Ensuring a stable supply of Mo-99 in the United States without the use of HEU

T. Heltemes[1], P. Karcz[2] and J. Dix[2]

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[1]Argonne National Laboratory, Lemont, Illinois, United States
[2]U.S. Dept. of Energy National Nuclear Security Administration,
Washington, District of Columbia, United States

— PERMANENT THREAT REDUCTION —

MATERIAL MANAGEMENT AND MINIMIZATION

CONVERT, REMOVE, DISPOSE

The United States program to develop non-HEU-based Mo-99 production

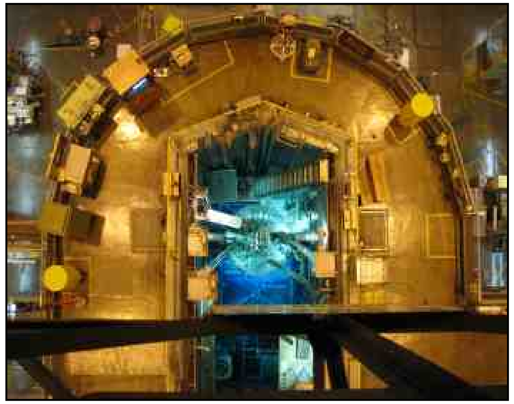
The significance of medical isotope production in nuclear nonproliferation

- The weekly global demand for Mo-99 used for Tc-99m imaging procedures is currently estimated at 333 6-day TBq (9000 6-day Ci)
  - » The Tc-99^{m} obtained from Mo-99 generators is used in approximately 80,000 imaging procedures per day world-wide
  - » Tc-99^{m} with a half-life of 6 hours, and the parent isotope Mo-99 with a half-life of 66 hours, cannot be stockpiled

- If only highly enriched uranium (HEU) is used for Mo-99 production, up to 70 kg of HEU per year would be required to satisfy the current demand

- The United States comprises about half of the demand for Mo-99, however no domestic production capacity had been available until recently
  - » Internationally-sourced Mo-99 produced with HEU requires the shipment of material long distances and material diversion is the primary proliferation risk

Example of a Tc-99m Generator
(Image courtesy of Lantheus Medical Imaging, Inc.)

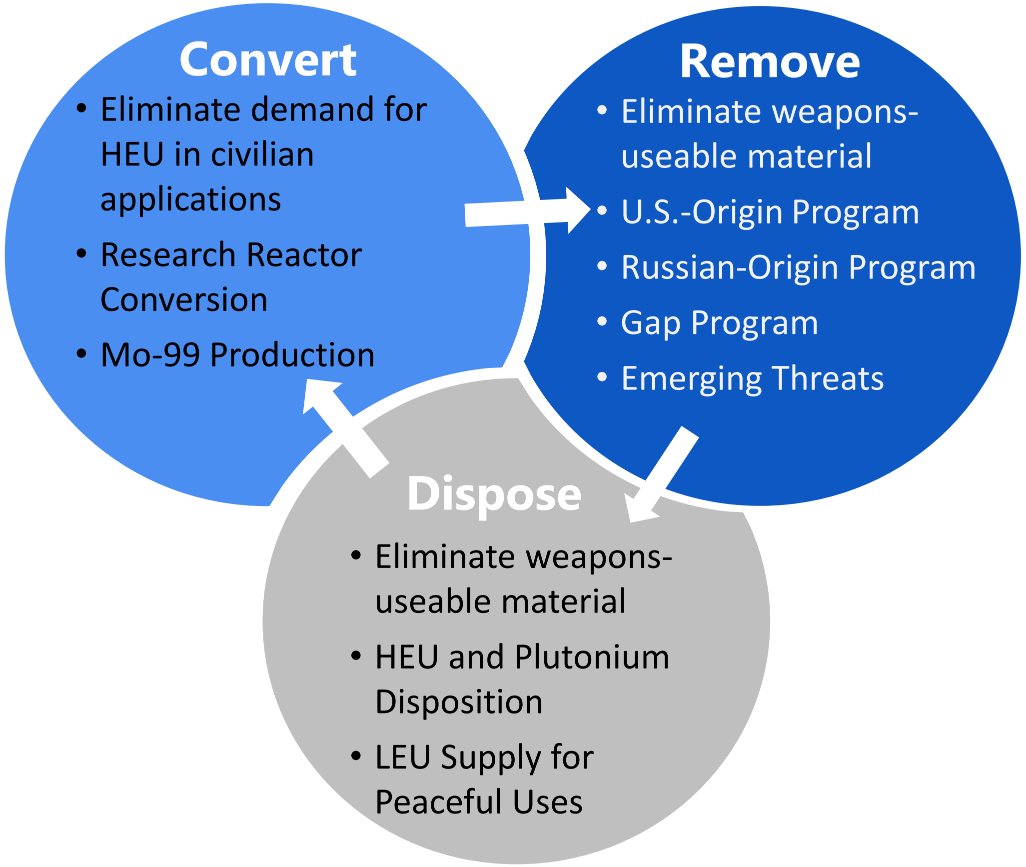


SAFARI-1 Reactor (South Africa)

