PNNL-22528, Rev. 1

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# Fuel Fabrication Capability Research and Development Plan

## Global Threat Reduction Initiative – Convert Program

**April 2014**

DJ Senor DE Burkes

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Pacific Northwest National Laboratory
Richland, Washington 99352

# Summary

The purpose of this document is to provide a comprehensive review of the mission of the Fuel Fabrication Capability (FFC) within the Global Threat Reduction Initiative Convert Program, along with research and development (R&D) needs that have been identified as necessary to ensuring mission success. The design and fabrication of successful nuclear fuels must be closely linked endeavors. Therefore, the overriding motivation behind the FFC R&D program described in this plan is to foster closer integration between fuel design and fabrication to reduce programmatic risk by ensuring the following:

- The manufacturing process consistently produces fuel with acceptable quality (i.e., meets or exceeds design requirements)
- The sensitivity of material properties and characteristics to manufacturing process parameters is clearly understood so adequate process specifications can be defined
- Fuel product specifications are realistic and achievable using the selected manufacturing methods
- A better linkage between the effect of process parameters on fuel performance, to ensure that changes or variability in manufacturing does not have an adverse effect on irradiation behavior.

These motivating factors are all interrelated, and progress addressing one will aid understanding of the others. The FFC R&D needs fall into two principal categories, 1) baseline process optimization, to refine the existing fabrication technologies, and 2) manufacturing process alternatives, to evaluate new fabrication technologies that could provide improvements in quality, repeatability, material utilization, or cost. The FFC R&D Plan examines efforts currently under way in regard to coupon, foil, plate, and fuel element manufacturing, and provides recommendations for a number of R&D topics that are of high priority but not currently funded (i.e., knowledge gaps). The plan ties all FFC R&D efforts into a unified vision that supports the overall Convert Program schedule in general, and the fabrication schedule leading up to the MP-1 and FSP-1 irradiation experiments specifically.

The FFC R&D Plan describes qualitative considerations to guide development of optimized or alternative manufacturing processes:

- Technical Merit – Does the process produce parts that meet product specification requirements?
- Reproducibility – Does the process consistently produce high-quality parts?
- 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 – Can the process be implemented effectively in a uranium production facility regulated by the U.S. Department of Energy and/or the Nuclear Regulatory Commission?
- Quality Assurance – Does the process lend itself to implementation in an NQA-1 manufacturing environment?

- Economics – Does the process offer lifecycle (not just capital) cost savings over the baseline process, including considerations of efficient use of uranium feedstock and scrap recycle?
- 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 new risks?

These qualitative criteria are grouped in the following fashion to produce a quantitative estimate of process maturity using established methodologies to support fabrication technology down-selection in advance of the MP-1 manufacturing campaign:

- Technical Maturity (Technical Merit, Reproducibility) – Defined by Technology Readiness Level derived from "U.S. Department of Energy Technology Readiness Assessment Guide," and "U.S. High Performance Research Reactor Project Technology Readiness Assessment Plan"
- Suitability for Implementation (Scaling, Throughput, QA, ES&H) – Defined by Manufacturing Readiness Level derived from "DoD Manufacturing Readiness Level Deskbook"
- Economics – Scoring based on estimated ratio of lifecycle cost impact to R&D plus capital cost investment
- Deployment Lead Time (Schedule, Risk) – Scoring based on the complexity of introducing the technology into existing production facilities including footprint, infrastructure, other customer needs, and manufacturing culture.

The fabrication technology decision gates and down-selection logic and schedules are tied to the schedule for fabricating the MP-1 fuel plates, which will provide the necessary data to make a final fuel fabrication process down-selection. Because of the short turnaround between MP-1 and the follow-on FSP-1 and MP-2 experiments, the suite of specimen types that will be available for MP-1 will be the same as those available for FSP-1 and MP-2. Therefore, the only opportunity to explore parameter space and alternative processing is between now and 2016 when the candidate processes are down-selected in preparation for the MP-1, FSP-1, and MP-2 plate manufacturing campaigns.

A number of key risks identified by the FFC are discussed in this plan, with recommended mitigating actions for those activities within FFC, and identification of risks that are impacted by activities in other areas of the Convert Program.

The R&D Plan does not include discussion of FFC initiatives related to production-scale manufacturing of fuel (e.g., establishment of the Pilot Line Production Facility), rather, the goal of this plan is to document the R&D activities needed ultimately to enable high-quality and cost-effective production of the fuel by the commercial fuel fabricator. The intent is for this R&D Plan to be a living document that will be reviewed and updated on a regular basis (e.g., annually) to ensure that FFC R&D activities remain properly aligned to the needs of the Convert Program. This version of the R&D Plan represents the first annual review and revision.

# Acronyms and Abbreviations

| | |
|---|---|
| ATR | Advanced Test Reactor |
| ATR-C | ATR critical assembly |
| B&W | Babcock & Wilcox |
| DOE | U.S. Department of Energy |
| DU | depleted uranium |
| DU-Mo | depleted uranium-molybdenum alloy |
| EBSD | electron backscatter diffraction |
| EDS | energy dispersive x-ray spectroscopy |
| EPJ | energetic pulse joining |
| ESD | electro-spark deposition |
| EU | enriched uranium |
| FD | Fuel Development pillar |
| FFC | Fuel Fabrication Capability pillar |
| FLA-ICP-MS | femtosecond laser ablation inductively-coupled plasma mass spectrometry |
| FY | fiscal year |
| GTRI | Global Threat Reduction Initiative |
| HEU | highly enriched uranium |
| HFIR | High Flux Isotope Reactor |
| HIP | hot isostatic press |
| HPRR | high performance research reactor |
| ICP-MS | inductively-coupled plasma mass spectrometry |
| ICP-OES | inductively-coupled plasma optical emission spectrometry |
| INL | Idaho National Laboratory |
| LEU | low enriched uranium |
| LEU-Mo | low enriched uranium-molybdenum alloy |
| MAQP | manufacturing and quality plan |
| MITR | Massachusetts Institute of Technology Reactor |
| Mo | molybdenum |
| MURR | Missouri University Research Reactor |
| NBSR | National Bureau of Standards Reactor |
| NNSA | National Nuclear Security Administration |
| PM | powder metallurgy |
| PNNL | Pacific Northwest National Laboratory |
| PVD | physical vapor deposition |
| QA | quality assurance |
| QRL | quality rigor level |

| | |
|---|---|
| R&D | research and development |
| RC | Reactor Conversion pillar |
| RERTR | Reduced Enrichment Research and Test Reactor |
| SEM | scanning electron microscopy |
| U-Mo | uranium-molybdenum alloy |
| UMoF | uranium-molybdenum alloy feedstock |
| UPF | Uranium Processing Facility |
| UT | ultrasonic testing |
| VAR | vacuum arc remelting |
| VIM | vacuum induction melting |
| WBS | work breakdown structure |
| XRF | x-ray fluorescence |

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# 1.0 Introduction

The purpose of this document is to provide a comprehensive review of the mission of the Fuel Fabrication Capability (FFC) within the Global Threat Reduction Initiative (GTRI) Convert Program, along with research and development (R&D) needs that have been identified as necessary to ensuring mission success. In Section 1.0, the role of the FFC within the Convert Program is outlined, as are relevant linkages to other aspects of the Program including Fuel Development (FD) and Reactor Conversion (RC). The motivation behind each of the identified R&D needs and the objectives of the R&D program is described in Section 2.0. Primary drivers include the need to 1) define a repeatable manufacturing process, 2) relate process parameters to material properties and characteristics, 3) contribute to definition of the product and process specifications, and 4) integrate FFC and FD R&D activities to focus on relevant characteristics and avoid duplication of effort. Descriptions of the individual activities planned to satisfy the R&D objectives are included in Sections 3.0, 4.0, 5.0, and 6.0 for coupon (uranium-molybdenum (U-Mo) fuel meat), foil (U-Mo fuel with diffusion barrier), plate (clad fuel), and element (multiple plate assemblies) manufacturing process development, respectively. Each of these four sections considers two principal categories of R&D, 1) baseline process optimization, to refine the existing fabrication technology, and 2) process alternatives, to evaluate new fabrication technology that could provide improvements in quality, repeatability, or cost. Section 7.0 describes a number of cross-cutting activities necessary for FFC to advance the state of the art in fuel fabrication. Section 8.0 discusses other considerations associated with FFC R&D efforts, including the criteria used for assessing commercial viability of manufacturing process, the methodology used for making technology down-selection decisions, quality assurance, and schedule. Section 9.0 describes the logic and plan for critical decision points and their relationship to manufacturing and process development needs, a listing of the manufacturing technologies that have been proposed for inclusion in the MP-1 irradiation experiment based on their current and projected state of maturity and potential for impacting fuel performance, a listing of knowledge gaps that are not currently being addressed within approved FFC scope, and a summary of risks that could impact FFC execution of the R&D Plan.

The intent is for this plan to be a living document that will be reviewed and updated on a regular basis (e.g., annually) to ensure that FFC R&D activities remain properly aligned to the needs of the Convert Program. This version of the FFC R&D Plan represents the first annual review and revision. The R&D Plan does not include FFC initiatives related to production-scale manufacturing of fuel (e.g., procurement of equipment, production contracts, etc.); rather, the goal of this plan is to document the R&D activities needed to enable high-quality and cost-effective production of the fuel by the commercial fuel fabricator.

## 1.1 Mission of the GTRI Convert Program

Operating within the U.S. Department of Energy (DOE)/National Nuclear Security Administration (NNSA), the GTRI mission is to reduce and protect vulnerable nuclear and radiological material located at civilian sites worldwide. In order to achieve this mission, GTRI has three pillars that provide a comprehensive approach to achieving this mission.

1. Convert research reactors and radioisotope production facilities from the use of highly enriched uranium (HEU) to low enriched uranium (LEU) fuel

2. Remove and facilitate disposition of excess nuclear and radiological materials
3. Protect high priority nuclear and radiological materials from theft and sabotage.

In support of the first pillar, the GTRI Reactor Conversion program (referred to in this document as the Convert Program) works with civilian research and test reactors operating with HEU fuel around the world. While NNSA provides enhanced physical protection systems at research and test reactors, converting the fuel used in these reactors to LEU permanently secures the site by removing the threat posed by continued HEU operations. As the manufacture, shipment and storage of the HEU fuel for these reactors can present an opportunity for terrorists to acquire the HEU they seek, eliminating the use of HEU in civilian research and test reactors by verifying the shutdown or conversion of these reactors to an LEU-based fuel provides permanent threat reduction (NNSA 2013b).

A key component of the GTRI Convert Program is conversion from HEU to LEU of six U.S. high performance research reactors (HPRRs) including the Advanced Test Reactor (ATR), the ATR critical assembly (ATR-C), the High Flux Isotope Reactor (HFIR), the National Bureau of Standards Reactor (NBSR), the Missouri University Research Reactor (MURR), and the Massachusetts Institute of Technology Reactor (MITR). The driver for conversion of these six reactors within the U.S. is to lead by example and influence international reactor operators to convert to a fuel that is less attractive for proliferators from a safeguards point of view, but effectively maintains the core mission and needs of the reactor. The scope described in this document is associated with fabrication of the LEU fuel for the six U.S. HPRRs.

## 1.2 Role of the Fuel Fabrication Capability

The U.S. HPRR portion of the Convert Program consists of three principal activities, referred to as pillars. These include FD, FFC, and RC. The overall objective of the FFC is to establish a cost-effective and efficient manufacturing process that can be implemented by a commercial entity to provide LEU fuel to the U.S. HPRRs after conversion from their existing HEU fuel. The baseline LEU fuel and fuel fabrication process was developed by the FD pillar. It consists of a plate-type fuel with a monolithic U-10Mo alloy foil bonded on two sides with a Zr diffusion barrier, and clad within an Al-base alloy. Ultimately, the RC pillar will employ the commercial product developed by FFC in conversion of the six U.S. HPRRs from their existing HEU fuel to the new LEU fuel.

Specifically, the FFC will:

- Transfer fabrication knowledge and processes to a commercial fuel fabricator
- Establish LEU manufacturing capability to support the conversion of the six U.S. HPRRs
- Demonstrate cost-effective and efficient production of developmental and production LEU fuel
- Procure initial reactor loadings to support conversion
- Fabricate demonstration and experiment fuel products as requested by the program.

The scope described in this R&D Plan is necessary to ensure that FFC can meet these objectives on a schedule and with product quality consistent with overall programmatic guidance. Technical challenges, budget limitations, and schedule disruptions will increase the risk that the FFC objectives cannot be met on the programmatic timeline described in Section 9.0. Further, it is important to note that this R&D Plan

does not address potential changes in the fuel manufacturing process to address irradiation performance issues. Irradiation testing and fuel performance analysis are the responsibility of the FD pillar. If irradiation testing or fuel performance modeling suggests that changes are needed to the fuel manufacturing process, changes to the R&D program outlined in this plan will be required. Such changes also have the potential to increase the risk that the FFC objectives cannot be met on the programmatic timeline.

The R&D activities described in this document are executed by a variety of organizations including national laboratories, universities, and commercial entities, as shown in Figure 1.1. Specifically, work is currently being conducted at Los Alamos National Laboratory, Idaho National Laboratory (INL), Pacific Northwest National Laboratory (PNNL), Y-12 National Security Complex, Babcock & Wilcox (B&W) Nuclear Operations Group, Manufacturing Sciences Corporation, Aerojet, and selected universities. While FFC management resides at PNNL, the FFC is not a PNNL program. It is a national effort within the overall Convert Program. Accordingly, work is apportioned based on considerations of technical capabilities, available capacity, and overall cost and schedule. Thus, the division of work described in this document is an optimization of the available resources to achieve the FFC objectives described above. If events warrant, scope may be moved from one organization to another, and if new scope is warranted, particularly if it is outside the envelope of current technologies, new organizations not currently involved may be approached to contribute.

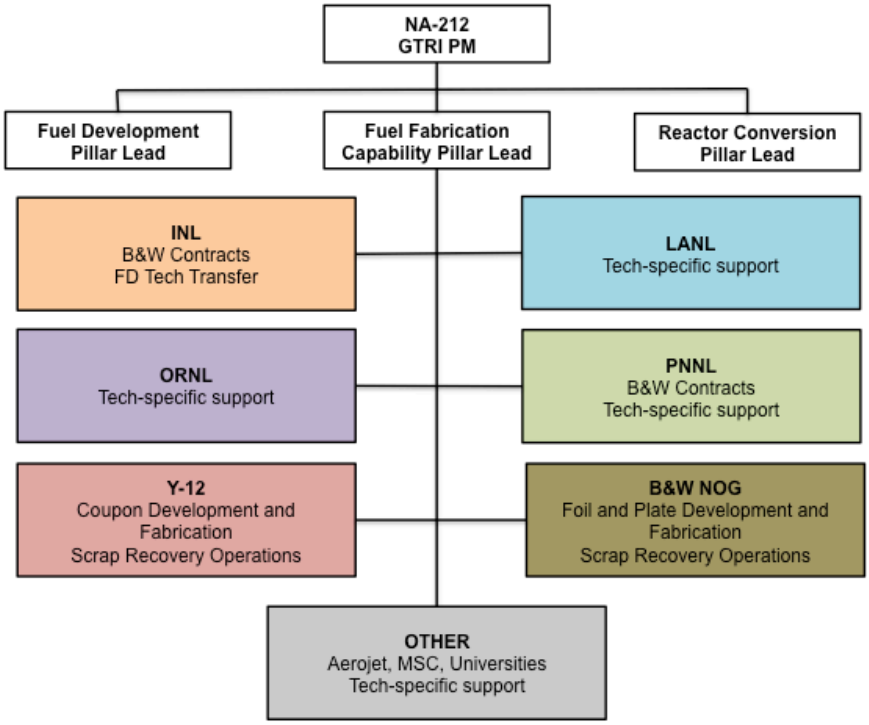


**Figure 1.1**. FFC Organizational Structure and Responsibilities

## 1.3 Fuel Fabrication Process Development to Date

The five U.S. HPRRs and one critical assembly addressed by the Convert Program currently utilize dispersion fuel consisting of HEU-containing particulate distributed throughout an Al-base alloy matrix.

The material form of the dispersion particulate varies, including $UAl_x$ for ATR and ATR-C (Gerstner et al. 2010), MITR (Newton 2011), MURR (Foyto et al. 2012), $U_3O_8$ for HFIR (Primm et al. 2006), and NBSR (Hanson and Diamond 2011). While dispersion fuel forms, including $U_3Si_2$ and U-Mo alloy dispersions in an Al-base alloy matrix, have been demonstrated for low power research reactors (<5 $MW_t$), the U density of dispersion fuels may not be adequate to preserve acceptable performance of HPRRs. Typical U density of dispersion fuels is 2.3 $g/cm^3$ for $UAl_x$, 3.2 $g/cm^3$ for $U_3O_8$, 6.0 $g/cm^3$ for $U_3Si_2$ (note that $U_3Si_2$ was only qualified for a density up to 4.8 $g/cm^3$), and 8.5 $g/cm^3$ for U-10Mo (Wachs et al. 2008). Therefore, development of monolithic U-Mo alloy fuels was undertaken starting in 2004, drawing on experience with metallic fuels in general and U-Mo alloy fuels in particular dating back to the 1950s (e.g., Fox et al. 1958, Shoudy et al. 1963). The U density of U-10Mo monolithic fuel is 15.3 $g/cm^3$ (Wachs et al. 2008), which has the potential to provide sufficient fissile material at less than 20% enrichment in $^{235}U$ to preserve the performance exhibited by the U.S. HPRRs currently using highly-enriched dispersion fuel.

The first irradiation experiments of U-10Mo monolithic fuel in a "mini-plate" configuration (1 in. x 4 in. x 0.055 in.) were conducted at ATR in 2005 under the Reduced Enrichment Research and Test Reactor (RERTR) program. Seven insertions were conducted over the next few years as part of the RERTR -6, -7A, -8, -9A, -9B, -10A, and -10B experiments at ATR. These were followed by irradiation experiments starting in 2008 that included larger fuel plates (2.21 in. x 22.5 in. x 0.05 in.) and were designated AFIP-2 and -3. These tests were conducted over a range of peak fuel temperatures, average fission density, average fission rate, and average heat flux to evaluate the irradiation behavior of the fuel over a variety of HPRR-relevant operating conditions. The tests evaluated irradiation performance of alloy compositions ranging from 7 wt% to 12 wt% molybdenum (Mo), a range of fuel meat to cladding thickness ratios, different foil configurations with and without diffusion barriers, Zr-base alloy cladding, and a variety of fabrication methods. The fabrication methods were developed in a laboratory setting to produce the RERTR- and AFIP-size plates and included variations in coupon reduction schedules, different diffusion barrier materials and application methods, variations in foil reduction schedules, and different fuel/cladding bonding methods. Based on the in-reactor and post-irradiation examination results from these experiments, the baseline fuel form and associated baseline fuel fabrication processes were identified (Robinson et al. 2009, Robinson et al. 2013). The irradiation experiments conducted before the down-selection of the final fuel form and fabrication processes did not include various HPRR-specific features such as contoured fuel meat or integral burnable absorbers. Subsequent irradiation experiments, including RERTR-12 and AFIP-4, -6, -6 MKII, and -7 were conducted after the down-selection. Several of these experiments experienced failures during irradiation; some were related to fuel performance while others were not. In addition, certain irradiation performance issues were identified after the RERTR-12 and AFIP-4 experiments. (PIE has not been completed on the AFIP-6, -6 MKII, or -7 experiments to date.) Despite these issues, the baseline fuel form and associated fabrication processes identified in Robinson et al. (2009) were provided to FFC for commercial technology transfer and scale-up to prototypic dimensions and throughput.

The FFC was initially created in 2007 to identify appropriate commercial entities for manufacturing of U-10Mo monolithic fuel with prototypic dimensions and throughput (assuming conversion of all six U.S. HPRRs using the same fuel form). This assessment was completed in 2009, and FFC then started working toward transferring the fuel fabrication technology developed by FD at the laboratory scale to a commercial manufacturer. Scoping studies were conducted to determine the feasibility of scaling the FD fabrication process to appropriate size and throughput to produce the four key stages of the

fuel: 1) U-10Mo fuel meat (coupons), 2) Zr diffusion barrier application to the fuel meat (foils), 3) bonding of the foils to the cladding (plates), and 4) assembly of plates into fuel elements. By 2011, the baseline processes for producing the base fuel form were fully defined (Moore and Marshall 2010; Park et al. 2010) and subsequent work focused on establishing a limited production facility to demonstrate prototypic-scale manufacturing of the fuel. More recently, the need became apparent for optimization of the baseline processes as well as consideration of alternative processes where they offer potentially significant product quality, cost, or throughput advantages. Consequently, in 2012, FFC embarked on an applied R&D program to evaluate fabrication parameters and their effect on manufacturing efficiency and product quality. In addition, FFC started considering the work that will be necessary to fully define acceptable manufacturing processes for "complex" fuel to include U.S. HPRR-specific features such as contoured fuel meat and integral burnable absorbers. The current FFC R&D effort described by this plan thoroughly addresses optimization and alternatives for "base" fuel manufacturing (i.e., flat fuel meat and no integral burnable absorbers), but includes only limited scope focused on "complex" fuel manufacturing. Concurrent with FFC R&D activities, the RC pillar is refining reactor-specific fuel element designs, and it appears that some reactor-specific features may not be necessary (e.g., cladding fins on MITR fuel plates, integral burnable absorbers in ATR fuel) so that "base" fuel applies to more of the candidate reactors than previously thought (Bergeron et al. 2013, Chase 2013).

# 2.0 Motivation and Objectives of FFC Research and Development

The overriding motivation for conducting the R&D activities described in this plan is the need to ensure the following:

- The manufacturing process consistently produces fuel with acceptable quality (i.e., meets or exceeds design requirements)
- The sensitivity of material properties and characteristics to manufacturing process parameters is clearly understood so adequate process specifications can be defined
- Fuel product specifications are realistic and achievable using the selected manufacturing methods
- A better linkage between the effect of process parameters on fuel performance, to ensure that changes or variability in manufacturing does not have an adverse effect on irradiation behavior.

These motivating factors are all interrelated, and progress addressing one will aid understanding of the others. The following sections expand on these motivating factors, define the specific objectives of the FFC R&D program, and explain how the FFC R&D program will reduce overall programmatic risk in these areas.

## 2.1 Lack of a Well-defined, Repeatable Process

Currently, the fuel fabrication process is not well defined. While manufacturing methods have been identified for each step in fuel fabrication, details associated with those processes have not been defined. For example, cold rolling has been identified as the method of choice for reducing the coupons to the desired thickness, primarily because of the ability to achieve specified dimensional tolerances (Meyer et al. 2012). However, acceptable degrees of cold work have not been specifically defined, and a range will likely be required due to differences in fuel meat thickness in plates for different reactors (and between plates in the same fuel element for some of the reactors). In addition, there is evidence that different microstructures can result for the same overall reduction depending on the specific reduction schedule. Aggressive early reduction steps followed by more moderate reduction steps can produce a different microstructure than a greater number of moderate reduction steps (Meyer et al. 2012). To ensure a truly repeatable fabrication process that meets all applicable design requirements, it is necessary to fully define each aspect of the process. In this way, unintended consequences resulting from operator-specific actions are avoided and yield is maximized. The ultimate goal in defining the fabrication process is the development of a Manufacturing and Quality Plan (MAQP) that provides a basis for process definition, review, and acceptance. Many of the FFC R&D activities described in this plan will inform the development of MAQPs that will meet the needs of the designer, fabricator, quality assurance organization, and ultimately, the reactor customer and regulator.

