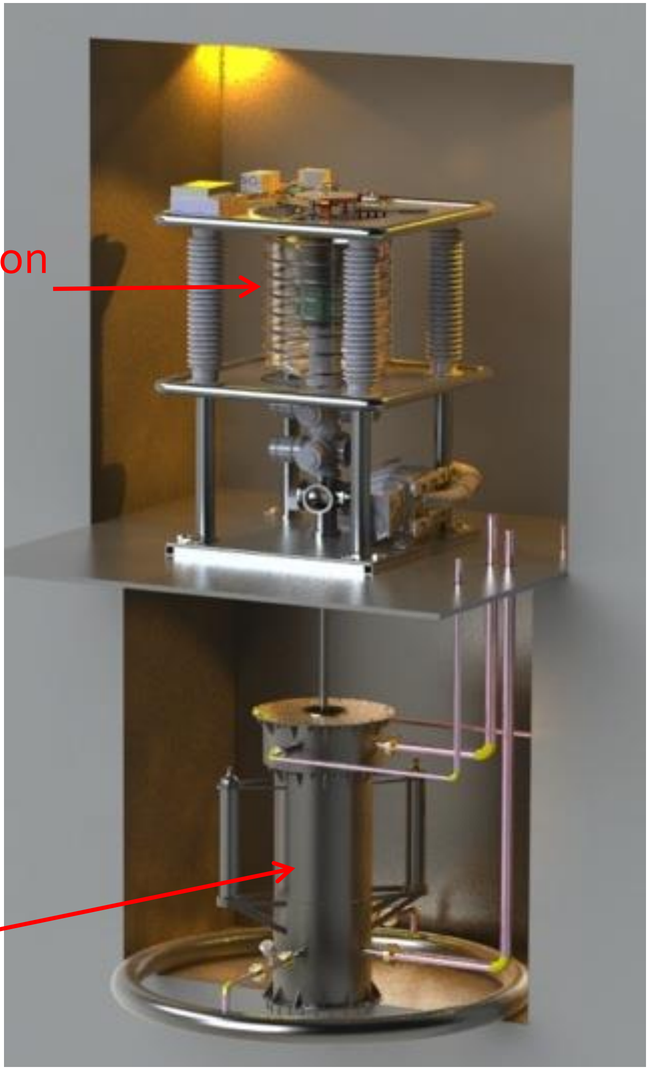
Isotopes

Solar Cells

Isotope Production (SHINE)

- PNL spun out SHINE Medical building facility to produce medical isotope molybdenum-99
  - 50,000 imaging procedures per day in US
  - Currently supplied by non-US reactors
  - Primarily supplied by HEU processes
  - Shortages starting 2018 due to reactor shutdowns

- SHINE facility will use 8 PNL neutron generators
  - DT systems produce $5x10^{13}$ n/s each
  - Coupled with subcritical LEU assembly
  - Capable of producing two-thirds of US moly-99 demand
  - Fission process ensures access to other isotopes, including I-131 and X-133



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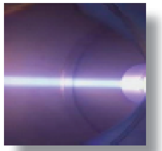
Making Moly-99

SHINE Medical Technologies

2 Accelerator

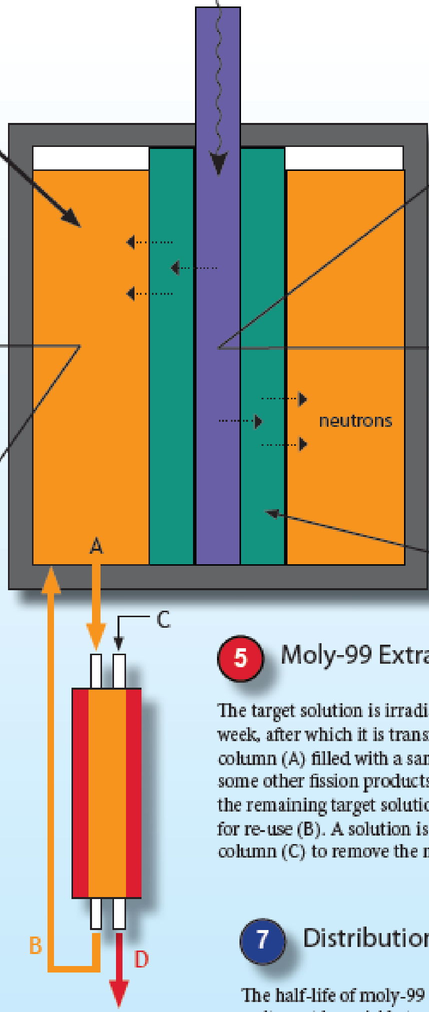
Deuterium ions are shaped into a beam and accelerated to about 10 million mph.



