

# Conceptual Process for the Manufacture of Low-Enriched Uranium/Molybdenum Fuel for the High Flux Isotope Reactor

September 2007

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Research Reactors Division

**CONCEPTUAL PROCESS FOR THE MANUFACTURE OF LOW-ENRICHED  
URANIUM/MOLYBDENUM FUEL FOR THE HIGH FLUX ISOTOPE REACTOR**

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September 2007

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## ACRONYMS

ATR	Advanced Test Reactor
DOE	Department of Energy
DU	depleted uranium
HEU	high-enriched uranium
HFIR	High Flux Isotope Reactor
HIP	hot isostatic press
HPRR	high-performance research reactors
INL	Idaho National Laboratory
LEU	low-enriched uranium
MIT	Massachusetts Institute of Technology
MURR	Missouri University Research Reactor
NIST	National Institute of Standards and Technology
NNSA	National Nuclear Security Administration
ORNL	Oak Ridge National Laboratory
RERTR	Reduced Enrichment for Research and Test Reactors Program



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## ABSTRACT

The U.S. nonproliferation policy “to minimize, and to the extent possible, eliminate the use of HEU in civil nuclear programs throughout the world” has resulted in the conversion (or scheduled conversion) of many of the U.S. research reactors from high-enriched uranium (HEU) to low-enriched uranium (LEU). A foil fuel appears to offer the best option for using a LEU fuel in the High Flux Isotope Reactor (HFIR) without degrading the performance of the reactor. The purpose of this document is to outline a proposed conceptual fabrication process flow sheet for a new, foil-type, 19.75%-enriched fuel for HFIR. The preparation of the flow sheet allows a better understanding of the costs of infrastructure modifications, operating costs, and implementation schedule issues associated with the fabrication of LEU fuel for HFIR.

Preparation of a reference flow sheet is one of the first planning steps needed in the development of a new manufacturing capacity for low enriched fuels for U.S. research and test reactors. The flow sheet can be used to develop a work breakdown structure (WBS), a critical path schedule, and identify development needs. The reference flow sheet presented in this report is specifically for production of LEU foil fuel for the HFIR. The need for an overall reference flow sheet for production of fuel for all High Performance Research Reactors (HPRR) has been identified by the national program office. This report could provide a starting point for the development of such a reference flow sheet for a foil-based fuel for all HPRRs.

The reference flow sheet presented is based on processes currently being developed by the national program for the LEU foil fuel when available, processes used historically in the manufacture of other nuclear fuels and materials, and processes used in other manufacturing industries producing a product configuration similar to the form required in manufacturing a foil fuel. The processes in the reference flow sheet are within the bounds of known technology and are adaptable to the high-volume production required to process ~ 2.5 to 4 tons of U/Mo and produce ~16,000 flat plates for U.S. reactors annually (~10,000 of which are needed for HFIR operations). The reference flow sheet is not intended to necessarily represent the best or the most economical way to manufacture a LEU foil fuel for HFIR but simply represents a “snapshot” in time of technology and is intended to identify the process steps that will likely be required to manufacture a foil fuel. Changes in some of the process steps selected for the reference flow sheet are inevitable; however, no one step or series of steps dominates the overall flow sheet requirements.

A result of conceptualizing a reference flow sheet was the identification of the greater number of steps required for a foil process when compared to the dispersion fuel process. Additionally, in most of the foil processing steps, bare uranium must be handled, increasing the complexity of these processing areas relative to current operations. Based on a likely total cost of a few hundred million dollars for a new facility, it is apparent that line item funding will be necessary and could take as much as 8 to 10 years to complete. The infrastructure cost could exceed \$100M.



## 1. INTRODUCTION

The U.S. nonproliferation policy “to minimize, and to the extent possible, eliminate the use of HEU in civil nuclear programs throughout the world”<sup>1</sup> has resulted in the conversion (or scheduled conversion) of many of the U.S. research reactors from high-enriched uranium (HEU) to low-enriched uranium (LEU)—low enriched meaning uranium having a <sup>235</sup>U content of less than 20% by weight. However, five high-performance research reactors (HPRRs) continue to operate on HEU fuel because there is currently available no suitable LEU fuel that will allow these reactors to meet their mission requirements: the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL), the Advanced Test Reactor (ATR) at the Idaho National Laboratory (INL), the National Institute of Standards and Technology (NIST) research reactor, the Missouri University Research Reactor (MURR) at the University of Missouri–Columbia, and the MITR-II reactor at the Massachusetts Institute of Technology (MIT). Of these reactors, the highest power density core and the most challenging to convert to LEU is the HFIR due to its unique involute-curved fuel plates and variable fuel loading along the span of each plate.

The fuel for HFIR is unique from that of other U.S. HPRRs because the fuel distribution must be contoured in a radial direction in each of the 540 fuel plates that comprise a HFIR fuel assembly. Each two-element assembly consists of a single outer element with 369 fuel plates and a single inner element with 171 fuel plates. In other DOE HPRRs, a reactor core contains multiple fuel elements with each fuel element containing 30 or fewer fuel plates.

Currently, the annual cost of the nuclear fuel consumed in the operation of HFIR is about 20% of the annual operating budget of ~\$60M. A HFIR core — also termed a fuel assembly — that currently costs ~\$1M must be replaced after each ~26-d operating cycle. The schedule of operation of HFIR for the foreseeable future calls for the consumption of 8 – 10 fuel assemblies/year. Obviously any major increase in the fuel costs will significantly impact the HFIR annual budget. Therefore any potential increase in costs associated with the conversion of HFIR to LEU must be understood well in advance by HFIR and DOE management. Over the course of the previous year, a study of the modifications to reactor infrastructure to implement LEU was completed, and an order of magnitude cost estimate for these modifications was reported in ref. 2. The purpose of this work has been to develop a better understanding of the costs of infrastructure modifications and operating costs associated with the fabrication of LEU fuel for HFIR.

During the current and immediate past fiscal years, a design for a new fuel for HFIR was developed based on a 90% uranium (LEU) - 10% molybdenum alloy composition (U-10Mo). This design is documented in refs. 2 and 3 with the material in ref. 3 expected to be included in an annual report for work conducted during fiscal year 2007. Preliminary analyses suggest that such an LEU fuel can maintain the HFIR neutron source performance at the level of current HEU fuel, given that the reactor thermal power is increased from the current level of 85 MW to 100 MW. Qualification of the fuel is the responsibility of the INL. Manufacture of the fuel will be the responsibility of a to-be-determined contractor, but specifications for the configuration and quality of the fuel are the responsibilities of the reactor operators. Reactor operators also bear financial responsibility for the production of the fuel. To estimate the financial impact on the HFIR operating budget of manufacturing the proposed LEU fuel, a study was undertaken to develop a conceptual production process — also termed a “reference flow sheet” — under the assumption that the LEU fuel would be qualified for use in the HFIR. While the constituents of the fuel qualification program are not the subject of this study, it is recognized that qualification of the proposed, foil-type HFIR fuel cannot be done independently of the development of a fabrication facility because the fabrication process and specific equipment impact the final product performance.

A goal of the national LEU conversion program is to develop a LEU fuel that will meet the performance objectives of the reactors targeted for conversion. In addition, the cost of fabricating such a fuel should not have a significant economic impact on the targeted facility's missions. As a first step in developing an understanding of the cost of fuel fabrication, the many steps required were identified as components of a "reference flow sheet." The purpose of this document is to present those components and provide data for order-of-magnitude cost estimates for fabrication facilities or facility modifications and operating costs for fuel fabrication. In developing this reference flow sheet, it was necessary to make some assumptions because all the steps required have not been defined completely or developed fully. Some of the many process steps identified subsequently will change during the course of fuel and process development; however, the magnitude of the infrastructure and operating cost estimates that can be derived from the current reference flow sheet will likely be largely independent of these future changes.

### 1.1 URANIUM/MOLYBDENUM FOIL AS A REFERENCE HFIR FUEL

In the context of this study, a foil is a thin sheet of alloy approximately 8 cm (3 in.) wide and 50 cm (20 in.) long by 300  $\mu\text{m}$  (12 mils) thick. The molybdenum content would be 10% by weight, and the uranium enrichment would be minimally less than 20 wt% (19.75wt%). A photograph of a depleted uranium/molybdenum foil is shown in Fig. 1.



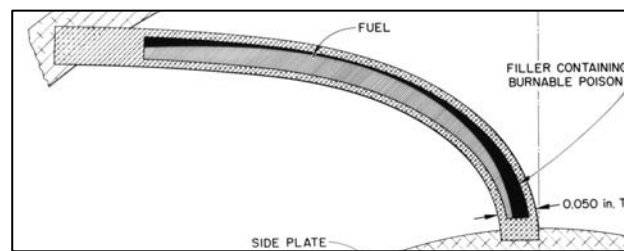
**Fig. 1. Prototypic foil fabricated at the BWXT/Y-12 Plant.**

A foil fuel appears to offer the best option for using an LEU fuel in HFIR because of the density of the alloy; a high-uranium loading is required to maintain the reactor performance at the level currently achieved with HEU fuel. Based on the previously reported neutronic studies,<sup>2,3</sup> the  $^{235}\text{U}$  loading in a HFIR LEU fuel will have to increase from the current 9.4 kg  $^{235}\text{U}$ /assembly in the HEU fuel to  $\sim 17$  kg  $^{235}\text{U}$ /assembly in an LEU fuel. The total fuel loading in HFIR will increase from  $\sim 10$  kg/assembly for the current  $\text{U}_3\text{O}_8$  HEU fuel to  $\sim 86$  kg for the U-10Mo LEU fuel. In addition, to meet the performance objectives of HFIR, the fuel profile within each LEU fuel plate will have to be graded not only in the radial direction as currently required for HEU but also in the axial direction to minimize flux peaking at the ends of the fuel plates.

Even though a dispersion fuel is compatible with existing fabrication capabilities and the HFIR could achieve "close to" current performance with a dispersion U-7Mo fuel, the foil fuel was chosen for the reference flow sheet because of the significant uncertainties in achieving the required density for the dispersion fuel. At the 90 kgU/assembly, a dispersion fuel will require 55 volume-percent (vol %) of the U/Mo in the fuel region (where the balance is aluminum; see Fig. 2 for current HEU fuel, region labeled fuel; a similar profile would exist for LEU fuel) at the current clad thickness of 0.254 mm (0.010 in). Highly loaded dispersion fuels of 55 vol % have been made and tested using spherical particles; however, a production process for achieving these high loadings does not exist even for a flat fuel profile. Producing HFIR fuel plates with the required homogeneity in the current radially profiled



fuel plate is a difficult operation involving manual manipulation of fuel and matrix powders and accounts for > 90% of rejected fuel plates in manufacturing. Achieving the required radial and axial fuel contour profiles with a highly loaded dispersion fuel required for HFIR has not been demonstrated and may not be economically achievable in a production process. Clad thinning with a highly loaded roll bonded dispersion fuel has always been a problem. The nominal 0.254 mm (0.010 in.) cladding thickness, currently used for the < 20 vol % loaded  $U_3O_8$  dispersion fuel, likely will have to be increased to accommodate some “dog boning” (undesired thickening of the fuel region at the top and bottom of the fuel plate) and clad thinning. Increasing the cladding thickness appreciably while maintaining a total plate thickness of 1.27 mm (0.050 in.) would result in a decrease in available volume for the fuel, thus requiring a loading greater than 55 vol. % which is likely not obtainable even with the most optimistic projections of process capabilities. Based on an understanding of the technology and production experience of dispersion fuels, it was judged unrealistic to expect that a fuel fabricator could reach the “required perfection” for fabricating a dispersion LEU fuel for HFIR.