## 2.2 Uncertain Relationship Between Process Parameters and Material Characteristics

Currently, there is incomplete understanding of the relationship between manufacturing process parameters and resulting material properties and characteristics. By defining the process as described in

Section 2.1, the parameter space for each manufacturing method will be bounded and the range of acceptable process parameter variability will be identified. Developing a thorough understanding of the impact of process parameter variation within this operational envelope is required to avoid locking the manufacturer into a very narrow range of acceptable process parameters that could impact product quality and yield. By understanding the sensitivity of material properties and characteristics (e.g., grain size and orientation, or carbide precipitate size and distribution) to changes in process parameters, the opportunity exists to relax specifications where appropriate and optimize the manufacturing process to achieve improved product quality and yield. In addition, understanding the relationship between processing and properties, even outside the range of process specifications, allows the designer to more easily disposition non-conformances resulting from unexpected process variations. Without this knowledge, the designer is forced to reject any product resulting from out-of-tolerance process parameters because of the uncertainty on product acceptability for its intended purpose. The goal of the FFC R&D activities addressing this issue is to generate models that can be used to refine process specifications.

## 2.3 Need for Clearly-Defined and Value-added Product Specifications

Currently, the fuel product specification is evolving under the auspices of FD and the Design Authority. The product specification is intended to provide guidance for FFC development of process specifications. The focus for the designer should be on properties and characteristics that can be measured in the fuel product in either intermediate or final condition. The fuel designer should have a clear understanding of the relationship between these properties and characteristics on irradiation performance. By developing appropriate product specifications, the designer can then ensure that fresh fuel exhibits the properties and characteristics that are known to demonstrate acceptable irradiation performance. By developing the understanding described in Section 2.2, the fabricator can ensure that appropriate process parameters are used during fabrication to provide the properties and characteristics in the product desired by the designer. In addition, the designer will have confidence that the product specification is realistic and can be achieved using the manufacturing methods defined and specified by the fabricator. Thus, the ultimate goal for many of the FFC R&D activities described in this plan is to provide feedback to FD regarding the feasibility of achieving the fuel product specification requirements.

## 2.4 Relationship between FFC and FD Research and Development Plans

Design and manufacturing of any product are very closely linked, and the development of product specifications, process specifications, MAQPs, and other related documents is an iterative process based on the observed performance of the product in question. Therefore, the final motivation behind the FFC R&D program described in this plan is to foster closer integration between FFC and FD efforts to reduce programmatic risk by ensuring common goals and shared vision.

A schematic representation of the iterative nature of understanding the relationship among processing, properties, and performance is shown in Figure 2.1, specifically for U.S. HPRR fuel. Fabrication process development studies should provide the understanding to connect the relationship between manufacturing processes and properties via fabrication process modeling. Similarly, an irradiation testing campaign should provide the understanding to connect the relationship between properties and performance in the reactor via fuel performance modeling. Finally, there should be a feedback loop that relates in-reactor performance back to manufacturing processes so that the right parameters are being controlled during

fabrication to ensure satisfactory performance. This feedback is provided via the fuel product specification. Figure 2.1 shows the areas of responsibility of both FFC and FD, and the interfaces between the two. While the feedback from performance to processing is captured in a relatively straightforward way by the requirements in the fuel product specification, the interface between properties relevant to fabrication and properties relevant to performance is less defined. It is this interface that the FFC R&D activities are designed to strengthen. The output of fabrication process development studies provides input to FD as a starting point for assessing irradiation performance. Similarly, the output of FD fuel performance modeling provides input to FFC in terms of desirable properties and characteristics from a performance perspective. This information then provides input to fabrication process models thereby closing the loop and ensuring that manufacturing processes can produce the properties of interest for fuel performance.

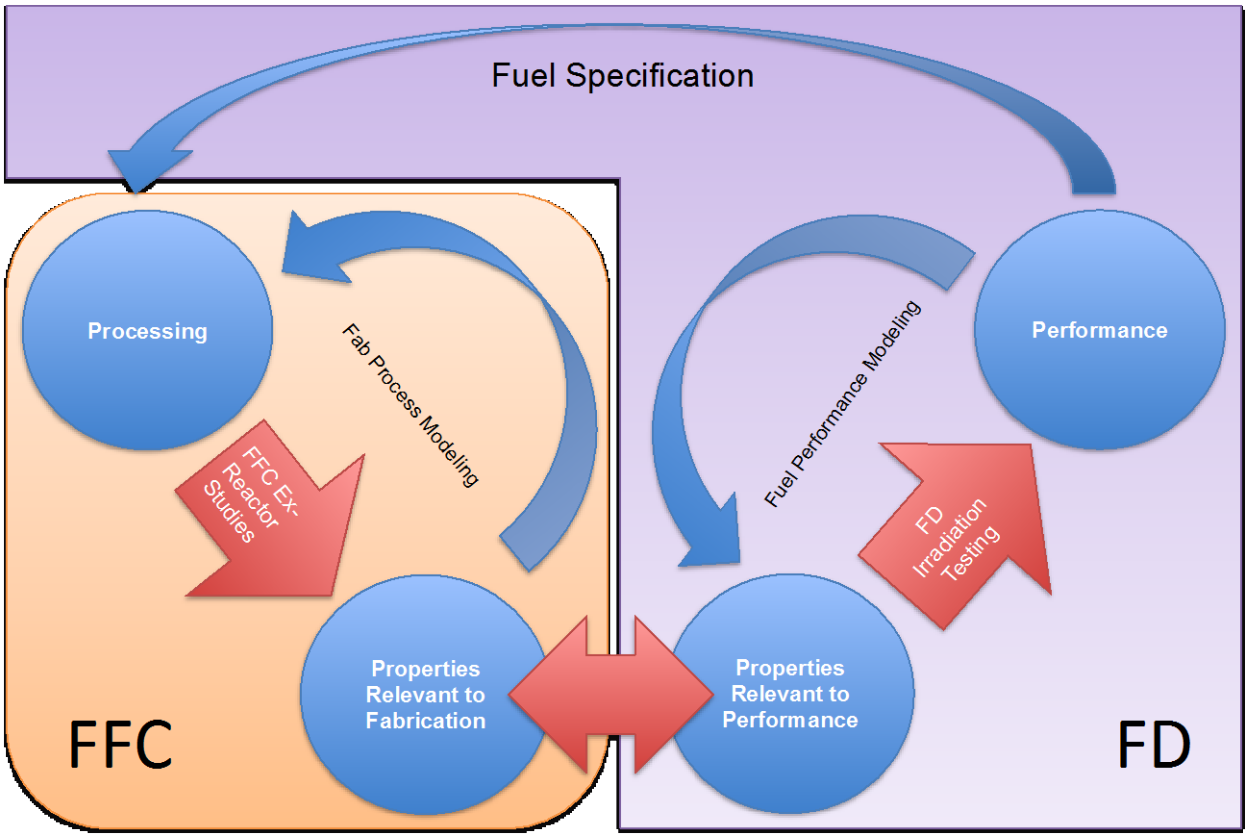


**Figure 2.1**. Schematic Representation of the Ideal Relationships in the Understanding of Processing, Properties, and Performance

Ultimately, the knowledge gained from the activities shown in Figure 2.1 must be incorporated in reactor-specific fuel designs, where the unique feature of each U.S. HPRR must be taken into account. However, fuel performance is only one part of the picture. Equally important is neutronic, thermal-hydraulic, and structural performance. Each of these four performance aspects interact with one another, so the relationships among them must be clearly understood and well integrated (i.e., the success of all depends on the success of each). Figure 2.2 is a schematic representation of the relationship among fuel performance (i.e., Figure 2.1) and the other aspects of reactor-specific fuel design. Each performance aspect, including fuel performance, must be successful if U.S. HPRR reactor conversions are going to be successful.

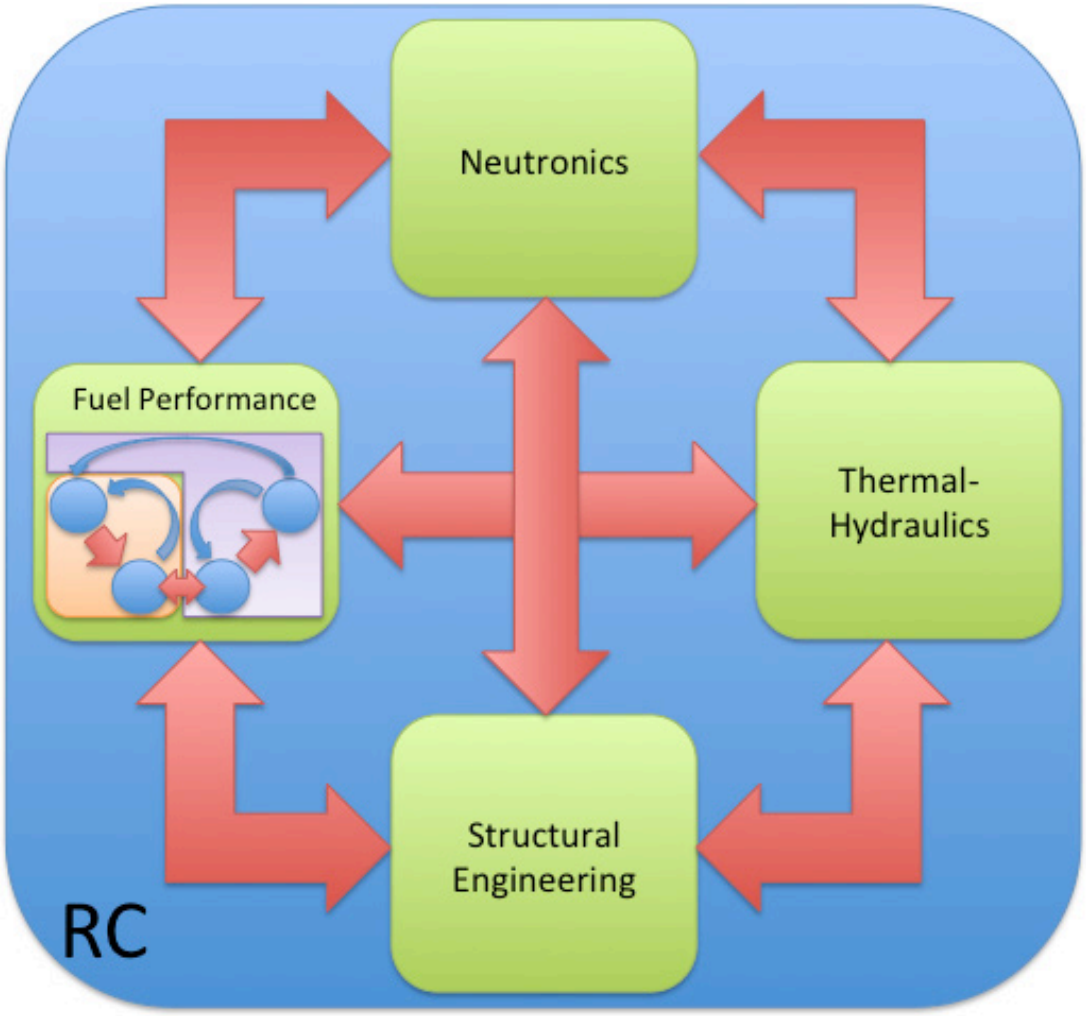


**Figure 2.2**. Schematic Representation of Relationships among the Four Principal Aspects of Reactor-Specific Fuel Design

By embarking on a closely-linked and integrated series of well-planned, disciplined R&D activities, FFC and FD can ensure that fuel fabrication and performance are well understood to support progress toward the common goal of producing effective LEU research reactor fuel at an affordable cost and in a sustainable manner. This will allow RC to execute reactor-specific fuel designs by taking into consideration all relevant fuel, neutronics, thermal-hydraulics, and structural performance issues to ensure successful reactor conversions. The R&D program described by this plan represents the FFC contribution to establishing an integrated Convert Program R&D effort ultimately leading to development and deployment of LEU research reactor fuel.

# 3.0 Coupon Manufacturing Research and Development

For the purposes of this document, coupon manufacturing encompasses all activities from U and Mo feedstock preparation through final surface finishing of the U-10Mo coupon (fuel meat). This portion of the baseline manufacturing process is shown in Figure 3.1, and the R&D activities described in this section are shown in Figure 3.2. The following subsections describe R&D efforts that are needed to optimize the baseline process as well as process alternatives that may offer improvements in quality, repeatability or cost. The numbers in parentheses following some of the subsection headings indicate the Convert Program work breakdown structure (WBS) under which the work is planned. The descriptions in the subsections below provide high-level summaries of past progress, current work scope, and future plans for each R&D activity. For more detail on specific work scope, please refer to the corresponding Task Work Plan for that WBS. If a subsection does not have a WBS associated with it, it is because this work is not currently included in the Convert Program planning basis. In these cases, inclusion in this document forms the basis for a recommendation to include the work in future FFC scope planning for the reasons described in the subsections below.

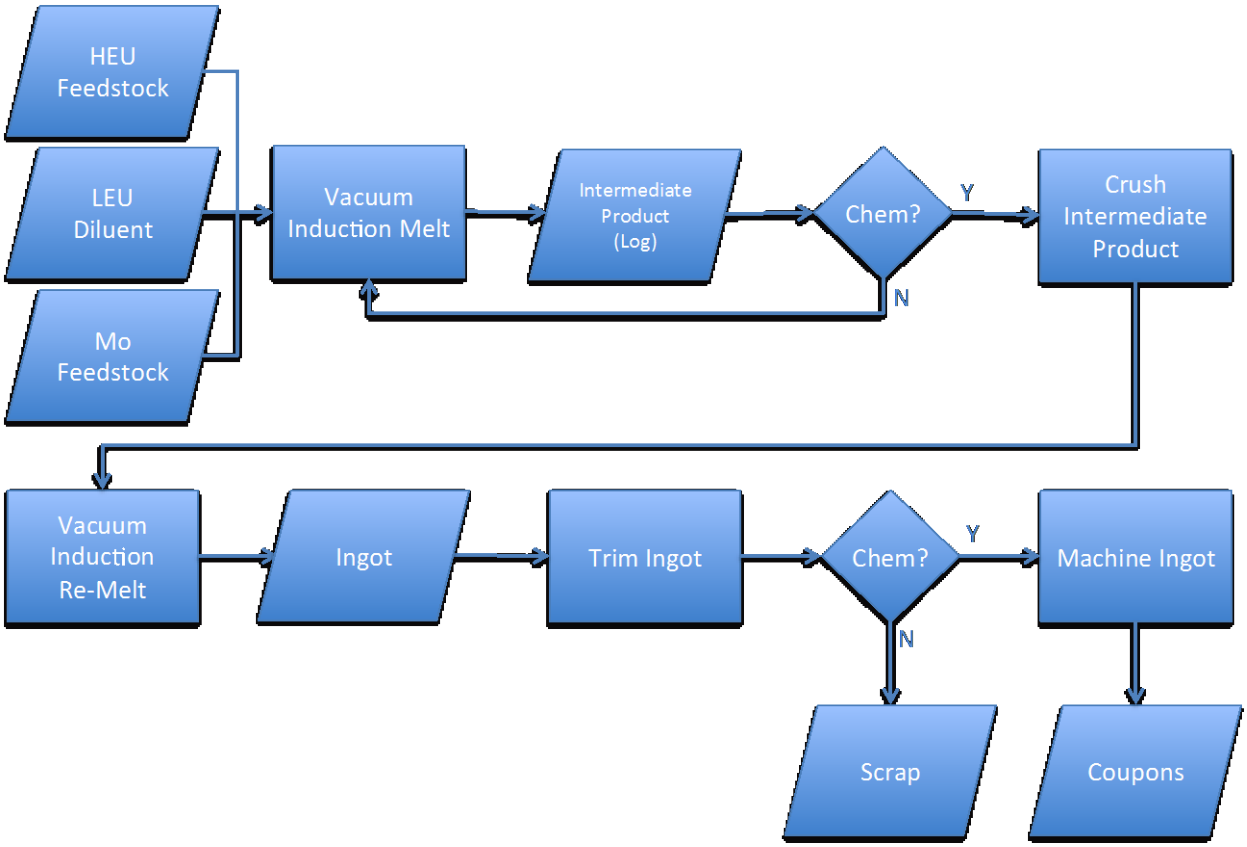


**Figure 3.1**. Simplified Flow Sheet for Current Baseline Coupon Manufacturing Process

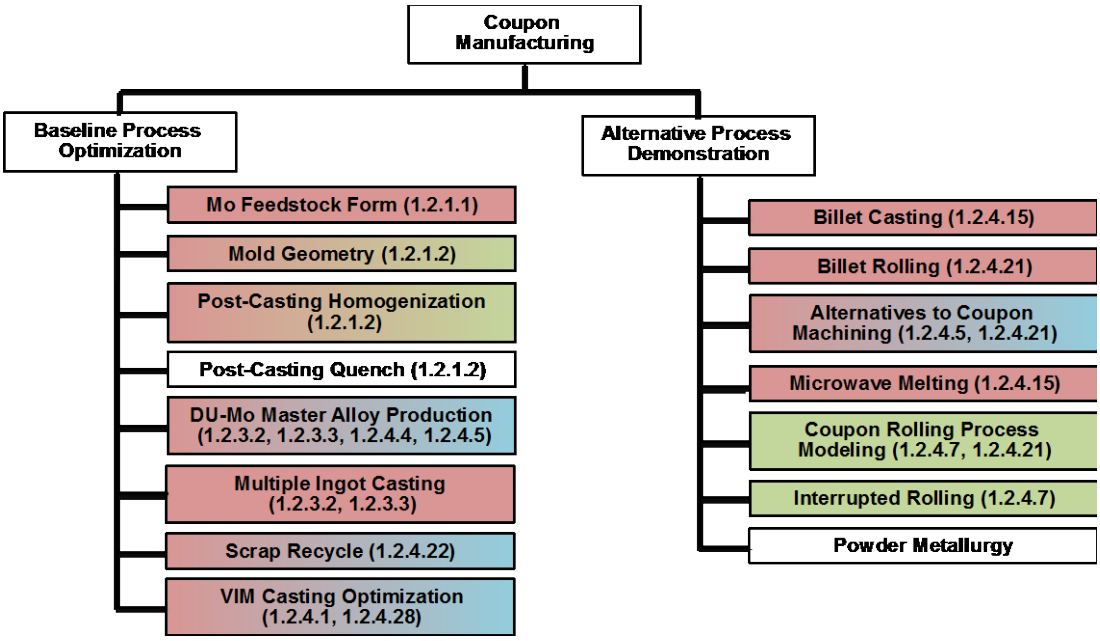


**Figure 3.2**. FFC Coupon Manufacturing R&D Activities Described in Section 3.0. The colors denote the responsible organization(s) for each activity and correspond to the colors in Figure 1.1. Multiple colors represent shared responsibility. The white boxes denote activities that are recommended but not currently funded.

## 3.1 Coupon Baseline Process Optimization

The principal process development needs for coupon manufacturing are related to improving cast product consistency, maximizing casting efficiency, improving casting yield, and producing consistently acceptable microstructures and dimensions in the final coupon product. Results from this portion of the R&D program will provide insight into material tendencies from which sampling plans can be better defined. Further, results from these investigations will define a process baseline so that time and cost saving measures can effectively be analyzed.

### 3.1.1 Molybdenum Feedstock Form (1.2.1.1)

This activity investigated the influence of Mo feedstock form on Mo purity and uniformity in the material used to cast plates, and was completed in fiscal year (FY) 2013. Three Mo feedstock forms were used to cast two intermediate logs each for subsequent casting development activities described in Sections 3.1.2 and 3.1.3. The Mo feedstock forms were powder, rod, and corrugated foil. Impurity concentrations of the depleted uranium (DU) feed material and the resulting logs (as a function of axial position) were determined by utilizing inductively-coupled plasma mass spectrometry (ICP-MS) or ICP-optical emission spectrometry (ICP-OES) and a LECO test (for carbon). Impurities of particular importance were C, Si, Fe, Cu, and Zr. The mass of DU and Mo for each alloy and casting run was reported, and in each case, the nominal Mo content was 10 weight percent (wt%). The results of the study, coupled with ingot casting studies described in Sections 3.1.2 and 3.1.3 demonstrated that the most effective Mo feedstock form was rod, based on comparison of skull percentage, carbon content, and silicon content (DeMint et al. 2013a). The rod feedstock will be used for all subsequent baseline coupon manufacturing development activities that include an intermediate (log) casting.

### 3.1.2 Mold Geometry (1.2.1.2)

This activity was enabled by the successful completion of the Mo feedstock investigation described in Section 3.1.1 to provide the necessary feed material. Following earlier studies on mold geometry using each of the three candidate Mo feedstock forms (DeMint et al. 2013a), the objective of the present study was to investigate the influence of mold geometry on impurity level and homogeneity of as-cast ingots in a single-ingot mold using Mo rod feedstock. The results will influence mold design (Section 3.1.12) and optimization of subsequent coupon processing steps in order to produce finished coupons with the desired microstructure. The ingots resulting from the present study provided material for subsequent foil rolling studies (Section 4.1.1).

Two mold geometries were used to produce DU-10Mo ingots with thicknesses of 0.200 in. and 0.375 in. A total of three ingots were cast from each of the molds, with one ingot of each thickness devoted to the post-casting homogenization study described in Section 3.1.3. The casting temperature was 1350°C, and the molds were coated with $Er_2O_3$. Three ingots of each thickness were subjected to radiography in the as-cast condition to evaluate the presence of any inhomogeneities, inclusions, or other defects. In addition, sacrificial samples were taken from each of these ingots for chemical analysis and microscopy. Various analytical methods were employed to determine the nominal concentrations of U, Mo, C, Si, Fe, and Zr. Finally, microstructural features such as grain size and microhardness were used to assess compositional uniformity (DeMint et al. 2013b).

Preliminary conclusions from the mold geometry study indicated no large porosity, coarse carbides (>20 μm), or gross Mo segregation was apparent. However, there was microstructural inhomogeneity in three forms: Mo segregation, grain size, and carbide size and distribution (Nyberg et al. 2013). Molybdenum segregation was most pronounced at the bottom of the ingots, grain size was larger at the top of the ingots, and carbides were finer and less evenly distributed at the bottom of the ingots (predominantly along grain boundaries). These inhomogeneities were likely the result of mold temperature gradients. However, it is possible that the inhomogeneities observed in the ingots could be overcome with optimized mold design and casting parameters (see Section 3.1.8). In addition, the 0.200 in. mold produced ingots with larger grain size than the 0.375 in. mold, but the 0.200 in. ingots had less Mo segregation than the 0.375 in. ingots. In general, dendritic microstructure was commonly observed in the 0.375 in. ingots. Finally, there were some variations from ingot to ingot, suggesting some degree of process variability.

### 3.1.3 Post-casting Homogenization (1.2.1.2)

Using one of the ingots from the 0.200 in. mold and one of the ingots from the 0.375 in. mold cast as part of the study described in Section 3.1.2, a four-hour homogenization treatment at 1000°C was performed in-mold after casting. Time and temperature was recorded using thermocouples located in the mold. After completion of the homogenization treatment, the furnace was allowed to cool to ambient temperature under vacuum. The ingots resulting from this study provided material for subsequent foil rolling studies (Section 4.1.1). The ingots were subjected to the same radiography, analytical chemistry, and microscopy examinations described in Section 3.1.2 for the mold geometry study (DeMint et al. 2013b).

