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OAK RIDGE Y-12 PLANT

LOCKHEED MARTIN

SPRAY CASTING PROJECT FINAL REPORT

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MANAGED BY
LOCKHEED MARTIN ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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SPRAY CASTING PROJECT FINAL REPORT

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August 1996

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EXECUTIVE SUMMARY

The U. S. Department of Energy Office of Science and Technology (DOE-OST) is examining waste minimization of depleted uranium (DU) manufacturing at the Oak Ridge Y-12 Plant. As part of this effort, a spray-casting project has been ongoing since 1991 to evaluate near-net-shape fabrication of DU and DU alloys for a variety of applications. A number of organizations have participated in this program since its inception, including Custom Spray Technologies (CST), MSE, Scientec, EG&G-Idaho, and the U. S. Air Force, with most of the actual spraying being conducted at CST and MSE. The most recent application (and the only one discussed in this report) under review for spray casting has been in the area of gamma shielding for high-level radioactive waste storage and transportation.

Based on earlier surrogate studies indicating the feasibility of spray casting uranium, a conceptual design for an intermediate facility was developed. An engineering analysis was made of the installation and operation of the intermediate facility in the Y-12 Plant. One conclusion from this analysis was that the intermediate facility needed to be divided into two phases because of technology and cost issues. Finally, a preliminary design of a production facility was developed.

From the engineering analysis, several technical issues—including nozzle material selection, requirements for handling overspray, and material properties evaluation of spray-cast product—must be resolved before a process can be developed. Some engineering concerns also need to be addressed concurrently with the technical issues. Although the spray-casting process seems to be a lower-cost alternative to conventional techniques, a detailed cost estimate will have to be prepared that includes design specification.

Existing facilities for uranium fabrication cannot produce the components required for the gamma shielding application. To produce these components using current techniques would require major capital facilities. The spray-casting process offers an alternative that will be less expensive if the technical and engineering issues can be resolved.

ABSTRACT

Lockheed Martin Energy Systems, Inc. (Energy Systems), along with other participating organizations, has been exploring the feasibility of spray casting depleted uranium (DU) to near-net shape as a waste-minimization effort. Although this technology would be useful in a variety of applications where DU was the material of choice, this effort was aimed primarily at gamma-shielding components for use in storage and transportation canisters for high-level radioactive waste, particularly in the Multipurpose Canister (MPC) application. In addition to the waste-minimization benefits, spray casting would simplify the manufacturing process by allowing the shielding components for MPC to be produced as a single component, as opposed to multiple components with many fabrication and assembly steps.

In earlier experiments, surrogate materials were used to simulate the properties (specifically reactivity and density) of DU. Based on the positive results from those studies, the project participants decided that further evaluation of the issues and concerns that would accompany spraying DU was warranted. That evaluation occupied substantially all of Fiscal Year 1995, yielding conceptual designs for both an intermediate facility and a production facility and their associated engineering estimates.

An intermediate facility was included in this study to allow further technology development in spraying DU. Although spraying DU to near-net shape seems to be feasible, a number of technical, engineering, and safety issues would need to be evaluated before proceeding with a production facility. This report is intended to document the results from the spray-casting project and to provide information needed by anyone interested in proceeding to the next step.

INTRODUCTION

Lockheed Martin Energy Systems, Inc. (Energy Systems), using funds obtained through the U. S. Department of Energy Office of Science and Technology (DOE-OST), has been exploring the feasibility of spray casting depleted uranium (DU) to near-net shape since 1991. A number of organizations have participated in this program since its inception, including Custom Spray Technologies, Inc. (CST), MSE, Inc. (MSE), Scientech, Inc., the U.S. Air Force (USAF), and EG&G-Idaho, with most of the actual spraying being conducted at CST and MSE. CST operated under contract to Energy Systems, whereas MSE received their funding directly from the U. S. Department of Energy (DOE)-USAF Memorandum of Understanding.

Before FY 1995, the focus of the project was on spraying surrogate materials. Detailed results from these experiments can be found in the following reports:

- *Summary Progress Report, Phase I: High-Density Trials*, SCIE-ORNL-101-92;
- *Phase I - Addendum I Draft Reports, Reactivity Experiments*, CST-2283;
- *Surrogate Alloy Experiments*, CST-2353; and
- *Heavy Metals Processing Near-Net Forming Summary Progress Report*, Y/Sub-94GSK39V/1, CST-2734.

The goal of the project was to determine if spray casting was a feasible alternative for producing DU parts from relatively small components to large (75 in. diam by 3 in. thick by 18 ft long) gamma-shielding components such as those needed for the Multipurpose Canister (MPC) application. DU components are now produced using a multistep process that requires final machining. Spray casting, if feasible, would replace this process with a single step that would require minimal final machining.

This report details FY 1995 activities, which include conceptual designs for both a production-scale facility for making components for MPC and an intermediate-scale facility for technology development of the process using DU. It was assumed for design purposes that the intermediate facility would use the current vacuum induction melt furnaces at the Y-12 Plant in Oak Ridge, Tennessee. The production facility for components sized for MPC would require either a new building or considerable modification of existing buildings. Although the conceptual designs are sized for MPC, the issues concerning spray casting of DU would need to be addressed regardless of the size of the applicable component. Therefore, although the study documented herein was focused on a specific need, the technology and the technical issues concerning DU have a much broader application. The CST Summary Report and the Y-12 Plant Engineering Report are included as Appendix A and Appendix B, respectively. Also included as Appendix C is an unsolicited proposal submitted by Montec Spray Manufacturing Systems that proposes the Osprey process as an alternative to the spray-casting process, which this program has evaluated.

The goal of the DOE-OST program (i.e., recommendations on the feasibility of spray casting DU) has been achieved with the submission of this report. No current funding has been identified to continue the spray-casting effort.

SPRAY CASTING IN SHIELDING APPLICATIONS

The spray-casting process consists of the following three steps:

1. supplying molten material at a controlled rate to the throat of a converging/diverging nozzle,
2. supplying heated gas to the inlet of the nozzle at pressures and flow rates such that the molten metal entering the throat of the nozzle is atomized and accelerated out of the nozzle, and
3. the deposition of the molten and semimolten plume on a substrate.

Temperatures and pressures are controlled so that the finely divided spray that is formed in the nozzle becomes a plume of molten droplets exiting the nozzle. The velocity and two-phase state of the droplet plume are such that when it impinges on the substrate, it forms splats that adhere to the substrate surface. Initially, the substrate is a prepared mandrel; subsequently, it becomes the solidified splats of sprayed material.

This process, like other thermal-spraying processes, is not 100% efficient. Not all of the molten material that enters the throat of the nozzle becomes part of the spray-cast product. The material that does not become part of the spray-cast part becomes small, solid, free particles with a size distribution on the order of tens of microns or less and is called "overspray."

DOE-OST is examining waste minimization of DU manufacturing at the Oak Ridge Y-12 Plant. As part of this effort, a spray-casting project has been ongoing since 1991 to evaluate near-net-shape fabrication of DU and DU alloys for a variety of applications. The most recent application (and the only one discussed in this report) under review has been in the area of gamma shielding for high-level radioactive waste storage and transportation. Another effort funded by DOE-OST in the area of DU waste minimization included a comprehensive evaluation of DU reuse options that was recently completed and documented in *Depleted Uranium Market Study*, Y/NA-1801.¹ A summary conclusion of that study was that the major high-potential market for DU is in products for shielding applications.

The basis for the conceptual design of a production facility was the Multipurpose Canister system, the development of which was funded by the DOE Office of Civilian Radioactive Waste Management (OCRWM) for the civilian spent nuclear fuel storage/disposal requirements. These canisters were designed to contain spent nuclear fuel and would, therefore, require gamma shielding. Figure 1 shows a conceptual Multipurpose Canister system that consists of a canister with a DU plug and a transportation cask with a DU cylinder. To distinguish manufacture of the canisters from manufacture of the canister components, the components will be referred to as Multipurpose Canister-Gamma Shielding Components (MPC-GSCs). To define a conceptual facility, the authors chose several component sizes and shapes that would be typical of those required for MPC-GSCs and other similar gamma-shielding containers for spent nuclear fuel and other high-level waste.

Uranium is the material of choice for gamma-shielding applications because of its high density (18.9 g/cc). Uranium has advantages over other high-density materials such as steel, lead, and concrete because uranium minimizes the overall container shielding material volume, which increases the payload for given exterior dimensions.

- 125 ton MPC has a depleted uranium (DU) gamma shield plug 2 in. thick, 58 in. dia., 2,000 kg DU
- Transportation cask has a DU cylinder 16 ft. long, 2 in. thick, 20 tons DU

Fig. 1. Multipurpose Canister system.

Other advantages are

- added robustness for transportation and handling,
- low thermal expansion for low-thermal-stress designs,
- a large safety margin against melting in a fire, and
- good thermal conductivity for decay heat removal and heat transfer.

Also, DOE is storing a large available inventory of uranium hexafluoride, which can be converted to DU for use in these shielding applications.

Disadvantages of uranium include the following:

- cost,
- poor corrosion resistance, and
- regulatory concerns.

Although lack of corrosion resistance is a disadvantage, it can be overcome by several techniques. The major cost drivers are the cost of the uranium and the cost of manufacturing.

CONVENTIONAL MANUFACTURING ISSUES²

Spray casting is an attractive option for producing the DU MPC-GSCs because the technique can produce the large sizes involved as a single component. Requirements for DU in MPC-GSCs are as follows:

1. monolithic or large components that can be easily assembled;
2. close tolerances for assembly, heat transfer, and maximum payload; and
3. minimum cost and minimum waste.

Current conventional manufacturing methods for DU components are unable to produce these components as single pieces.

Figures 2 and 3 illustrate two conventional approaches for producing MPC-GSCs, a cast process and a wrought process. Wrought processing produces better and more uniform mechanical properties. DU produced by either method has poor corrosion protection; this can, however, be improved by alloying. Table 1 illustrates the differences in mechanical properties between the two processes. Figure 2 is an illustration of a basic wrought process. Limitations of this process are the size of the vacuum induction melting (VIM) furnaces, the dimensional accuracy of the formed part, and the machining required on all joined edges and ends. Figure 3 is an illustration of a basic casting process. Limitations of the casting process are the size of the VIM furnaces, the dimensional accuracy of the casting, and the machining required on the joints. The limitations of the equipment preclude any current DU fabricator from producing concentric rings that could be stacked.

Table 1. Differences in mechanical properties of the cast and wrought processes.

Material	Yield strength (ksi)	Tensile strength (ksi)	Elongation (%)
Unalloyed uranium (as cast)	30	61	6
Unalloyed uranium (wrought)	33	128	20

The product from the processes illustrated in either Fig. 2 or Fig. 3 would require an assembly. This assembly could be accomplished either by stacking many sections as depicted in the figures or by welding several segments into rings and then stacking the rings into an assembly. The stacking method, due to tolerance buildup and assembly methods, will result in longitudinal gaps that are unacceptable to the MPC design concept. This fact eliminates this method of assembly as an option without significant design changes, which would increase cost and reduce payload.

Wrought DU can be welded by electron-beam or gas-tungsten arc techniques, but section thicknesses required for the MPC-GSC components have never been done. The facilities do not exist for welding components of this size by either the electron-beam or the gas-tungsten arc technique. The logistics required to set up for welding at this scale are extremely complicated. Solutions would

Fig. 2. Wrought process flow diagram.

Fig. 3. Cast process flow diagram.

have to be found for many problems. Development programs would also be required to develop a process for welding these heavy sections. Even if these problems were solved, the strength and ductility would be significantly reduced in the weld area.

Designers of high-level waste (HLW) shipping containers have indicated in workshops on the MPC system that the tolerances from either a cast or a wrought process like those illustrated in Figs. 2 and 3 would be unacceptable. Therefore, all cast or wrought segments would require machining on all surfaces before mechanical assembly. Machining all surfaces produces a large quantity of DU machine turnings, which then become a major waste stream. No current technology is available for recycling machine turnings while maintaining the product quality expected for MPC-GSCs. Welding contributes additional waste per assembly because of the amount of additional machining stock required to compensate for weld distortion. In addition to the costs associated with the wastes, the machining operations required would increase significantly the cost per assembly of MPC-GSCs.

Processes for large cast rings and large ring-rolled forgings (for only cylindrical components) are technically feasible but are beyond existing capability. Either of these processes would require major capital investment and a significant development program. Casting large rings is the simpler of the two processes, but it produces a product with poor mechanical properties and would require machining on all surfaces. The ring-rolled forging is a more complicated process. This process begins with a casting and, through ring rolling, produces a wrought product that would also require machining on all surfaces. Practically, neither of these processes would be sized to produce a monolithic cylinder but rather would be sized to produce rings for assembly.

ENERGY SYSTEMS APPROACH TO SPRAY CASTING

Earlier work on spray casting involved Energy Systems; Custom Spray Technologies, Inc. (CST) in Rigby, Idaho; and MSE, Inc., in Butte, Montana. Since 1991, Energy Systems has been involved in spray casting as a waste-minimization initiative for DU, working with both CST under subcontracts and MSE as a co-investigator funded separately through DOE-OST and the U. S. Air Force (USAF). Both CST and MSE are recognized experts in the area of spray casting, specifically the Controlled Aspiration Process (CAP) at CST and the Pressure-Controlled Atomization Process (PCAP) at MSE. These processes are complementary technologies for spray-casting components. In FY 1994, the emphasis of the spray-casting program changed from small, near-net-shape components to the large MPC-GSCs.

The deliverable for the program in FY 1995 was a conceptual design of the spray-casting process for producing near-net-shape parts for MPC-GSCs and the associated hardware requirements. To accomplish this goal, the technical and engineering expertise of CST, MSE, and Energy Systems were combined. CST's primary involvement was in process knowledge, engineering capability, and laboratory experience. All earlier work on a DU surrogate material was conducted on a laboratory scale at CST. MSE contributed process knowledge, engineering capability, and an automated spray-casting prototype facility of similar size to the CST facility.³ Neither facility, however, has the capability to spray DU.

The Y-12 Plant project staff directed the work at CST and coordinated it with the MSE program. In addition, the Y-12 Plant has 40 years of experience in DU processing, including engineering, equipment, processing, quality, certification, radiological contamination control, and all other health and safety issues associated with producing DU components. Concurrently, the Y-12 Plant project staff were working on the use of DU in both MPC and other high-level-waste shipping containers.

An initial planning meeting was held with attendees from CST, MSE, Energy Systems, and DOE-Oak Ridge Operations. Energy Systems personnel included subject matter experts on DU manufacturing and individuals knowledgeable of the MPC program. This meeting led to the following results:

1. a prioritized list of issues that needed to be addressed in the conceptual design;
2. a flow diagram depicting the process flow, beginning with the preparation of feed stock and ending with the shipment of the product;
3. a decision that an intermediate facility would be required to answer some of the process uncertainties before committing to a final design of a production facility; and
4. a decision that a conceptual design of a production facility was also needed.

After this meeting, the issues list was divided into issues pertinent to the intermediate facility and issues pertinent to the production facility. Functional requirements for both the intermediate facility and the production facility were established. (Functional requirements for the intermediate facility and the production facility are given in Tables 2 and 3, respectively. Dimensions and shapes given in Table 3 are not specific to MPC but are intended to encompass the range of gamma shielding requirements for the world market.) The issues lists and the functional requirements were iterated with the participants.

Table 2. Functional requirements for the intermediate spray system

1. Capable of fabricating the following components:

Cylinder	48 in. OD 3 in. thick 12 in. long
Disk	48 in. diam 3 in. thick
Rectangular component	24 in. x 24 in. x 12 in. long outer dimensions 2 1/2 in. thick Radii in all four outside edges ~4 1/2 in. Radii in all four inside corners ~1/2 in.
2. Operate in a batch mode with a maximum of 2200 kg of molten DU available. (Minimum batch size is 100 kg.)
3. VIM is the process for melting the DU feed for the spray system. The transfer of molten DU to the spray system must be specified.
4. Capable of being installed in a DU operating area at the Y-12 Plant.
5. Use an inert cover gas to prevent oxidation of DU during fabrication.
6. Processing of the argon gas through the system must be defined.
7. Maximum oxygen level in the chamber is 0.02%.
8. Spray chamber operates at ambient pressure.
9. No water in the spraying chamber.
10. Spray deposition efficiency of at least 90%.
11. Capable of demonstrating the deposition rate specified for the production spray system.
12. Spray deposition must be well controlled and monitored by an operator.
13. Capable of testing and evaluating the nozzle concepts from both CST and MSE.
14. Maximum deposit porosity of 1%.
15. Allow for controlled oxidation of DU overspray particles in chamber after component fabrication is complete.
16. Collection system for overspray in chamber required.
17. Sampling system for particulate in chamber exhaust required.
18. Waste streams must be identified, and sizes of the waste streams must be estimated.
19. Capable of heating nozzle/tundish to a maximum of 1600°C.
20. Capable of heating the gas temperatures to a maximum of 1600°C.
21. Must meet all federal, state, and local laws. Must meet DU regulations set by DOE or appropriate regulating body.

Table 3. Functional requirements for production spray system

1. Capable of making a DU cylinder having the following nominal dimensions:
 75 in. OD
 18 ft high
 3 in. thick
 Capable of making a DU disk having the following dimensions:
 75 in. diam
 3 in. thick
 Rectangular component:
 24 in. x 24 in. x 18 ft long outer dimensions
 2 1/2 in. thick
 Radii on all four outside edges ~4 1/2 in.
 Radii on all four inside edges ~1/2 in.
2. An argon gas cover is required to prevent oxidation of DU during fabrication.
3. Spray-deposition efficiency of at least 90%. The goal is to optimize this deposition to >95% efficiency. High spray-deposition efficiency will be a goal of the intermediate facility.
4. Spray-deposition rate of at least 5 kg/min.
5. Allow for controlled oxidation of the DU overspray particles in the chamber after the cylinder fabrication has been completed.
6. Maximum deposit porosity of 1%. This porosity is to be uniformly distributed throughout the product. This porosity and distribution will be determined and verified in the intermediate facility. (The actual requirements in production will probably be a gamma-attenuation scan for 100% attenuation at the minimum wall thickness.)
7. Operate in continuous spray. (Could be fed either continuously or by repeating batches, depending on the nozzle.)
8. Minimum nozzle life—nozzle or nozzle setup—equal or exceed the duration of the spray run. (Do not replace the nozzle during a spray run.)
9. Nozzle/tundish heating capabilities will be 15% greater than continuous operating conditions. Component temperatures are expected to be 1600°C. Operating conditions and component maximum temperatures will be established in the intermediate facility.
10. No water may be exposed to the liquid metal or the hot solid metal.
11. Spray deposition must be well controlled and monitored by the operations team. A method or methods of communications between members of the team is required during operation.
12. The spray chamber operates nominally at ambient pressure. The system will be able to be evacuated and backfilled with argon.
13. The maximum O₂ level (oxygen and water combined) in the chamber is 0.02%.
14. The maximum nitrogen in the chamber is 2000 ppm.
15. Gas heating capabilities will be 15% greater than the continuous operating conditions. The maximum temperature is expected to be 1600°C. Gas heating requirements will be established in the intermediate facility.

Table 3. (continued)

16.	Must meet all federal, state, and local laws. Must meet DU handling regulations set by DOE or appropriate regulating body.
17.	Must have a gas recycle purification system.
18.	Must have a leak rate on the chamber of 1×10^{-4} atmospheric cc/s.
19.	DU is traditionally melted for casting by a VIM process. VIM or equivalent melting for feed for spraying is required.
20.	The DU feed stock should require minimum processing before use in this system.
21.	Identify waste streams and approximate quantities. (This is a collective function of CST, MSE, and Energy Systems.)
22.	Waste handling requirements are defined by Energy Systems following identification of waste streams by the joint team in Item 21.
23.	Capable of cladding an entire DU cylinder with a 1/4-in.-thick stainless steel cladding. (Optional)

CST assumed the lead role in developing the initial conceptual design for the intermediate spray facility and the production-scale facility. They published a report, *Heavy Metals Processing Near-Net-Shape Spray Forming*, detailing their work (see Appendix A). The Y-12 Plant analyzed the initial intermediate facility conceptual design to determine the feasibility of installing the intermediate facility in the existing Y-12 Plant DU facility. The Y-12 Plant engineering analysis is included as Appendix B. In late 1995, project personnel received an unsolicited proposal from Montec Associates, Inc., that proposed an alternate liquid metal spray-casting technology for producing DU MPC-GSCs (see Appendix C). The following sections discuss the primary conclusions from each of these appendices.

REPORT SUMMARIES

CST REPORTS

The primary finding from the CST report is that spray casting is a feasible technique for producing near-net-shape uranium components for MPC-GSCs. However, work to date on spray casting a surrogate alloy is not representative enough of the problems associated with spraying DU to allow scaling from current capability to a production-scale facility for MPC-GSCs. Because of these scaling issues, an intermediate system conceptual design was prepared.

The intermediate system conceptual design is presented as Task 3 in Appendix A. CST addressed the functional requirements and problems and presented potential solutions.

Task 2 in Appendix A is a presentation of the production facility conceptual design. CST offers a concept, based on the functional requirements for this facility, for a production facility that addresses size and potential solutions to some of the defined problems. **NOTE:** This is a starting point and a generic definition for the production facility, but the issues for the intermediate facility must be resolved before any further design effort is expended.

ENERGY SYSTEMS ENGINEERING ANALYSIS

Using the CST conceptual designs and the work done at MSE as a basis, the Y-12 Plant project personnel conducted an engineering analysis of installing the intermediate facility in existing facilities at the Y-12 Plant. The Y-12 Plant has an existing DU foundry capable of casting 2200 kg of uranium. This foundry has the equipment, infrastructure, and support services needed to meet the majority of the requirements for the intermediate facility, and the use of the existing foundry avoids the need to build a new facility.

Project personnel formulated a plan for the intermediate facility. Because several issues had to be resolved, the personnel decided to divide the intermediate facility into two different phases. Phase I of the operation of the intermediate facility will study the spray-casting process using up to 50-kg batches of uranium. Small-diameter disks and hollow tubes will be spray cast during Phase I consistent with the 50-kg batch sizes. These dimensions are, therefore, smaller than those given in Table 2. Disks ranging from 20 in. diam x 1/2 in. thick to 10 in. diam x 2 in. thick and hollow tubes ranging from 8 in. OD, 6 in. ID, and 6 in. long to 12 in. OD, 11 in. ID, and 8 in. long would be representative of the spray castings produced. This range of dimensions will permit the study and optimization of the following aspects:

1. the effective life of spray nozzles made of different materials with different nozzle designs;
2. the handling and controlled oxidation of the overspray material;
3. the as-sprayed properties of DU;
4. the interface between the gas heater, spray nozzle, and tundish;
5. the development of a process-control algorithm; and
6. the overall process.

Phase I will also provide data for a better estimate of both operating costs and capital costs of a production facility.

After successful Phase I operation of the intermediate facility, the facility will be upgraded for Phase II to handle 2200-kg batches of uranium and up to 2250 scfm of argon. At this point, a decision must be made as to whether to recycle the argon. This decision will be based on an economic analysis that will consider the number of runs required, the amount of gas needed, and the location of a recycling unit. The design criteria for the Phase II upgrades will be reviewed and revised as needed based on the experience gained in Phase I.

The Phase II operation of the intermediate facility will demonstrate the feasibility of scaling the process developed during Phase I to spray-casting rates that would be required in a full-scale production plant for large gamma-shielding parts. During Phase II operation, prototypical (in thickness or cross section) parts would be spray cast to demonstrate further the capability of the process to spray cast quality parts. Disks 48 in. in diameter and 3 in. thick and hollow cylinders 48 in. OD, 42 in. ID, and 12 in. long would be spray cast as part of the Phase II operation. Spraying of a 24-in.-square, 12-in.-long tube with a 2 1/2-in. wall thickness, an inside radius of 1/2 in., and an outside radius of 4 1/2 in. is proposed as a demonstration of the ability to spray cast square and rectangular tube shapes. These sizes are consistent with Table 2.

Preliminary cost estimates for Phase I and Phase II have been prepared and are included in Appendix B. These estimates include only facility costs, excluding such things as direct, direct support, and process development manpower requirements. The estimates also do not include costs associated with safety documentation and readiness reviews.

The Y-12 Plant engineering analysis discusses several technical concerns and issues that require engineering solutions. The major technical concerns are the service life of the spray nozzles, the handling requirements for the overspray, and the density and mechanical properties of the spray-cast product. In addition, the argon requirements for the Phase II facility could be a significant cost consideration for advancing from Phase I to Phase II operation.

Because DU is a dense, reactive metal with a relatively high melting point, the materials and design for the nozzle will require development to optimize service life. The nozzle as discussed herein includes the spray nozzle and the nozzle/tundish interface. Little work has been done on materials compatibility between molten uranium and nozzle materials. Several material candidates have been suggested based on earlier process experience. These materials are either ceramics, blends of ceramics, cermets, or refractory metals that are surface treated with either nitrogen or carbon or both. Ultimately, the optimum nozzle material will depend on compatibility, erosion rate, manufacturability, and cost. Because of the temperature ranges involved, the coefficients of thermal expansion of the different materials that interface with the nozzle must be evaluated, thus affecting the interface between the gas heater, the tundish, and the spray nozzle.

As was mentioned earlier, the spray-casting process is not 100% efficient. The overspray, which consists of very small particles of metallic uranium, are pyrophoric when exposed to air because of their large surface area-to-mass ratio. Phase I will demonstrate that the overspray material can be collected properly in an inert atmosphere and can be either oxidized in a controlled manner or properly disposed.

Because the spray-cast material is an equiaxed, fine-grained structure, the mechanical properties of the spray-cast material are expected to approach the mechanical properties of wrought DU. Spray casting achieves this structure by controlling the parameters such that the uranium strikes the substrate as fine, semimolten droplets that then develop a fine-grain microstructure as they solidify. A small amount of porosity might occur, potentially causing the density of the spray-cast material to be slightly lower than the density of the wrought material. This porosity is not expected to affect the mechanical properties, but it will reduce slightly the gamma-attenuation properties

proportionally to the decrease in density. Therefore, an increase in thickness will be required to overcome this decrease in density.

The maximum available argon flow rate in the foundry is 80 scfm. The conceptual design assumes that the argon will not be recycled during Phase I operation and that this flow rate will be adequate for Phase I studies. If the flow rate is inadequate, the argon system would have to be augmented, thus increasing costs significantly.

Phase II is estimated to require an argon flow rate of 2250 scfm, which will be accomplished by a steam-powered vaporization system and will require larger piping than that used for Phase I. A decision of whether to recycle the argon in Phase II will be made after successful completion of Phase I operation and will be based on the cost and space requirements of a recycling unit versus the cost of single use of argon.

MONTEC REPORT

Montec Spray Manufacturing Systems submitted an unsolicited proposal titled *Osprey Thermal Spray Processing of Depleted Uranium*. (It is included in this document as Appendix C.) The Montec report proposes using the Osprey process as an alternative to the spray-casting process for producing MPC-GSCs. The earlier involvement and work for DOE by one of the report's authors, John C. Tierney, provided insight to the Y-12 Plant approach to the MPC manufacturing issues. Montec has an agreement with Osprey Metals to thermally spray nuclear materials for this application.

Osprey is a rapid solidification metallurgical forming technology capable of generating semifinished and compound products in the form of billets, tubes, and flats in a single, integrated operation. The process comprises the steps of providing a source of molten metal, converting the metal into a spray of fine droplets by gas atomization, and directing the droplet at collecting surfaces, where they recombine to form a high-density, semifinished product, or preform. This preform can be either used in the as-sprayed condition or subsequently processed by conventional metal-working operations.

The advantage of this process is that it is a commercial process that has been used for aluminum, stainless steel, and numerous alloys. Osprey was formed in 1974 to develop and license the Osprey Preform Process; in 1977, it diversified to develop technology for the production of gas-atomized metal powders. A major benefit of the Osprey process is that the atomizer body does not come into direct contact with liquid material, thereby eliminating nozzle erosion and reaction problems.

This process, like the spray-casting process, has never been used with DU. System differences exist between the spray-casting process and the Osprey process that would require different facility configurations. In addition, some uncertainty exists as to whether the properties of the Osprey DU product would approach those of wrought DU, but this uncertainty has not been evaluated. This issue should be studied further before committing to an intermediate facility design. This report also recommends using the foundry at the Y-12 Plant for an intermediate facility and includes a plan for a development program and a preliminary cost estimate.

MSE REPORT

MSE submitted a report, *Department of Energy-Office of Science and Technology Spray-Casting Project Final Report*², to DOE in January 1996. This report documented the research and development work that they had conducted on Phase III of the spray-casting project.

MSE's Phase III began in 1991 and included the following tasks:

- developing a reliable high-temperature, inert-gas heating system and an electric metal feed system;
- installing a six-axis robotic arm;
- replacing an induction coil nozzle/tundish heating system with a graphite-resistive heating element;
- designing, making, and installing a vacuum/pressure chamber to control atmosphere and contain particle overspray; and
- installing a 0.02- μ m filter to control particle emissions from the process.

MSE spray-casting work included making prototypic cylinders of copper and nickel that were 4 in. long, 3 in. in diameter, and 1/4 in. thick. The report documents MSE's participation in the program.

Conclusions and recommendations from MSE include the following:

1. with the development of nozzles made from suitable materials, the MSE process should be applicable to the making of DU; and
2. DU should be sprayed on a small scale to prove that the material can be thermally sprayed into an acceptable engineering material.

CONCLUSIONS AND RECOMMENDATIONS

Current capabilities for producing DU products are probably unacceptable to the designers of the MPC-GSC-type gamma-radiation shields because of the assembly requirements and costs.

Spray casting is a new technology that could produce the monolithic structures required for MPC-GSCs, but it is an unproven technology for fabricating uranium. Several technical issues—including nozzle material selection, overspray handling requirements, and material properties evaluation of spray-cast product—must be resolved before a process can be developed for these large components. Some engineering concerns also need to be addressed concurrently with the technical issues.

The recommended approach for resolving these issues is to design and install an intermediate facility in the Y-12 Plant Uranium Foundry. Although the spray-casting process seems to be a lower-cost alternative to conventional techniques, a detailed cost estimate will have to be prepared that includes design specifications for MPC-like components. Both the Controlled Aspiration Process (CAP), developed by CST, and the Pressure-Controlled Atomization Process (PCAP), developed by MSE, should be evaluated in this facility.

This study did not evaluate the Osprey process; however, the vendor provided information independently. If the Osprey process were to be considered as a DU forming technology, experiments should first be conducted with a uranium surrogate material to determine feasibility before proceeding to a conceptual design. This conceptual design could then be subjected to the same type of evaluation as the CAP and PCAP technologies. If possible, this evaluation should be completed before the conceptual design of the intermediate facility is finalized so that, if it is viable, the intermediate facility could be designed to include an evaluation of the Osprey process. Because these processes are different in their atomization techniques and physical layout, adding the Osprey process would increase the cost of the facility.

When 2000-kg uranium parts have been spray cast successfully in the intermediate facility, the conceptual design of a production facility should proceed. Based on the intermediate facility operation, either the CAP, PCAP, or Osprey process could be chosen for the production facility.

This report is intended to provide the background information and status of the spray-casting project necessary to allow interested investigators to decide on the viability of this process and gives recommendations for pursuing the technology. **Note:** Although this report focuses on the fabrication of MPC-like components, the spray-casting technology should be feasible for fabrication of any DU component for which a near-net shape is desired or needed.

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APPENDIX A

HEAVY METALS PROCESSING
NEAR-NET-SHAPE SPRAY FORMING
INFORMAL SUMMARY PROGRESS REPORTS
TASK 1 - TASK 2 - TASK 3

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July 31, 1995

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under Contract DE-AC05-84OR21400

PREFACE

This volume contains three (3) Informal Summary Task Reports issued by Custom Spray Technologies, Inc. (CST) under subcontract to Martin Marietta Energy Systems, Inc. (MMES). Each section is a separate, working document that details the work effort and activities associated with the respective task, Task 1 through Task 3, outlined in the Statement of Work.

The Informal Summary Task 1 Report, issued April 17, 1995, has been reprinted and is the first section of this volume. The second section provides information specific to Task 2 and the Production Facility. Task 3 information, presented in the third section, outlines the Intermediate System and its activities. Informal report information is conceptual and not intended to address engineering design criteria.

The purpose for consolidating the informal reports is to enable this volume to serve as a singular, ready reference for the initial working documentation pertinent to Task 1 through Task 3 information.

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*Each Informal Report is a standalone submittal. Refer to each Task Report for the respective Contents.