**Fig. 2. Fuel profile inside current HEU inner element fuel plate.**

For a foil fuel, there are still significant uncertainties in the performance of this fuel. In both dispersion and foil fuel, accommodating fission gases during irradiation is the primary concern. Uranium metal containing > 7% Mo seems to be capable of retaining the fission gases in the fuel structure in small bubbles (i.e., submicron) – a prerequisite for predictable, low magnitude swelling during irradiation. Reaction of the U/Mo with the aluminum in the cladding or matrix must be avoided to retain the structure necessary for retention of these fission gases in small bubbles. In a foil fuel, a diffusion barrier between the fuel meat and cladding will likely be required to meet this requirement. The use of a silicon-aluminum alloy to obtain a tight diffusion bond and diffusion barrier of  $U(Al,Si)_3$  provides historical precedent [ref. 4]. Several other materials (such as nickel and niobium) show promise as diffusion barriers but have not been demonstrated to achieve tight diffusion bonds - bond discontinuities seen in rolled and isostatically pressed plates [refs. 5 and 6]. Bonding issues unique to HFIR include the stresses and strains that may be present at the bond interfaces during forming and irradiation from the relatively sharp radii of curvatures in the involute shaped fuel plates. In foil fuel, the bonding of the fuel meat to the cladding is the major area of uncertainty. Understanding of bond interface structure before and after irradiation will be required.

The U-10Mo alloy composition was chosen because the alloy is well within the performance window for low swelling, provided the best performance in irradiation tests conducted to date in the Advanced Test Reactor (ATR), and the addition of slightly more molybdenum above the required 7% minimum does not significantly affect the fuel loading achievable or nuclear properties.

## **1.2 COMPARISON TO CURRENT, HEU, DISPERSION FUEL CYCLE**

Comparisons of the foil and current dispersion fuel fabrication are shown in Fig. 3 in a simplified process flow diagram. A more detailed flow sheet of the current HFIR HEU dispersion process with a cross reference to the applicable LEU foil fuel plate process steps documented in this report is

presented in Appendix A. Additional descriptions of the current HFIR HEU fuel fabrication processes are in refs. 7 – 10.

In the foil process, there are more steps with the attendant increased in-process inventory levels and hold points. Furthermore, there are significant differences in complexity-of-operations for the foil process when compared to the current dispersion fuels. In a dispersion fuel, a single source of fuel particles can be used to make many different types of fuel plates (i.e., 2 types of plates for HFIR, 1 for NIST, and 19 for UAl powder-clad-in-Al ATR elements). In the foil fuel, these different plate types are differentiated before the foils are rolled or cast and processed separately through the remainder of the plate fabrication steps. Additionally, in most of the steps in the foil process, bare uranium alloy must be handled for several operations as contrasted to the current HEU dispersion operation where the fuel/aluminum powder mixture is immediately clad as a billet. The differences in the two operations – more unclad uranium-bearing material steps in the foil process than in the dispersion process - leads to increased potential for airborne and surface radioactive contamination in the foil process relative to the dispersion process. The potential for contamination increases the complexity in certain foil processing areas relative to the current dispersion process. Operations with a potential for radioactive contamination must be performed in radioactive contamination regulated zones. These zones require special air handling provisions, change rooms, special personal protective clothing, and exit monitoring for the workers. In Fig. 3, the processes requiring special handling provisions, e.g. glove boxes, are shown in yellow-tinted boxes.

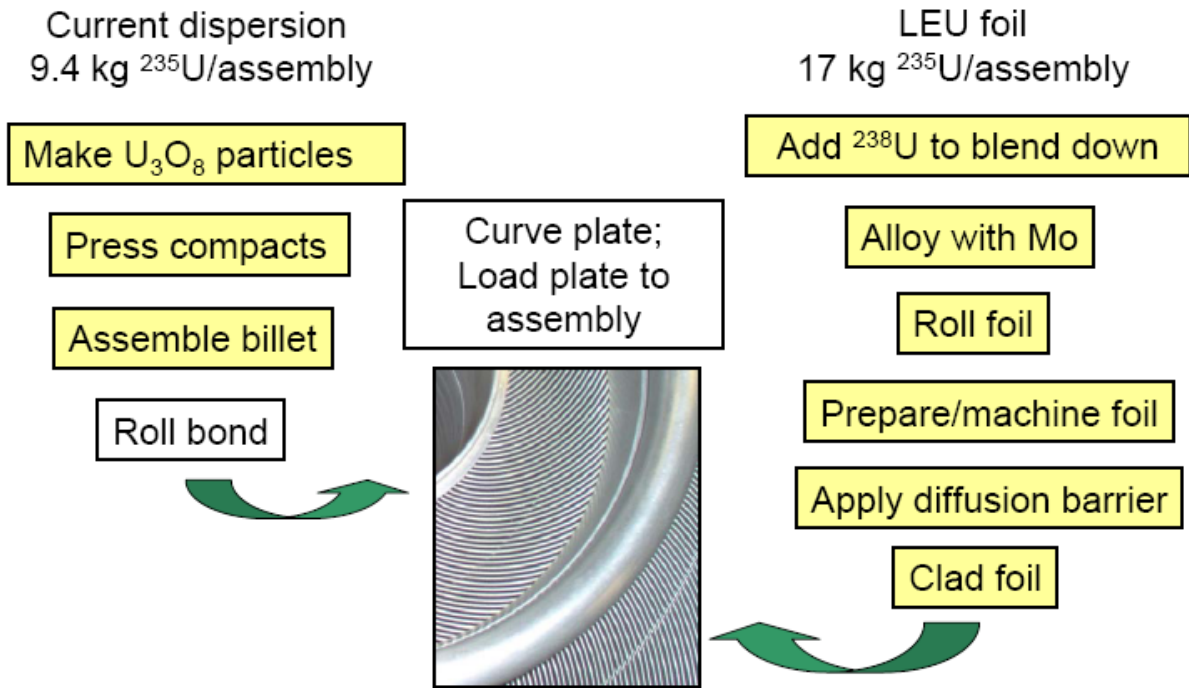


Fig. 3. Simplified comparison of process steps for current HEU fuel and foil-based LEU fuel.

## 2. SIZING OF FABRICATION OPERATIONS

In the current HFIR HEU fuel plate fabrication process, manufacturing the flat plates represents about 60 - 70% of the cost of a fuel assembly. The processes after making flat plates would be comparable for the LEU fuel processes. For all LEU dispersion or foil fuel processes, the blend-down (93% enriched to 20% enriched)\* and alloying-with-molybdenum steps would be required. In making foil fuel, it was assumed that the rolling of flat foils would be a common step for all U.S. HPRRs. The HFIR-specific process steps are primarily associated in producing the foils with the required axial and radial fuel contour profiles.

### 2.1 <sup>235</sup>U CONSUMED IN U. S. HIGH-PERFORMANCE RESEARCH REACTORS

Fuel fabrication for the conversion of the HPRR to LEU is a much larger task than the previous conversion from HEU of a number of relatively low-power reactors by the use of uranium silicide fuel. Conversion of a low-power reactor mainly involves the fabrication of a single replacement core assembly that could then operate for many years without change. In contrast, the HPRRs consume fuel at a much higher rate that requires the replacement of entire fuel assemblies several times a year. For HFIR, eight to ten fuel assemblies (cores) are planned to be consumed annually.

Currently in the U.S. ~ 250 kg of HEU is consumed annually with HFIR and ATR accounting for ~70% of this consumption. With an LEU fuel, at the same operating conditions, the U.S. HPRRs will consume about 450 kg of <sup>235</sup>U/year, assuming the conversion rate of (17/9.4 x 250) as determined in neutronic studies for the conversion of HFIR to LEU. Because there will not be any changes in reactor cycle lengths (performance of reactors unchanged), the number of fuel plates consumed in the U.S. HPRRs will remain constant at ~15,000 fuel plate/year.

### 2.2 FOIL FUEL PRODUCTION REQUIREMENTS FOR HFIR

For the HFIR foil fuel, the production requirements for the various process steps were determined by the facility's planned annual consumption of fuel plates (540 plates/assembly times 10 assemblies/year) and assuming a yield for each of the various process steps. The production requirements for the various process steps required to fabricate a LEU fuel for HFIR are shown in Table 1. The yields assumed in this study, also shown in Table 1, were relatively optimistic values based on the judgments of experts familiar with similar process steps when in a full production mode. In development and startup production, the yields will likely be lower than the values listed in the table. As can be seen, the overall yield through the process is ~ 50%.

To meet the annual production requirements for LEU fuel, some capacity above the annual consumption rate will be required to build inventories of fuel assemblies. Because of the variability of the sole source fuel suppliers (BWXT Y-12 and BWXT/NOD — Lynchburg) and the time required to complete a fuel assembly, an inventory of LEU fuel elements will have to be established and maintained at the reactor location. In the current HEU process, a minimum of 6 months is required to complete a single HFIR fuel element starting with fuel particles. This period is not likely to decrease

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\* One could assume that 20% enriched uranium would be purchased from a commercial facility rather than downblended from HEU. The current policy of the government is that since the uranium discharged from all five high-performance reactors is still classified as HEU, the HEU material is simply assigned to a particular reactor for a time, that reactor operation pays for any subsequent processing of the fuel, and then the spent but still HEU fuel is returned to the government. The proposal presented here — downblending HEU to LEU— is the procedure that is currently used in supplying LEU silicide fuel to American reactors.

in fabricating LEU fuel. Currently, the inventory of HEU fuel elements for HFIR is relatively low – adequate to sustain the reactor operations for ~ 2 – 3 years. To build the inventory of LEU fuel elements to the desired historical 4-year level, it was assumed that an annual production capacity of 50% greater than the consumption rate will be required for HFIR LEU fuel elements. This initial, increased production period would not necessarily be the value used to size the production facility. The increased production in initial years relative to “equilibrium” years could be achieved by added shifts of employees or by staggered introduction of LEU into U.S. reactors.

**Table 1. LEU foil fuel production requirements for HFIR†**

<b>Processes (reverse order)</b>	<b>Needed output plates</b>	<b>Yield (%)</b>	<b>Needed input plates</b>	<b>U-10Mo (kg)</b>
Plate assembly	5,400	90	6,000	1,061
Diffusion barrier	6,000	90	6,667	1,179
Foil preparation	6,667	85	7,843	1,387
Rolling foil	7,843	85	9,227	1,631
Alloying	9,227	85	10,855	1,919
Blend-down	—	75	—	2,559
Inventory buildup (50% greater than annual for first few years)	—	—	16,283	3,759

† Typical yields for U<sub>3</sub>O<sub>8</sub> powder production in the current, HEU process are 50-55%; yield meaning that portion of one batch of input material that ultimately is delivered for loading to a fuel plate. Unacceptable product is collected and recycled though not "tagged" to the source batch. Some, indeed, is lost to "waste" which is not really waste in the sense of the common use of the English word but is instead a stream of material that is lost to the U<sub>3</sub>O<sub>8</sub> production process but will be used by another process. This definition of “yield” is used in Table 1.