The results indicated that in-mold homogenization after casting offers some benefit in Mo uniformity for the 0.200 in. ingots, but not the 0.375 in. ingots. Grain size was observed to increase after

homogenization, and carbide size and sphericity increased after homogenization also (Nyberg et al. 2013). However, if the thicker ingots are judged more desirable (e.g., they allow introduction of greater cold work for direct ingot-to-coupon rolling, see Section 3.2.2), it is possible that an optimized mold design (see Section 3.1.8) could improve the ability of in-mold homogenization to improve Mo uniformity and microstructure.

### 3.1.4 Post-casting Quench (1.2.1.2)

To evaluate the effects of post-homogenization heat treatment cooling rate on Mo uniformity and other microstructural features, it is useful to compare the baseline process (natural cooling under vacuum) to a forced cooling (quench) process. More rapid cooling could potentially improve Mo uniformity by reducing time at temperature and minimizing decomposition of the desirable γ-U phase. Even if rapid cooling does not offer Mo uniformity or other microstructural benefits, it could potentially improve throughput (by minimizing cooling time) that could reduce costs in a manufacturing setting.

Ingots produced in the studies described in Sections 3.1.2 and 3.1.3 could potentially be used for this study if not dedicated to one of the other activities already identified in this plan. Failing that, new coupons would need to be cast, using Mo rod feedstock and the same casting processes described in Sections 3.1.3 and 3.1.4. To evaluate the impact of cooling rate on coupon microstructure, non-destructive analysis including radiography, and destructive analysis including optical metallography, scanning electron microscopy (SEM), energy dispersive x-ray spectroscopy (EDS), XRD, and chemical analysis (ICP-MS, ICP-OES, and/or LECO) to analyze for U, Mo, Si, Fe, Zr, and C would be performed. Additional microstructural features of interest would include grain size, microhardness, phase composition, and the presence, size, and distribution of second-phase precipitates.

### 3.1.5 DU-Mo Master Alloy Production (1.2.3.2, 1.2.3.3, 1.2.4.4, 1.2.4.5)

Three separate technologies are being investigated to produce a depleted uranium-molybdenum (DU-Mo) master alloy that can be downblended with HEU to cast ingots from which coupons can be produced. The baseline process involves vacuum induction melting (VIM) casting the DU/NU diluent with HEU while simultaneously alloying with Mo. This process is presently conducted in a high security facility that is not necessary for work with DU materials. One possibility associated with a master DU-Mo alloy is that its production could be separated from the facility needed to perform downblending, potentially reducing coupon cost while increasing throughput. Development of master DU-Mo alloy casting parameters and options occurs in conjunction with a number of other activities (see Section 3.1.6).

The first master alloy option is a VIM/vacuum arc remelting (VAR) processing route being developed at LANL. The two-step melting process consists of first casting a composite U-Mo electrode by VIM or fabricating a box electrode from VIM-cast and wrought DU and Mo plate. This is followed by VAR of the electrode, using either a small or large melt pool, to produce a 6 in. diameter (180 kg) ingot. VAR of this ingot requires a 30 minute run, producing about 100 g of molten alloy per second. A final parameter to be explored is whether a single VAR step is adequate to produce the desired homogeneity or whether a double VAR step is required. This study draws on previous LANL experience producing homogeneous U-Nb alloys by a similar process (Cadden et al. 1974). One of the master alloys produced using this approach will be blended with DU (acting as a surrogate for HEU) to produce coupons for hot and cold

co-rolling as described in Section 4.1.3. Further evaluation will be conducted to determine whether large molds capable of accommodating the 180 kg ingot size are feasible at Y-12.

The second master alloy option consists of alloying DU with Mo using only VIM and casting into 2 in. diameter rods. This technology is currently being tested by Aerojet where all necessary process parameters, procedures, etc. to establish the capability to produce master alloy were developed. Aerojet produced 227 kg of DU-Mo alloy in 17 ingots that were 2 in. diameter and 26 in. long. This material was delivered to Y-12 for use in the study described in Section 3.1.6. The homogeneity of the delivered product is crucial to the downstream success of coupon and foil rolling. Therefore, to demonstrate the validity of the Aerojet method, it was necessary to statistically sample the product at the Aerojet facilities and analyze the chemistry at Y-12. The Mo and C content was relatively consistent in each of the ingots. The Mo content target was 12.6 wt%, with an allowable range of 12-13 wt%. The ingots had Mo content of 12.0-12.2 wt%, which was lower than the target, but within the allowable range. The C content was 192-208 ppm (Y-12 NSC 2012).

The third master alloy option consists of alloying DU with Mo using traditional arc-melting, resulting in approximately 500 g U-Mo feedstock (UMoF) buttons. This technology is being developed at Y-12 to identify the necessary parameters, procedures, etc. to supply UMoF for the studies described in Section 3.1.6.

In all three options, the resulting master alloys will be characterized for homogeneity of Mo and for impurity content. The parameters and process constraints of each master alloy technology will be evaluated in addition to determining the ease with which the master alloy can be introduced to the downblending process step to cast ingots. Any improvements to the Mo homogeneity of the final product, reductions in process cost, and/or improvements to throughput are highly desirable.

### 3.1.6 Multiple Ingot Casting (1.2.3.2, 1.2.3.3)

To improve casting efficiency with an intermediate melt, it is desirable to match as closely as possible the mass of the as-cast ingots to the mass of the intermediate logs. One way to do this is to cast as many as three to five ingots simultaneously instead of one. This also potentially reduces the need to mix multiple logs to produce coupons, which could improve material traceability. To support initial development of the commercial fabrication facility, a total of 96 low enriched uranium-molybdenum (LEU-Mo) and 96 DU-Mo coupons are needed. Each batch of 96 coupons will be divided into subsets that will allow for investigation of different process variables.

The 96 LEU-Mo coupons will be divided into two batches of 48 coupons each. One batch of 48 coupons were cast using an arc-melted DU-Mo feedstock (UMoF) produced by Y-12, and a second batch of 48 coupons were produced using the DU-Mo master alloy prepared by Aerojet (see Section 3.1.5). To produce each batch of 48 coupons, 10 intermediate logs were required (assuming 2.5 as-cast ingots per log). From each set of 10 logs, 12 coupons were cast using the baseline single-ingot mold (i.e., 12 pours) and 12 ingots were cast using a three-ingot book mold (i.e., four pours). The overall yield during production of the ingots in the three-plate mold was approximately 50% due to mis-pours. During FY 2013, a design review was completed that identified numerous recommendations for improvement in the three-ingot mold design and casting process (Y-12 NSC 2013). These recommendations will be implemented in the fabrication of the 96 DU-Mo coupons.

The 96 DU-Mo coupons will be divided into two batches. The first batch will consist of 66 coupons fabricated by blending Mo rod feedstock and DU in an intermediate log casting. The log casting will be crushed to produce broken metal pieces that will be re-melted and cast into a three-ingot mold. A total of 11 pours will result in 33 ingots from which 66 coupons can be machined. The second batch consists of 30 coupons fabricated by arc-melting with UMoF, followed by blending with DU (to simulate downblending with HEU) and casting directly into the final three-ingot mold, thus omitting the intermediate log casting step. A total of five pours will be performed resulting in 15 ingots from which 30 coupons can be machined.

All of the LEU-Mo and DU-Mo as-cast ingots will be machined to 6.00 in. x 4.00 in. x 0.125 in. Data will be collected to correlate the appearance, area, character, and distribution of surface defects with the depth of machining required to eliminate them. These data will help optimize the casting and post-casting machining processes in the future, and they will provide input and benchmark comparisons to computational modeling work (see Section 3.1.8) being conducted in parallel with the experimental work.

### 3.1.7 Scrap Recycle (1.2.4.22)

The baseline U-Mo casting process produces as-cast plates at about 0.2 in. thick. This is currently a two-step casting process, resulting in ~10% of the feed material going to skull oxide scrap. The current baseline process uses a band saw to cut coupon blanks from the ingot, resulting in saw fine scrap from the blade and scrap from excess material around the coupon. The large excess pieces are currently consolidated and recycled. After cutting the coupon blanks, the baseline process machines the plate to $0.125 \pm 0.013$ in. thick with a surface finish of 63 μin or better, resulting in a large volume of scrap (approximately 35% of the ingot is currently discarded as scrap in this process step). The machine turnings and saw fines are currently stored under a coolant due to their pyrophoricity. The amount of scrap generated (currently not recycled) and the storage of material under coolant is unacceptable to the long-term sustainability of the program. This study will investigate potential methods to recycle the fine U-Mo scrap material and also to process scrap/waste to a form that is easier to store and subsequently recycle.

Five possibilities for dealing with the skulls, turnings, and fines will be studied:

- Briquette and recast the U-Mo alloy as-is
- Briquette and purify through electrorefining to U metal
- Convert to oxide and purify U by sublimation of $MoO_3$
- Dissolve U-Mo and purify by precipitation
- Plasma arc melting of U-Mo alloy.

The first two methods are the best candidates for the machine turnings, since oxidation rates are lower than U metal because of the Mo content. The machine turnings will be washed to remove the coolant and other organic contaminants, which would lead to unacceptable carbon contamination or exceed other contaminant limits in the specification. The washed chips will be briquetted and the alloy recast via VIM from the briquettes. The final alloy chemistry will be sampled. With direct casting in the first method, contaminants such as carbon and various oxides are expected to be high. The second method offers a possible solution if oxide and carbon impurities are problematic by electrorefining prior to consolidation.

A potential concern is the degree of separation of the U and Mo constituents during electrorefining. During FY 2013, Y-12 demonstrated approximately 90% yield for the briquetting and recasting process. Yields were substantially improved when the turnings were stored under vacuum. Development of optimum cleaning processes is still under way. The electrorefining process provided up to 85% yield, with no detectable Mo impurities in the electrorefined U product. Based on these results, both briquetting options merit further development (Woerner 2013).

The third and fourth methods are a good candidate for saw fines and skull oxides. Since the skulls are partially oxidized in processing, the easiest path is to complete the oxidation of the U and Mo to $U_3O_8$ and $MoO_3$, respectively. The $MoO_3$ should sublime at 1150°C in an air atmosphere leaving behind purified $U_3O_8$. In the fourth method, the saw fines and oxides will be dissolved in $HNO_3$. Part of the Mo will precipitate as $MoO_3$ and will be removed by centrifugation. The supernatant will be treated with $H_2O_2$ to precipitate the uranium as $UO_4$-$H_2O$ that will be converted to $U_3O_8$ in a furnace at 600°C. For both methods, the oxide chemistry will be sampled and compared to specification requirements and the $MoO_3$ will be disposed of as waste. During FY 2013, work on the oxide conversion process demonstrated that while the alloy was successfully converted to oxide, there was no simultaneous sublimation of $MoO_3$. Research on the dissolution/precipitation process did not result in significant purification of the U using either $H_2O_2$ or ADU precipitation. In addition, the $H_2O_2$ precipitation process resulted in foaming, which introduces concerns in a production setting. Based on these results, no further work is contemplated on either of these processes (Woerner 2013).

The fifth method, which is currently not funded, addresses the fact that the VIM induction field used in the first two methods typically does not couple well with briquettes because of insufficient metallic density. In this approach, the turnings would be melted via plasma arc into an ingot that can be recycled directly. An additional advantage of the plasma arc melting approach is that the turnings do not necessarily have to be degreased before melting because volatile contaminants will not be incorporated in the resulting ingot. As with the first two methods, the final ingot chemistry would be sampled to determine compliance with specification requirements.

### 3.1.8 VIM Casting Optimization (1.2.4.1, 1.2.4.28)

The existing VIM casting process must be improved to ensure consistent ingot quality (Mo homogeneity, density, impurities, inclusions, and microstructure), high throughput, and minimal scrap and waste. One aspect that contributes to these factors is mold design. This study will evaluate and optimize design and process features of the three-ingot mold (see Section 3.1.6) and the billet mold (see Section 3.2.1). The first step will be replication of the Y-12 process at LANL using highly instrumented molds following the current baseline process. Based on these experimental studies, models will be constructed using commercial codes to optimize both design features (wall thickness, etc.) and process parameters (temperature, insulation, etc.). Results to date from LANL suggest that the alloy in the top of the billet mold is solidifying before the rest of the billet, leading to the porous material observed by Y-12 (see Section 3.2.1) (Aikin and Dombrowski 2014). The proposed solution is to cast horizontally, rather than vertically, and incorporate slightly thinner mold walls. Recommended casting parameter changes include a decrease in the pour temperature for the billet mold and an increase in pour temperature for the three-ingot mold.

Inclusions in the U-10Mo ingots, specifically carbides and oxides, are problematic for a number of fabrication processes including hot and cold rolling. There is also evidence that large inclusions are detrimental for fuel performance. Therefore, another aspect of improving the VIM casting process is evaluating methods for reducing the concentration of carbide and oxide inclusions in the U-10Mo ingots. A proposed study (currently not funded) would evaluate the feasibility of using porous ceramic filtration and/or the use of carbide- or oxide-forming dopant additions during casting for this purpose. Experiments with filters and dopants would produce ingots that will be evaluated for inclusion concentration and morphology.

## 3.2 Coupon Process Alternatives

There are several alternative processes under consideration for coupon manufacturing. Some address streamlined casting operations that yield a billet that can be directly reduced by rolling to near final coupon dimensions. Others have to do with reducing the coupon all the way from an as-cast (in the case of billet casting) or as-cast/as-machined (in the case of the baseline process) dimension to the final U-Mo fuel meat dimension (0.006–0.020 in.). This approach will be necessary if an alternative method to apply the Zr barrier is identified by the studies described in Section 4.2 (or if future FD irradiation experiments reveal that a Zr barrier is not required for particular HPRRs). Currently, Y-12 plans to transition to microwave melting in the future, as an alternative to the current VIM process, so microwave melting is an alternative that must be evaluated. Finally, there are alternative coupon machining and finishing methods that could minimize or eliminate the large volume of fine scrap produced by the baseline coupon machining process.

### 3.2.1 Billet Casting (1.2.4.21)

The baseline U-Mo casting process produces plates that are about 0.2 in. thick. These plates are subsequently machined to 0.125 ± 0.013 in. with a surface finish of 63 μin or better, resulting in high costs, constrained throughput, and a large volume of scrap. One option to improve the process is to cast ingots and then directly roll them to 0.125 in., thereby eliminating much of the costly machining process and significantly improving material yield. One option for doing this would be to cast large ingots, referred to as billets, to minimize the number of melt pours and potentially increase casting throughput. The as-cast billets are 1 in. thick and 5 in. x 5 in. in cross-section. The assumption is that each billet would provide enough material for four ATR-size coupons (4 in. x 6 in. x 0.125 in.), as opposed to two coupons from the current size ingot. In each case, the billets are radiographed and sampled to evaluate chemical homogeneity, defects, second-phase inclusions, and microstructure. The billets will provide starting material for the billet rolling studies described in Section 3.2.2.

During FY 2013, six billets were successfully cast. The top of the castings exhibited a porous region, but it may be possible to address this with better mold design and casting parameters. Information from the billet casting study has been provided to the VIM casting optimization study described in Section 3.1.8. In general, the billets exhibited Mo content between 9.00 and 10.50 wt% at the top, middle, and bottom, with average Mo concentrations less than 10 wt%. Carbon content ranged from 220 to 396 ppm, and Si content ranged from 30 to 82 ppm.

### 3.2.2 Billet Rolling (1.2.4.21)

If direct billet casting proves feasible (see Section 3.2.1), the resulting billets will need to be rolled at least to final coupon dimensions. If one of the alternate Zr deposition methods proves feasible (see Section 4.2), then the billets will need to be rolled to intermediate or even final foil dimensions. This study will investigate the feasibility of rolling reduction from 1 in. thick billets to coupon and foil dimensions. In addition, the study will also investigate the influence of billet rolling technique on the final coupon. Unidirectional rolling and cross-rolling will be investigated. Three of the 5 in. x 5 in. x 1 in. billets were rolled in a unidirectional fashion, while the other three were rolled in a cross-directional fashion. The as-rolled billets were carefully measured to validate the rolling models developed by the studies described in Section 3.2.5. Results were mixed, with the minimum target of four coupons per billet achieved for only two of the six billets. One of the unidirectionally-rolled billets exhibited an alligator failure, while other billets exhibited brittle failures during sectioning. The rolled billets resulting from the study will provide material for the coupon machining studies described in Section 3.2.3 and foil rolling studies described in Sections 4.1.1 and 4.1.2.

### 3.2.3 Alternatives to Coupon Machining (1.2.4.5, 1.2.4.21)

The baseline coupon manufacturing process casts U-Mo ingots at 0.2 in. thick. The resulting casting is then machined to 0.125 ± 0.013 in. thick with a surface finish of 63 μin or better. Approximately 35% of the as-cast material is machined and discarded as scrap in this process step. The basis for the baseline coupon thickness and surface finish requirements is not well defined. However, the current cost to machine a coupon and the amount of scrap generated is not sustainable beyond initial U.S. HPRR conversion. This study will investigate three potential alternatives to the machining process. While some degree of machining will still be required to size the coupon, a majority of the cost and scrap is associated with thickness and surface finish requirements. Each of these alternative processes is compatible with some form of coupon bare rolling to reduce scrap volume. The three alternative processes investigated in this study are:

- Pickling of the cast ingot to remove the oxide surface and then bare rolling the ingot to the specified coupon thickness and surface finish
- Utilizing a belt sander (also referred to as a time-saver) to remove thin layers from the surface of the cast plate and then bare rolling the plate to the specified coupon thickness and surface finish
- Utilizing electro-discharge machining (EDM) to cut coupons from an ingot.

Each alternative process yields different challenges that must be addressed. For the pickling process, current production safety basis requirements and equipment availability must be evaluated as well as processes for dealing with the disposition of the pickling solution, because it cannot be treated in existing HEU processing streams. For the time-saver process, the feasibility study will include assessments of available equipment, installation of identified equipment into the uranium production facility (i.e., criticality concerns, facility safety concerns, etc.), disposition of the powder generated and potential production impacts. Because the use of a time-saver on radioactive material is not currently an existing capability within the facility, the evaluation of this method will be limited to the feasibility study only. For the EDM process, the recast layer left behind after machining will need to be evaluated to determine its impact on subsequent process steps. If it needs to be removed, a process will have to be considered, and the waste streams associated with that removal process will need to be evaluated in the context of the manufacturing facility. All three processes will be evaluated for their ability to achieve the required dimensional and surface finish requirements.

The understanding developed by the study described above will be applied to the rolled billets described in Section 3.2.2. These rolled billets will be subjected to three different coupon cutting methods including sawing, shearing, and EDM. The process time, edge condition, and surface condition of the coupons will be evaluated and compared. It is assumed that at least four coupons will be obtained from each rolled billet. The coupons will be utilized for further foil rolling studies described in Sections 4.1.1 and 4.1.2.

A slightly different application of EDM being evaluated at LANL is cutting coupons from a large billet (as opposed to cutting coupons from a smaller ingot as described in the preceding paragraphs). This process provides an alternative method for reducing the thickness of a large billet compared to billet rolling as described in Section 3.2.2. The benefits of EDM versus rolling include reduced machining costs, increased capability to achieve tighter tolerances, stress-free/burr-free machined surfaces eliminating the need for milling, and the ability to machine complex shapes if needed. Kerf losses are reduced with EDM compared to conventional machining, so scrap generation is lower. Better reliability is also possible because EDM is controlled by a computer. A large billet will be acquired from the study described in Section 3.1.5, and it will be cut into coupons (3 in. x 4 in. x 0.125 in.) using EDM. The edges and heat affected zone (recast layer) will be removed using nitric acid. A Zr-coated DU-Mo foil will be produced from one of the EDM-cut coupons to demonstrate that no deleterious effects result from the machining process. The interface between the Zr and the DU-Mo will be characterized by optical and SEM.

### 3.2.4 Microwave Melting (1.2.4.15)

The casting technology selected for the future Uranium Processing Facility (UPF) at Y-12 is microwave melting. As a result, it is necessary to evaluate microwave melting for production of U-10Mo alloys. One concern with microwave melting is that its melt pool is not as turbulent as VIM casting and may not result in adequate mixing to ensure alloy uniformity. However, it is possible that, if properly mixed, microwave melting might offer some advantages over induction melt casting in impurity content. Preliminary studies funded by Y-12 outside the Convert Program suggested that microwave melting had the potential to produce homogeneous U-Mo log castings (Cook et al. 2012). However, the earlier studies did not incorporate recent developments in the baseline U-Mo casting process. A study has been undertaken within the Convert Program that will produce log castings using UMoF, to determine if suitably uniform logs can be produced via microwave melting. The logs will subsequently be re-cast into the single-ingot mold, to mimic the current baseline process. If microwave melting continues to show promise, future work will consider optimized insulation materials consistent with the proposed Y-12 entombment in the melter, elimination of the intermediate (log) casting, and use of the three-ingot mold.

### 3.2.5 Rolling Process Modeling (1.2.4.7, 1.2.4.21)

To support development of the billet casting and rolling fabrication process described in Sections 3.2.1 and 3.2.2, a computational model will be developed to evaluate rolling process parameters. This model will be applied to the billet casting and bare rolling alternative process in much the same manner as described in Section 3.1.9 for optimization of the baseline coupon reduction process. In addition, the model will be used to evaluate further thickness reduction of the coupons to final U-Mo foil thickness in the event that one or more of the alternative Zr application processes described in Section 4.2 proves promising. With these processes, it is envisioned that the U-Mo coupon would be reduced from the as-cast plate or billet dimensions to the final fuel meat thickness at which point the Zr would be applied.

The model developed in this study will also be used to predict the results of, and evaluate process options for, foil rolling. This effort will provide guidance to experimental studies on both hot and cold foil rolling described in Section 4.1.6. The study will evaluate process parameter variations to optimize the baseline reduction process (both hot and cold rolling) from U-Mo coupons ready for Zr co-rolling or bare rolling in the event that an alternative Zr deposition method is applied (see Section 4.2).

### 3.2.6 Interrupted Rolling (1.2.4.7)

A series of interrupted rolling studies will be conducted to evaluate the evolution of ingot geometry and microstructure during hot and cold rolling to final coupon dimensions to support bare rolling as an alternative to the baseline coupon machining process, or as an alternative method of foil production in the event that an alternative Zr deposition method is selected (see Section 4.2). Specimens will be evaluated after selected rolling reductions between as-cast ingot dimensions and final coupon dimensions. Characterization will include ultrasonic inspections to identify macroscopic defects, optical and SEM (with electron backscatter diffraction, EBSD) to observe grain size and orientation and distribution/composition of second-phase inclusions, and evaluation of surface finish. The study will consider the impact of the various coupon characteristics on downstream processing such as Zr barrier application and co-rolling to final foil dimensions, and make recommendations for optimized process parameters to improve product quality, increase yield, and/or decrease cost. Preliminary conclusions suggest the Mo inhomogeneities observed in as-cast ingots (see Section 3.1.2) are not eliminated by rolling. In general, the grain size did not change and the carbide particles retained their as-cast aspect ratio.

The experimental interrupted rolling methodology will also be applied to evaluating process parameters for the billet rolling process described in Section 3.2.2. Evaluation of the surface finish and microstructure will aid process optimization in conjunction with the understanding gained from the computational rolling model.