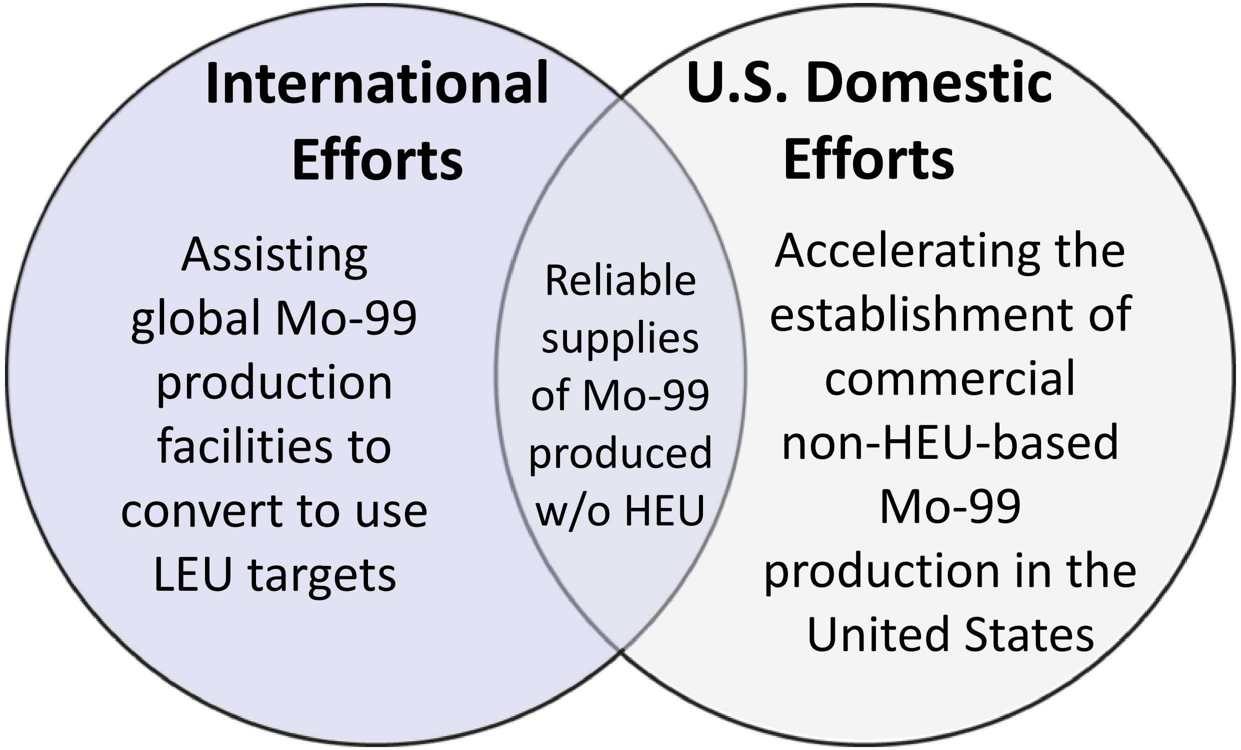
Shortages of Mo-99 in 2009 and 2010 due to the unexpected shut down of two major production facilities highlighted the need for new, non-HEU-based Mo-99 production in the United States

The DOE/NNSA Office of Material Management and Minimization's role in nuclear nonproliferation

The NNSA Office of Material Management and Minimization mission



The NNSA M3 Office of Conversion Goal: HEU minimization with Mo-99 production



The U.S. domestic program is guided by the American Medical Isotope Production Act (AMIPA) of 2012

Domestic Technology Neutral Program	**Uranium Lease & Takeback Program**
Public Participation & Reports	**Sunset Provision to End HEU Exports for Medical Isotope Production**

- Direct funding of potential domestic producers through competitively awarded cooperative agreements
  - » 50/50 cost sharing agreement for authorized developmental expenses
- Indirect funding of potential domestic producers through U.S. national laboratory technical support
  - » Laboratory support is available to *any* potential producer, not limited to cooperative agreement partners
  - » Laboratories provide technical support and resources to accelerate the development of non-HEU based Mo-99 production technologies

