Metal Fuel Fabrication Safety and Hazards

Nicole L. LaHaye
Global Nuclear Science & Technology
Fuel Fabrication Overview

• Six general steps →
• Additionally:
  ▪ Scrap Recycle
  ▪ Material Storage
• Hazards
  ▪ Fire/pyrophoricity
  ▪ Reactive or toxic chemicals
  ▪ Radiation
  ▪ Nuclear criticality
• Caveats
  ▪ Information mainly from older government operations
  ▪ May not cover all processes in future license applications involving new technology
  ▪ Hazards may vary with changes in processes, operations, or scale
Step 1: Feedstock Preparation

Feedstock Preparation
- Dissolution
- Separation
- Purification
- Enrichment
- Conversion

Reduction to Metal → Alloying → Casting

Machining / Thermomechanical Processing
- Shearing
- Extrusion
- Hot/Cold Rolling
- Pilgering
- Annealing

Element / Assembly Fabrication
- Diffusion Barrier
- Cladding
- Sodium Bonding
- Swaging
- Welding
- Surface Finishing
- Straightening
- Wire Wrapping
Feedstock Preparation from Ore

- Mining/leaching
- Chemical purification/refinement
  - Ion exchange
  - Solvent extraction
- Further purification
- Denitration/calcination
- Conversion to UF\textsubscript{6}, enrichment
- Conversion to UF\textsubscript{4}
Feedstock Preparation Processes

Feedstock Preparation from Used Fuel (Fuel Reprocessing)

- Removal from subassemblies
- Decladding of fuel elements
  - Mechanically
  - Chemically
- Chemical purification/refinement
  - Melt refining
  - Dissolution and solvent extraction

(Photo: Hesson et al., “Description and proposed operation of the fuel cycle facility for the second experimental breeder reactor (EBR-II),” Argonne National Laboratory, ANL-4605, April 1963)
Pyrophoricity
- Uranium oxide
- Hydrogen gas
- Oxygen gas
- Used fuel
  - Self heating
  - Sodium

Chemical
- Uranium
  - Fumes
  - Oxide powder
- Acids
- HF
- Fluorine gas

Radiation
- Ore
  - Radium and daughters
- Fuel reprocessing
  - Fission products
  - Sodium-24
  - Uranium-236

Nuclear Criticality
- MERMAIDS
- Negligible for natural uranium without special moderator
- Unexpected precipitation or settling
- Vessels with favorable configuration
Step 2: Reduction to Metal

Feedstock Preparation
- Dissolution
- Separation
- Purification
- Enrichment
- Conversion

Reduction to Metal → Alloying → Casting

Machining / Thermomechanical Processing
- Shearing
- Extrusion
- Hot/Cold Rolling
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- Annealing

Element / Assembly Fabrication
- Diffusion Barrier
- Cladding
- Sodium Bonding
- Swaging
- Welding
- Surface Finishing
- Straightening
- Wire Wrapping
Reduction of Uranium Halides by Metals

- $\text{UF}_4 + 2\text{Ca} \rightarrow \text{U} + 2\text{CaF}_2$
- $\text{UF}_4 + 2\text{Mg} \rightarrow \text{U} + 2\text{MgF}_2$

DOR is very similar:

- $\text{UO}_2 + 2\text{Ca} \rightarrow \text{U} + 2\text{CaO}$
- $\text{UO}_2 + 2\text{Mg} \rightarrow \text{U} + 2\text{MgO}$

Other Reduction Methods

- Electrolytic reduction
  - \( \text{UO}_2 + 4\text{Li} \rightarrow \text{U} + 2\text{Li}_2\text{O} \)

- Disproportionation or thermal decomposition of uranium halides
  - \( \text{UL}_4(g) + \text{heat} \leftrightarrow \text{U}(s) + 2\text{I}_2(g) \)

Reduction to Metal Hazards

Pyrophoricity
- Uranium metal
- Slag/skull
- Calcium
- Magnesium

Chemical
- Uranium
  - Fumes
  - Oxide powder
- Calcium

Radiation
- Dispersion and contamination
  - UF$_4$
  - Uranium oxide

Nuclear Criticality
- >100 kg reduction of natural uranium
- <2.2 kg reduction of low-enriched uranium
- Higher enrichments == smaller charges
Steps 3 and 4: Alloying and Casting

Feedstock Preparation
- Dissolution
- Separation
- Purification
- Enrichment
- Conversion