Deuterium beam

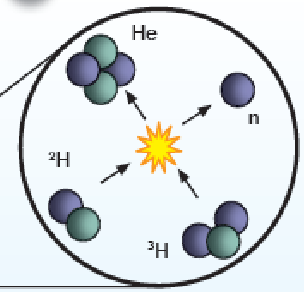
1 Target Solution

Uranium metal is dissolved and made into water-based uranyl sulfate.



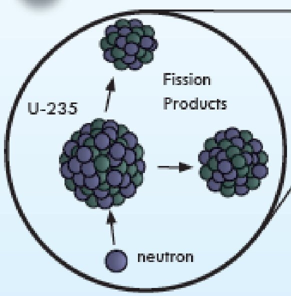
Neutron Multiplier

3 Gas Target Chamber



Deuterium (^{2}H) ions undergo fusion with tritium (^{3}H) gas targets, resulting in helium (He) nuclei and free neutrons (n). These neutrons then pass through a neutron multiplier into the target solution tank.

4 Nuclear Fission



Neutrons cause the uranium nuclei to undergo fission. This process creates several elements as fission products, with about six percent of fission events producing moly-99.

5 Moly-99 Extraction

The target solution is irradiated for approximately one week, after which it is transferred through an extraction column (A) filled with a sand-like material. Moly-99 and some other fission products stick to the column, and the remaining target solution is returned to the process for re-use (B). A solution is then pumped through the column (C) to remove the moly-99 (D).

6 Purification

A lab-scale chemical process purifies the moly-99 to meet pharmaceutical standards and customer specifications.

7 Distribution

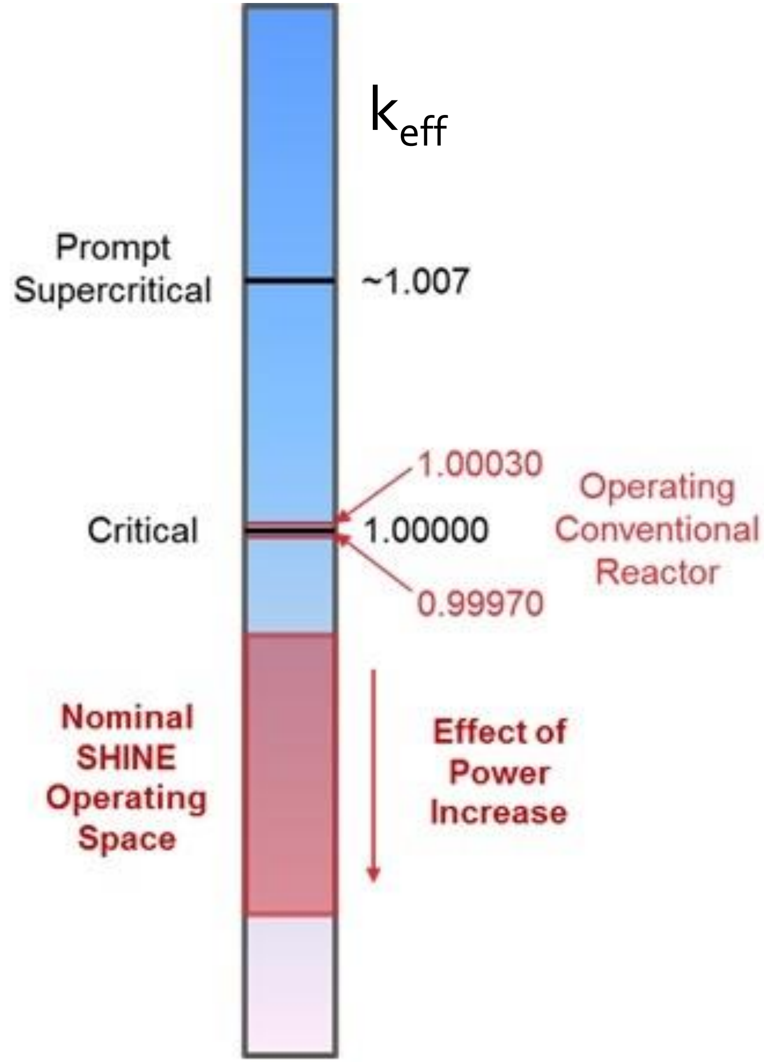
The half-life of moly-99 is only 66 hours, so it must be quickly transported to be used in the medical industry. Moly-99 will be flown from the SHINE production facility in Southern Wisconsin to our customers, where it will be packaged and sent to hospitals for use in procedures such as stress tests and bone scans. Moly-99 is used in over 50,000 procedures every day in the U.S. alone.