### 3. BLEND-DOWN TO < 20% <sup>235</sup>U

Production of the LEU for the U-10Mo alloy (termed “blend-down”) occurs by mixing HEU with natural or depleted uranium (DU) to achieve an enrichment that will be less than 20 wt. % <sup>235</sup>U after allowances for uncertainties in analytical chemistry and process variations within a batch. Blend-down will be required as opposed to enrichment for all LEU fuel types because essentially all the suitable enriched uranium in the U.S. stockpile has enrichment in the order of ~93 wt. % <sup>235</sup>U in total uranium (commercial light water reactors use uranium enriched up to less than 5 wt. % <sup>235</sup>U). The majority of this material is stored in cylindrical annular metal ingots of ~20 kg each. The depleted uranium suitable for blend-down is also stored mainly as metal in slabs of ~200 kg each. Most experience in blend-down has been for making an oxide fuel for light-water reactors using surplus HEU no longer needed for military purposes and has used solution blending to achieve the required enrichment levels of < ~5 wt. % <sup>235</sup>U in uranium. If solution mixing were used for blend-down then dissolution, mixing, precipitation (or dry processing) and bomb reduction steps would all be required to produce a metal suitable for alloying with molybdenum metal. Because the stockpiles for both enriched uranium and DU are already in metal form, solution or other comparable nonmetallic blending processes would be an added complication and likely not an appropriate step for a LEU metal alloy fuel as the final product.

Even though both down-blending and alloying processes involve expensive melting processes, combining the blend-down with the molybdenum alloying step was rejected for the production operation. In the short term, with relatively low startup production requirements and limited melting capacity available within the industry, these steps might be combined. However, in the long term it was decided that these two steps should be separate due to (1) known quality assurance and accountability requirements to certify that the LEU is < 20 wt. % <sup>235</sup>U in total uranium, (2) the potential need to process on the order of 10 metric tons of uranium metal annually to convert all existing U.S. HPRRs to LEU, (3) the possibility of performing the alloying in a lower safeguards security area once the material is converted from HEU to LEU (depending on the relative batch sizes), and (4) larger batch sizes than required for HEU due to the higher, per-assembly uranium loading.

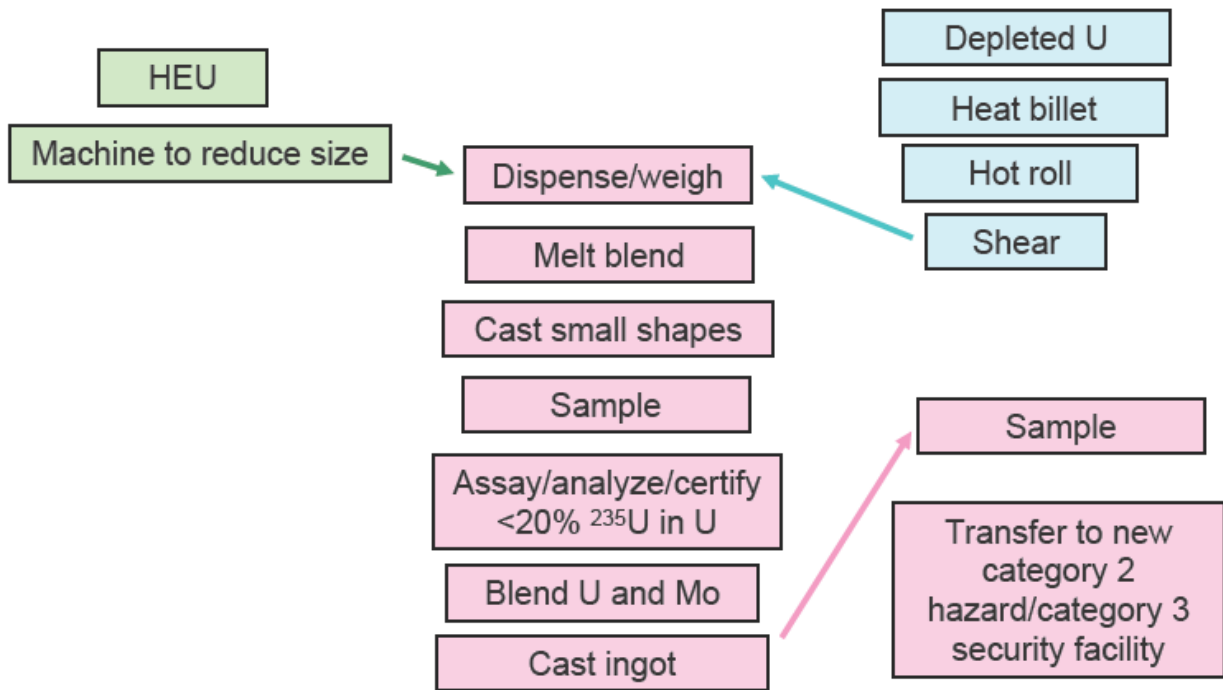
The steps in the reference blend-down processes are shown in Fig. 4. In the ~30-kg batch melting process suitable for HEU, the configuration of the existing annular HEU (~ 4-in.-diameter by ~ 6-in.-high; ~20-kg each) metal shapes in the U.S. stockpile are too large and must be reduced in size. Typically at the Y-12 Plant these shapes are reduced in size by machining. Significant quantities of DU in the stockpile exist in the form of metal in large slabs of ~200 kg each. Typically these large slabs are reduced in size by first hot rolling to reduce the thickness to ~ ½ in. and then sheared into smaller pieces. Size reduction by this process is assumed in the reference flow sheet.‡

Using the size-reduced pieces of HEU and DU; a 30-kg melt batch would be weighted and dispensed

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‡ One reviewer noted that a hydride-dehydride process could be an alternate method of producing finely divided HEU and DU powders that could then be blended. The same technique could work for producing U-10Mo powder from the clean scrap. Use of hydride-dehydride could minimize carbon contamination by reducing the number of melting steps required overall. Powder blending of the uranium powders (including scrap) could be simple and effective if both powders were physically identical. Use of powder dosing could allow precise measurement of U-content in the large batch sizes. The process was not considered as a reference due to the introduction of hydrogen into a full-scale-sized industrial process and the lack of existing facilities for this process on the scale needed. The reviewer also suggested that another option for preparing the source uranium metal for mixture would be to freeze with dry ice or other cryogenic gas and crush in a mechanical press. The metal would shatter into shards if cooled below ductile-brittle transition temperature. This technique was not chosen for the reference flow sheet due to lack of current experience.

into melt crucibles. The melt crucibles will likely be graphite with some appropriate coating (erbium oxide or zirconium oxide) to minimize reaction of the melt with the crucible walls. The introduction of carbon into the metal is of some concern with regard to both corrosion resistance and potential for debonding of the product with aluminum and so should to be minimized. A vacuum melting process will be used to heat the crucible to ~1200°C in the melt blending step. In the vacuum melt processes at Y-12, heating of the melt crucible by either induction or microwave energy is comparable. After the melt blend step, the melt would be cast into small shapes or buttons (about 200 g each) that would be convenient for sampling and alloying with molybdenum in the subsequent alloying step. A developed process for casting small shapes does not exist but is under consideration by Y-12 personnel. In industrial processes, melt buttons are a common form for alloying.



**Fig. 4. Conceptual representation of blend-down and alloying operations.**

After melt blending the LEU buttons would be assayed, analyzed for trace elements, and certified to contain < 20%  $^{235}\text{U}$  and meet the trace elements specifications for research reactors. § Typically the uranium metal would be required to meet an impurity specification comparable to the one developed for Russian-derived enriched uranium metal use in U.S. research reactors. This specification is shown in Table 2. The accountability requirement for special nuclear materials is to be maintained to within 1 g. This requirement requires frequent physical inventory and accounting for HEU streams.

The recycle of clean scrap LEU and the non-recyclable waste stream generated in this process step will affect the infrastructure and operating costs and must be considered in a reference flow sheet. In a melt process, the generation of significant quantities of clean scrap material, e.g. casting runners, is

§ One potential perturbation in the blend-down is the possibility that multiple enrichment values will be required by ATR to meet its performance objectives. The reference flow sheet is for one enrichment value of 19.75%  $^{235}\text{U}$  in total uranium. Processing multiple enrichments would not change the reference flow sheet appreciably but would have major negative economic consequences in manufacturing at blend-down and other processing steps.

inherent and is normally recycled into the melt batches. As much as 20 – 30% clean scrap can be generated and must be considered in sizing the facilities. The yields listed included the internal recycle of this clean scrap, and thus the level of internal recycle had no impact on the yields.

The waste streams generated in the blend-down step that potentially could contain significant quantities of uranium include slag, used graphite melt crucibles, and furnace air filters. Under current practices at Y-12, the uranium contained in these wastes would be considered below economically recoverable quantities and disposed as low-level radioactive waste. Other radioactive waste generated in this process would include room air filters, discarded personal protective clothing, and miscellaneous other waste generated within the regulated zone. All of this waste would require packaging and disposal as low-level radioactive material.

The overall assumed yield of 75% for the melt blend step, including the recycle of clean scrap, was based on the judgment of personnel at Y-12 who are experienced with the uranium melting processes. The production quantities that must be processed in the blend-down step for HFIR will be about 2.5 - 4 metric tons of U/Mo alloy. The compounding of the assumed yields for the other production steps had more influence on the initial uranium quantity required for the blend-down step than the assumed yield for blend-down step alone. As HFIR accounts for about one-third of the U.S. requirements for HPRR LEU, the blend-down quantity required for all U.S. HPRRs will likely be in the order of 7.5 – 12 metric tons. For HFIR, this quantity will require melt blending operation of about one 17-27 kg batch per day, assuming an availability of 200 d/year for the melting facilities. In a dedicated blend-down facility for LEU, processing ~1 to 3 batches/d is a reasonable production level.