Reduction to Metal → Alloying → Casting

Machining / Thermomechanical Processing
- Shearing
- Extrusion
- Hot/Cold Rolling
- Pilgering
- Annealing

Element / Assembly Fabrication
- Diffusion Barrier
- Cladding
- Sodium Bonding
- Swaging
- Welding
- Surface Finishing
- Straightening
- Wire Wrapping
Alloying and Casting Processes

• Co-reduction
• Arc melting
• Vacuum Induction Melting
  ▪ Injection casting
  ▪ Gravity-fed casting
• Microwave Casting
• Others
  ▪ Centrifugal casting
  ▪ Continuous casting
  ▪ Cold crucible casting
Alloying and Casting Hazards

**Pyrophoricity**
- Resistive heating of VIM coil
- Uranium metal
  - Casting skull
- Alloyed uranium
- Calcium (co-reduction)
- Magnesium (co-reduction)

**Chemical**
- Uranium
  - Fumes
  - Oxide powder
- Calcium

**Radiation**
- TRU
- Dispersion/contamination
  - Americium
  - Plutonium
- Uranium daughter products
- Melt refining
  - Gas
  - Skull

**Electrical**
- Electrical arcing
- Power supply damage or failure
- Corona effect depends on coil voltage, coil surface temperature, chamber pressure, and dielectric properties of surrounding materials

**Nuclear Criticality**
- Water-cooled induction coils
- Maximum safe fissile mass is 10.5 kg [Stephen and Reddy]
- Mis-pours
  - Crucible cracking
  - Metal freezing
Step 5: Machining/Thermomechanical Processing

Feedstock Preparation
- Dissolution
- Separation
- Purification
- Enrichment
- Conversion

Reduction to Metal → Alloying → Casting

Machining / Thermomechanical Processing
- Shearing
- Extrusion
- Hot/Cold Rolling
- Pilgering
- Annealing

Element / Assembly Fabrication
- Diffusion Barrier
- Cladding
- Sodium Bonding
- Swaging
- Welding
- Surface Finishing
- Straightening
- Wire Wrapping
Machining and Thermomechanical Processing Hazards

**Pyrophoricity**
- Uranium fines and chips
- Friction interface during machining
- NaOH in water or acid

**Chemical**
- Uranium
- TCE
- Triton DF-16
- NaOH
- Nitric acid
- HF

**Radiation**
- TRU
- Dispersion and contamination
  - Radioactive dust generated during machining

**Nuclear Criticality**
- Adequate fuel spacing makes criticality negligible
- Buildup of uranium fines and chips
Step 6: Element/Assembly Fabrication

- Feedstock Preparation:
  - Dissolution
  - Separation
  - Purification
  - Enrichment
  - Conversion

- Reduction to Metal

- Alloying

- Casting

- Machining / Thermomechanical Processing:
  - Shearing
  - Extrusion
  - Hot/Cold Rolling
  - Pilgering
  - Annealing

- Element / Assembly Fabrication:
  - Diffusion Barrier
  - Cladding
  - Sodium Bonding
  - Swaging
  - Welding
  - Surface Finishing
  - Straightening
  - Wire Wrapping
Element/Assembly Fabrication

SFR Rod-Type Fuel

- Weld lower end plug to tubing
- Weld and wrap wire
- Load jackets with sodium
- Insert fuel slugs
- Settling furnace
- Load with tag gas
- Insert & weld upper end plug
- Sub-assembly

Plutonium Rod-Type Fuel

- Assemble co-extrusion billet
- Weld
- Outgas & extrude
- Decontaminate & straighten
- Radiograph
- Machine ends
- Radiograph & bond test
- Degrease & etch
- Inspect & measure

Plate-Type Fuel

- Apply cladding via HIP
- Shear can & extract clad fuel
- Shear excess cladding
- Thin cladding
- Form plates
- Stack plates into assembly
- Place & weld end caps
- Apply anti-corrosion coating
Element/Assembly Fabrication Hazards

**Pyrophoricity**
- Uranium
- Finely divided aluminum or zirconium
- Sodium

**Chemical**
- Sodium
- NaOH
- Nitric acid
- HF

**Radiation**
- Minimal to no contamination has been observed

**Nuclear Criticality**
- Adequate fuel spacing makes criticality negligible
Scrap Recycle

• Sources of scrap
  - CaF$_2$ (or other reduction slag)
  - Filter cakes
  - Floor washings
  - Oxides
  - Metal chips/turnings from various processes

