Design and Evaluation of Processes for Transmuter Fuel Fabrication

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Design and Evaluation of Processes for Transmuter Fuel Fabrication

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Design and Evaluation of Processes for Transmunder Fuel Fabrication

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• Survey of Existing Fabrication Processes
• Machinery for Manufacturing
• Process Automation: Concepts and Methodology
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Summary

- **Project Objective**: examine autonomous robotic fuel fabrication processes with regard to hot cell and equipment design, operations, and costs.

- Fabrication processes for different fuel types differ in terms of equipment types, throughput, and cost.

- Design options are restricted by the requirement to employ only radiation-hardened machinery and components.

- **Benefit to DoE**: decision support for the selection of the most suitable manufacturing process.
The Problem

**Nuclear waste reduction:** Spent fuel quantities estimated at 86,000 metric tons must be safely stored for 10,000 years. Only about 1,000 tons are actinides and long-lived fission products.

**Transmutation:** Reduce the long term toxicity of long-lived fission products (mostly Pu and actinides such as Am, Cm, Tc, I).
Transmuter Fuel Fabrication

DOE Roadmap 1999:

- Aqueous processes: UREX, PUREX
- Electrolytic processes: PYRO-A, PYRO-B

Typical Scenario

- Powder processing: Oxide or Nitride Fuel
- Metallic Fuel
Fuel Fabrication Processes

Basic Manufacturing Options:

1. Metallic Casting
2. Powder Processing, e.g. MOX fuels (several possible configurations)
Potential Fuel Types

1) Metal Alloy

- Casting or PM (Powder) fabrication
- High density
- Low smear density and gas plenum required for high burnup
- Requires liquid metal bond
- Behavior well understood, fuel performance model available
Fuel Fabrication Processes

Manufacturing Sequence for Cast Metallic Fuel (ANL):
1. Cast fuel slugs. Pins are 4 to 5mm dia. and 0.8 m to 1.5 m long.
2. Insert fuel slugs into cladding tube.
3. Add bond phase (Na) in cladding tube
4. Seal cladding tube by welding end fitting onto the tube
5. Inspect fuel pin (radiography, dimensional, and clad defects)
Metal Fuel by Injection Casting

TRU metal feedstock

induction melting, injection casting

mold stripping

encapsulation

bonding

seal welding

Broken Mold = Waste!
Fuel Fabrication Processes
ANL Experience with Metallic Fuel Fabrication

- Simple, rapid production process
- Volatility of americium is problematic (Trybus, et. al. (1993))
- 40% Am loss
- Evaporation rate of $\leq 5$ g/s from melt surface
- Ca, Mg impurities from Molten salt separation process caused eruptions
Fuel Fabrication Processes

**Ceramic Fuels**

**Manufacturing Sequence for Ceramic Fuel:**

1. Manufacture particles by wet chemical process or direct reaction (1 to 30 um dia.)
2. Compaction of particles into pellet form.
3. Sinter pellets at 1400°-1800°C.
4. Inspect pellets
5. Assemble pellets into cladding tube
6. Add bonding material (He or Na)
7. Seal cladding tube by welding
8. Inspect assembled fuel pin (radiography, dimensional and clad defects)
Fuel Fabrication Processes ANL Concepts
MOX Fabrication Process  
(Siemens)
Fuel Fabrication Processes
ANL General Comments on Powder Processing

- Lower processing temperatures
- Densification of metals assisted by application of force
- Extrusion, swaging, drawing
- Densification of nitrides by thermally driven sintering process only (hot pressing is probably not practical)
- Dispersions and metal alloy fuels possible
- Powder processing is only viable route for nitride fuels
- Uniform distribution of components
- Diffusion barrier easily incorporated
Fuel Fabrication Processes
ANL General Comments on Fuel Fabrication Routes

Powder Processing Disadvantages

- Requires formation and handling of fine powder
- Hydriding/dehydriding requires hydrogen
- Texturing possible on extrusion of metals
Transmuter Fuel Fabrication Issues:

- Hot cell required
- Criticality concerns mandate small batch sizes
- Large fuel quantities suggest process automation
- Equipment for hot cell operation must be identified or developed.
- Material flow and operational sequence
- Long term reliability must be ensured
- Design must prove the ability to cope with a wide range of contingencies (e.g. equipment failures, spillage, breakage)
Pellet fabrication procedures

Three processes for Americium Fuel Fabrication (Haas et al.), 1998
Flow sheet for americium target fabrication INRAM process 1 ton Am/year

IM* Powder
9 tons/year
IM Pellet Pressing
40,000 p/day
IM Pellet Calcination
40,000 p/day

Active Solution Preparation
2000 I/year

Immersion Tank (1)
40,000 p/day

Pellet drying Oven (1)

Pellet calcination Oven (1)

Pellet sintering Oven (2)

Pellet controls

Pin filling/welding machines (4)
200 pins/day

Am dissolution
Crushing

Scraps

* Inert Matrix

Americium Fuel Fabrication for 1 ton of Am/year (Haas et al.), 1998
Fertigungsprozess im Brennelementwerk der ANF Lingen

UF₆-Trockenkonversion

UF₅ Dry conversion

Fuel rod assembly

Komponenteneingang

Brennelementmontage

BE waschen u. trocknen

BE-Endkontrolle

BE-Lager

BE-Montage

BE-Transportbehälter

Tablettenherstellung

Pellet production

Tabletteninspektion

Scheibensilo

Helium Leaksuchanlage

Skelettmontage

BS-Endkontrolle

Anreicherungsmessanlage

Schweissmaschine (obere Endstopfen)

