NIOWAVE'S CLOSED LOOP FUEL CYCLE FOR DOMESTIC PRODUCTION OF MO-99 AND OTHER ISOTOPES

PRESENTED AT WOSMIP CONFERENCE
MAY 27, 2021

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OUTLINE

- Niowave Background
    - Medical isotope company
    - Program overview
- Mo-99 Radiochemistry
    - Fuel Cycle
    - Scale-Up Plan
- Mo-99 Program Review
    - Uranium Target Assembly
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    - Mo-99 Chemistry
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    - Target Fabrication
- Emissions
    - Niowave Emissions strategy
    - Emissions Monitoring

NIOWAVE BACKGROUND

NIOWAVE, INC.

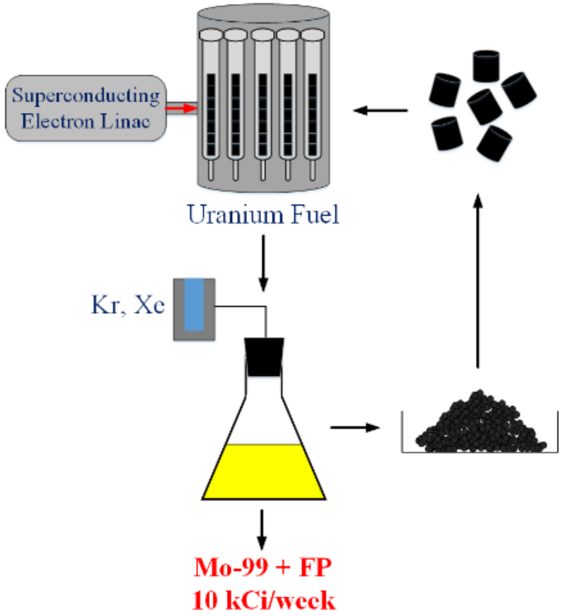
- Spun off from MSU’s National Superconducting Cyclotron Laboratory in 2005
- Began building accelerator components for US and international laboratories
- Built up infrastructure and know-how to operate superconducting linacs.
- Now focused on using accelerators to produce radioisotopes for nuclear medicine

Lansing, Michigan Headquarters

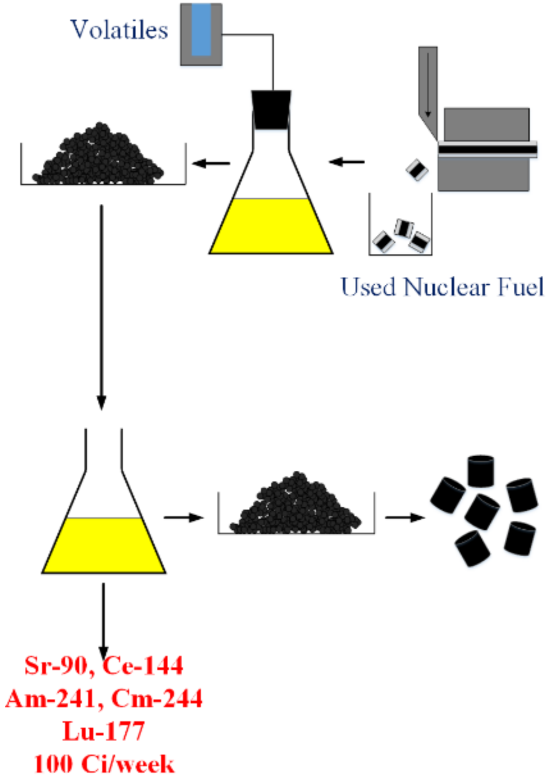
NIOWAVE
Accelerating Your Particles

PROGRAM OVERVIEW

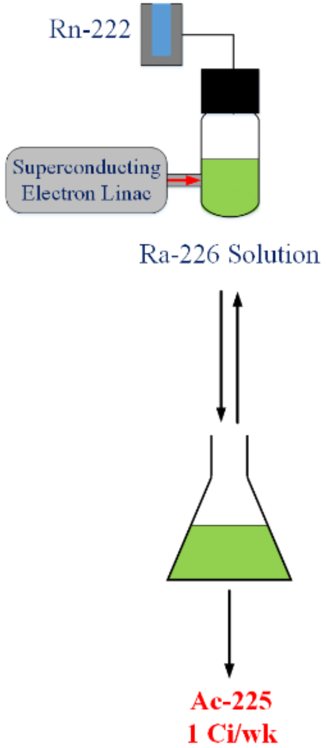
Mo-99 Program



Reactor Program



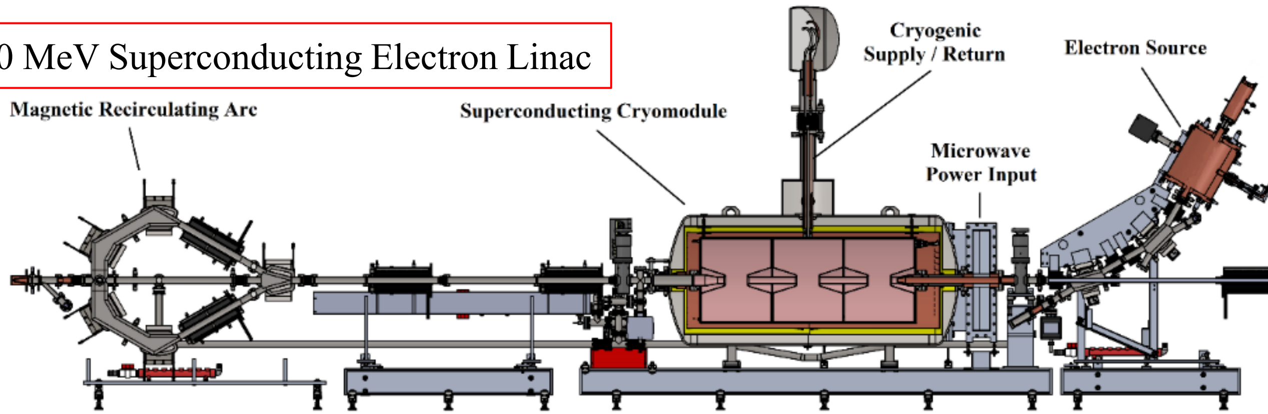
Ac-225 Program

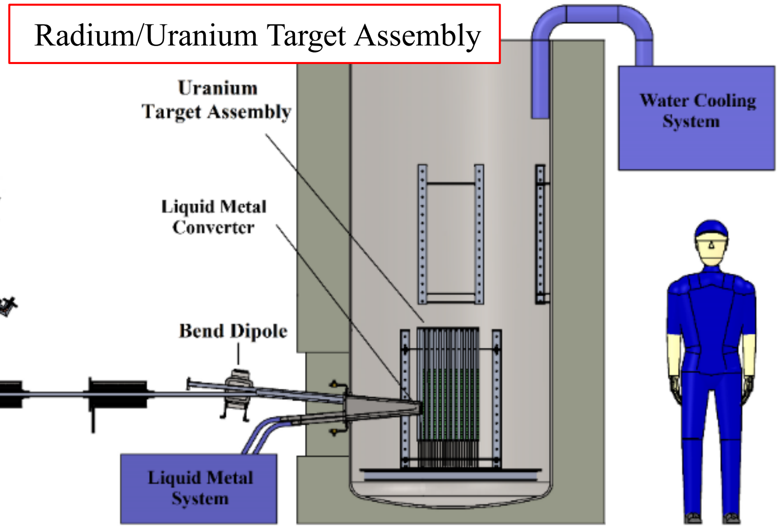


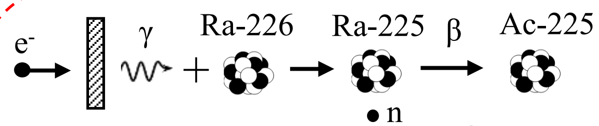
THERAPEUTIC α &β EMITTERS

Niowave manufactures radioisotopes from radium and uranium

Uses a superconducting electron linear accelerator without the need for a nuclear reactor

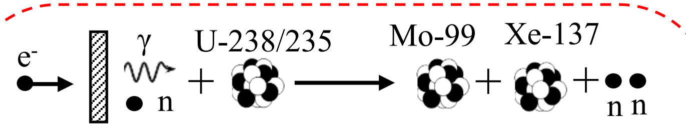






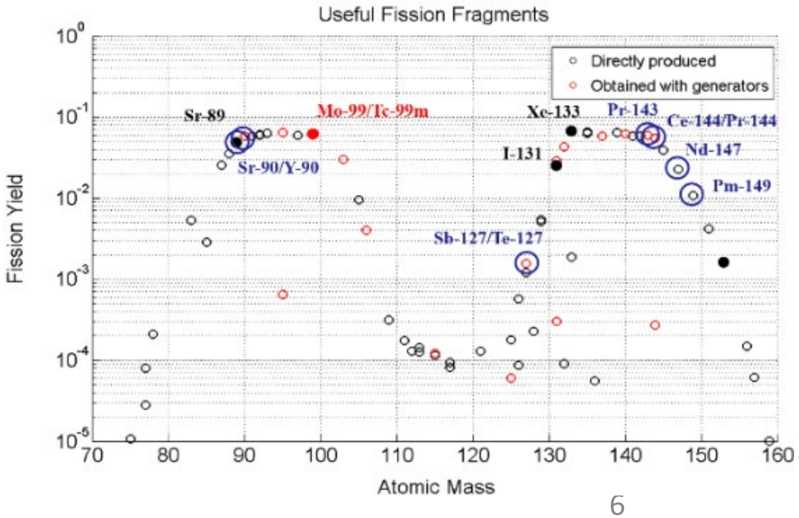
Radium (Ra-226) α emitters

Ac-225	10 d
Rn-222	3.8 d
Po-210	138 d
Bi-210	5.0 d
Bi-213	46 m
Bi-214	20 m
Pb-214	27 m