EXECUTIVE SUMMARY

Significant research and development conducted at the CST Laboratory from 1991 through September 1994 has demonstrated the feasibility of utilizing Spray Forming Technology for near-net-shape manufacturing of components from high-density, reactive metal feedstock.

The feasibility of designing, constructing, and operating a high-density material spray facility at the Oak Ridge Y-12 Plant is being explored by MMES. Integral to this study is a conceptual design for a spray forming system capable of spraying depleted uranium (DU) located at the Y-12 Facility. One product line being considered is the Multipurpose Canisters (MPCs) which will be used for high level radioactive waste storage and transportation.

This series of Informal Summary Task Reports is intended to serve as a preliminary list for what will be involved to implement Spray Forming Technology into the heavy metals processing industry for the manufacture of MPC shielding components.

Prior to design and construction of a full-scale Production Spray Facility, Intermediate Spray Activities must be conducted. The Intermediate System will serve to demonstrate the Proof-of-Principle for the larger Production System. The design for an Intermediate Spray System will precede the design for a full-scale Production System. The Intermediate System must be capable of producing an as-sprayed product representative of the product required for the MPC shielding components. Intermediate Spray Activities include, but are not limited to: (1) Confirmation of a nozzle system capable of spraying DU at a minimum throughput of 300 kg per hour, (2) Characterization of discharge gases and overspray particulates, and (3) Confirmation that the end-product is acceptable in the as-sprayed form. The as-sprayed product requirements must satisfy mechanical properties, density, and gamma attenuation characteristics. Based on the need for Intermediate Spray Activities, conceptual designs for two spray systems are required.

Review meetings and presentations for exchanging technical input and discussing progress-to-date were an integral part of the work scope. Because of the inherent relationship of the two spray systems, it was necessary to work the development of the conceptual designs for both systems in parallel. The final conceptual design will be authored by MMES technical personnel and will integrate MMES' expertise, capabilities, and existing facilities.

1. INTRODUCTION

U.S. Department of Energy facilities responsible for processing heavy metals continue to evaluate advanced technologies that simplify component fabrication, reduce handling operations, and minimize hazardous wastes.

As an application for such advanced technology, a potential solution for easing the Federal burden of radioactive waste containment is being explored by Martin Marietta Energy Systems, Inc. (MMES) in conjunction with Custom Spray Technologies, Inc. (CST). Technical personnel at MMES and CST are currently studying the feasibility of developing a spray system capable of manufacturing products from the depleted uranium (DU) located at the Oak Ridge Y-12 Facility. One product line being considered is the Multipurpose Canisters (MPCs) which will be used for high level radioactive waste storage and transportation.

Informal report information contained in this submittal is presented in three sections. The Task 1 segment relates Program direction as discussed during the initial Planning Meeting held at the Y-12 Facility March 22-23, 1995. Task 1 also addresses MMES' process requirements for conceptual designs as known during the first meeting. Task 2 provides information specific to the Production Spray System. The production system will be designed to manufacture gamma shielding components of specified dimensions for the Multipurpose Canisters. These canisters will contain high level radioactive waste and will require gamma shielding. To distinguish manufacture of the canisters from manufacture of the canister components, the components will be referred to as Multipurpose Canister-Gamma Shielding Components (MPC-GSCs). Task 3 documents the Intermediate Spray System and activities. The Intermediate Spray System will be designed to produce MPC-GSCs of specified dimensions from DU feedstock.

1.1 OBJECTIVES

Significant research and development conducted at the CST Laboratory from 1991 through September 1994 has demonstrated the feasibility of utilizing Spray Forming Technology for near-net-shape manufacturing of components from high-density, reactive metal feedstock. In particular, the spray forming process may be suited for production of large MPC-GSCs which would be a part of the MPCs

identified for high level radioactive waste storage and transportation.

The objective of this Program is to aid MMES at the Oak Ridge Y-12 Facility in the development of a conceptual design for a spray forming system capable of spraying depleted uranium. In concert with this objective, a recommendation is needed on the feasibility of producing MPC-GSCs fabricated from DU.

Establishing the criteria necessary to design a spray forming system requires a complete understanding of the processing problems of the feedstock being consolidated to a final product. Other critical factors in system design include control of process emissions to the environment, personnel operating and maintenance hazards, control of process inefficiencies such as excessive overspray, and the microstructure requirement of the as-sprayed product.

The objective of the Intermediate System Activities is to demonstrate that a spray system can produce an acceptable as-sprayed product. Scalability of the process to the full production spray facility must also be demonstrated.

This phase of the Program was structured to enable personnel with expertise in the uranium processing field to review and comment on the progress-to-date information. Likewise, review and input from personnel in the environmental, safety and health arenas will need to be solicited. Comments from these reviews will be evaluated by MMES for incorporation into the final conceptual design for the spray forming system. The final design will be authored by MMES technical personnel and will integrate MMES' expertise, capabilities, and current facilities relative to uranium processing.

1.2 BACKGROUND

The following information is provided for those individuals who may not have immediate access to previous Program reports that link utilization of Spray Forming Technology with heavy metals processing research.

Prior to the present investigation of potential manufacture of products from depleted uranium, feasibility of the spray forming process capabilities was demonstrated through three experimental

phases of Program activity. These studies demonstrated the feasibility of the patented Controlled Aspiration Process (CAP). This process aspirates molten metal from an integral tundish into a converging/diverging nozzle. There the metal stream is efficiently nebulized into a directed mist of fine droplets which rapidly cool in flight before solidifying against a substrate. In Phase I, efforts were focused on confirming the viability of spraying high-density metals, where molten gold was used to simulate the melting points, fluid densities, and heat capacities of uranium and uranium alloys. The Phase I - Addendum I work involved reactivity experiments using aluminum (Al) and one spray trial using a surrogate alloy as feedstock. These experiments were conducted in the Phase I spray chamber. It was determined in the second portion of the Addendum I experiments that the surrogate alloy (49.6% Tungsten, 49.6% Iron, and 0.8% Carbon) could be sprayed using machinable ceramics. Further activities included the Extended Surrogate Alloy Experiments.

Following completion of the Surrogate Alloy experiments, MMES has initiated a feasibility study to investigate the potential of using Spray Forming Technology to manufacture products from depleted uranium. The intended end product is a system for spraying depleted uranium. Development of an engineering data base is also required. The product line of interest to MMES is the manufacture of MPC-GSCs. Private, commercial, and Governmental concerns associated with the storage, transportation, and handling of spent nuclear fuel make fabrication of MPC components from DU a critical area of pursuit.

Previous reports on Program activities include: "Summary Progress Report, Phase I: High-Density Trials, SCIE-ORNL-101-92", Phase I - Addendum I Draft Reports entitled, "Reactivity Experiments, CST-2283", and "Surrogate Alloy Experiments, CST-2353". The series of Informal Summary Task Reports presented in this publication requires the reader be familiar with the findings and conclusions of the Extended Surrogate Alloy Experiments entitled, "Heavy Metals Processing Near-Net-Forming Summary Progress Report, CST-2734."

1.3 WORK SCOPE

The conceptual designs and technical information published during this informal reporting phase are in developmental stages and, therefore, are presented as working documents, subject to

change as Program activities evolve. Information contained in this submittal is conceptual and not intended to address engineering design criteria. During the first Planning Meeting, attendees were advised that August 1, 1995, was the desired date for all conceptual design information to be received by MMES. The decision to publish several informal reports without extensive revision was made in order to accommodate the need for rapid dissemination of information and to support the work effort at MMES.

Data from previous spray forming activities was reviewed and factored into the conceptual designs where applicable. A list of General Problems was generated and prioritized during the first Planning Meeting. Draft Functional Requirements for the Production Spray System and the Intermediate Spray System were then developed. Due to the inherent relationship of the two spray systems, it was necessary to develop the Task 2 and Task 3 conceptual designs in parallel.

Review meetings and presentations for exchanging technical information and discussing progress-to-date were an integral part of the work scope. Technical presentations were presented during March, April, and June. A presentation will be prepared by CST for the Final Review Meeting scheduled for August 9, 1995, at the Y-12 Facility. The presentation will consist of an overview of Task 1 through Task 3 information with emphasis on the Intermediate System Activities. Following this meeting, CST is prepared to review and comment on the End of Project Report prepared by MMES.

The Statement of Work was issued as a flexible document which could be modified as required. As a result of information exchanged during the first Planning Meeting, MMES technical personnel determined that it would be more beneficial for Program requirements to apply sample analyses funding toward a conceptual design for a production scale spray system. Modification "A", issued during May 1995, restated Task 2 activities to incorporate the conceptual design for a Production Spray System. Additionally, a Task 2 Outline listing the activities to be performed replaced the original Test Plan which required additional sample analyses from previously conducted work. Modification "B", issued during July 1995, identified July 31, 1995 as the submittal date for the combined publication of the Task 1, Task 2, and Task 3 submittals.

1.4 TASK DESCRIPTION

Subsequent to the modifications, the Program effort was organized into the following Tasks.

Task 1. Establish Criteria for Near-Net-Shape Spray Forming System Conceptual Design

- Informal Summary Report on Conceptual Design to MMES

Task 2. Evaluation of the Spray Forming Process

- Task 2 Outline
- Complete Task 2 Outline and Submit Informal Task 2 Summary Report to MMES

Task 3. Conceptual Design for Spray Forming Process

- Complete Input for Conceptual Design of Process and Facility and Submit Informal Task 3 Summary Report to MMES
- Provide Review and Comments for an End of Project Report Prepared by MMES

Task 4. Exchange of Technical Information

- One Presentation at MSE, Inc.
- Two Technical Presentations at MMES of Conceptual Design

The technical presentation provided by CST during the first Planning Meeting was presented at no additional cost to the Program. Weekly Progress Reports were also submitted to MMES throughout the Program.

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**CRITERIA FOR CONCEPTUAL DESIGN
NEAR-NET-SHAPE SPRAY FORMING
FACILITY**

**INFORMAL SUMMARY PROGRESS REPORT
TASK 1**

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CST-1075

CRITERIA FOR CONCEPTUAL DESIGN
NEAR-NET-SHAPE SPRAY FORMING
FACILITY

INFORMAL SUMMARY PROGRESS REPORT
TASK 1

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1. INTRODUCTION

This Informal Summary Report requires the reader be familiar with the findings and conclusions of the Extended Surrogate Alloy Experiments; see "Heavy Metals Processing Near-Net-Forming Summary Progress Report, CST-2734" published in September 1994.

Previous experimental results obtained at the Custom Spray Technologies, Inc. (CST) Laboratory have revealed the potential for constructing a spray forming system to aid in the manufacture of depleted uranium products. In particular, the spray forming process may be suited for production of large Multipurpose Canisters (MPCs) identified for high-level radioactive waste gamma shielding components. Establishing the criteria necessary to design a spray forming system requires a complete understanding of the processing problems of the feedstock being consolidated into a final product. Other critical factors in system design include process emissions to the environment, personnel operating and maintenance hazards, and the microstructure requirement of the as-sprayed product.

This submittal addresses the following topics: (1) Enumerate the problems of major importance, (2) List the priority assigned to each of these problems and identify where the concerns are being implemented into the design process, and (3) Present the progress-to-date on the conceptual designs being prepared for Tasks 2 and 3.

Informal Reports issued to Martin Marietta Energy Systems, Inc. (MMES) under this Program will be working documents. The objective of this Program is to aid MMES personnel in developing a conceptual design of a spray forming system capable of spraying depleted uranium. The Intermediate Spray System will be capable of operating at production scale levels and will demonstrate the ability to scale a system to produce large, spray formed castings. The MMES Program structure allows for review of the design progress-to-date by personnel with expertise in the uranium processing field and individuals in the environmental, health, and safety arenas. Comments from reviews will be evaluated by MMES personnel for incorporation into the final conceptual design for the spray forming system. The input from Program participants will serve to integrate the conceptual design presented by CST with the processing demands in the heavy metals industry.

2. ESTABLISH CRITERIA FOR NEAR-NET-SHAPE SPRAY FORMING SYSTEM CONCEPTUAL DESIGN

A Planning Meeting was held at the Oak Ridge Y-12 Plant on March 22-23, 1995. Attendees included personnel from the U.S. Department of Energy - Oak Ridge; Martin Marietta Energy Systems, Inc. - Oak Ridge, TN; Custom Spray Technologies, Inc. - Rigby, ID; and MSE, Inc. - Butte, MT. The spray forming process was presented in general terms to personnel in the heavy metals processing field. Personnel in the processing field briefed attendees on the current MMES processing techniques and elaborated on potential hazards in heavy metals processing. Attendees openly exchanged information relative to a conceptual design for a spray forming system capable of spraying depleted uranium.

Previous Program accomplishments and the concept of a linear, aspirated nozzle were presented. Explanations included how metal throughput of the spray system could be increased to a level commensurate with MMES' processing requirements. The metal throughput for a spray system required for the Heavy Metals Processing Industry has not been demonstrated using uranium as a feedstock. Throughput of a linear nozzle, commensurate with production requirements, could be demonstrated prior to committing funds for construction of a Production Facility. Follow-up discussions led to the general consensus that design of an Intermediate Spray System would be necessary prior to fabrication and operation of a full production scale unit. Options, including pilot scale and full production systems, were discussed. At MMES' direction, a conceptual design for an Intermediate Spray System capable of operating at production scale levels and demonstrating the ability to scale a system to produce large, spray castings will be pursued.

This intermediate system could produce a cylinder with the following dimensions: 3-in. wall thickness, 36-in. inside diameter, and 12-in. height. This end product would confirm: 1) Net forming the more difficult approximate shape that conforms to manufacturing requirements, and 2) Manufacturing this end product at a rate commensurate with production requirements.

As a result of the determination that an Intermediate Spray System is necessary, Task 2 will document a first estimate, conceptual design for the production scale facility. This early conceptual presentation will incorporate past experimental results

with the conceptual design for the Intermediate Spray System to be presented in Task 3.

Two potential candidates for the choice of substrate material were discussed. A graphite disk or thick-walled cylinder would offer low coefficient of expansion and has already been demonstrated as a compatible material in uranium processing. The second option was a metal cylinder which would remain a part of the as-sprayed product. Types of metal that would be compatible for this application are under investigation.

2.1 FABRICATION/OPERATION CONCERNS

To maintain perspective of the design issues, a list of major problems was developed by the attendees. Items on the initial list were then prioritized. The items are numbered sequentially with problems of highest priority listed first. For reference, the list is included as Appendix A.

Priorities 1 and 2: Following identification of the preferred type of nozzle/tundish assembly and feedstock assembly, materials for these components will be recommended. Priority 3: Results from the previous surrogate alloy experiments can provide a general basis for developing a powder handling system. Suggestions for sizing the powders will be contained in the Test Plan for Task 2. Batch mode operation for the Intermediate Spray System will combine problems 4, 5, and 6 of Appendix A into a single operating procedure, specifically, how to safely access the system following each spray trial. In the Task 2 conceptual design submittal, these items will likely be considered as separate issues.

As the Program progresses, the lower level issues itemized in Appendix A will be assessed and factored into the conceptual design, as appropriate. The current Statement of Work is described in Appendix B. As a result of the March 1995 Planning Meeting, a conceptual design for a production facility has been incorporated into Task 2. In order to accommodate Program requirements as they evolve, the Statement of Work is subject to further refinement.

3. EVALUATION OF THE SPRAY FORMING PROCESS

3.1 TEST PLAN OUTLINE

1. Correlate previous results with information obtained during the first MMES Planning Meeting at Y-12 March 22-23, 1995.
2. Provide recommendations for any additional analyses of previous experimental data that may be beneficial.
 - 2.1 Size analyses of powders from the Extended Surrogate Alloy Experiments.
 - 2.2 Analyses of nozzle wear on components used to perform the Extended Surrogate Alloy Experiments.
3. Preliminary Conceptual Design for a Production Facility Spray Forming System.
 - 3.1 Right angle cylinders: 75-in. diameter; 54-in. height; 3-in. wall thickness.
 - 3.2 Solid disks: 75-in. diameter; 3-in. thickness.
4. Perform additional work on previous data and/or results as directed by MMES.
5. Prepare Informal Summary Report, Task 2 outline for MMES review and comment.
6. Issue Informal Summary Report, Task 2.

3.2 CONCEPTUAL DESIGN - PRODUCTION FACILITY (PROGRESS-TO-DATE)

The potential size of the end product for the MPC is anticipated to be a 75-in. diameter canister that measures 54-in. in length and has a wall thickness of 3 in. Approximately 100 of these canisters would be manufactured from depleted uranium.

During the Planning Meeting at Oak Ridge, the potential for assembling canisters from rings of various heights was discussed. The fabricated rings would have different heights, thereby allowing

Figure 1. Nested Ring Assembly.

assembly of different canister lengths with overlapping seams. This arrangement could provide larger cylinders while requiring rings be net formed with a variety of dimensions. This approach could result in considerable savings for construction of the first production facility. Although the production facility would be designed to produce a canister of specified dimensions, it could also be used to make rings of a variety of sizes (i.e., multiple diameters to 75 in.; multiple heights to 84 in.; and multiple thicknesses). This concept would allow fabrication potential for a large variety of cylindrical containers. A schematic of a nested ring arrangement is illustrated in Figure 1.

The production facility capable of manufacturing this type of ring could utilize smaller, less expensive nozzle assemblies and still maintain an acceptable throughput for the production system. The spray forming system could be comprised of linear nozzle assemblies mounted on platforms with a convenient feedstock supply. A cylindrical substrate would rotate on its vertical axis. The platforms would move vertically along the surface of the cylindrical substrate. There would be sufficient platforms with feedstock to allow for potential system failure of any one platform assembly. Schematics of the side view and top view of this concept are presented in Figure 2 and Figure 3 respectively. Each platform would be approximately 3-ft. square with the capacity to hold one batch of sheared plate from the rolling facility or receive a liquid feed to the tundish from a bottom pour vacuum induction furnace (Illustration in Progress). The power and gas lines would enter from overhead and be mounted to the platform. Sufficient flex would be required to allow movement of the platform during the

Figure 2. Side View: Production Scale; Large Diameter Cylinders.

Figure 3. Top View: Vertical Axis; Multiple Diameters and Heights.

production process. For small cylinders that have a 3-ft. diameter, a 3-in. wide nozzle would be recommended. When spraying 75-in. diameter cylinders, nozzles up to 6-in. wide could be used.

The configuration for spraying large diameter disks will be illustrated in Figure 4 and included in later reporting. A preliminary flow sheet for production operation is depicted in Figure 5.

PRODUCTION SCALE FACILITY
(Concept in Progress)

**Figure 4. Production Scale Facility - Flat Disk:
75-in. Diameter; 3-in. Thickness.**

Figure 5. Production Operation Flow Sheet.

4. CONCEPTUAL DESIGN FOR INTERMEDIATE SPRAY SYSTEM (Progress-to-Date)

4.1 CRITERIA OUTLINE FOR INTERMEDIATE SPRAY FORMING SYSTEM

A synopsis of spray system components and design criteria requirements has been formulated. The outline presented below is a first draft and subject to additions and/or deletions depending on input from MMES.

Intermediate Spray System - Design Criteria Factors

Nozzle/Tundish Assembly Issues

Feedstock fed directly into tundish?

Pour liquid into tundish?

Operate a 3-in. wide nozzle, then a 6-in. wide nozzle:

- 1) Demonstrate production throughput.
- 2) Verify scalability.

Nozzle will require tailoring for spraying depleted uranium.

Machine the first spray components; design so castable?

Evaluate ceramic and metal-to-ceramic interfacing.

Assembly support critical.

Resistance Heating?

Induction Heating?

Not impossible, however, water in the area of molten or hot uranium would cause extreme safety concerns.

Furnace Design Issues

Cost effective to use existing capabilities?

Single batch process for each run.

Bottom pour to tundish.

Sealed system, accessed after cool down.

Gas Heater Design Issues

Machine the first components; design so castable?

Substrate Issues

Graphite disk/cylinder - separates from end product.

Metal cylinder - separates or remains with end product:
3-in. thick, 36-in. diameter (both materials),
and 12-in. height product.

Motion of cylinder in plume:

Axis Horizontal:

Axis of cylinder horizontal lends to
nozzle scaling activities and particle
discharge containment.

Axis Vertical:

Axis of cylinder vertical will require
increased substrate speed when scaling
nozzle.

Power Delivery Issues

Type of control.

Gas heating.

Nozzle/Tundish heating.

Chamber Issues

Requirements for safety, technical, and environmental
monitors.

Dimensions, specifications, quality control, and
inspections.

Attaches to medium furnace?

Attaches to large furnace?

Can accommodate feedstock fed directly to tundish?

Unit attaches to chamber for feeding to tundish?

Would then detach for attaching chamber to
furnace for liquid pour.

Powder collection during operation?

Visual determination of process preferred.

Some means of determining the appearance of the
consolidated material during the system operation
would aid in final nozzle tailoring.

Personnel Health/Safety Considerations

Environmental/Quality Control Issues

Other Regulatory Requirements

Certification

4.2 NOZZLE OUTPUTS

Progress-to-date on the Intermediate Spray System design includes typical outputs anticipated from using linear nozzles. Tables 1 and 2 depict representative summary data. These outputs would be the design criteria for the nozzles utilized during the initial experiments. Maximum outputs of the linear nozzles in depleted uranium would be a part of the Intermediate Proof-of-Concept phase.

4.3 INTERMEDIATE SYSTEM (In Progress)

- Needs and Advantages.
- Operations.
- Objectives.

TYPICAL DATA SUMMARY - INITIAL OUTPUT - ASPIRATING NOZZLES

Table 1. Aspirating Nozzle: 3" Width and 0.15" Height

Nozzle Supply Pressure	Mass Ratio (Gas-to-Metal)	<u>Throughput</u>			<u>Power Requirements in Kilowatts</u>				
		Gas	Metal	Units	Theoretical Gas	Theoretical Metal	Commercial Gas	Commercial Metal	MMES Metal
5.3 psi ⇔ 20 psia (Tundish nearly empty)	1:1	44.3	44.3	g/s	30	8.8	60	17.3	13.2
		2.7	2.7	kg/min					
		159.4	159.4	kg/hr					
11.3 psi ⇔ 26 psia (Tundish nearly empty)	2.5:1	65.3	26.1	g/s	44	5.2	88	10.2	7.8
		3.9	1.6	kg/min					
		235.0	94.0	kg/hr					
15.3 psi ⇔ 30 psia (Tundish nearly empty)	4:1	76.2	19.1	g/s	52	3.8	104	7.5	5.7
		4.4	1.1	kg/min					
		274.4	68.6	kg/hr					

Table 2. Aspirating Nozzle: 3" Width and 0.20" Height

Nozzle Supply Pressure	Mass Ratio (Gas-to-Metal)	Throughput		Power Requirements in Kilowatts					
		Gas	Metal	Units	Gas	Metal	Commercial	Gas	Metal
5.3 psi ⇌ 20 psia (Tundish nearly empty)	1:1	59.1	59.1	g/s	40	11.7	80	23.1	17.6
		3.5	3.5	kg/min					
		212.6	212.6	kg/hr					
11.3 psi ⇌ 26 psia (Tundish nearly empty)	2.5:1	87.0	34.8	g/s	59	6.9	118	13.6	10.4
		5.3	2.1	kg/min					
		313.3	125.3	kg/hr					
15.3 psi ⇌ 30 psia (Tundish nearly empty)	4:1	101.7	25.4	g/s	69	5.0	138	9.9	7.5
		6.0	1.5	kg/min					
		366.0	91.5	kg/hr					

4.4 TYPICAL COMPONENT AND PARAMETRIC VALUES

4.4.1 Particle Velocities

There has not been sufficient experimental data to establish general particle velocities for the aspirating nozzle. Crude velocities and/or maximum values for particle velocities could be approximated by:

- Calculate gas velocities in the nozzle throat for the various conditions.
- Multiply by the ratio of the nozzle throat area to the plume area at the substrate.
- Use the gas-to-metal mass ratio and conservation of momentum to further reduce velocity.
- Realize a significant portion of momentum will be lost in breaking up the metal stream.
- Consider temperature of the aerosol at the substrate.

4.4.2 Particle Size Expectations

Particle size depends on several variables. The figures below are suggested and are only to be assessed in the roughest nature.

• Gas-to-Metal Mass Ratio: 4.0:1 or Larger	8-25 μm
• Gas-to-Metal Mass Ratio: 2.5:1	20-40 μm
• Gas-to-Metal Mass Ratio: 1.0:1	30-70 μm

At this time, it is anticipated to design a system on the basis of the 2.5:1 ratio or more preferably the 1.0:1 ratio.

4.4.3 System/Component Parameters

Nozzle Body:	1200-1300°C
Gas Heater Body:	950-1400°C
Gas Temperature in Nozzle Throat:	850-1300°C
Melt Temperature (Tundish):	1180-1250°C

PHASE II: Production Spray Facility

Incorporate a series of spray units into a Production Spray System as illustrated in Figures 2 and 3.

This approach would require a large number of identical spray units. This would likely generate savings in the cost of each unit since minimum orders for set-up charges at the commercial level could be met.

**Figure 6. Intermediate System: Vertical Axis Rotation;
Substrate Supported by Floor.**

In the system depicted in Figure 6, a cylindrical substrate would mount on a table with the axis of the cylinder being at right angles to the spray plume. The cylinder would rotate in front of the nozzle and the entire assembly would move closer and farther from the nozzle to accommodate a constant nozzle exit to substrate separation. To provide the desired width, the cylinder would also require a vertical motion of 12 in. It would be desirable to have the substrate 4 to 6 in. wider than the finished product. The spray plume would then have a surface for consolidation regardless of the relative position of the nozzle and substrate.

An alternate approach would be to have the nozzle and the coil which preheats the feedstock mounted on a platform with flexible utility leads. This approach would require a slightly larger chamber, however, it would be a closer approximation to the conceptual, production facility illustrated in Figures 2 and 3. The cylindrical substrate would then rotate at a controlled rate between 0 and 5 revolutions per minute (rpm).

This type of arrangement would make the handling of overspray powders difficult. The irregular gas flow exiting the chamber and the high density of uranium would cause the majority of overspray powders to be deposited on the floor and on the flat surfaces that are lower than the spray plume. These surfaces would be collection areas for the larger overspray powders.

In the system illustrated in Figure 7, a cylindrical substrate is suspended from an overhead beam with the axis of the cylinder held at right angles to the spray plume. The cylinder would rotate in front of the nozzle and the entire assembly would move closer and farther from the nozzle to accommodate a constant nozzle exit

Figure 7. Intermediate System: Vertical Axis Rotation; Substrate Supported Overhead.

to substrate separation. The cylinder would also require a vertical motion of 12 in. to provide the desired width. It would be desirable to have the substrate 4 to 6 in. wider than the finished product. The spray plume would then have a surface for consolidation regardless of the relative position of the nozzle and substrate.

An alternate approach would be to have the nozzle assembly and the coil which preheats the feedstock mounted on a platform with flexible utility leads. This approach would require a slightly larger chamber, however, it would also be a closer approximation to the conceptual, production facility illustrated in Figures 2 and 3. The cylindrical substrate would then rotate at a controlled rate between 0 and 5 rpm.

**Vertical Axis - Rotating Cylinder/Disk
Supported By Chamber Floor**

Figure 8. Conceptual Substrate Illustration.

With the substrate mounted on an overhead beam, the floor area beneath the substrate would be free of obstructions. This would allow smooth gas flow while exiting the chamber and would also provide smooth surfaces for removing the larger powders that will not remain in the gas stream. Baffles could be included to further enhance the concentration of powders for later particle recovery.

In either type of mounting for the vertical axis substrate, purge flows could be used to prevent powders from collecting within the components of the substrate system (see Figure 8). If gas cylinders were used for supporting some of the weight, these gas

cylinders could be designed to operate with controlled leaking. This would prevent fine powders from entering the various chambers or bearing areas.

Using the vertical axis substrate, increased substrate speeds would be required to demonstrate a nozzle having a greater width. Scaling the nozzle width would be limited by the curvature of the cylinder. It is estimated the nozzle could be 4-in. wide without changing the consolidation effects. This would allow the substrate surface to nozzle exit distance to vary 0.1 in. due to the curvature of the substrate.

Figure 9. Intermediate System: Horizontal Axis Rotation; Substrate Supported Overhead.

Figure 9 illustrates a cylindrical substrate with the axis of rotation horizontal and at right angles to the spray plume. The axis of the substrate would be slightly above the spray plume, thereby enabling the nebulizing gas to be preferentially deflected downward in the direction of rotation. Proper baffling in this type of arrangement would provide the optimum handling of overspray and discharge gases. As the discharge gases exit the chamber, an

inertial type of separation could occur. This would provide a collection area for the largest portion of overspray particles. A small percentage gas flow around the separator could be established to ensure that very small particles (i.e., those having equivalent aerodynamic diameters of 5 microns or less) would not form a particle cloud in the exit region of the spray chamber. This nominal gas flow would also minimize small particle deposition on the walls in the exit region of the separator.

The horizontal type rotating axis would provide a better rotating surface for scaling the nozzle from 3-in. wide to 6-in. wide.

5. RECOMMENDATIONS AND FINDINGS

Implementing Spray Forming Technology into heavy metals processing will be approached through development of a refined, conceptual design for an Intermediate Spray System. Demonstrating scalability of the process to the full production spray facility will be paramount to conceptual design of the Intermediate Spray System.

Prerequisite to implementing a conceptual design of a spray system capable of spraying depleted uranium, an information base to identify and clarify design criteria is required. This submittal is the first in a series of Informal Reports from CST to MMES. Documentation from CST to MMES, in the form of working papers that incorporate conceptual design progress-to-date, will provide input for establishing the conceptual design for the Program.

During the recent Planning Meeting, MMES advised attendees that August 1, 1995, is the desired date for all conceptual design information to be received by MMES. Based on that, comments from Program participants versed in spray forming and MMES capabilities and requirements are being solicited. This blend of expertise will compliment the range of alternatives and will enable pros and cons of options to be evaluated by MMES. Results of the information base will aid MMES in the presentation of a conceptual design for a production scale spray forming facility to be operated at the Oak Ridge National Laboratory.

APPENDIX A

GENERAL PROBLEMS BY PRIORITY
(March 1995)

GENERAL PROBLEMS BY PRIORITY

Priority Established by Group Consensus
March 22-23, 1995 Planning Meeting

Priority	Fabrication/Operation Concern
1	Nozzle/Tundish Issues (Fabrication, Erosion)
2	Material Feed Issue
3	Handle Overspray (Can gas flow be increased enough to remove overspray?)
4	How to Load/Unload Parts Without Exposing Chamber
5	Health Physics/Industrial Hygiene (1) Pyrophoric (2) Radiological Contamination/Control
6	Maintenance; Personnel Access to Chamber
7	Mandrel Considerations/Designs - Permanent Mandrel? (1) Material Compatibility
8	Rate of Spray (Net formed product sagging?)
9	Atmosphere Requirements for Chamber?
10	Sizing/Shape Considerations (1) Diameters to 8 ft.? (2) Intermediate/Final
11	How to Move Part in Plume (1) Rotating Table (2) Robot
12	Is Post Spray Treatment Needed?
13	How Thick Can We Spray Without Cracking?

APPENDIX B

STATEMENT OF WORK
(Revised March 1995)

Revised 3/8/95

**STATEMENT OF WORK
SPRAY FORMING
KEA73**

Background

Spray Forming is an emerging technology which has demonstrated production capabilities in the hundreds of pounds per hour range. Previous work in this area has demonstrated the feasibility of this process for Near-Net-Shape (NNS), high density metal component manufacturing. This process could prove beneficial in manufacturing of high density metal components, such as depleted uranium plates for High Level Radioactive Waste (HLRW) gamma shielding components. The advantages in Spray Forming of HLRW gamma shielding components is that significantly larger components with NNS tolerances can be manufactured with less operations than any other current technology. Spray Forming HLRW components would significantly reduce waste and cost and would produce a higher quality product. A conceptual design of a NNS spray process and a conceptual design of hardware for a high density material spraying facility are needed.

Scope of Work

This effort will be divided into the following tasks requiring the listed deliverables:

Task 1. Establish Criteria for Near-Net-Shape Spray Forming System Conceptual Design

Seller will review data from previous spray forming activities and attend a program participants meeting at MMES in Oak Ridge to review MMES process requirements. The Seller will identify requirements for conceptual design of a spray forming system in an Informal Summary Report.

DeliverablesDue Dates

Informal Summary Report on
Conceptual Design Criteria to
MMES

*21 days after meet-
ing at MMES
(April 17, 1995)

Weekly status report to MMES

Thursdays

* Meeting date scheduled for March 22-23, 1995.