Cooperative agreement partner non-HEU-based Mo-99 production technologies

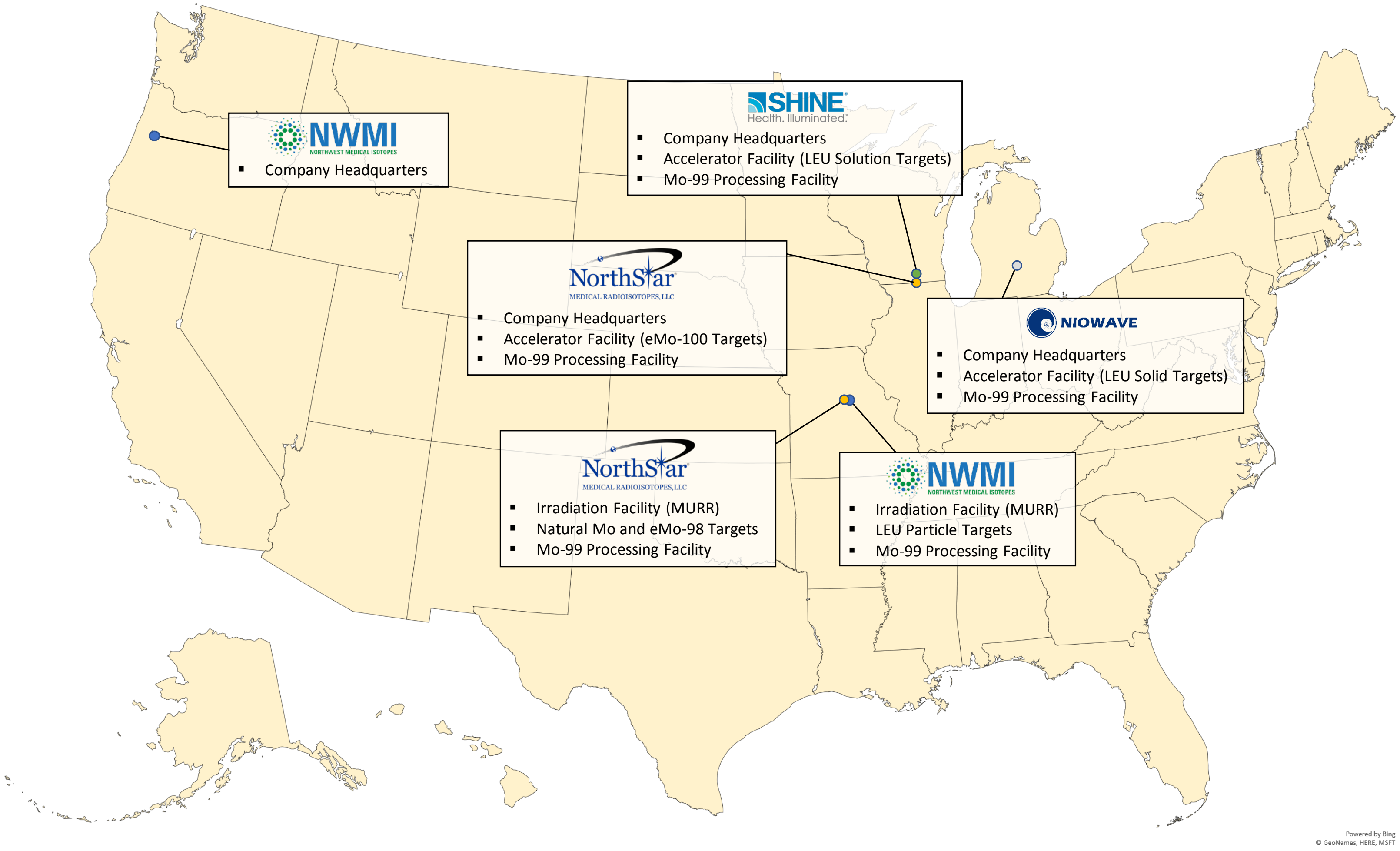
Domestic companies that have partnered with the NNSA on Mo-99 production with cooperative agreement funding

- NorthStar Medical Radioisotopes
  - » Headquarters in Beloit, Wisconsin, United States
  - » Neutron Capture on natural molybdenum and enriched Mo-98 at the University of Missouri Research Reactor (MURR)
  - » Future accelerator production of Mo-99 using enriched Mo-100 at the Beloit facility

- SHINE Medical Technologies
  - » Headquarters in Janesville, Wisconsin, United States
  - » Accelerator-driven production of Mo-99 using LEU solution targets

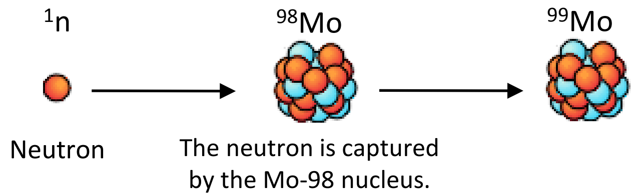
- Niowave, Inc.
  - » Headquarters in Lansing, Michigan, United States
  - » Accelerator-driven production of Mo-99 using LEU solid targets

- Northwest Medical Isotopes
  - » Headquarters in Corvallis, Oregon, United States
  - » Fission of LEU microspheres at MURR