Uranium (U-235/238) β emitters

Mo-99→ Tc-99m	I-131
Sb-127→Te-127	Xe-133
Ba-140→La-140	Sr-89
Ce-143→Pr-143	Y-91
Sr-90→Y-90	Ce-141
Ce-144→Pr-144	Nd-147
	Pm-149

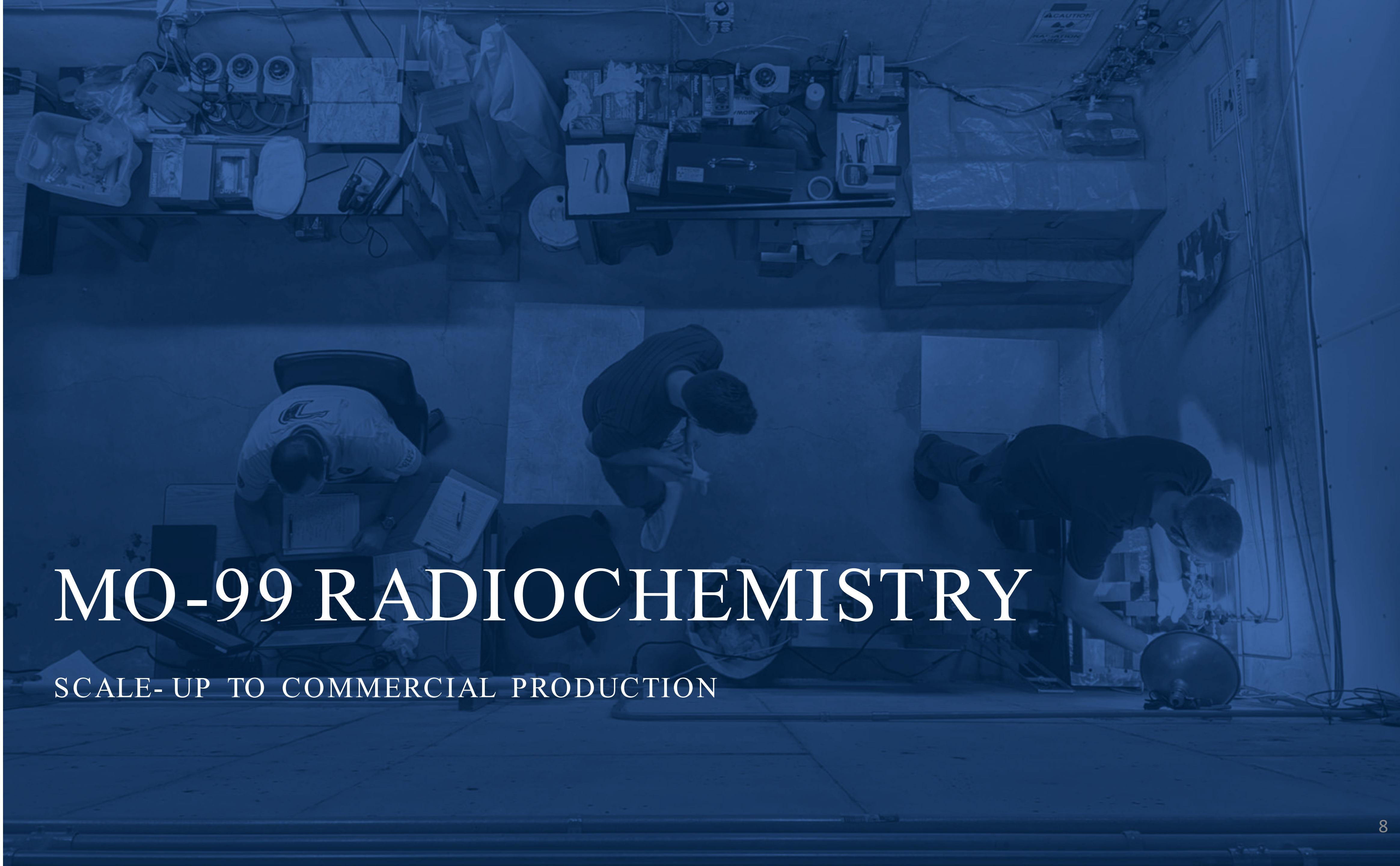


MO-99 PROGRAM PHASE CHART

Category		Phase 1	Phase 2	Phase 3	
Production Level		Demo	Pilot	Commercial	
LEU Inventory	Total On-Site	1.8 kgU	4.5 kgU	100 kgU	
	Core	1.6 kgU	4.5 kgU	24 kgU	28 kgU
k_{eff}		0.43	0.62	0.95	0.99
Accelerator		5 MeV 310 W (Be)	15 MeV 26 kW 20 MeV 10 kW	40 MeV 646 kW	40 MeV 123 kW
Fission Power		23 mW	230 W	230 kW	
Activity Produced[1]		1 mCi batches	10 Ci/week	10 kCi/week	
Radiochemicals Produced		Mo-99→Tc-99m I-131, Xe-133	Sr-89, Y-91, Ce-141, Nd-147, Pm-149	Sb-127→Te-127 Ba-140→La-140 Ce-143→Pr-143	
NRC	License Type	Materials	Materials	TBD	
	Regulatory Process[2]	10 CFR 30, 70	10 CFR 30, 70	10 CFR 30, 51, 70 (50 TBD)	
FDA Regulatory Process		-	Facility Registered	DMF[3] Filed / Referenced	
Location		HQ	HQ / Airport	Airport Campus	
Completion Date		~~Dec 2018~~ COMPLETE	Dec 2021	Dec 2023	

[1]*10 kCi/week Mo-99 EOB = 1,550 6 day Ci/week Mo-99*
[2]*Including 10 CFR 20, 3X, 40, 7X*
[3]*Drug Master File*

