CASTING PRODUCT TERMINOLOGY

- **SKULL**
- **INTERMEDIATE PRODUCT**
- **AS-CAST PLATE**
- **HOT TOP**
- **FRAME**
- **AS-CAST COUPONS / INGOTS**
- **MULTI-PLATE CASTING**
- **MACHINED COUPON / INGOT**
COMMERCIAL VIABILITY

Qualitatively, the considerations for deciding whether or not to continue development of a particular optimized or alternative manufacturing process include:

- **Technical Merit** – Does the process produce parts that meet product specification requirements?
- **Reproducibility** – Does the process consistently produce high-quality parts?
- **Economics** – Does the process offer life-cycle cost savings over the baseline process after considering R&D and capital investments?
- **Scaling** – Does the process scale to full prototypic part dimensions?
- **Throughput** – Does the process lend itself to high-volume throughput without sacrificing its advantages?
- **Environment, Safety, and Health** – Is the process amenable to implementation under prototypic manufacturing ES&H protocols?
- **Quality Assurance** - Does the process lend itself to implementation in an NQA-1 manufacturing environment?
- **Schedule** – Can the process be developed and implemented in time to meet the Convert Program schedule for fuel down-selection?
- **Risk** – Does the process mitigate existing risks or introduce any new risks?
## Material Utilization

<table>
<thead>
<tr>
<th>Case</th>
<th>Baseline</th>
<th>Baseline</th>
<th>Custom coupons w/ machining</th>
<th>Custom coupons w/ machining</th>
<th>Custom coupons w/ skim cut</th>
<th>Custom coupons w/ skim cut</th>
<th>Custom coupons as-cast</th>
<th>Custom coupons as-cast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foils per coupon</td>
<td>1</td>
<td>Multiple</td>
<td>1</td>
<td>Multiple</td>
<td>1</td>
<td>Multiple</td>
<td>1</td>
<td>Multiple</td>
</tr>
<tr>
<td>Castings/Yr</td>
<td>1,603</td>
<td>1,125</td>
<td>581</td>
<td>573</td>
<td>858</td>
<td>855</td>
<td>914</td>
<td>917</td>
</tr>
<tr>
<td>235U Input (kg/yr)</td>
<td>4,907</td>
<td>2,255</td>
<td>1,779</td>
<td>1,754</td>
<td>2,625</td>
<td>2,616</td>
<td>2,799</td>
<td>2,805</td>
</tr>
<tr>
<td>LEU-Mo Annual</td>
<td>5.6%</td>
<td>7.9%</td>
<td>9.2%</td>
<td>9.3%</td>
<td>12.4%</td>
<td>12.4%</td>
<td>12.4%</td>
<td>12.3%</td>
</tr>
<tr>
<td>LEU-Mo Annual Yield</td>
<td>9.0%</td>
<td>12.1%</td>
<td>15.3%</td>
<td>15.6%</td>
<td>17.7%</td>
<td>17.8%</td>
<td>17.4%</td>
<td>17.3%</td>
</tr>
<tr>
<td>LEU-Mo Annual Yield</td>
<td>N/A</td>
<td>N/A</td>
<td>17.5%</td>
<td>17.5%</td>
<td>22.7%</td>
<td>23.3%</td>
<td>23.6%</td>
<td>23.6%</td>
</tr>
</tbody>
</table>

1 Assumes no material recycle
2 Assumes frame, machining chips, and non-conforming coupons are recycled
3 Assumes width limitation increased from 5” to 6”, shearing width allowance reduced from 1” to 0.1”, and two 4.25” x 8” ingots are produced per plate by sectioning horizontally, with material recycle

ANALYSIS OF PARAMETERS

MATERIAL LIMITATIONS AND IMPLICATIONS

• Amount of material required for steady-state operations will inherently increase
  • Current reactor HEU designs require 231 kg total U delivered
  • Current reactor LEU designs require ~2,100 kg total alloy delivered (~1,890 kg total U)
  • U working inventory will be greater to overcome lower process yields associated with monolithic fuel (previous slide)

• Cost implications
  • Processing cost per kg of LEU alloy likely to be less than or equal to HEU, but much more material is required
  • LEU manufacturing hours per plate (including foil rolling) are currently projected to be 20% (MITR) to 151% (HFIR) higher than current HEU manufacturing hours per plate

• Zr implications
  • Co-rolling produces foil scrap that has Zr, and the Zr must be removed prior to re-introducing the U into the working inventory
  • Removal of Zr from the fuel design results in a minimum reduction of 12.3% in operational steps and 7.4% in process hours
  • Significant capital (likely >$40M) will be required to establish and deploy a capability to recover U from Zr coated scrap
  • The annual operating costs to recover anticipated Zr coated scrap are estimated to be $15M or greater
  • Success of an alternative Zr application technology will positively impact the amount of Zr coated scrap that is produced
IMPURITY IMPLICATIONS