**Table 2. Y-12 Standard chemical specification of uranium metal**

Element	Symbol	Units	LEU	EBC factor
Uranium (metal)	U	wt %	99.880%	
<sup>232</sup> U <sup>a</sup>	<sup>232</sup> U	µg/gU	0.002	
<sup>234</sup> U	<sup>234</sup> U	wt %	0.260%	
<sup>235</sup> U ± 0.20 wt %	<sup>235</sup> U	wt %	19.75%	
<sup>236</sup> U	<sup>236</sup> U	µg/gU	4600	
Trans-U (alpha)	TRU	Bq/gU	100.0	
Activation product	ActProd	Bq/gU	100.0	
Fission products	Gamma	Bq/gU	600.0	
Aluminum	Al	µg/gU	150.0	0.0000
Arsenic	As	µg/gU	TBR <sup>b</sup>	0.0008
Beryllium	Be	µg/gU	1.0	0.0000
Boron	B	µg/gU	1.0	1.0000
Cadmium	Cd	µg/gU	1.0	0.3172
Calcium	Ca	µg/gU	100.0	0.0002
Carbon	C	µg/gU	350.0	0.0000
Chromium	Cr	µg/gU	50.0	0.0008
Cobalt	Co	µg/gU	5.0	0.0089
Copper	Cu	µg/gU	50.0	0.0008
Dysprosium	Dy	µg/gU	5.0	0.0818
Europium	Eu	µg/gU	5.0	0.4250
Gadolinium	Gd	µg/gU	5.0	4.3991
Iron	Fe	µg/gU	250.0	0.0006

**Table 2. (continued)**

<b>Element</b>	<b>Symbol</b>	<b>Units</b>	<b>LEU</b>	<b>EBC factor</b>
Lead	Pb	μg/gU	5.0	0.0000
Lithium	Li	μg/gU	2.0	0.1439
Magnesium	Mg	μg/gU	50.0	0.0000
Manganese	Mn	μg/gU	24.0	0.0034
Molybdenum	Mo	μg/gU	100.0	0.0004
Nickel	Ni	μg/gU	100.0	0.0011
Niobium	Nb	μg/gU	TBR	0.0002
Nitrogen	N	μg/gU	TBR	0.0019
Phosphorus	P	μg/gU	50.0	0.0000
Potassium	K	μg/gU	TBR	0.0006
Samarium	Sm	μg/gU	5.0	0.5336
Silicon	Si	μg/gU	100.0	0.0000
Silver	Ag	μg/gU	TBR	0.0083
Sodium	Na	μg/gU	25.0	0.0003
Tin	Sn	μg/gU	100.0	0.0000
Tungsten	W	μg/gU	100.0	0.0014
Vanadium	V	μg/gU	30.0	0.0014
Zinc	Zn	μg/gU	TBR	0.0002
Zirconium	Zr	μg/gU	250.0	0.0000
Total impurities		μg/gU	1200	
Equivalent boron content <sup>c</sup>			3.0	

<sup>a</sup>The “Alpha activity” reflects measured *transuranium* elements to include americium-241, curium-243/244, neptunium-237, plutonium-238, and plutonium-239/240. Such measurement will be in picocuries per gram (pCi/g). An arithmetic conversion will result in a converted upper limit of 6757 pCi/g.

<sup>b</sup>TBR means value “To Be Reported.”

<sup>c</sup>EBC factors are taken from ASTM C1233-97, “Standard Practice for Determining Equivalent Boron Contents of Nuclear Materials.” EBC calculation will include boron, cadmium, dysprosium, europium, gadolinium, lithium, and samarium.



#### 4. LEU ALLOYING WITH MOLYBDENUM

In the alloying step, LEU metal will be alloyed with molybdenum by melting, casting, and rolling into blanks for hot rolling individual fuel foils. Even though the U-10Mo alloy has a melting point of ~1200°C, obtaining the required homogeneous alloy with molybdenum is not a simple task because of the high (2623°C) melting point of the molybdenum constituent. A re-melt step was included in the reference flow sheet to obtain the required homogeneity.\*\* The current practice for making dispersion fuel particles by alloying uranium with aluminum or silicon in “bee hive” type arc furnaces may be applicable for small quantities of U-Mo alloy for foils but is probably not applicable for the larger scale that will be required to roll foils for full-sized plates. In addition, arc melting for alloying the high-melting-point molybdenum with uranium in the cold copper hearth used in these types of “bee hive” furnaces can result in significant copper contamination in the melt.

The alloying process is also shown in Fig. 4. Melt buttons of LEU and molybdenum would be dispensed by weight into a melt crucible for a batch. In the reference process, a 17-27 kg batch size is assumed based on known technology at Y-12. In the future, a larger LEU batch size may be warranted to obtain some economies of scale. As in blend-down, the assumed melt crucibles are graphite with some appropriate coating (erbium oxide or zirconium oxide) to minimize reaction of the melt with the crucible walls. The introduction of carbon into the metal is still of some concern and should be minimized. A vacuum melting process will be used to heat the crucible to >1200°C in the alloying step. In the vacuum melt processes at Y-12, heating of the melt crucible by either induction or microwave energy is comparable. Plasma arc melting could be considered in the future but was not the process selected as reference. After the alloying step, the melt would be cast into ingots that would be hot rolled into blanks of appropriate thickness for hot rolling the foils. The casting step might be combined with the initial hot rolling step in a dedicated LEU-molybdenum alloy production line in the future.

In the reference process, the individual blanks are prepared by hot rolling (~ 930°C) the cast ingot into a plate of about 2.54 mm (~0.100 in.) thick, then it is sheared into individual blanks of appropriate length and width for rolling the individual fuel foils. For HFIR, the foil blanks would be sized to 10 cm (~ 4 in.) wide by 7.5 cm (~3 in.) long to allow for trimming of the finished foil. It might be advantageous to make the blanks 15 cm (~6 in.) long and roll two foils from a single blank by shearing the foil during the hot rolling processes similar to the way HFIR fuel plates are currently hot rolled (two fuel compacts per billet loaded to the rolling mill). At this stage each foil would be marked for identification and tracking throughout subsequent process steps.

Individual blanks will be prepared for hot rolling to individual plate fuel foils based on current practices at Y-12. However, preparing and handling the large number of blanks (~10,000 blanks/year for HFIR at equilibrium) required at this stage in production may not be appropriate when operating at full production quantities. Because two different widths and, correspondingly, two different thicknesses of fuel foils will be required for HFIR and 19 different widths for ATR, future consideration should be given to rolling the alloy for blanks in wider widths (perhaps 61 cm [24 in.]) and lengths that could be slit and sheared to make appropriately sized individual blanks.

The recycle and waste streams generated in this process step are comparable to the blend-down step

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\*\* If powder-based, alternative processes mentioned in previous footnotes, were used, then use of powdered Mo (powder metallurgy is sometimes used to produce “ingots” of Mo) could be investigated. Homogenization of the Mo and U powders prior to melting might allow a single melt, eliminating the re-melt step. Lack of experience led to this concept being designated as an alternative, rather than the reference process.

and will affect the infrastructure and operating costs. In the alloying process, the generation of significant quantities of clean scrap (trimmings) is inherent and is usually recycled into the melt batches. As much as 20 – 30% of clean scrap can be generated and must be considered in sizing the facilities. The yields listed included the recycled clean scrap and thus had no effect on the yields assumed.

Typically the alloyed uranium metal will also be required to meet a trace element specification comparable to the one shown in Table 2. The specification for the  $^{235}\text{U}$  enrichment was assumed to be 19.75% with a maximum variation of  $\pm 0.25\%$  to ensure that the  $^{235}\text{U}$  content never exceeds 20%. With a 20%  $^{235}\text{U}$  in uranium, the alloy is still considered special nuclear material with an accountability requirement to within 1 g. This requirement will necessitate frequent physical inventory and accounting of LEU.

The waste streams generated in the alloying step that potentially could contain significant quantities of uranium include slag, used graphite melt crucibles, and furnace air filters. As noted previously, under current practices at Y-12, the uranium contained in these wastes would all likely be considered below economically recoverable quantities and disposed as low-level radioactive waste. Other radioactive waste generated in this process would include room air filters, discarded personal protective clothing, and miscellaneous other waste generated within the regulated zone. All of these wastes would require packaging and disposal as low-level radioactive material.

The overall assumed yield of 85% for the alloying step was based on the judgment of personnel at Y-12 experienced with the uranium alloying processes. The production quantities that must be processed in the alloying step for HFIR amounts to  $\sim 2$  metric tons of LEU-10Mo alloy annually. More importantly are the  $\sim 10,000$  individual blanks that will have to be processed annually for HFIR. This quantity equals to  $\sim$  two 25-plate lots per day for HFIR, assuming a facility availability of 200 d/year. In a dedicated facility for LEU, processing two HFIR plate lots/day is equivalent to the current production level for HEU for all U.S. reactors at BWXT's Lynchburg facility (production at Lynchburg with existing equipment and 1 shift of operators is two, 24-plate lots per day). For LEU, these high production quantities could be processed in a specifically designed dedicated facility for LEU. However, these large production quantities are outside the scope that can be processed in existing or planned "job shop" type facilities.

## 5. ROLLING OPERATIONS FOR FOIL FUEL

In the reference flow sheet, the foil rolling process is common to all HPFRs with the exception that different widths and thicknesses will likely be required for each reactor. For HFIR, two foil thicknesses will be required; about 305  $\mu\text{m}$  ( $\sim 0.012$  in.) thick for the inner fuel elements and about 406  $\mu\text{m}$  ( $\sim 0.016$  in.) for the outer elements. The “as rolled” width of the finished foils for both HFIR elements will be wider (about 8.9 cm [ $\sim 3.5$  in.]) than the finished fuel core specifications to allow a margin for trimming.

The reference process for the foil rolling step is shown in Fig. 5. In this process, the individual foil blanks of  $\sim 250$   $\mu\text{m}$  thick would be hot and cold rolled to the desired thickness for subsequent processing. Rolling of uranium metal into foils to  $<250$ - $\mu\text{m}$  thick is well-documented technology, and some demonstration, full-size uranium fuel foils have been rolled. However, the rolling of uranium foils with the dimensional control that will be required in a production process has not been demonstrated. Uranium metal alloys work-harden rapidly during rolling, and the billets must be annealed at  $\sim 930^\circ\text{C}$  between each hot rolling pass. A 10 – 20% reduction-per-pass hot rolling schedule can be achieved to a thickness of  $\sim 500$   $\mu\text{m}$ . The finished foil thickness is achieved by cold rolling. In cold rolling, after only 50  $\mu\text{m}$  ( $\sim 0.002$ -in.) reduction in thickness, annealing is required. A salt bath to maintain the temperature at the required  $930^\circ\text{C}$  has been used at Y-12 for annealing uranium alloys between rolling passes for many years and is the reference annealing process. In a dedicated LEU production line, other annealing techniques (i.e., infrared heating) may be more efficient and should be considered in the future. The thickness of the finished foils needs to be controlled to within at least  $\sim 25$   $\mu\text{m}$  (0.001 in.) within each foil and among foil-to-foil production. At this stage in development, no information is available concerning the statistical variation of the foil rolling process.

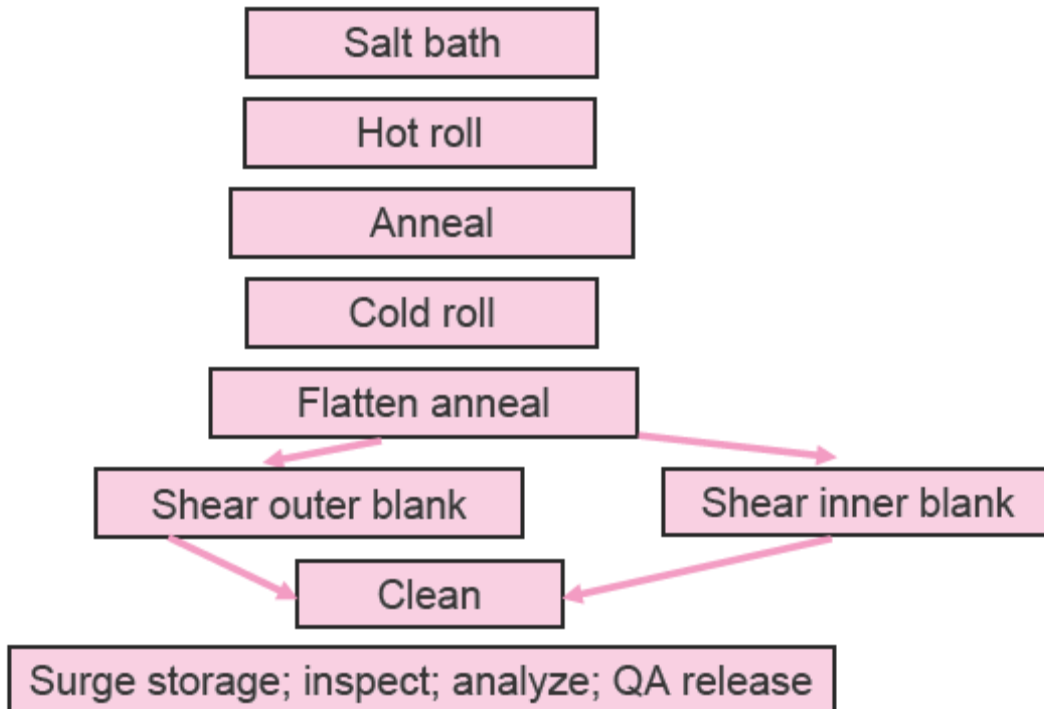


Fig. 5. Conceptual foil rolling operations.