Task 2. Evaluation of the Spray Forming Process

Based on process requirements obtained in Task 1, Seller shall review original data from the Extended Surrogate Alloy Experiments previously conducted in project. Seller will recommend further data reduction and/or further specimen analyses from the previously conducted work. The recommended actions shall be contained in a test plan to be submitted to MMES. The test plan shall detail technical activities, a breakdown of the price of Task 2, and schedule.

Following MMES review and concurrence of the test plan, the Seller shall conduct the test program detailed in the test plan and prepare and submit an Informal Task 2 Summary Report to MMES.

Deliverables

Due Dates

Test Plan for evaluation of
spray forming

*Forty-Five (45) days
after MMES meeting
(May 8, 1995)

Complete activities in plan and
submit Informal Task 2 Summary
Report to MMES

*Four (4) months after
MMES meeting
(July 24, 1995)

Weekly status report to MMES

Thursdays

Task 3. Conceptual Design for Spray Forming Process

Seller shall provide technical and engineering expertise to aid MMES in producing a conceptual design of a NNS Spray Forming System (to include support facility). Seller's input shall include hardware requirements for a proposed high density material spraying facility.

Deliverables

Due Dates

Complete input for conceptual design
of process and facility and submit
Informal Task 3 Summary Report to MMES

08/01/95

Provide review and comments for an
End of Project Report prepared by MMES

09/01/95

Weekly status report to MMES

Thursdays

* Meeting date scheduled for March 22-23, 1995.

Task 4. Exchange of Technical Information

The Seller shall provide exchange of technical information through three briefings: two at MMES facilities and one at MSE, Inc. facilities at direction of MMES.

<u>Deliverables</u>	<u>Due Dates</u>
Presentation at MSE, Inc. (One presentation)	08/01/95
Technical presentation at MMES of conceptual design (Two presentations)	09/01/95

Martin Marietta Energy Systems Contacts

Primary Technical Contact at Y-12 will be J. E. Thompson (615-574-2503)

Alternate Technical Contact at Y-12 will be S. R. Churnetski (615-576-5922)

APPENDIX C

CONCEPTUAL SKETCHES
FOR
REVIEW AND COMMENT*

*Program personnel and individuals authorized to review information contained within this conceptual design submittal are requested to provide comments on the information in general and on the Conceptual Sketches in Appendix C. To aid reviewers, Appendix C pages are perforated and facsimile information for transmitting comments to CST is provided on the back of the General Notes/Comments pages. A copy of comments to CST will be submitted to MMES.

PROS**CONS**

Figure 6c. Figure 6 for Review and Comment.

PROS**CONS**

Figure 7c. Figure 7 for Review and Comment.

Vertical Axis - Rotating Cylinder/Disk
Supported By Chamber Floor

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Figure 8c. Figure 8 for Review and Comment.

PROS

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Figure 9c. Figure 9 for Review and Comment.

General Notes and Comments - Task 1, 4/95
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General Notes and Comments - Task 1, 4/95

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**CUSTOM SPRAY
TECHNOLOGIES, INC.**

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328 North 4000 East
Rigby, Idaho 83442

CST-2125

**HEAVY METALS PROCESSING
PRODUCTION FACILITY CONCEPTUAL DESIGN
INFORMAL SUMMARY PROGRESS REPORT
TASK 2**

Lloyd Watson
Custom Spray Technologies, Inc.
Rigby, Idaho 83442-5533

July 31, 1995

Prepared and Published by
CUSTOM SPRAY TECHNOLOGIES, INC.

328 North 4000 East
Rigby, ID 83442-5533

for

Oak Ridge Y-12 Plant
P.O. Box 2009, Oak Ridge, TN 37831-8169
managed by
MARTIN MARIETTA ENERGY SYSTEMS, INC.

for the
U.S. DEPARTMENT OF ENERGY
under Contract DE-AC05-84OR21400

CST-2125

HEAVY METALS PROCESSING
PRODUCTION FACILITY CONCEPTUAL DESIGN

INFORMAL SUMMARY PROGRESS REPORT
TASK 2

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1. INTRODUCTION

This informal report is the second in a series of working documents issued by Custom Spray Technologies, Inc. (CST) under subcontract to Martin Marietta Energy Systems, Inc. (MMES). Material contained in this submittal presents conceptual design information for the Production Spray System and completion of activities referenced in Task 2 of the modified Statement of Work.

The production system will be designed to manufacture gamma shielding components of specified dimensions for the Multipurpose Canisters (MPCs). These canisters will contain high level radioactive waste and will require gamma shielding. To distinguish manufacture of the canisters from manufacture of the canister components, the components will be referred to as Multipurpose Canister-Gamma Shielding Components (MPC-GSCs).

To aid the reader in visualizing the scope of the Production Facility and in understanding the rationale for the Intermediate Activities, the proposed conceptual design for the Production Spray System precedes the conceptual design for the Intermediate Spray System. In lieu of approaching the conceptual design of the Production System in light of the design of the Intermediate System, the author has conceptualized from the full-scale Production Facility to the need for Intermediate Spray Activities (e.g., Work could be performed in a spray assembly chamber which could become a physical part of the Production Facility). The rationale for this is that pilot, investigatory work could be performed using the spray assembly component designed for the Production Facility. Activities could be directed toward establishing an engineering data base for spray forming depleted uranium. Major areas of consideration would include: (1) Confirmation of a nozzle system capable of spraying DU at a minimum throughput of 300 kg per hour, (2) Characterization of discharge gases and overspray particulates, and (3) Confirmation that the end product is acceptable in the as-sprayed form. It is paramount to understand that criteria established during activities in any one of these areas provide Go/No-Go decision points.

The Draft Functional Requirements for the Production Spray System were reviewed by attendees during the June 29, 1995 Review Meeting. Several additional areas and items required for the Production Spray System were identified during that meeting. A

list of modified requirements is in process at MMES. A copy of the draft requirements, as issued June 29, 1995, is included as Appendix A. The requirements outline the minimum criteria the system must meet. Based on continuing input, the list remains subject to change. A copy of the Task 2 Outline is provided as Appendix B.

1.1 OVERVIEW

Major areas of concern arise when developing a spray forming system which utilizes nozzles designed for spraying large throughputs of metal. These concerns are amplified when the process being developed is for use in the depleted uranium industry. If Spray Forming Technology is employed as a process to aid in the manufacture of MPC-GSCs, the cylindrical, as-sprayed end products must meet the following dimensions: 18 feet in length, greater than 6 feet in diameter, and 3-inch wall thicknesses. The high density of depleted uranium results in an end product which can weigh over 50 tons. With end products of this size, the recommended means for handling and transporting the products is a rail system.

An illustration which provides a conceptual understanding of what will be required for a spray system to manufacture products from DU that satisfy the stated dimensions is detailed in Figure 1. In order to display the spray assemblies, the metal feed system is not shown in this illustration. The four (4), dotted spheres were identified as required areas during the June 1995 Review Meeting and will be included in a modified list of functional requirements to be issued by MMES. These areas have been incorporated into the drawing but will not be covered in detail in this report. The five (5) major areas identified numerically in Figure 2 will be illustrated independently as each area is discussed. When applicable, the top, side, and/or end views of illustrations are provided for clarity. For ease in referencing these major system areas, Figure 2 has been enlarged and is included as a foldout (see Figure 21, page 30).

Figure 1. Conceptual Overview - Spray Forming
Production Facility.

Figure 2. Conceptual Overview Illustrating Major Spray Areas.

Figure 3. Area 1 Identified for Transporting and Handling Components and End Products.

3. SYSTEM OPERATION - CYLINDER

A system operating scenario was needed to develop a method for the handling of discharge gases and particulates. This preliminary scenario required that certain assumptions be made. Confirmation of these assumptions will be required during performance of the Intermediate Spray Activities.

3.1 PRODUCTION SYSTEM OPERATING ASSUMPTIONS

- (a) A nozzle system can be constructed to produce an acceptable as-sprayed product with a 1:1 gas-to-metal mass ratio.
- (b) The nozzle system will produce a minimum of 300 kg per hour.
- (c) The nozzle supply gas will be heated to 1600°C.
- (d) Argon (Ar) purge gases can be directed to remove thermal energy generated from heating the argon supply gas and from cooling and solidifying the depleted uranium.
- (e) 200°C is an acceptable average temperature of the chamber exhaust gases.
- (f) Purge gases can be chilled to 0°C prior to entering the chamber.
- (g) A melt temperature of 1300°C for depleted uranium is acceptable.
- (h) The substrate and as-sprayed cylinder can be maintained at 100°C.
- (i) Cyclone separation of particles at 1 micron actual diameter (4 micron aerodynamic diameter) will be sufficient.
- (j) Baffling can be provided that will ensure proper gas velocities to remove an acceptable percentage of the overspray powders from the chamber.

3.2 SYSTEM PROCESS CRITERIA

With the assumptions outlined in Section 3.1, calculations can be made to determine gas flows and particle separation techniques.

This approach is an iterative process. If calculations yield results that contradict one of the assumptions, then the assumption will be modified and appropriate design changes will be effected.

3.3 ARGON REQUIREMENTS

The first determination to be made is the theoretical amount of argon and power that is necessary to comply with assumptions a,b,c, and e.

If the metal throughput is 300 kg per hour and the gas-to-metal mass ratio is 1:1, then the nozzle supply requires 300 kg per hour. It is important to note that this is sensitive to the gas-to-metal mass ratio (e.g., if the ratio is 5:1, then 1,500 kg per hour of argon would be needed).

The theoretical power requirements for heating 300 kg/Hr of argon from 20°C to 1600°C can be approximated by using data from a Periodic Table of the Elements (Cat. No. S-18806, Sargent-Welch Scientific Company).

$$(83 \text{ g/s}) \times (0.520 \text{ J/g}^\circ\text{K}) \times (1580^\circ\text{K}) = 68 \text{ kJ/s} = 68 \text{ kW}$$

(A gas-to-metal mass ratio of 5:1 would require 340 kW)

If the purge gas enters the chamber at 0°C, the purge flow required to cool the nebulizing gas to 200°C would be:

$$(300 \text{ kg/Hr}) \times (1400^\circ\text{K}) / (200^\circ\text{K}) = 2,100 \text{ kg/Hr}$$

(This value would be 10,500 kg/Hr for a 5:1 mass ratio)

The final requirement for the purge gas is to cool the depleted uranium.

To account for heat of fusion:

$$(8.520 \text{ kJ/mol}) / (238 \text{ g/mol}) \times (83 \text{ g/s}) = 3 \text{ kJ/s} = 3 \text{ kW}$$

To account for temperature change of 1200°K = 1200°C:

$$(83 \text{ g/s}) \times (0.12 \text{ J/g}^\circ\text{K}) \times (1200^\circ\text{K}) = 13 \text{ kJ/s} = 12 \text{ kW}$$

The total power required to account for the theoretical heating and melting of depleted uranium would be approximately 15 kW. To account for this power by cooling the as-sprayed product

with an argon purge experiencing an average temperature change of 200°C would require 144 g/s argon, or 519 kg/Hr. The calculations can be summarized as follow:

<u>Nozzle Supply Requirements</u>	<u>Mass Flow</u>	<u>Heat to 1600°C</u>
1:1 gas/metal mass ratio	300 kg/Hr	68 kW
5:1 gas/metal mass ratio	1,500 kg/Hr	340 kW

<u>Argon Purge Required</u>	<u>Cooling Ar</u>	<u>Cooling DU¹</u>	<u>Total</u>
1:1 mass ratio	2,400 kg/Hr	519 kg/Hr	2,919 kg/Hr
5:1 mass ratio	12,000 kg/Hr	519 kg/Hr	12,519 kg/Hr

As a result of these calculations, the total theoretical flow of argon through the system would be 2,919 kg/Hr for purge and 300 kg/Hr for nozzle supply. 3,219 kg/Hr approximates 1,600 cfm.

The actual flow through the system depends dramatically on the gas-to-metal mass ratio that can be obtained in the nozzle. As the different areas of the conceptual design are discussed, 1,000 cfm will represent the total flow of argon. This flow will serve to approximate how large the discharge lines and other components will need to be. Moving large amounts of gas at low pressures could increment the cost of the finished product a few cents per pound. Depending on the type of contamination in the discharge gases, purification and filtration costs could become quite significant. With the argon being recycled, the process could be feasible having five times this flow.

¹Industry may have more applicable values for constants to determine thermal gains and losses than what is available in the Periodic Table.

4. DISCHARGE GAS COOLING AND HANDLING - AREA 2

Included in Area 2 is the handling of the discharge gases after the bulk of particulate has been removed through inertial separation techniques. A brief functional description of these components is provided. Availability of components as "off-the-shelf" items will play a significant role in the engineering design of this area.

- Banks of filter assemblies for small particulate removal.
- A gas purification system for removing oxygen, nitrogen, and other possible gases entering the system.
- Blower and/or pumping units to provide gas exchange through the closed system.
- Heat exchangers and/or cooling towers to cool the chamber exhaust to ambient temperatures.
- An array of valves and interdependent control valves which direct and control flow of the discharge gases.
- A liquid argon storage vessel to provide initial system back-fill and potential make-up gases during operation.

Figure 4 illustrates a configuration of the major components for Area 2.

4.1 FILTER ASSEMBLY - AREA 2

The first of these major components, the filter assembly, would consist of several filter elements. The number of filter elements necessary for system operation is not available at this time. For the purpose of conceptual illustration, 125 cubic feet of filter volume will represent each filter assembly. The definitive number of elements required can be determined during the Intermediate Spray System Activities. Each filter element would be capable of handling the gas flow through the system and would be comprised of two cartridge banks arranged in series. The primary bank for each filter element would be capable of handling the gas flow. Following this cartridge bank, there would be a sensing monitor. The monitor would determine if the particulate matter had been removed from the gas stream. This would include a

Figure 4. Area 2, Discharge Gas Cooling and Handling.

detector for DU. The pressure drop across the primary cartridge bank could be monitored to determine filter loading. Following the primary bank, there would be a secondary cartridge bank which would ensure protection against failure of the primary bank. In the event the sensors following the primary cartridge detect a failure, the filter element would be disconnected from service. The secondary cartridge unit would prevent emissions until the gas flow through the failed element could be terminated. Sensors following the secondary cartridge would verify that no emissions occurred during the filter element shut down.

Figure 5 illustrates a possible filter element designed using HEPA cartridges preapproved for use in the radioactive processing

Figure 5. Single Filter Element - 1,000 cfm.

industry. A filter assembly using six filter elements of this design would measure approximately 6-feet wide, 9-feet high, and have an overall length of 9 feet. If it was determined that one assembly of this nature could provide filtering for the construction of one depleted uranium cylinder, then back-up assemblies would be required. The back-up assemblies would provide for filter maintenance and interchange to allow continuous operation of the production system.

4.2 GAS PURIFICATION - AREA 2

In the Area 2 illustration (see Figure 4), gas purification would occur after the particulates have been removed from the discharge gases. Acceptable impurities identified thus far are less than 0.02% oxygen and water combined and less than 0.2% nitrogen. Depending on the purification units available in industry, the exhaust gases may require cooling to a specific temperature prior to entering this unit.

4.3 BLOWER AND/OR PUMPING UNITS - AREA 2

Blower units are illustrated following the gas purification. One unit is before the cooling towers and one unit is after the cooling towers. For moving large volumes of gases, blower units (centrifugal and multistage turbine assemblies) are normally less expensive to operate than pumping (positive displacement) units. The blower units are applicable when the required gas pressures are low. It may be necessary to incorporate high volume pumps as well as blower units to provide nozzle supply pressures. A pumping system will be required for the Vacuum Induction Melting (VIM) furnace units and for evacuating the system prior to fabrication. This pumping system may be a part of the discharge gas cycle, or it may be more cost efficient to have the pumping system separate from the discharge cycle.

4.4 GAS COOLING - AREA 2

Large volume cooling is generally accomplished with gas-to-air heat exchange units. These are low maintenance and low operating cost units, however, these units do require a large amount of space for installation. Standard size units are approximately 2-ft long x 4-ft wide x 12-ft high. Several of these units would be required for the production system. The units would likely be located outside the facility on a cement pad measuring approximately 8 ft x 30 ft. Alternative units are argon-liquid-to-air heat exchange and solid state (Peltier-effect) chill plates. These units require considerably less volume (up to 10% the volume of argon-to-air units). Electrical power and a routine maintenance schedule are required for operation when using argon-liquid-to-air and solid state heat exchange units.

4.5 FUNCTIONAL REQUIREMENTS FOR GAS FLOW - AREA 2

Controlling the flow of the discharge gases will require insitu monitoring of sensors and subsequent control of valves. A partial list of functional requirements for the valve system includes the following:

- Maintaining a constant nozzle supply pressure.
- Maintaining a constant purge flow.
- Provide make-up argon to maintain purity and pressure requirements.
- Potentially discharge to exhaust tower if oxygen or nitrogen levels are too high while compensating with make-up argon from the liquid storage vessel.
- Potentially direct flow from cooling towers back through the purification system or through a secondary purification system for additional conditioning.
- Potentially mix a portion of the gases from the cooling towers with discharge gases at the chamber exit to assist initial cooling at chamber exhaust.

Several of these functions may require more than one "purification-blower-tower" assembly.

5. SPRAY ASSEMBLY - AREA 3

The area housing the spray assembly presents a number of critical problems relative to operation of the Production Spray System. At the present time, solutions to these problems are proposed based on past experience and certain assumptions. Problems discussed in this section include: Hot Gas Recycling, Particle Separation, and Baffling Within the Chamber to Entrain the Particulate Matter. Other problems involve the VIM Furnace Configuration, Continuous Feed of Tundish, and Continuous Feed of Melt Furnace. The scope required to investigate spray assembly problems is greater than can be addressed in this report.

Figure 6 illustrates some of the major components of a set of spray assemblies. This illustration serves to give a proportionate portrayal of the components. When actual dimensions are available,

Figure 6. Area 3, Major Components of Spray Assemblies with Area 3A Identified.

drawings should be readdressed. A feed system for the furnaces is not included. Area 3A of Figure 6 deals with particle separation from the discharge gases. This area has been identified as a sub-

area for two reasons:

- (1) The particle separation system is a critical portion of the spray assembly. In this pictorial, it is behind the section of spray assemblies and, therefore, is not visible.
- (2) As the Program develops, this sub-area of the spray assembly will be frequently referenced.

5.1 SPRAY ASSEMBLY, HOT GAS RECYCLING - AREA 3

Based on the assumptions and calculations in Section 3, approximately 2,800 kg/Hr of argon at an average temperature of 200°C will exit the chamber. Baffling will direct the exiting argon in a manner to entrain the particulates generated by the spray process. With these conditions, the temperature profile across the diameter of the exit tube (illustrated as a 24-inch diameter in Figures 7 and 8) will not be constant. The gas near the center of the exit tube may be as high as 300°C while the gas near the exit tube walls may be as low as 100°C.

An assembly could be designed to reroute 300 kg/Hr of the hot gases from the 24-inch diameter exit tube. This assembly would include a cyclone system to separate 1-micron diameter (4-micron aerodynamic diameter) depleted uranium particulate from the gas stream. The gas stream would then pass through a 12-inch diameter return line to the nozzle supply regulator. This hot gas line would be equipped with filters to remove any remaining particulate. Sensors would be necessary to confirm that all particulate had been removed. If the sensors detected particulate, the gas would be returned to the main exhaust system. This could be accomplished by actuating a bypass valve using the sensor indication. A blower unit would provide proper pressure drops to regulate the amount of flow to the supply regulation assembly (see Figures 7 and 8).

The system to recycle the hot gases would require components which could operate at 200°C or higher. The savings would be the power requirements needed to cool the argon gas to room temperature and then reheat the argon gas for the nozzle supply. At a maximum, this would be equivalent to changing the temperature of argon gas approximately 400°C. It will be necessary to determine the cost of the high-temperature components required and the associated maintenance costs for operation. At this time, it does not appear this will be a cost effective effort.

Figure 7. Area 3, Spray Assembly, Hot Gas Recycling, End View.

Figure 8. Area 3, Spray Assembly, Hot Gas Recycling, Top View.

6. SPRAY ASSEMBLY, PARTICLE SEPARATION - AREA 3A

A major concern will involve handling overspray powders from the DU spray processing system. Although it may not be efficient to recycle hot gas as discussed in Section 5, the density of the depleted uranium particles make these particles good candidates for cyclone separation. A possible means for removing the majority of particles from the exhaust gas exiting the spray assembly chamber would be a cyclone system, or a system comprised of a combination of virtual impactors and cyclones.

A virtual impactor is a device which separates an aerosol stream into two flow streams. One of the flow streams has 90% of the volumetric flow with 10% of the particulate, while the second flow stream accounts for 10% of the volumetric flow with 90% of the particulate. In this application, the 10% volumetric flow stream would pass through a cyclone or cyclone system where particulate matter could be collected in a hopper.

The component arrangement would first concentrate the discharge gases from the chamber through a primary orifice. The diameter of the orifice would measure approximately 3 inches. The discharge line containing the 10% volumetric flow stream would be down stream from the primary orifice and would have an inside diameter slightly less than the primary orifice. The output from the cyclone would feed into a blower unit and back to the discharge line from the chamber or directly to the main filter assembly.

From past experience with overspray powders, there is a small amount of integrated mass associated with the particles of diameter less than 1 micron. Cyclones typically function well at separation diameters (i.e., cut points) of 5 microns (aerodynamic) and larger. Based on the high density of depleted uranium, a cyclone designed to operate with a 4-micron cut point will separate depleted uranium particles having actual diameters of 1 micron. (The aerodynamic diameter is defined as the diameter of the unit density sphere that has the same settling velocity as the particle. "Aerosol Technology," W.C. Hinds)

Using a discharge flow of 2,800 kg/Hr for the chamber exhaust gases, the virtual impactor would separate this flow into 280 kg/Hr (100 cfm) directed to the cyclone and 2,520 kg/Hr (900 cfm) remaining in the discharge line to the filter assemblies (see Figure 9).

Figure 9. Area 3A, Particle Separation with Virtual Impactor and Cyclone.

Geometric design of inertial separating devices depends on the characteristics of the aerosol (i.e., particle size, gas temperature, gas velocities, etc.). Using general virtual impactor and cyclone design characteristics and the assumptions listed previously for the discharge gases, approximate design parameters can be identified.

6.1 PARTICLE SEPARATION PARAMETERS - CHAMBER EXHAUST

- Pressure Drop Across Virtual Impactor: 1 psi
- Virtual Impactor Primary Orifice: 3.2" dia.
- Discharge from Virtual Impactor with 90% Volumetric Flow: 24" dia. (Reynolds Number (Re) 70K)
- Discharge from Virtual Impactor with 10% Volumetric Flow: 3.0" dia.

- Pressure Drop Across Cyclone: 7 psi
- Cyclone Entrance Tube: 3.0" dia.
- Cyclone Entrance: 1.5" x 3.0" dia.
- Cyclone Exit: 3.0" dia.
- Cyclone Exit Line to Filter Assembly: 12" dia. (Re 16K)
- Overall Cyclone Length: 24"

Design parameters can be more accurately identified following the design experiments completed during the Intermediate Spray Activities.

6.2 CHAMBER BAFFLING FOR DISCHARGE GASES

To accommodate an 18-ft long, 6-ft diameter DU cylinder and the substrate assembly for articulation, the production system spray chamber will have approximate dimensions of 85-ft long and 8-ft diameter. This chamber includes the spray assemblies area plus the 35-foot long section on either side of the spray assemblies. The production system chamber will have a volume in excess of 4,000 cubic feet. The volume of the chamber where spray activities are occurring is illustrated as 12-ft long (600 cubic feet). A primary concern is filling the entire chamber with airborne particles during the spray process. Airborne DU particles are small in diameter (0.2 microns and smaller) and can be readily transported with gas flows. They have a high surface-to-volume ratio and present pyrophoric dangers. Gas flows within the production system chamber must assure these small particles are carried out of the chamber in the exhaust gases.

Functions of the argon purge gas will be to cool the as-sprayed DU cylinder and to carry the particulate matter to a collection point at the chamber exit. The high density of DU causes small particles to have high settling velocities. This, in turn, requires high gas velocities to keep the particles entrained.

One method to increase gas velocities around the nozzle spray plume and along the chamber walls where larger particles may accumulate is with baffling to direct the gas flow. The baffling could be a C-shaped piece of channel which would be located under

the spray plume (see Figure 10). The sides of the channel could extend past the spray plume. The channel would extend under the rotating substrate with the bottom of the channel removed where the gases exit the chamber. Gas entries of various shapes could be located at designated points along the sides of the channel (see Figure 11).

Figure 10. Baffling for Directing Purge Flow.

Purge gases could be introduced in the area of the channel and also along the chamber wall away from the spray area (see Figure 12). This would allow additional cooling of the as-sprayed DU. The size of the openings in the channel and the separations between the as-sprayed product and the channel edge would have to be selected to assure gases were entering through the proper areas (see Figure 11).

Figure 11. Area 3, Baffling Assembly Directing Overspray, End View.

Figure 12. Area 3, Purge Gases Cooling the As-sprayed DU and Removing Overspray, Top View.

Baffling would have to be installed in a manner to allow removal of the completed cylinder and substrate assembly. Sufficient room could be allowed between the end of the mandrel and the rail car support for the substrate. When the rail car reached the baffling area, the baffling could be rotated to the top of the chamber to allow the rail car to pass beneath the baffling (see Figure 11).

7. PRODUCTION SYSTEM SPRAY CHAMBER, CYLINDER - AREA 4

The spray chamber for producing the 18-ft long and 6-ft diameter DU cylinders will be simple in design. It will consist of two 8-ft diameter tubes sufficient in length to contain the substrate and rail cars which support and rotate the substrate. At this time, the projected length of each tube is approximately 35 ft. Inside the spray chamber, rails will be mounted for linear motion of the substrate assembly. The two tubes will require uniform support along their entire length. The weight of the chamber tubes, as well as roughly 100 ton of substrate assembly and DU cylinder weight, will be factored into the overall design. The tubes will mount on opposite ends of the spray assembly chamber. At the far end of one tube, an interlock chamber will provide access to the as-sprayed end product without directly exposing personnel and without exposing the interior of the spray chamber to air. The interlock chamber will have to be evacuated and backfilled with argon during its use. The end cover plate for the interlock chamber could have clamping assemblies with appropriate vacuum seals to facilitate removal following completion of each spray run. A conceptual illustration of the production system spray chamber is shown in Figure 13.

Figure 13. Area 4, Illustration of Production System Chamber for MPC-GSC Cylinder.

7.1 SUBSTRATE ASSEMBLY

It is envisioned the substrate assembly would consist of two small railroad cars with heavy rotating shafts mounted on each car. These shafts would face each other during operation. A mandrel would complete the structural integrity of the assembly (see Figure 14). The mandrel would have a small separation from the rail car

Figure 14. Conceptual Illustration - Substrate Assembly.

to ensure baffling assemblies could rotate out of the way. Locking pins could attach the mandrel to the rotating shafts or the shaft and mandrel joint could be a tapered spline with a locking pin. Following completion of a DU cylinder, the assembly could be transported to a disassembly area. A crane would support the mandrel and the DU cylinder while the rail cars were removed. The mandrel could then be held in various positions during removal of the DU cylinder from the mandrel.

Information is not available at this time to estimate how thick the graphite would be, what effect spraying the DU onto the graphite would have on the graphite, or how well the graphite would hold the DU cylinder to the mandrel after spraying. These issues must be determined prior to construction of the Production Facility.

7.2 METAL FEED ASSEMBLY

A functional requirement of the Production Spray System is to

operate in a continuous spray mode until the as-sprayed product is complete. A DU cylinder with an 18-ft length, 6-ft diameter, and 3-inch wall thickness will require in excess of 50 tons of feedstock. The current technology for processing DU requires melting in a vacuum. There is an abundant source of DU feedstock at the Y-12 Facility. The feedstock is in the form of ingots that measure approximately 10-in. long x 24-in. wide x 36-in. high. Each ingot weighs less than 2,500 kg.

A furnace would be located above each nozzle/tundish assembly with the requirement that each tundish be capable of accepting a 2,500 kg charge of molten DU with some established headroom. It may be necessary to isolate the furnace from the spray system while adding a charge to the furnace. If heavy equipment could access the furnace area, each furnace could have a chamber above the spray assembly that it was supplying with DU. This chamber could be accessed independently to supply the furnace with DU ingots.

A rail system could be implemented to deliver the ingots, individually, to the furnaces. A straddle car could be used for each ingot with a winch system to lower the ingot into the furnace (see Figure 15). The straddle car would pass through a series of interlock gates to isolate the furnace from the ambient surrounding. A narrow gap in the rails would be needed to allow the interlocks to close. The straddle car could be designed with drive wheels on either end to allow passage over the narrow gap in the rail system. The furnaces would also be isolated from each other. Having deposited the ingot in a furnace, the straddle car could pass through the system to retrieve another ingot (see Figure 16). A ceramic lid, over the furnace, could protect the straddle car and ingot from radiant heating as well as reducing losses in the furnace area (see Figure 17). A pumping system with appropriate valving would serve to cleanse the system before the furnace area was accessed. The pumping system would also provide an independent vacuum in the furnace areas while melting the respective charges.

Figure 15. Ingot Transported By Straddle Car.

Figure 16. Metal Feed System Schematic, Top View.

Figure 17. Metal Feed System Schematic, Side View.

Depending on the life cycle of the furnace liners, the straddle car might also retrieve a liner from the furnace area with the next car providing a liner and ingot. A similar rail system could be designed where the rails are above the transport device.

8. PRODUCTION SYSTEM SPRAY CHAMBER, DISK - AREA 5

Components required to complete the gamma shielding for one MPC Canister could include two disks. The disks function as end pieces for the cylinder. Each disk has a thickness of 3 inches and a 75-in. diameter. Spray forming a disk requires a distinctly different articulation than spray forming a cylinder. The chamber required to spray form a disk will be significantly smaller than the chamber to spray form a cylinder that measures 18-ft in length.

At this time, it is anticipated that a dedicated system will be used to produce the disks for the MPC-GSCs. The system for net forming the disks will be in the same vicinity as the system used to produce the as-sprayed cylinders. This will enable dual use of the gas handling components illustrated in Area 2. If disks are fabricated at a location remote from the area where the cylinders are fabricated, replication of the gas discharge equipment would be necessary. An illustration of the equipment that would be needed at a remote location is shown in Figure 18. The spray chamber for spray forming the disk is also displayed in this figure, however, the spray chamber and gas discharge equipment are not connected in this illustration.

Figure 18. Area 5, Illustration of Production System Chamber and Accessories for MPC-GSC Disk.

8.1 SYSTEM OPERATION, DISK

It is likely that more than one size nozzle would be used to spray form the disk. A smaller nozzle would provide better edge contours on the disk with less overspray. The spray assembly could be the same unit that is used for the spray assembly unit on the cylinder production system. The end pieces for the assembly could have extensions to provide sufficient room for substrate manipulation. One of the ports, used for purge gases in the cylinder production system, could be used for a smaller nozzle assembly.

The production time for the disks has not been defined, however, at a minimum, two disks per month would need to be manufactured (i.e., two disks per month would accommodate the production rate of one cylinder per month). This would require relatively small melting capabilities. If it is determined more cost effective to manufacture several disks and shut the system down, then larger melting capabilities might be required.

The melting of DU and delivery to the nozzle/tundish assembly for the production of the MPC-GSC Disks will be addressed at a later date.

A moderate spray rate for the large nozzle in the production system for the disk would be 150 kg/Hr (42 g/s). A 75-in. diameter, 3-in. thick disk, weighing in excess of 4,000 kg, would require approximately 27 hours production time. A small nozzle could be designed to aid in forming the disk's circumference and reduce overspray. This nozzle would operate at 36 kg/Hr (10 g/s). Using two nozzles in this system would also lower the production time to less than a 24-hour shift.

By using two nozzles, the spray pattern of the large nozzle could be maintained a small distance from the edge of the as-sprayed disk (see Figure 19, Position 1). As the substrate is articulated so the pattern from the large nozzle is applying material from one side of the disk to the other side of the disk, the small nozzle could do edge detailing (see Figure 19, Position 2).

Cooling the as-sprayed product in the disk system will not be as critical a problem as cooling the product in the cylinder system. With the disk located horizontal, a structural base can be

Figure 19. Area 5, Illustration of Spray Assembly, Top View.

used to prevent sagging or warping. Careful contouring of the graphite mold could consolidate a majority of the overspray at the edges of the disk (see Figure 20). The consolidated ring could then be removed and remelted in a subsequent production run.

8.2 DISCHARGE GASES - AREA 5

The location of the discharge gases from the spray system producing disks is illustrated beneath the spray chamber (see Figure 20). The majority of particles will be extracted from the gas discharge as the gases exit the spray chamber. The particle collection system for the disk will be similar to the particle collection system for the cylinder, however, it will require provisions for different exhaust gas flows and temperatures.