• Methods
  - Dissolution and traditional treatment (like feedstock preparation)
  - Direct fluorination
  - Electrorefining
Scrap Recycle Hazards

**Pyrophoricity**
- Uranium scrap
- Nitric acid dissolution
- Hydrogen gas
- HCl + H2O2 dissolution

**Chemical**
- Uranium
  - Fumes
  - Oxide powder
- Acids
- HF
- Fluorine gas

**Radiation**
- Minimal

**Nuclear Criticality**
- MERMAIDS
- Negligible for natural uranium without special moderator
- Unexpected precipitation or settling
- Vessels with favorable configuration
Storage of Fuel, Fines/Scrap, and Other Waste

• Unsuccessful methods for stabilization of uranium scrap
  ▪ Recovery by melting—melting was only achieved in outer regions; fire risk was increased from friction during compaction of scrap pieces
  ▪ Alloying with aluminum—no uranium was measured in the Al matrix; only fresh scrap can be treated using this method
  ▪ Wet chemical oxidation (a LANL procedure in which sodium hypochlorite reacts with U to form UOH, then sodium thiosulfate reacts with UOH to form UO$_2$)—significant amounts of liquid waste are generated
  ▪ Burning

• Calcination is most favorable method
  ▪ High throughput
  ▪ Simple operation
  ▪ Control of reaction rate
Storage Hazards

**Pyrophoricity**
- Uranium metal
- Storage in water
- Hydrogen from corrosion
- Metal-water reaction
- Acetylene gas
- Vehicle fuel

**Chemical**
- Nitrates in liquid waste
- Hydrogen from corrosion
- Metal-water reaction
- Pyrophoric metals
- Acetylene gas
- Vehicle fuel
- Lead

**Radiation**
- Release
  - Kinetic or potential energy
  - Pyrophoric materials
  - Flammable materials
  - Natural phenomena
  - External events
  - Direct radiation exposure

**Nuclear Criticality**
- Kinetic energy initiating cask or container damage
- Drop potential
- Fissionable materials in storage liners
Summary

• Proper procedures, management, and training can help to decrease incident occurrence
• Hazardous events are unlikely to occur with hazard mitigations in place
## Pyrophoricity Hazard Mitigation

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Hazard Mitigation Recommendation</th>
<th>Fuel Fabrication Step</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyrophoricity</td>
<td>Store unstable oxide powder in closed metal containers</td>
<td>Feedstock Preparation</td>
</tr>
<tr>
<td></td>
<td>Employ adequate ventilation to prevent buildup of flammable or oxidizing gases</td>
<td>Feedstock Preparation</td>
</tr>
<tr>
<td></td>
<td>Employ adequate airflow for heat removal from self-heating</td>
<td>Feedstock Preparation from Used Fuel</td>
</tr>
<tr>
<td></td>
<td>Operate under an inerted atmosphere</td>
<td>Feedstock Preparation from Used Fuel (sodium)</td>
</tr>
<tr>
<td></td>
<td>Store fines/chips/swarf under liquids</td>
<td>Reduction to Metal</td>
</tr>
<tr>
<td></td>
<td>Use solid, oxygen-free, high-conductivity copper for VIM coil</td>
<td>Alloying and Casting</td>
</tr>
<tr>
<td></td>
<td>Reuse casting heel to reduce scrap/waste</td>
<td>Alloying and Casting</td>
</tr>
<tr>
<td></td>
<td>Control speed and use coolant during machining to reduce heat created</td>
<td>Machining and Thermomechanical Processing</td>
</tr>
<tr>
<td></td>
<td>Co-extrude fuel cores and cladding to reduce the quantity of fuel alloy chips generated and the amount of machining required</td>
<td>Machining and Thermomechanical Processing</td>
</tr>
</tbody>
</table>
Pyrophoricity Hazard

- Main hazard from uranium metal and uranium alloy fuel fabrication
- Frank Kamenetskii parameter

\[ \delta = \frac{V \cdot \Delta H \cdot C \cdot T_r}{h \cdot A \cdot T_\infty} e^{-T_r+1} \]

- \( \delta \geq 1 \) suggests ignition
- Increasing the overall heat transfer coefficient changes slab from ignitable to no ignition

(Photo: Burkes, “RPL 48 Metal Cutting Operations Evaluation,” PNNL, April 2018)
## Chemical Hazard Mitigation