After cold rolling, the fuel foils must be flattened. In the reference process, flattening is accomplished by the phenomena of creep, using dead weights on top of the fuel foils at the annealing temperature. This is analogous to the process used in the current HEU fabrication process to flatten aluminum fuel plates after cold rolling. After flattening, the fuel foils would be cut to their finished dimensions by using a blanking die and shearing.

Inspection of the finished foils would consist of dimensional and surface inspection covering 100% of the plate surface and destructive metallographic examination of samples for grain structure and micro-structural phases. The weight of each finished foil would be measured and recorded for accountability. Engineering drawings and specifications will have to be developed for the inner and outer flat fuel foils. The specification will need to be linked to the finished foil specifications in the next section.

The waste streams generated in rolling of flat foils would primarily consist of rejected fuel foils and trimmings from the blanking of finished flat foils. Some part of this waste stream might be considered clean scrap and recycled in the melting step in the alloying process. Other parts would be considered disposable waste. Under the current practices at Y-12, the uranium contained in this waste would again likely be considered below economically recoverable quantities and disposed as low-level radioactive waste. As noted previously, other radioactive waste generated in this process would include room air filters, discarded personal protective clothing, and miscellaneous other waste generated within the regulated zone.

The overall assumed yield of 85% for the flat foil rolling process was based on individual foils accepted at this step and was based on the judgment of personnel experienced with the manufacture of HFIR fuel plates. The production quantity that must be manufactured in flat foil rolling is 9227 individual foils, initially, for HFIR alone. This quantity equals to approximately two 24-plate lots per day for HFIR, assuming a facility availability of 200 d/year. In a dedicated facility for LEU, processing two HFIR plate lots/day is a production level comparable to the current level of production for HEU at BWXT in Lynchburg, Va. For LEU, these high-production quantities could be processed in a specifically designed dedicated facility for LEU.

## 6. FOIL PREPARATION FOR ASSEMBLY

The foil preparation step for HFIR differs from other U.S. HPRR because of the requirement that the flat fuel foil must be contoured in both the radial and axial directions to minimize power peaking due to the nuclear flux peaking at the edges and ends of the fuel plates during operation in the reactor. Minimizing this power peaking is necessary to allow HFIR to maintain the current, HEU-fuelled level of performance. The need for the axial fuel profile is unique to a LEU HFIR fuel because the current HFIR HEU dispersion fuel is contoured only in the radial direction.

Achieving the required contours on 305- and 406- $\mu\text{m}$ -thick flat foils has not been demonstrated. Several approaches could be considered, and one feasibility study of rolling the contour was performed at Y-12 with some success. Vapor deposition for forming the HFIR foil with a contour was proposed by ORNL as a possible alternate approach, but after a study of the flow sheet requirements, it was decided that this process was not likely viable because of the difficulties anticipated in preparing a suitable feed from the existing uranium metal stockpile and the large production quantities required. Vapor deposition for the application of a diffusion barrier and/or the aluminum cladding to the HFIR contoured foils are a more attractive alternate processes to consider. Commentary and description of vapor deposition processes are presented in the Appendix B.

A simple rolling process may not be capable of achieving the required dimensional control on the non-symmetrical radial profiles required. Regardless, the axial contour required would necessitate a separate forming step. Other conventional metal forming techniques (i.e., forging or swaging) might be applicable in forming the contours, but these techniques have some of the same drawbacks as rolling. At this stage of development, machining the required profile appears to be the most direct approach of achieving the required profile within the likely dimensional tolerances that will be allowed. Machining will lead to a large quantity of clean scrap in the form of metallic fines.

In considering machining of the required profiles on the flat foils, the applicability of the HFIR HEU-type curve contour (see Fig. 2) on such thin foils was not apparent and would require a more complex machining operation to form the required curved contour. With the thin foils, a curved contour would approach a straight line for all practical purposes. In the HFIR HEU dispersion fuel, the one-sided radial contour, which is formed by a powder metallurgical technique, may not be the best configuration for a HFIR LEU fuel foil. A foil symmetrical about its axial midplane may be easier to machine or form, and such a symmetrical foil would provide significant benefits in the subsequent diffusion barrier application, cladding preparation, bonding, and involute forming steps. Comparable, industrially manufactured metal foils with tapered edges symmetrical about its axial midplane include double-edged razor blades. Razor blades are produced by the millions worldwide.

After determining that symmetrical straight contoured fuel foils would not have any negative impacts on a LEU fuel performance in HFIR, the foils contours shown in Fig. 6 were selected for the reference foil designs. The end contours would be formed by machining in a separate operation. The design parameters for the reference contoured foils required for a HFIR LEU fuel are shown in Table 3.

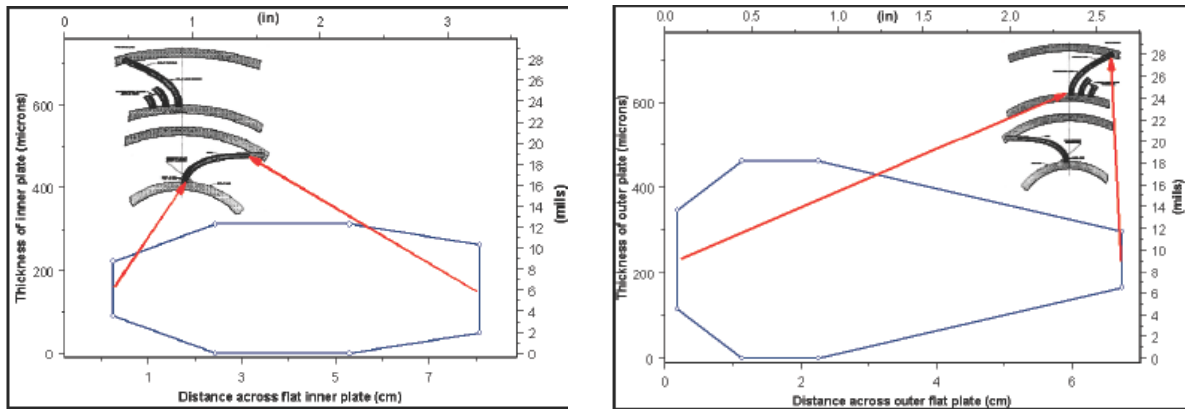


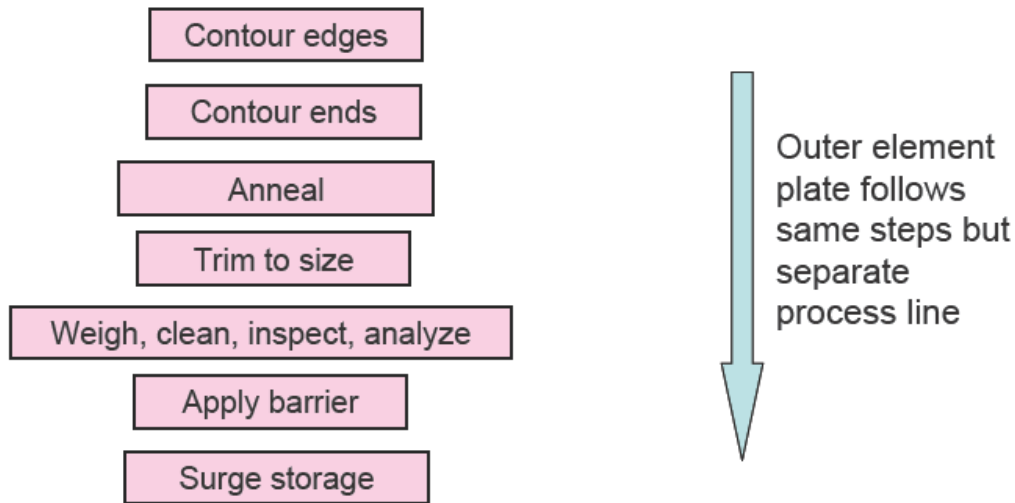
Fig. 6. Flat edge profiles for inner element fuel plate (left) and outer element fuel plate (right).

Table 3. HFIR LEU contoured foils design parameters

Design parameters	Outer foil	Inner foil
Fuel foils width, in.	2.758	3.143
Fuel foils length, in.	19.980	19.980
Fuel foils average thickness, in.	0.011	0.011
Fuel foils maximum thickness, in.	0.016	0.012
Edge taper length — reference edge, in.	0.035	0.750
Edge thickness — reference edge, in.	0.009	0.005
Edge taper length — opposite edge, in.	1.750	1.000
Edge thickness — reference edge, in.	0.005	0.008
End taper length — both ends, in.	1.000	0.500
End thickness — both ends, in.	0.003	0.003
Weight of contoured foil, g	169.4	193.1

The allowed tolerances will be a basis for the LEU HFIR fuel specification; however, tolerances on the dimensions and weights listed in the table were not assigned because the tolerances that will be allowed within the envelope of the HFIR safety requirements and performance objectives have not been developed. Also, data on statistical variations in machining contoured foils have not been generated. As shown, the nominal weights of the finished foils were calculated to be 193 g U/Mo for the inner plate foil and 167 g U/Mo for the outer plate foil. In a foil fuel, variations in the average thickness of the foils of  $25 \mu\text{m}$  (0.001 in. therefore  $\pm 0.0005$  in.) could affect the foil weight by as much as 6 – 8% or up to about  $\sim 15$  g in an inner plate, which is  $\sim 3$  g in  $^{235}\text{U}$  content. By comparison, in HFIR HEU dispersion fuel, the  $^{235}\text{U}$  content in each plate is known to within  $< 0.050$  g based on the dispensed weights of the powders contained in each fuel plate.

The reference flow sheet for the preparation of the outer and inner HFIR foils for assembly into the cladding is shown in Fig. 7. Most of this flow sheet is based on engineering assessments of the applicability of comparable processes within the metal processing industry. Essentially none of this technology has been developed for U/Mo foils. Machining is the reference for forming for the radial (edges) and axial (ends) contours for HFIR fuel foils. The flow sheet also includes the steps for applying a diffusion barrier to the surfaces of the formed foils and would be common to all HPRRs.