To aid in particle removal, baffling in the disk system will be designed to accommodate the rotation of the substrate as well as the linear motion required. The majority of particle removal will occur at the gas exhaust exit. There may be a small particle collection system at each exhaust port, or the two ports may be

combined to form a single discharge with one larger particle collection system. Purge gases can be used to aid in particle removal and product cooling where necessary. After the particles have been removed, the discharge gas will be cycled through Area 2 for conditioning and reuse.

Figure 20. Area 5, Spray Assembly, End View.

Figure 21. Conceptual Overview Illustration

erating Major Spray Areas.

9. COST OF PRODUCTION - MPC-GSC

The total raw products required for completing the gamma shielding for one canister can be calculated. Power requirements can be estimated and subsequent operating costs computed. Estimates for ceramic costs and wear can be determined. Based on these calculations, a list of expenses to operate the production system can be summarized. It is important to remember that the list of operating expenses is the minimum cost associated with operating a production system. These costs assume that large throughputs can be achieved through the nozzle at low gas-to-metal mass ratios. Further, it assumes the as-sprayed product will meet the requirements for metallurgical properties and attenuation for gamma shielding. The composition and quantity of the overspray, while using DU as feedstock, has not been determined. Costs can vary significantly depending on results obtained during performance of the Intermediate Spray Activities.

9.1 RAW MATERIAL AND PRODUCTION COSTS FOR SHIELDING ONE MPC

It is important to obtain operating costs of the Spray Forming Production Facility as early as possible. A preliminary list of items requiring expense values for producing one cylinder is presented in this section. This list has estimated values for certain itemized expenses. The importance of the list at this time is to document the relative costs of the various items. This accounting also demonstrates the magnitudes of raw materials that could be required. As the costs for items become more definitive, the list will need to be updated. When additional costs of operating are determined, these will also be added to the list.

It can be noted that the argon is priced as a once-through cost of \$0.50 per kg. Although current plans are to recycle the argon, all the potential impurities in the gas discharge have not been identified. The cost of recycling argon may be comparable to the price of purchasing argon. At this time, the best estimate for argon is the current price of argon.

Raw Material and Production Costs for Shielding One MPC

(D R A F T)

<u>Depleted Uranium</u>	<u>Kilograms</u>	<u>Dollars</u>
Completed Cylinder	49,179	
Completed Disks (2)	8,210	
Overspray Generated (Assume 5%)	<u>2,869</u>	
Total Metal Sprayed:	60,258	
Waste from Melt Processing (2%)	<u>1,205</u>	
Total Feedstock (Gov't Furnished):	61,463	

<u>Argon</u>	<u>Kilograms</u>	<u>Dollars</u>
Nozzle Supply (Assume 1:1 Mass Ratio)	60,258	~30.1K
Cool Nozzle Supply (Assume 1:1 Mass Ratio) (2,400 kg/Hr for 201 Hrs)	482,400	~241.2K
Cool Depleted Uranium (144 kg/Hr for 201 Hrs)	28,944	~14.5K
Total Argon Required:	<u>571,602</u>	<u>285.8K</u>

<u>Labor</u>	<u>Hours</u>	<u>Dollars</u>
Preparation of System to Spray		
Installation of Substrate Assembly		
Operation of Feed and Melt Systems	300	15.0K
Operation of Spray Chamber Components	300	15.0K
Disassembly of Substrate		
Chamber Maintenance Each Run		
Spray Component Maintenance Each Run		
Furnace Maintenance Each Run		
System Check Each Run		
Product Quality Check		
Total Labor Required:	<u>600</u>	<u>30.0K</u>

<u>Power</u>	<u>Kilowatts</u>	<u>Dollars</u>
Melting Depleted Uranium at 83 g/s	32	
Heating Furnace Ceramics	32	
Radiant Heat & Induction Coil Cooling Loss	<u>32</u>	
Total Continuous Furnace Power Required:	96	
201 Hrs @ 96 kW - 19,296 kW Hrs @ 10¢/Hr		1.9K
Argon Heating (Assumes 1:1 Mass Ratio)	30	
Heating Nozzle Component Ceramics	40	
Radiant Heat & Induction Coil Cooling Loss	<u>50</u>	
Total Spray Component Power Required:	120	
201 Hrs @ 120 kW - 24,120 kW Hrs @ 10¢/Hr		2.4K

Other Labor
 Crucible/Linear Ceramics for Melting
 Nozzle/Tundish Ceramics for Spraying
 Coating for Substrate Mandrel
 Gas Heater Ceramics
 Processing Overspray Powders (2,869 kg)

10. RECOMMENDATIONS AND FINDINGS

Recommendations specific to this feasibility study include, at a minimum, the following:

- Waste Stream Identification.
 - Expand on Cost Summary, Section 9; e.g., cost of processing overspray powders and waste from melt processing, etc.
- Identify an Equipment List for Each of the Five (5) Areas Represented in Figure 2.
- Delineate Major Equipment Specifications.
- Determine Potential Sites for Production Facility Location at Y-12 Plant.
- Identify Health/Safety Regulations.
- Identify Area Emission and Local Operating Requirements.
- Identify Local, State, Federal, DOE, and DU Regulations.
- Evaluate Industrial Expertise and Participation.

APPENDIX A

DRAFT FUNCTIONAL REQUIREMENTS
FOR PRODUCTION SPRAY SYSTEM*
TASK 2

*As presented by MMES during June 29, 1995 Review Meeting at Y-12 Facility.

DRAFT

Functional Requirements for Production Spray System

(June 29, 1995 - Review Meeting)

1. Capable of fabricating a DU cylinder having the nominal dimensions of:

Diameter	75 inches O.D.
Height	18 feet
Thickness	3 inches

Capable of fabricating a DU disk having dimensions of:

Diameter	75 inches
Thickness	3 inches

Rectangular Component:

24 inches x 24 inches x 18 feet long outer dimensions
2-1/2 inches thick
Radii on all 4 outside edges ~ 4-1/2 inches
Radii on all 4 inside edges ~ 1/2 inch

2. An argon gas cover is required to prevent oxidation of DU during fabrication.
3. Spray deposition efficiency of at least 90%. Goal is to optimize this deposition to greater than 95% efficiency. High spray deposition efficiency will be a goal of the Intermediate Facility.
4. Spray deposition rate of at least 5 kilograms per minute.
5. Allow for controlled oxidation of the DU overspray particles in chamber after cylinder fabrication has been completed.
6. Maximum deposit porosity of 1%. This porosity is to be uniformly distributed throughout the product. This porosity and distribution will be determined and verified in the Intermediate Facility. (The actual requirements in production will probably be a gamma attenuation scan for 100% attenuation at the minimum wall thickness.)
7. Operate in continuous spray. (Could be fed by repeating batches or continuous depending on nozzle.)
8. Minimum nozzle life - nozzle or nozzle setup - equal or exceed the duration of the spray run. (Do not replace nozzle during spray run.)
9. Nozzle/Tundish heating capabilities will be 15% greater than continuous operating conditions. Component temperatures are anticipated to be 1600°C. Operating conditions and component maximum temperatures will be established in the Intermediate Facility.

Draft Functional Requirements for Production Spray System (Cont'd)
(June 29, 1995 - Review Meeting)

10. No water may be exposed to the liquid metal or hot solid metal.
11. Spray deposition must be well controlled and monitored by operations team. A method or methods of communications between members of the team during operation is required.
12. Spray chamber operates nominally at ambient pressure. The system will have the capability of being evacuated and back-filled with argon.
13. Maximum O₂ level, oxygen and water combined, in chamber is 0.02%.
14. Maximum nitrogen in chamber is 2,000 ppm.
15. Gas heating capabilities will be 15% greater than the continuous operating conditions. Maximum temperature is anticipated to be 1600°C. Gas heating requirements will be established in the Intermediate Facility.
16. Must meet all Federal, State, and local laws. Must meet DU handling regulations set by DOE or appropriate regulating body.
17. Must have gas recycle purification system.
18. Must have leak rate on chamber of 1×10^{-4} atmospheric cc/sec.
19. DU is traditionally melted for casting by a Vacuum Induction Melting (VIM) process. VIM or equivalent melting for feed for spraying is required.
20. DU feedstock should require minimum processing before use in this system.
21. Identify waste streams and approximate quantities. This is a collective function of CST, MMES, and MSE.
22. Waste handling requirements defined by MMES following identification of waste streams by the joint team in item 21.
23. Capable of cladding entire DU cylinder with a 1/4 inch thick stainless steel cladding. (Optional requirement.)

APPENDIX B

TASK 2 OUTLINE

May 8, 1995

**TASK 2 OUTLINE
SPRAY FORMING
76Y-KEA73V**

1. Correlate previous results with information obtained during the first MMES Planning Meeting at Y-12 March 22-23, 1995.
2. Data analyses and review of past results will occur as specifically related to: (a) Developing Conceptual Design of Production Facility in Task 2, and (b) Developing Conceptual Design of Intermediate Spray System in Task 3.
3. Preliminary Conceptual Design for a Production Facility Spray Forming System.
 - 3.1 Right angle cylinders: 75-in. diameter; 216-in. height; 3-in. wall thickness.
 - 3.2 Solid disks: 75-in. diameter; 3-in. thickness.
 - 3.3 Feasibility of providing a metallic coating or cladding on the surface of the net-formed depleted uranium products. This would occur in the facility the right angle cylinders and/or disks are net formed.
4. Perform additional work on previous data and/or results as directed by MMES.
5. Prepare Informal Summary Report - Task 2 for MMES review and comment.
6. Issue Informal Summary Report - Task 2.

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**HEAVY METALS PROCESSING
INTERMEDIATE SYSTEM CONCEPTUAL DESIGN
INFORMAL SUMMARY PROGRESS REPORT
TASK 3**

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HEAVY METALS PROCESSING
INTERMEDIATE SYSTEM CONCEPTUAL DESIGN
INFORMAL SUMMARY PROGRESS REPORT
TASK 3

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1. INTRODUCTION

This informal report is the third, and final, in a series of working documents issued by Custom Spray Technologies, Inc. (CST) under subcontract to Martin Marietta Energy Systems, Inc. (MMES). Material contained in this submittal presents conceptual design information for the Intermediate Spray System and hardware requirements for a proposed high-density material spraying facility referenced in Task 3 of the modified Statement of Work.

Based on the determination that Task 2 would include a conceptual design for a Production Spray System, the scope of Task 3 was directed to accommodate a conceptual design for a system to perform Intermediate Spray Activities.

Intermediate Activities are critical to demonstrating the scalability of the spray forming process prior to proceeding with design and construction of the production scale spray facility. The Production Facility will manufacture gamma shielding components of specified dimensions for the Multipurpose Canisters (MPCs). These canisters will contain high level radioactive waste and will require gamma shielding. To distinguish manufacture of the canisters from manufacture of the canister components, the components will be referred to as Multipurpose Canister-Gamma Shielding Components (MPC-GSCs).

To aid the reader in visualizing the scope of the Production Facility and in understanding the rationale for the Intermediate Activities, the proposed conceptual design for the Production Spray System has preceded the conceptual design for the Intermediate Spray System. In lieu of approaching the conceptual design of the Production System in light of the design of the Intermediate System, the author has conceptualized from the full-scale Production Facility to the need for Intermediate Spray Activities (e.g., Work could be performed in a spray assembly chamber which could become a physical part of the Production Facility). The rationale for this is that pilot, investigatory work could be performed using the spray assembly component designed for the Production Facility. Activities would be directed toward establishing an engineering data base for spray forming depleted uranium. At a minimum, major areas of consideration would include: Size and chemistry of particles in overspray powders, collection efficiency for overspray as a function of purge, baffle design,

nozzle throughput of gas and metal, nozzle and nozzle/tundish designs, continuous feed of nozzle/tundish assembly, as-sprayed product quality, etc.

The Draft Functional Requirements for the Intermediate Spray System were reviewed during the June 29, 1995 Review Meeting. A copy of the draft requirements, as issued during the June meeting, is included as Appendix A. The requirements outline the minimum criteria the system must meet. Based on continuing input, the list remains subject to change.

2. HARDWARE ILLUSTRATIONS

During Task 1, illustrations for review and comment were provided the participants. These illustrations stimulated discussions relative to articulating nozzles, vertical orientation of cylinders vs. horizontal orientation of cylinders, metal feed systems, etc. With regard to pros and cons of these various topics, this section presents the recommendations-to-date for the Intermediate Spray Activities. In most instances, the illustrations will serve to indicate what needs to be designed. Suggestions are intended to stimulate input and not to suggest a specific design.

2.1 SPRAY CHAMBER - INTERMEDIATE ACTIVITIES

As specified in the Draft Functional Requirements, the spray chamber must accommodate components with the following dimensions: (1) Cylinders: 48-in. Outside Diameter, 3-in. Thick, and 12-in. Length; (2) Disks: 48-in. Diameter and 3-in. Thick; and (3) Rectangular Cylinders/Components: 24-in. x 24-in. x 12-in. Long Outer Dimensions, 2-1/2 in. Thick, with Radii for all 4 Outside Edges of approximately 4-1/2" and Radii for all 4 Inside Corners of approximately 1/2-in. Additionally, the spray system must be capable of operating in a batch mode from the existing Vacuum Induction Melting (VIM) furnaces located at the Y-12 Plant.

A spray assembly section with end pieces, as depicted for the Production System (Task 2, page 16), would satisfy these dimensional requirements. Following successful Proof-of-Concepts achieved during the Intermediate Activities, this assembly section could become a part of the Production Facility. However, it is more likely that the assembly would be maintained in operation at MMES to serve in on-going development of the technology. Newly developed applications could then be incorporated into the Production System.

It is envisioned that the most cost effective product to spray would be the 4-ft diameter right cylinder. Articulation in front of the nozzle assembly for spraying this product only requires rotation and translation of the substrate (see Figure 1). Overspray characteristics and metal throughputs for the spray forming system could be identified early in the Program. Properties of the as-sprayed product (e.g., gamma attenuation and density) could be assessed relative to spray parameters. With

(a) End view.

(b) Top view.

Figure 1. Location of 48" Diameter Cylinder.

these milestones accomplished, a Go/No-Go decision could be made relative to suitability of the technology to Heavy Metals Processing.

The rectangular component would require a sophisticated positioning technique to assure that discharge gases were directed downward and that a uniform wall thickness was obtained. When spraying a 24-in. side, the mandrel would need to move vertically. The mandrel would have to translate closer and farther from the nozzle, while rotating, in order to produce a uniform corner. To produce the 12-in. length, the assembly would have to move horizontally through the spray plume (see Figure 2).

For producing the disk, the spray chamber assembly could be oriented in the same manner illustrated for the Production System (Task 2, page 29), however, supplying the tundish from existing MMES VIM furnaces would be difficult. An alternative approach would be to design a substrate assembly capable of supporting the rotating disk in a vertical position (see Figure 3). The chamber would then have the same horizontal orientation for the metal feed attachment as shown in Figures 1 and 2. When operating with the nozzle spraying horizontally, the spray chamber assembly could be attached under the existing VIM furnace arrangement via an adapter.

It may be deemed necessary to provide an interlock chamber with an interlock gate as illustrated in the Production Facility (Task 2, Page 22). The spray chamber for the Intermediate Activities would be mounted on a rolling assembly for positioning under the VIM furnaces. This feature may be sufficient to move the system to an approved area for removal of the as-sprayed products. This area would also be used for internal inspections of the spray system chamber. Evaluations of this nature are in the discovery phase.

2.2 SUBSTRATE ASSEMBLY

A graphite mandrel, with a Yttria coating, is projected to be an acceptable surface for the as-sprayed product. The mandrel could be mounted on a rail car assembly similar to the illustration shown in Task 2, page 23. With this type of mounting, the spray assembly chamber would need to be slightly wider than depicted or a short extension on the end piece would need to be added as shown in Figure 3. An alternative would be an overhead, single rail mounting. The rail could be supported at both ends of the chamber

(a) End view.

(b) Top view.

Figure 2. Location of 24" Rectangular Cylinder.

(a) End view.

(b) Top view.

Figure 3. Location of 48" Diameter Disk.

with a carriage unit to move the suspended mandrels (see Figure 4). It is desirable to have the area beneath the mandrel free from obstruction. This will aid in smooth gas flows to remove overspray and reduce the efforts required for chamber maintenance. Baffling can be installed to further assure particle removal.

**Figure 4. Suspended Mandrels Illustrated for
48" Diameter Cylinder.**

2.3 DISCHARGE GAS HANDLING

During the first Proof-of-Principle exercises to determine quantities and chemistry of overspray powders, there will be minimal requirements to process argon. Experimental data will also be documented relative to the amount of nozzle supply and purge gases required. It is projected that the chamber exhaust could be discharged to the atmosphere after particle separation and filtration for these operations. In other words, initial experiments will be using once-through argon.

Having gathered an adequate operating data base, the type of gas discharge system that will be needed can now be determined. The system must comply with the local Tennessee Air Quality Regulations, as well as all applicable Federal, DOE, and DU regulations.

2.4 SYSTEM ILLUSTRATION

Design of the spray assembly chamber must accommodate several major areas of operating interest during the spray exercises (see Figure 5). These areas include:

- Ability to melt in the tundish during preliminary spray runs.
- An adapter assembly with pour spout to connect to VIM furnace capabilities.
- Gas monitoring within chamber area and at area(s) of discharge to determine potential concentrations of contamination.
- Particle collections within chamber area to determine size distributions and chemistry.
- Full particle separation at chamber exhaust for discharge to atmosphere and/or recycling.
- Gas purification or treatment for discharge to atmosphere and/or recycling.

Figure 5. Spray System Schematic.

3. HARDWARE AND SYSTEM REQUIREMENTS

This section addresses facility operating issues associated with operating a spray system. Issues include:

- Determining by-products generated during the spray forming process.
- Facility requirements to operate the spray system.
- Optimizing component geometry and operating parameters for cost effective operation.

3.1 CHAMBER OPERATING ISSUES

Design criteria are needed for engineering a spray system to operate in a continuous mode for an extended time. These criteria are dependent on the parametric settings of the spray assembly (e.g., As the throughput of metal is increased, the temperature of the ambient surrounding will increase.). During the Intermediate Spray Activities, sensors for determining chamber parameters should be utilized. Results will indicate operating requirements that need to be met. A list of suggested parameters to be monitored is included in Appendix B.

3.2 ARGON REQUIREMENTS

Gas requirements must be tailored to the maximum need during the Intermediate Activities. To demonstrate a 6-in. wide linear nozzle with a 1:1 gas-to-metal mass ratio may require a total argon flow of 3000 kg/Hr. The nozzle supply requirement (300 kg/Hr) would be approximately twice the requirement of a 3-in. wide nozzle (see Table 1, Task 1, page 12). The gas temperature may reach 200°C. By the end of the Intermediate Spray Activities, the minimal requirements for the chamber exhaust system must be capable of handling this discharge.

Prior to conducting these exercises, it is anticipated that a 3-in. wide nozzle will be used. During these exercises, gas-to-metal mass ratios may be varied from 1:1 to 4:1. With a 4:1 mass ratio, nozzle supply flows could reach 400 kg/Hr. This could require 4000 kg/Hr total flow. Gas exit temperatures could reach 200°C. It will not be necessary to operate under these conditions for extended periods of time. Spray runs at these conditions may

last 10 minutes. The exhaust system would need to handle 400 kg/Hr (700 g/s) of argon at 200°C for 10 minutes.

3.3 POWER REQUIREMENTS

Current technology in the DU Processing Industry requires that DU be melted in a vacuum. For the early stages of development in a spray forming system, it is desirable to have the heating of the spray components independent, however, induction heating may still be the method of choice. The spray components include the gas heater, nozzle, and tundish. When pouring from the VIM furnace, the pour assembly is also a consideration. When using induction heating, power requirements would approximate the following:

Gas Heater Assembly	110 kW
Nozzle Assembly	10 kW
Tundish Assembly	40 kW
Pour Tube Assembly	20 kW

3.4 OPTIMIZATION - COMPONENT COILS

When using inductive heating for the spray components, the efficiency of the system can be remarkably improved by matching coil turns and coil diameters to the frequency of the generator and the component within the coil. It is important for safety reasons that for this application coil cooling be achieved with argon gas. The discharge from the component coil cooling can be cycled to the nozzle supply to reduce the amount of heating required by the gas heater. It has not yet been determined if the coil cooling cycle for the components would be better in series or with the coils cooled in parallel.

After determining the voltage and current requirements for the heating coils to produce proper operating temperatures within the individual spray components, the results can be compared. In most applications, the coils can be operated in series with a common generator. Individual tuning for coupling variances during operation can be accomplished with transformers and capacitors.

A list of suggested coil parameters to be monitored is presented in Appendix B.

4. SPRAY FORMING PARAMETERS TO OPTIMIZE

4.1 SYSTEM OPERATION

For initial exercises in the Intermediate System, it is suggested that small charges be melted in the tundish. The spray assembly would be brought up to operating temperature in a vacuum. When the DU has melted, the power to the gas heater and nozzle will be increased to accommodate operation of the spray nozzle. Estimated operating conditions for a linear aspirating nozzle are given in Section 4.4.3 of Task 1.

The mandrel for the 48-in. diameter right cylinder could be used as the substrate. For convenience and/or cost savings, a smaller diameter mandrel could be chosen. Surface speeds passing through the spray plume would be directed at 1-10 inches per minute.

Properly oriented sampling lines could withdraw chamber gases for gas analyses. Particle sampling could be accomplished with conventional devices modified for use with DU. These also would require appropriate sampling lines.

Viewing the system operation could be accomplished through cameras in sealed housings or fiber optics with appropriate lens arrangements. Purging the video windows with argon would aid in cooling the window and would also serve to keep the viewing window clear.

The data acquisition system (DAS) will require dynamic data linking to process controllers, as well as dynamic display for the system operators. It would be especially useful if the video monitoring could be time-linked to the DAS. Past experience has shown that for data logging purposes, a collection of the spray parameter set every second is adequate. Smart sensors could aid in several of the process control requirements.

4.2 GAS HEATER

A substantial amount of the power requirements are needed for heating the nozzle supply gas. Improving the efficiency of the gas heater can significantly reduce the power requirements for the spray forming system. The gas heater component is responsible for elevating the temperature of the gas from ambient to the minimum

required for smooth nozzle operation. For an aspirating nozzle, this can range from two-thirds the melting point of the material being sprayed to 100°C above the melting point (see Task 1, section 4.4.3).

A ceramic connector is normally used at the gas heater entrance to provide a thermal barrier. Boron nitride is a suitable material. The gas heater body can be fabricated from graphite or a high temperature metal such as molybdenum. The material must withstand 40 psi at the highest temperature anticipated.

A list of suggested gas heater parameters to be monitored is presented in Appendix B.

4.3 NOZZLE/TUNDISH ASSEMBLY

This assembly can be configured in a variety of fashions to satisfy various operating requirements. The design criteria of this assembly is tailored for minimum energy consumption of the system. As gas heater temperatures are decreased, temperatures in these components must be increased. Optimization must consider the set of all spray components.

A more serious concern than efficiency for this component is the structural engineering integrity to satisfy the operational demands the process requires. In this process application, over 2 metric ton of material will need to cascade into the tundish without breaking or cracking ceramic components. At the same time, the nozzle will need to aspirate metal smoothly from the same tundish while producing a uniform spray.

While the structural design requirements seem extreme, ceramic component compatibility has to be addressed at the same time that ceramic to molten uranium compatibility is being addressed. Temperature gradients within the system will depict the type of ceramic interfaces that can be used. The ceramic components will need to be cast to specification or machinable ceramics will need to be identified that are compatible with the process. The ceramic adhesives and sealants used in the system must be cured well above operating temperatures to assure minimal outgasing throughout the spray process.

Recommendations for the design and operation of the spray components including the gas heater, nozzle, and tundish require a

work scope beyond that which can be addressed in this publication. A list of suggested nozzle/tundish parameters to be monitored is presented in Appendix B.

4.4 SUBSTRATE ASSEMBLY

A difficult task while tailoring an aspirating nozzle is determining the quality of the as-sprayed product and correlating the results to the operating parameters of the system. The number of spray runs required to fully tailor a spray system can be significantly reduced by having the surface position of the substrate time-linked to the data collection system. This feature would allow a set of designed experiments to be conducted during one spray trial.

Other data collected at the substrate surface can provide data points for enthalpy calculations for improved product quality and cooling requirements. It is more beneficial if these measurements are also time-linked to the system operating data base.

A list of suggested nozzle/tundish parameters to be monitored is presented in Appendix B.

4.5 FURNACE AND POUR SPOUT ASSEMBLY

A functional requirement of the Intermediate System is to operate from one of the existing, bottom pour, VIM furnaces at the Y-12 Plant. These furnaces can provide melt charges ranging in size from a minimum of 100 kg to a maximum of 2500 kg. It is envisioned that a successful spray run utilizing the smaller melt charge would precede a spray run requiring a larger charge.

To minimize precipitates forming in the pour tube, it is suggested that the operating temperature of the tube be slightly hotter than the furnace pour temperature. Likewise, the tundish would have a slightly higher temperature than the pour tube.

During spray runs requiring small charges in the furnace, there would be less heat capacity in the molten DU. This can be compensated for with the pour tube heating.

4.6 PRODUCT ANALYSES

It will be important to have a short turnaround time for the analyses of the as-sprayed products. The analyses will provide input for varying the operating parameter sets. When the repeatability of an as-sprayed product can be demonstrated, then designed experiments can be performed to determine which spray parameter sets will provide acceptable products. Further data comparisons will yield optimal operating conditions for minimum energy consumption of the overall system.

A list of suggested operating parameters to be determined are presented in Appendix B. Some of these parameters will be measured during preliminary spray operations, while others will be predicted by the designed experiment sets. It is common practice to operate the system at one or more of the predicted optimum values to validate the experimental test set.

5. SUPPORT FACILITY REQUIREMENTS

Since power and gas supplies will have to be made available at one of the VIM furnace locations, it may be cost effective to always operate the system at the furnace site. Should this interrupt the normal work load of the furnace area, then a second location with power and gas supplies would be necessary.

An area where the chamber can be fully inspected periodically will be necessary to confirm that overspray is not accumulating and that no excessive problems or contamination are developing. This area could be another candidate for operation when the tundish is used for melting in the preliminary spray runs.

5.1 CERAMIC ASSEMBLY AND CURING

It is envisioned that several component assemblies will be evaluated during the Intermediate Spray Activities. Assembly and installation of these components require ceramic cements and adhesives. Although components can be cured with the power supplies used for operation, a preferred method of curing would be to use a drying furnace with temperature control. Internal dimensions would need to be approximately 3 feet on each side. The outgasing during system heat-up and operation can be reduced by curing the ceramics at the system operating temperatures.

5.2 SUBSTRATE ASSEMBLY/DISASSEMBLY

Preparation of the substrate assembly can be quite involved. The assembly might consist of a metal mandrel for integrity with a coated graphite exterior. Temperature sensing devices will need to be placed at various locations. Thicknesses of graphite and graphite coatings will be tested. There may be interchangeable drive assemblies that need maintenance.

This area will require machine shop support. A dedicated machine shop area capable of handling ceramics would be preferred. Ceramic machining could also support the spray component assembly area.

5.3 PRODUCT EVALUATION AND CHRONOLOGY

This area would be used for processing and maintaining the as-sprayed products after the products have been removed from the

substrate assembly. It is desirable to archive a portion of the sprayed sample as removed from the substrate. A data log is maintained to identify the spray experiment that produced the sample. As additional information about the sample is obtained (e.g., density, porosity, grain size, etc.), it is useful for this information to be included in the data log.

During this phase of development, there are often results from the spray run that should be maintained with the sample or at least identified in a manner that enables the sample to be easily retrieved at a later date for review and/or comparison of sample results.

6. RECOMMENDATIONS AND FINDINGS

Recommendations specific to this feasibility study include the following:

- Develop an Experimental Plan.
- List Equipment Requirements.
- Delineate Major Equipment Specifications.
- Determine Time Frame and Schedule of Activities to include a Program Cost Estimate.

"LIST IN PROGRESS"

APPENDIX A

DRAFT FUNCTIONAL REQUIREMENTS
FOR INTERMEDIATE SPRAY SYSTEM*
TASK 3

*As presented by MMES during June 29, 1995 Review Meeting at Y-12 Facility.

DRAFT**Functional Requirements for Intermediate Spray System**

(June 29, 1995 - Review Meeting)

1. Capable of fabricating the following components:

Cylinder:

48 Inches Outside Diameter
3 Inches Thick
12 Inches Length

Disk:

48 Inches Diameter
3 Inches Thick

Rectangular Component:

24 Inches x 24 Inches x 12 Inches Long Outer Dimensions
2-1/2 Inches Thick
Radii for all 4 Outside Edges ~ 4-1/2 Inches
Radii for all 4 Inside Corners ~ 1/2 Inch

Chamber will accommodate a substrate which will provide articulation to spray the three components, cylinder, disk, and rectangular described above. The initial evaluation will be on the cylindrical component. If the cylindrical component satisfies the product criteria and is cost effective, then fabrication of the more complicated disk and rectangular component manipulation in the same system would be undertaken.

2. Operate in a batch mode with a maximum of 2200 Kg. of molten DU available from existing Vacuum Induction Melting Furnaces at Y-12. (Minimum batch size is 100 Kg.)
3. Vacuum Induction Melting (VIM) is the process for melting the DU feed for Spray System. The melter shall nominally be an existing furnace in a DU operating area at the Y-12 plant. The means and method for transfer of molten DU to the Spray System, incorporating full isolation between the melter and the Spray System when appropriate, must be specified.
4. Capability to melt from 10 to 50 Kg charge of DU in the tundish for initial spray tests.
5. Capable of being installed and operated in a DU operating area at the Y-12 plant.

Draft Functional Requirements for Intermediate Spray System (Cont'd)
(June 29, 1995 - Review Meeting)

6. Use Argon cover gas to prevent oxidation of DU during fabrication.
7. Processing of the Argon gas through the system must be defined. Requirements shall include evaluation of the use of argon recycled in the Intermediate System. Inclusion of oxygen and water removal means, including application to side streams, shall be evaluated.
8. Maximum oxygen level, oxygen and water combined, in the chamber is 0.02%.
9. Maximum nitrogen level in the chamber is 2,000 ppm.
10. Spray chamber operates nominally at ambient pressure. The system will have the capability of being evacuated and back-filled with argon.
11. No water shall be used in any system or subsystem which has access to the interior of the spraying chamber.
12. Spray deposition efficiency of at least 90%. Goal is to optimize the process to greater than 95% efficiency.
13. Capable of demonstrating the deposition rate specified for the Production Spray System.
14. Spray deposition must be well controlled and monitored by operations team.
15. Capable of testing and evaluating the nozzle concepts from both CST and MSE.
16. The process capabilities for porosity size and distribution, gamma attenuation, density, and mechanical properties will be defined. The goal is a maximum deposit porosity of 1%. This porosity is to be uniformly distributed throughout the product.
17. Allow for controlled oxidation of DU overspray particles in chamber after component fabrication is complete.

Draft Functional Requirements for Intermediate Spray System (Cont'd)
(June 29, 1995 - Review Meeting)

18. Collection system for overspray in chamber, which can approach quantitative collection efficiency and also provide particle chemistry and particle size distribution of the overspray, is required.
19. Sampling system for particulate in chamber exhaust required.
20. Waste streams must be identified, and sizes of the waste streams must be estimated.
21. Capable of heating nozzle/tundish to a maximum of 1600°C.
22. Capable of heating the gas temperatures to a maximum of 1600°C.
23. Must meet all Federal, State and local laws. Must meet DU regulations set by DOE or appropriate regulating body.