Reactivity and Criticality

- K_{eff} is a measure of reactivity
- K_{eff}=1 is sustained criticality
- The reactivity of the subcritical assembly decreases with temperature because solution becomes less dense

Start Up With Solution at Room Temperature →

Operating Conditions With Solution at 60 C →



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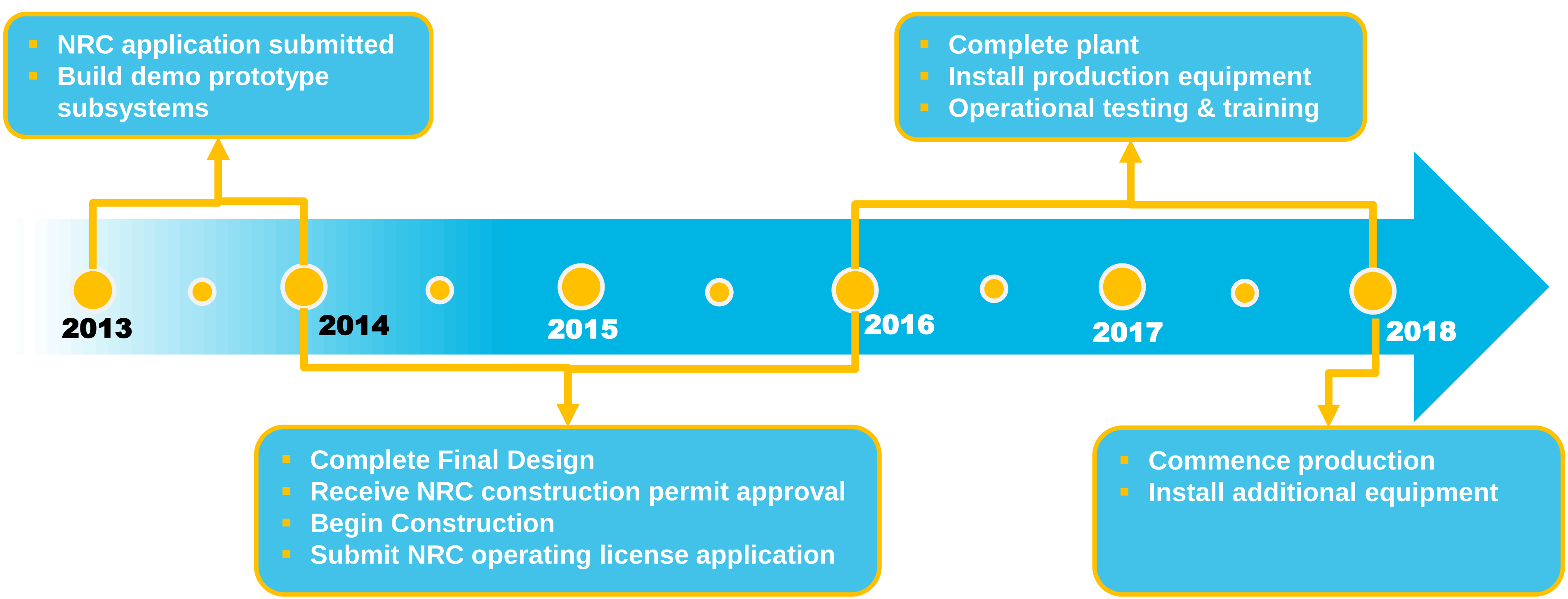
Facility and Licensing

- Site selected (Janesville, WI)
  - Land purchased
  - Directly across from airport
- Construction Permit application submitted to NRC
  - Submitted May 31st 2013
  - Includes Environmental Report and Preliminary Safety Analysis
  - Majority of RAI process complete
- Preliminary facility design complete
  - Basis for the safety analysis
  - Approximate facility size ~ 55,000 ft^2

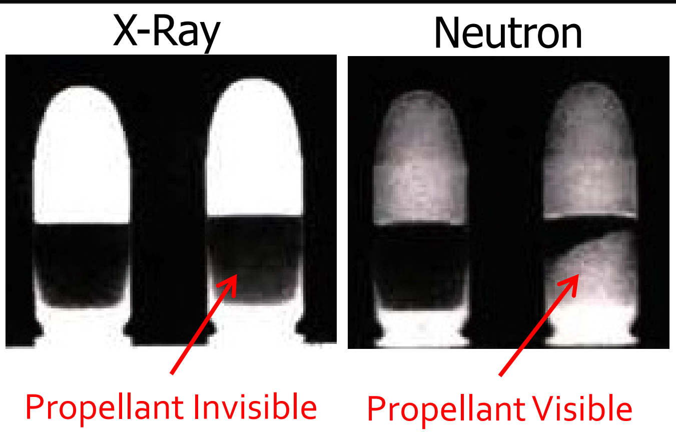
SHINE Schedule: Production Early 2018

- Resources have been appropriated to risk reduction; however, not doing everything in parallel that could be done
- Estimated commercial production date now in early 2018