NorthStar Medical Radioisotopes

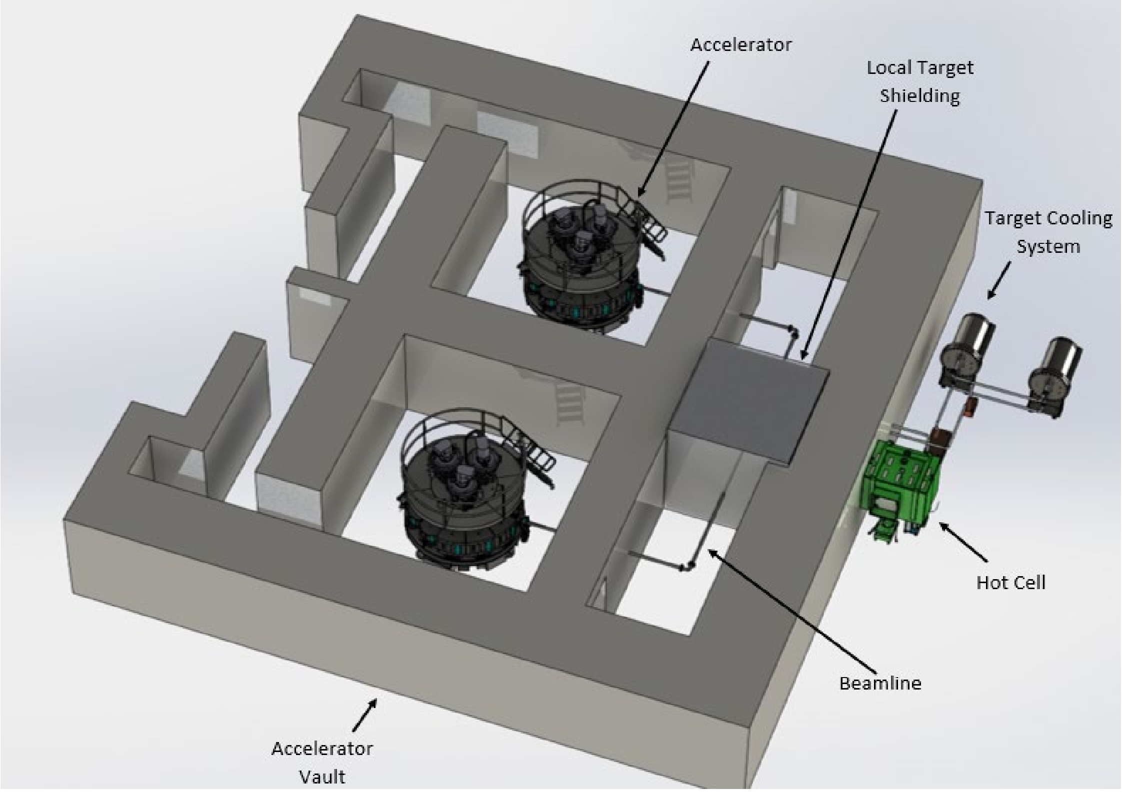
- NorthStar produces Mo-99 by irradiating natural molybdenum disks in the University of Missouri Research Reactor (MURR) located in Columbia, Missouri, United States.
- Mo-99 production in natural molybdenum disks results from neutron capture by the $^{98}Mo(n,\gamma)^{99}Mo$ reaction.
- Molybdenum-98 (Mo-98) is present in natural molybdenum as a 24.1 atom% isotopic constituent.
- NorthStar plans to upgrade to enriched (>95 wt%) Mo-98 targets in the future, which will result in a four-fold increase in production capacity.



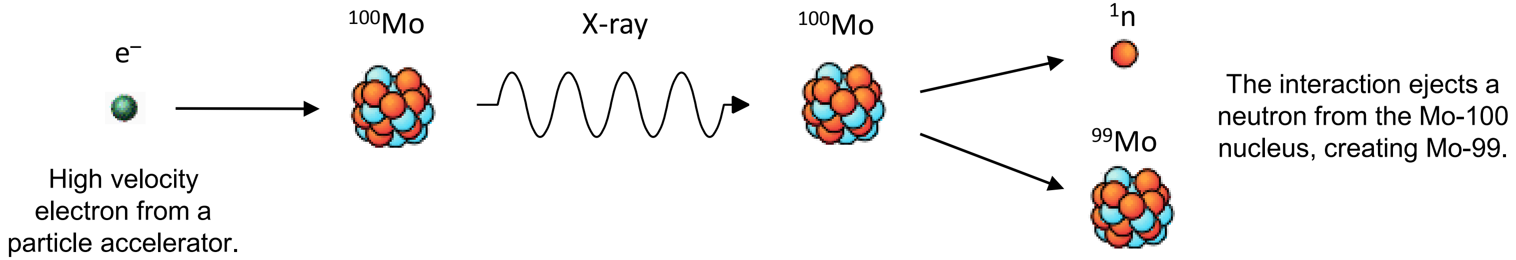
- NorthStar relies on a proprietary method to extract high-specific activity Tc-99m from low-specific activity Mo-99. This extraction is achieved via NorthStar's RadioGenix® System, an alternative to the traditional Tc-99m generator used by radiopharmpacies. With an installed RadioGenix® System, a radiopharmacy:
    1. Receives Mo-99 solution vessels from NorthStar;
    2. Elutes the Tc-99m sodium pertechnetate used for diagnostic procedures; and
    3. Ships used source and waste vessels from the RadioGenix® System back to NorthStar.
- The U.S. Food and Drug Administration (FDA) has approved Tc-99m from Mo-99 produced at MURR by the irradiation of natural molybdenum targets for use in patients.
    - » The first Mo-99 shipment from MURR that resulted in Tc-99m doses dispensed by the RadioGenix® System and used in patients occurred on 19 November, 2018.
    - » Since this date, NorthStar has been producing a weekly uninterrupted supply of Mo-99 to radiopharmacies in the United States.

