ACCELERATOR-PATHWAY FOR $^{99}$MO PRODUCTION WITHOUT HIGHLY ENRICHED URANIUM

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Mo-99 Topical Meeting
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OUTLINE

- Support for SHINE Medical Technologies
  - Phase 1 mini- and micro-SHINE experiments gas generation results
  - Transition to mini-SHINE phase 2 experiments
- Support for NorthStar Medical Isotopes
  - Beamline design
    - Beamline configuration
    - Beam diagnostic
    - High power targets
  - Van de Graaff testing for product development
SHINE SUPPORT: ARGONNE MINI-SHINE EXPERIMENT

- Argonne’s mini-SHINE experiment uses fissioning of uranyl-sulfate solutions using photo-neutron target at Argonne electron linac to produce Mo-99. This experiment is designed to:
  - Study the effects of fission on target-solution chemistry and radiolytic off-gas generation
  - Demonstrate the recovery and purification of Mo-99 from an irradiated target solution
  - Produce Mo-99 to ship to potential Tc-99m generator manufacturer partners

Phase 1 (completed January 2016)
- Linac was operated at 35 MeV and 10 kW beam power on the Ta target
- 5 L solution (140 g-U/L) were irradiated with neutrons generated through gamma-n reaction in tantalum target
- Maximum solution fission power was \( \leq 0.05 \text{ kW/L} \)
- Up to 2 Ci of Mo-99 was produced per run

Phase 2
- Experiment will be conducted at 35 MeV beam energy and up to 20 kW beam power
- 20 L solution will be irradiated with neutrons generated in a depleted-uranium (DU) target (Zr clad DU discs were manufactured at LANL)
- Maximum solution fission power will be \( \leq 0.5 \text{ kW/L} \)
- Up to 20 Ci of Mo-99 will be produced
1% safety limit for maximum hydrogen gas concentration in head space of mini-SHINE experiment has significantly constrained gas generation measurements. Oxygen addition had to start 30-60 min into irradiation. Hydrogen concentration reached steady-state in ~100 min. After that time no addition of oxygen to the headspace was necessary.
GAS GENERATION IN MICRO-SHINE EXPERIMENTS

- Small samples ~2 ml were irradiated in dry tubes of the mini-SHINE experimental setup.
- Gas generation rates were measured using flow through approach, which kept concentration of hydrogen below 1%.
- Irradiation of the samples with different enrichments allowed separation of gas generation due to fission and photon radiolysis.
- Fraction of gas production due to fission fragment radiolysis in LEU solution to total gas production is ~67%.
GAS GENERATION IN MICRO-SHINE EXPERIMENTS LEU

LINAC Microshine Gas Measurements
(LEU, U-Sulfate at 157 gU/L, 12/14/15)

- Hydrogen generation rate for LEU ~75 mole/kWh of fission power in solution
PHASE 2 MINI-SHINE IRRADIATION SETUP

- 20L Tank
- DU Target
- Cooling Line Connection Tube
- Target Cask
- Shielded Box
- Weld Connection
- Beam Line
- Vacuum Tube Extension
- e⁻
- DU Target Connection
OVERVIEW OF 20 L PROCESS TANK DESIGN

- Instrument and Dry Well Penetrations
- Outer Cooling/Moderator Tank
- Target Sleeve Thru both Tanks
- Heat Exchanger/Condenser Inside of Tank
- Connections for Top Cooling Coil and Condenser/Heat Exchanger and Process
- Removable Flange
- View Port
- Process Fluid Level
- Inner Process Tank

Overall Tank Assembly Size: ø22” x 22” H
General configuration of Phase 2 mini-SHINE experiment stays the same as Phase 1 experiment
- Single shielded separation glove box replaces two glove boxes used in Phase 1
- Relocation of equipment based on lessons learned from Phase 1
SUPPORT FOR NORTHSTAR MEDICAL RADIOISOTOPES

- **Major challenges**
  - Efficient delivery of high power electron beam to the target
  - Stability of the beam position on the target
  - High power beam tune-up and diagnostic
  - Cooling of high power density target
### Beam Line Configurations for Accelerator Based Production Facility

- Beam line elements: 1-linac, 2-fast acting gate valve, 3-quad magnets, 4-bending magnets, 5-OTR and IR cameras, 6-Beam stop, 7-non-linear beam optics, 8-beam position monitors, 9-collimator, 10-target, 11-gate valve vacuum sensor, 12-rastering magnet, 13-270° magnet.
BEAM LINE COMPONENTS
DEVELOPMENT AND TESTING

- 20° two bend achromatic magnet system was designed and will be installed and tested in October 2016.
- Beam position monitors were installed and tested during multiple production runs. Software for control and data acquisition was developed.
- Performance of the fast acting beam valve system was evaluated in a facility relevant configuration.
- High power collimator and beam stop was designed and fabricated. Those components will be tested in September 2016.
# MATERIALS SELECTION FOR HIGH POWER TARGET

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (Kg/m³)</th>
<th>Thermal Conductivity (W/m-°C)</th>
<th>Maximum Stress (MPa)</th>
<th>Minimum Window Thickness (mm)</th>
<th>Maximum Temperature (°C)</th>
<th>Figure of Merit (FOM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>INCONEL 718</td>
<td>8,221</td>
<td>17.3</td>
<td>456</td>
<td>1.15</td>
<td>403</td>
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<td>INCONEL 706</td>
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<td>AerMet 100</td>
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<td>2024-T81 Aluminum</td>
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<td>6061-T6 Aluminum</td>
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<td>Titanium alloy</td>
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\[ FOM = \frac{\rho t}{\rho_I t_I} \]

\( \rho \) = density of material to be evaluated
\( t \) = minimum acceptable thickness of material to be evaluated
\( \rho_I \) = density of INCONEL 718
\( t_I \) = minimum acceptable thickness of INCONEL 718

\[ FOM = \text{Factor of Merit} \]
FINAL MATERIAL CANDIDATES FOR TARGET WINDOW

- Results of the thermal modeling are shown here as plots of temperature (°C)
- Stress due to pressure loading plotted as stress intensity in MPa

<table>
<thead>
<tr>
<th>Material</th>
<th>Maximum Beam Power (kW)</th>
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</thead>
<tbody>
<tr>
<td>Inconel 718</td>
<td>18</td>
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<td>Beryllium</td>
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<tr>
<td>250 Maraging Steel</td>
<td>39</td>
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</table>
VAN DE GRAAFF (VDG) ACCELERATOR

Testing of radiation stability of process equipment

- Radiation damage tests using the VDG
- Effects of photon radiation on HDPE bottles containing $\text{K}_2\text{MoO}_4$ in 6 M KOH
- Zero to 6.5 MRad shown (up to twice calculated dose expected)
- Testing of RadioGenix generator components
SUMMARY

- Scope of phase 1 mini-SHINE experiment was completed in January 2016.
- Gas generation rates were measured in phase 1 micro-SHINE experiments and results are in good agreement with literature data.
- Installation of phase 2 mini-SHINE equipment is nearly complete. Commissioning of the phase 2 mini-SHINE experimental setup will start in September 2016.
- Different configurations of the beam line were evaluated. 90° or 270° configuration is proposed for the production facility.
- Beam position monitors and the fast acting gate valve system were tested in plant relevant conditions.
- High power beam dump and collimator were designed and built and will be tested in September 2016.
- Components of the RadioGenix system were tested at Van de Graaff accelerator. Results of those tests are helping NorthStar in developing a more robust system and in the FDA approval process.
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