**Fig. 7. Procedure for preparing foils for assembly in clad.**

Because of the thousands of HFIR LEU foils that will need to be processed annually, contour forming of HFIR foils may be best suited by a specially designed computer-controlled automated machine that would include feeding of the foils for edge and end contouring, automatic dimensional inspections, weighting, and surface inspection of the end products. Most likely the machining operation would be done by either cutting or grinding using a cutting fluid. The cutting fluid should minimize uranium contamination in the processing area, but special containment enclosures will be required. The dimensional inspection should be capable of a resolution of 12  $\mu\text{m}$  ( $\sim 0.0005$  in.) and the weighing to  $\sim 0.010$  g. The foil surfaces should be free of scratches and gouges of some specified depth and length (i.e., about 50  $\mu\text{m}$  [ $\sim 0.002$  in.] deep and 2.5 cm [ $\sim 1$  in.] long). Standards for surface defects will be required.

After forming and inspection, the foils may require trimming to meet a uranium loading tolerance, and the surfaces must be cleaned for application of a diffusion barrier. The reference flow sheet assumes that trimming will be necessary. In the reference flow sheet, the trimming and cleaning of the foil surfaces are accomplished using an acid leaching process. Trimming for weight control of the foils could also be accomplished by machining or grinding the flat surfaces. The proper cleaning of metal surfaces for plating or sputter coating of the diffusion barrier is extremely important to the successful application of the coating. Acid cleaning for this purpose is established technology. It is possible that this work or the trimmings from the work may need a controlled, inert atmosphere.

The application of silicon in an adherent layer of U (Al,Si)<sub>3</sub> (a coating  $< 25$   $\mu\text{m}$  [0.001 in.] thick) has shown promise as a diffusion barrier but the detailed requirements have not been established.<sup>††</sup> A thin coating could be applied to the foil surfaces either by physical vapor disposition (sputtering) or by an electroplating process. Electroplating — well known technology for coating metal surfaces — was selected as the reference process. After coating, the thickness and integrity of the coating will require nondestructive inspection to confirm specified thickness and detect any flaws. Several techniques for determining the coating thickness (for instance a capacitance probe) are available commercially.

<sup>††</sup> The formation of a tight adherent layer of U (Al,Si)<sub>3</sub> may create an effective diffusion bond and diffusion barrier below 350°C. It is possible that applying Al 4047 as a 0.0762 mm foil between the fuel foil and clad with hot pressing could create an effective barrier.

In the processing of a foil, the dimensional inspection data and weight of each foil after contour forming and trimming will constitute the primary information for certifying an individual fuel plate for homogeneity and uranium content. Homogeneity scanning by X-ray attenuation, as currently done for dispersion fuels, should not be required though bonding of the foil and clad must be assured.

The uranium waste streams generated in the foil preparation for assembly step would primarily consist of particles from machining, sludges from acid leaching, and rejected foils. Most of the foils rejected before application of a diffusion barrier might be considered clean scrap and recycled in the melting step in the alloying process. Some other rejected foils would be considered waste that would likely be considered below economically recoverable quantities and disposed as solid low-level radioactive waste. The materials would have to be treated and packaged before discarding as solid low level-waste. Other solid radioactive waste generated in this process would include room air filters, discarded personal protective clothing, and miscellaneous other waste generated within the regulated zone. All of these wastes would require packaging and disposal as low-level radioactive waste.

The combined, assumed yield for foil preparation step and diffusion barrier step is 75% and was an assumption based on the judgment of personnel experienced with the manufacture of HFIR fuel plates. The production quantity that must be manufactured in foil preparation for assembly is ~7843 individual foils annually for HFIR alone (see table 1 with 50% inventory buildup it would 12,000). This quantity equals to ~ 1.5 to three 24 plate lots per day for HFIR assuming a facility availability of 200 days per year.



## 7. ALUMINUM CLAD PREPARATION

The configuration of the aluminum hardware for foil fuel plates will be significantly different from the “picture frame” hardware used in making roll-bonded dispersion fuel plates at a ~8:1 reduction ratio. For foil fuel plates, the friction stir welding or hot isostatic pressure (HIP) bonding processes currently being developed for LEU fuels require that the aluminum hardware be able to receive the finished foils and be close to the overall finished fuel plate dimensions. The reference cladding hardware for the HFIR foil fuel plates will be two matching aluminum strips ~10 cm (4 in.) wide by ~60 cm (24 in.) long, containing contoured recessed areas 150 – 200  $\mu\text{m}$  (0.006 – 0.008 in.) deep to place the finished foils in a “clam shell” type configuration. A clam shell configuration will require Al-to-Al bonding on only one plane. Picture frame type aluminum hardware with Al-to-Al bonding on two planes might be appropriate for rectangular-shaped foils, but this configuration is not likely applicable to the contoured foils required for HFIR.

The reference flow sheet for aluminum cladding preparation is shown in Fig. 8. In preparing the cladding, a burnable poison equal to  $0.0164 \text{ g} \pm 0.0016 \text{ g } ^{10}\text{B}$  must be homogeneously incorporated into the cladding for the HFIR inner fuel plates. In the current HEU dispersion fuel, this poison is added to the filler powder as natural boron (20%  $^{10}\text{B}$ ) carbide powder during the making of the fuel compacts for roll bonding. For a foil fuel, including the burnable poison in the cladding is the reference method and will require the procurement of a special lot of aluminum alloy 6061 TO sheet stock with a boron content of ~ 750 ppm. Procuring such a special lot of aluminum sheet may be difficult and will likely entail the purchase and processing of an entire 10,000-lb billet of the aluminum alloy into the required 760- $\mu\text{m}$  (~0.030-in.) thick by 10-cm (4-in.) wide by 20-cm (8-in.) long sheets. For the outer fuel plates the 750- $\mu\text{m}$ -thick (finished plate thickness ~1250  $\mu\text{m}$ ) sheets would be procured as commercial alloy 6061 with the O temper in 102-cm by 204-cm (4-ft by 8-ft) sheets and dedicated for nuclear service. The aluminum sheets for the inner and outer plates would be sheared into strips of appropriate width [~10 cm (~ 4 in.)] and length [~60 cm (~ 24 in.)]. In procuring commercial aluminum plate for the outer plates, consideration should be given to the boron content (specified as < 30 ppm B). ‡‡

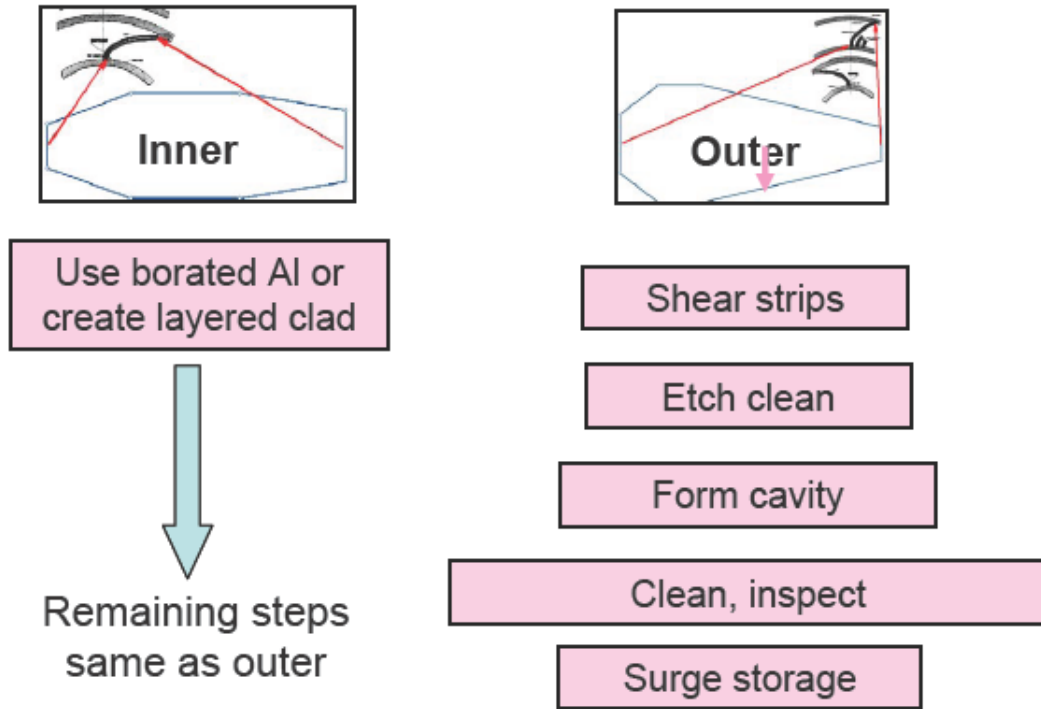
The fabrication of the aluminum hardware components can be done in a conventional fabrication shop and finished aluminum hardware components delivered to the nuclear fuel fabricator or can be performed at the fuel fabricator. Machining of aluminum is well-established technology, provides the most direct route for forming the cavities in the cladding strips within the likely required tolerances, and is the reference process. The contoured cavity could be made by using profiled cutting tools on a horizontal mill similar to the way the grooves are cut in the side plates for box type fuel elements (MIT and NIST reactors). Die forming techniques such as embossing or forging could be considered if dictated by economics. Because of the relatively large surface area of 375  $\text{cm}^2$  (~ 60  $\text{in}^2$ ) for the recess cavity, a forming press with about a million pounds force may be required to achieve the unit force of ~ 15,000 psi that likely will be necessary to cold form the recesses.

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‡‡ One reviewer indicated that the “etch clean” step shown in Fig. 8 may not be required. Regarding application of a boron layer, some commercial power reactor fuel is fabricated with integral burnable poisons by spray-coating  $\text{UO}_2$  pellets with zirconium diboride,  $\text{ZrB}_2$ ; aluminum boride comes in two compounds  $\text{AlB}_2$  and  $\text{AlB}_{12}$  that are used in some electronics applications. A boron-containing coating could be sprayed on to the aluminum clad. However, such a layer would concentrate helium production from neutron capture in boron into a narrow, contiguous zone. One, boron-coated foil experienced 90% swelling under irradiation in the ATR. Since borated aluminum is available commercially and since coated aluminum would require some technology development, borated aluminum was selected for the reference flow sheet.

Dimensional inspection of the finished hardware is performed using conventional measuring tools. Inspection for surface defects is done visually.

Cleaning of the finished hardware components will be required for subsequent bonding operations and should be performed after inspection to protect the surfaces from contamination. The aqueous cleaning process using a caustic dip, water rinse, nitric acid dip followed by a hot water rinse that is currently used for cleaning the aluminum hardware for roll bonding is assumed in the reference flow sheet. In this process at least 12  $\mu\text{m}$  (0.0005 in.) is removed from the bonding surfaces to ensure a clean surface. The existing cleaning facilities at the nuclear fabricator likely could be used for this step.



**Fig. 8 Process steps for aluminum cladding.**

The yield for the aluminum clad preparation step was assumed to be 90%. At this yield, the quantity of clad hardware pieces required is  $\sim 90$  pieces/d assuming a conventional shop availability of 200 d/year. The 90 pieces/d will require an automated dedicated machine. The waste generated in this process step will primarily be clean aluminum scrap that could be sold for recycling. The cleaning step will generate some hazardous liquid waste that must be treated and disposed in a prescribed manner to meet environmental regulations.