NorthStar Medical Radioisotopes (cont'd.)

- In addition to the production of Mo-99 at MURR, NorthStar is also building the capability to produce Mo-99 in their Beloit facility by electron-beam irradiation of enriched (>95 wt%) molybdenum-100 (Mo-100) targets undergoing a $^{100}Mo(\gamma,n)^{99}Mo$ reaction via the induced Bremsstrahlung radiation.



(Image courtesy of NorthStar Medical Radioisotopes)



SHINE Medical Technologies

- SHINE intends to produce Mo-99 from the fission of LEU liquid targets by the $^{235}U(n,f)^{99}Mo$ reaction.

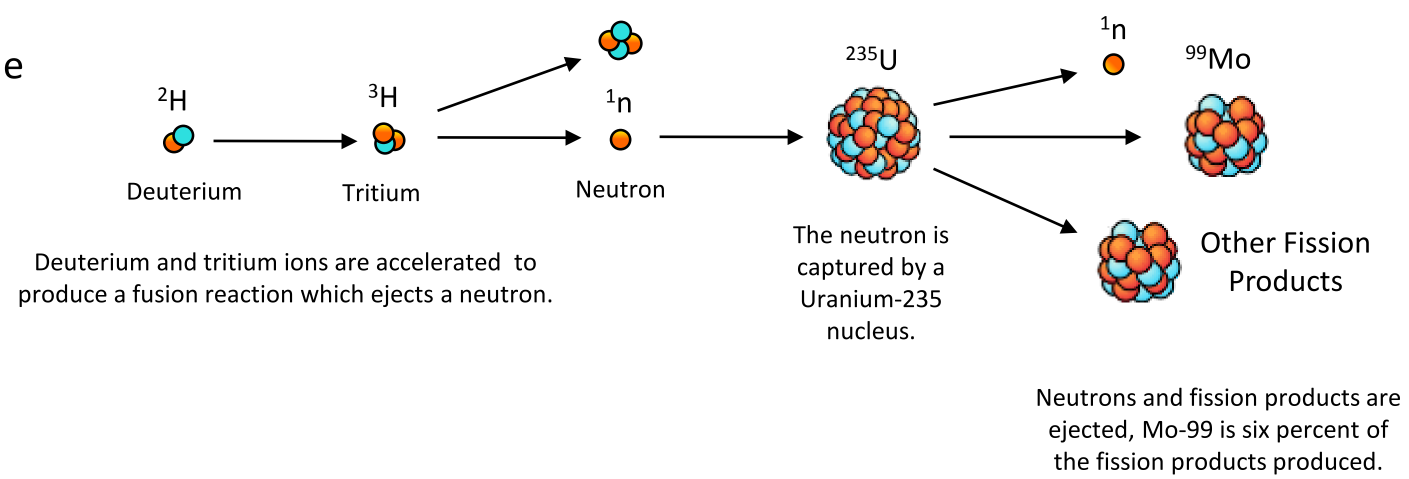
- SHINE will use a compact ion beam linear accelerator to drive the fission reaction in a subcritical liquid target.
  - » The ion beam accelerator drives a steady-state beam of deuterium ions into a tritium gas target to produce the population of 14 MeV neutrons by the $^{3}H(^{2}H,n)^{4}He$ fusion reaction, driving LEU fission in the liquid target.
  - » The ion beam accelerator technology to be used for the production of Mo-99 at SHINE has been demonstrated at over 5.5 days of continuous run time (>99%uptime) and an output of 4.6×10^{13} n s^{-1}.

- The liquid target used for Mo-99 production will consist of a water-cooled and moderated LEU uranyl sulfate salt dissolved in sulfuric acid.

- The SHINE isotope production facility will have the capacity to operate up to eight irradiation units, consisting of a paired accelerator and LEU liquid target.