### 3.2.7 Powder Metallurgy Coupon Fabrication

If an efficient powder metallurgy (PM) processing route could be identified for production of coupons, it could provide benefits that carry all the way through foil and plate fabrication. For example, if coupons could be formed to near-net shape directly, there would be obvious benefits in reducing coupon casting and machining effort. In addition, PM coupon fabrication might offer some advantages to ensuring uniform distribution of Mo and $^{235}U$, depending on the form of the starting powders. Further, there are some parallels with current dispersion fuel fabrication methods that might streamline process development and fuel qualification efforts. Finally, PM coupon fabrication (i.e., to net shape) would offer obvious benefits for contoured fuel fabrication for HFIR. In addition to these possible advantages, however, such a process might also lend itself to simultaneous, or at least simplified sequential, Zr coating application. With proper dimensional control, a Zr-coated PM coupon could be directly used in several proposed alternative plate assembly processes such as net-shape hot isostatic press (HIP) bonding (Section 5.2.1) or hot pressing (Section 5.2.2).

# 4.0 Foil Manufacturing Research and Development

Foil manufacturing encompasses all activities from the finished U-10Mo coupon described in Section 3.0 through the final fuel foil that consists of the U-10Mo fuel meat in its final prototypic dimensions and bonded to a Zr diffusion barrier. This portion of the baseline manufacturing process is shown in Figure 4.1 and the R&D activities described in this section are shown in Figure 4.2. The following sections describe R&D efforts that are needed to optimize the baseline process as well as process alternatives that may offer improvements in quality, repeatability, or cost. As described in Section 3.0, numbers in parentheses following some of the subsection headings indicate the Convert Program WBS under which the work is planned. If a subsection does not have a WBS associated with it, it is because this work is not currently included in the Convert Program planning basis. In these cases, inclusion in this document forms the basis for a recommendation to include the work in future FFC scope planning for the reasons described in the subsections below.

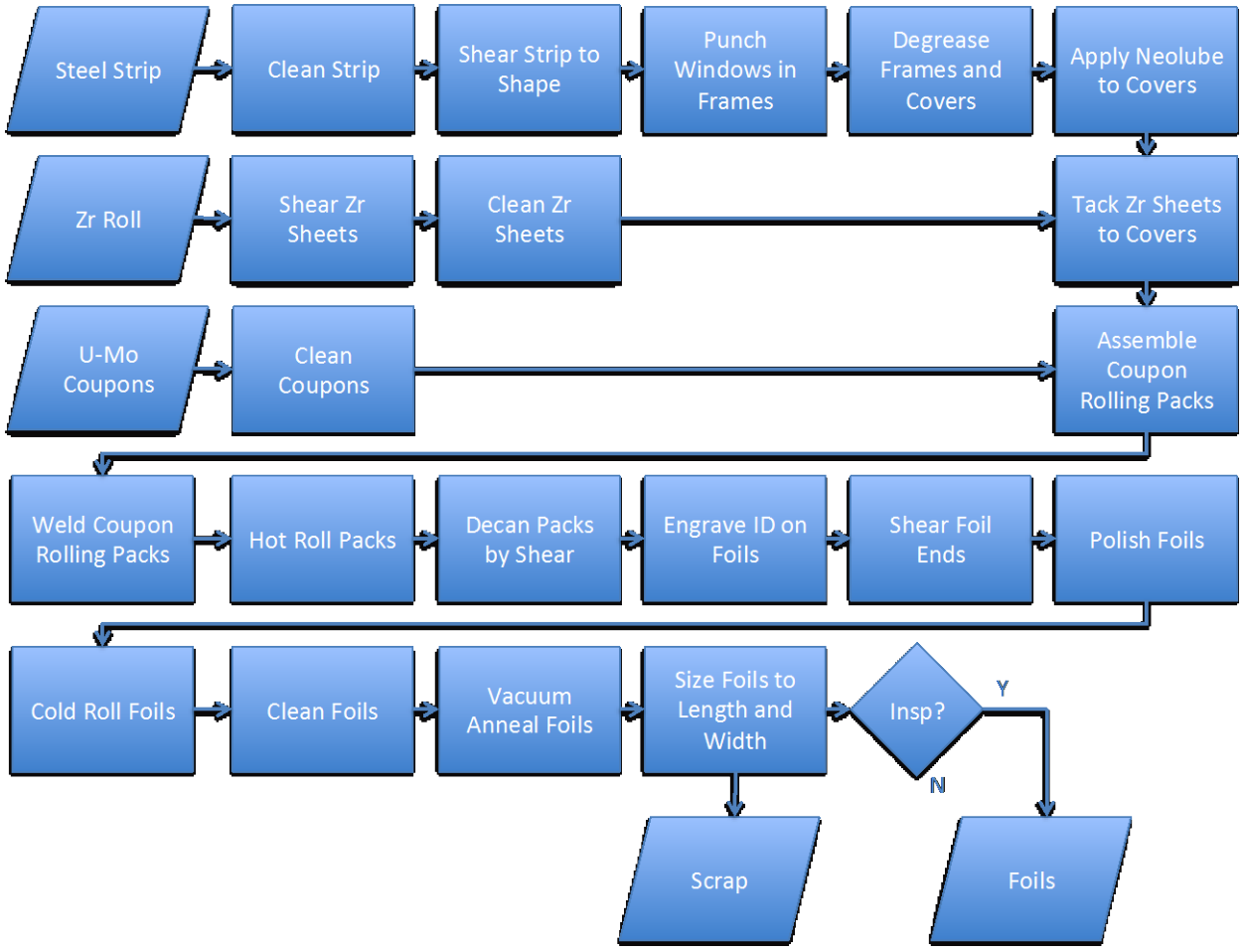


**Figure 4.1**. Simplified Flow Sheet for Baseline Foil Manufacturing Process

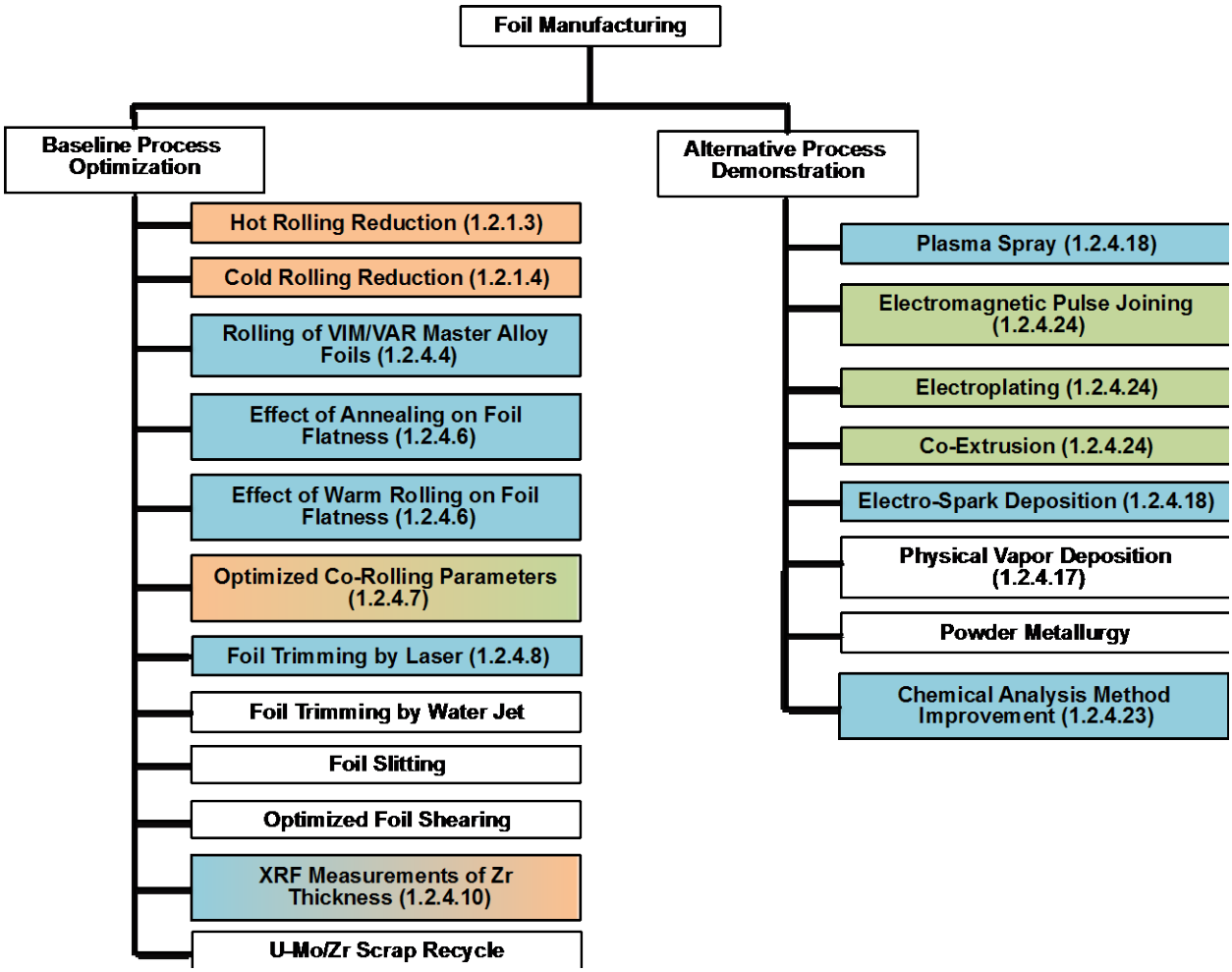


**Figure 4.2**. FFC Foil Manufacturing R&D Activities Described in Section 4.0. The colors denote the responsible organization(s) for each activity and correspond to the colors in Figure 1.1. The white boxes denote activities that are recommended but not currently funded.

## 4.1 Foil Baseline Process Optimization

The principal process development needs for foil manufacturing are related to improving as-rolled product consistency, uniform diffusion barrier thickness, acceptable U-Mo and Zr microstructure, foil flatness, and material utilization. Based on the assumption that there is a desirable set of material properties and characteristics (defined by the product specification) that provides the opportunity for good fuel performance as shown in Figure 2.1, the objective of the baseline process optimization studies in the following sections is to identify methods to produce foils in a high yield, low waste, and cost-effective fashion. To this end, consideration will be given both to processing and performance characteristics.

### 4.1.1 Hot Rolling Reduction (1.2.1.3)

This study investigates the hot rolling process utilized to bond the Zr to the U-10Mo alloy and to reduce the machined coupons prepared in the study described in Section 3.1.3 to a standard sheet thickness of 0.040 in. (~0.045 in. including Zr). The purpose of these experiments is to define a process

baseline against which time, cost, and material saving measures can effectively be analyzed. The results of the experiments provided valuable input into the modeling studies described in Section 3.2.5.

The series of experiments conducted here involves canning all 32 DU-10Mo coupons prepared in the study described in Section 3.1.3 sandwiched between two layers of Zr sheet in a mild steel (SAE 1018) can. Since two different (0.200 in. and 0.375 in.) coupon thicknesses are produced (as a result of the casting experiments in Sections 3.1.1 and 3.1.2) and two different foil thicknesses are needed for the cold rolling studies described in Section 4.1.2, three different Zr sheet thicknesses are needed to ensure that the final Zr thickness is nominally the same for each rolled plate (i.e., 0.001 in. thick on either side of the finished foil). The thicker coupons are attractive in that they provide more mass to support fabrication of foils for HPRRs with longer fuel plates.

The hot rolling schedule varied depending on the starting plate thickness (i.e., thicker plates underwent greater reduction with more passes than thinner plates). All hot rolling was done at nominally 650°C utilizing a box furnace to pre-heat the canned foils. The roll separating force and temperature (entry and exit) for each pass was measured and recorded using infrared thermometry. At the end of each pass (or at a minimum at the end of each series of passes), the spread (i.e., increase in pack width) of the roll pack was measured and recorded. Upon completion of the prescribed rolling schedule, the roll pack was annealed at 650°C for 45 minutes, after which the pack was removed from the box furnace and allowed to cool naturally to ambient temperature. The Zr-coated DU-10Mo sheets were sheared from the roll can, inspected visually for any defects or anomalies, and weighed. Some of the foils produced were designated for characterization (Zr thickness via x-ray fluorescence (XRF), optical microscopy, microhardness, and microstructural characteristics) while others were dedicated to the cold rolling studies described in Section 4.1.2.

### 4.1.2 Cold Rolling Reduction (1.2.1.4)

This study investigated the cold rolling process utilized to uniformly reduce the Zr-coated DU-10Mo monolithic foils prepared in the hot rolling study (Section 4.1.1) to a final specified thickness. The starting foil thickness were nominally 0.045 in. As a result of utilizing different initial Zr layer thicknesses, the final Zr thickness on either side of the foil after cold rolling should have been nominally 0.001 in.

For each cold rolling campaign, the number of cold roll passes given to each foil with each nominal target thickness was similar. However, it was noted that foils with a thinner nominal target thickness received more cold work than those foils with a thicker nominal target thickness. The length and width of each foil was measured after completing cold rolling. Foil thickness measurements were taken at 10 locations with micrometer/caliper and Zr layer thicknesses were measured at corresponding locations using handheld XRF. The foils were sheared to 25 in. long and were nominally 3 in. wide. One of the foils from each batch was dedicated to metallographic characterization.

A fundamental observation resulting from the studies described in Section 4.1.1 and this section was that foils rolled from thicker coupons had much lower yield than foils rolled from thinner coupons (Moore and Fox 2013). The average yield for the 0.325 in. thick coupons was 58%, while the 0.140 in. thick coupons had an average yield of 80%. In general, the difference in yield was attributed to defects occurring during hot rolling such as Zr layer blistering and debonding.

### 4.1.3 Rolling of VIM/VAR Master Alloy Foils (1.2.4.4)

Two of the coupons produced in the VIM/VAR master alloy study described in Section 3.1.5 will be dedicated to hot and cold co-rolling to evaluate the suitability of the master alloy process for producing adequate foils. One coupon will be machined, canned, hot co-rolled, then decanned and cold co-rolled. Another coupon will be homogenized after casting, bare rolled, machined, canned, hot co-rolled, then decanned and cold co-rolled. The resulting foils will be inspected for defects and radiographed for low density defects. Results obtained from these activities will be compared with results obtained as part of the studies described in Sections 3.1.3, 4.1.1, and 4.1.2 to evaluate the effect of the separate alloying and downblending steps on downstream foil processing.

### 4.1.4 Effect of Annealing Parameters on Foil Flatness (1.2.4.6)

Experience with the AFIP-7 and RERTR-FE foils has demonstrated a tendency for foils to curve after cold co-rolling. Furthermore, coiling foils for subsequent shipment resulted in unexpected cracking. One contributing factor to these experiences and observations may have been the amount of cold work imparted into the foils, which currently is not specified. The rolling schedule for those experiments produced roughly 65% cold work in the foils as compared to 25% cold work produced by the baseline rolling schedule originally developed by FD. The main driver for this deviation was the limitation of production-scale processing equipment. Whether or not the eventual product specification allows this range of cold work for a given final foil thickness, some flexibility will be needed to obtain the full range of prototypic foil thicknesses from a "standard" rolling coupon size. Further, final foil trimming to the tight tolerances proposed to date will be much more successful for fully flat foils than those with curvature. A connection between foil flatness before HIP bonding and difficulty in machining the cladding to achieve dimensional tolerances without violating minimum cladding thickness requirements has also been hypothesized.

Annealing in vacuum has been suggested as one way to help reduce curvature and flatness issues in cold co-rolled foil. It has also been suggested as a way to increase process yield for rolling the foil to the 0.008 in. fuel meat thickness being considered for some of the U.S. HPRRs. Annealing is also commonly used in metals processing to help remove non-uniform plastic deformation such as kinks, bends, and twists, sometimes in combination with mild stress from a metal weight placed on the foil. Optimum annealing temperature (in vacuum) has not been established to date.

This study addresses the effects of five different vacuum annealing conditions (60 minutes at 550, 600, 650, 700, and 750°C with an oil quench) on the flatness of co-rolled foils having various combinations of hot work (65–91%) and cold work (5–75%). The foils were flattened by a load of 90 lb during annealing. The results to date are similar to those noted in the study described in Section 4.1.3. The thickness of the foils is relatively uniform (as long as at least 25% cold work is applied to the foil), but the variability in the Zr layer is considerable regardless of the cold reduction. The effect of coiling after annealing will be evaluated by examining the foils for cracks or other macroscopic damage. The fuel-Zr interfaces will be characterized by optical and SEM to determine the effect of annealing on the interface microstructure. Foils produced by this effort that are not dedicated to destructive analysis may be utilized in other optimization and demonstration activities (Alexander et al. 2014).

### 4.1.5 Effect of Warm Rolling on Foil Flatness (1.2.4.6)

As a complement to the cold co-rolling and annealing study described in Section 4.1.4, the effect of warm co-rolling at 250°C on foil flatness will be evaluated and compared to cold co-rolling. The U-Zr interfaces will be characterized by optical and SEM to determine the effect of warm rolling on the interface structure. In addition, the foils will be evaluated for surface finish, thickness, and residual stress.

### 4.1.6 Optimized Co-rolling Parameters (1.2.4.7)

This study seeks to optimize the existing Zr co-roll bonding process parameters to improve fabrication performance and guide manufacturing of test articles for upcoming irradiation experiments. Alloy coupons for this study will be prepared via machining of vacuum-annealed alloy plate material; 0.125 in. thick plate was sectioned into coupons for the rolling study. Four DU-10Mo coupons (3.5 in. x 5 in.) will be used for the study.

The first round of experiments will focus on hot rolling reduction factor (2.5x, 4x, 7.5x), time at elevated temperature (650°C), and typical vs. aggressive rolling. The cold rolling component of the first round study will involve typical, skin, and aggressive per-pass cold rolling schedules. Cold rolled foils will not be annealed after cold rolling. Characterization of the cold rolled foils will include x-radiography to evaluate fuel meat homogeneity, dimensional measurements to evaluate foil thickness uniformity and flatness, optical microscopy to investigate Zr thickness uniformity, U-Mo and Zr grain size and orientation, and defects (second-phase inclusions, cracks, etc.), SEM to observe the condition of the U-Zr interaction layer, microhardness to characterize localized mechanical properties of the U-Mo and Zr, and tensile testing to characterize bulk mechanical properties of foils.

Based on results of the first round, and using input from the rolling model developed by the study described in Section 3.2.5, a second round test matrix will be formulated after identifying the most promising process parameters explored during the first round. The focus of the second round of experiments will be to fine-tune these process parameters to yield flat foils of uniform thickness (including Zr barrier thickness), minimization or elimination of macroscopic foil defects (e.g., edge cracking, Zr barrier layer debonding), and maximized yield/minimized processing cost.

Other parameters that will be computationally investigated using the model developed in the study described in Section 3.2.5 include evaluation of alternative rolling can (i.e., picture frame) materials to better match the mechanical properties of the foil materials, alternative rolling can end configurations, and alternative rolling can designs. As part of these efforts, better mechanical properties data (e.g., compression data to yield flow stresses and hot XRD to understand time-temperature-transformation relationships in the U-10Mo alloy) were generated to provide input into process parameter selection and mechanical modeling studies (Joshi et al. 2014). Finally, computational evaluation of rolling mill parameters such as roll size and rolling speed will be conducted in an effort to better match the mill to the materials being reduced.

Virtually all of the hot rolled foils processed at INL during FY 2013 exhibited undesirable features such as rough surface texture after decanning and edge cracks, despite a variety of rolling schedules. This suggests changes are needed either in the starting material characteristics or fundamental aspects of the hot rolling process (e.g., the can material). In addition, the interaction layer between the Zr and the U-

10Mo was not continuous when the integrated time at temperature at 650°C was less than 120 minutes, suggesting that co-rolled foils produced under these conditions might not have an adequately bonded Zr layer.

There was relatively good uniformity in foil thickness within a given foil, with slightly more variability in foil-to-foil thickness reproducibility. There was significant variability in the XRF-measured Zr thickness within a given foil (on the order of ±0.0005 in.), and the average thickness was less than the targeted 0.001 in. Measurements of Zr layer thickness from optical micrographs resulted in even higher variability (±0.001 in.), and the average thickness when measured from optical micrographs was slightly higher than 0.001 in, suggesting that the XRF measurements were biased low. The roughness of the hot rolled foils (see Section 4.1.1) appeared to contribute to the variability in Zr layer thickness after cold rolling. In addition, there was some evidence of discontinuous interaction layers after cold rolling, even in foils that had continuous layers after hot rolling, raising questions about adherence of the Zr layer.

### 4.1.7 Foil Trimming by Laser (1.2.4.8)

The baseline process of trimming foils to shape via mechanical shearing currently produces undesirable mechanical deformation and a shear lip along the cut edge that causes a poor fit with the pocket machined in the Al clad, and possibly increased reactivity with the Al clad material. This study will compare dimensional accuracy, cut quality, and reactivity of sheared edges of Zr-clad stainless steel foil surrogates with those produced by laser processing. The objective of this study is to identify improvements in dimensional control of foil edges, and reduced damage and reactivity of the U-Mo fuel meat with the Zr barrier and Al 6061 cladding. The study will also consider how to address U accountability with regard to process losses in a manufacturing setting. Laser cutting can be accomplished in at least two modes: ablation and melting with liquid expulsion. In this study, laser ablation was optimized with Type 304 stainless steel as a surrogate material, and will be developed further for use on U-Mo. Specific experimental goals include optimizing the laser cutting parameters to achieve dimensional and mass tolerances while minimizing kerf and heat damage to surrounding material, adapting the parameters for use with a range of foil thicknesses, and identifying methods for dealing with U vapor produced during cutting. The process will then be demonstrated on Zr-clad U-Mo foils for subsequent use in evaluating plate manufacturing via can-less HIP (see Section 5.1.4) and subsequent laser cutting of plates (see Section 5.1.5).

### 4.1.8 Foil Trimming by Water Jet (1.2.4.26)

A possible alternative to the shearing process currently used to trim foils to shape is water jet cutting. This process is used commercially in a variety of industries for cutting materials including food, leather, polymers, metals/alloys, and engineered and natural (e.g., granite) ceramics. Commercially-available water jet cutting systems range in size from a few square feet to hundreds of square feet, so the process is amenable to full-size foil (or plate) trimming, including complex fuel shapes relevant to HFIR. The process produces no heat-affected zone in the workpiece. There are a number of process parameters that require investigation including working pressure, desirability of using abrasives or pure water, nozzle size and design, cutting speed, distance from nozzle to workpiece (affects kerf), and positioning accuracy and precision (i.e., repeatability). The study would also need to consider how to address U accountability with regard to process losses in a manufacturing setting.

### 4.1.9 Foil Slitting

Foil slitting is a modest variation of foil shearing that has been employed at the bench scale to fabricate experimental test foils to date. Slitting offers an advantage over raw shearing in that a higher productivity can be achieved and foils can be sized to width simultaneously, as opposed to sequential shearing each side of the foil separately. Slitting is especially attractive for the processing of longer fuel foils (24–48 in.) where the foil may have a tendency to walk during a pure mechanical shearing operation, resulting in non-uniform widths. A foil slitter has been procured and is awaiting installation in the pilot-production line being established at B&W NOG. Preliminary studies have been completed by FD on a similar piece of equipment located at INL (Moore 2014). Lessons learned from that study include the importance of aligning the foil parallel to the cutting blades and ensuring that the end of the foil is square so that it feeds straight into the slitter. The ability of the co-rolling process to produce flat foils is also critical to getting good results in the slitting operation, highlighting the importance of the parameter optimization study described in Section 4.1.6. It is not anticipated that a significant amount of R&D will be required to prove-in a foil slitting method, but to date, the process has not been demonstrated.