Thermal Neutron Radiography

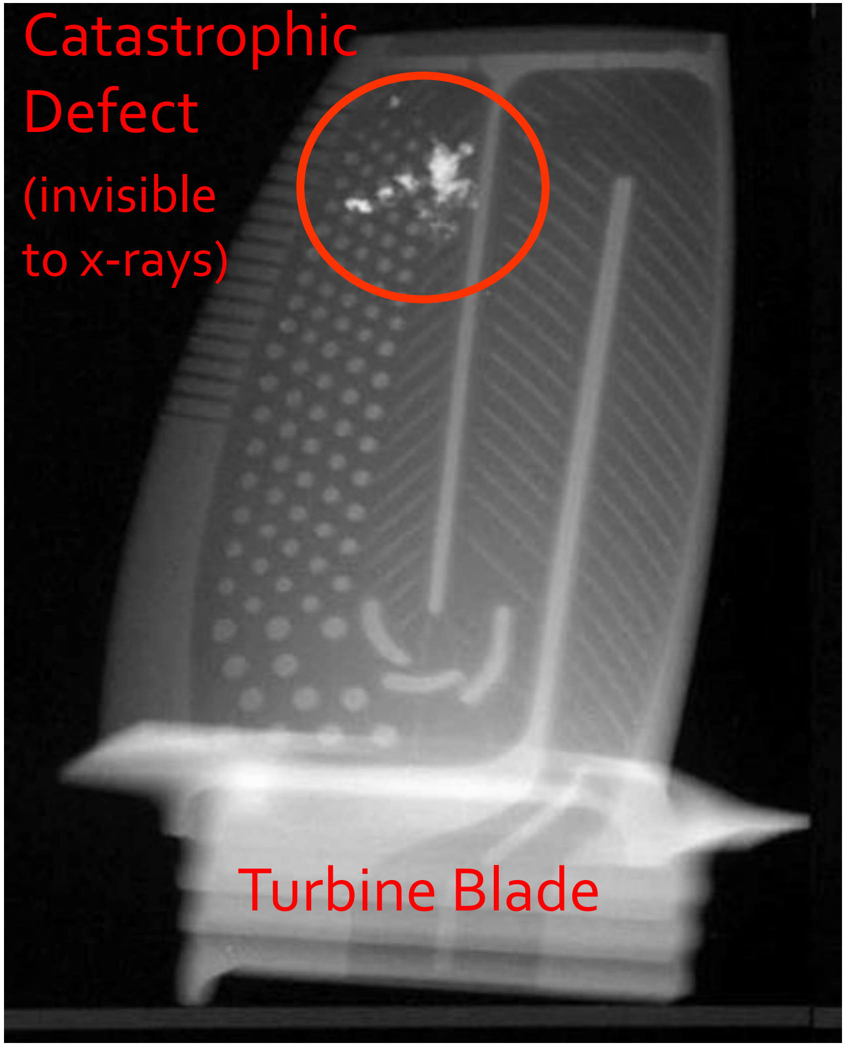
- Army goal: image every shell with neutrons
  - Defective munitions kill soldiers
  - Army has sought a solution for decades
  - PNL source reduces image time from 20+ hrs to minutes
- Army is developing new Q/A requirements that will use neutrons
- PNL is on contract with US Army:
  - First prototype delivered in 2013
  - Contract for commercial prototype awarded in late 2014
    - Army working to create new testing requirements