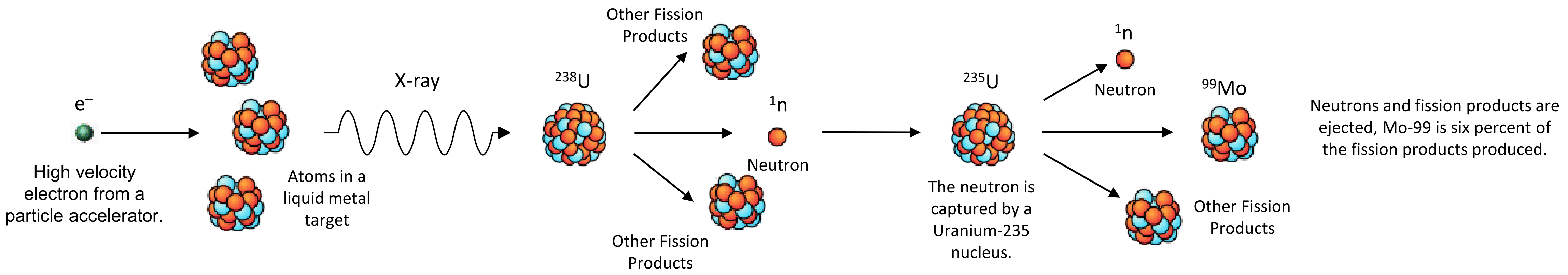
- At the end of irradiation, Mo-99 is extracted from the liquid target, the uranium and acid concentrations are adjusted and the liquid target is reused in a future irradiation cycle.

- The Mo-99 produced at SHINE will be shipped to Tc-99m generator manufacturers utilizing the existing supply chain.



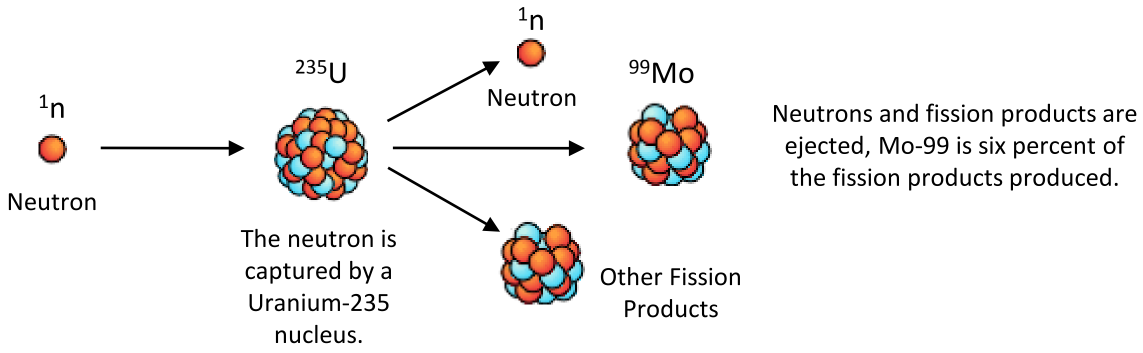
Niowave, Inc.

- Niowave intends to produce Mo-99 from the fission of LEU solid targets by the $^{238}U(\gamma,f)^{99}Mo$ and $235U(n,f)^{99}Mo$ reactions.
- Niowave will use a two-pass 20 MeV superconducting electron linear accelerator to drive an electron beam at nearly 40 MeV into a liquid metal target.
- The Bremsstrahlung radiation (x-rays) from the electrons impinging on the liquid metal target drives the photo-fission reaction, $^{238}U(\gamma,f)^{99}Mo$, with the neutrons produced from this reaction driving the U-235 fission reaction, $^{235}U(n,f)^{99}Mo$.
- The LEU targets used by Niowave will consist of a water-cooled and moderated array of pressed uranium oxide pellets in a subcritical configuration.
- At the end of irradiation, the LEU pellets are dissolved, forming a solution of LEU uranyl nitrate salt in nitric acid.
- Mo-99 is extracted from the uranyl nitrate solution, the raffinate is purified, the purified uranyl nitrate is calcined and the resulting uranium oxide is pressed into pellets for use in future irradiation cycles.