APPENDIX B

PARAMETRIC SETTINGS FOR SPRAY SYSTEM
TASK 3

Parametric Settings for Spray System

Chamber Parameters:

Ambient Temperature of Chamber
Chamber Wall Temperature
Argon Temperature at Chamber Exit
Wall Temperature at Chamber Exit
Gas Chemistry Within Chamber
Gas Chemistry at Chamber Exit
Gas Chemistry at Substrate Surface
Particle Distribution Within Chamber (w/Chem Analyses)
Particle Distribution at Chamber Exhaust (w/Chem Analyses)
Argon Mass Flow of Purge Gas
Viewing of: Plume exiting nozzle
 Consolidation at surface, and
 Pour assembly

Gas Heater/Nozzle/Tundish Coil Parameters:

Voltage Across Gas Heater Induction Coil
Current Through Gas Heater Induction Coil
Argon Temperature Entering Gas Heater Induction Coil
Argon Temperature Exiting Gas Heater Induction Coil
Argon psia Entering Gas Heater Induction Coil
Argon psia Exiting Gas Heater Induction Coil

Gas Heater Parameters:

Temperature of Gas Heater Body at Gas Heater Entrance
Temperature of Gas Heater Body at Gas Heater Exit
Gas Heater Connector Temperature
Argon Temperature Entering Gas Heater
Argon Temperature Exiting Gas Heater
Argon Mass Flow Entering Gas Heater
Argon psia Entering Gas Heater
Argon psia Exiting Gas Heater

Parametric Settings for Spray System (Cont'd)

Nozzle/Tundish Parameters:

Nozzle Body Temperature (Near Liquid Orifice)
 Liquid Metal Temperature at Tundish Surface
 Liquid Metal Temperature at Liquid Orifice(s)
 Argon psia Entering Nozzle
 Average Plume Temperatures at Nozzle Exit

Substrate Parameters:

Surface Position Relative to Nozzle Exit
 Surface Speed Through Plume
 Surface Temperature at Consolidation

Operating Parameters To Be Determined:

Parameter Sets Which Produce an Acceptable Product

- Argon Supply Temperature
- Argon Supply psia
- Tundish Temperature
- Nozzle Body Temperature
- Substrate Temperature
- Substrate Speed
- Application Thickness

Minimum Operating Temperatures

Optimize Parameter Sets for Minimum Energy Consumption

Substrate Motion Relative to Operating Parameters

- Process Control Algorithms and Schemes

Cooling Profile of Consolidated Material

Total Particulate in Discharge Gas

Particulate Mass Distribution in Discharge Gas

Particulate Chemistry of Each of the Mass Categories

APPENDIX C

WORKSHEETS*

TASK 3

*Appendix C contains a representative sample of worksheets developed over the period of Informal Task Reporting. Data from these worksheets was used to determine the values presented throughout this publication. The prime purpose for including copies of these worksheets is to provide technical reviewers with the constants used in calculations, such as, material density. Clarification specific to how the calculations are performed will be offered during the August 9, 1995 Review Meeting.

200t	A	B	C	D	E	F	G	H	I
1	DRAFT WORKSHEET								
2	c:\95mm\tsk3\3clca.wb1 pg 200t		Nozzle 3" wide, 0.2 depth			area =			0.6 sq. in.
3	Minimum gas flow; maximum suction; Gas-to-Metal mass ratio 1.0:1.0								381 0.000
4	Upstream Pressure	18.00 PSIA	1241100 dyne/cm ²			5.6 psi		0.379	
5	Orifice Area	3.871 cm ²							
6		0.6 in ²							
7	Gas Constant	8.31E+07 dyne cm/k mol	2.08E+06 dyne cm/k g			Furnace: max/min/Av			
8	Air Temperature	1300.0 deg C	1573 deg K			Large: 2500/100/220			
9	Specific Heat Ratio	1.667				Med: 400/50/350			
10	Downstream Pressur	12.4 PSIA	854980 dyne/cm ²						
11	Atomic Wt. of Gas	39.948 g/mol	Argon: Heating						
12	Mdot for Subsonic	55.89 g/sec	55.9 g/sec			37.8 kilowatts			
13	Mdot for Sonic	60.99 g/sec	3.4 Kg/minute						
14	" dia to give area	0.874	201.2 Kg/hour						
15	flow in Lpm subsoni	1879.6	Uranium: Heating Melting Total						
16	flow in Lpm sonic	2051.4	9.1 2.0 11.1			kW			
17	flow in scfm sub son	66.4	Power Supply Required:			21.8 kW			
18	flow in scfm sonic	72.5	MMES Power Required:			kW			
19	Medium gas flow; Gas-to-Metal mass ratio 2.5:1.0								553 0.001
20	Upstream Pressure	24.00 PSIA	1654800 dyne/cm ²			11.6 psi		0.506	
21	Orifice Area	3.871 cm ²							
22		0.6 in ²							
23	Gas Constant	8.31E+07 dyne cm/k mol	2.08E+06 dyne cm/k g						
24	Air Temperature	1300.0 deg C	1573 deg K						
25	Specific Heat Ratio	1.667							
26	Downstream Pressur	12.4 PSIA	854980 dyne/cm ²						
27	Atomic Wt. of Gas	39.948 g/mol	Argon: Heating						
28	Mdot for Subsonic	81.18 g/sec	32.5 g/sec			54.9 kilowatts			
29	Mdot for Sonic	81.32 g/sec	1.9 Kg/minute						
30	" dia to give area	0.874	116.9 Kg/hour						
31	flow in Lpm subsoni	2730.3	Uranium: Heating Melting Total						
32	flow in Lpm sonic	2735.1	5.3 1.2 6.4			kW			
33	flow in scfm sub son	96.5	Power Supply Required:			12.7 kW			
34	flow in scfm sonic	96.6	MMES Power Required:			kW			
35	High gas flow; Gas-to-Metal mass ratio 4.0:1.0								646 0.001
36	Upstream Pressure	28.00 PSIA	1930600 dyne/cm ²			15.6 psi		0.59	
37	Orifice Area	3.871 cm ²							
38		0.6 in ²							
39	Gas Constant	8.31E+07 dyne cm/k mol	2.08E+06 dyne cm/k g						
40	Air Temperature	1300.0 deg C	1573 deg K						
41	Specific Heat Ratio	1.667							
42	Downstream Pressur	12.4 PSIA	854980 dyne/cm ²						
43	Atomic Wt. of Gas	39.948 g/mol	Argon: Heating						
44	Mdot for Subsonic	94.50 g/sec	23.7 g/sec			64.1 kilowatts			
45	Mdot for Sonic	94.88 g/sec	1.4 Kg/minute						
46	" dia to give area	0.874	85.4 Kg/hour						
47	flow in Lpm subsoni	3178.3	Uranium: Heating Melting Total						
48	flow in Lpm sonic	3191.0	3.8 0.8 4.7			kW			
49	flow in scfm sub son	112.3	Power Supply Required:			9.3 kW			
50	flow in scfm sonic	112.8	MMES Power Required:			kW			
51									

150Atm	A	B	C	D	E	F	G	H	I
1	DRAFT WORKSHEET								
2	c:\95mm\tsk3\t3clca.wb1 pg 150atm Nozzle 3" wide, 0.15 depth area = 0.45 sq. in.								
3	Minimum gas flow; maximum suction; Gas-to-Metal mass ratio 1.0:1.0 362 0.000								
4	Upstream Pressure	20.00 PSIA		1379000 dyne/cm ²		5.3 psi	0.421		
5	Orifice Area	2.903 cm ²							
6		0.45 in ²							
7	Gas Constant	8.31E+07 dyne cm/k mol		2.08E+06 dyne cm/k g		18"; 5 sec - 3.6"/sec			
8	Air Temperature	1300.0 deg C		1573 deg K		18"; 29 sec - 0.6"/sec			
9	Specific Heat Ratio	1.667				113" dia - 0.03-0.004 rev/sec			
10	Downstream Pressure	14.7 PSIA		1013565 dyne/cm ²		Chse: 0.3 - 2.1 rpm for Sbstr			
11	Atomic Wt. of Gas	39.948 g/mol				Argon: Heating			
12	Mdot for Subsonic	44.29 g/sec		44.3 g/sec		29.9		kilowatts	
13	Mdot for Sonic	50.83 g/sec		2.7 Kg/minute					
14	" dia to give area	0.757		159.4 Kg/hour					
15	flow in Lpm subsonic	1489.5				Uranium: Heating Melting Total			
16	flow in Lpm sonic	1709.5				7.2 1.6 8.8		kW	
17	flow in scfm sub son	52.6				Power Supply Required:		17.3 kW	
18	flow in scfm sonic	60.4				MMES Power Required:		kW	
19	Medium gas flow; Gas-to-Metal mass ratio 2.5:1.0								534 0.001
20	Upstream Pressure	26.00 PSIA		1792700 dyne/cm ²		11.3 psi	0.548		
21	Orifice Area	2.903 cm ²							
22		0.45 in ²							
23	Gas Constant	8.31E+07 dyne cm/k mol		2.08E+06 dyne cm/k g					
24	Air Temperature	1300.0 deg C		1573 deg K					
25	Specific Heat Ratio	1.667							
26	Downstream Pressure	14.7 PSIA		1013565 dyne/cm ²					
27	Atomic Wt. of Gas	39.948 g/mol				Argon: Heating			
28	Mdot for Subsonic	65.26 g/sec		26.1 g/sec		44.1		kilowatts	
29	Mdot for Sonic	66.08 g/sec		1.6 Kg/minute					
30	" dia to give area	0.757		94.0 Kg/hour					
31	flow in Lpm subsonic	2194.9				Uranium: Heating Melting Total			
32	flow in Lpm sonic	2222.3				4.2 0.9 5.2		kW	
33	flow in scfm sub son	77.6				Power Supply Required:		10.2 kW	
34	flow in scfm sonic	78.5				MMES Power Required:		kW	
35	High gas flow; Gas-to-Metal mass ratio 4.0:1.0								623 0.001
36	Upstream Pressure	30.00 PSIA		2068500 dyne/cm ²		15.3 psi	0.632		
37	Orifice Area	2.903 cm ²							
38		0.45 in ²							
39	Gas Constant	8.31E+07 dyne cm/k mol		2.08E+06 dyne cm/k g					
40	Air Temperature	1300.0 deg C		1573 deg K					
41	Specific Heat Ratio	1.667							
42	Downstream Pressure	14.7 PSIA		1013565 dyne/cm ²					
43	Atomic Wt. of Gas	39.948 g/mol				Argon: Heating			
44	Mdot for Subsonic	76.24 g/sec		19.1 g/sec		51.5		kilowatts	
45	Mdot for Sonic	76.24 g/sec		1.1 Kg/minute					
46	" dia to give area	0.757		68.6 Kg/hour					
47	flow in Lpm subsonic	2564.1				Uranium: Heating Melting Total			
48	flow in Lpm sonic	2564.2				3.1 0.7 3.8		kW	
49	flow in scfm sub son	90.6				Power Supply Required:		7.5 kW	
50	flow in scfm sonic	90.6				MMES Power Required:		kW	
51									

200Atm	A	B	C	D	E	F	G	H	I
1	DRAFT WORKSHEET								
2	c:\95mm\tsk3\3clca.wb1 pg 200atm		Nozzle 3" wide, 0.2 depth area =			0.6 sq. in.			
3	Minimum gas flow; maximum suction; Gas-to-Metal mass ratio 1.0:1.0							362	0.000
4	Upstream Pressure	20.00 PSIA	1379000 dyne/cm ²			5.3 psi	0.421		
5	Orifice Area	3.871 cm ²	Iron Theor: 0.7						
6		0.6 in ²	Iron Data: 1.3			1.98			
7	Gas Constant	8.31E+07 dyne cm/k mol	2.08E+06 dyne cm/k g			Furnace: max/min/Av			
8	Air Temperature	1300.0 deg C	1573 deg K			Large: 2500/100/2200			
9	Specific Heat Ratio	1.667				Med: 400/50/350			
10	Downstream Pressure	14.7 PSIA	1013565 dyne/cm ²						
11	Atomic Wt. of Gas	39.948 g/mol	Argon: Heating						
12	Mdot for Subsonic	59.05 g/sec	59.1 g/sec			39.9 kilowatts			
13	Mdot for Sonic	67.77 g/sec	3.5 Kg/minute						
14	* dia to give area	0.874	212.6 Kg/hour						
15	flow in Lpm subsonic	1986.0	Uranium: Heating Melting Total						
16	flow in Lpm sonic	2279.3	9.6 2.1 11.7 kW						
17	flow in scfm sub son	70.2	Power Supply Required: 23.1 kW						
18	flow in scfm sonic	80.5	MMES Power Required: kW						
19	Medium gas flow; Gas-to-Metal mass ratio 2.5:1.0							534	0.001
20	Upstream Pressure	26.00 PSIA	1792700 dyne/cm ²			11.3 psi	0.548		
21	Orifice Area	3.871 cm ²							
22		0.6 in ²							
23	Gas Constant	8.31E+07 dyne cm/k mol	2.08E+06 dyne cm/k g						
24	Air Temperature	1300.0 deg C	1573 deg K						
25	Specific Heat Ratio	1.667							
26	Downstream Pressure	14.7 PSIA	1013565 dyne/cm ²						
27	Atomic Wt. of Gas	39.948 g/mol	Argon: Heating						
28	Mdot for Subsonic	87.01 g/sec	34.8 g/sec			58.8 kilowatts			
29	Mdot for Sonic	88.10 g/sec	2.1 Kg/minute						
30	* dia to give area	0.874	125.3 Kg/hour						
31	flow in Lpm subsonic	2926.5	Uranium: Heating Melting Total						
32	flow in Lpm sonic	2963.1	5.6 1.2 6.9 kW						
33	flow in scfm sub son	103.4	Power Supply Required: 13.6 kW						
34	flow in scfm sonic	104.7	MMES Power Required: kW						
35	High gas flow; Gas-to-Metal mass ratio 4.0:1.0							623	0.001
36	Upstream Pressure	30.00 PSIA	2068500 dyne/cm ²			15.3 psi	0.632		
37	Orifice Area	3.871 cm ²							
38		0.6 in ²							
39	Gas Constant	8.31E+07 dyne cm/k mol	2.08E+06 dyne cm/k g						
40	Air Temperature	1300.0 deg C	1573 deg K						
41	Specific Heat Ratio	1.667							
42	Downstream Pressure	14.7 PSIA	1013565 dyne/cm ²						
43	Atomic Wt. of Gas	39.948 g/mol	Argon: Heating						
44	Mdot for Subsonic	101.65 g/sec	25.4 g/sec			68.7 kilowatts			
45	Mdot for Sonic	101.66 g/sec	1.5 Kg/minute						
46	* dia to give area	0.874	91.5 Kg/hour						
47	flow in Lpm subsonic	3418.9	Uranium: Heating Melting Total						
48	flow in Lpm sonic	3418.9	4.1 0.9 5.0 kW						
49	flow in scfm sub son	120.8	Power Supply Required: 9.9 kW						
50	flow in scfm sonic	120.8	MMES Power Required: kW						
51									

Calc1	A	B	C	D	E	F	G	H	I	J	K	L	M	N
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DRAFT WORKSHEET

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Print Block: Calc1: A1..N71

SPRAY RATES AND THICKNESSES; SUBSTRATE SPEEDS; LINEAR NOZZLE HORIZONTAL ORIENTATION

DEPLETED URANIUM

48" ID x 3" thick x 12" length:	48	3	12	1 g/cc =	0.03613 lb/cu.in.	0.15665 rpm_mult.
5768 Volume in Cu.In.	3938	Weight in lbs	18.9 g/cc =	0.68279 lb/cu.in.U	48	Disk Dia. "
94520 Volume in cc	1786	Weight in kg	1 lb/cu.in.=	27.6804 g/cc	3	Disk Thk. "
481 Cu.In./in. of length	328	Weight in lbs per in. length			3707	Disk lbs
3101 CuCm/ cm of length	59	Weight in kg per cm length			1681	Disk kg

	dia.	thick	lgth			
36" ID x 3" thick x 12" lgth:	36	3	12	1 g/cc =	0.03613 lb/cu.in.	0.20886 rpm,mult.
4411 Volume in Cu.In.	3012	Weight in lbs		18.9 g/cc =	0.68279 lb/cu.in.U	36 Disk Dia. "
72280 Volume in cc	1366	Weight in kg		1 lb/cu.in.=	27.6804 g/cc	3 Disk Thk. "
368 Cu.In./in. of lgth	251	Weight in lbs per in. lgth				2085 Disk lbs
2371 CuCm/ cm of lgth	45	Weight in kg per cm lgth				946 Disk kg

Table 1. Aspirating Nozzle: 3" width and 0.15" height

Pattern of this nozzle will approximate an area of 2" x 4" (5 cm X 10 cm) on the substrate at a distance of 4" (10 cm) from the liquid orifices of the nozzle.

At a production rate of 44 g/s: 44 5 10

Horizontal Axis				Vertical Axis			
Surface Speed of Substrate				Surface Speed of Substrate			48" dia.
Substrate Speed	Cladding Thickness			Substrate Speed	Cladding Thickness		rev/min
0.05 cm/s	46.56 mm	1.8331 in.		0.05 cm/s	93.12 mm	3.6662 in.	0.0078
0.1 cm/s	23.28 mm	0.9166 in.		0.1 cm/s	46.56 mm	1.8331 in.	0.0157
0.5 cm/s	4.66 mm	0.1833 in.		0.5 cm/s	9.31 mm	0.3666 in.	0.0783
1 cm/s	2.33 mm	0.0917 in.		1 cm/s	4.66 mm	0.1833 in.	0.1566
2 cm/s	1.16 mm	0.0458 in.		2 cm/s	2.33 mm	0.0917 in.	0.3133
3 cm/s	0.78 mm	0.0306 in.		3 cm/s	1.55 mm	0.0611 in.	0.4699
4 cm/s	0.58 mm	0.0229 in.		4 cm/s	1.16 mm	0.0458 in.	0.6266
5 cm/s	0.47 mm	0.0183 in.		5 cm/s	0.93 mm	0.0367 in.	0.7832
6 cm/s	0.39 mm	0.0153 in.		6 cm/s	0.78 mm	0.0306 in.	0.9399
10 cm/s	0.23 mm	0.0092 in.		10 cm/s	0.47 mm	0.0183 in.	1.5665
15 cm/s	0.16 mm	0.0061 in.		15 cm/s	0.31 mm	0.0122 in.	2.3497
20 cm/s	0.12 mm	0.0046 in.		20 cm/s	0.23 mm	0.0092 in.	3.1330
25 cm/s	0.09 mm	0.0037 in.		25 cm/s	0.19 mm	0.0073 in.	3.9162
30 cm/s	0.08 mm	0.0031 in.		30 cm/s	0.16 mm	0.0061 in.	4.6994

At a production rate of 26 g/s: 26 5 10

Horizontal Axis				Vertical Axis			
Surface Speed of Substrate				Surface Speed of Substrate			36" dia.
Substrate Speed	Cladding Thickness			Substrate Speed	Cladding Thickness		rev/min
0.05 cm/s	27.51 mm	1.0832 in.		0.05 cm/s	55.03 mm	2.1664 in.	0.0104
0.1 cm/s	13.76 mm	0.5416 in.		0.1 cm/s	27.51 mm	1.0832 in.	0.0209
0.5 cm/s	2.75 mm	0.1083 in.		0.5 cm/s	5.50 mm	0.2166 in.	0.1044
1 cm/s	1.38 mm	0.0542 in.		1 cm/s	2.75 mm	0.1083 in.	0.2089
2 cm/s	0.69 mm	0.0271 in.		2 cm/s	1.38 mm	0.0542 in.	0.4177
3 cm/s	0.46 mm	0.0181 in.		3 cm/s	0.92 mm	0.0361 in.	0.6266
4 cm/s	0.34 mm	0.0135 in.		4 cm/s	0.69 mm	0.0271 in.	0.8355
5 cm/s	0.28 mm	0.0108 in.		5 cm/s	0.55 mm	0.0217 in.	1.0443
6 cm/s	0.23 mm	0.0090 in.		6 cm/s	0.46 mm	0.0181 in.	1.2532
10 cm/s	0.14 mm	0.0054 in.		10 cm/s	0.28 mm	0.0108 in.	2.0886
15 cm/s	0.09 mm	0.0036 in.		15 cm/s	0.18 mm	0.0072 in.	3.1330
20 cm/s	0.07 mm	0.0027 in.		20 cm/s	0.14 mm	0.0054 in.	4.1773
25 cm/s	0.06 mm	0.0022 in.		25 cm/s	0.11 mm	0.0043 in.	5.2216
30 cm/s	0.05 mm	0.0018 in.		30 cm/s	0.09 mm	0.0036 in.	6.2659

At a production rate of 19 g/s: 19 5 10

Horizontal Axis				Vertical Axis			
Surface Speed of Substrate				Surface Speed of Substrate			
Substrate Speed	Cladding Thickness			Substrate Speed	Cladding Thickness		
0.05 cm/s	20.11 mm	0.7916 in.		0.05 cm/s	40.21 mm	1.5831 in.	
0.1 cm/s	10.05 mm	0.3958 in.		0.1 cm/s	20.11 mm	0.7916 in.	
0.5 cm/s	2.01 mm	0.0792 in.		0.5 cm/s	4.02 mm	0.1583 in.	
1 cm/s	1.01 mm	0.0396 in.		1 cm/s	2.01 mm	0.0792 in.	
2 cm/s	0.50 mm	0.0198 in.		2 cm/s	1.01 mm	0.0396 in.	
3 cm/s	0.34 mm	0.0132 in.		3 cm/s	0.67 mm	0.0264 in.	
4 cm/s	0.25 mm	0.0099 in.		4 cm/s	0.50 mm	0.0198 in.	
5 cm/s	0.20 mm	0.0079 in.		5 cm/s	0.40 mm	0.0158 in.	
6 cm/s	0.17 mm	0.0066 in.		6 cm/s	0.34 mm	0.0132 in.	
10 cm/s	0.10 mm	0.0040 in.		10 cm/s	0.20 mm	0.0079 in.	
15 cm/s	0.07 mm	0.0026 in.		15 cm/s	0.13 mm	0.0053 in.	
20 cm/s	0.05 mm	0.0020 in.		20 cm/s	0.10 mm	0.0040 in.	
25 cm/s	0.04 mm	0.0016 in.		25 cm/s	0.08 mm	0.0032 in.	
30 cm/s	0.03 mm	0.0013 in.		30 cm/s	0.07 mm	0.0026 in.	

DRAFT WORKSHEET

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Print Block: Calc2: A1...N71

SPRAY RATES AND THICKNESSES; SUBSTRATE SPEEDS; LINEAR NOZZLE HORIZONTAL ORIENTATION

DEPLETED URANIUM

48" ID x 3" thick x 12" length:	48	3	12	1 g/cc =	0.03613 lb/cu.in.	0.15665 rpm,mult.
5768 Volume in Cu.In.	3938	Weight in lbs	18.9 g/cc =	0.68279 lb/cu.in.U		
94520 Volume in cc	1786	Weight in kg	1 lb/cu.in.=	27.6804 g/cc		
481 Cu.In./in. of length	328	Weight in lbs per in. length				
3101 CuCm/ cm of length	59	Weight in kg per cm length				

36" ID x 3" thick x 12" length:	36	3	12	1 g/cc =	0.03613 lb/cu.in.	0.20886 rpm,mult.
4411 Volume in Cu.In.	3012	Weight in lbs	18.9 g/cc =	0.68279 lb/cu.in.U		
72280 Volume in cc	1366	Weight in kg	1 lb/cu.in.=	27.6804 g/cc		
368 Cu.In./in. of length	251	Weight in lbs per in. length				
2371 CuCm/ cm of length	45	Weight in kg per cm length				

Table 2. Aspirating Nozzle: 3" width and 0.20" height

Pattern of this nozzle will approximate an area of 2" x 4" (5 cm X 10 cm) on the substrate at a distance of 4" (10 cm) from the liquid orifices of the nozzle.

At a production rate of 59 g/s: 59 5 10

Horizontal Axis				Vertical Axis			
Surface Speed of Substrate		Cladding Thickness		Surface Speed of Substrate		Cladding Thickness	
Substrate Speed				Substrate Speed			48" dia. rev/min
0.05 cm/s	62.43 mm	2.4580 in.		0.05 cm/s	124.87 mm	4.9161 in.	0.0078
0.1 cm/s	31.22 mm	1.2290 in.		0.1 cm/s	62.43 mm	2.4580 in.	0.0157
0.5 cm/s	6.24 mm	0.2458 in.		0.5 cm/s	12.49 mm	0.4916 in.	0.0783
1 cm/s	3.12 mm	0.1229 in.		1 cm/s	6.24 mm	0.2458 in.	0.1566
2 cm/s	1.56 mm	0.0615 in.		2 cm/s	3.12 mm	0.1229 in.	0.3133
3 cm/s	1.04 mm	0.0410 in.		3 cm/s	2.08 mm	0.0819 in.	0.4699
4 cm/s	0.78 mm	0.0307 in.		4 cm/s	1.56 mm	0.0615 in.	0.6266
5 cm/s	0.62 mm	0.0246 in.		5 cm/s	1.25 mm	0.0492 in.	0.7832
6 cm/s	0.52 mm	0.0205 in.		6 cm/s	1.04 mm	0.0410 in.	0.9399
10 cm/s	0.31 mm	0.0123 in.		10 cm/s	0.62 mm	0.0246 in.	1.5665
15 cm/s	0.21 mm	0.0082 in.		15 cm/s	0.42 mm	0.0164 in.	2.3497
20 cm/s	0.16 mm	0.0061 in.		20 cm/s	0.31 mm	0.0123 in.	3.1330
25 cm/s	0.12 mm	0.0049 in.		25 cm/s	0.25 mm	0.0098 in.	3.9162
30 cm/s	0.10 mm	0.0041 in.		30 cm/s	0.21 mm	0.0082 in.	4.6994

At a production rate of 35 g/s: 35 5 10

Horizontal Axis				Vertical Axis			
Surface Speed of Substrate		Cladding Thickness		Surface Speed of Substrate		Cladding Thickness	
Substrate Speed				Substrate Speed			36" dia. rev/min
0.05 cm/s	37.04 mm	1.4582 in.		0.05 cm/s	74.07 mm	2.9163 in.	0.0104
0.1 cm/s	18.52 mm	0.7291 in.		0.1 cm/s	37.04 mm	1.4582 in.	0.0209
0.5 cm/s	3.70 mm	0.1458 in.		0.5 cm/s	7.41 mm	0.2916 in.	0.1044
1 cm/s	1.85 mm	0.0729 in.		1 cm/s	3.70 mm	0.1458 in.	0.2089
2 cm/s	0.93 mm	0.0365 in.		2 cm/s	1.85 mm	0.0729 in.	0.4177
3 cm/s	0.62 mm	0.0243 in.		3 cm/s	1.23 mm	0.0486 in.	0.6266
4 cm/s	0.46 mm	0.0182 in.		4 cm/s	0.93 mm	0.0365 in.	0.8355
5 cm/s	0.37 mm	0.0146 in.		5 cm/s	0.74 mm	0.0292 in.	1.0443
6 cm/s	0.31 mm	0.0122 in.		6 cm/s	0.62 mm	0.0243 in.	1.2532
10 cm/s	0.19 mm	0.0073 in.		10 cm/s	0.37 mm	0.0146 in.	2.0886
15 cm/s	0.12 mm	0.0049 in.		15 cm/s	0.25 mm	0.0097 in.	3.1330
20 cm/s	0.09 mm	0.0036 in.		20 cm/s	0.19 mm	0.0073 in.	4.1773
25 cm/s	0.07 mm	0.0029 in.		25 cm/s	0.15 mm	0.0058 in.	5.2216
30 cm/s	0.06 mm	0.0024 in.		30 cm/s	0.12 mm	0.0049 in.	6.2659

At a production rate of 25 g/s: 25 5 10

Horizontal Axis				Vertical Axis			
Surface Speed of Substrate		Cladding Thickness		Surface Speed of Substrate		Cladding Thickness	
Substrate Speed				Substrate Speed			
0.05 cm/s	26.46 mm	1.0415 in.		0.05 cm/s	52.91 mm	2.0831 in.	
0.1 cm/s	13.23 mm	0.5208 in.		0.1 cm/s	26.46 mm	1.0415 in.	
0.5 cm/s	2.65 mm	0.1042 in.		0.5 cm/s	5.29 mm	0.2083 in.	
1 cm/s	1.32 mm	0.0521 in.		1 cm/s	2.65 mm	0.1042 in.	
2 cm/s	0.66 mm	0.0260 in.		2 cm/s	1.32 mm	0.0521 in.	
3 cm/s	0.44 mm	0.0174 in.		3 cm/s	0.88 mm	0.0347 in.	
4 cm/s	0.33 mm	0.0130 in.		4 cm/s	0.66 mm	0.0260 in.	
5 cm/s	0.26 mm	0.0104 in.		5 cm/s	0.53 mm	0.0208 in.	
6 cm/s	0.22 mm	0.0087 in.		6 cm/s	0.44 mm	0.0174 in.	
10 cm/s	0.13 mm	0.0052 in.		10 cm/s	0.26 mm	0.0104 in.	
15 cm/s	0.09 mm	0.0035 in.		15 cm/s	0.18 mm	0.0069 in.	
20 cm/s	0.07 mm	0.0026 in.		20 cm/s	0.13 mm	0.0052 in.	
25 cm/s	0.05 mm	0.0021 in.		25 cm/s	0.11 mm	0.0042 in.	
30 cm/s	0.04 mm	0.0017 in.		30 cm/s	0.09 mm	0.0035 in.	

Calc3	A	B	C	D	E	F	G	H	I	J	K	L	M	N
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DRAFT WORKSHEET

c:\95mm\tsk3\3clca.wb1 pg Calc3

Print Block: Calc3: A1..N71

SPRAY RATES AND THICKNESSES; SUBSTRATE SPEEDS; LINEAR NOZZLE HORIZONTAL ORIENTATION

DEPLETED URANIUM

dia. thick lgth

48" ID x 3" thick x 12" lgth: 48 3 12 1 g/cc = 0.03613 lb/cu.in. 0.15665 rpm,mult.

5768 Volume in Cu.In. 3938 Weight in lbs 18.9 g/cc = 0.68279 lb/cu.in.U

94520 Volume in cc 1786 Weight in kg 1 lb/cu.in.= 27.6804 g/cc

481 Cu.In./in. of lgth 328 Weight in lbs per in. lgth

3101 CuCm/ cm of lgth 59 Weight in kg per cm lgth

dia. thick lgth

36" ID x 3" thick x 12" lgth: 36 3 12 1 g/cc = 0.03613 lb/cu.in. 0.20886 rpm,mult.

4411 Volume in Cu.In. 3012 Weight in lbs 18.9 g/cc = 0.68279 lb/cu.in.U

72280 Volume in cc 1366 Weight in kg 1 lb/cu.in.= 27.6804 g/cc

368 Cu.In./in. of lgth 251 Weight in lbs per in. lgth

2371 CuCm/ cm of lgth 45 Weight in kg per cm lgth

Aspirating Nozzle: 6" width and 0.15" height

Pattern of this nozzle will approximate an area of 2" x 7" (5 cm X 18 cm) on the substrate at a distance of 4" (10 cm) from the liquid orifices of the nozzle.

At a production rate of 88 g/s: 88 5 18

Horizontal Axis

Vertical Axis

Surface Speed of Substrate

Surface Speed of Substrate

48" dia.

Substrate Speed

Cladding Thickness

Substrate Speed

Cladding Thickness

rev/min

0.05 cm/s 51.73 mm 2.0368 in.

0.05 cm/s 186.24 mm 7.3324 in.

0.0078

0.1 cm/s 25.87 mm 1.0184 in.

0.1 cm/s 93.12 mm 3.6662 in.

0.0157

0.5 cm/s 5.17 mm 0.2037 in.

0.5 cm/s 18.62 mm 0.7332 in.

0.0783

1 cm/s 2.59 mm 0.1018 in.

1 cm/s 9.31 mm 0.3666 in.

0.1566

2 cm/s 1.29 mm 0.0509 in.

2 cm/s 4.66 mm 0.1833 in.

0.3133

3 cm/s 0.86 mm 0.0339 in.

3 cm/s 3.10 mm 0.1222 in.

0.4699

4 cm/s 0.65 mm 0.0255 in.

4 cm/s 2.33 mm 0.0917 in.

0.6266

5 cm/s 0.52 mm 0.0204 in.

5 cm/s 1.86 mm 0.0733 in.

0.7832

6 cm/s 0.43 mm 0.0170 in.

6 cm/s 1.55 mm 0.0611 in.

0.9399

10 cm/s 0.26 mm 0.0102 in.

10 cm/s 0.93 mm 0.0367 in.

1.5665

15 cm/s 0.17 mm 0.0068 in.

15 cm/s 0.62 mm 0.0244 in.

2.3497

20 cm/s 0.13 mm 0.0051 in.

20 cm/s 0.47 mm 0.0183 in.

3.1330

25 cm/s 0.10 mm 0.0041 in.

25 cm/s 0.37 mm 0.0147 in.

3.9162

30 cm/s 0.09 mm 0.0034 in.

30 cm/s 0.31 mm 0.0122 in.

4.6994

At a production rate of 52 g/s: 52 5 18

Horizontal Axis

Vertical Axis

Surface Speed of Substrate

Surface Speed of Substrate

36" dia.

Substrate Speed

Cladding Thickness

Substrate Speed

Cladding Thickness

rev/min

0.05 cm/s 30.57 mm 1.2036 in.

0.05 cm/s 110.05 mm 4.3328 in.