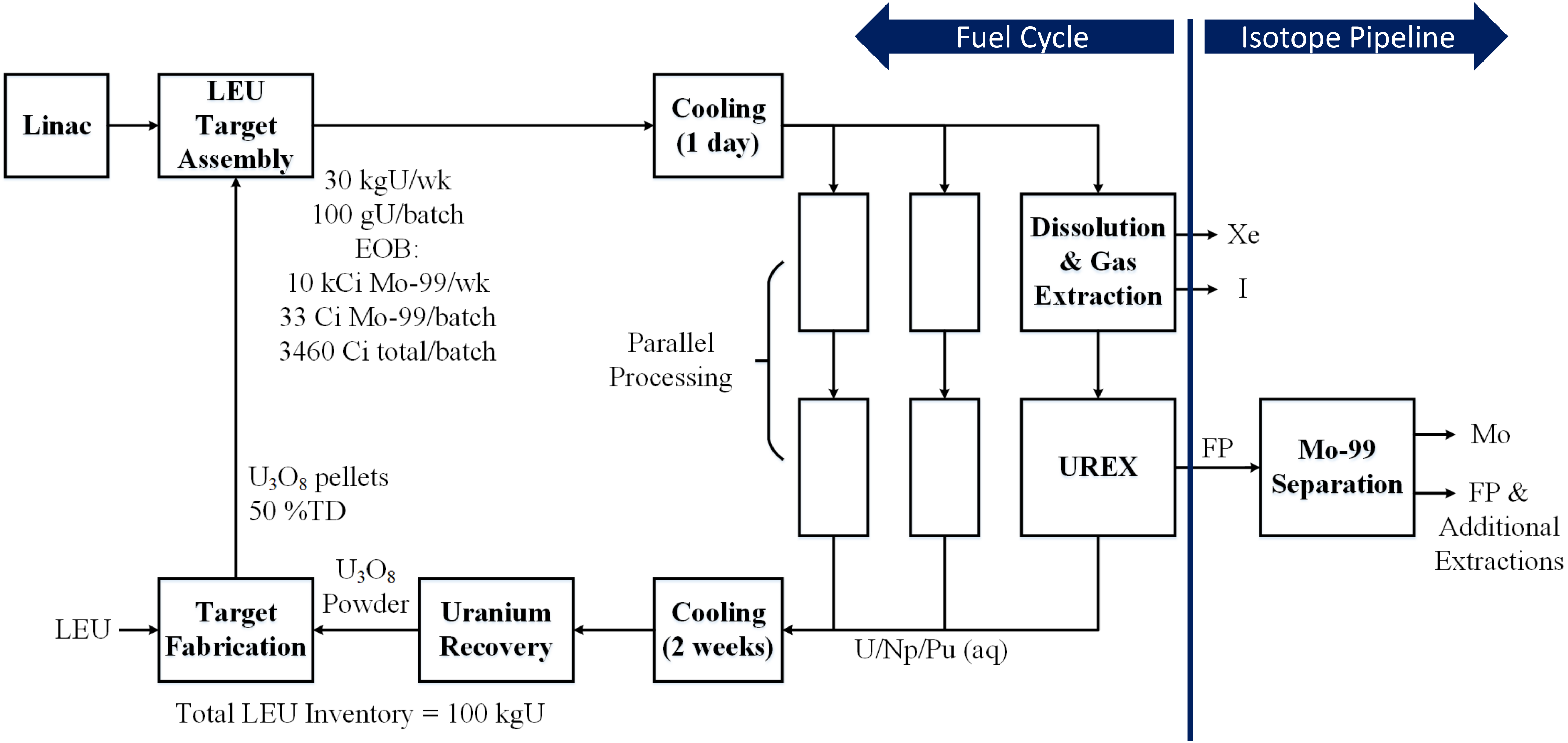
01/11/2021



MO-99 RADIOCHEMISTRY

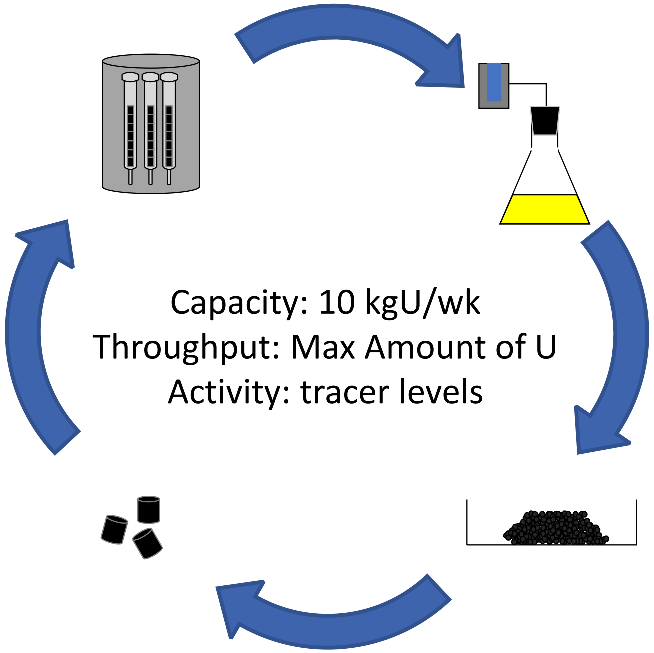
SCALE- UP TO COMMERCIAL PRODUCTION

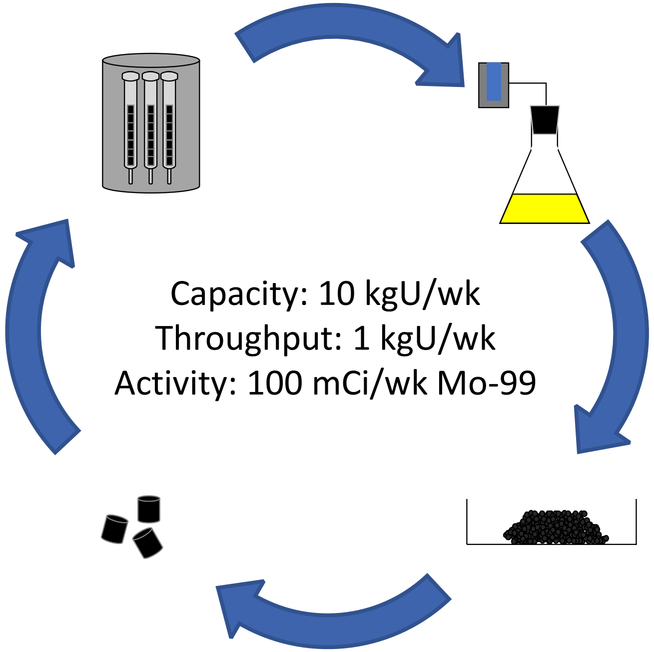
MO-99 PROGRAM RADIOCHEMISTRY

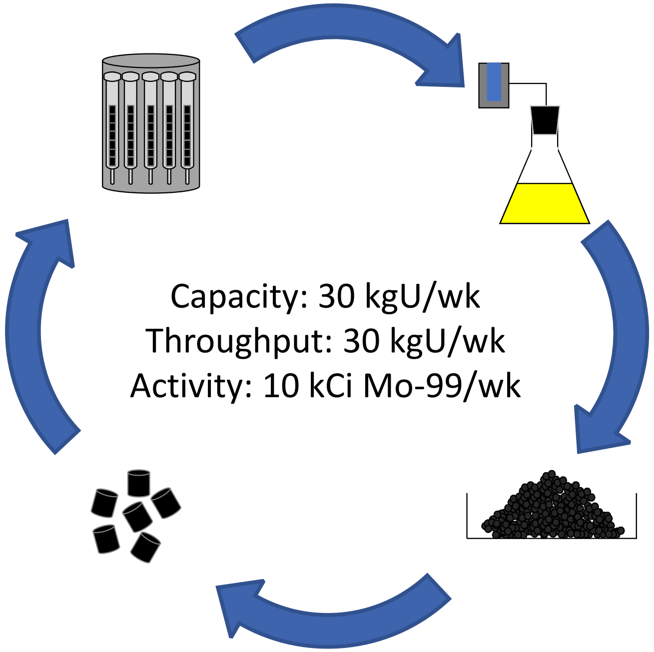


RADIOCHEMISTRY SCALE UP PLAN

Phase II - NERD	Phase II - Airport	Phase III







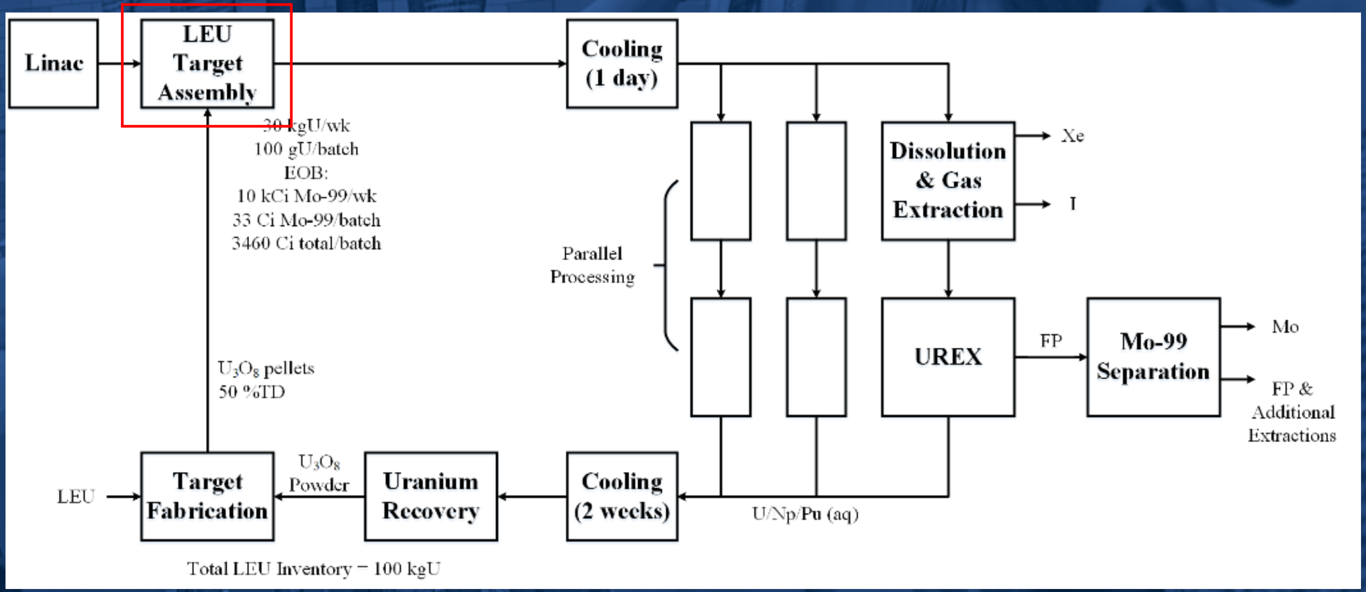
Phase II - NERD	Phase II - Airport	Phase III
1 line	1 line	3 parallel lines
Capacity: 10 kgU/wk	Capacity: 10 kgU/wk	Capacity: 30 kgU/wk
Cold Operation & Max Amount of U	Limited Operation = 1 kgU/16.8 hrs	24/7 operation

GOAL – MO-99 PHASE 2 RADIOCHEMISTRY

- The goal of this work is to produce one fully integrated model isotope processing line for the Mo-99 program which performs the entire fuel cycle as well as Mo-99 and other fission product purification, packaging, and assay for sale.
  - Capacity: 10 kgU/week
  - Throughput: 1 kgU/week
  - Activity: 100 mCi/week Mo-99 and other FPs