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<tr>
<td>Chemical</td>
<td>Employ adequate ventilation or respiratory protection to prevent exposure to uranium fumes, oxide powder, and metal fines, as well as other chemicals used in the fuel fabrication process</td>
<td>Feedstock Preparation Reduction to Metal Alloving and Casting Machining and Thermomechanical Processing</td>
</tr>
<tr>
<td></td>
<td>Have calcium gluconate on hand to treat HF exposure</td>
<td>Feedstock Preparation Scrap Recycle</td>
</tr>
<tr>
<td></td>
<td>Substitute NF₃ for gaseous HF of F₂ due to its lower chemical toxicity</td>
<td>Feedstock Preparation Scrap Recycle</td>
</tr>
<tr>
<td></td>
<td>Use personnel protection equipment (PPE) when working with chemicals as necessary (apron, chemical-resistant clothing, gloves, safety glasses, face shield)</td>
<td>Feedstock Preparation Machining and Thermomechanical Processing Element/Assembly Fabrication Scrap Recycle</td>
</tr>
<tr>
<td></td>
<td>Employ corrosion-resistant materials such as monel where necessary</td>
<td>Feedstock Preparation Reduction to Metal Scrap Recycle</td>
</tr>
</tbody>
</table>
Chemical Hazard

• Fuel fabrication process employs many acids and caustic chemicals
• Uranium fumes and oxide powder are highly toxic
  ▪ Heavy metal poisoning from inhalation
  ▪ Occupational exposure presents only a limited increase in cancer risk
• Degreasing and decontamination agents
## Radiation Hazard Mitigation

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<th>Fuel Fabrication Step</th>
</tr>
</thead>
</table>
| Radiation             | Use PPE when working with radioactive materials as necessary (lab coat, gloves, safety glasses, respirator) | Feedstock Preparation  
Reduction to Metal  
Alloying and Casting  
Machining and Thermomechanical Processing |
|                       | ALARA precautions (limiting time exposed and increasing distance from source)                     | Feedstock Preparation  
Reduction to Metal  
Alloying and Casting  
Machining and Thermomechanical Processing  
Element/Assembly Fabrication  
Scrap Recycle |
|                       | Conduct operations in hot cells                                                                   | Feedstock Preparation from Used Fuel  
Alloying and Casting (TRU, melt refining)  
Machining and Thermomechanical Processing (TRU) |
|                       | Employ adequate ventilation or respiratory protection to prevent exposure to uranium fumes, oxide powder, and metal fines | Feedstock Preparation  
Reduction to Metal  
Alloying and Casting  
Machining and Thermomechanical Processing |
|                       | Conduct operations in a glovebox                                                                  | Alloying and Casting  
Machining and Thermomechanical Processing |
|                       | Wipe fuel to remove surface contamination                                                          | Alloying and Casting |
Radiation Hazard

- Mainly present as contamination concerns
  - Use of ventilation or gloveboxes
  - Traps in the exhaust system
- Uranium is only weakly radioactive
  - DU emits fairly intense $\beta$ radiation
- Employ ALARA principles
- Occupational exposure to uranium presents only a limited increase in cancer risk
## Nuclear Criticality Hazard Mitigation

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</tr>
</thead>
<tbody>
<tr>
<td>Nuclear Criticality</td>
<td>Use vessels that do not allow for favorable criticality geometries or conditions</td>
<td>Feedstock Preparation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reduction to Metal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alloying and Casting</td>
</tr>
<tr>
<td></td>
<td>Limit the size of charges</td>
<td>Scrap Recycle</td>
</tr>
<tr>
<td></td>
<td>Avoid water cooling of induction coils</td>
<td></td>
</tr>
</tbody>
</table>

## Electrical Hazard Mitigation

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<th>Fuel Fabrication Step</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical</td>
<td>Clean fuel dust from furnace to avoid corona arcing</td>
<td>Alloying and Casting</td>
</tr>
<tr>
<td></td>
<td>Check induction coil for adequate coil spacing and problems with the coil insulator to prevent arcing</td>
<td>Alloying and Casting</td>
</tr>
<tr>
<td></td>
<td>Use appropriate coil material</td>
<td>Alloying and Casting</td>
</tr>
</tbody>
</table>
Nuclear Criticality Hazard

- Mass
- Enrichment
- Reflection
- Moderation
- Absorption
- Interaction
- Density
- Shape

• Observe proper criticality safety as determined by analysts and engineers
• Historical criticality accidents during fuel fabrication attributed to unsafe geometry, reflection, or both
• Most reported accidents occurred between 1958 and 1964
Thank you