Images taken by US Army with PNL system

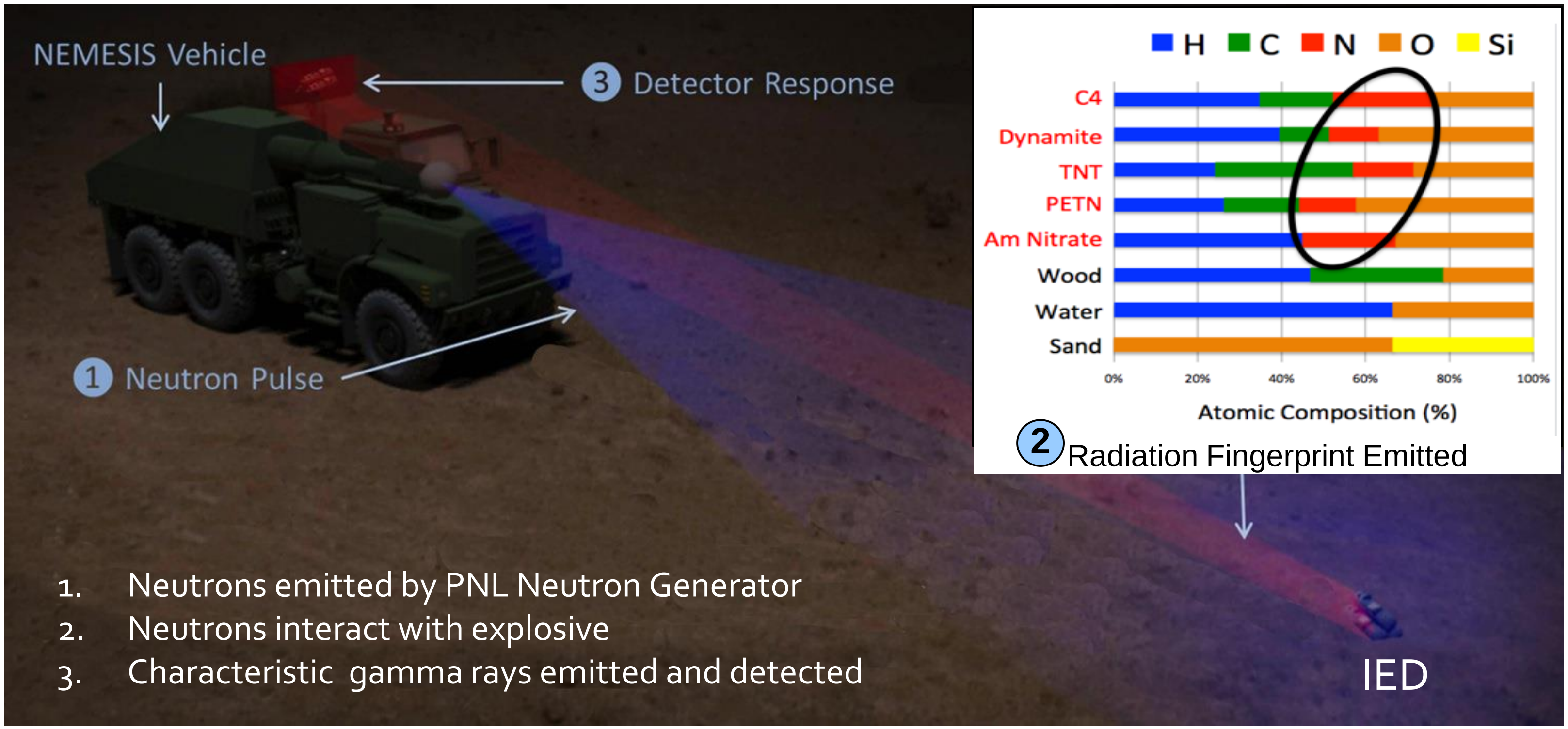
Commercial Radiography

- Neutrons only viable solution for key components:
  - Turbine blades
  - Composite wing structures
  - Batteries/Fuel Cells
  - Helicopter blades
- Access to neutrons limited to only a few reactor/national lab sites
  - Must compete for beam time
  - Expensive
  - Cannot solve real-time problems
- In-house prototype under development



Explosives Detection

- PNL neutron source can meet DoD need for standoff IED detection
  - Army funded prototype complete; testing underway
  - Follow-on DoD funding anticipated for next-generation prototype
  - Potential to save thousands of lives annually



Nuclear Material Detection

- Nuclear smuggling: largest-magnitude threat to US Homeland
- DHS spent $billions on passive "portal monitors"
  - Cannot detect shielded SNM
  - Neutron cans overcome this problem with active interrogation
- PNL neutron source strength gives unmatched detection sensitivity
- Total market is $Billions, but depends on DHS adoption

Summary

- PNL has developed high yield, gas and solid target neutron generator for several different applications
  - Isotope production
  - Neutron Radiography
  - Explosives and SNM detection
- Measured neutron yield of 3×10^{11} DD n/s
- Future development efforts underway
  - Increase voltage/current for higher DD yield (5×10^{11} DD n/s)
  - Further miniaturization of neutron generator
  - Transition to tritium target (5×10^{13} DT n/s)

Thank You!

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