0.0104

0.1 cm/s 15.29 mm 0.6018 in.

0.1 cm/s 55.03 mm 2.1664 in.

0.0209

0.5 cm/s 3.06 mm 0.1204 in.

0.5 cm/s 11.01 mm 0.4333 in.

0.1044

1 cm/s 1.53 mm 0.0602 in.

1 cm/s 5.50 mm 0.2166 in.

0.2089

2 cm/s 0.76 mm 0.0301 in.

2 cm/s 2.75 mm 0.1083 in.

0.4177

3 cm/s 0.51 mm 0.0201 in.

3 cm/s 1.83 mm 0.0722 in.

0.6266

4 cm/s 0.38 mm 0.0150 in.

4 cm/s 1.38 mm 0.0542 in.

0.8355

5 cm/s 0.31 mm 0.0120 in.

5 cm/s 1.10 mm 0.0433 in.

1.0443

6 cm/s 0.25 mm 0.0100 in.

6 cm/s 0.92 mm 0.0361 in.

1.2532

10 cm/s 0.15 mm 0.0060 in.

10 cm/s 0.55 mm 0.0217 in.

2.0886

15 cm/s 0.10 mm 0.0040 in.

15 cm/s 0.37 mm 0.0144 in.

3.1330

20 cm/s 0.08 mm 0.0030 in.

20 cm/s 0.28 mm 0.0108 in.

4.1773

25 cm/s 0.06 mm 0.0024 in.

25 cm/s 0.22 mm 0.0087 in.

5.2216

30 cm/s 0.05 mm 0.0020 in.

30 cm/s 0.18 mm 0.0072 in.

6.2659

At a production rate of 38 g/s: 38 5 18

Horizontal Axis

Vertical Axis

Surface Speed of Substrate

Surface Speed of Substrate

Substrate Speed

Cladding Thickness

Substrate Speed

Cladding Thickness

0.05 cm/s 22.34 mm 0.8795 in.

0.05 cm/s 80.42 mm 3.1663 in.

0.1 cm/s 11.17 mm 0.4398 in.

0.1 cm/s 40.21 mm 1.5831 in.

0.5 cm/s 2.23 mm 0.0880 in.

0.5 cm/s 8.04 mm 0.3166 in.

1 cm/s 1.12 mm 0.0440 in.

1 cm/s 4.02 mm 0.1583 in.

2 cm/s 0.56 mm 0.0220 in.

2 cm/s 2.01 mm 0.0792 in.

3 cm/s 0.37 mm 0.0147 in.

3 cm/s 1.34 mm 0.0528 in.

4 cm/s 0.28 mm 0.0110 in.

4 cm/s 1.01 mm 0.0396 in.

5 cm/s 0.22 mm 0.0088 in.

5 cm/s 0.80 mm 0.0317 in.

6 cm/s 0.19 mm 0.0073 in.

6 cm/s 0.67 mm 0.0264 in.

10 cm/s 0.11 mm 0.0044 in.

10 cm/s 0.40 mm 0.0158 in.

15 cm/s 0.07 mm 0.0029 in.

15 cm/s 0.27 mm 0.0106 in.

20 cm/s 0.06 mm 0.0022 in.

20 cm/s 0.20 mm 0.0079 in.

25 cm/s 0.04 mm 0.0018 in.

25 cm/s 0.16 mm 0.0063 in.

30 cm/s 0.04 mm 0.0015 in.

30 cm/s 0.13 mm 0.0053 in.

Calc4	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	DRAFT WORKSHEET													
2	c:\95mm\tsk3\3clca.wb1 pg Calc4 Print Block: Calc4: A1..N71													
3	SPRAY RATES AND THICKNESSES; SUBSTRATE SPEEDS; LINEAR NOZZLE HORIZONTAL ORIENTATION													
4	DEPLETED URANIUM dia. thick lngth													
5	48" ID x 3" thick x 12" lngth: 48 3 12 1 g/cc = 0.03613 lb/cu.in. 0.15665 rpm,mult.													
6	5768 Volume in Cu.In. 3938 Weight in lbs 18.9 g/cc = 0.68279 lb/cu.in.U													
7	94520 Volume in cc 1786 Weight in kg 1 lb/cu.in.= 27.6804 g/cc													
8	481 Cu.In./in. of lngth 328 Weight in lbs per in. lngth													
9	3101 CuCm/ cm of lngth 59 Weight in kg per cm lngth													
10	dia. thick lngth													
11	36" ID x 3" thick x 12" lngth: 36 3 12 1 g/cc = 0.03613 lb/cu.in. 0.20886 rpm,mult.													
12	15947 Volume in Cu.In. 10888 Weight in lbs 18.9 g/cc = 0.68279 lb/cu.in.U													
13	261321 Volume in cc 4939 Weight in kg 1 lb/cu.in.= 27.6804 g/cc													
14	1329 Cu.In./in. of lngth 907 Weight in lbs per in. lngth													
15	8574 CuCm/ cm of lngth 162 Weight in kg per cm lngth													
16	Aspirating Nozzle: 6" width and 0.20" height													
17	Pattern of this nozzle will approximate an area of 2" x 7" (5 cm X 18 cm) on the substrate at a distance													
18	of 4" (10 cm) from the liquid orifices of the nozzle.													
19	At a production rate of 118 g/s: 118 5 18													
20	Horizontal Axis Vertical Axis													
21	Surface Speed of Substrate Surface Speed of Substrate 48" dia.													
22	Substrate Speed Cladding Thickness Substrate Speed Cladding Thickness rev/min													
23	0.05 cm/s 69.37 mm 2.7311 in. 0.05 cm/s 249.74 mm 9.8321 in. 0.0078													
24	0.1 cm/s 34.69 mm 1.3656 in. 0.1 cm/s 124.87 mm 4.9161 in. 0.0157													
25	0.5 cm/s 6.94 mm 0.2731 in. 0.5 cm/s 24.97 mm 0.9832 in. 0.0783													
26	1 cm/s 3.47 mm 0.1366 in. 1 cm/s 12.49 mm 0.4916 in. 0.1566													
27	2 cm/s 1.73 mm 0.0683 in. 2 cm/s 6.24 mm 0.2458 in. 0.3133													
28	3 cm/s 1.16 mm 0.0455 in. 3 cm/s 4.16 mm 0.1639 in. 0.4699													
29	4 cm/s 0.87 mm 0.0341 in. 4 cm/s 3.12 mm 0.1229 in. 0.6266													
30	5 cm/s 0.69 mm 0.0273 in. 5 cm/s 2.50 mm 0.0983 in. 0.7832													
31	6 cm/s 0.58 mm 0.0228 in. 6 cm/s 2.08 mm 0.0819 in. 0.9399													
32	10 cm/s 0.35 mm 0.0137 in. 10 cm/s 1.25 mm 0.0492 in. 1.5665													
33	15 cm/s 0.23 mm 0.0091 in. 15 cm/s 0.83 mm 0.0328 in. 2.3497													
34	20 cm/s 0.17 mm 0.0068 in. 20 cm/s 0.62 mm 0.0246 in. 3.1330													
35	25 cm/s 0.14 mm 0.0055 in. 25 cm/s 0.50 mm 0.0197 in. 3.9162													
36	30 cm/s 0.12 mm 0.0046 in. 30 cm/s 0.42 mm 0.0164 in. 4.6994													
37	At a production rate of 70 g/s: 70 5 18													
38	Horizontal Axis Vertical Axis													
39	Surface Speed of Substrate Surface Speed of Substrate 36" dia.													
40	Substrate Speed Cladding Thickness Substrate Speed Cladding Thickness rev/min													
41	0.05 cm/s 41.15 mm 1.6202 in. 0.05 cm/s 148.15 mm 5.8326 in. 0.0104													
42	0.1 cm/s 20.58 mm 0.8101 in. 0.1 cm/s 74.07 mm 2.9163 in. 0.0209													
43	0.5 cm/s 4.12 mm 0.1620 in. 0.5 cm/s 14.81 mm 0.5833 in. 0.1044													
44	1 cm/s 2.06 mm 0.0810 in. 1 cm/s 7.41 mm 0.2916 in. 0.2089													
45	2 cm/s 1.03 mm 0.0405 in. 2 cm/s 3.70 mm 0.1458 in. 0.4177													
46	3 cm/s 0.69 mm 0.0270 in. 3 cm/s 2.47 mm 0.0972 in. 0.6266													
47	4 cm/s 0.51 mm 0.0203 in. 4 cm/s 1.85 mm 0.0729 in. 0.8355													
48	5 cm/s 0.41 mm 0.0162 in. 5 cm/s 1.48 mm 0.0583 in. 1.0443													
49	6 cm/s 0.34 mm 0.0135 in. 6 cm/s 1.23 mm 0.0486 in. 1.2532													
50	10 cm/s 0.21 mm 0.0081 in. 10 cm/s 0.74 mm 0.0292 in. 2.0886													
51	15 cm/s 0.14 mm 0.0054 in. 15 cm/s 0.49 mm 0.0194 in. 3.1330													
52	20 cm/s 0.10 mm 0.0041 in. 20 cm/s 0.37 mm 0.0146 in. 4.1773													
53	25 cm/s 0.08 mm 0.0032 in. 25 cm/s 0.30 mm 0.0117 in. 5.2216													
54	30 cm/s 0.07 mm 0.0027 in. 30 cm/s 0.25 mm 0.0097 in. 6.2659													
55	At a production rate of 50 g/s: 50 5 18													
56	Horizontal Axis Vertical Axis													
57	Surface Speed of Substrate Surface Speed of Substrate													
58	Substrate Speed Cladding Thickness Substrate Speed Cladding Thickness													
59	0.05 cm/s 29.39 mm 1.1573 in. 0.05 cm/s 105.82 mm 4.1661 in.													
60	0.1 cm/s 14.70 mm 0.5786 in. 0.1 cm/s 52.91 mm 2.0831 in.													
61	0.5 cm/s 2.94 mm 0.1157 in. 0.5 cm/s 10.58 mm 0.4166 in.													
62	1 cm/s 1.47 mm 0.0579 in. 1 cm/s 5.29 mm 0.2083 in.													
63	2 cm/s 0.73 mm 0.0289 in. 2 cm/s 2.65 mm 0.1042 in.													
64	3 cm/s 0.49 mm 0.0193 in. 3 cm/s 1.76 mm 0.0694 in.													
65	4 cm/s 0.37 mm 0.0145 in. 4 cm/s 1.32 mm 0.0521 in.													
66	5 cm/s 0.29 mm 0.0116 in. 5 cm/s 1.06 mm 0.0417 in.													
67	6 cm/s 0.24 mm 0.0096 in. 6 cm/s 0.88 mm 0.0347 in.													
68	10 cm/s 0.15 mm 0.0058 in. 10 cm/s 0.53 mm 0.0208 in.													
69	15 cm/s 0.10 mm 0.0039 in. 15 cm/s 0.35 mm 0.0139 in.													
70	20 cm/s 0.07 mm 0.0029 in. 20 cm/s 0.26 mm 0.0104 in.													
71	25 cm/s 0.06 mm 0.0023 in. 25 cm/s 0.21 mm 0.0083 in.													
72	30 cm/s 0.05 mm 0.0019 in. 30 cm/s 0.18 mm 0.0069 in.													
73														

DRAFT WORKSHEET

The substrate is a rotating right cylinder with the axis of the cylinder horizontal.

Linear Nozzle with 0.15" Height

Nozzle Horizontal, 44&88 g/s, G1

Nozzle Horizontal, 26&52 g/s, G3

Nozzle Horizontal, 19&38 g/s, G5

Linear Nozzle with 0.20" Height

Nozzle Horizontal, 59&118 g/s, G7

Nozzle Horizontal, 35&70 g/s, G9

Nozzle Horizontal, 25&50 g/s, G11

The thickness of the mass deposition of uranium depicted in the graphs above does not allow for parallel motion of the nozzle relative to the substrate (i.e., along the axis of the cylinder).

The substrate is a rotating right cylinder with the axis of the cylinder horizontal.

Linear Nozzle with 0.15" Height

Linear Nozzle with 0.20" Height

The thickness of the mass deposition of uranium depicted in the graphs above does not allow for parallel motion of the nozzle relative to the substrate (i.e., along the axis of the cylinder).

DRAFT WORKSHEET

SPRAY RATES AND THICKNESSES; SUBSTRATE SPEEDS; LINEAR NOZZLE HORIZONTAL ORIENTATION

DEPLETED URANIUM

	dia. in.	thick in.	lngh in.			
48" ID x 3" thick x 216" lngth:	48	3	216	1 g/cc =	0.03613 lb/cu.in.	0.15665 rpm,mult.
103824 Volume in Cu.In.	70890	Weight in lbs		18.9 g/cc =	0.68279 lb/cu.in.U	48 Disk Dia. "
1701364 Volume in cc	32156	Weight in kg		1 lb/cu.in.=	27.6804 g/cc	3 Disk Thk. "
481 Cu.In./ in. of lngth	328	Weight in lbs per in. lngth				3707 Disk lbs
3101 CuCm/ cm of lngth	59	Weight in kg per cm lngth				1681 Disk kg

	dia. in.	thick in.	lngh in.			
36" ID x 3" thick x 216" lngth:	36	3	216	1 g/cc =	0.03613 lb/cu.in.	0.20886 rpm,mult.
79395 Volume in Cu.In.	54210	Weight in lbs		18.9 g/cc =	0.68279 lb/cu.in.U	36 Disk Dia. "
1301043 Volume in cc	24590	Weight in kg		1 lb/cu.in.=	27.6804 g/cc	3 Disk Thk. "
368 Cu.In./ in. of lngth	251	Weight in lbs per in. lngth				2085 Disk lbs
2371 CuCm/ cm of lngth	45	Weight in kg per cm lngth				946 Disk kg

Production Rate: One Canister Fabricated per Month

		Argon price 5/95:		0.52 J/(gmDegK) Ar		238.029 g/mole, U	
		2.00	2.50	\$/100 cu.ft.		0.12 J/(gmDegK) U	
1 lb =	9.671 scf	0.19	0.24	\$/lb		118 Hrs 48" dia. using 1: 6" wide nozzle	
1 kg =	21.32 scf	0.43	0.53	\$/kg		88 Hrs 75" dia. using 1: 6" wide nozzle	
		42.64	53.30	cents/kg		1 Nozzle @ 300 kg/Hr output	
		426.4	533	\$/metric ton		1600 Degrees C for Nebulizing Gas	
						1350 Degrees C for Uranium Melt	

Argon Nebulizing Gas Required			
Table Quantities in Thousand Metric Tons			
Gas/Metal Mass Ratio	Total Canisters		
	12	100	250
1:1	0.43	3.55	8.88
2:1	0.85	7.10	17.76
4:1	1.70	14.21	35.52
10:1	4.26	35.52	88.80

Cost of Argon Nebulizing Gas			
2 \$/100 cu.ft.			
Table Quantities in Million Dollars			
Gas/Metal Mass Ratio	Total Canisters		
	12	100	250
1:1	0.18	1.51	3.79
2:1	0.36	3.03	7.57
4:1	0.73	6.06	15.15
10:1	1.82	15.15	37.86

Cost of Argon Nebulizing Gas			
2.5 \$/100 cu.ft.			
Table Quantities in Million Dollars			
Gas/Metal Mass Ratio	Total Canisters		
	12	100	250
1:1	0.23	1.89	4.73
2:1	0.45	3.79	9.47
4:1	0.91	7.57	18.93
10:1	2.27	18.93	47.33

Theoretical Power Required for Heating & Melting			
Table Quantities Using 118 Hrs for Tank Completion			
Nebulizing Argon 1600 Deg C:		Uranium Melt @ 1350 Deg C:	
Kilowatts		Kilowatts	
1:1	69	17	
2:1	139	17	
4:1	277	17	
10:1	693	17	

Estimated Power Required for Heating & Melting w/Losses			
Table Quantities Using 118 Hrs for Tank Completion			
Nebulizing Argon 1600 Deg C:		Uranium Melt @ 1350 Deg C:	
Kilowatts		Kilowatts	
1:1	139	26	
2:1	277	26	
4:1	555	26	
10:1	1387	26	

Consider consolidating one 0.025" layer of U across the surface of the 48" dia., 216" lngth cylinder:

Allowing for the purge gas to enter at 0 Deg C and exit at

U: $(252,000) \cdot (0.12) \cdot (1250) / 53 / 60 = 11.9$ kilowatts
 Ar: $(242,000) \cdot (0.52) \cdot (200) / 53 / 60 = 11.9$ kilowatts
 Heat of Fusion U: $(8.52) / (238) \cdot (88) = 3.1$ kilowatts
 Ar Nebulizing Gas: $(88) \cdot (0.52) \cdot (1400) = 73$ kilowatts

It is anticipated the nozzle can be tailored to operate at a 1:1 gas-to-metal mass ratio, however, the spray system will also require various purge flows to keep the system clean and aid in particle collection. In addition, the process will require purge flows to cool the as-sprayed cylinder and disk after consolidation onto the substrate. An optimistic estimate for total argon required would be the values indicated by the 4:1 mass ratio. A more conservative estimate would be the 10:1 values. With these quantities of inert gas requirements, the additional tables indicate the cost of the inert gas if it was purchased at today's prices (i.e., 2 -2.5 dollars per 100 standard cubic feet) and discharged to the atmosphere. The gas requirements for the production spray system indicate it would be cost effective to recycle the gas through cooling towers. Recycling the gas would also produce a closed loop production system which would be environmentally favorable. With a closed loop system, it can also be cost effective to use a Helium mix for increased cooling properties.

ReFr	A	B	C	D	E	F	G	H	I	J
1	DRAFT WORKSHEET									
2				@ 1atm	Specific					
3		Newtonian	Kinematic	@ 273K	Heat	Temp.				
4		Viscosity	Viscosity	Density	Capacity	Deg C				
5		poises	Stoke	g/L	J/gK	Viscosity				
6	Argon	0.00021		1.784	0.52	0.0				
7	Helium	2.7E-05		0.1787	5.193	-257.4				
8	Nitrogen	-2.2E-05		1.251	1.04	-21.5				
9	Oxygen	0.00019		1.429	0.92	0.0				
10								200 Deg C, gas		
11								473 Deg K gas		
12	Reynolds #: (dia)*(vel)*(den)/(visc)			Froud #: (vel sqd)/(grav)*(dia)				cm, tube length		
13	30.48 cm		diameter of tube or sphere					280 kg/hr, mass flow		
14	103.523 cm/s		average velocity in tube or far from sphere					77.7778 g/s, mass flow		
15	0.00021 poises		newtonian viscosity - g/cm*s - dyne*sec/cm sqd					729.66 cm sqd, tube area		
16	0.00103 g/cc		density @ 200 Deg C & 1 atm					(vel)=(mdot)/((den)*(area))		
17	stoke		kinematic viscosity - unit of "stoke" - cm sqd/sec							
18	980 cm/s-sqd		acceleration of gravity							
19	15501 Reynolds #									
20	0.35879 Froud #									
21										
22	Re # < 2000 laminar flow regime									
23	Re # > 4000 turbulent flow regime									
24	3000 < Re # < 18,000 unstable laminar flow - turbulent flow									
25										
26										
27										
28										
29										
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31										
32										
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50										

ReFr	A	B	C	D	E	F	G	H	I	J
1	DRAFT WORKSHEET									
2				@ 1atm	Specific					
3		Newtonian	Kinematic	@ 273K	Heat	Temp.				
4		Viscosity	Viscosity	Density	Capacity	Deg C				
5		poises	Stoke	g/L	J/gK	Viscosity				
6	Argon	0.00021		1.784	0.52	0.0				
7	Helium	2.7E-05		0.1787	5.193	-257.4				
8	Nitrogen	-2.2E-05		1.251	1.04	-21.5				
9	Oxygen	0.00019		1.429	0.92	0.0				
10								200 Deg C, gas		
11								473 Deg K gas		
12	Reynolds #: (dia)*(vel)*(den)/(visc)			Froud #: (vel sqd)/(grav)*(dia)				cm, tube length		
13	60.96 cm			diameter of tube or sphere				2520 kg/hr, mass flow		
14	232.928 cm/s			average velocity in tube or far from sphere				700 g/s, mass flow		
15	0.00021 poises			newtonian viscosity - g/cm*s - dyne*sec/cm sqd				2918.64 cm sqd, tube area		
16	0.00103 g/cc			density @ 200 Deg C & 1 atm				(vel)=(mdot)/((den)*(area))		
17	stoke			kinematic viscosity - unit of "stoke" - cm sqd/sec						
18	980 cm/s-sqd			acceleration of gravity						
19	69754.3 Reynolds #									
20	0.90818 Froud #									
21										
22	Re # < 2000 laminar flow regime									
23	Re # > 4000 turbulent flow regime									
24	3000 < Re # < 18,000 unstable laminar flow - turbulent flow									
25										
26										
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31										
32										
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50										

imp1	A	B	C	D	E	F	G	H	I
1	DRAFT WORKSHEET								
2	Flow for virtual impactor w/(50 f/s exit velocity for cyclone design following vir. imp.) on chamber exhaust								
3	Upstream Pressure	14.70 PSIA	1013565.0 dyne/cm ²						
4	Orifice Area	51.887 cm ²	1kg = 21.32 scf						
5		8.042496 in ²	1648.2 vel. calc.						
6	Gas Constant	8.31E+07 dyne cm/k mol	2080204.3 dyne cm/k g						
7	Air Temperature	200.0 deg C	473.0 deg K						
8	Specific Heat Ratio	1.667	0.001784 Density @ 273K & 1atm(gm/cc)						
9	Downstream Pressure	12.92 PSIA	890834.0 dyne/cm ²						
10	Atomic Wt. of Gas	39.948 g/mol							
11	Mdot for Subsonic	778 g/sec							
12		0.639211632							
13	Mdot for Sonic	1218 g/sec							
14	* dia to give area	3.200							
15	flow in Lpm subsonic	26176							
16	flow in Lpm sonic	40950							
17	flow in scfm sub son	924.9							
18	flow in scfm sonic	1447.0							
19	Velocity Total	258.8 14.7psi, 200Deg C(cm/s)	8.5 f/s vel. in 2f dia chamber exit						
20	Velocity Nozzle	117.2 14.7psi, 200Deg C(cm/s)	3.8 f/s vel. in 1f dia Nz return						
21	Velocity Purge	229.5 14.7psi, 200Deg C(cm/s)	7.5 f/s vel. in 2f dia to cooling towers						
22	vel = (mdot)/(den)/(area)								
23	Determine orifice diameter for vir imp exit at 50f/s for cyclone design(200C return to nozzle supply)								
24	mass flow	88 g/s from f13							
25	density	0.001030 g/cc @ 200C & 14.7psi, e8*273/e7							
26	vel required	1524 cm/s, from 50 f/s							
27	calculation	8.45 d = 2*(mdot/pie/vel/den)^0.5 - cm							
28	calculation	3.33 ori dia - inches							
29	Choose 3.2" dia upstream orifice for vir imp 1.78 psi drop across vir imp entrance w/ chbr 14.7psia								
30			@ 1atm	Specific					
31		Newtonian	Kinematic	@ 273K	Heat	Temp.			
32		Viscosity	Viscosity	Density	Capacity	Deg C			
33		poises	Stoke	g/L	J/gK	Viscosity			
34	Argon	0.0002096		1.784	0.52	0.0			
35	Helium	2.7E-05		0.1787	5.193	-257.4			
36	Nitrogen	-2.16E-05		1.251	1.04	-21.5			
37	Oxygen	0.000186		1.429	0.92	0.0		200 Deg C, gas	
38								473 Deg K gas	
39	Reynolds #: (dia)*(vel)*(den)/(visc)	Froud #: (vel sqd)/(grav)*(dia)		cm, tube length					
40	30.48 cm	diameter of tube or sphere		316.8 kg/hr, mass flow					
41	117.13 cm/s	average velocity in tube or far from sphere		88 g/s, mass flow					
42	0.0002096 poises	newtonian viscosity - g/cm*s - dyne*sec/cm sqd		729.7 cm sqd, tube area					
43	0.001030 g/cc	density @ 200 Deg C & 1 atm		(vel)=(mdot)/((den)*(area))					
44	stoke	kinematic viscosity - unit of "stoke" - cm sqd/sec							
45	980 cm/s sqd	acceleration of gravity							
46		Tot 2f dia	Nz 1f dia	Prg 2f dia					
47	17538 Reynolds #	77505	17549	68730					
48	0.4593 Froud #								
49									
50	Re # < 2000 laminar flow regime 12.92 psia of line to cooling towers								
51	Re # > 4000 turbulent flow regime								
52	3000 < Re # < 18,000 unstable laminar flow - turbulent flow								
53									

imp2	A	B	C	D	E	F	G	H	I
1	DRAFT WORKSHEET								
2	Flow for virtual impactor w/(50 f/s exit velocity for cyclone design following vir. imp.) on chamber exhaust								
3	Upstream Pressure	12.92 PSIA	890834.0 dyne/cm ²						
4	Orifice Area	51.837 cm ²	1kg = 21.52 scf						
5		8.69223416 in ²	1643.2 vel. calc.						
6	Gas Constant	8.31E+07 dyne cm/k mol	2080204.3 dyne cm/k g						
7	Air Temperature	200.0 deg C	473.0 deg K						
8	Specific Heat Ratio	1.667	0.001784 Density @ 273K & 1atm(gm/cc)						
9	Downstream Pressure	12.897 PSIA	889248.2 dyne/cm ²						
10	Atomic Wt. of Gas	39.948 g/mol							
11	Mass flow for Subsonic	88 g/sec	kg/hr	kg/min	g/s	scfm			
12		0.00209638	2800	46.7	778	994.9	total		
13	Mass flow for Sonic	1070 g/sec	2483	41.4	690	882.3	purge		
14	" dia to give area	3.327	317	5.3	88	112.6	nozzle		
15	flow in Lpm subsonic	2956		0.0	0	0.0			
16	flow in Lpm sonic	35992		0.0	0	0.0			
17	flow in scfm sub son	104.4		0.0	0	0.0			
18	flow in scfm sonic	1271.8		0.0	0	0.0			
19	Velocity Total	258.8	14.7psi, 200Deg C(cm/s)			8.5	f/s vel. in 2f dia chamber exit		
20	Velocity Nozzle	117.2	14.7psi, 200Deg C(cm/s)			3.8	f/s vel. in 1f dia Nz return		
21	Velocity Purge	229.5	14.7psi, 200Deg C(cm/s)			7.5	f/s vel. in 2f dia to cooling towers		
22	vel = (mdot)/(den)/(area)								
23	Determine orifice diameter for vir imp exit at 50f/s for cyclone design(200C return to nozzle supply)								
24	mass flow	88 g/s from f13							
25	density	0.001030 g/cc @ 200C & 14.7psi, e8*273/e7							
26	vel required	1524 cm/s. from 50 f/s							
27	calculation	8.45 d = 2*(mdot/pia/vel/den)^0.5 - cm							
28	calculation	3.33 ori dia - inches							
29	Choose b28 dia min. exit orifice for vir imp 1.78 psi drop across vir imp entrance w/ chbr 14.7psia								
30			@ 1atm	Specific					
31		Newtonian	Kinematic	@ 273K	Heat		Temp.		
32		Viscosity	Viscosity	Density	Capacity		Deg C		
33		poises	Stoke	g/L	J/gK		Viscosity		
34	Argon	0.0002096		1.784	0.52		0.0		
35	Helium	2.7E-06		0.1787	5.193		-257.4		
36	Nitrogen	-2.16E-06		1.251	1.04		-21.5		
37	Oxygen	0.000186		1.429	0.92		0.0		
38							200 Deg C, gas		
39							473 Deg K gas		
40	Reynolds #	(dia)*(vel)*(den)/(visc)	Froude #:	(vel sqd)/(grav)*(dia)	cm, tube length				
41		30.48 cm		diameter of tube or sphere	316.8 kg/hr. mass flow				
42		117.13 cm/s		average velocity in tube or far from sphere	88 g/s. mass flow				
43		0.0002096 poises		newtonian viscosity - g/cm*s - dyne*sec/cm sqd	729.7 cm sqd. tube area				
44		0.001030 g/cc		density @ 200 Deg C & 1 atm	(vel)=(mdot)/(den)*(area)				
45		stoke		kinematic viscosity - unit of "stoke" - cm sqd/sec					
46		980 cm/s sqd		acceleration of gravity					
47			Tot 2f dia	Nz 1f dia	Prg 2f dia				
48		17536 Reynolds #	77505	17549	68730				
49		0.4593 Froude #							
50	0.023 psi drop across vir imp exit								
51	12.897 psia hot return gas to cyclone								
52	Re # < 2000 laminar flow regime								
53	Re # > 4000 turbulent flow regime								
54	3000 < Re # < 10,000 unstable laminar flow - turbulent flow								

C:\95mm\tsk2\impcyc.wb1 G2

—△— Particle Diameter

C:\95mm\Tsk2\impcyc.wb1 G3

—○— Unit Particle Settling Velocity

APPENDIX B

NOTICE

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APPENDIX B

Energy Systems Engineering Analysis

Prepared by

**J. L. Heck
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1. INTRODUCTION

This document describes the spray-casting process as a proposed alternative to the conventional processes available in existing U.S. Department of Energy (DOE) facilities and private industry for making large, depleted uranium (DU) components. Because parts can be made by spray casting to near-net shape, including stepped features, the amount of scrap generated would tend to be small, and the machining required on the DU would be minimal. This spray-casting process—which uses the Pressurized Controlled Aspiration Process (PCAP) developed by MSE, Inc., and the Controlled Aspiration Process (CAP) developed by Custom Spray Technologies (CST)—is a relatively new thermal spraying process. However, a commercial spray-casting process, the Osprey process, has been used successfully for at least the past 10 years for various industrial applications. CST's spray-casting studies are documented in CST Report CST-2125, July 31, 1995. MSE, Inc., has also been spray casting relatively small nickel-alloy and copper parts for the past several years, and has presented papers about such work at the last two thermal spraying conferences sponsored by the American Society of Metals.

To date, no one has experience in spray casting uranium; because uranium is a dense and reactive metal, some process development is required to determine an optimum process for spraying DU. Other issues to be addressed in development studies include the following:

- material compatibility,
- the percentage of theoretical density that can be attained,
- the material properties that can be attained in as-spray-cast components,
- the amount of scrap generated in the form of overspray, and
- how overspray material can be handled.

The Oak Ridge Y-12 Plant has some experience handling small-diameter material similar to that which would be produced as overspray in the spray-casting process.

This document discusses briefly the spray-casting process and presents a plan for implementing this process to produce large, DU components suitable as gamma shields for shipping casks for spent fuel elements. The document proposes a preliminary design for an intermediate-scale facility to develop and demonstrate the spray-casting process for uranium. The operation of such a facility would provide design criteria and process information needed both to design a full-scale production facility and to estimate the costs of a production facility.

This document is based on both a review of the work done by CST and MSE on the spray casting of metals and the application of this work to spray casting of DU. Although the Y-12 Plant in Oak Ridge, Tennessee, has no experience in spray casting, it has a great deal of experience in conventional processing and handling of DU. This experience includes chemical processing; casting; rolling, forming, and forging of shapes; making uranium alloys; heat treating; machining, and handling of scrap material generated by these processes. Lockheed Martin Energy Systems, Inc., also has significant experience in other thermal-spraying processes such as plasma spraying of materials other than uranium and gas atomization of highly reactive material such as lithium compounds.

Much of the information in this document is excerpted from both the CST report mentioned earlier and the work done by MSE, but this information was applied specifically to spray casting of uranium in the Intermediate Facility proposed to be installed in the H-1 Foundry at the Y-12 Plant.

2. URANIUM SPRAY CASTING PROCESS DESCRIPTION OVERVIEW

Several patented processes have been proposed for spray casting uranium. Two processes in particular, the Pressurized Controlled Aspiration Process (PCAP), developed by MSE, and the Controlled Aspiration Process, proposed by CST, are the bases for this report. The Osprey process has also been proposed for consideration for spray casting the gamma shields (see App. C). Several preliminary development and design studies have been performed, (see Custom Spray Technologies, Inc., *Informal Summary Progress Reports, Task 1 - Task 2 - Task 3*, CST-2125, July 31, 1995).

The spray-casting process consists of the following three steps:

1. supplying molten material at a controlled rate to the throat of a converging/diverging nozzle and
2. supplying heated gas to the inlet of the nozzle at pressures and flow rates such that the molten metal entering the throat of the nozzle is atomized and accelerated out of the nozzle.
3. the deposition of the molten and semi-molten plume on a substrate.