- Current material allocated to support LEU-Mo contains a high amount of impurities, particularly C
  - The role of C during processing is being investigated, but the role in performance is not clear
  - C specification will dictate how much material can be recycled
  - Alternatively, virgin or recovered material can be purified
    - Gettering (introduction of an additional element) or filtering
- Future technologies
  - Microwave melting has been dictated as the sole process for the Uranium Processing Facility
  - Lower C concentrations in U melts
  - May not be realized with U-Mo if an alloying step is required in the microwave
  - An increase in Si concentration has been consistently observed in development studies

HEU – 900 ppm C
DU – 100 ppm C
Casting – 25 ppm C

CASTING, INGOTS AND BARE ROLLING

• Impetus
  • Reduce cost by eliminating process steps (e.g. intermediate casting, cutting plates, machining coupons)
  • Improve yield and reduce scrap by rolling ingots directly to final coupon thickness, followed by more appropriate sizing methods

• Implications
  • A coupon cut from an as-rolled ingot will have very different microstructure than a coupon machined from an as-cast plate
  • Can a microstructure acceptable for foil processing and irradiation performance be produced by controlling appropriate process parameters?

• Status
  • LANL and Y-12 working together to optimize crucible design, mold design and casting parameters – improvements in each have been identified
  • PNNL work on interrupted rolling and microstructural characterization providing insight into rolling and homogenization parameters to produce a microstructure that is superior to as-cast
    • Grain size control
    • Uniform Mo distribution with no Mo-depleted zones along grain boundaries
    • Small, high aspect ratio, uniformly dispersed carbide precipitates along grain boundaries

• Outlook for MP-1
  • It appears likely that use of skim cut or as-cast ingot combined with bare rolling will be incorporated in the FY16 baseline fabrication process
**Optimized VIM Casting**

Original Design

"Horizontal" Mold Redesign with Warmer Casting Parameters

**Courtesy:** D. Dombrowski and R. Aikin, LANL

H. Longmire, Y-12
U-Mo Homogenization

800°C-4hrs
GS: 25-30 µm

800°C-8 hrs
GS: 25-30 µm

800°C-16 hrs
GS: 25-30 µm

800°C-24hrs
GS: 10-30 µm Seems bimodal

800°C-48hrs
GS: 25-40 µm

1000°C-16hrs
Larger than 100 µm
BARE ROLLING OF INGOTS

- 5 Processes – 3, 4 and 5 require alternate Zr application; 1 and 2 most developed
  1. Baseline – machine, hot roll-bond – low yield (<10%)
  2. Hot roll and hot roll bond – higher yield (<25%)
  3. Cold roll
  4. Hot and cold roll
  5. Hot and cold roll with intermediate anneals

With and without Homogenization

![Graph showing thickness and rolling direction]

- Slight Edge Cracking but contained

Courtesy: D. Paxton and C. Lavender, PNNL
BARRIER COATING ALTERNATIVES

• Impetus
  • Reduce cost by eliminating process steps (e.g. canning for hot rolling, separating Zr from U-Mo in scrap recycle)
  • Improve material utilization by reducing Zr-coated waste
  • Improve control of foil dimensions and mass, as well as minimize the amount of inspection technologies that must be developed for co-rolled foils

• Implications
  • Microstructure of co-rolled Zr barriers may be difficult to reproduce with alternate coating methods
  • Some alternative processes more suitable for thick (~25 μm) coatings, some for thin (<10 μm) coatings
  • Some alternative processes inherently coat foil edges, some do not
  • Minimal requirements for Zr barrier properties (i.e., thickness uniformity, grain size, porosity)

• Status
  • Based on progress to date, the two methods most likely to be mature enough in time to support the MP-1 fabrication campaign are plasma spray and electrochemical plating
    • Plasma spray demonstrated and characterized at LANL on DU-10Mo foils 4” x 24”
    • Electrochemical plating demonstrated at PNNL on surrogate substrate – characterization and demonstration/scale-up on DU-10Mo foils still to be done
    • Commercial vendors are in the process of being secured to scale-up each technology (equipment capable of coating 4” x 48” parts)

• Outlook for MP-1
  • Plasma spray coating will not coat foil edges due to fixturing and line-of-sight coating
  • Electrochemical plating will coat foil edges due to electrical field effects
ELECTROPLATING

Polymer Swagelok Fitting

Bellows

Reference

Gate Valve

Anode Lead

Alumina Insulator Cathode lead

Inconel Cover Tube

Zirconium Crucible

Roll Foil

De-Can

Clean

Cut

Debur

Surface Prep

Plate

Salt Removal / Clean

Courtesy: D. Paxton, G. Coffey, K. Meinhardt, and L. Pederson, PNNL
PLASMA SPRAY

Courtesy: D. Dombrowski and K. Hollis, LANL
CLAD BONDING OPTIMIZATION

• Impetus
  • Cost savings by eliminating process steps (e.g. HIP can assembly/disassembly)
  • Near net shape processing would minimize the amount of post HIP machining

• Implications
  • Characteristics of desirable foil-to-clad bond must be defined to compare alternative processes
  • Condition of bond around foil edges
  • Time at temperature (scale up and concern over transformation)

• Status
  • There is no active work on any alternative to the HIP process in FY15
  • An optimized HIP can design developed by LANL is being transferred to B&W
  • The “can-less” HIP option is also being pursued by LANL, but further development and technology transfer is required

• Outlook for MP-1
  • The optimized HIP can design will be used to bond multiple mini-foils within a 4” x 24” plate
  • The can-less HIP approach will require use of existing equipment at B&W not currently devoted to fabrication of research reactor fuel
OPTIMIZED HIP

Courtesy: D. Dombrowski and K. Clarke, LANL
CANLESS HIP OPTION

Note perturbations in S/L interface.