MO-99 PROGRAM REVIEW

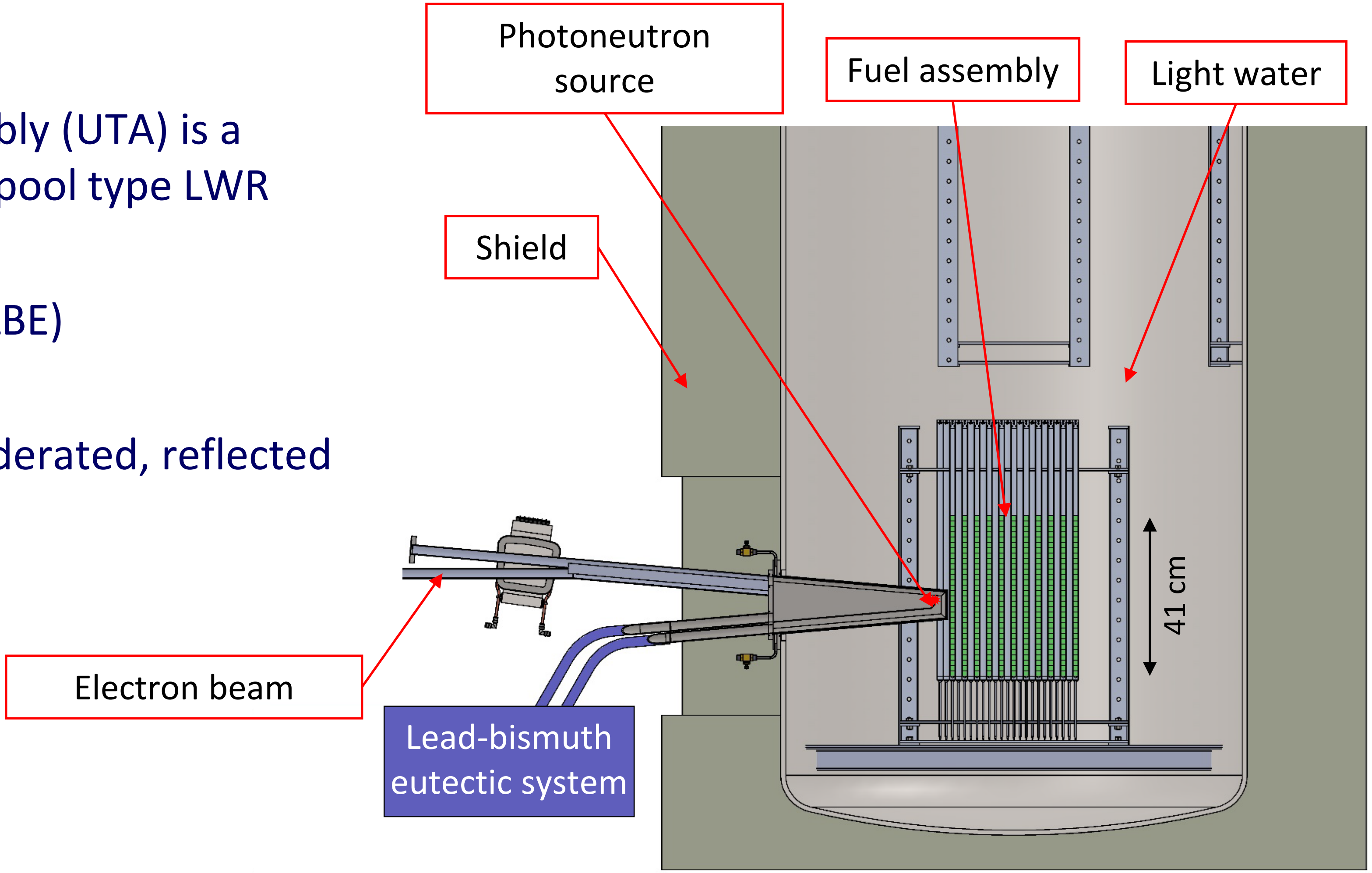
CURRENT STATUS & NEXT STEPS



URANIUM TARGET ASSEMBLY

URANIUM TARGET ASSEMBLY

- The Uranium Target Assembly (UTA) is a subcritical assembly, open-pool type LWR
  - Electron linac driven
  - Photoneutron source (LBE)
  - Uranium oxide fuel
  - Light water cooled, moderated, reflected



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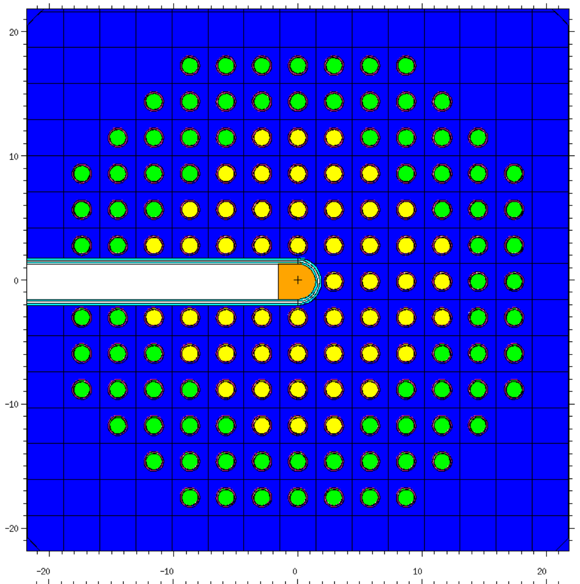
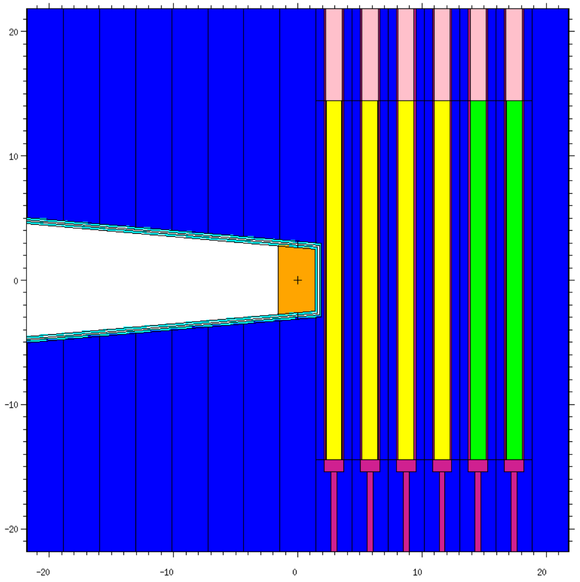
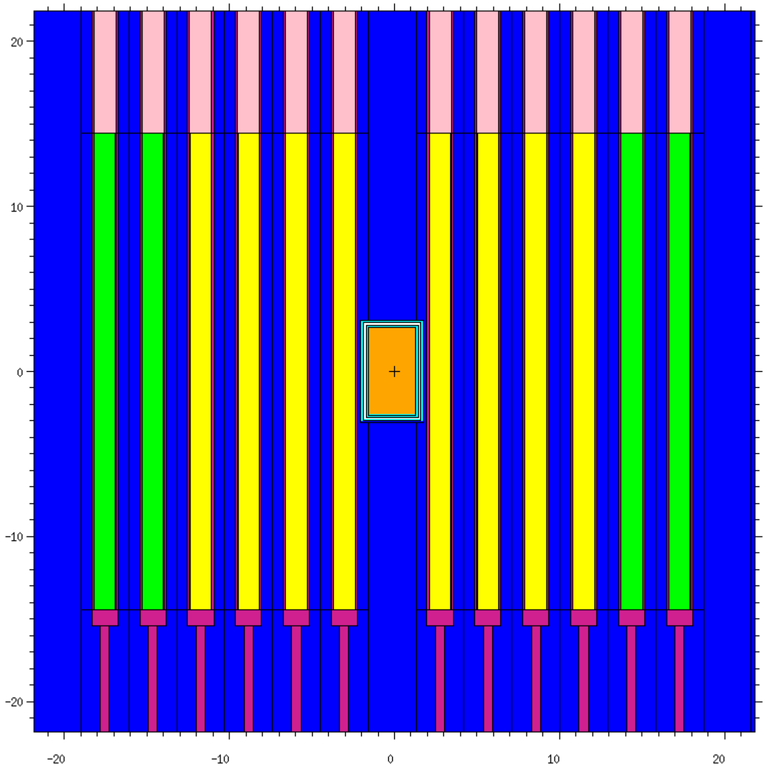
UTA-2 CURRENT DESIGN

Neutron Source		
Electron beam energy (MeV)	15	20
Electron beam power (kW)	17.3	7.0
Neutron converter	Lead-Bismuth Eutectic	
Neutron source $\left(\frac{n}{s}\right)$	5.5×10^{12}	
Mechanical		
Fuel loading - LEU (kgU)	7.000	
Fuel loading - NU (kgU)	11.577	
^{235}U enrichment (wt%)	9.75	
^{235}U fuel loading in LEU (gU)	682.5	
U_3O_8 fuel density $\left(\frac{g}{cm^3}\right)$	4.15	
Fuel type	U_3O_8	
Fuel pellet radius (cm)	0.65	
Cladding type	Al 6061	
Cladding OD and Wall Thickness (cm)	1.5875 and 0.1245	
Number of fuel rods LEU	52	
Number of fuel rods NU	86	
Lattice type	Square	
Core pitch (cm)	2.9	
Fuel height (cm)	28.818	
Neutronics		
Fission energy per electron $\left(\frac{J}{e}\right)$	3.187×10^{-14}	1.056×10^{-13}
k_{eff}	0.70342 ± 0.00014	
Thermal flux level $\left(\frac{n}{cm^2 \cdot s}\right)$	1.5×10^{10}	
Fission power (W)	230	
Fraction of fission power in NU/LEU	0.12/0.88	
Fuel burnup per cycle $\left(\%\text{ and } \frac{MWD_t}{MTHM}\right)$	1.0×10^{-5} and 0.088	
Isotope Production		
^{99}Mo Activity $\left(\frac{Ci}{wk}\right)$	10	
Irradiation cycle length (days)	7	