Temperatures and pressures are controlled so that the finely divided spray formed in the nozzle becomes a plume of molten droplets exiting the nozzle. The velocity and two-phase state of the plume droplets are such that when they impinge on the substrate, the droplets form splats and adhere to the substrate surface. Initially, the substrate is a prepared mandrel and subsequently becomes the solidified splats of sprayed material. The authors recognize that this process, like other thermal-spraying processes, is not 100% efficient. Not all of the molten material that enters the throat of the nozzle becomes part of the spray-cast product. The material that does not become part of the spray-cast part becomes small, solid, free particles with a size distribution on the order of tens of microns or less and is called "overspray."

The process may be operated as a single-batch process, a continuous process, or a semicontinuous process consisting of multiple, sequential batch processes. In the latter two cases, the size limit of a part that can be made depends on the size of the spray-casting chamber and the mandrel manipulation equipment, assuming that at least two tundishes and spray-nozzle assemblies can be used independently in the process. Apparently, it is practical to use this technology to spray cast relatively long, large-diameter, hollow cylinders or large, flat disks as single parts as an alternative to conventional fabrication techniques that would require relatively complex assembly techniques.

There may be a small amount of porosity, potentially causing the density of the spray-cast material to be slightly lower than the density of wrought material. Generally, the spray-cast material is a fine-grained structure in contrast to the coarse-grained structure of conventional vacuum induction DU castings. Therefore, the mechanical properties of the as-spray-cast material are expected to be superior to those of conventional as-cast uranium and are expected to approach the mechanical properties of wrought uranium. The slightly reduced density, however, will reduce the gamma-attenuation properties proportionally to the decrease in density. Therefore, an increase in thickness will be required to overcome the decrease in density. The actual spray-cast density of uranium is thought to be 95% or more of the theoretical density of wrought uranium. The speed of impact, the fluid state of the splats, and the adherence of the splats to each other on the substrate affect this reduction in density.

To spray cast material into desired shapes and thicknesses, one must move the mandrel and/or the nozzle so that the spray plume is directed to deposit the proper amount of material on the substrate. The maximum deposition rate per unit area is directly proportional to the local heat dissipation rate, which causes thermal gradients, thermal stresses, and differential thermal expansion in the substrate. This concern is common to any thermal-spraying process. The effect of thermal stresses developed during spray casting will be evaluated, and the process will be controlled either by limiting the acceptable temperature range of the substrate during spraying or by other means so that thermal stresses do not have a harmful effect on the quality of the spray-cast part.

Because uranium is a dense and very reactive metal with a relatively high melting point (1132°C) three potential areas of concern exist that need process development to determine if a production spray-casting facility is technically and commercially viable. The first concern is that the atomizing/carrier gas and the atmosphere in the spray-casting chamber must be inert. Large quantities of argon will be required to spray cast a large uranium part. The filtered argon chamber exhaust gas can be either exhausted or recycled, but if it is recycled, it will require purification, cooling, and compression. This need is not a technical issue that requires process development but rather is an economic consideration.

The second process issue is the overspray, which consists of very small particles of metallic uranium. This overspray is pyrophoric when exposed to air because of its large surface area-to-mass ratio. The development studies will demonstrate that the overspray material can be collected properly in an inert atmosphere and can be either oxidized in a controlled manner and disposed of or, if practical, reused in the process.

The third concern is the service life of the spray nozzle. Many materials will not be suitable for such service and will be eroded too quickly to be used in a production facility. The second and third issues will require some process development, the extent of which is not now known. But there is also no reason to believe that practical solutions cannot be found to permit the operation of a production-scale facility.

To implement this process for the manufacture of gamma shield components with the quality control necessary to ensure that specified product requirements are met, the following process systems can be identified as necessary parts of the spray-casting process:

1. Spray delivery system
 - Integral heated tundish/spray nozzle system
 - Furnace/tundish
 - Heated spray nozzle
 - Atomizing gas preheater (close-coupled to nozzle)
2. Environmental control system
 - Spray-casting chamber
 - Tundish isolation chamber
 - Gas-handling system
 - Vacuum system
 - Argon gas supply
 - Offgas-handling system
 - Controlled oxidation gas supply system
3. Mechanical systems
 - Transport system for loading/unloading substrate
 - Substrate manipulator
 - Overspray collection system (interacts with offgas-handling system)
4. Control and data collection system

Detailed requirements for each process subsystem depend on both the particulars of spray casting of DU and the specific requirements of the parts to be made. In addition, other support functions will be required, including the following:

- fabrication of new mandrels and refurbishment of used mandrels,
- removal of cast parts from mandrels,
- removal of the oxide skull from the tundish liner where uranium charge is melted, and
- discharge or recycle of the argon spray-casting chamber offgas after the overspray has been removed.

3. DEPLETED URANIUM SPRAY-CASTING PROCESS IMPLEMENTATION

Although the spray-casting process has yet to be demonstrated for uranium, other materials that have similar melting points, similar densities, and are reactive in air have been spray cast by MSE, CST, and Osprey. Although this development work indicates that it is possible to use the spray-casting process to spray cast uranium components, this fact should be clearly demonstrated and process development studies should be done before a large capital commitment is made to make the large gamma shielding components such as the proposed Multi-Purpose Canister (MPC) gamma shield.

The rest of this document proposes and describes in detail an Intermediate Spray Casting Facility. This facility is proposed to be located in the H-1 Foundry in Building 9998 at the Y-12 Plant. The Intermediate Facility will be implemented in phases to minimize the financial risk of the project while providing sound technical process development of a production facility. As much as possible, existing Y-12 Plant facilities will provide support functions (e.g., mandrel fabrication and refurbishment, removal of cast parts from mandrels, removal of the oxide skull from tundish, a stack to discharge filtered spray-casting offgas, and disposal of oxidized overspray material). The operation of the Intermediate Facility will determine, in detail, all process requirements of a production facility and will be used to estimate the capital and operating costs of a production facility.

Spray casting will be evaluated in the Intermediate Facility with the following process parameter optimization goals:

- to minimize the gas-to-metal mass flow ratio,
- to minimize the amount of overspray generated,
- to maximize the nozzle life, and
- to produce spray-cast parts that have suitable density and mechanical properties.

Specific process parameters to be studied in the optimization include the following:

- nozzle inlet temperature and pressure, uranium mass flow rate, and superheat;
- the stand-off distance between the nozzle and the substrate;
- the surface speed and temperature of the substrate;
- the atomizing gas composition; and
- the geometry of the nozzle.

Nozzle materials and specific nozzle designs will be tested to maximize nozzle life and optimize nozzle performance. The effects of the purity of the argon atmosphere in the spray-casting chamber on the material properties of the spray-cast part will also be evaluated. The collection and processing of the uranium overspray material will be studied to develop methods for doing so in a production facility.

In addition, the Intermediate Facility will be used to determine the tolerances to which components can be spray cast to near-net shape to minimize machining of as-sprayed parts. Other uranium candidate alloys, such as uranium-molybdenum and uranium-chrome alloys, could be evaluated for spray casting. Uranium-molybdenum alloys are thought to have better as-sprayed properties than uranium, whereas uranium-chrome alloys have lower melting points. Lower operating temperatures have the potential to enhance significantly the service life of a spray nozzle.

The purpose of Phase One of the operation is to study in detail the spray-casting process as it applies particularly to uranium but at metal and argon flow rates that would be lower than production-scale flow rates. The Phase One operation will minimize both the capital investment required and the modifications to the existing foundry to verify and optimize a viable spray-casting process.

The purpose of Phase Two of the operation is to demonstrate that this process can be scaled up to production metal-spraying rates. Phase Two of the operation will require additional capital costs to

upgrade facilities to supply, heat, cool, filter, and discharge large flow rates of argon. Larger nozzles will be made, a means to transfer molten metal from an existing casting furnace to the tundish will be provided, and other equipment will be modified as necessary to demonstrate production-scale spray-casting rates.

Phase One of the operation of the Intermediate Facility will study the spray-casting process using up to 50-kg batches of uranium. Small-diameter disks and hollow tubes will be spray cast during Phase One consistent with the 50-kg batch sizes. Disks ranging from 20 in. in diameter by 1/2 in. thick to 10 in. in diameter by 2 in. thick and hollow tubes ranging from 8 in. outside diameter (OD), 6 in. inside diameter (ID) by 6 in. long to 12 in. OD, 11 in. ID, and 8 in. long would be representative of the spray castings produced. This range of dimensions will permit the study and optimization of the following:

- the effective life of spray nozzles made of different materials with different nozzle designs;
- the handling and controlled oxidation of the overspray material;
- the as-sprayed properties of the depleted uranium and various alloys;
- the interface between the gas heater, spray nozzle, and tundish;
- the development of a process-control algorithm; and
- the overall process.

After successful Phase One operation of the Intermediate Facility, the facility will be upgraded for Phase Two to handle 2200-kg batches of uranium and up to 2250 scfm of argon. At this point, a decision must be made as to whether to recycle the argon. This will be an economic analysis. The number of runs required, the amount of gas needed, and the location of a recycling unit will be considered. The tundish and the spray-casting chamber used during Phase One are designed to accommodate the size and capacities required for Phase Two and will not need to be upgraded. The rotation axis of the substrate manipulator will be relocated to maintain the proper stand-off distance for spraying larger-diameter hollow tubes in Phase Two. This relocation is a minor modification that requires a new mounting plate for the drive motor (see Sect. 4.1.8.). The remaining subsystem components will have to be upgraded because of the higher gas-flow requirements. A transfer line will be fitted between an existing foundry furnace to the tundish for Phase Two operation as discussed earlier.

The design criteria for the Phase Two upgrades will be reviewed and revised as needed based on the experience gained in Phase One. The maximum flow rates of argon required, the capacity of the argon heater, and the capacity of the off-gas system equipment are now based on the assumption that the mass flow rate of argon through the spray nozzle is twice that of the mass flow rate of molten uranium. If this argon flow is determined to be excessive, the needed capacities of the argon vaporizer, the argon gas heater, and the off-gas handling equipment will be reduced accordingly. This reduction will decrease both the capital costs of the Phase Two upgrade and the operating costs of Phase Two.

The Phase Two operation of the Intermediate Facility will demonstrate the feasibility of scaling the process developed during Phase One to spray-casting rates that would be required in a full-scale production plant for large gamma-shielding parts. This metal deposition rate is assumed to be 5 kg/min, or 300 kg/h. During Phase Two operation, parts that are prototypic in thickness or cross section would be spray cast to demonstrate further the capability of the process to spray cast quality parts. Disks 48 in. in diameter by 3 in. thick and hollow cylinders 48 in. OD, 42 in. ID by 12 in. long would be spray cast as part of the Phase Two operation. A 24-in.-square tube with a 2 1/2-in. wall thickness, 12 in. long with an inside radius of 1/2 in. and an outside radius of 4 1/2 in. is proposed as a demonstration of the ability to spray cast square and rectangular tube shapes.

Based on the successful Phase Two operation, a production facility can be designed to meet the quality and schedule requirements of large uranium components such as large gamma-shield components required for the MPC. The capital and operating costs of such a facility would also be well understood. Such a production facility potentially could supply a world market for gamma shields for shipping casks or for other applications requiring large uranium shapes.

4. INTERMEDIATE SPRAY-CASTING FACILITY

The Intermediate Spray-Casting Facility will be located in the H-1 Foundry of Building 9998 at the Oak Ridge Y-12 Plant. This area routinely casts 2500-kg ingots of DU using bottom-loading, vacuum-induction furnaces. The H-1 Foundry has facilities for the following tasks:

- coating graphite with an yttria (Y_2O_3) wash,
- stripping ingots from molds,
- cleaning uranium oxide from coated graphite parts, and
- performing other activities that support a uranium foundry.

Argon at mass flow rates of 80 scfm, three-phase electric power, and cooling tower water for process cooling are readily available. The adequacy of this gas flow rate as it relates to the nozzle diameter size will be evaluated. The impact on facility safety documentation and the need for air and water permits will also be minimized. Therefore, locating the Intermediate Spray-Casting Facility in the H-1 Foundry will permit the use of existing equipment and utility services as much as practical to save time and money in implementing Phase One operation.

As stated earlier, the Intermediate Facility will be operated in two phases to permit the process to be studied and optimized in a shorter period of time with less overall financial risk. These two phases are described in detailing the rest of this document.

4.1 Intermediate Facility, Phase One

The Intermediate Spray-Casting Facility configured for Phase One consists of equipment modules that are combined to spray cast DU and candidate uranium alloys into various shapes weighing up to 50 kg. The amount of argon used by the Intermediate Facility will be limited to 80 scfm, which is the amount now available for use in the H-1 Foundry without facility upgrades. Present design envisions 10% of the argon gas flows through the nozzle as an atomizing gas, and 90% of it is used to purge the spray chamber, to remove heat, and to entrain and carry away overspray material. Furthermore, the ratio of the mass flow rate of argon to metal through the nozzle is assumed to range between two and one. Eight scfm of argon is approximately 6.1 g/s; therefore, the mass flow rate of metal will range between 3.1 and 6.1 g/s. Based on the assumptions of gas-to-metal ratios ranging from 2:1 to 1:1 and a nozzle argon flow rate of 8 scfm, a spray-casting run will last from 2 to 4 h. For lower argon and metal flow rates, the time for a spray-casting run can last 8 h or longer. The process flowsheet is shown in Fig. 1.

The equipment modules for Phase One of the Intermediate Spray-Casting Facility are those listed in Sect. 2. A detailed physical and process description of each equipment module is given in the following subsections.

4.1.1 Furnace/Tundish

The tundish is a 35-kW, three-zone, resistance-heated vacuum melting furnace. During Phase One operation, it will be loaded with up to 50 kg of uranium, evacuated, furnace charge melted, and then backfilled with argon before melting the furnace charge. It will also have the capacity to receive 2200 kg of molten uranium from an external furnace during Phase Two operation. The maximum operating temperature of the tundish is 1600°C, and it will be capable of maintaining the melt within $\pm 15^\circ\text{C}$ of the set point temperature. The operating pressure of the tundish will range from -14.7 to +14.7 psi. The pressure inside the tundish will be monitored and controlled as stated earlier, because this pressure will be an important process parameter affecting the mass flow rate of molten metal to the nozzle. The pressure of the molten metal delivered to the nozzle is equal to the sum of the static head of liquid metal and the gas pressure inside the tundish.

The crucible or tundish liner will be yttria-coated graphite or another material suitable to contain the molten uranium charge. The outlet of the tundish crucible will be a small orifice to be connected to the throat of the spray-casting nozzle. The main portion of the tundish exterior will consist of a cylindrical stainless steel shell with flanged connections at each end. Power feed-through collars will be attached to each flanged connection. The bottom feed-through collar will support and provide power to the lower and middle heating elements, and the top feed-through collar will support and provide power to the upper heating element. The top of the tundish shell will attach to the top feed-through collar and be easily removable both to provide maintenance access to the tundish crucible and to allow for loading a charge into the tundish.

The base of the tundish will be attached to the bottom feed-through collar and will indirectly support the crucible inside the tundish and provide a structural feature for attaching the tundish to the spraying chamber. Rigidized carbon-felt insulation will thermally insulate the heating elements and the crucible from the tundish shell. The bottom of the crucible will be shaped and sloped so that the melt will be directed to the small outlet in the bottom for input to the spray nozzle.

4.1.2 Heated Spray Nozzle

The spray nozzle is a converging/diverging nozzle that receives molten metal at its throat and heated gas at the converging inlet. The heated gas breaks up the molten metal flow into small droplets and accelerates the droplets toward the substrate. The nozzle is heated to help ensure that the molten metal droplets arrive at the substrate at the proper temperature. The average size and velocity of the droplets, the distribution of droplet size and velocity in the spray plume, and the shape of the spray plume are greatly influenced by both the nozzle geometry and the heated gas flow rate. These factors affect both the spray-casting rate and the deposition efficiency. Maximizing the deposition efficiency improves the casting rate and minimizes the amount of overspray material that must be collected and handled properly. One of the main goals of Phase One operation of the Intermediate Facility is to optimize the design of process components such as the nozzle.

The details of the nozzle design and the interface between the spray nozzle, the tundish, and the gas heater are not well defined at this point in the preliminary design. The spray nozzle is located at the bottom of the tundish crucible inside the tundish enclosure. The outlet of the nozzle is directed at the substrate, which is controlled by a manipulator inside the spray chamber.

Nozzle designs and the actual configurations of the nozzle, the tundish, and the gas heaters are available for both the MSE and the CST spray processes. These processes have not been used to spray uranium but have been used to spray materials with similar melting points, densities, etc. As stated earlier, it is not clear that a suitable nozzle material has been identified at this time for spraying DU. Several material candidates have been suggested based on earlier process experience. These materials have been used successfully for handling molten uranium such as the rheocasting of uranium-6% niobium and other development efforts. These materials are either ceramics, blends of ceramics, cermets, or refractory metals that are surface treated with either nitrogen or carbon or both. Ultimately, the optimum nozzle material will depend on the material sprayed, which can be either DU or an alloy. Several alloys offer advantages; uranium-molybdenum might provide better mechanical properties than spray-cast uranium, and uranium-chrome has a significantly lower melting temperature. Uranium-chrome alloys might provide an adequate spray-cast gamma shield at a significantly lower cost because the nozzle life might be longer, and the initial cost of the nozzles might be lower.

4.1.3 Atomizing Gas (Argon) Preheater

The argon gas heater will have the capacity to heat a minimum of 6.1 g/s (8 scfm) of argon from 20° to 1600°C. The inlet to the gas heater will be the mass flow rate controlled from the argon gas supply manifold. Argon will be heated by graphite resistance heaters requiring a low voltage and high alternating current (ac) power supply. The outlet gas temperature will be controlled by a closed-loop, Proportional Integral Derivative (PID) controller to the power supply. The outlet temperature and the mass flow rate are important process parameters to be controlled.

The gas heater will be insulated and sealed to prevent excessive heat loss or leakage from contaminating the purity of the argon gas supplied to the inlet of the spray nozzle. A major design interface is that of the gas heater to the spray nozzle. To meet system requirements, the interface will be designed to allow for the thermal expansion in both the gas heater and the spray nozzle internals and to prevent leakage into or out of the gas heater so that all the argon that enters the heater will exit the spray nozzle entraining the uranium spray droplet plume. A small in-leakage of air will be detrimental to both the life of the graphite heaters and the final product quality.

Gas heaters with power supplies and controls, such as those needed for the Intermediate Facility, are available from several suppliers and are procured by a functional specification. MSE procured a gas heater similar to the one needed for Phase One of the Intermediate Facility, and they are using it at their thermal spraying facility.

4.1.4 Spray-Casting Chamber

Figures 2 and 3 show the spray-casting chamber. The chamber is cylindrical with flanged torispherical heads attached at each end. It is approximately 11 ft long and 6 ft in diameter. One end is a hinged door to permit loading and unloading of the substrate and to provide maintenance access to the chamber interior. The spray-casting chamber is designed to operate from -14.7 to +14.7 psi. It is designed and constructed to have an integrated leak rate of not greater than 1×10^{-6} standard cc/s. A pressure-relief valve is provided to prevent the pressure inside the chamber from increasing above the design pressure. The discharge from the relief valve is directed to the off-gas system, which contains a back-flow preventer to maintain an inert atmosphere inside the chamber. All removable penetrations and flanges are sealed using two o-rings (as described in Sect. 4.1.5 and shown in the two sketches). Viewports are provided in the chamber to allow operators to verify visually the function of the spray nozzle, the substrate manipulator, and other internal components. Not included in the figures are options for being able to clean and provide routine maintenance. Some possibilities would be glove ports for cleaning overspray or performing some maintenance, mechanisms or equipment that would allow isolation of certain components to allow repair or replacement without bringing the chamber to atmosphere, and an airlock for loading.

The spray-casting chamber contains a substrate manipulator that can be arranged in two configurations, the first to spray round or rectangular cylinders and the second to spray flat disks. Tracks are located inside the chamber to guide the axial motion of the substrate manipulator and to drive it in and out of the chamber when the access door is open to load mandrels and to unload sprayed parts. The substrate manipulator is described in detail in Sect. 4.1.8.

The chamber mechanically supports the tundish such that the spray plume from the spray nozzle is directed at the substrate through a port near the center of the chamber. A baffle is located inside the chamber to help direct the overspray material to the gas outlet of the chamber and help minimize the amount of small particulates of DU that collect inside the chamber. Argon is also introduced into the chamber at various locations to remove heat, maintain the inert atmosphere inside, and assist in particulate removal. The overspray baffle configuration will vary with the part being sprayed, and the

function of these baffles will be optimized with the argon gas purge flows as part of the Intermediate Facility development effort.

4.1.5 Argon Gas Supply and Vacuum Manifolds

The argon gas supply manifold will supply argon to all process equipment to maintain an inert atmosphere throughout and to the gas heater to be used as an atomizing/carrier gas in the nozzle. The pressure of argon supplied to each component is regulated, and pressure-relief valves prevent the argon supply pressures from being excessive. The capacity of the argon supply manifold is limited to 80 scfm.

Each time the process is restarted, all components first will be evacuated by large, two-stage mechanical vacuum pump(s) before being backfilled with argon to establish an inert atmosphere. After this evacuation and backfill, a continuous purge of argon will be provided to maintain the inert atmosphere. This evacuation-and-backfill technique will also be used to replace cyclone separator hoppers and filter housings during routine operation of the off-gas-handling and dust- (overspray) collection equipment. For Phase One, argon will be used in a once-through mode and rejected to the atmosphere after appropriate filtration.

All seals in process vessels are static and will be accomplished by using a pair of elastomeric o-rings. The volume between each pair of o-rings will be maintained at a slight overpressure of argon, causing any leakage in the seals to introduce argon into either the vessels or the environment. The lines in the manifold that supply the seal overpressure contain a pressure transducer, flow meters, and a flow switch. Any detectable flow will alert the operator that a seal has failed so that appropriate action can be taken. These leak-control features have been used successfully in many instances to maintain inert atmosphere inside process vessels.

The maximum oxygen content within the process from all sources (e.g. air, water vapor, etc.) is not expected to exceed 20 ppm at the start of spray-casting operations, and the maximum nitrogen level is not expected to exceed 2000 ppm. The atmosphere in the spray chamber, tundish, gas heater inlet, and outlet to the existing exhaust stack will be monitored to ensure that the atmosphere quality requirements are met. The operator will be alerted when the quality of the atmosphere is not maintained within specifications.

During the actual spray casting, the mass flow rate of argon supplied to the spray nozzle through the gas heater will be closed-loop controlled. This part of the manifold will contain fine absolute filters to protect the hot wire mass flow meter used to measure the mass flow rate of argon. The mass flow rate of argon to the nozzle is one of the key process parameters that must be controlled to optimize the spray-casting process.

The pressure of the argon supplied to the tundish will be closed-loop controlled so that the pressure of the molten uranium feed to the spray nozzle can be carefully monitored and controlled. The optimum pressure of the melt at the inlet of the nozzle is different for the two different spray processes to be evaluated in this facility, the PCAP process patented by MSE and the CAP process patented by CST. Control of this parameter will effectively control the mass flow rate of the molten metal for a given nozzle configuration and argon gas flow rate.

A rack of 12 argon bottles provides a back-up supply of argon to shut the system down safely and orderly if a plant argon supply problem occurs. This feature is important because the overspray material is pyrophoric, and the molten uranium is a very reactive substance that will react with oxygen, nitrogen, and almost all other gases that are not noble gases. If a problem situation occurs, the flow of molten metal to the nozzle will be stopped and the melt in the tundish will be allowed to resolidify in place using the back-up supply of argon. The inert atmosphere in the process equipment can be maintained with the purge flow of argon or evacuated using the system vacuum pump, depending on the particular situation.

4.1.6 Off-Gas-Handling and Dust-Collection System

Four modules process the spray-casting chamber offgas: a cyclone separator, a gas cooler, a high-efficiency particulate air (HEPA) filter, and a backflow preventer. In addition, there is a special exhaust gas sampling system that operates in parallel with the off-gas-handling equipment and collects samples of the off gas to study the size distribution, shape, and other characteristics of the overspray material.

The first stage of chamber exhaust filtration will be a cyclone separator. The cyclone hopper will be designed to contain the collected material for safe removal and transport by enclosing it in an inert atmosphere glove box. The second stage of filtration will be a filter system. Backflow-prevention and pressure-relief systems will be incorporated with the off-gas-handling system.

The chamber off-gas sampling station collects a specific flow volume of exhaust gas and removes the entrained particulates. The particulates are collected in stages, depending on their size and density, permitting the determination of the size distribution and fraction of overspray that is entrained in a given volume of exhaust gas. This information is needed to evaluate the design of chamber baffles and exhaust ports in minimizing the amount of overspray material that remains inside the chamber. Characterizing the particulates in the off-gas stream permits the design of the off-gas-handling equipment for Phase Two operation to be optimized for removing the particulate material. Other components associated with the sampling stations are automatic sampling valves, shut-off valves, check valves, and stainless steel piping. The sampling stations will be enclosed in a two-port, inert-atmosphere glove box.

4.1.7 Controlled Oxidation System

After a spray-casting run is complete, but before the chamber is opened to unload the sprayed part and provide maintenance to the chamber, a means is provided to introduce air into the chamber at controlled rates to oxidize slowly the overspray material that has settled and remains in the chamber. Instrument air is metered into the chamber carefully to increase the oxygen content slowly to control the oxidation rate of the overspray material. The air inlet mass flow rate and the oxygen content of the spray chamber atmosphere will be monitored to verify the controlled oxidation process. This monitoring ensures that the residual overspray material is no longer pyrophoric and helps provide safe personnel access to the spray-casting chamber.

4.1.8 Substrate Manipulator

The substrate manipulator has three coordinated axes of motion, two translational and one rotational, and is capable of positioning mandrels for spraying both disks and round, hollow tubes. Square or rectangular tubes with corner radii can also be spray cast in the Intermediate Facility. The manipulator can spray cast disks or tubes with a diameter of up to 48 in. (See Figs. 2 and 3.)

The first axis is a linear drive that moves a carriage axially along the spray-casting chamber. The stroke of the drive is 84 in. and allows the carriage to be driven to a load-and-unload station outside the chamber to facilitate handling of spray-cast parts and mandrels.

The second axis moves the carriage normal to the first axis parallel to the centerline of the spray nozzle and has a stroke of 12 in. This stroke will permit the manipulator to spray cast both 42-in.-ID cylinders and square and rectangular tubes of which the inside corner-to-corner dimension is greater than 19 in.

The third axis is a rotation. The frame that contains the rotator can be positioned so that the axis of rotation is either perpendicular to the spray nozzle axis for spray casting hollow tubes or parallel to the nozzle axis for spray casting disks. The faceplate of the rotator is compatible with both a mandrel holder for a disk or a tube, as shown in Figs. 2 and 3. The referenced sketches show the manipulator configured

for the larger Phase Two shapes to be sprayed. The smaller-diameter disks sprayed in Phase One can be sprayed on the same manipulator configuration as the disks in Phase Two. The smaller-diameter cylinders sprayed in Phase One require that the axis of the rotation be located closer to the spray nozzle to maintain the proper stand-off distance between the nozzle and the substrate. This task is accomplished by mounting a different rotator mounting plate on the horizontal carriage that locates the substrate properly with respect to the spray nozzle. (This configuration is not shown in the referenced sketches.)

The drive motors are direct current (dc) servomotors with sealed integral encoders. One of the drive motors is located outside the chamber; the other two motors are located on the carriage, which can be driven outside the chamber for maintenance access. Because the overspray material would cause wear, binding of drive components, and premature failure of moving mechanical components, drive screws, gearboxes, and other such components will be shielded by covers. The V-groove wheels that ride on the tracks that guide the carriage axially inside the chamber will have wipers to prevent the overspray material from building up on the tracks. All bearings are sealed to maximize their life.

A three-axis programmable servocontroller permits both disks and tubes to be sprayed in a programmed mode. The area swept by the spray nozzle can be held constant so that the stand-off distance can be maintained properly. These parameters will be established to maximize both the deposition rate and the deposition efficiency of the process and to limit thermal gradients in the spray-cast parts. The rotation axis and the translation axis parallel to the spray nozzle will be coordinated to permit spray casting of square and rectangular shapes.

4.1.9 Control and Data Collection

The process monitoring and control system is computer based with input and output circuits to control and monitor the entire spray-casting process. PID control is provided for the temperature and pressure control of the tundish, the argon mass flow rate and the outlet gas temperature of the gas heater, the temperature of the nozzle, and the mass flow rate of instrument air into the spray chamber for the controlled oxidation of the overspray material inside the chamber after a spray casting run is complete. The system provides consistent process control, data acquisition, process alarms, ease of process change, and a central point of operation. The control system is modular and expandable to meet the developmental needs of the Intermediate Facility. Video cameras and recorders will assist the operators in monitoring and reviewing the spray-casting process.

For Phase One operation, approximately 170 input and output signals are identified for the process control and monitoring of the spray-casting operation. When the facility is upgraded to Phase Two operation, approximately 21 additional inputs and outputs will be added to the control system. Table 1 is a list of process monitoring and control signals.

4.1.10 Electric Power Distribution

The electrical power will be provided for the Intermediate Facility from an existing feeder circuit in the H-1 Foundry. The feeder circuit will be terminated at a single disconnection point and power then will be distributed to the various system loads of the spray-casting equipment, including the following:

- the argon spray gas heater,
- the tundish heaters,
- the spray nozzle heaters,
- the substrate manipulator,
- the mechanical vacuum pump, and
- the process monitor and control system.

**Table 1. Intermediate spray-casting facility conceptual design
monitoring and controls design worksheet**

	Type	I/O	
Monitoring and controls		191	
Spray cast-facility M & C, Phase I		170	
Spray systems M & C		55	
Argon component (supply and heating)		20	LEGEND
Argon inlet pressure	M	I	I = Input
Total argon mass flow	M/C	I/O	O = Output
Argon filter pressure	M/A	I/O	M = Meter/Analyzer
Heater coil voltage	M/C	I/O	C = Controller
Heater coil current	M	I	A = Alarm/Annun.
Heater temperature	M	I	S = Switch/Sensor
Heater surface temperature	M	I	
Open/close cooling water inlet	S/C	I/O	
Cooling water pressure	M	I	
Argon temperature entering heater	M	I	
Argon temperature exiting heater	M	I	
Heater pressure	M	I	
Open/close argon inlet	S/C	I/O	
Open/close vacuum line	S/C	I/O	
Metal Component		24	
Heater coil voltage stage I	M/C	I/O	
Heater coil current stage I	M	I	
Heater temperature stage I	M	I	
Heater coil voltage stage II	M/C	I/O	
Heater coil current stage II	M	I	
Heater temperature stage II	M	I	
Heater coil voltage stage III	M/C	I/O	
Heater coil current stage III	M	I	
Heater temperature stage III	M	I	
Metal temperature near orifice	M	I	
Tundish press	M/C	I/O	
Open/close argon inlet	S/C	I/O	
Open/close vacuum line	S/C	I/O	
Tundish surface temperature	M	I	
Open/close cooling system inlet	S/C	I/O	
Cooling system pressure	M	I	
Tundish level/metal mass	M	I	
Nozzle		7	
Nozzle body temperature	M	I/O	
Heater coil voltage	M/C	I/O	
Heater coil current	M	I	
Heater surface temperature	M	I	
Plume temperature	M	I	

Table 1. (continued)

	Type	I/O
Substrate		4
Nozzle-to-surface distance	M	I
Surface speed through plume	M	I
Surface temperature at consolidation	M	I
Substrate temperature nominal	M	I
Video		
Vessel environment system M & C		32
Ambient temperature of chamber	M	I
Argon purge mass flow rate	M	I
Chamber wall temperature	M	I-14
Argon temperature at chamber exit	M	I
Wall temperature at chamber exit	M	I
Gas chemistry within chamber	M	I
Gas chemistry at chamber exit	M	I
Gas chemistry near substrate surface	M	I
Particle distribution chamber (w/chemical analysis)	M	I
Particle sampling system on/off	S/C	I/O
Chamber pressure	M	I
Open/close vacuum line	S/C	I/O
Atmospheric pressure	M	I
Open/close cooling system inlet	S/C	I/O
Cooling system pressure	M	I
Manipulator System		24
X-Coordinate	S/C	I/O
Y-Coordinate	S/C	I/O
Z-Coordinate	S/C	I/O
X-Speed	S/C	I/O
Y-Speed	S/C	I/O
Z-Speed	S/C	I/O
Angular about X-Coordinate	S/C	I/O
Angular about Y-Coordinate	S/C	I/O
Angular about Z-Coordinate	S/C	I/O
Angular about X-Speed	S/C	I/O
Angular about Y-Speed	S/C	I/O
Angular about Z-Speed	S/C	I/O
Sealing System		9
Argon seal pressure	M	I
Argon flow in main seal line	S/A	I/O
Argon flow in branch lines - 6 each	S-6	I-6
Exhaust System		6
Off-gas line pressure	M	I
HEPA filter pressure	M	I
Temperature entering heat exchanger	M	I
Temperature exiting heat exchanger	M	I
Heat exchanger on/off	S/C	I/O

Table 1. (continued)

	Type	I/O
Facility Systems		14
Argon system		4
Argon main valve position	S/C	I/O
Argon pressure	M	I
Argon temperature	M	I
Vacuum system		3
Vacuum pump on/off	S/C	I/O
Vacuum line pressure	M	I
Controlled oxidation system		3
Air mass flow	S/C	I/O
Air pressure	M	I
Cooling System		4
Position main cooling valve	S/C	I/O
Cooling system pressure	M	I
Cooling system temperature	M	I
Contingency (20%) spare I/O		30
Spray Cast Facility M & C, Phase II		21
Spray Systems M & C Mod		5
Miscellaneous mods		5
Vessel Environmental System M & C Mod		3
Miscellaneous mods		3
Manipulator M & C Mod		2
Miscellaneous mods		2
Facility Systems Mod		3
Miscellaneous mods		3
Pour Tube M & C		8
Temperature of pour tube body		I
Temperature of metal entering pour tube		I
Temperature of metal exiting pour tube		I
Temperature of Metal exiting pour tube		O
Mass flow of argon		I
Mass flow of argon		O
Pressure of body		I

The electric power distribution will be upgraded for Phase Two operation for the increased electrical loads required for the new spraying gas heater, a heated transfer line between the tundish and an existing casting furnace, and other Phase Two equipment. Table 2 is a summary of the electrical loads.