Courtesy: D. Dombrowski and T. Lienert, LANL
To quantify “commercial viability,” FFC has adopted a Technology Readiness Level approach with consideration in four categories that address the various qualitative requirements:

- **Technical maturity** (technical merit, reproducibility)
  - Definitions of TRLs derived from “US Department of Energy Technology Readiness Assessment Guide,” DOE G 413.3-4, 2009

- **Suitability for implementation** (scaling, throughput, ES&H, QA)
  - Definitions of MRLs derived from “DoD Manufacturing Readiness Level Deskbook,” v. 2.21, 2012

- **Economics** (life-cycle cost advantages for given R&D and capital investment)
  - Scoring based on estimated ratio of life-cycle cost impact to R&D and capital investment
  - Technologies at less than TRL-4 are scored in accordance with the TRL because the technology is not mature enough to make valid cost estimates

- **Lead time for deployment** (schedule, risk)
  - Scoring based complexity of introducing the technology into existing production facilities (i.e. Y-12 and B&W NOG) including footprint, infrastructure, other customer needs, manufacturing culture, etc...
  - Technologies at less than TRL-4 are scored in accordance with the TRL, as with economics
### Downselection Methodology

<table>
<thead>
<tr>
<th>Level</th>
<th>Technology Readiness Level</th>
<th>Manufacturing Readiness Level</th>
<th>Economics</th>
<th>Schedule</th>
<th>Example FFC Campaign</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Basic principles observed and reported</td>
<td>Basic mfg implications identified</td>
<td>1</td>
<td>1</td>
<td>Feasibility Studies</td>
</tr>
<tr>
<td>2</td>
<td>Technology concept formulated</td>
<td>Mfg concepts identified</td>
<td>2</td>
<td>2</td>
<td>Small-scale demonstration under relevant conditions</td>
</tr>
<tr>
<td>3</td>
<td>Critical characteristic proof of concept</td>
<td>Mfg proof of concept</td>
<td>3</td>
<td>3</td>
<td>Scale-up demonstration (e.g. minimum 24” foil)</td>
</tr>
<tr>
<td>4</td>
<td>Validation in laboratory environment</td>
<td>Capability to produce components in lab environment</td>
<td>Low</td>
<td>Extremely complex</td>
<td>MP-1</td>
</tr>
<tr>
<td>5</td>
<td>Laboratory-scale validation in relevant environment</td>
<td>Capability to produce prototypical components in production-relevant environment</td>
<td>Fair</td>
<td>Very complex</td>
<td>FSP-1/MP-2</td>
</tr>
<tr>
<td>6</td>
<td>Pilot-scale validation in relevant environment</td>
<td>Capability to produce prototypical system in production-relevant environment</td>
<td>High</td>
<td>Average complexity</td>
<td>ET-1/DDE</td>
</tr>
<tr>
<td>7</td>
<td>Full-scale demonstration in relevant environment</td>
<td>Capability to produce prototypical system in production environment; ready for pilot line production</td>
<td>Very High</td>
<td>Less than average complexity</td>
<td>ET-2</td>
</tr>
<tr>
<td>8</td>
<td>Actual system completed and qualified</td>
<td>Pilot line capability demonstrated; ready for low-rate initial production</td>
<td>Extremely high</td>
<td>Relatively simple</td>
<td>Initial conversion core</td>
</tr>
<tr>
<td>9</td>
<td>Actual system operated over full range of expected conditions</td>
<td>Low-rate production demonstrated</td>
<td>Baseline</td>
<td>Baseline</td>
<td>Steady-state conversion cores</td>
</tr>
</tbody>
</table>
PLANS/PATH FORWARD

• Advancement of worthy technologies to TRL-4
• Facilitate transfer of technology from laboratories to production organizations
• Start-up and qualification of pilot line equipment and processes at B&W
• Prepare and Implement Manufacturing and Quality Plans for MP-1
• Fabrication of MP-1 experiment products
• Fuel Fabrication Process Downselect

2014-2016
2015-2017
2020
BACKUP SLIDES
OVERVIEW OF PILLAR ACTIVITY

Scope

• FFC focused on process development consistent with acceptable fuel performance

• Process optimization to reduce fuel manufacturing costs and improve HEU utilization

Approach

• Key processing issues identified and being addressed

• Continue to develop process improvements and alternatives

• Some process alternatives have been or will be discontinued

Integration with other Pillars