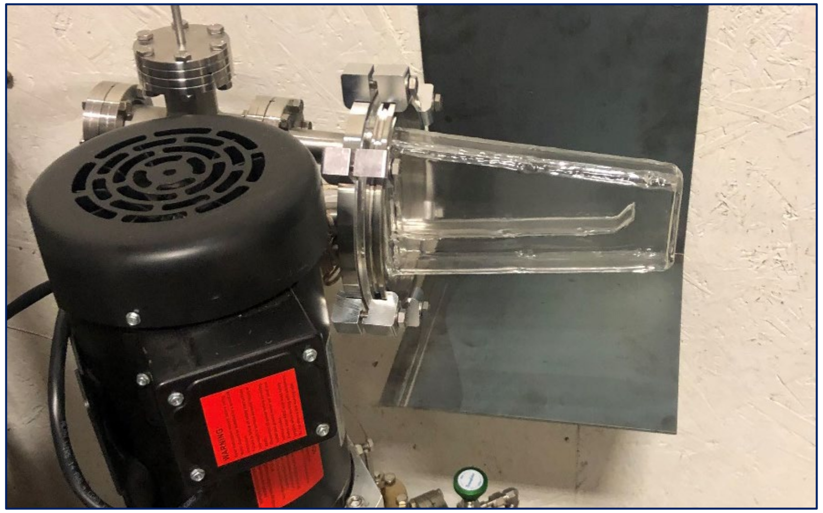


OPERATIONAL SOURCE &URANIUM TARGET ASSEMBLY

Neutron source Install

Operational & uranium Target Assembly

Quartz Converter Model



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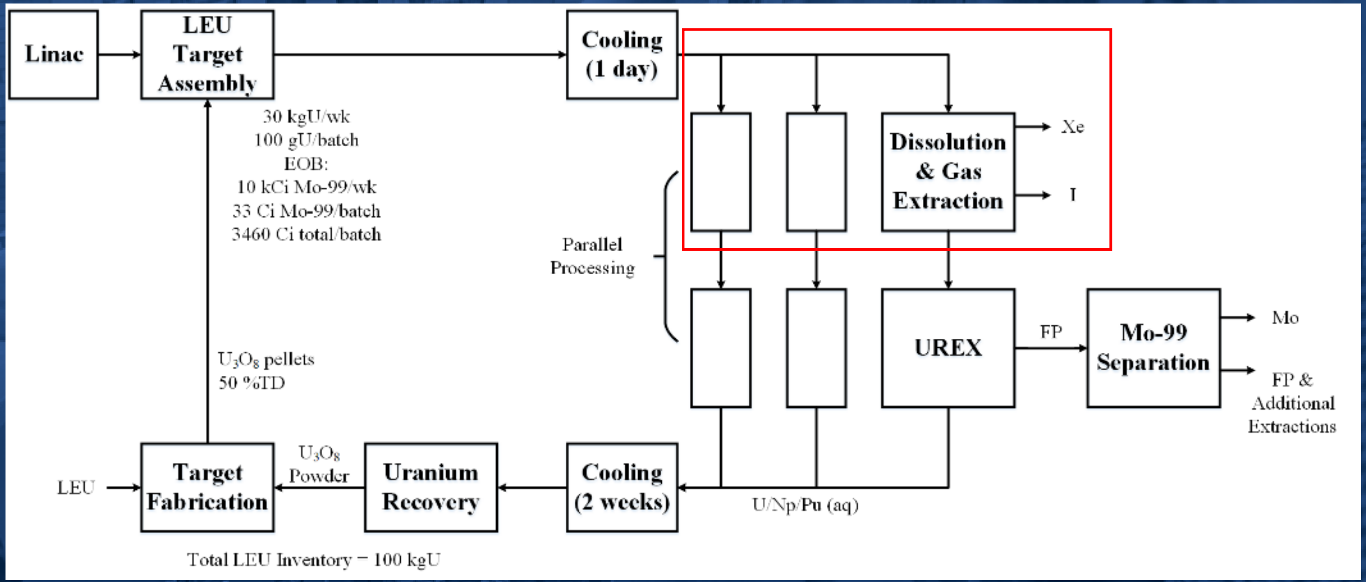
Accelerating Your Particles



DISSOLUTION &GAS EXTRACTION

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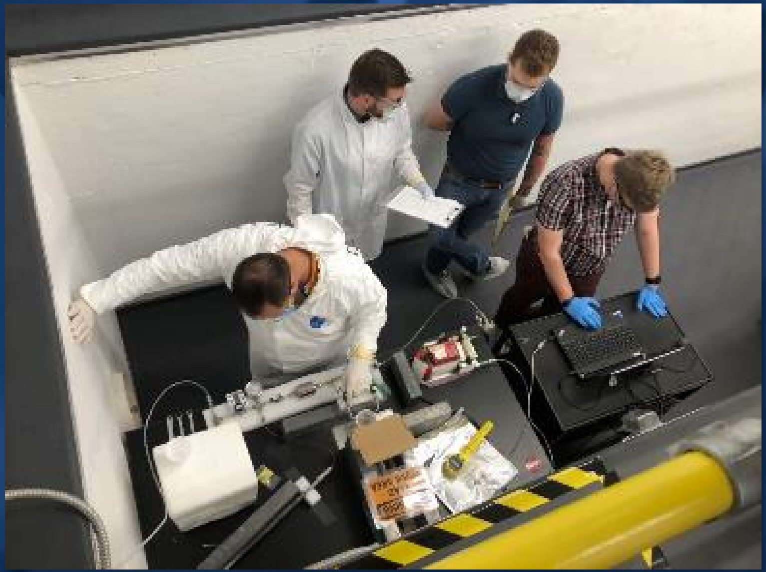

Uranium dissolution:

- Dissolve in nitric acid at room temperature under vacuum

Xenon capture:

- Liquid nitrogen cooled SS cup
- 80 % yield for sale
- No iodine observed

Iodine capture:

- 6 M NaOH bubbler, 100 °C uranyl nitrate, 3-hour capture time.
- 50 % yield for sale
- Residual I captured on silver zeolite filter or remaining in solution.

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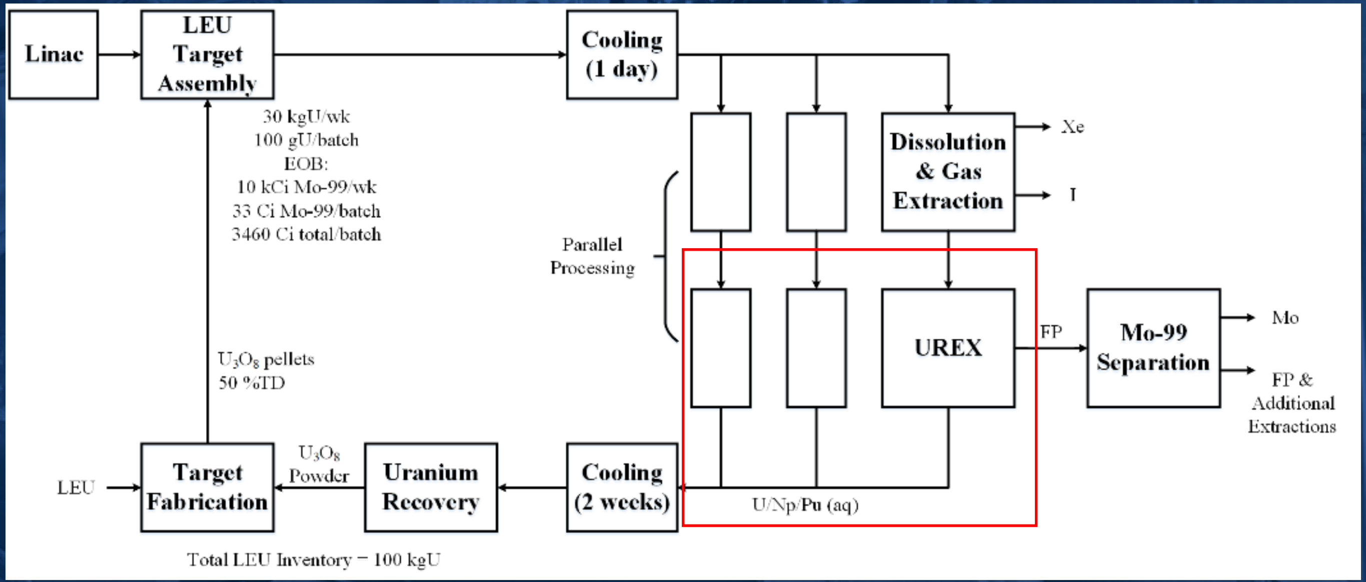
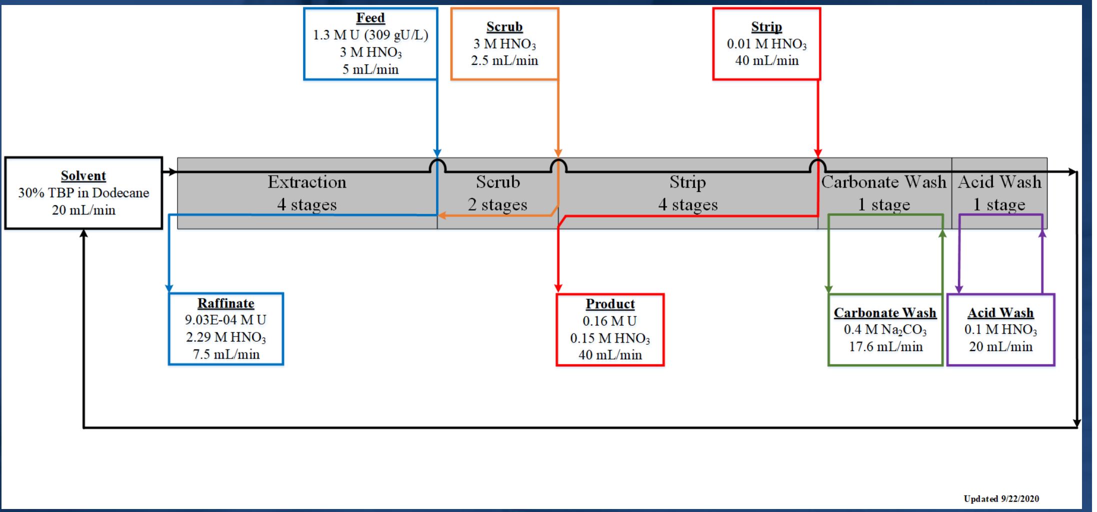
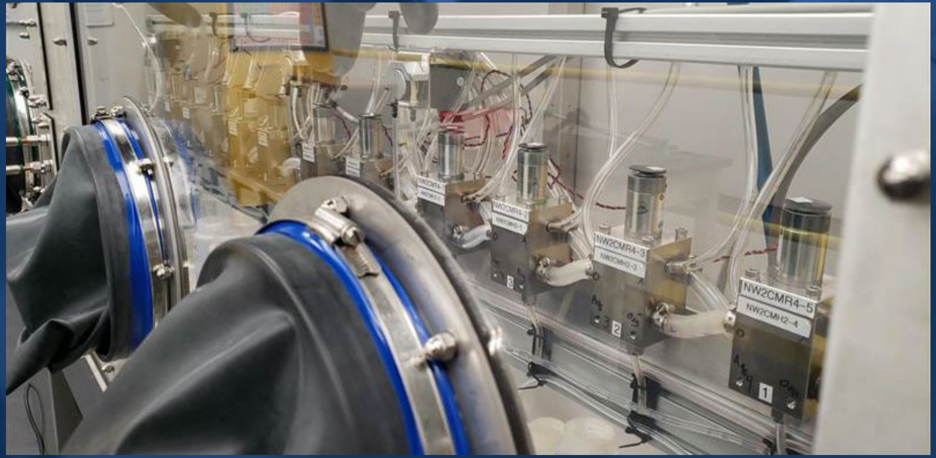
Accelerating Your Particles