BS-Lademaschine

Welding Machine

Brennstabfertigung

Fuel Rod Manufacturing

Sinterofen

Schleifmaschine

Grinder

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DEPARTMENT OF MECHANICAL ENGINEERING
Possible Configuration for Powder Processing Fabrication Work Cell (e.g. Oxide or Nitride Fuel)
Possible Configuration for Metallic Fuel Fabrication Work Cell
## Preliminary Cost Estimates, Metallic Fuel Fabrication.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Estim. Cost US $</th>
<th>Estimated Area requirement ft²</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Induction furnace + Preparation Area</td>
<td>2.0 Million</td>
<td>50</td>
<td>Source: ANL West</td>
</tr>
<tr>
<td>Reusable Mold</td>
<td>500K</td>
<td></td>
<td>No standard process exists. Conventional methods have not been adapted to hot cell use.</td>
</tr>
<tr>
<td>Fuel Pin Assembly Unit (Insertion, Encapsulation, bonding and welding)</td>
<td>2.0 Million</td>
<td>40</td>
<td>Custom equipment</td>
</tr>
<tr>
<td>3 Robots, approx. 1.5 m work envelope at 270 deg. range</td>
<td>1.5 Million</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Inspection stations 1 (slugs) and 2 (pins) (20 sq.ft. ea.)</td>
<td>2 Million</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Machining Unit (Grinder)</td>
<td>500K</td>
<td>20</td>
<td>Provide for Dust Containment</td>
</tr>
<tr>
<td>Supervision (cameras and controllers)</td>
<td>500k</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>Product storage</td>
<td></td>
<td>30</td>
<td></td>
</tr>
<tr>
<td><strong>Total Equipment</strong></td>
<td><strong>$9 Million</strong></td>
<td><strong>240 sq.ft.</strong></td>
<td></td>
</tr>
</tbody>
</table>
## Preliminary Cost Estimates, Powder Processing

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Estim. Cost in US $</th>
<th>Estimated Area requirement $\text{ft}^2$</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blender</td>
<td>50K</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Pellet press</td>
<td>500K</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Sintering oven</td>
<td>1.5 Million</td>
<td>100</td>
<td>Custom equipment</td>
</tr>
<tr>
<td>Machining Center (Grinder)</td>
<td>500K</td>
<td>20</td>
<td>Custom equipment. Dust seal and dust suppression required. E.g.: wet process would reduce dust and surface temperatures during grinding.</td>
</tr>
<tr>
<td>Pellet Inspection Station</td>
<td>1 Million</td>
<td>10</td>
<td>Custom equipment</td>
</tr>
<tr>
<td>Fuel Pin Assembly Unit (Pellet insertion, encapsulation and bonding, welding)</td>
<td>2 Million</td>
<td>40</td>
<td>Custom equipment</td>
</tr>
<tr>
<td>3 Robots, approx. 1.5 m work envelope ea. at 270 deg. range</td>
<td>1.5 Million</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Supervision (cameras and controllers)</td>
<td>500k</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product storage</td>
<td></td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Final Inspection station (Fuel rod dimensions and weld)</td>
<td>1 Million</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td><strong>Total Equipment</strong></td>
<td>$8.55M</td>
<td><strong>310 ft}^2</strong></td>
<td></td>
</tr>
</tbody>
</table>
Metallic Fuel Fabrication:

A single manufacturing cell would require approx. 200 sq. ft. of hot cell space at a cost of approx. $30,000/ft² or $7.2M for the hot cell space. Total installation cost approx. $16.2 Million.

Powder Processing:

A single manufacturing cell would require approx. 310 sq. ft. of hot cell space at a cost of approx. $30,000/ft² or $9.3M for the hot cell space. Total installation cost approx. $17.85 Million.
Fuel Fabrication Processes

Generic issues common to all fuel types:

- TRU Waste (e.g. Am vapor, dust from powder)
- Dimensional Inspection, intermediate and final
- Heating or melting
- Assembly: e.g. placement of pins or pellets into cladding tube

Issues in Powder Processing:

- Manufacture uniform particles
- Compact particles into some aggregate form (e.g. pellets)

Other needs:
- Welding
- Sintering
- Injecting He or Na into cladding tube
Commercially available Equipment:

- Robots for Hot Cells
- Nuclear Manufacturing Equipment
- Camera Systems (CCD and GaAs)
- Wireless Communication Systems (GaAs)
Manufacturing Automation Modeling

Support of the following elements of the plant design process:

Plant sizing, e.g. placement of equipment, determination of hot cell dimensions.

Determination of the adequacy of current generation sensors and robotics

Possible R&D needs for development of new technologies.

Capability for extensive simulations of contingency and accident simulations, resulting in shortened duration of mock-up experiments and enhanced reliability of plant operations.
Fuel Fabrication Equipment

Wälischmiller Robot:
• Modular design
• All drives and Sensors in Base
• 30 to 240 kg Load capacity
Solid Modeling of Processes

The candidate fuel manufacturing processes are being modeled using the following simulation software tools:

- MSC Visual Nastran (Dynamics)
- ProEngineer (Solid Modeling)
- Matlab (Control System)
Solid Modeling of Processes

Interactive GUI process simulation: Two Robots Workcell. Created with Visual Nastran.
Solid Modeling of Processes

Simulation example

Interactive GUI process simulation: Grasping a Pellet. Created with Visual Nastran.
Fuel Fabrication Processes

Conclusion

Transmuter fuels will likely be manufactured in automated hot cell facilities.

Our project objective is the conceptual design of automated hot cell manufacturing facilities for various fuel types.

We are in the process of developing a comprehensive solid model of workcell robotics and control, which will allow detailed simulations of process dynamics.

The design options will be compared in terms of complexity, reliability, and cost.
Design and Evaluation of Processes for Transmuter Fuel Fabrication

End of Presentation