Northwest Medical Isotopes

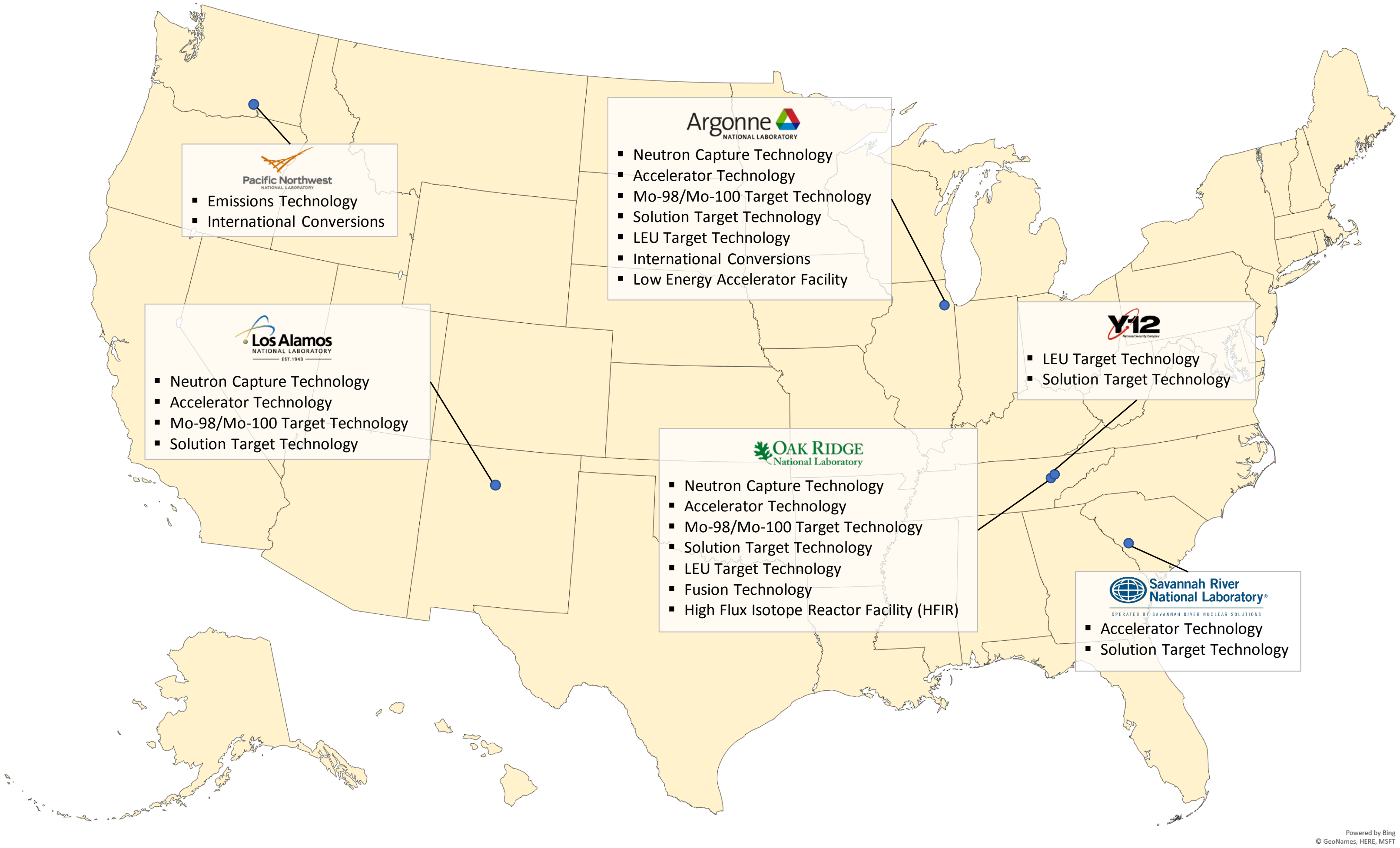
- NWMI intends to produce Mo-99 from the fission of LEU solid targets by the $^{235}U(n,f)^{99}Mo$ reaction.
- NWMI has developed a process to produce LEU microspheres, which are used in the fabrication of irradiation targets in a fleet of U.S. based university research reactors.
- The flagship reactor in this fleet is MURR, which will provide the first irradiation services to NWMI.
- NWMI is constructing a target fabrication and Mo-99 radioisotope production facility (RPF) in Columbia, Missouri, United States, in close proximity to MURR.
- At the end of irradiation, the targets will be retrieved from MURR or another reactor in the fleet and shipped to the RPF.
- Once received at the RPF, the targets will be disassembled and the microspheres dissolved.
- Mo-99 will be extracted, the raffinate from the extraction will have the fission products removed and the purified LEU solution will be converted back into microspheres for use in targets for a future irradiation cycle.



United States national laboratory support for non-HEU-based Mo-99 production technology development

U.S. National Laboratories Supporting the NNSA Mo-99 Technology Development Program

- Argonne National Laboratory
  - » Argonne, Illinois, Untied States
- Los Alamos National Laboratory
  - » Los Alamos, New Mexico, United States
- Oak Ridge National Laboratory
  - » Oak Ridge, Tennessee, United States
- Pacific Northwest National Laboratory
  - » Richland, Washington, United States
- Savannah River National Laboratory
  - » Aiken, South Carolina, United States
- Y-12 National Security Complex
  - » Oak Ridge, Tennessee, United States



Argonne National Laboratory

Argonne National Laboratory (ANL) provides a robust range of support for Mo-99 technology development. ANL is home to a Low-Energy Accelerator Facility (LEAF) and radiochemistry laboratories. LEAF houses a 50 MeV electron linear accelerator and a 3 MeV Van de Graaff electron accelerator.