Pacific Northwest
NATIONAL LABORATORY


Linac
LEU Target Assembly
Cooling (1 day)
30 kgU/wk
100 gU/batch
EOB:
10 kCi Mo-99/wk
33 Ci Mo-99/batch
3460 Ci total/batch
Dissolution & Gas Extraction
Xe
I
Parallel Processing
UREX
FP
Mo-99 Separation
Mo
FP & Additional Extractions
U3O8 pellets
50 %TD
LEU
Target Fabrication
U3O8 Powder
Uranium Recovery
Cooling (2 weeks)
U/Np/Pu (aq)
Total LEU Inventory ~ 100 kgU

UREX





UREX

Current Status:

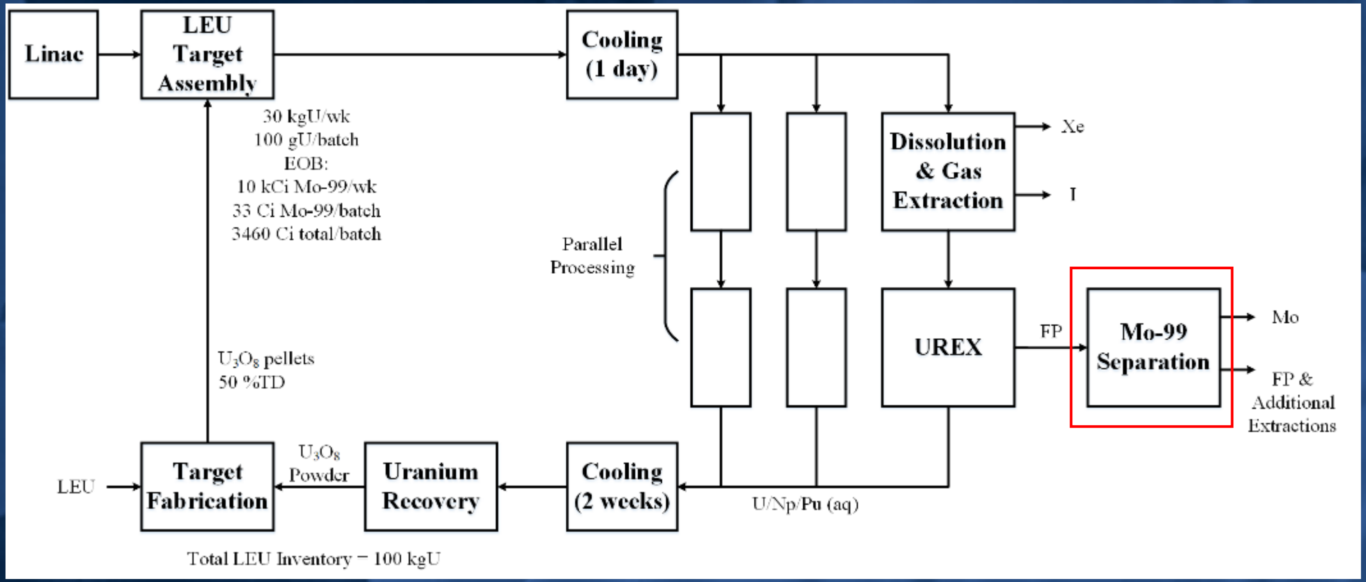
- Designed & fabricated centrifugal contactor system to separate fission products from uranium
- Successfully tested a 12-stage centrifugal contactor bank with irradiated uranium
- Uranium and fission product extractions are benchmarked with AMUSE modeling provided by Argonne
- Solvent clean-up and recycling testing in progress under guidance from SRNL

Next Steps:

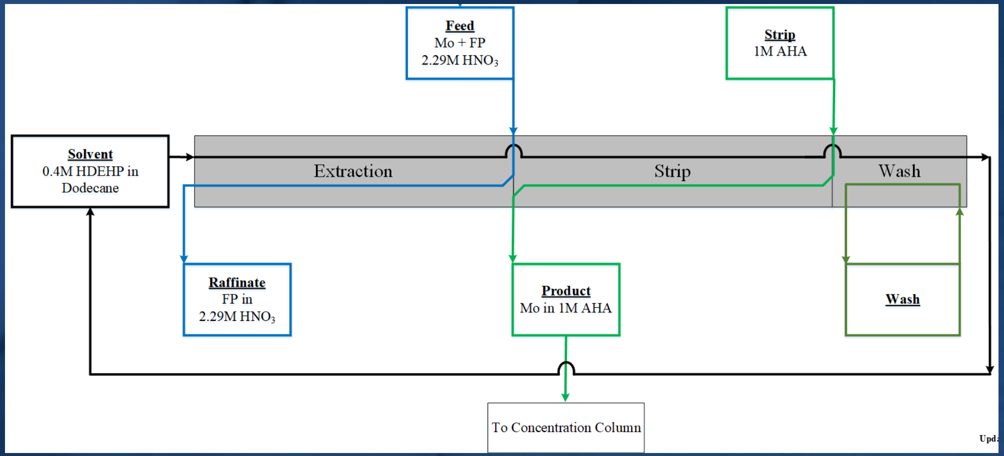
- Implementation of shielding for handling higher activities
- Throughput and longevity testing

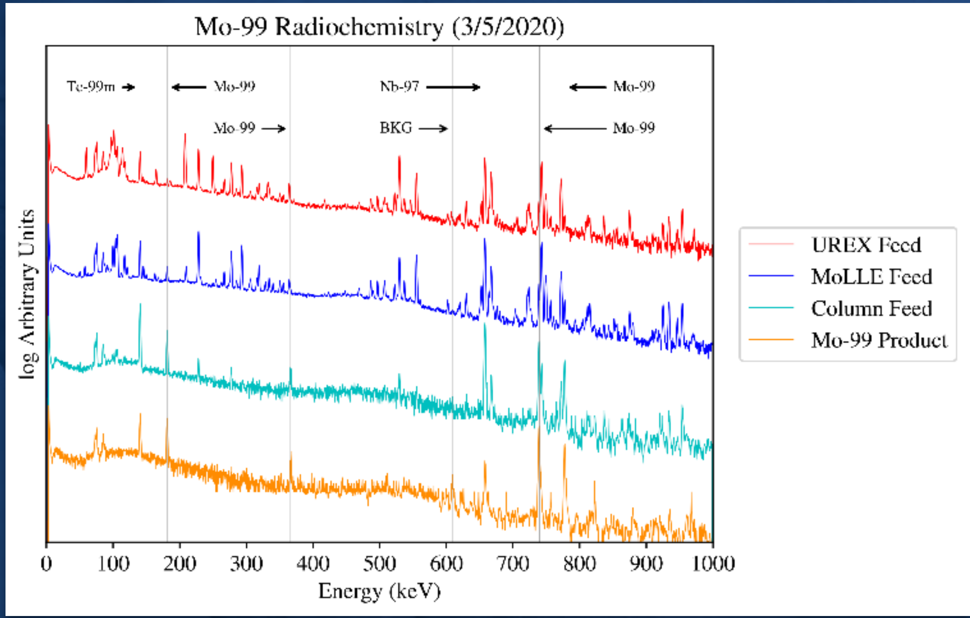
Argonne NATIONAL LABORATORY
UNLV
SRNL SAVANNAH RIVER NATIONAL LABORATORY OPERATED BY SAVANNAH RIVER NUCLEAR SOLUTIONS

NIOWAVE Accelerating Your Particles



MO-99 CHEMISTRY





MO-99 CHEMISTRY

Current Status:

- Mo-99 extracted from a UREX raffinate using a novel liquid liquid extraction technique, then purified and concentrated using an anion exchange column
- Process demonstrated at the bench top scale with irradiated uranium using separatory funnels
- Initial testing in centrifugal contactors is ongoing

Next Steps:

- Testing of MoLLE process in centrifugal contactors using irradiated uranium

Publication Pending: M. Alex Brown, et.al., “Recovery of High Specific Activity Molybdenum-99 from Accelerator-Induced Fission on Low-Enriched Uranium for Technetium-99m Generators.” Scientific Reports

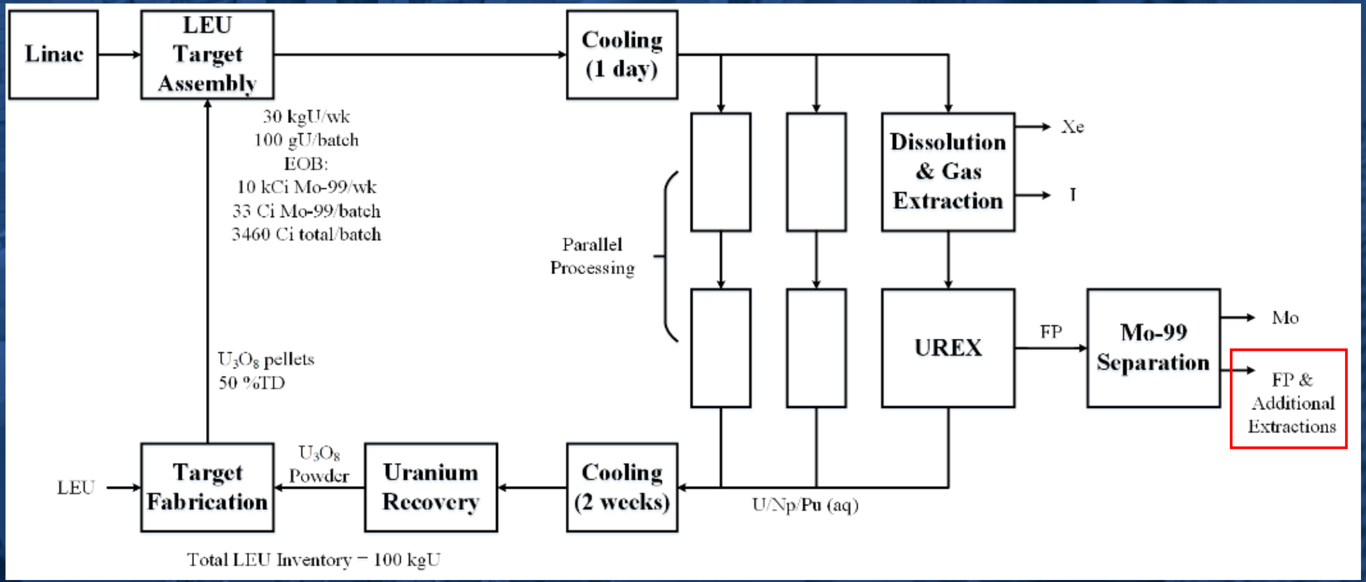
Argonne NATIONAL LABORATORY UNLV SRNL SAVANNAH RIVER NATIONAL LABORATORY OPERATED BY SAVANNAH RIVER NUCLEAR SOLUTIONS