### 4.1.10 Optimized Foil Shearing

One option for improving the edge geometry of foils that may involve less development and new infrastructure is optimization of the existing shearing process. By controlling the angle of the shear, the gap between shears, the applied load, and the rate of load application, it may be possible to produce a sharper edge with reduced or eliminated shear lip. The investigation of optimized foil shearing could be included as part of (or complementary to) the equipment prove-in process currently planned to begin at B&W NOG in FY 2014, but this activity is not currently funded or planned.

### 4.1.11 X-Ray Fluorescence Measurements of Zr Thickness (1.2.4.10)

After Zr co-rolling, the thickness of the foil must be measured and the foil must be inspected for gross material density variations, voids, and inclusions. The most appropriate method for the thickness and density measurements over large areas is moderate-energy (160 kV) digital radiography. However, the thickness of the Zr barrier must be known to within ±0.0002 in. because the Zr affects the x-ray attenuation. An XRF method has been demonstrated to measure the Zr thickness between 0.0005 in. and 0.002 in. with resolution of 0.0001 in. This technique is fast (10 s), accurate, portable (can be handheld), and measures the coating thickness with a 0.2 in. diameter spot size. The goal of this study is to develop and validate measurement techniques that can be used in foil manufacturing to determine Zr thickness. The feasibility of the technique has already been demonstrated, and the present study is focused on calibration and demonstration in a foil manufacturing context. The system will also be used in conjunction with plate manufacturing (see Section 5.1.6).

### 4.1.12 U-Mo/Zr Scrap Recycle Process Development

A study is currently underway to support U-Mo coupon scrap recycle process optimization (see Section 3.1.7), and an initial feasibility study has been done to evaluate foil scrap recycle (Joy 2012). While feasibility was demonstrated, there are outstanding issues with regard to product purity and process details associated that require further investigation. Recycling of foils is complicated relative to coupons by the addition of Zr to the U-Mo coupons. Scrap produced during trimming or by rejected foils must be

separated into the U-Mo and Zr constituents (or U, Mo, and Zr constituents) before it can be recycled. A further complication is that the U-Mo (or U and Mo) separated from the Zr must be recycled into coupon manufacturing, which is performed by a different organization than foil manufacturing. Therefore, the two organizations must work together to ensure the recycle products meet the necessary feed material requirements. Many of the foil process alternatives discussed in the following section address this very issue by attempting to minimize the process steps after the Zr is applied to the U-Mo coupon (e.g., by applying the Zr coating after the U-Mo coupon is rolled to the final fuel meat thickness) to improve yield and reduce scrap. If the Zr deposition process alternatives discussed in Section 4.2.1 are unsuccessful and co-rolling is the method selected in the final fuel fabrication down-selection, then a better defined method for separating and recycling the enriched U will be required to minimize waste to the extent possible.

## 4.2 Foil Process Alternatives

The principal foil manufacturing process alternatives are focused on improved methods for depositing the Zr diffusion barrier on the U-Mo fuel meat. This is perhaps the most problematic aspect of the baseline HPRR fuel manufacturing process. This process is time-consuming and expensive, but it also has proved problematic in terms of ensuring consistent product quality and there are significant implications for HEU material utilization. There are many issues associated with the foils that are addressed by the optimization studies described in Section 4.1, and it is possible that optimization of the process can improve product quality and consistency. However, one aspect of the co-roll bonding process that cannot be optimized in this fashion is material utilization (i.e., yield). When the co-rolled foils are trimmed, the excess material consists of Zr diffusion bonded to the U-Mo fuel meat. Thus, the Zr and U-Mo cannot be easily separated and recycled. The current baseline process is estimated to generate over 750 kg/yr of U-Mo/Zr scrap in full production. As discussed in Section 4.1.12, currently there is no scrap recycle process to remove the Zr from the U-Mo, and development of such a process is complicated by the very nature of the diffusion bond between the Zr and the U-Mo. Therefore, it is likely that the co-roll bonding process will result in significant waste, which is problematic both in terms of low yield on finished foils, but also poor utilization of scarce resources (i.e., HEU).

### 4.2.1 Alternative Zr Application Methods

The goal of the studies described in the following subsections is development of a process to apply the Zr to a U-Mo foil of final (or near-final) dimensions (i.e., 0.008–0.025 in.). Replacing co-roll bonding of Zr to U-Mo with an alternative method will simplify the rolling process (no canned rolling), possibly resulting in higher yield, better control of foil dimensions and mass, and reduced waste (no rolling cans). This could potentially address not only the scrap and material utilization issues, but also provide a process better suited to producing high quality, repeatable Zr dimensions and microstructure (see Sections 4.1.2 and 4.1.4 for discussions of Zr thickness variability after co-rolling). A further advantage of some of the alternative processes is that they could potentially be applied to contoured fuel shapes such as those required for HFIR. A challenging requirement for any alternative process is to produce a strong bond between the Zr and U-Mo fuel meat while minimizing formation of intermetallic phases that may trap fission gases and lead to clad debonding (i.e., blisters or pillowing).

#### 4.2.1.1 Plasma Spray (1.2.4.18)

Plasma spraying is being considered as a means of applying Zr to U-Mo foils after rolling to final thickness. In addition, plasma spraying can be used to deposit Mo as an alternative diffusion barrier that has the advantage of lower cost fuel recycle than fuel with a Zr diffusion barrier. Zirconium and Mo plasma sprayed diffusion barriers were previously demonstrated on "mini-plates" of 1 in. x 4 in. x 0.15 in. size but need to be demonstrated on a larger scale to evaluate the feasibility of the process for production. The present study seeks to scale up the technology to foils of a size relevant for full-scale plate production. Characterization of the plasma sprayed foils includes microscopy and surface condition, including thickness and roughness of the applied barrier. Preliminary results have demonstrated the feasibility of the plasma spray coating process on 24 in. long foils for subsequent application of Al 6061 cladding via HIP (see Sections 5.1.3 and 5.1.4). Thickness control and uniformity are relatively good, and the foils are covered except for the edges and small areas adjacent to the edges where the fixturing grips the foils during coating (Hollis 2014). Future work in this area will include evaluation of plasma spray for depositing Zr on contoured foils, and plasma spraying as a means of applying burnable absorbers to fuel or cladding, as dictated by design studies for HPRR conversion.

#### 4.2.1.2 Energetic Pulse Joining (1.2.4.24)

A feasibility study was performed to evaluate the applicability of the energetic pulse joining (EPJ) method for depositing Zr on U-Mo coupons (Paxton et al. 2013). The EPJ process utilizes a rapid discharge of a capacitor bank to produce a locally intense magnetic field that is directed via careful tooling design into a workpiece to create high velocity motion over very short time periods (<1 ms). The workpiece (in this case, Zr foil) is directed toward a substrate material with which it mechanically or metallurgically bonds due to the high velocity imparted (up to 300 m/s). Ideally, the workpiece is highly conductive so that it responds strongly to the electromagnetic pulse; however, poor conductors can also be accelerated via the use of a conducting driver plate. The EPJ method is used commercially for forming high-conductivity materials such as Al and Cu (e.g., expanding or shrinking cylindrical tubing to size), and it is used to join dissimilar materials that cannot be welded.

The feasibility study evaluated deposition of Zr foil on a stainless steel surrogate substrate. Two methods were considered, including displacement of the Zr foil via electromagnetic force using a driver plate, and direct displacement of the Zr foil via electrohydraulic force. The Zr foil motion was characterized using high-speed cameras, and process parameters were varied to investigate their effect on bond integrity and uniformity. The resulting coatings were characterized using optical microscopy and SEM/EDS/EBSD, as necessary, to evaluate bond integrity and microstructure. The results of the feasibility study demonstrated that high-quality bonds between Zr and the stainless steel substrate could be obtained with proper process control, but only over relatively small areas. The ability to control the process to the extent that would allow suitable bonding over a full-scale fuel foil appeared very challenging. For these reasons, further development of the EPJ process was discontinued at the end of FY 2013.

#### 4.2.1.3 Electroplating (1.2.4.24)

A feasibility study was performed to evaluate the applicability of electrochemical methods for depositing Zr on surrogate foil materials (Mo and Au). Because of the reactivity of Zr, a traditional

aqueous electrolyte cannot be used for electroplating. The electrolytes used to deposit Zr are mixtures of $ZrF_4$ and alkali fluorides (in the case of this study, LiF-NaF-$ZrF_4$). The workpiece is used as the cathode, and a carbon or Zr electrode is inserted into the molten salt to serve as the anode. By controlling temperature and current density, the $ZrF_4$ is disassociated, resulting in the $Zr^{4+}$ ions traveling to the workpiece where they are deposited in a coating layer. If properly controlled, the coatings can be very dense and uniform in thickness. Atmosphere control is very important to the quality of the deposited Zr coating, with oxygen and water contents as low as possible. The electroplating process results in a mechanical bond, so it avoids formation of intermetallic layers between the Zr and U-Mo.

Process characteristics such as temperature, current density, and time were evaluated for their effect on coating microstructure. The resulting coatings were characterized using optical microscopy and SEM/EDS, as necessary, to evaluate bond integrity and microstructure. The preliminary results were very encouraging, after identifying appropriate process parameters. Very dense and uniform Zr coatings were produced on the surrogate substrates, with thicknesses very close to 0.001 in. To achieve these thicknesses, plating times were less than 10 minutes, which lends itself to a high throughput production environment (Coffey et al. 2014). Future work on the electroplating process will include installation of a plating apparatus in a facility that will allow Zr deposition on small (e.g., miniplate dimensions) U-Mo substrates.

#### 4.2.1.4 Co-Extrusion (1.2.4.24)

Zirconium-clad U metal fuels have a significant high-volume manufacturing history (e.g., for Pu production reactor fuel at the Hanford Site). However, the addition of 10 wt% Mo results in a significantly higher strength alloy than $\alpha$-U, requiring higher forces for extrusion. The mechanical properties testing effort described in Section 4.1.6 provided input to the co-extrusion study to enable proper selection of equipment and process parameters. Initial feasibility was evaluated by co-extruding Zr on a stainless steel surrogate substrate in a cylindrical geometry. The study then demonstrated extrusion of an un-clad U-10Mo alloy canned in a Cu alloy. The extrusion was approximately 14 in. long with 0.3 in. diameter. The microstructure was heavily banded due to Mo segregation in the starting billet. The billet also had relatively high Si content, and the Si intermetallics and carbides in the as-cast billet were fractured after extrusion (Lavender et al. 2013). The study considered a number of process parameters including extrusion temperature, force, speed, choice of lubricants (e.g., glass or polymer-based), hot and cold rolling reductions, and intermediate anneals. Future work will include demonstrating the extrusion process on Zr-clad U-10Mo along with shaped extrusions that might be attractive for contoured fuel shapes. After extrusion to bond the Zr and U-10Mo, the workpieces will be further reduced by rolling, both for flat and contoured foil shapes. The Zr coatings will be characterized using optical microscopy, SEM/EDS/EBSD, and XRD to evaluate bond integrity, coating thickness uniformity, and microstructure of the coating and substrate.

#### 4.2.1.5 Electro-spark Deposition (1.2.4.18)

There is some concern within FD that diffusion bonding of the U-Mo fuel meat to the Al 6061 cladding along the foil edges could be problematic with respect to fission gas accumulation, swelling, and cracking during irradiation. Some of the alternative Zr deposition techniques are amenable to coating edges to final dimensions while others are not. Further, if the current baseline process of Zr co-roll bonding can be optimized sufficiently the edges will still have no barrier coating. The electro-spark

deposition (ESD) process is being considered for applying a diffusion barrier material (e.g., Zr) to finished foil edges in conjunction with either co-rolled Zr or one of the alternative deposition methods. The ESD process is akin to welding in which a consumable electrode is used to deposit the electrode material with very precise position control, which makes it attractive for the thin edges of fuel foils. Like welding, ESD creates a metallurgical bond that must be evaluated for its potential impact on fuel performance. The thickness, density, roughness, and diffusion layers with surrogate fuel foils will be characterized. If a Mo diffusion barrier is ultimately desired, ESD could be used to deposit Mo around the foil edges.

#### 4.2.1.6 Physical Vapor Deposition (1.2.4.17)

Physical vapor deposition (PVD) offers another option for depositing Zr on U-Mo coupons in their final dimensions (i.e., 0.008–0.025 in. thick). There are two approaches for producing PVD coatings, evaporation and sputtering. In evaporation, a solid or molten coating material is sublimed or evaporated by application of localized heating (via electrical resistance, laser, electron beam, etc.) and deposited on an appropriately positioned substrate. In sputtering, a solid target composed of the coating material is bombarded with ions to eject atoms that are then deposited on the substrate. Because of the high vapor pressure and reactivity of Zr, sputtering may be more suitable for diffusion coatings on U-Mo fuel. Both methods are typically conducted under high vacuum, requiring large coating chambers for full-size (48 in. long) foils. Deposition rates are relatively slow and line-of-sight, but advantages of PVD methods include high coating density, fine grain structure, and good thickness uniformity (given proper control in the orientation of source and substrate). An advantage for PVD, much like plasma spray, is that it could be used to deposit Mo as easily as Zr. Another advantage for the HPRR fuel application is that these methods are typically conducted at or near room temperature, resulting in little diffusion between coating and substrate materials. As with most coating methods, proper attention to substrate surface preparation is required to ensure adequate adhesion. The proposed study would conduct a feasibility investigation into PVD (both evaporation and sputtering) as a means of applying Zr and/or Mo diffusion barriers to U-10Mo fuel foils. The study would also include an evaluation of appropriate coating systems for both development work and, if proven feasible, production-scale manufacturing.

#### 4.2.1.7 Zr Deposition on Powder Metallurgy Coupons

If a suitable process can be developed for producing PM coupons as described in Section 3.2.7, particularly if it produces near-net-shape coupons, some of the alternate Zr deposition techniques discussed in the previous sections should be evaluated for applicability. However, another possibility is the use of PM methods to deposit the Zr also, either simultaneous with coupon forming, or in a subsequent operation. Such an approach offers potential benefits not only to coupon and foil fabrication, but also to plate fabrication as described in Section 5.0.

### 4.2.2 Chemical Analysis Method Improvement (1.2.4.23)

The femtosecond laser ablation inductively-coupled plasma mass spectrometry (FLA-ICP-MS) method for characterizing chemical composition offers some advantages over existing baseline techniques (e.g., ICP-MS or ICP-OES). The advantages for nuclear fuel characterization include 1) elemental characterization of both bulk and trace composition, 2) isotopics of major elements, 3) rapid analysis, 4) little to no sample preparation, 5) depth profiling, 6) homogeneity of sample, and 7) high accuracy and

precision analyses. Conventional methods of analysis require significant sample preparation involving dissolution of the specimen and eventual measurement for composition and isotopics. FLA-ICP-MS avoids time-consuming sample preparation by directly sampling the specimen and rapidly providing elemental composition and isotopics. The utilization of femtosecond laser ablation offers reduced matrix dependence, quantitative sampling and highly accurate analysis of the sample.

The proposed study would demonstrate the feasibility of using FLA-ICP-MS to characterize DU-10Mo and LEU-10Mo foils for elemental composition and U isotopics. These foil samples will include the Zr barrier coating and will offer a good test of the depth profiling and quantitative capabilities of the instrument. The primary focus of this effort will be demonstrating accuracy and precision of the technique using both a known cast alloy reference material as well as exploring low volume deposition technology for calibration. In addition, conventional laser ablation ICP-MS and high resolution ICP-MS with sample dissolution will be conducted to compare with the performance of the FLA-ICP-MS instrument.

# 5.0 Plate Manufacturing Research and Development

Plate manufacturing encompasses all activities from the finished Zr-coated U-10Mo foil described in Section 4.0 through to the final Al 6061-clad fuel plate in its final dimensions. This portion of the baseline manufacturing process is shown in Figure 5.1 (HIP can assembly) and Figure 5.2 (plate manufacturing), and the R&D activities described in this section are shown in Figure 5.3. The following sections describe R&D efforts that are needed to optimize the baseline process as well as process alternatives that may offer improvements in quality, repeatability, or cost. As described in Sections 3.0 and 4.0, numbers in parentheses following some of the subsection headings indicate the Convert Program WBS under which the work is planned. If a subsection does not have a WBS associated with it, it is because this work is not currently included in the Convert Program planning basis. In these cases, inclusion in this document forms the basis for a recommendation to include the work in future FFC scope planning for the reasons described in the subsections below.

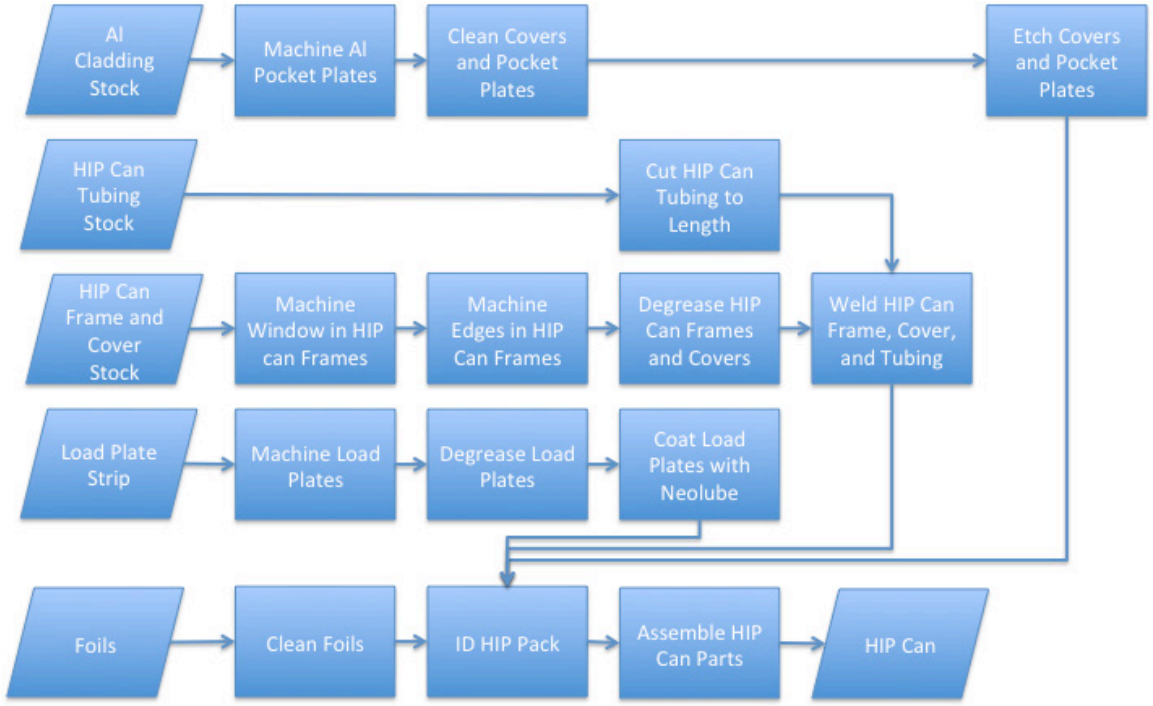


**Figure 5.1**. Simplified Flow Sheet for Baseline HIP Can Assembly Process

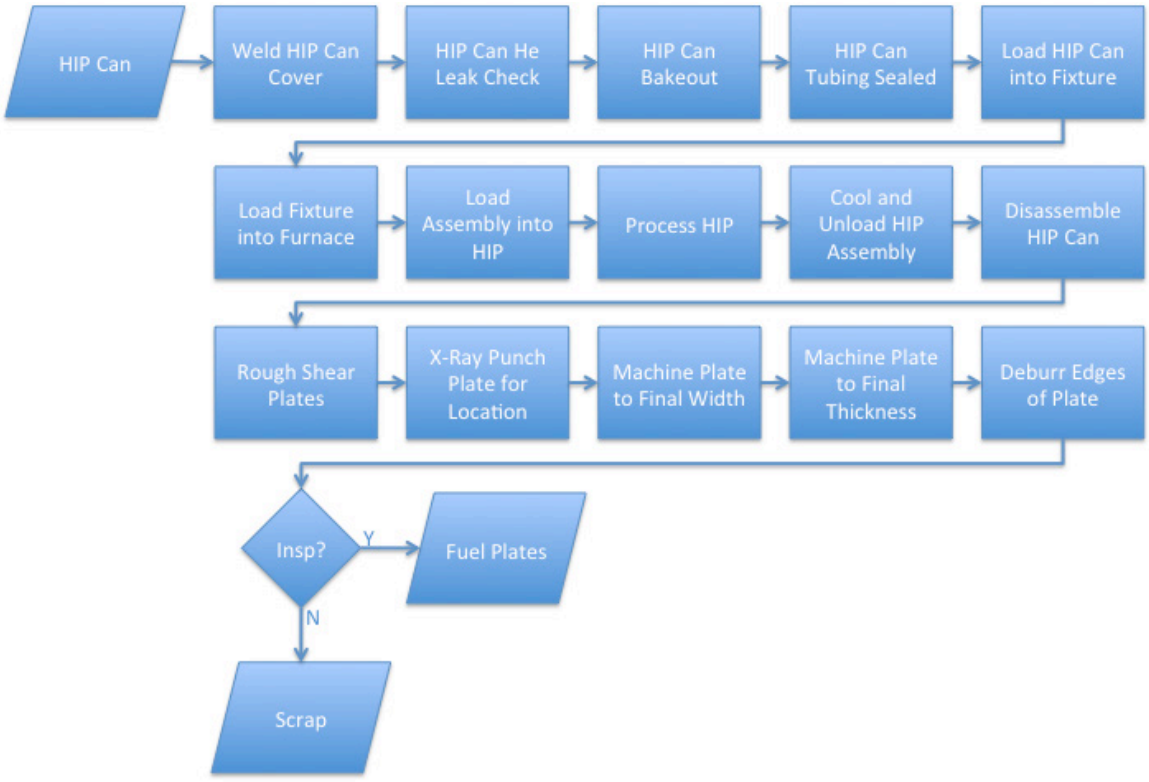


**Figure 5.2**. Simplified Flow Sheet for Baseline Plate Manufacturing Process

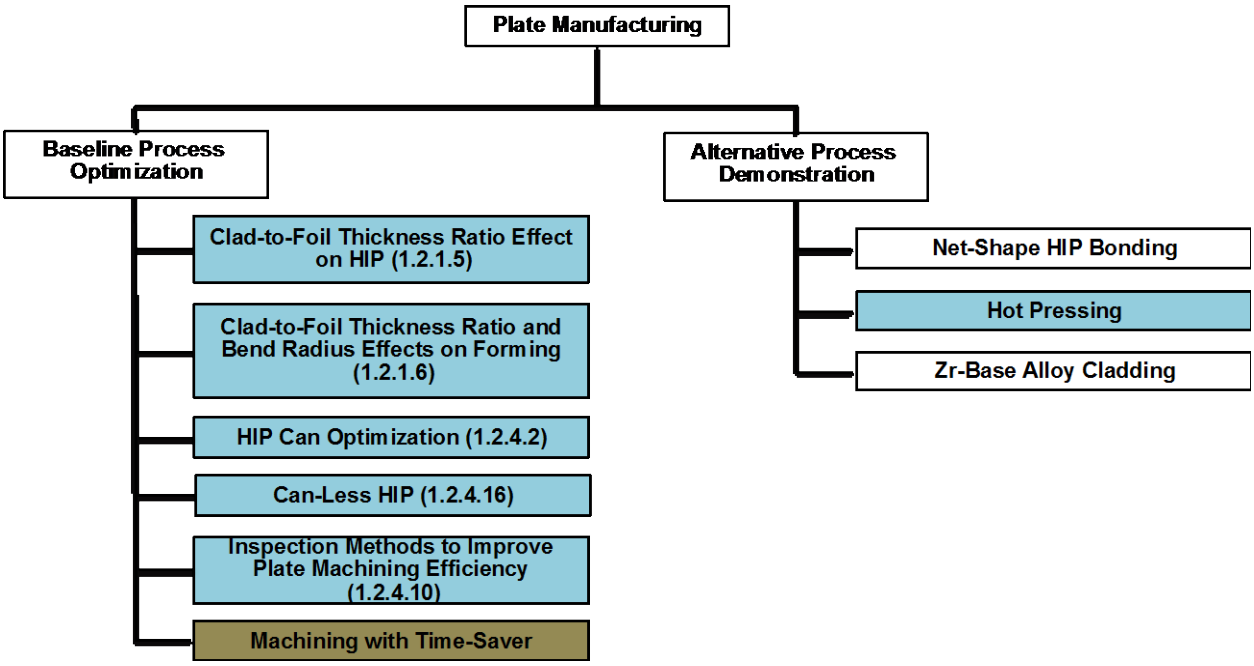


**Figure 5.3**. FFC Plate Manufacturing R&D Activities Described in Section 5.0. The colors denote the responsible organization(s) for each activity and correspond to the colors in Figure 1.1. The white boxes denote activities that are recommended but not currently funded.