In developing the cladding preparation flow sheet, applying the diffusion barrier in the cladding using Alclad™ type materials was considered. Alclad was successfully used in the fabrication of some research reactor fuel plates in the late fifties and sixties. Applying the diffusion barrier to the clad rather than to the fuel foil is a possible, alternative process and should be considered if difficulties are encountered in applying a diffusion barrier to the foil.

## 8. LEU FUEL PLATE ASSEMBLY

As in most of the other process steps, the assembly of LEU foil fuel plates through the critical bonding step will require the use of a different technology than has been used for manufacture of the dispersion fuel plates. The assembly of foil plates for HFIR and other HPRRs will be similar and will consist of placing the finished foils into the cladding hardware and bonding the foils and the aluminum edge cladding in one step. The bonding process and its effects on the performance of the fuel during irradiation is one of the larger uncertainties of the LEU foil fuel. After bonding, with the exception of trimming the plates to thickness, the reference flow sheet for flat foil fuel plates has the same steps currently used in manufacturing the HEU dispersion fuel plates.

The dimensional requirements for the finished HFIR flat fuel plates are shown in Table 4.

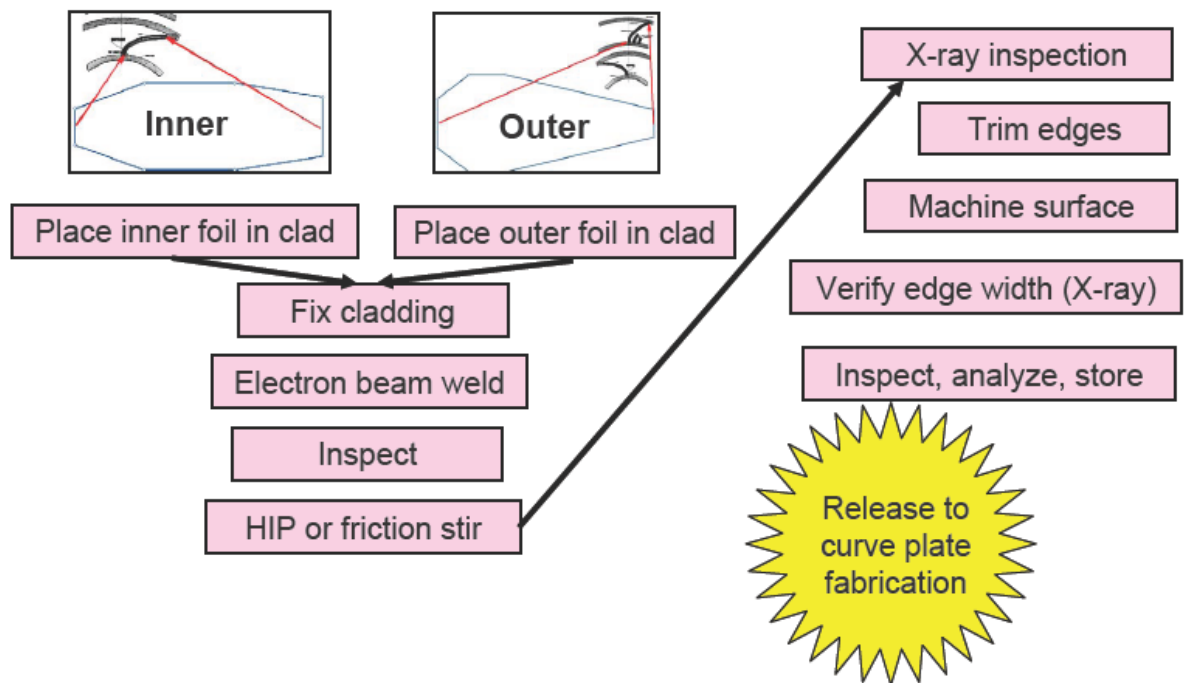
**Table 4. Dimensional requirements for HFIR flat fuel plates**

	Outer plate		Inner plate	
	Nominal	±	Nominal	±
Overall width	3.188	0.001	3.626	0.001
Length	24	0.002	24	0.002
Thickness	0.0502	0.0004	0.0502	0.0004
Inside edge margin	0.194	0.012	0.2025	0.016
Outside edge margin	0.2365	0.013	0.2805	0.055
End clad margin	2.011	0.125	2.011	0.125

In the production of HEU fuel plates, the finished fuel plate thickness is controlled at the nominal to within  $2.5 \mu\text{m}$  ( $\pm 0.0001$  in.) by etching. Precise plate dimensions are needed to maintain a constant metal-to-water ratio throughout the reactor fuel assemblies.

The reference flow sheet for the assembly of LEU fuel plates is shown in Fig. 9. The inner and outer fuel plates required for HFIR can be assembled in campaigns on a common production line if adequate production capacity is provided. Assembly of the finished foils into the clam shell aluminum cladding hardware may require a “clean room” type environment to minimize surface contamination of the bonding surfaces. The reference for assembly is manual, but automated assembly in a controlled environment could be required to control surface contamination for bonding.

Hot isostatic pressing (HIP) was selected as the reference for bonding because this process is more adaptable to the high production volumes that will be required for the LEU fuels. Multiple plates can be processed simultaneously by HIP. The friction stir welding process, which is a single-plate incremental process, may provide a bond with characteristics more favorable to the performance of the fuel in the reactor because of the lower time at temperature required to achieve bonding. However, the recognized need by the LEU program for a diffusion barrier probably leads to HIP as a viable process for bonding LEU fuel plates. For a HIP process, the fuel plate assembly must be sealed before HIP. The reference for this sealing is electron beam welding, which will provide an evacuated sealed fuel plate assembly. An alternate for sealing the assembly would be the use of disposable aluminum foil bags that could be evacuated.



**Fig. 9. Proposed process for final assembly of fuel plates.**

In the HIP process the welded fuel assemblies will be subjected to an isostatic pressure of  $\sim 10,000$  psi while being heated to a temperature in the range of  $500^{\circ}\text{C}$ . The HIP uses an autoclave (pressure vessel) and will require special facilities to meet safety requirements. The cycle time of HIP is likely to be  $\sim 8$  h, and perhaps 50-100 plates can be processed in a autoclave unit in each cycle.

After bonding, with the exception of trimming the foil fuel plates to thickness, the reference flow sheet for foil flat fuel plates has the same steps currently used in manufacturing the HEU dispersion fuel plates. In the reference flow sheet, the position of the fuel core within each bonded fuel plate will be determined and marked by punching positioning holes using the real time X-ray system currently used in the production of HFIR HEU dispersion fuel plates. After marking the location of the fuel cores, the edges would be trimmed to the finished dimensions using a die punch similar to that used in manufacturing HFIR fuel plate.

The as-bonded thicknesses of HFIR foil fuel plates will not be within the required tolerances (Table 4) and will have to be trimmed to meet the dimensional requirements of a finished flat plate. In the reference flow sheet, a mechanical surface plane will be used to trim the thickness of foil containing fuel plates. Grinding or some other machining process might be used. Because of the possibility of disrupting the aluminum-to-foil bonding, hot or cold rolling is likely not a viable process to consider. Regardless, after trimming, acid leaching to achieve the final thickness, as is currently required in manufacturing HFIR HEU fuel plates, likely will also be required for the foil fuel.

The reference flow sheet for nondestructive inspection of the finished flat foil fuel plates will be the same as currently used for HEU dispersion fuel plates. This inspection includes the real time X-ray system for end and edge cladding determinations and ultrasonic inspection for blister and nonbonded areas using the water-coupled ultrasonic detection system currently used for HFIR HEU flat fuel plates. The real time X-ray system could be modified (software) to determine that the fuel contour

(hump) is oriented correctly in the fuel plate. The hand-operated “hump gage” used to verify the correct orientation of the fuel contour in current HEU fuel could also be used.

Manual inspection of the finished flat foil fuel plates will be as currently performed for HEU and will include visual inspection for surface defects and dimensional inspection of the finished plates. Destructive examination of sample plates comparable to the current practice will be required to evaluate the bonding.

The yield for the plate assembly step was assumed to be 90%. This will require an assembly capacity of ~ 50 fuel plates/d or ~ 2 plate lots/d (25 plates/lot) assuming availability of 200 d/year. Three plate lots per day will require a dedicated assembly line with some automated materials handling.

The waste generated in this process step will be primarily rejected fuel plates. The acid leaching step will generate some hazardous liquid waste that must be treated and disposed in a prescribed manner to meet environmental regulations.

The study reported here ends with the creation of a flat plate. Subsequent steps in the HFIR fuel element fabrication process (refs. 8 and 9) would be the same for both the current, HEU process and the proposed LEU process. However, though the processes are the same, in the forming of a curved, involute shape, the two fuels could act differently. Over 40 years of production, the integrity of the fuel/clad interface for the current, dispersion fuel under the forming operation has been shown to be adequate. Debonding of fuel from clad due to the forming stress is not a significant problem with the current dispersion fuel. Engineering tests would have to be performed to show a comparable level of performance with LEU foils.



## 9. COSTS AND IMPLEMENTATION SCHEDULE

Deriving costs and schedules for a new fuel must, at least, be based on an understanding of the manufacturing requirements and steps necessary for such a fuel. The identified reference flow sheet and corresponding quantities of materials that need to be processed provide a basis for order-of-magnitude cost estimates of infrastructure modifications, operating costs, and implementation schedule associated with the fabrication a LEU fuel for HFIR.

In the analysis of the production requirements for HFIR LEU foil fuel, it is apparent that the foil processes and the scale of the production required (2.5 tons of U/Mo; 10,000 plates annually) are not compatible with existing or planned manufacturing facilities at Y-12 or Lynchburg, and a dedicated facility or facilities will be required. The existing dispersion fuel fabrication lines cannot be stopped and the manufacturing equipment replaced with the foil processing equipment without disrupting the fuel supply to the HPRRs and other university research reactors. It will likely take at least four to five years to install and test the foil fabrication equipment, qualify and certify the production, and build a working inventory of foil fuel required for each HPRR. Because of the quantities of nuclear materials involved in foil fabrication, any new processing facilities must be designed, constructed, and operated to meet the requirements of the Nuclear Regulatory Commission and/or DOE for such facilities. At this point with limited detail data, speculative estimates of the infrastructure costs and schedule can only be derived by inference from known or estimated costs of similar or comparable facilities.

The magnitude of the infrastructure costs of new foil fabrication facilities may be inferred from cost developed from other comparable facilities. The 30-year Y-12 modernization effort that has been estimated to cost several billion dollars is probably the most applicable example for estimating the magnitude of the infrastructure costs for new LEU fabrication facilities. Within the Y-12 modernization plan is a new processing facility that will contain many of the processes required in a LEU fuel fabrication line. This facility has a pre-conceptual design cost projection of ~\$2 billion. A foil fabrication line would be ~ 10 – 20% of this facility, inferring a magnitude cost of more than \$100M for a LEU foil fuel fabrication facility. In a feasibility cost study to move the existing HEU fabrication line from Lynchburg to Idaho that was performed several years ago, cost was in the order of \$100M with a significant portion of this cost for constructing a new line item facility. From these costs, the infrastructure costs for a foil fuel fabrication line will likely be in the order of \$100 million and could easily be several hundreds of millions of dollars. Likely, line item funding will be necessary and will take on the order of 8 – 10 years to complete the steps required by DOE Order 413.