NIOWAVE Accelerating Your Particles

NIOWAVE
Accelerating Your Particles

UNLV

MICHIGAN STATE UNIVERSITY
Founded 1855



OTHER ISOTOPES

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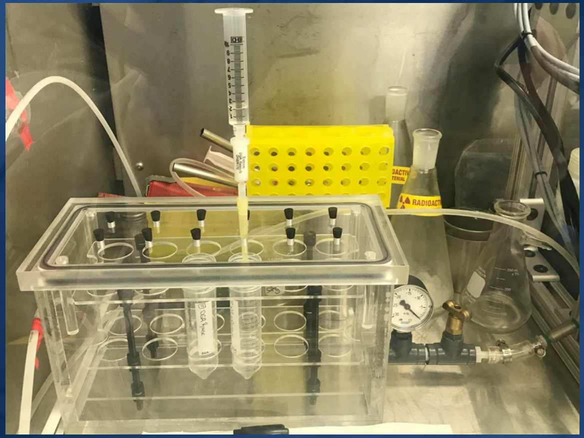


Current Focus

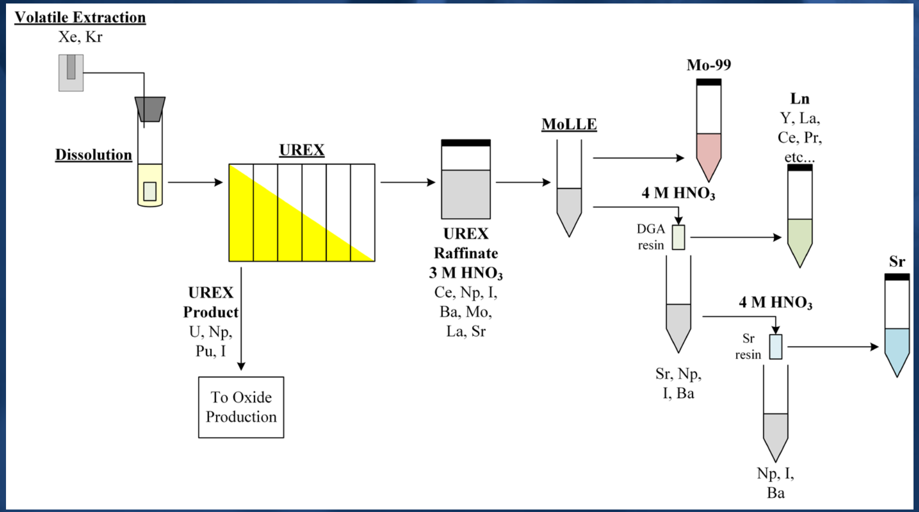
Ce/Pr, Ln Group, Sr/Y

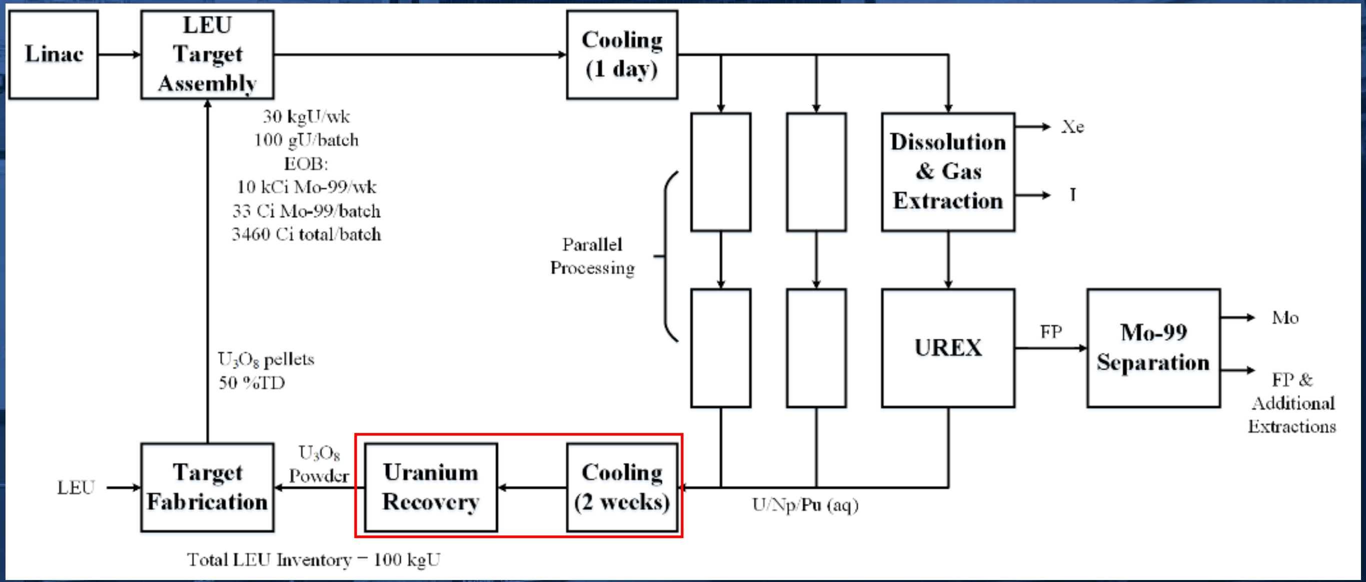
On the Docket

Ba/La, Ln Individual (Nd, Pm, Sm), Ru, Rh, Sb, Te, Zr/Nb

Other Isotopes:

- Extraction of isotopes from MoLLE raffinate
  - Lanthanides: Group separation from MoLLE raffinate followed by individual isolation
    - Ce: electrochemical oxidation followed by LLE
  - Sr: Separation and purification from MoLLE raffinate





URANIUM RECOVERY

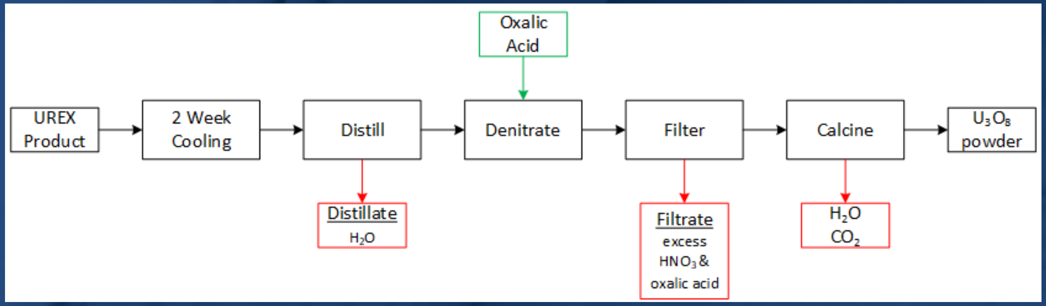
URANIUM RECOVERY

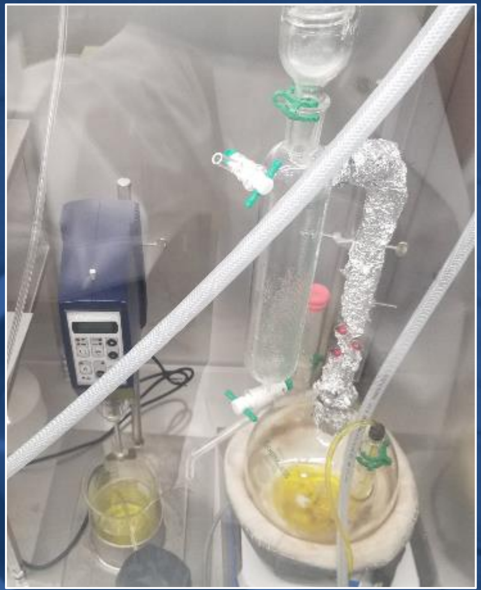
Current Status:

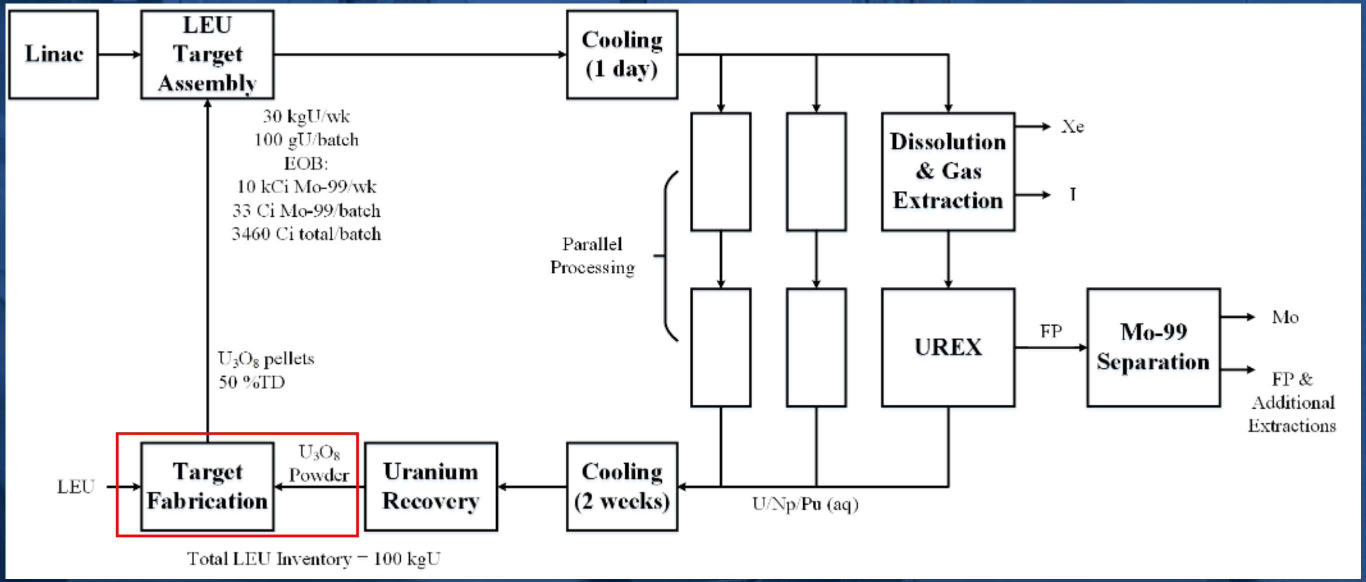
- Uranyl nitrate is distilled then precipitated using oxalic acid. Uranyl oxalate is filtered then calcined to produce U_3O_8.
- Successfully recovered U_3O_8 from uranyl nitrate after UREX at 40 gU scale.