## 5.1 Plate Baseline Process Optimization

The principal process development needs for plate manufacturing are related to improving the efficiency of HIP processing and optimizing plate machining and trimming operations. Much of the cost associated with plate manufacturing is associated with these process steps. Specifically, anything that can improve dimensional control (with acceptable throughput) such that plates can be HIPed and machined to final thickness with high confidence they will meet minimum cladding thickness requirements will result in time and material utilization savings that ultimately lower the production cost.

### 5.1.1 Clad-to-Foil Thickness Ratio Effect on HIP (1.2.1.5)

Previous work by FD has suggested that clad surface cleanliness, applied pressure, and applied temperature affect Al-to-Al bond quality (Hackenberg et al. 2013). The previous work suggests that successful Al-to-Al bonding does not depend strongly on the characteristics of the U-10Mo foil. Therefore, this study will use a single foil type produced in the cold rolling study described in Section 4.1.6, and will not vary foil characteristics as an experimental parameter. Wide applicability of HIP bonding to relevant fuel dimensions will be evaluated by cladding two different U-10Mo foil thicknesses (0.009 in. and 0.022 in.) with two different Al 6061 cladding thicknesses (0.38 in. top and 0.32 in. bottom) for a total plate thickness of 0.70 in.

The surface finish and flatness of the HIPed plates will be evaluated after bonding. These characteristics largely dictate the cost of downstream processing steps. There is a balance to be struck between minimizing costs of downstream processing such as machining, and preserving the minimum cladding thickness. While net shape HIPed plates may be practical after further process optimization, there are not sufficient data at the present time to address this issue (see Section 5.2.1). Surface finish and plate thickness will be assessed, with application of confocal microscopy as needed. The as-HIPed surface finish will be compared to the surface finish of typical HEU dispersion fuel plates. This will lead to the identification of methods to improve surface finish, and identify the degree to which methods need to be employed. At least one plate from each batch will be allocated towards demonstration of surface finish techniques. Ultrasonic testing will be conducted to evaluate potential areas not bonded and determine minimum cladding thickness (min-clad) values on each plate. The centering of the plate in the thickness dimension will be determined from these data. Flash thermography may be conducted to evaluate potential areas not bonded and to determine thermal diffusivity of the plate. These methods may be evaluated as potential quality control techniques.

At least one plate from each batch will be dedicated to metallography and microhardness measurements to evaluate the integrity of the Al-Al bond and Al-Zr bond, and evaluate any variations/deviations as a result of the HIP process. Samples for metallography and microhardness will be sectioned from the sacrificial plates at a minimum of five locations (including both ends of the plate and the center). Metallography will be used to note any microstructural anomalies in the plate, foil, and along the fuel-clad interface, while microhardness will be used to determine the structural changes/variations of the foil as a result of the HIP process step. A minimum of two nanocantilever test specimens and two controlled bulge test specimens will be prepared from the sacrificial plate in the same locations as the metallographic samples (one nanocantilever and one controlled bulge test specimen on either side).

The remainder of the as-HIPed plates will be prepared as necessary for machining to one of two final dimensions for use in subsequent studies (Sections 5.1.2 and 5.1.3). Finishing will be by gang milling and utilize in-situ measurements of minimum cladding thickness from a handheld ultrasonic testing unit and a handheld X-ray fluorescence unit. Surface finish and thickness measurements will be performed on all 32 plates.

### 5.1.2 Clad-to-Foil Thickness Ratio and Bend Radius Effects on Forming (1.2.1.6)

Many fuel element designs for HPRRs require plates to be curved with radii of curvature from approximately 2.5 in. (e.g., inner fuel plate in MURR) to approximately 5.5 in. (e.g., outer fuel plate in MURR). This study investigates the plate forming process utilized to form the aluminum alloy 6061 clad, Zr-coated U-10Mo monolithic foil to a specified radius of curvature. Thirty-two plates prepared in the study described in Section 5.1.1 are utilized for this activity, some formed to 2.5 in. radius of curvature, some formed to 5.5 in. radius of curvature, and the remainder formed to the median radius of curvature for the U.S. HPRRs (4.197 in.). This will provide three sets of data for each of the clad-to-foil thickness ratios that will be used to improve a non-linear forming computational model.

Two plates from each set will be progressively formed in roughly 1 in. increments from 5.5 in. radius of curvature to 2.5 in. Fabricated plates will be successively formed to smaller radii of curvature with interim visual and non-destructive evaluation. All formed plates will be photographed and have curvature quantified. One of each two-formed plates with 2.5 in. radius of curvature will have three metallographic samples taken (end, center, end). The samples will be examined by optical metallography and/or SEM for cracks and/or delamination at the Al/Al and Al/Zr interfaces.

One plate from a set formed to 2.5 in. radius of curvature will be sliced into eight pieces. A heat treatment will be done to simulate in-service temperature at eight different hold times. Formed samples will be measured for changes in curvature for various times at temperature. This is to evaluate the hypothesis that there may be thermally-activated reduction in residual stress at in-service temperatures that may result in shape change with some potential for channel blockage. Curvature before and after will be measured. Samples that show greater than 5% change in curvature will be sampled for metallographic specimens, nanocantilever bond strength tests, and controlled bulge tests.

If available, ultrasonic testing (UT) will be utilized to identify any delaminations or weaknesses that develop as a result of the forming operations. Thermography may also be used as an alternative technique to identify any delaminations or weaknesses (when compared to baseline measurements taken in the study described in Section 5.1.1) that develop as a result of the forming operation.

### 5.1.3 HIP Can Optimization (1.2.4.2)

This study will focus on optimization of the HIP can for Al 6061 cladding of Zr co-rolled LEU-10Mo fuel foils, using stainless steel, Zr co-rolled DU-10Mo surrogate fuel, and/or Al-only plates without fuel surrogate. Variables to examine include improving efficiency of fabrication/welding of the HIP cans, decreasing/eliminating the need for machining HIP can parts, evaluating alternate HIP can designs (formed/tubular cans and cans with increased fuel plate capacity), and, in parallel, further parting agent studies (refinement of Neolube or $Mo_2S$ application techniques). In addition, the use of alternate

materials (i.e., carbon steel versus stainless steel, or thinner materials) for HIP can materials, effects of shorter bake-out periods, and the effects of multiple HIP cycles (i.e., if a HIP cycle is prematurely halted, is it viable to re-HIP a can) will also be examined. Finite element analysis will be utilized in conjunction with the experimental work to model HIP can parts to inform the design work and support down-selection from suggested designs.

During FY 2013, design, fabrication, and experimental studies on formed HIP cans demonstrated the viability of the concept at lengths of 25 in., with up to 13 plate packs in the can. The formed HIP cans were successfully fabricated, loaded, welded via e-beam in vacuum, HIPed, and decanned (Clarke et al. 2013, Clarke et al. 2014). Based on this success, the concept will be further developed using approximately half-length (10 in.), full-width (5 in.) formed HIP cans produced via hydroforming. The results from this study will inform another round of experiments with commercially-procured 24-in. formed HIP cans. Optimization efforts will focus on can wall thickness, can depth, and can corner radii. In addition, studies will evaluate the use of TIG welding as an alternative to e-beam. Finite element modeling work will continue as the HIP can design and process evaluations evolve. The plates from the various HIP studies will be characterized to determine dimensional stability, repeatability, and final fuel plate quality (including bond quality evaluations).

### 5.1.4 Can-Less HIP (1.2.4.16)

As described in Section 5.1.3, there are many aspects to HIP can design, fabrication, and use that impact the quality and cost of fuel plates. An alternative to optimizing the HIP can design is elimination of the HIP can entirely. The purpose of this study is to evaluate the feasibility of HIP processing fuel plates directly, without the use of the stainless steel HIP can. Previous studies (Montalvo et al. 2013) have shown promise that properly prepared Al 6061 cladding surfaces can bond successfully (i.e., with observable grain growth across the bond line). Initial analyses have shown the potential for significant labor reductions, while also potentially increasing throughput.

During FY 2013, can-less HIP development scaled-up to larger specimens than previously tested and evaluated a fixture for hanging full-scale plates during HIP processing. Four fuel plates comprised of Al 6061 cladding and stainless steel fuel foil surrogate were electron beam welded in vacuum. Use of an electron beam weld allows sealing and evacuation of the assemblies in a single step. The plates were hanged from an appropriately-designed fixture during HIP. The results indicated promise for the method, and work will continue in FY 2014 to refine the welding process, the HIP fixture, and the HIP process.

The flatness and thickness of all HIPed plates will be measured, and UT imaging will be performed to evaluate bonding across the various interfaces. Two of the plates will be bend-tested to assess bonding and the remaining two plates will be examined via optical and SEM. Grain growth across the bond line will be evaluated with polarized optical microscopy and with EBSD in the SEM.

Future work will use results obtained in FY 2013 and FY 2014 to produce two full-scale plates with DU-Mo foils. The foils produced in the study described in Section 4.1.7 will be used to assemble these plates. These plates will be evaluated after HIP processing via dimensional measurements, UT, and bend testing.

### 5.1.5 Inspection Methods to Improve Plate Machining Efficiency (1.2.4.10)

After HIP processing, there is significant time and cost associated with inspecting and machining the fuel plate to final dimensions. For cladding thicker than 0.025 in., conventional pulse-echo UT instruments provide reliable measurements, but for thinner cladding XRF and/or through-thickness UT methods may offer improved resolution, efficiency, and insensitivity to surface condition. Determining the thickness of the cladding over the fuel meat is a time-consuming but critical process during machining. If the minimum cladding thickness is violated, the plate must be scrapped. Thus, accurate and rapid measurement of the cladding thickness is critical to ensuring an efficient plate machining process that maximizes yield. Depending on the plate thickness, either XRF or through-thickness UT methods could provide the necessary data.

The fuel meat may not be properly centered in the Al clad after HIPing since the Al is close to the plastic limit and will flow. Thus, it is imperative to know the location of the edges of the fuel meat after HIP processing so the Al may be trimmed in the proper location. This can be done most accurately and easily with through-transmission ultrasonic transducers or single-sided dual transducers. While the UT pulse echo technique can be problematic if the Al is not sufficiently smooth, there should be little difficulty with the transmission UT techniques because the signal will dramatically drop during transmission through the fuel meat. Depending on the resolution required for edge sensing, a custom transducer array or focused transducer may be designed and fabricated.

The goal of this study is to develop and validate measurement techniques that can be used in plate manufacturing to 1) locate fuel edges in a plate, and 2) determine Al cladding thickness before and during machining to verify the location of the fuel foil. To this end, automated XRF and UT systems that measure the parameters described above for implementation on a machine tool so operators have rapid feedback to guide machining is being investigated.

The feasibility of the technique has already been shown (Summa 2013) and the present study is focused on calibration, demonstration, and implementation on fabrication machines. Specifically, the study will optimize XRF and UT methods for specific foil dimensions and specific machine tools. This will start with an assessment of specific fuel foil geometries and other relevant parameters potentially impacting cladding measurement, modeling as appropriate to assess impact of aforementioned parameters, and surveying of machining stations associated with fabrication of specific foils. Experimental work will progress to fine-tune measurement parameters for specific foil types. The study will evaluate the impact of residual stress after HIPing on XRF and UT measurement accuracy and resolution. After demonstration on small samples, the techniques will be scaled up to accommodate 24 and 48 in. long plates. Use of the inspection methods on the Zr coatings produced by the studies described in Section 4.2.1 will be investigated to evaluate applicability. Consideration will be given via modeling studies to applying the methods to curved plates and contoured foils.

### 5.1.6 Machining with Time-saver (1.2.5.6)

The baseline plate machining process after HIP processing is to remove material with a mill on one side of the plate at a time, while determining cladding thickness between machining passes via UT to ensure that the minimum cladding thickness specification is not violated. Any waviness in the foil will complicate this process because the thickness of Al 6061 cladding will vary with position. To simplify and speed up the thickness machining process, a possible optimization would be the use of a belt sander,

referred to as a time-saver. A similar process is being considered for coupon machining (see Section 3.2.3). A requirement of the time-saver is that it produces a surface finish at least comparable to that produced by milling. The advantage is that it could be applied to both sides of the fuel plate simultaneously, which increases throughput but also could improve product quality by allowing better stress management. A study on this topic would evaluate processing time, surface finish, and dimensional control.

## 5.2 Plate Process Alternatives

The principal plate manufacturing process alternatives are focused on more efficient methods for bonding the Al 6061 cladding around the foil. In addition to the time and cost associated with preparing the HIP cans themselves, there is significant time and cost associated with machining the plates to final dimensions after HIP processing. Another possible alternative to the baseline manufacturing process is replacing the Al 6061 cladding with a Zr-base alloy for increased strength and potentially improved burnup capacity and accident tolerance. This would entail significant changes to the manufacturing process, but could also potentially eliminate the need for a diffusion barrier between the fuel meat and the cladding.

### 5.2.1 Net-shape HIP Bonding

Net-shape HIP bonding could be an attractive alternative plate processing method with the potential to significantly reduce cost associated with post-HIP bonding machining. If process modifications employed in foil manufacturing result in a consistently flat, well-characterized fuel foil, then the feasibility of net-shape HIP bonding increases dramatically. At present, thick Al sheets are used for bonding the clad to the fuel foil. This step requires significant machining and significant non-destructive evaluation to ensure that the fuel plate meets final dimensional requirements. Due to the complex stress state of the fuel plate, final machining can be quite challenging. Use of net-shape HIP bonding would promote use of Al sheets that are closer to the final dimensions of the fuel plate, which would eliminate a significant portion of the final machining. Such a change would also likely result in increased throughput and reduced processing costs. This alternative has not been investigated in great detail to date as a result of the challenges associated with fabricating a repeatable, flat fuel foil. However, if progress is made in the studies described in Section 4.0, then net-shape HIP bonding deserves closer investigation.

### 5.2.2 Hot Pressing (1.2.4.27)

In its current form, the HIP process used for cladding the fuel foils with Al 6061 cladding applies essentially a uniaxial load to bond the cladding to the fuel foil and itself. There might be advantages to finding a more straightforward method for applying this axial load at appropriate elevated temperatures. Hot pressing might offer an alternative approach that would utilize simpler equipment with a smaller footprint. This alternative also offers an opportunity to eliminate the use of an external steel can to accomplish bonding (i.e., the Al clad would essentially become the can (similar in concept to can-less HIP, Section 5.1.4)).

The proposed study will determine the optimal temperature/pressure/time combinations for hot pressing that can be successfully used to fabricate plates with equivalent or superior performance relative to those produced by HIP. The ultimate goal is to compare the equipment footprint, cost, and efficiency

of the hot press process to the HIP process for fabricating full scale fuel plates. Initial feasibility will be evaluated by pressing small samples (e.g., 3 in. x 3 in.) on a 15 ksi unit. Surface preparation will draw on the experience developed in the can-less HIP study (Section 5.1.4). If successful, later experiments would proceed on a larger press with samples of full-size plate dimensions.

### 5.2.3 Zr-Base Alloy Cladding

There is currently an effort underway within the Convert Program, but outside FFC, to evaluate the advantages and disadvantages of replacing Al 6061 cladding with a Zr-base alloy (Marra 2012). Zr-base alloy cladding was briefly considered during development of U-Mo dispersion fuel, but significant fuel development and manufacturing development work would be required to bring it to the necessary level of technological maturity. Depending on the outcome of the assessment currently underway (results were expected in late FY 2013, but have not yet been released), a number of fuel fabrication processes would need to be evaluated including the method of bonding the cladding to the U-Mo fuel meat and to itself, surface preparation before bonding, trimming to shape, machining to final thickness (or producing net-shape fuel plates), inspecting cladding thickness, etc. Using a Zr-base alloy would require a number of other metallurgical factors to be considered in conjunction with evaluating process parameters including residual stress in the bonded plates, effect of alloy texture on fabrication processes, and oxidation/hydrogen uptake during processing.

# 6.0 Element Manufacturing Research and Development

The intent of the Convert Program is to develop and qualify fuel plates for the six U.S. HPRRs that, externally, are as similar to existing dispersion fuel plates as possible. Thus, the monolithic U-Mo fuel plates should be amenable to existing fuel element manufacturing processes. A possible exception to this that would require investment in R&D activities is the use of borated side plates in the fuel element in the event that burnable absorbers cannot be incorporated into the fuel meat, diffusion barrier coating, or fuel plate cladding (e.g., for MURR transition core, ATR, and HFIR). While borated Al-base alloys are commercially available, some effort would be required to demonstrate the applicability of existing fuel element manufacturing processes with the borated side plates. The presence of boron in the side plates will affect their mechanical properties, which could have an effect on their swaging behavior, and it will affect their chemical composition, which could have an effect on their welding behavior. Similarly, if Zr-base alloys are adopted for fuel cladding as described in Section 5.2.3, then modifications to existing fuel assembly manufacturing processes will be required (Figure 6.1).

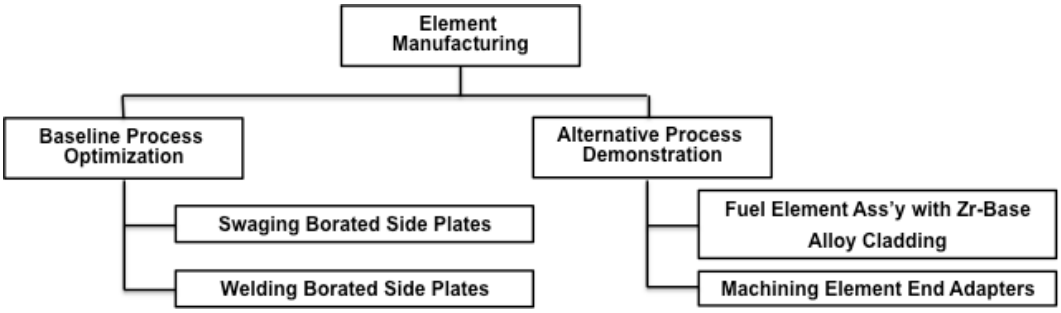


**Figure 6.1**. FFC Element Manufacturing R&D Activities Described in Section 6.0. The white boxes denote activities that are recommended but not currently funded.

## 6.1 Swaging Borated Side Plates

Two of the U.S. HPRRs (MURR and ATR) are considering the use of borated side plates to achieve neutronics performance objectives with LEU fuel (in the case of MURR only for the initial transition from HEU to LEU). Both of these reactors currently utilize swaging for attaching the fuel plates to the side plates. Estimates of the required boron concentration in the side plates range from 2000 to 3000 ppm for both reactors, and it is likely that the side plate designs could be similar for both. Because MURR will not require a large quantity of these borated side plates, commonality of design with ATR is highly desirable to minimize manufacturing costs. Boron concentrations in this range will impact the mechanical properties of the Al-base alloy side plates, and development will be needed not only in the manufacture and inspection of the new side plates, but also with regard to assembling fuel elements. Thus, development activities will be needed to evaluate swaging methods and determine the best technique for attaching the fuel elements to the borated side plates.

## 6.2 Welding Borated Side Plates

The other U.S. HPRR that may require borated side plates for optimum neutronics performance with LEU fuel is HFIR. It is likely that the HFIR side plate design will differ significantly from the eventual designs for MURR and ATR, and the HFIR fuel elements are welded to the side plates, rather than

swaged as for the other four U.S. HPRRs. The presence of boron (and other alloying addition changes that might be required) will have an impact on the welding behavior of the side plates. Thus, a separate development effort will be required for the HFIR design to address side plate manufacturing and attachment of fuel elements to the side plates.

## 6.3 Fuel Element Assembly with Zr-Base Alloy Cladding

In the event that Zr-base alloy fuel cladding is a viable alternative (see Section 5.2.3), development efforts will be required to address both swaging and welding behavior into the side plates for each HPRR. It is possible that a significant departure from current swaging/welding capability would be required to fabricate fuel elements containing a Zr-base alloy clad. In addition, materials compatibility studies would need to be investigated to ensure that any assembly process employed would not introduce an undesired performance consequence.

## 6.4 Machining Element End Adapters

Element end adapters are currently produced by casting. Modern computer-controlled machining systems allow the possibility of efficiently producing these complex parts. Besides eliminating the casting operation, savings potentially could be realized by eliminating the need for certain inspections that are required to address defects specific to the casting process (e.g., voids).

# 7.0 Cross-cutting Research and Development Efforts

There are R&D efforts that have an impact across multiple aspects of fuel fabrication and therefore cannot be categorized as coupon, foil, plate, or element processes. Currently, there are three areas that need to be addressed to support many of the individual processes described in Sections 3.0 through 6.0, including: 1) source material availability, 2) manufacturing process modeling, and 3) digital radiography. These three areas are described in detail in the following subsections and shown in Figure 7.1.

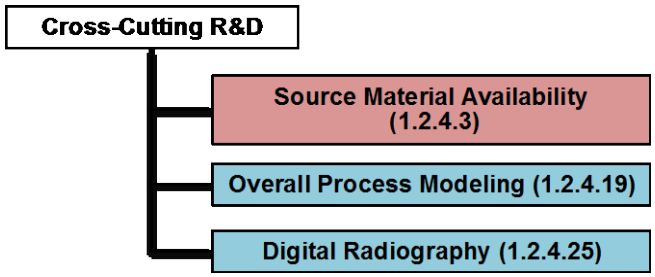


**Figure 7.1**. Cross-cutting FFC R&D Activities Described in Section 7.0. The colors denote the responsible organization(s) for each activity and correspond to the colors in Figure 1.1.