Enabling a reliable supply of Mo-99:

- ANL supports DOE/NNSA's domestic CA partners by working to
  - » Demonstrate fission and photo-nuclear production of Mo-99;
  - » Conduct radiation stability testing of equipment and process chemistry;
  - » Evaluate Mo-99 targetry through MCNPX and heat deposition modelling;
  - » Conduct thermal-hydraulic analysis of the target system;
  - » Design beamline and facility shielding; and
  - » Conduct target and accelerator protection during production runs.

- ANL also assists international Mo-99 producers with chemical processes relevant to conversion from HEU to LEU targets.

Argonne National Laboratory (cont'd.)

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Process development and scale-up for Mo-99 producers:

- Support the development of processes for Mo-99 recovery and purification:
  - » Optimize, scale-up and automate processes for hot cell operations;
  - » Develop analytical tests for trace-metal detection in complex matrices;
  - » Meet European Pharmacopeia purity specs; and
  - » Characterize waste disposition pathways.
- Develop and demonstrate processing equipment produced by advanced manufacturing methods:
  - » Metal and non-metal 3D printed annular centrifugal contactors
  - » Evaluate equipment performance and materials corrosion

Los Alamos National Laboratory

Los Alamos National Laboratory (LANL) provides the Mo-99 program with expertise in multiphysics systems modeling, accelerator component research and development and facility radiation shielding design.

- Support for accelerator-based Mo-99 Production
  - » Target design and testing, both in and out of beam;
  - » Cooling system design using helium;
  - » Target insertion scheme; and
  - » Facility and shielding layouts.

- Support LEU solution target Mo-99 Production
  - » 2D and 3D computational fluid dynamics (CFD) validation modeling of LANL's historic uranyl nitrate solution reactor, SUPO; and
  - » Experiment design and modeling of a radiolytic gas bubble experiment to be conducted at ANL using the electron LINAC.

Oak Ridge National Laboratory

Oak Ridge National Laboratory (ORNL) supports Mo-99 production research and development in the area of fundamental materials science on both unirradiated and irradiated materials. ORNL also has expertise in hot cell chemistry and testing, neutronics modeling and simulation, radioactive material shipping and additive manufacturing. ORNL is home to the High Flux Isotope Reactor (HFIR), which has experimental capacity with high-intensity neutron fluxes and cold neutron science.

- Optimizing accelerator target design and fabrication using powder metallurgy and additive manufacturing for accelerator targets;
- Materials selection and neutron irradiation testing for the LEU solution targets;
- Test irradiation target design and qualification in support of LEU dispersion target reactor qualification; and
- Test irradiation target design, qualification, irradiation and shipment to support neutron capture targets.

Pacific Northwest National Laboratory

Pacific Northwest National Laboratory (PNNL) supports the Mo-99 program with research and development activities in the areas of radioxenon transport and emissions abatement, process modeling, non-destructive and destructive post-irradiation examination (PIE) and hot cell radiochemistry.

- Develop a PNNL multiphysics model for producers' xenon abatement adsorbent beds:
  - » Develop a universal adsorption bed model that can answer questions about xenon abatement trap designs and adsorbent effectiveness;
  - » Incorporate heat of decay from high activity radioxenon gas emissions trapped on abatement beds; and
  - » Evaluate ambient temperature bed designs and cooled bed designs.
- Adsorption process modeling:
  - » COMSOL Multiphysics enables modelling adsorption processes coupled to heat transfer.
- Hiden gravimetric adsorption analyzer development:
  - » Can output the rate of uptake, as well as the final amount adsorbed, at a given pressure and temperature.
- Adsorption breakthrough instrument development:
  - » Can perform breakthrough experiments for gas mixtures.

Savannah River National Laboratory

Savannah River National Laboratory (SRNL) supports the Mo-99 program in the areas of tritium processing systems development, optimization of uranium dissolution flowsheets and Mo-99 processing chemistry residue management.

- Development of tritium handling and purification systems such as the Thermal Cycling Adsorption Column (TCAP) and Micro-TCAP;
- Optimization of uranium dissolution using a parametric analysis of dissolution conditions and constraints;
- Development of actinide processing flowsheets and analytical techniques;
- Development of radiological material disposition strategies;
- Development of Mo-99 extraction and purification residue management strategies; and
- Development of tritium handling and component detritiation strategies.

The Y-12 National Security Complex

The Y-12 National Security Complex (Y-12) supports the Mo-99 program with uranium component engineering research and development as well as LEU inventory management.

- LEU oxide solid target technology
  - Analysis of pellets that make up the uranium target assembly manufactured by producers along with the U_3O_8 oxide from the pellets;
  - Optimizing the conversion process from metal to oxide;
  - Aiding in pellet pressing optimization; and
  - Optimizing and scaling up uranium recovery from irradiated pellets.

- LEU dispersion solid target technology
  - Design, develop and fabricate dispersion target plates that utilize a uranium core in an aluminum frame that is encased in aluminum cladding.

- LEU monolithic foil solid target technology
  - Design, develop and fabricate high-density annular targets that utilize a rolled foil uranium core encased between inner and outer aluminum tubing.

Questions?

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