Next Steps:

- Optimize operational steps to increase throughput
- Size equipment for kilogram batches of uranium







TARGET FABRICATION

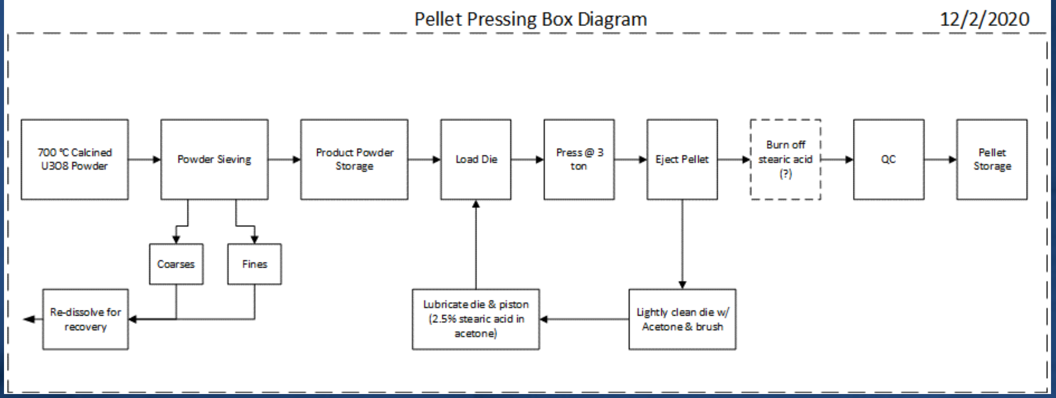
TARGET FABRICATION

Target Fabrication:

- Processed and pressed powder into pellets at high quality.
- 60 % theoretical density green pellets.

- Sieving
  - ZrO grinding media used to produce 0.2-20 µm mesh size powder

- Pressing
  - 5 gU pellet produced using a 3 ton force with steric acid lubrication



Y-12 National Security Complex

Oak Ridge National Laboratory

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EMISSIONS

NIOWAVE Accelerating Your Particles

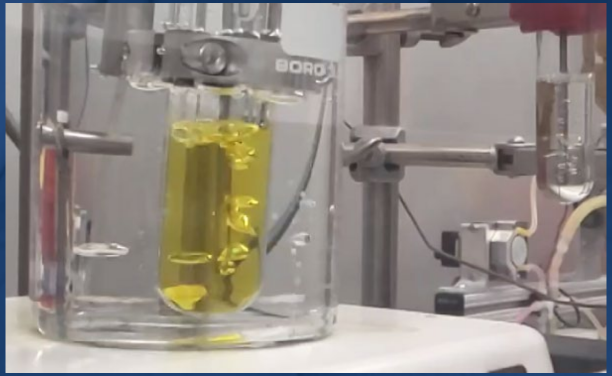
EMISSIONS FROM ISOTOPE PRODUCTION AT NIOWAVE

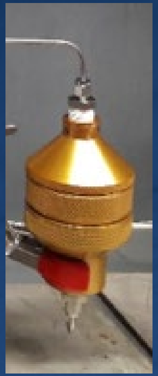
- Iodine and Xenon are highest activity & most restrictive isotopes that will come out of isotope production (fission).

- **Iodine**
  - <u>Primary:</u> sparge uranyl nitrate and capture in NaOH bubbler
  - <u>Abatement</u>: silver zeolite trap

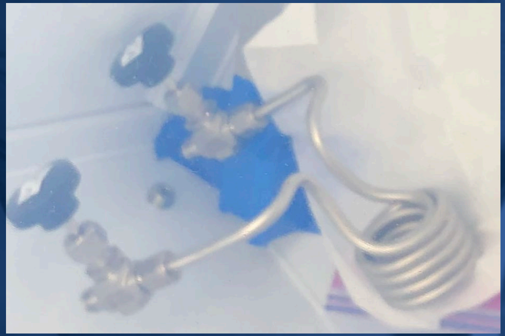
- **Xenon:**
  - <u>Primary:</u> liquid nitrogen cooled coil
  - <u>Abatement:</u> liquid nitrogen cooled (-120 C) charcoal trap.
  - <u>Detection:</u> Xe stack monitor (HPGe)

Iodine:





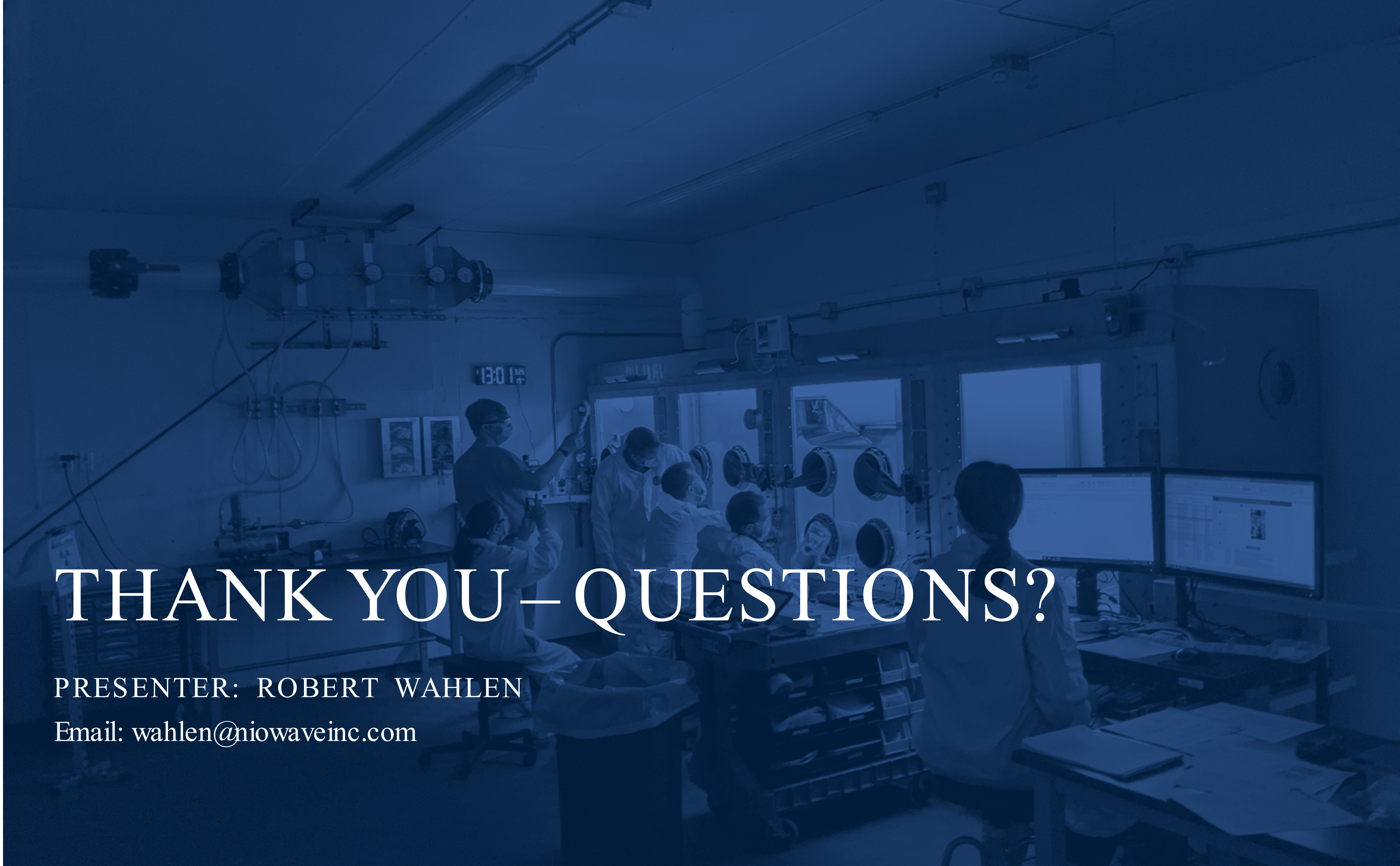
Xenon:



Insert picture of xenon abatement trap here!

STACK MONITOR

- PNNL funded Mirion stack monitor installed at Niowave in Q1 2021.
- Successfully delivered, installed, and connected to the stack.
- System will detect emissions during pilot scale operations of Mo-99 production and separation starting in Q4 2021.



THANK YOU – QUESTIONS?

PRESENTER: ROBERT WAHLEN

Email: wahlen@niowaveinc.com