## 7.1 Source Material Availability (1.2.4.3)

In addition to the technical work scope described in the FFC R&D Plan, there is an activity underway to identify the availability of DU and EU to support the significant number of coupons that will be needed to support the R&D efforts as well as production runs for irradiation experiments and eventual reactor conversion. For the available materials, an assessment of their material properties, chemistry, dimensions, etc. will be conducted to understand the amount of work involved in preparing these feed materials for use in various aspects of the Convert Program. Like the R&D Plan itself, this material assessment will be updated on an as-needed basis (e.g., annually) to stay current with anticipated programmatic requirements (Hanlon 2013).

## 7.2 Process Modeling (1.2.4.19)

There is an effort underway to develop discrete-event process models of the full range of fuel manufacturing processes with the intent of enabling cost-benefit trade studies for various fabrication options. To date, this effort has produced a detailed simulation model of most of the baseline manufacturing operations (Jackson and Medina 2013). During FY 2014, the process models are being updated with Y-12 specific data for each of the relevant coupon fabrication process steps. The primary development goal is to provide a flexible data-driven system that could be readily altered to provide "what-if" analyses. Ideally, the model provides a tool to evaluate costs and benefits of manufacturing choices such as those described above in Sections 3.0 through 6.0. For example:

- Implications of implementing a separately-alloyed and downblended feedstock material
- Insertion of a foil annealing process to address foil quality and manufacturing yields
- Impacts of a can-less HIP procedure and alternate Zr barrier application techniques

- Implications of adopting alternatives to HIP processing for plate manufacturing
- Comparisons of alternative fuel cladding materials and fabrication techniques.

Further development of the models will include incorporating new or modified baseline processes, evaluating process alternatives as data becomes available for input, adding manufacturing data required to enable production risk assessments, and exploring synergies between dispersion fuel and monolithic fuel manufacturing.

## 7.3 Digital Radiography (1.2.4.25)

This study supports development of digital radiography for non-destructive quality control testing in a manufacturing environment. The technique could be applied to both foils and plates, hence its inclusion under cross-cutting R&D efforts. The emerging fuel product specification will require inspection for cracks, density variations, and other physical parameters. These inspections are very challenging after the Zr is bonded to the foil and after the foil is bonded inside the Al 6061 cladding. Digital radiography may offer a time- and cost-effective method to perform the necessary inspections. The proposed study will involve B&W NOG to identify optimum radiography systems and operating procedures.

# 8.0 Other Considerations

Besides the technical and economic considerations described in Sections 3.0 through 6.0 for the various manufacturing processes, there are a number of other considerations that must be taken into account when planning the FFC R&D program. Among these are a determination of commercial viability, quality assurance (QA) requirements, and the overall Convert Program schedule. As the optimized or alternative manufacturing processes are evaluated, after establishing their technical and economic validity, their suitability for implementation in a prototypic-scale, production-throughput manufacturing environment will dictate whether further development is warranted. In addition, any optimized or alternative process must be amenable to implementation under full QA and safety rigor in a commercial production environment. If a process is not suited to full-scale implementation with appropriate process control, calibration standards, and qualified inspection methods, it will not offer an improvement to the baseline process regardless of its technical merit. Finally, there are numerous programmatic drivers that dictate when decisions must be made. If a process cannot be developed on the time scale needed to support the final fuel down-selection in 2020, then further expenditure may not be justified despite potential advantages.

## 8.1 Commercial Viability

There are numerous considerations when deciding whether or not to continue development of a particular optimized or alternative manufacturing process. Qualitatively, these considerations include the following:

- Technical Merit – Does the process produce parts that meet product specification requirements?
- Reproducibility – Does the process consistently produce high-quality parts?
- 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 – Can the process be implemented effectively in a uranium production facility regulated by the U.S. Department of Energy and/or the Nuclear Regulatory Commission?
- Quality Assurance – Does the process lend itself to implementation in an NQA-1 manufacturing environment?
- Economics – Does the process offer lifecycle (not just capital) cost savings over the baseline process, including considerations of efficient use of uranium feedstock and scrap recycle?
- 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 new risks?

These qualitative criteria are grouped in the following fashion to produce a quantitative estimate of process maturity using established methodologies to support fabrication technology down-selection in advance of the MP-1 manufacturing campaign:

- Technical Maturity (Technical Merit, Reproducibility) – Defined by Technology Readiness Level (TRL)
- Suitability for Implementation (Scaling, Throughput, QA, ES&H) – Defined by Manufacturing Readiness Level (MRL)
- Economics – Scoring based on estimated ratio of lifecycle cost impact to R&D plus capital cost investment
- Deployment Lead Time (Schedule, Risk) – Scoring based on the complexity of introducing the technology into existing production facilities including footprint, infrastructure, other customer needs, and manufacturing culture.

The TRL is derived from criteria defined in the U.S. DOE Technology Readiness Assessment Guide (DOE 2011), and the U.S. HPRR Project Technology Readiness Assessment Plan (NNSA 2013c). After determining that a given technology qualifies as a critical technology element using the criteria defined in NNSA (2013c), a quantitative TRL value is determined for each technology by answering a series of standardized yes/no questions related to the technological state of process development. Similarly, the MRL is derived from criteria defined in the DoD Manufacturing Readiness Level Deskbook (DoD 2012) by answering a series of standardized yes/no questions related to the manufacturing maturity of the process. The economics (E) criterion is based on an estimated ratio of the capital (C) cost (including R&D, equipment procurement, facility modifications, installation, and initial demonstrations from a given point in time forward; not including past investment) to the estimated annual product savings (P) relative to the baseline process. However, for technologically immature processes (TRL <4), the Economics rating is set equal to the TRL value because the process is not mature enough to make valid lifecycle, R&D, or capital cost estimates. The deployment lead time (DLT) criterion is based on the complexity of introducing the technology into existing production facilities (i.e., Y-12 and B&W NOG) incorporating considerations of footprint, infrastructure, other customer needs, and manufacturing culture. Like the E value, the DLT criterion for immature processes (TRL <4) is set equal to the TRL value because workplace impacts are not yet clearly defined.

The current Convert Program planning assumption is that only manufacturing technologies included in the MP-1 experiment will be eligible for consideration in the final fuel manufacturing down-selection decision. Based on the criteria for determining TRL included in the U.S. HPRR Technology Readiness Assessment Plan, the manufacturing campaign for the MP-1 irradiation experiment is normalized by FFC at a TRL value of 4. Therefore, the ultimate goal for the R&D activities described in this plan is to achieve a TRL/MRL/E/DLT score of 4, within the schedule constraints described in Section 9.2, in order to be considered for inclusion in the MP-1 irradiation experiment and eligible for consideration in the fuel down-selection decision. The basis for assigning TRL, MRL, E, and DLT scores, and the FFC interpretation of the relevant TRL for each fabrication campaign (based on MP-1 as a TRL-4), is summarized in Table 8.1.

**Table 8.1**. Summary of the Basis for Assigning TRL, MRL, E, and DLT Scores for FFC Manufacturing Technologies

| TRL | FFC Fabrication Campaign | TRL Criteria | MRL Criteria | E Criteria | DLT Criteria |
|---|---|---|---|---|---|
| 1 | Prove feasibility | Basic principles observed and reported | Basic manufacturing implications identified | Not enough information | Not enough information |
| 2 | Demonstration under relevant conditions | Technology concept and/or application formulated | Manufacturing concepts identified | Not enough information | Not enough information |
| 3 | Scale-up demonstration | Analytical and experimental critical function and/or characteristic proof-of-concept demonstrated | Manufacturing proof-of-concept developed | Not enough information | Not enough information |
| 4 | MP-1 | Component and/or system validation in laboratory environment | Capability to produce the technology in laboratory environment | Cost to deploy is significantly higher than product savings (C/P > 1.5) | Time to commercial deployment ≥ 5 yr |
| 5 | FSP-1/MP-2 | Laboratory scale, similar system validation in relevant environment | Capability to produce prototype components in a production relevant environment | Cost to deploy is greater than product savings (1.1 < C/P ≤ 1.5) | Time to commercial deployment 3–5 years |
| 6 | ET-1/DDE | Engineering/pilot-scale, prototypical system validation in relevant environment | Capability to produce system or subsystem in a production relevant environment | Cost to deploy is comparable to product savings (0.9 < C/P ≤ 1.1) | Time to commercial deployment 18–36 months |
| 7 | ET-2 | Full-scale, prototypical system demonstrated in relevant environment | Capability to produce components or subsystems in a production environment | Cost to deploy is less than product savings (0.5 < C/P ≤ 0.9) | Time to commercial deployment is 6–18 months |
| 8 | Initial conversion core | Actual system completed and qualified | Pilot line capability demonstrated for full system; ready to begin low rate initial production | Cost to deploy is significantly less than product savings (C/P ≤ 0.5) | Time to commercial deployment less than 6 months |

The TRL, MRL, E, and DLT values have been determined for each of the optimized and alternative processes described in this R&D Plan, and are summarized in Table 8.2. It is important to note that the values described represent a snapshot in time valid at the time this version of the FFC R&D Plan was issued. Each of the R&D activities described in this plan culminates in one or more decision points that will determine the course of future development work. In part, these decision points are based on the TRL, MRL, E, and DLT scores. The relationships between the R&D activities and their interdependent decision points are described in Section 9.1.

**Table 8.2**. Summary of TRL, MRL, E, and DLT Scores for Manufacturing Technologies Included in the FFC R&D Plan

| Technology | WBS | Section | TRL | MRL | E | DLT | Steps to Advance to Next Level |
|---|---|---|---|---|---|---|---|
| Coupon Manufacturing | | | | | | | |
| Optimized VIM Casting | 1.2.1.1<br>1.2.1.2<br>1.2.4.1<br>1.2.4.28 | 3.1.1, 3.1.2, 3.1.3, 3.1.4, 3.1.8 | 3 | 3 | 3 | 3 | Finalize and document key process parameters and optimized mold design(s); document plan for introduction into Y-12 casting operations |
| UMoF Master Alloy | 1.2.3.2<br>1.2.3.3<br>1.2.4.5 | 3.1.5 | 2 | 3 | 2 | 2 | Initiate scaling studies; identify risks and mitigation strategies; finalize and document key process parameters; define throughput scale-up equipment requirements; verify process simulation veracity; document plan to introduce selected technology into a relevant production facility |
| VIM/VAR Master Alloy | 1.2.4.4 | 3.1.5 | 1 | 2 | 1 | 1 | Perform small-scale experiments and compare to expectations; document plan for scale-up and introduction into a relevant production facility |
| Three-Ingot Mold With Intermediate Melt | 1.2.3.2<br>1.2.3.3 | 3.1.6 | 2 | 4 | 2 | 2 | Initiate scaling studies; identify risks and mitigation strategies; finalize and document key process parameters; define throughput scale-up equipment requirements; verify process simulation veracity |
| Three-Ingot Mold Without Intermediate Melt | 1.2.3.2<br>1.2.3.3 | 3.1.6 | 1 | 3 | 1 | 1 | Complete feasibility studies and document results |
| Scrap Recycle | 1.2.4.22 | 3.1.7 | 2 | 2 | 2 | 2 | Sublimation and precipitation methods discontinued |
| Billet Casting | 1.2.4.21 | 3.2.1 | 2 | 3 | 2 | 2 | Initiate scaling studies; identify risks and mitigation strategies; finalize and document key process parameters; define throughput scale-up equipment requirements; verify process simulation veracity; document plan to introduce selected technology into a relevant production facility |

**Table 8.2**. (contd)

| Technology | WBS | Section | TRL | MRL | E | DLT | Steps to Advance to Next Level |
|---|---|---|---|---|---|---|---|
| Coupon Manufacturing | | | | | | | |
| Rolling to Final Thickness | 1.2.4.7<br>1.2.4.21 | 3.2.2, 3.2.5, 3.2.6 | 2 | 3 | 2 | 2 | Identify optimized process parameters to improve yield; initiate scaling studies; identify risks and mitigation strategies; finalize and document key process parameters; define throughput scale-up equipment requirements; verify process simulation veracity; document plan to introduce selected technology into a relevant production facility |
| Machine to Final Thickness | 1.2.1.2 | n/a | 3 | 3 | 3 | 3 | Finalize and document key process parameters; document plan for incorporation into Y-12 machining operations |
| Pickling | 1.2.4.5 | 3.2.3 | 1 | 1 | 1 | 1 | Perform small-scale experiments and compare to expectations; define manufacturing requirements and assess for feasibility |
| Machining with Time-Saver | 1.2.4.5 | 3.2.3 | 1 | 2 | 1 | 1 | Perform small-scale experiments and compare to expectations; document plan for scale-up and introduction into a relevant production facility |
| Machining with EDM | 1.2.4.21 | 3.2.3 | 1 | 1 | 1 | 1 | Perform small-scale experiments and compare to expectations; define manufacturing requirements and assess for feasibility |
| Microwave Melting | 1.2.4.15 | 3.2.4 | | | | | |
| Powder Metallurgy | n/a | 3.2.7 | 1 | 1 | 1 | 1 | Perform small-scale experiments and compare to expectations; define manufacturing requirements and assess for feasibility |
| Foil Manufacturing | | | | | | | |
| Hot Rolling | 1.2.1.3<br>1.2.4.4<br>1.2.4.7 | 4.1.1, 4.1.3, 4.1.6 | 2 | 3 | 2 | 2 | Finalize and document key process parameters; document feasibility of process scale-up; document plan for incorporation into B&W NOG pilot line |
| Cold Rolling | 1.2.1.4<br>1.2.4.4<br>1.2.4.7 | 4.1.2, 4.1.3, 4.1.6 | 3 | 4 | 3 | 3 | Finalize and document key process parameters; socument plan for incorporation into B&W NOG pilot line |

**Table 8.2**. (contd)

| Technology | WBS | Section | TRL | MRL | E | DLT | Steps to Advance to Next Level |
|---|---|---|---|---|---|---|---|
| Foil Manufacturing | | | | | | | |
| Annealing | 1.2.4.6 | 4.1.4 | 2 | 2 | 2 | 2 | Finalize and document key process parameters; demonstrate feasibility on small-scale prototypic materials; document feasibility of process scale-up |
| Warm Rolling | 1.2.4.6 | 4.1.5 | 1 | 2 | 1 | 1 | Perform small-scale experiments and compare to expectations; document plan for scale-up and introduction into B&W NOG pilot line |
| Sizing by Laser Ablation | 1.2.4.8 | 4.1.7 | 1 | 2 | 1 | 1 | Define manufacturing requirements and assess for feasibility; refine equipment design parameters |
| Sizing by Water Jet | 1.2.4.26 | 4.1.8 | 1 | 1 | 1 | 1 | Demonstrate basic functionality in a simulated environment; perform small-scale experiments and compare to expectations |
| Sizing by Slitting | n/a | 4.1.9 | 1 | 1 | 1 | 1 | Demonstrate basic functionality in a simulated environment; perform small-scale experiments and compare to expectations; define manufacturing requirements and assess for feasibility; refine equipment design parameters |
| Optimized Shearing | n/a | 4.1.10 | 1 | 3 | 1 | 1 | Demonstrate basic functionality in a simulated environment; perform small-scale experiments and compare to expectations |
| XRF Measurement of Zr Thickness | 1.2.4.10 | 4.1.11 | 2 | 2 | 2 | 2 | Finalize and document key process parameters; demonstrate feasibility on small-scale prototypic materials; document feasibility of process scale-up |
| U-Mo/Zr Scrap Recycle | n/a | 4.1.12 | 2 | 3 | 2 | 2 | Finalize and document key process parameters; document feasibility of process scale-up; document plan for incorporation into B&W NOG pilot line |
| Plasma Spray | 1.2.4.18 | 4.2.1.1 | 2 | 3 | 2 | 2 | Finalize and document key process parameters; document feasibility of process scale-up; document plan for incorporation into B&W NOG pilot line |
| Energetic Pulse Joining | 1.2.4.24 | 4.2.1.2 | 1 | 1 | 1 | 1 | Discontinued |

**Table 8.2**. (contd)

| Technology | WBS | Section | TRL | MRL | E | DLT | Steps to Advance to Next Level |
|---|---|---|---|---|---|---|---|
| Foil Manufacturing | | | | | | | |
| Electroplating | 1.2.4.24 | 4.2.1.3 | 2 | 2 | 2 | 2 | Finalize and document key process parameters; demonstrate feasibility on small-scale prototypic materials; document feasibility of process scale-up |
| Co-extrusion | 1.2.4.24 | 4.2.1.4 | 1 | 1 | 1 | 1 | Demonstrate co-extrusion of Zr and U-Mo; define manufacturing requirements and assess for feasibility |
| Electro-Spark Deposition | 1.2.4.18 | 4.2.1.5 | 1 | 1 | 1 | 1 | Perform small-scale experiments and compare to expectations; define manufacturing requirements and assess for feasibility; refine equipment design parameters |
| Physical Vapor Deposition | 1.2.4.17 | 4.2.1.6 | 1 | 1 | 1 | 1 | Perform small-scale experiments and compare to expectations; define manufacturing requirements and assess for feasibility; refine equipment design parameters |
| Powder Metallurgy | n/a | 4.2.1.7 | 1 | 1 | 1 | 1 | Perform small-scale experiments and compare to expectations; define manufacturing requirements and assess for feasibility; refine equipment design parameters; document feasibility of process scale-up |
| Chemical Analysis Improvement | 1.2.4.23 | 4.2.2 | 1 | 1 | 1 | 1 | Perform small-scale experiments and compare to expectations; define manufacturing requirements and assess for feasibility; refine equipment design parameters; document feasibility of process scale-up |
| Plate Manufacturing | | | | | | | |
| Baseline HIP | 1.2.1.5<br>1.2.1.6 | 5.1.1, 5.1.2 | 4 | 4 | 4 | 4 | Fabricate plates at low throughput in a relevant environment (e.g. MP-1 fabrication campaign); complete final technical report |
| Formed HIP Can | 1.2.4.2 | 5.1.3 | 2 | 2 | 2 | 2 | Finalize and document key process parameters; document feasibility of process scale-up; document risks and mitigation strategies for manufacturing development |
| Can-less HIP | 1.2.4.16 | 5.1.4 | 2 | 2 | 2 | 2 | Initiate scaling studies; finalize and document key process parameters; document feasibility of process scale-up; document risks and mitigation strategies for manufacturing development |

**Table 8.2**. (contd)

| Technology | WBS | Section | TRL | MRL | E | DLT | Steps to Advance to Next Level |
|---|---|---|---|---|---|---|---|
| Plate Manufacturing | | | | | | | |
| Advanced Plate Inspection | 1.2.4.10 | 5.1.5 | 2 | 2 | 2 | 2 | Finalize and document key process parameters; document feasibility of process scale-up; document risks and mitigation strategies for manufacturing development |
| Machining with Time-Saver | n/a | 5.1.6 | 1 | 3 | 1 | 1 | Demonstrate basic functionality in a simulated environment; perform small-scale experiments and compare to expectations |
| Net-Shape HIP | n/a | 5.2.1 | 1 | 1 | 1 | 1 | Demonstrate basic functionality in a simulated environment; perform small-scale experiments and compare to expectations; define manufacturing requirements and assess for feasibility; refine equipment design parameters |
| Hot Pressing | 1.2.4.27 | 5.2.2 | 1 | 2 | 1 | 1 | Demonstrate basic functionality in a simulated environment; perform small-scale experiments and compare to expectations |
| Zr-Base Alloy Cladding | n/a | 5.2.3 | 1 | 1 | 1 | 1 | Demonstrate basic functionality in a simulated environment; perform small-scale experiments and compare to expectations; define manufacturing requirements and assess for feasibility; refine equipment design parameters |
| Element Manufacturing | | | | | | | |
| Swaging Borated Side Plates | n/a | 6.1 | 1 | 2 | 1 | 1 | Demonstrate basic functionality in a simulated environment; perform small-scale experiments and compare to expectations |
| Welding Borated Side Plates | n/a | 6.2 | 1 | 2 | 1 | 1 | Demonstrate basic functionality in a simulated environment; perform small-scale experiments and compare to expectations |
| Fuel Element Assembly with Zr-Base Alloy Cladding | n/a | 6.3 | 1 | 1 | 1 | 1 | Demonstrate basic functionality in a simulated environment; perform small-scale experiments and compare to expectations; define manufacturing requirements and assess for feasibility; refine equipment design parameters |

**Table 8.2**. (contd)

| Technology | WBS | Section | TRL | MRL | E | DLT | Steps to Advance to Next Level |
|---|---|---|---|---|---|---|---|
| Element Manufacturing | | | | | | | |
| Machining Element End Adapters | n/a | 6.4 | 1 | 2 | 1 | 1 | Demonstrate basic functionality in a simulated environment; perform small-scale experiments and compare to expectations |
| Cross-Cutting Technology | | | | | | | |
| Process Modeling | 1.2.4.19 | 7.2 | 3 | n/a | n/a | n/a | Benchmark models to initial operation of B&W NOG pilot line; document manufacturing trade studies (e.g., impact of Zr on manufacturing costs) |
| Digital Radiography | 1.2.4.25 | 7.3 | 1 | 1 | 1 | 1 | Demonstrate basic functionality in a simulated environment; perform small-scale experiments and compare to expectations; define manufacturing requirements and assess for feasibility; refine equipment design parameters |

## 8.2 Quality Assurance

The QA requirements for the Convert Program are documented in the "GTRI Convert Program Quality Assurance Program Document" (NNSA 2013a). Overall, each program participant is expected to have a DOE- or NNSA-approved QA program that complies with the requirements of DOE Order 414.1, or its equivalent, as well as the requirements specified in 10 CFR 830.120, as applicable for radiological work. The QA Program Document describes a graded approach that is applied using assigned quality rigor levels (QRLs) for specific activities at national laboratories. In general, QRL-2 or -3 is consistent with the high-level QA requirements described by DOE Order 414.1 and 10 CFR 830.120. For QRL-1 activities, a QA program compliant with the requirements of NQA-1 (2000 or later) will be required. Each participating national laboratory will be required under the QA Program Document to develop a cross-reference matrix demonstrating compliance with the appropriate requirements. These matrices will be coordinated by each of the three pillar leads for R&D work within their scope of responsibilities.

According to the guidance in the QA Program Document, activities directly related to NRC licensing actions including facility safety analyses, experiments, tests, reactor-specific design and analyses, and design code verification and validation are all designated QRL-1. Activities that inform policy and key programmatic decisions, reports to Congress and other stakeholders, analyses to support NEPA compliance documents, and cost estimates that support critical decisions are designated QRL-2. Routine R&D activities such as feasibility studies, pre-conceptual and conceptual designs, exploratory trade studies, and conceptual modeling are designated QRL-3. In addition to the requirements described above, QRL-2 activities shall undergo peer review per the requirements in Appendix C of the QA Program Document, and QRL-3 activities shall undergo a technical review per the requirements in Appendix B of the QA Program Document. Contracts with universities or other subcontractors shall flow the requisite QA requirements for the appropriate QRL level as described above. The QA Program Document notes that the specified requirements are minimums, and additional QA requirements can be imposed on individual activities at the discretion of the FD, FFC, and RC pillar managers. In general, the majority of the activities described in this R&D Plan will fall into QRL-2 or -3, but the determination of QRL will be documented in the work package for each activity, and the QRL will be communicated to the performing organization via the individual task work plans. Work that is directly related to producing test specimens for the MP-1 irradiation experiment (i.e., the actual fabrication of MP-1 specimens) will be considered QRL-1.