The operating cost of a foil fuel can only be inferred from the current operating cost of fabricating HEU flat dispersion fuel plates and analysis of the added complexity of fabricating foil fuel plates. Currently, the cost of manufacturing HFIR HEU dispersion flat fuel plates is ~\$1150 each (includes fuel particle preparation). The operating cost of making a flat foil fuel plate based on the added steps and the complexity of more process steps and the increased number of these steps that must be performed in a contamination zone will certainly be more expensive than for a dispersion fuel plate. The fabrication cost – operating cost not total cost - of a foil fuel plate could easily be twice the current value for dispersion, HEU fuel.

In the fabrication of fuel elements containing foil fuel plates, a number of other steps will be required. In the reference flow sheet presented, the other manufacturing steps were not presented because they were assumed to be the same as in making elements containing dispersion fuel plates. In the current manufacturing of HFIR HEU fuel elements containing dispersion fuel plates, fabrication of the flat fuel plates represents about two-thirds of the total costs of an element. In a foil fuel, the costs of the flat plates will likely represent a larger percentage.





## 10. CONCLUSIONS

A “reference flow sheet” is one of the first planning steps in the development of a manufacturing capacity for a LEU foil fuels and can be used to develop a work structure, a critical path schedule, and identify development needs. The reference flow sheet presented in this report is a HFIR-specific reference flow sheet. The need for an overall reference flow sheet for all HPRRs has been identified by the national program office. This report could provide a starting point for the development of this reference flow sheet for a foil based fuel for all HPRRs.

The reference flow sheet presented is based on processes being developed for the LEU foil fuel when available, processes used historically in manufacture of other nuclear fuels and materials, and processes used in other manufacturing industries producing a product configuration similar to the form required in manufacturing a foil fuel. The processes in the reference flow sheet are within the bound of known technology and adaptable to high-volume production required to process ~ 2.5 tons of U/Mo and produce ~10,000 flat plates annually for HFIR. The reference flow sheet is not intended to represent necessarily the best or the most economical way to manufacture a LEU foil fuel for HFIR but simply represents a “snapshot” in time of technology and is intended to identify the process steps that will likely be required to manufacture a foil fuel. Changes in some of the process steps selected for the reference flow sheet are inevitable; however, no one step or series of steps dominates the overall flow sheet requirements.

In the overall assessment of the reference flow sheet presented, the increased number of steps required is striking when compared to the dispersion fuel process. Increasing the number of steps increases the number of hold points and resulting in-process inventory levels. In the foil reference flow sheet, the number of different types of uranium-bearing foils is much greater than the corresponding step in the current, dispersion fuel fabrication process. In the current process, a relatively small number of “master blends” of uranium-bearing material and aluminum are created. This small number of blends is replaced by a much larger number of unique-geometry foils which, in turn, must be rolled and processed separately throughout the remainder of the plate fabrication steps. Additionally, in most of the foil processing steps, bare uranium must be handled, which increases the complexity of these processing areas.

In the analysis of the production requirements for HFIR LEU foil fuel, it is apparent that the processes and the scale of the production required (~2.5 tons U/Mo; ~ 10,000 plates annually) are not compatible with existing or planned manufacturing facilities at Y-12 or Lynchburg, and a dedicated facility or facilities will be required. The existing dispersion fuel fabrication lines cannot be stopped and replaced with the foil processes without disrupting the fuel supply to the HPRRs and other university research reactors. It will likely take at least four to five years to install and test the foil fabrication equipment, qualify and certify the production, and build a working inventory of foil fuel required for each HPRR. It is apparent that line item funding will be necessary and will take about 8 – 10 years to complete. The infrastructure costs for new foil fuel fabrication facilities will likely be in the order of \$100M and could easily be several hundreds of millions of dollars. The operating costs of making flat foil fuel plates based on the added steps and the complexity of more process steps and the increased number of these steps that must be performed in a contamination zone will certainly be more expensive than for dispersion fuel plates. The fabrication cost of a foil flat fuel plate could easily be twice the current operating costs. It is also very important to recognize that qualification of the proposed foil-type HFIR fuel cannot be done independently of the development of a fabrication facility, because the fabrication process and specific equipment impact the final product performance.

In the reference flow sheet presented, manufacturing steps subsequent to flat plate production and required in fabricating the fuel elements were not presented because they were assumed to be the same as in making elements containing dispersion fuel plates. However, if the foil fuel experiences debonding under involute plate forming, a different forming process from the current cold die forming process may be required. The radii of curvatures in the involute shaped HFIR fuel plates are relatively sharp and the bond integrity can be disrupted during cold forming this shape or add stresses that may cause failure of the bond during operation in the reactor. As a “zero defects” quality level cannot be achieved by inspection, the plate forming process itself must inherently achieve a “zero defects” quality level in bond integrity to be acceptable.

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**Appendix A**  
**SIDE-BY-SIDE COMPARISON OF CURRENT HEU AND PROPOSED**  
**LEU FLOW SHEETS**

**Table A.1. Components of current, HEU, dispersion fuel flow sheet corresponding to proposed LEU processes**

<b>HEU dispersion fuel Process</b>		<b>Section of this report with corresponding LEU production process</b>
<b>Major process step designation (location where step performed)</b>	<b>Component of major process step</b>	
Processing of uranium into U <sub>3</sub> O <sub>8</sub> powder (Y-12)	Burn metal turnings to create oxide	3 and 4
	Dissolve oxide with acid	
	Precipitate oxide	
	Centrifuge	
	Calcine	
	Sinter	
	Crush/Grind	
	Screen	
	Sinter	
	Screen	
	Inspect for proper size distribution, surface area, trace elements, record assay	
Arrange shipment to Lynchburg		
Creation of fuel compacts (Lynchburg)	Receive U <sub>3</sub> O <sub>8</sub> powder; obtain Al powder and B <sub>4</sub> C	5 and 6
	Weigh	
	Blend	
	Load Die	
	Contour Powder	
	Press	
	Anneal	
Inspect dimensions, weight; check for defects		
Fabrication of Al frames and covers (Lynchburg)	Procure Al Alloy 6061 Sheet	7
	Shear	
	Blank	
	Degrease	
	Inspect surface finish and dimensions	
Fabrication of flat plates (Lynchburg)	Assemble compacts into frame; add top and bottom covers	8
	Weld Billet	
	Hot Roll	
	Anneal	
	Blister Inspect	
	Cold Roll	
	Anneal	
	Radiograph/punch	
	Blank to size	
Inspect dimensions; ultrasonic test for blisters, bonding; homogeneity (fuel grading); outer fuel region dimensions (radiography), plate thickness		

**Table A.2. Components of current, HEU, dispersion process which should be the same for LEU fuel (not discussed in report)**

<b>Major process step designation (location where step performed)</b>	<b>Component of major process step</b>
Forming of curved plates (Lynchburg)	Quality control release of flat plate
	Form involute
	Clean
	Inspect contour, surface finish
	Quality control release of curved plate
Manufacture of side plates for elements (Lynchburg)	Procure Al 6061 Tubing
	Machine inner/outer diameter
	Machine weld grooves
	Inspect dimensions
	Slot for fuel Plates
	Debur
	Degrease
Manufacture of end adapters for elements (Lynchburg)	Inspect dimensions
	Procure Al 6061 Tubing
	Machine inner/outer diameter
	Machine weld preparation
Element assembly (Lynchburg)	Inspect
	Load plates into slots
	Install Teflon™ spacers
	Inspect for protrusion and concentricity
	Before weld test sample; pull test, visual inspection, metallography
	Preheat element
	Weld plates into element
	Inspect dimensions, melt through, channel spacing
	After weld test sample; pull test, visual inspection, metallography
	Machine for adapter welds
	Weld End Adapters
	Visual inspection; radiograph welds
	Rout machine outer diameter
	Machine inner diameter
	Finish machine outer diameter
	Inspect dimensions
	Engrave element identification
	Clean
	Inspect for burrs, chips, workmanship, cleanliness
	Certify elements for delivery to ORNL
Send elements to ORNL	

## **Appendix B**

### **VAPOR OR SPRAY DEPOSITION PROCESSES FOR LEU FABRICATION**

Chemical vapor deposition, physical vapor deposition, and plasma spray deposition are processes proposed by ORNL that potentially might be applicable for forming the HFIR U/Mo foil with the required contour. Chemical and physical vapor deposition processes are capable of building substrates atomistically respectively by the decomposition of a gaseous vapor containing the desired metal or by the vaporization (sputter) of the desired metal alloy in a vacuum. In the plasma spray process, metal powder is melted into droplets and sprayed onto a target. Vapor and plasma spray deposition can potentially build a substrate on a target to a specified configuration using a computer-controlled raster deposition pattern. Using this computer control technique, the plasma spray process is used for rapid prototyping complex metal shapes and for limited production. The vapor deposition and plasma metal spray processes require high temperatures and high-purity inert atmospheres or vacuum for processing.

The plasma spray process requires spherical powders with precise control of the size distribution of the feed powders. The flow sheets required for preparing a suitable feed from the existing uranium metal stockpile for either vapor deposition or spraying are complex processes that are not compatible with the other processes required for fabricating foils for other HPRRs. In addition, the foil formed by either vapor deposition or plasma spraying most likely will need to be applied to and removed from a target, further complicating the process flow sheet. All of these deposition processes are incremental type processes that are likely not readily adaptable to the required high production level of ~ 4 metric tons or ~10,000 plates/year required for HFIR foil fabrication. For these reasons, ORNL decided not to pursue research of vapor deposition or plasma spray further for producing a contoured foil for HFIR as a reference process.

Physical vapor deposition by sputtering the diffusion barrier on the metal foils is relatively known technology and warrants further development as a backup to the reference plating process. Silicon or some other appropriate metal can likely be deposited on a foil by sputtering in a high vacuum. The inherent low deposition yields of the diffusion barrier material on the foils may be of some limited concern. In this process, after cleaning the foil surfaces, the foils would be placed in a vacuum chamber with the diffusion barrier metal, the chamber evacuated, and the barrier material heated and sputtered onto the foil surfaces. Inspection of the finished plated foils for defects and thickness can be performed with instruments available in industry for this purpose.

For bonding the cladding to the foils, plasma spraying of the aluminum cladding onto the contoured foils was considered. The plasma spray process is relatively well-developed technology, and systems can be purchased commercially. The application of this technology for bonding and forming the aluminum cladding is not straightforward and presents some concerns, particularly for ensuring the structural integrity of the finished cladding. In a plasma spray process, it is unlikely that a fully dense cladding layer can be deposited onto the foil, and a subsequent densification step will be required. In the finished aluminum cladding, undetected defects will likely result in fuel failures in a reactor. Because of the inherent nature of the spray deposition process to produce some defects in a deposited layer, it is unlikely that any inspection technique can ever achieve a “zero” defect level that will be required for a plasma spray fuel plate cladding. For this reason the plasma spray process was eliminated from further consideration as a possible method for bonding the cladding to the foil. The plasma spray process could be considered for application of a diffusion barrier if needed in the future.





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