## 8.3 Schedule

There is a limited window of opportunity to make manufacturing process changes (either optimization of the existing process or alternative processes) for the HPRR conversion fuel, as illustrated by the Convert Program schedule shown in Figure 8.1. Down-selection of candidate manufacturing processes based on the R&D described by this plan must occur in 2016, after which candidate fuel plates for the MP-1 experiment must be fabricated for insertion in ATR in early 2017. Given the current ATR schedule and the duration needed for MP-1, the insertion date cannot slip if the experiment is to be completed before the ATR Core Internals Changeout in late 2018. It is expected that several manufacturing options will be included in MP-1 and FSP-1 (see Section 9.2), but the overall Convert Program schedule dictates that the final prototypic fuel form and manufacturing process be down-selected after PIE is completed on the MP-1 experiment in 2020. This means that all of the down-selected candidate manufacturing

processes must be carried in parallel until that time. Because there is insufficient time to manufacture fuel for the third insertion of MP-1 as well as the FSP-1 and MP-2 experiments using the down-selected prototypic process, all candidate plates for these experiments must be produced at nearly the same time as the plates for the first two insertions of MP-1. As a result, the work described by this R&D plan is very important, because it will form the basis for the ultimate prototypic production process (except possibly for very minor tweaks to certain process parameters). The only opportunity to explore parameter space and alternative processing is between now and 2016 when the candidate processes are down-selected in preparation for the MP-1, FSP-1, and MP-2 plate manufacturing campaigns.

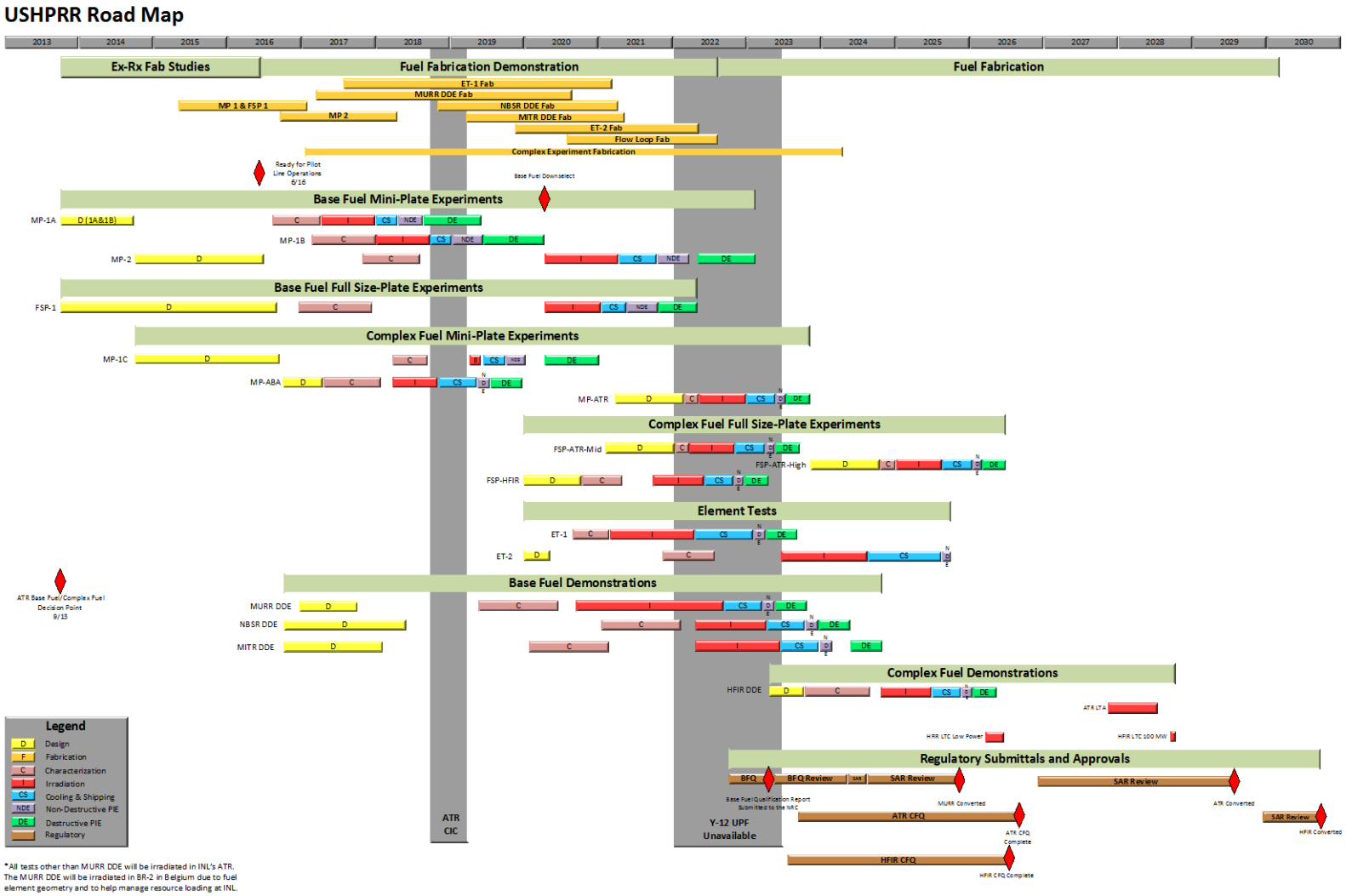


**Figure 8.1**. Convert Program Schedule Showing Key Fuel Down-selection Decision Points That Drive Manufacturing Process Research and Development Needs

# 9.0 Summary and Recommendations

This plan provides an integrated overview of R&D needs that have been identified as necessary for ensuring that FFC is positioned to provide high-quality, cost-effective manufacturing processes consistent with the overall needs of the Convert Program. Section 9.1 describes decision points for each of the research topics such that they support the ability of FFC to produce candidate down-selection fuels for the MP-1, MP-2, and FSP-1 irradiation campaigns so that a final fuel down-selection decision can be made following the second insertion of the MP-1 experiment (MP-1B). In addition to describing work currently planned and funded, the R&D Plan identifies a number of areas that require attention to meet this objective. The fabrication technologies that are currently included in recommendations to FD for inclusion in the MP-1 irradiation experiment are listed in Section 9.2. Recommendations for additional work, schedule drivers for the additional work, and recommended decision points for initiating the additional work are discussed in Section 9.3. Finally, a number of risks are considered in Section 9.4 that have the potential to impact the R&D program as defined in this plan, and therefore have the potential to impact the ability of FFC to meet Convert Program objectives on the specified schedule. Recommendations are provided for actions to mitigate the likelihood of realizing these risks.

## 9.1 Decision Points

Figure 9.1 shows the schedule for the activities described in the FFC R&D Plan along with the logic for making fuel fabrication technology down-selection decisions in advance of the MP-1 experiment. The R&D activities are listed down the left-hand side of the figure, along with the WBS numbers associated with it. The activities are divided into coupon, foil, and plate fabrication technologies, and they correspond to the activities described in the text in Sections 3.0, 4.0, and 5.0, respectively. Activities in black text represent baseline process optimization studies, while those in blue text represent alternative manufacturing technologies. Solid lines indicate activities that are currently funded within the Convert Program, while dashed lines indicate activities that are not currently funded. Within the categories of coupon, foil, and plate fabrication technologies, there are groupings of activities that feed into particular decision points, indicated by pink diamonds. The activities feeding into each of the decision points have earlier decision gates associated with them indicated by the solid circles. Continuation of work beyond the initial decision gates will require assessment against the criteria described in Section 8.1 before making funding decisions for subsequent work. Solid black circles indicate completed decision gates. In the event that a decision was made to continue development of the technology, a solid line will extend from the completed decision gate to the next decision point. If a decision is made to terminate further development, the line will terminate at the completed decision gate. Decision gates in the future are indicated by yellow, green, red, or blue circles, with the color corresponding to the organization responsible for that activity. Several activities have been terminated as of this writing because initial studies did not warrant further development including energetic pulse joining and several options for coupon scrap recycle. Further, current planning assumptions for MITR are based on recent design studies that demonstrate that fins will not be required in the conversion fuel (Bergeron et al. 2013). As a result, no development activities to develop/demonstrate fin machining on plates are currently planned.

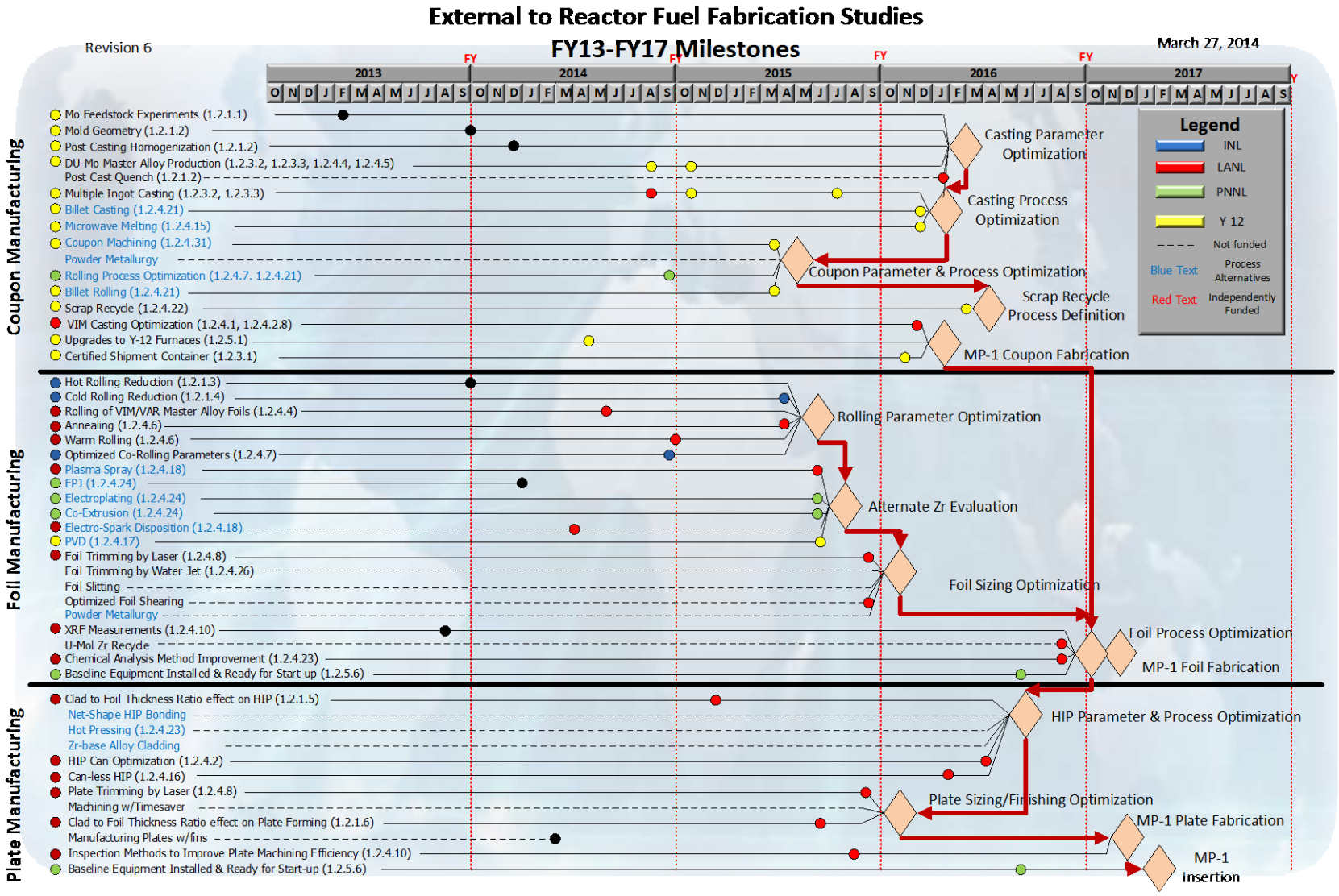


**Figure 9.1**. FFC Research and Development Down-selection Milestones Supporting the Overall Convert Program Schedule

While Figure 9.1 only shows the initial decision gates, technologies may be required to pass several gates before reaching the ultimate decision point for each grouping of activities. The goal of the FFC R&D effort is to generate the information necessary to make informed down-selection decisions by the time the decision points are reached. The timing of the decision points themselves is contingent on the schedule for the MP-1 experiment, and the relevant MP-1 fabrication milestones are indicated in Figure 9.1. It is evident from Figure 9.1 that some technology areas have more schedule "float" than others, primarily due to higher technical maturity in these areas. It is also evident that the timing of the decision points can be adjusted as needed to support the MP-1 experiment. The currently-expected insertion date for MP-1 is shown in Figures 8.1 and 9.1, but the remainder of the decision points in Figure 9.1 are based on the current integrated project schedule that has not incorporated the change in expected MP-1 insertion dates. Given the short period of time available in Figure 9.1 for plate fabrication, it is likely that this activity will need to begin earlier, causing predecessor activities to also be shifted to earlier dates. However, moving the decision points to earlier dates may reduce the number of viable alternative technologies or the degree of optimization in the baseline process. Note that the outcome of the decision points is not necessarily the selection of one set of optimized fabrication parameters or a single alternate technology, but rather the identification of all baseline process optimization and alternate manufacturing technologies that meet the down-selection criteria. Thus, all of the candidate parameters and technologies that successfully pass the decision points will be, in principle, available for fabrication of test specimens for the MP-1, FSP-1, and MP-2 irradiation experiments.

Because of the short turnaround between MP-1 and the follow-on FSP-1 and MP-2 experiments as shown in Figure 8.1 and discussed in Section 8.3, the suite of specimen types that will be available for MP-1 will be the same as those available for FSP-1 and MP-2. In fact, the parent plates for all three tests might be fabricated during the same fabrication campaign or separated by only a short period of time in separate fabrication campaigns.

## 9.2 Manufacturing Technologies Proposed for Inclusion in MP-1

Based on the technical maturity of the coupon, foil and plate manufacturing technologies as shown in Table 8.1 and Figure 9.1, the FFC has proposed a set of technologies for inclusion in the MP-1 irradiation experiment. The technologies selected are those that, at the present time, are 1) judged to have potential to reach a TRL of at least 4 before the MP-1 fabrication campaign begins in 2016, and 2) have the potential to affect fuel properties or characteristics that could potentially impact fuel performance.

The optimized baseline plate manufacturing process in 2016 is expected to incorporate several of the technologies described in this R&D Plan based on progress to date, including use of DU-Mo master alloy feedstock in some form, separate alloying and downblending without an intermediate (log) casting, three-ingot mold casting, some form of ingot thickness reduction by rolling, optimized canned hot and cold co-rolling, optimized foil annealing, foil slitting, and an optimized (formed) HIP can. Alternatives to processes in this FY 2016 baseline proposed for inclusion in the MP-1 test matrix include 1) Zr deposition via plasma spray, 2) Zr deposition via electroplating, and 3) plate pressing via can-less HIP. In order to realize these technologies, several complementary technologies must also progress to a TRL of 4 including some form of ingot (or billet) direct rolling and bare foil reduction via hot and/or cold rolling. Improved inspection techniques to verify fuel meat and Zr layer thickness are also highly desirable.

While the intent for MP-1 fabrication is to utilize prototypic manufacturing processes in a prototypic manufacturing environment (i.e., Y-12 and B&W NOG) to the extent possible, some of the alternative manufacturing technologies to be tested in MP-1 will not have advanced to the point of installation at these facilities. Further, until the fuel down-selection decision is made after MP-1 irradiation is completed, it is not cost- or space-efficient to include all alternatives at the manufacturing facilities. Therefore, several of the alternatives are expected to be fabricated at national laboratories, including plasma spray coating (LANL), electroplating (PNNL), and can-less HIP (LANL). The schedule shown in Figure 8.1 and the manufacturing technology down-selection logic shown in Figure 9.1 are being closely coordinated between FFC and FD to ensure that the MP-1 test matrix includes all relevant and available technologies that potentially could impact fuel performance, while ensuring that deliverables between FFC and FD support the experiment schedule. If the schedule is accelerated because of external factors (e.g., change in core internals changeout schedule at ATR), this could affect the availability of selected alternative technologies if they have not advanced to the desired TRL. Similarly, the availability of selected alternative technologies may be jeopardized if they do not progress to a TRL of 4 as quickly as currently expected (e.g., due to funding constraints or unexpected equipment availability issues). To mitigate these risks on the MP-1 experiment, FFC has recommended that sufficient baseline test specimens be manufactured to fill experiment positions vacated by technologies that are not available by the delivery dates shown in Figures 8.1 and 9.1. Of course, if these technologies are not available in time for irradiation in MP-1, then they will not be candidates for the final fuel down-selection following MP-1, as described in Section 8.3.

## 9.3 Knowledge Gaps

As described in Sections 3.0 through 6.0, there are a number of recommended studies that are not currently funded to support baseline process optimization or alternative manufacturing technologies associated with coupon, foil, plate, and element fabrication. These R&D topics are referred to here as “knowledge gaps” that need to be addressed to ensure all relevant options are considered when optimizing the existing manufacturing processes or evaluating alternate technologies. In this way, confidence will be high that the final down-selected fuel form represents the best value for money and the lowest technological risk. Many of these activities are potential mitigation to the manufacturing-specific risks defined in more detail in Section 9.4. By not pursuing these activities, the Convert Program is accepting risks specific to these technologies. The knowledge gaps identified in the R&D Plan include the following:

- Coupon manufacturing
  - Post-casting quench (Section 3.1.4)
  - Powder metallurgy coupon fabrication (Section 3.2.7)
- Foil manufacturing
  - Foil trimming by water jet (Section 4.1.8)
  - Optimized foil shearing (Section 4.1.10)
  - U-Mo/Zr scrap recycle process development (Section 4.1.12)
  - Electro-spark deposition for coating foil edges (Section 4.2.1.5)
  - Physical vapor deposition (Section 4.2.1.6)
  - Zr deposition on powder metallurgy coupons (Section 4.2.1.7)

- Plate manufacturing
  - Plate machining with timesaver (Section 5.1.6)
  - Net-shape HIP bonding (Section 5.2.1)
  - Hot pressing (Section 5.2.2)
  - Zr-base alloy cladding (Section 5.2.3)
- Element manufacturing
  - Swaging borated side plates (Section 6.1)
  - Welding borated side plates (Section 6.2)
  - Fuel element assembly with Zr-base alloy cladding (Section 6.3)
  - Machining element end adapters (Section 6.4).

From the list above, it is clear that most of the existing knowledge gaps are associated with foil, plate, and element manufacturing. There has been significant emphasis on coupon manufacturing because its product is the source material for all later manufacturing operations, and consequently, it has the earliest decision points as shown in Figure 9.1. However, the two areas listed above under coupon manufacturing must be addressed soon or the possible opportunity to improve coupon manufacturing via these two topics will be lost due to schedule pressure as indicated in Figure 9.1. While there is slightly more time to address the foil and plate manufacturing topics in the list above, these R&D topics (with a couple of exceptions, e.g., foil slitting) also tend to be less mature and will require significant development if initial feasibility studies show promise. Therefore, work on these topics also should start soon (e.g., FY 2014) in order to give them the time necessary to mature and offer a meaningful assessment of their potential.

Two of the element manufacturing topics (swaging borated side plates and welding borated side plates) specifically address complex fuel issues. There are other manufacturing knowledge gaps associated with complex fuel that are not included in the list above, such as reduction (e.g., rolling or extrusion) of contoured fuel meat and application of diffusion barriers to contoured fuel meat. While the first two insertions of MP-1 are specifically geared to evaluating base fuel irradiation performance, the third insertion of MP-1 and potentially MP-2 will need to include specimens relevant to complex fuel. As discussed in Sections 8.3 and 9.1, the schedule shown in Figure 8.1 does not allow time to incorporate feedback from MP-1 before the FSP-1 and MP-2 fuel specimens must be fabricated. Therefore, R&D on complex-specific topics must be conducted in parallel with the remainder of the work necessary to enable fabrication of the MP-1 test specimens.

Another potential knowledge gap not included in the list above, and currently receiving little attention is deposition of diffusion barrier materials other than Zr. There is some evidence to suggest that Mo might serve as an adequate diffusion barrier between the U-Mo fuel meat and the Al-base alloy cladding. An attractive feature of Mo as a diffusion barrier is that recycle issues associated with separating the fuel meat from the diffusion barrier are eliminated because Mo is already present in the fuel composition. Several of the alternative Zr deposition methods may be amenable to depositing Mo (e.g., thermal spray, electro-spark deposition, physical vapor deposition, electroplating, and powder metallurgy methods). Therefore, opportunities to evaluate Mo as an alternative to Zr should be considered while pursuing the R&D activities described in Section 4.2.

Two of the topics in the list above (Zr-base alloy cladding and fuel element assembly with Zr-base alloy cladding) are dependent on decisions that have not yet been made by the Convert Program. If the ongoing

consideration of Zr-base alloy cladding provides a recommendation to evaluate this fuel form, then these studies will be necessary. Alternatively, if a decision is made not to pursue Zr-base alloy cladding, then these studies will not be needed. Therefore, the timing on decision whether or not to pursue these recommended studies is tied to the outcome of the Zr cladding study (Marra 2012). However, the window to address these issues in time to support the MP-1 experiment is rapidly closing.

## 9.4 Risks

Specific risks that have been identified within individual FFC WBS categories are described in the U.S. HPRR risk register (NNSA 2013d) along with mitigating actions that are within direct control of FFC to implement. Some of the risks cross pillar boundaries and thus will require higher-level coordination of mitigating actions (e.g., delays in producing the fuel specification). The FFC will continue evaluating risks and updating the risk register on a regular basis.

A significant high-level risk is the overall risk to the program resulting from the ultimate fuel product fabrication method down-selection decision that must be made after PIE is completed on the second insertion of the MP-1 irradiation experiment. Because there is not enough time in the schedule to implement changes to fabrication processes after this down-selection decision is made before the fuel for the FSP-1 and MP-2 experiments must be fabricated, there is a risk that unexpected performance issues discovered during FSP-1 or MP-2 could challenge the down-selection decision. If this risk is realized, it would not be possible to continue fuel qualification on the schedule shown in Figure 8.1 if it resulted in significant changes to the down-selected fuel fabrication process. A corollary to this risk is that all the fuel for the MP-1, FSP-1, and MP-2 irradiation experiments must be fabricated at nearly the same time as the MP-1 fabrication campaign to ensure that all possible candidates for down-selection are available on a schedule that supports the FSP-1 and MP-2 experiments. Thus, the definition of the MP-1 test matrix is of considerable importance to the program, not only to ensure that fuel is available for the FSP-1 and MP-2 tests rapidly following the MP-1 experiment, but also to include in the MP-1 first and second insertions the appropriate fuel configurations and test parameters to minimize the risk of unexpected performance issues during FSP-1 or MP-2. In particular, it would be prudent for the first two insertions of MP-1 to consider including ATR- and HFIR-relevant operating conditions (originally not planned until the third insertion of MP-1), off-normal operating conditions (originally not planned until MP-2), and size effects (originally not planned until FSP-1).

The risk that is currently impacting MP-1 down-selection is an insufficient foil and plate specification may cause manufacturing problems or failures in irradiation tests. An insufficient specification may result from limited technical oversight, coordination, and direction and may cause a restart of the program with significant cost and schedule impacts. To help mitigate this risk, the FFC team provides technical expertise to the MP-1 working group, institutes quarterly FFC meetings to address technical challenges relating to specification, and engages the specification design authority in bi-weekly conference calls related to fuel fabrication.

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