4.2 INTERMEDIATE FACILITY, PHASE TWO

The main effort of Phase Two operation will be to demonstrate spray-casting rates of approximately 5 kg/min needed to produce large components, such as the MPC gamma shields, and to demonstrate that the nozzle life will be adequate for producing these large parts. The nozzle will be larger to handle approximately 14 times the metal flow rate compared to that in Phase One, and the nozzle life should be long enough to permit one nozzle to spray more than 2200 kg of material without degradation.

The tundish will receive a 2200-kg charge of molten uranium from an existing casting furnace by a heated transfer line. The temperature in the tundish will maintain the uranium in the liquid state at the proper temperature and pressure for spray casting. The heated transfer line will be installed between an existing casting furnace that will be modified to accommodate the transfer line.

It is necessary to increase the capacity of the argon gas flow rate to an estimated maximum of approximately 2250 scfm. This requirement assumes a gas-to-metal mass flow ratio of 2:1, i.e., for every kilogram of metal sprayed through the nozzle, 2 kg of argon is required. It also assumes that 10% of the total argon is flowing through the spray nozzle with the remaining 90% used to purge the system and cool the gas-outlet temperature of the spray chamber to approximately 200°C. Therefore, a maximum of 225 scfm of argon will be heated and used as an atomizing and carrier gas flowing through the spray nozzle, and a maximum of 2025 scfm will be used to purge, cool, and remove overspray from the chamber. If this assumption proves too conservative (based on the operation of Phase One), and if a gas-to-metal mass flow ratio of 1:1 is adequate, the total argon gas flow requirement is reduced to 1125 scfm. The instrumentation and control system will be upgraded with additional sensors and more input and output channels. Some sensors will be replaced with those having the necessary range to monitor high gas flow rates.

The argon will be supplied by a steam-powered vaporization system. The vaporization equipment will supply a maximum of 2250 scfm of argon. The system will require 1650 lb/h of 250-psi saturated steam. This steam will be available from the Y-12 Plant central steam system. The Phase One argon piping will require significant size increases to accommodate the increased flows.

To handle the increased gas-flow requirements, the argon gas heater and the off-gas-handling equipment will have to be scaled up to handle a gas flow rate that is 28 times greater than that of Phase One operation. Design issues (such as whether the capacity of the existing H-1 Foundry stack is adequate to handle the increased flow of argon and the cost effectiveness of recycling the waste argon versus a once-through off-gas system) will have to be examined. Final design for Phase Two will not be complete until operating experience has been gained from Phase One to minimize further financial and technical risks.

**Table 2. Intermediate spray-casting facility conceptual design
electrical design worksheet**

	HP	kW	Amps @ 480 V, 30
Power required, Phase I		100	121
Power required for the spray vessel		100	121
Lighting		5	6
Monitoring and controls		1	1
Manipulator	20		27
Tundish heating		35	42
Gas heating		30	36
Exhaust/filter/recirculation system	5		7
Vacuum system	1		1
Additional power required, Phase II		133	161
Power required for the spray vessel		111	134
Lighting		0	0
Monitoring and controls		0	0
Manipulator	0		
Tundish heating		0	0
Gas heating		100	120
Exhaust/filter/recirculation system	10		14
Vacuum system	0		0
Power required for the pour tube		22	26
Pour tube heating	0	20	24
Lighting		1	1
Monitoring and controls		1	1
Total power required		234	281

5. SUMMARY COST ESTIMATE

A preliminary cost estimate was prepared to design, build, and install the Intermediate Facility in the H-1 Foundry at the Y-12 Plant. Because of the preliminary and uncertain nature of some details of this facility, a 50% contingency was applied to the estimated procurement costs, and a 30% contingency was applied to all other portions of the estimates. The appendix is a summary of this cost estimate.

APPENDIX C

Appendix C

PROJECT SYNOPSIS

**OSPREY THERMAL SPRAY PROCESSING
OF
DEPLETED URANIUM**

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EXECUTIVE SUMMARY

Currently, the Department of Energy-Office of Technology Development (DOE-OTD) is examining waste minimization of depleted uranium manufacturing at the Y-12 Plant in Oak Ridge, Tennessee. One of the activities underway is a study to thermally spray non-uranium materials to near-net shapes for development of a process system which will eventually spray uranium. Because of these activities and the Y-12 expertise in specialized DU processing work, this proposal will use the Y-12 facility as a point of reference for the development of an intermediate process system to spray depleted uranium (DU).

Large diameter cylindrical structures can be directly fabricated from DU materials using the Osprey thermal spray process. The monolithic structures provide gamma shielding in the transportation cask for the multipurpose canister (MPC) which is currently being developed by the Department of Energy (DOE) for storing, transporting, and disposing of high level radioactive waste materials. The same Osprey process is suitable for fabrication of the large diameter DU disks which are used as gamma shielding end plugs for the MPC. The Osprey process offers substantial fabrication cost savings and is proposed for fabrication of a monolithic structure.

The proposed innovative application for the Osprey process is especially profound, as fabrication of a monolithic structure for gamma shielding on the transportation cask is not possible with existing DU fabrication capabilities. In addition, currently proposed methods to fabricate the DU shielding employ standard fabrication methods. This scheme requires the gamma shield have a segmented design, requiring multiple fabrication and machining steps and complex assembly methods that must meet exacting tolerances. The Osprey fabrication process precludes many of the fabrication issues that encumber the proposed fabrication scheme.

As an optional fabrication technique, the inside and outside surfaces of the DU cylindrical shield can be sprayed with materials (such as stainless steel) for cladding purposes. The process can be sized to spray an entire 58 ton gamma shield in 12 hours (based on an 176 lb/min deposition spray rate). The Osprey process system can also accommodate spraying batch loads in order to use existing vacuum induction melt furnaces at the Y-12 facility in Oak Ridge, Tennessee. Using a batch approach, 24 reloads of the large induction melt (VIM) furnaces would be required to produce a shield 75 inches in diameter by 3 inches thick by 18 feet long. Production rates using the batch process would vary from one shield every two weeks to one shield every four weeks (dependent upon on the number of loads sprayed per day).

The Osprey process was developed in the early 1970's through the 1980's and has been licensed in the United States, Germany, Sweden, and Japan. The largest production plant built to date is the Babcock and Wilcox system which is designed to spray 33 inch diameter tubes, 15 feet long for the United States Navy.

The Osprey process is well characterized and is routinely used to fabricate large diameter tubes several inches thick by 25 feet long that have less than 1% porosity. Process versatility includes demonstrated commercial capabilities to produce a broad range of aluminum alloys for aircraft applications, copper alloys and composites, numerous hard to produce special high alloy steels, superalloys such as inconels, nimonics, hastelloys, Stellites and intermetallics, also for aircraft service. Consequently, it is anticipated that the Osprey process will prove to be well suited for the production of DU gamma shielding.

A breakdown of estimated costs for an intermediate plant to spray large diameter cylinders for the transportation cask and end plugs for the MPC is provided. The estimated cost to install an Osprey plant at a DOE facility, such as the Y-12 Plant in Oak Ridge, is \$16 million with an uncertainty of 25%, and allows for a production rate of one shield per month. Although cost estimates for the currently proposed DU gamma shielding fabrication process are not available, a comparison of the fabrication techniques indicates there may be significant cost advantages to the Osprey process over existing processing methods.

By using the Osprey process for the production of gamma shielding, it is believed that DOE can be provided a cost-effective method of producing an integral component for the MPC and transportation cask. Fabrication of the gamma shielding will allow DOE to comply with the Nuclear Waste Policy Act of 1982, and 1987 amendments for transporting nuclear materials to a national repository for spent nuclear fuel.

1. INTRODUCTION

Disposing of the long-lived, radioactive by-products of nuclear power plants is a problem that has tasked the industry for its 40-year history and to date, no nation has established a permanent disposal site for its radioactive wastes. All the high-level waste from nuclear power plants consists of spent uranium fuel in solid form, and according to the Nuclear Energy Institute (NEI), a typical nuclear power plant produces about 20 metric tons of spent fuel each year. All the spent fuel produced by the U.S. nuclear energy industry to date would cover an area the size of a football field to a depth of about three yards. Currently, spent fuel is stored at nuclear power plant sites either in steel-lined concrete vaults filled with water or in above ground steel or steel-reinforced concrete casks.

According to the Nuclear Waste Policy Act of 1982, and amendments in 1987, the Department of Energy (DOE) is required to set up a national repository for the permanent isolation of the industry's spent nuclear fuel by January 31, 1998. In 1987 Congress designated Yucca Mountain, Nevada, as the only potential repository site to undergo full-scale suitability studies. After several law suites with the state, which at first refused to issue the permits to DOE for drilling boreholes, digging trenches, and other such work, studies finally got underway in March 1992. Assuming no further delays, and if the NRC issues a construction license for the facility, DOE could start accepting nuclear waste in 2010. By then, however, it is expected that nearly 80 of the nuclear power plants across the country will have run out of on-site storage capacity -- absent state and local permission to expand their storage space -- the plants will have shut down and possibly be decommissioned before their 40-year license's expire.

Already, six nuclear power plants have run out of storage space for spent fuel rods in their on-site, continuously monitored, water-filled concrete vaults or containing pools, and a few have begun storing their nuclear overflow in above-ground, concrete casks. These dry-type casks are being allowed in some cases provided the utility eventually moves the casks to another site and pursues other energy sources. How the casks will be transported is another question.

DOE is currently evaluating a design for the multipurpose canister (MPC) and transportation cask that could be used for storing, transporting, and disposing of spent nuclear fuel. The new design potentially offers considerable standardization, simplification, and cost savings for both utilities and the federal waste management system. They could possibly be used as an interim solution to the storage problem until a repository site has opened -- provided the physical and political problems are overcome. A request for proposal (RFP) for the design of the MPC and transportation cask has already been issued and a contractor has been selected to design the canister. Typically, the canister must survive a 30-foot drop onto a flat unyielding surface; a 40-inch drop onto a vertical steel rod; exposure to a 1475°F temperature for 30 minutes, and maintain integrity when submerged under 50 feet of water for eight hours.

The containers of spent nuclear fuel will be transported from nuclear power plants to storage and disposal facilities either by rail or by truck. Currently, transportation casks used to ship high-level waste typically have walls several inches thick, with shielding materials sandwiched between outer and inner shells.

This paper proposes a fabrication method that uses a well developed and characterized commercial thermal spray process to produce monolithic gamma shielding structures and end plugs from depleted uranium (DU) for the MPC and the transportation cask.

2. OPPORTUNITY

2.1 Identification of Need -- Technical

By using DU as a shielding material on the MPC and transportation cask, two problems can be solved: 1) the thickness of a DU shield is less than other shielding construction materials such as stainless steel which increases capacity of the MPC; and 2) storage and monitoring of DU or uranium hexafluoride (UF_6) owned by DOE would be reduced.

Current DU manufacturing facilities cannot produce a monolithic cylinder for the MPC and several fabrication alternatives have been proposed. The fabrication limitation is due to current equipment capabilities of DU manufacturers. For example, limitations at the Y-12 plant are the size of the vacuum melt induction furnaces (VIM's) and the rolling mill. One alternative that could be done at the Y-12 is to fabricate the cylindrical gamma shield in segments (similar to construction of a wood barrel). A second alternative that has been proposed is to roll DU billets into rings and then weld the rings together. Both approaches are feasible, but would be extremely costly and time consuming and both processes generate waste streams. Regardless of the fabrication technique selected to fabricate the gamma shielding, a complete manufacturing approach from cradle to grave will have to be developed.

Additionally, DU disks, 6 feet in diameter by 3 inches thick, must also be fabricated for end plugs on the MPC. Cladding of the DU is another option to be considered. Stainless steel (or other materials) could be clad on the inside and outside of the gamma shield to achieve a polished finished.

A possible solution to existing DU fabrication facility limitations, such as at the Y-12, can be addressed by thermally spraying monolithic structures to their final dimensions using the Osprey process. The Osprey process is a technology that has been producing a wide range of tubular products from a large selection of metals and has been commercially developed in more than 20 applications. The process is essentially a rapid solidification technique for direct conversion of liquid metal into tubular form making it possible to manufacture tubes without hot working. Osprey offers a reduced number of operational steps to produce tubular products. The Osprey process has also produced billets which have direct application for fabrication of large diameter DU disks. *In fact, a single Osprey system is proposed to fabricate the large diameter DU gamma shield cylinders and end plugs for the MPC.*

2.2 Identification of Need -- Regulatory

The Nuclear Waste Policy Act of 1982 and its 1987 amendments established a framework for ensuring the safe interim storage, transportation, and permanent disposal of high-level radioactive waste. The act as amended charges the DOE with the following:

- Locating, building, and operating a deep-mined, geologic repository for high-level nuclear waste.
- Locating, building, and operating a Monitored Retrievable Storage (MRS) facility for short-term, interim storage of spent fuel.
- Developing a transportation system that safely links U.S. nuclear power plants, the MRS, and the permanent repository.

To comply with the Nuclear Waste Policy Act of 1982 to locate and build a permanent high-level waste repository, The DOE originally selected nine locations in six states that met the criteria for consideration as potential sites. In 1985, DOE selected three sites for further, intensive scientific study: 1) Yucca Mountain, Nevada; 2) Deaf Smith County, Texas; and 3) Hanford, Washington.

However, in 1987, Congress amended the Nuclear Waste Policy Act and designated Yucca Mountain as the only site to undergo further scrutiny. The "site characterization" is expected to last 10 years, cost 6 billion, and involve more than 2000 scientists, engineers, and technicians. The site characterization study focuses on four key subjects: earthquakes, volcanoes, and water movement through rock. The forth focus is the performance of the canisters (which contain the waste) over long periods of time.

The Monitored Retrievable Storage (MRS) facility called for in the 1987 amendment is intended to provide short-term, continuously monitored, above ground storage for spent fuel until the permanent repository is ready. The amendment established the position of the Nuclear Waste Negotiator whose role was to identify a state or American Indian tribe willing to host an MRS facility.

The negotiator's office established guidelines for interested states and tribes to obtain a DOE grant that would help them study the feasibility of an MRS in their jurisdiction. In August of 1993, two tribes announced they were prepared to begin negotiations with the federal government; however, in October of 1993, Congress terminated further funding. The Mescalero Apache Tribe in New Mexico sought and received funding from nearly three dozen utilities across the country to pursue construction of an MRS facility on its reservation. The governor of New Mexico and the legislature opposed this project; however, it's uncertain that the governor or the legislature has any authority to stop the Mescaleros from building and operating a storage facility, because the tribe is a sovereign nation. The issues associated with the location of a short-term and a permanent repository are not yet complete and legislation is still on-going.

In addition to the Nuclear Waste Policy Act of 1982 and its amendments in 1987, the Environmental Protection Agency has adopted a requirement for a 10,000-year time frame for assessing the performance of any proposed permanent, underground repository for spent fuel. In order for the DOE to meet the 10,000 year requirement, two approaches have been considered. The first approach is to prove that natural barriers assisted by a relatively short-lived waste package can meet the 10,000 year requirement. The second approach is to design a robust waste package that can assist the natural barriers in meeting the 10,000 year requirement.

2.3 Identification of Need -- Market

In order to support the Nuclear Waste Policy Act for transportation to a permanent repository and for transportation to a Monitored Retrievable Storage (MRS) facility, DOE is evaluating the MPC design. In a pre-conceptual design, DU was shown as a potential material for the MPC end plugs and the transportation cask gamma shield. The advantages of using DU for end plugs and the gamma shield are as follows:

- Highest density for greatest absorption capacity;
- Maximum payload for package size and weight;
- Added robustness for transportation and handling;

- Low thermal expansion for low thermal stress designs;
- Large safety margin against melting in a fire; and
- Good thermal conductivity for decay heat removal and transfer.

Using the Osprey process to fabricate the large cylindrical monolithic shielding structure and end plugs on the MPC, is a cost-effective method for producing the DU components.

Initial estimates indicate that 8000 end plugs and 200 reusable gamma shields will be fabricated in the U.S. Additional markets may also exist over seas in Japan, the United Kingdom, and France which all have nuclear power programs.

3.0 OSPREY PROCESS DESCRIPTION

3.1 Osprey Process Description Summary

The Osprey process is a rapid solidification metallurgical forming technology capable of generating semi-finished and compound products in the form of billets, tubes and flats, in a single integrated operation. A typical tubular product is shown in Figure 1.

The process comprises the steps of providing a source of molten metal, converting the metal into a spray of fine droplets by gas-atomization, and directing the droplet at collecting surfaces where they recombine to form a high density, semi-finished product, or preform. This preform can either be used in the as-sprayed condition or be subsequently processed by conventional metal working operations.

Figure 2 shows the fabrication process for large stainless steel tubes as practiced at AB Sandvik Steel plant in Sandviken, Sweden. The production of tubes (up to 16 inches in diameter with wall thicknesses of 2 inches and lengths of 30 feet) is achieved by atomizing a stream of molten metal and collecting the resulting spray on a rotating/advancing mandrel.

Figure 1. Typical tubular product from Osprey process. The outer diameter and ends of the tube have been machined.

THE OSPREY TUBE PROCESS

Sandvik Plant for 1 tonne melts Tube size 8m x 0.4m Ø

Spray Deposition rate
80kg/min.

Inspection of as sprayed tube

Stainless steel deposit after machining

Figure 2. Fabrication process for large stainless steel tubes as practiced at the AB Sandvik Steel plant in Sandviken, Sweden.

The conditions of the deposition are depicted in Figure 3. These conditions are governed in such a manner that a layer of semi-solid/semi-liquid metal of controlled thickness is maintained at the surface of the preform throughout the deposition operation. Rapid solidification occurs during flight and convective cooling after deposition on the surface resulting in reduced segregation and a fine homogeneous microstructure. Due to the existence of the constant layer of semisolid/semisolid metal at the surface of the preform throughout the deposition operation, fully dense preforms with homogenous microstructure, irrespective of preform thickness, can be manufactured. The preform can be final machined or cold rolled if desired.

3.2 Benefits of Process

Rapid solidification of the sprayed droplets result in preforms which are characterized, by a fine, uniform grain-size without macro-segregation, irrespective of the thickness of the deposit. Consequently, the process can be used to manufacture products in a wide range of alloys and is particularly advantageous for processing alloys which are difficult, or impossible, to hot-work by conventional ingot metallurgy. Furthermore, the process can be used to develop new alloy compositions and to produce reinforced metal-matrix composites (MMC) by the simple introduction of ceramic particles into the atomized spray during the deposition operation. Compound (or clad) products can be also formed by spray-depositing and bonding an alloy (and/or MMC) onto a preheated tube, bar, strip, etc., with then remains as integral part of the product during subsequent processing.

Economic benefits arise from the significant reduction in the number of process operations compared to both ingot and powdered metallurgy (PM) technology.

3.3 Osprey Process Metallurgy

The Osprey process starts with a liquid metal source and after gas atomization and deposition, results in a product with a fine equiaxed grain size without macro segregation. The control of the deposition is the heart of the Osprey process.

By altering the gas atomizing and deposition conditions, the process can be controlled to produce microstructures from a typical cast structure to actual powder production. The flexibility of the process is such that a useful operation window can be identified of any given shape and for each part of the shape. By controlling operating parameters, the ideal structure can be obtained throughout the product, independent of the position with the preform.

The microstructure of the deposited slurry of metal will be a mixture of semi-solid droplets (including dendrites), liquid droplets and fully solidified particles. Because of the velocity of the impacts (300 to 600 ft/sec) the surface will be very turbulent and well stirred. The rate of addition of particles to the surface is an important feature to the success of the Osprey process over others.

Figure 3. Diagram of Osprey deposition process.

The high rates of material deposition are responsible for maintaining a partially liquid region on the metal surface, which promotes the mixing and remelting processes that produce a very homogenous, dense metallic deposit.

The Osprey process produces a fine structure, by annealing out any preexisting dendrites, using the sub-grains contained in the well-mixed surface as nucleation sites for the final solidification of the remaining liquid. Subsequent layers deposited on the top surface may cause remelting of the segregated grain boundary layer leading to a more uniform grain size as the smaller crystals disappear.

Figure 4. Typical microstructure obtained from Osprey process for Stellite 6 material.

The solidification rate is rapid for particles in flight and on deposition, but very slow after deposition leading to a homogenous structure which rarely exhibits the remains of the dendritic or cellular growth structure of the powder particles due to a liquid phase annealing period. Production of various semi-finished shapes with a good microstructure is possible by careful control of the deposition condition, and an understanding of the solidification mechanisms. A typical microstructure is shown in Figure 4.

3.4 Osprey Applications and Process Development Status

The Osprey process is a mature technology that was initially developed in the early 1970's. The process has attained international acceptance and is currently utilized in numerous commercial metal processing facilities worldwide. This versatile liquid spray technology is used over a broad range of applications, which includes powder metals production, preforms of various shapes, e.g., disks, billets, tubes, rings, metal matrix composites (combination of metals and ceramics) and the production of composition materials. The metals used include stainless and special steels, copper alloys, aluminum alloys, super alloys and titanium. The diversity of applications for these materials include automotive, petrochemical, electronic and aerospace fields. Additional discussions of Osprey applications are provided in the Appendix A.

Osprey's technology licenses involve the sale of comprehensive patents, know-how, training and specialized equipment. Highly customized plant and equipment are designed and constructed to meet specifications and requirements provided by the customer.

4. PROPOSED APPLICATION OF PROCESS

Currently, a depleted uranium manufacturing waste minimization program sponsored by the DOE-OTD is investigating and developing a technology for DU manufacturing to produce near-net shape castings that have high density and low porosity at the Y-12 Plant in Oak Ridge. Development will include a conceptual design of the process and the hardware for the process. The process under consideration to thermally spray DU is known as the Pressure Controlled Atomization Process (PCAP). The PCAP is a new thermal spray process that atomizes molten materials in a De Laval converging-diverging nozzle. The system has demonstrated high density capabilities at low deposition rates on developmental pilot-scale equipment and is being considered as a means for producing monolithic gamma shielding structures for the MPC. However, the process would have to be scaled up from cylinders that are 3 inches in diameter by 4 inches in length by 0.25 inches thick to cylinders that are 5-6 feet in diameter by 18-20 feet in length by 2-3 inches thick (a factor of 50 times in diameter). Additionally, the atomizing nozzle contacts the liquid material and is a significant problem area for spraying a reactive material such as depleted uranium.

By comparison, the proposed system using the Osprey process has gas atomizers that do not contact the liquid metal. Only the tundish would come into contact with the liquid uranium and it can be handled exactly like a graphite crucible in a VIM furnace. As envisioned, the Osprey process can produce a monolithic structure fabricated from DU. If required by the MPC design, the gamma

Figure 5. Cross-section of layered gamma shield envisioned for the transportation cask.

Using a density of 1200 lb/ft³ and a deposition efficiency of 85%, DU shielding approximately 1/4 inch thick can be produced from each 5000 lb load for an 18 foot length (based on a 72 inch starting

shield can be clad inside and outside with stainless steel or other acceptable materials. Figure 5 shows a cross-section of the layered gamma shield for the MPC. The process would start by sizing a stainless steel mandrel or collector to the inside diameter desired for the finished shield (Note: the mandrel thickness would be sized to support the load of the sprayed DU). The large diameter stainless steel mandrel would then be mounted horizontally in a manipulation device. Preheating and spraying the mandrel are the next steps, however, it is not clear at this time if the DU shield will be produced by continuous spraying or spraying a single 5000 lb load the entire length of the mandrel and then reloading and spraying until the desired thickness has been achieved.

diameter). Using a typical spray deposition rate of 176 lb/min, a 5000 lb load would be sprayed in 30 minutes with a twin-scan atomizer arrangement. At this rate, a 3 inch thick shield would be produced in 24 reloads of the large furnace and based on past operating history at the Y-12, two loads, or a total of 10000 lb can be melted a day. This results in a production rate of one gamma shield every 2 weeks; or one gamma shield every 4 weeks if only a 5000 lb load is sprayed a day. Whether continuous or intermittent, the Osprey process has the capability to produce the gamma shield for the MPC and the transportation cask. Once 2-3 inches of DU have been sprayed on the full length of the stainless steel mandrel, the mandrel is removed from the sprayed DU cylinder by a broaching operation. With the stainless steel removed the ends of the as-sprayed cylinder are cropped and can be recycled as feedstock for the production of the next gamma shield. Some post spray work may be necessary depending on the design requirements for mechanical properties and tolerances of the MPC design. If cladding is required by the new design, the process would start as before by sizing a stainless steel mandrel or collector to the inside diameter desired for the finished shield. The mandrel would then be mounted horizontally in a manipulation device, preheated, and sprayed. Once 2-3 inches of DU have been sprayed on the full length of the stainless steel mandrel, a final coating of stainless steel will be applied to the DU to form a stainless steel shell on the gamma shield. Again, some post spray work may be conducted depending on the design requirements for mechanical properties and tolerances of the MPC. Since the inside and outside are stainless steel, no direct machining of DU would be required. Depending on the design tolerances and specified surface roughness, the Osprey process may be able to produce a finished product with final machining required only on the stainless steel ends. Figure 6 shows a cross-section of the layered shield design.

The fabrication of large diameter disks for end plates on the MPC can also be manufactured with the Osprey process. In fact, the disks can be manufactured with the same system used to produce the gamma shield. Two processing techniques are available to process the end plugs for the MPC. The first option can be accomplished by starting with a DU disk manufactured by existing processes to the largest diameter possible with current equipment capabilities. The conventionally formed DU disks are mounted in the manipulation device in the spray chamber and the outside edge of the disk is preheated and sprayed with DU to the desired width and diameter. The second option is to produce a complete DU disk using the Osprey process. This would be accomplished by starting with a small solid diameter mandrel of DU. As with the large diameter disk, the surface would be preheated and then sprayed to the desired size (width and diameter). Using the Osprey process for either option requires finish machining for the end plugs. To maintain the spray distance during operation, the manipulation device will move vertically as it rotates. A photograph of liquid metal being sprayed onto a preform is shown in Figure 7.

Figure 6. Cross-section showing technique for finishing ends of gamma shield.

4.1 Processing System Description

The major components in the Osprey system for spraying DU are:

- Spray system which consists of an entrance, deposition, and extraction chambers.
- Vacuum induction melting furnace with bottom pouring capabilities.
- Tundish and atomizer for directing and controlling the deposition rate of the spray process.
- Mandrel and manipulation device for horizontal and rotational movement.
- Overspray collection and injection system.
- Process control system

Figure 7. End view of a large diameter tube being formed by the Osprey process -- in progress.

Processing a gamma shield starts with the fabrication of a stainless steel mandrel machined by conventional means to the finished inside diameter required by the MPC design. After fabrication, the mandrel is loaded and connected to the manipulating system which provides both horizontal and rotational motion. The mandrel and manipulation device are then moved and properly positioned into the spray chamber. The chamber is sealed and a vacuum system evacuates the chamber to the desired pressure. The chamber is then backfilled with argon and the chamber returns to atmospheric pressure. Next, DU is loaded into graphite crucibles coated with an Y_2O_3 (yttria) wash and then the crucible and DU are loaded into the bottom loading vacuum induction melt furnace (VIM). Once loaded, the VIM is positioned and connected to the tundish assembly above the Osprey atomizing system (the tundish assembly is isolated from the main spray chamber allowing the VIM furnaces to be removed and reloaded for batch spraying).

The VIM furnace is evacuated, purged with argon, and then heated to melt the DU. Simultaneously, the stainless steel mandrel is preheated as the VIM furnace heats up. Once at the desired operating temperature, pressures for the argon gas

atomizer and the movement of the spray mandrel are controlled from pre-programmed software. The isolation valve between the spray chamber and the tundish assembly is then opened and the plug in the bottom pouring graphite crucibles is removed and liquid DU pours into the tundish assembly. The argon atomizing gas directs the particles of atomized DU onto the surface of the rotating mandrel to form a coating. The process continues until a 1/4 inch thick coating has been applied to the 18 foot length of the mandrel. When the 5000 lb charge from the VIM furnace has been sprayed, the chamber is isolated from the tundish assembly to maintain an inert atmosphere in the spray chamber. The tundish and VIM furnace cool to room temperature and the furnace is removed and reloaded for the next spray. The process continues until the desired thickness of DU has been achieved. The

Figure 8. Schematic of envisioned Osprey processing system.

The envisioned Osprey processing system is depicted in Figure 8.

If cladding is required on the DU gamma shield, stainless steel or other cladding materials could be loaded into the VIM furnace, melted and transferred to the tundish and atomized and sprayed onto the outside of the DU (coating thickness for the stainless steel will depend on requirements for final machining on the outside diameter). When the spray is complete, the layered gamma shield moves into the extraction chamber and is isolated from the deposition and entrance spray chambers and the layered product is removed from the spray system.

The desired physical properties of uranium produced by the as-sprayed product are shown in Table I.

TABLE I. Physical properties of uranium.

	Yield Strength (ksi)	Tensile Strength (ksi)	Percent Elongation
Unalloyed Uranium (as Cast)	30	61	6
Unalloyed Uranium (wrought)	33	128	20

4.2 Technical Comparison to Alternative or Existing Methods

Using existing DU processes, such as at the Y-12 plant, to fabricate the gamma shield presents significant production challenges. Two approaches have been proposed to produce the shielding; however, both casting or wrought processing of depleted uranium would result in segmented shields leading to fabrication and design issues such as:

- Material specifications
- Joint configuration and joining process and associated problems (welding etc.)
- Assembly and handling of segments
- Joint efficiencies for 100% gamma attenuation
- Final assembly of shield and handling

Producing a segmented cylindrical shield using casting process capabilities requires numerous unit operations to produce the segment. Figure 9 shows the number of processing steps required to produce wrought uranium products with current Y-12 process capabilities. If the cost of assembly and final machining is factored in, it could very well exceed the cost of fabrication of all the segments. The major steps required to cast a single segment includes loading the charge, vacuum induction melting, pouring and casting, cleaning, sawing excess, milling the edge to fit in the cylindrical assembly, inspection after machining, and then final assembly. Preliminary designs for the segmented shield would require six segments to form a 75 inch diameter shield with each segment having a 6 foot length. Therefore, a total of 18 segments would be required to fabricate a 75 inch diameter by 18 foot long shield. DU waste streams are generated during cleaning, cutting, machining, and final assembly.

The same problems exist for producing wrought DU segments except there are more unit operations. Major steps in producing wrought DU includes: loading a charge, vacuum induction melting, pouring, salt bath preheating, processing on a rolling mill, cutting, salt bath preheating, forming the segment to shape, cleaning the segment, milling the edge to fit in the cylindrical assembly, inspection after machining, and then final assembly.

In either case, the cost of production and the cost of disposing waste streams generated in producing the DU shield would be significant.

4.3 Design and Process Issues

Design and process issues for using the Osprey process to produce the monolithic structure of DU are:

- Material specifications
- Final dimensional tolerances

- Overspray
- Porosity and effect on gamma attenuation
- Argon gas for atomization and environment control
- Non-contact atomizing nozzle
- Multi-atomizer configuration

The main design issues associated with the proposed Osprey process are overspray, porosity in the deposit, size of the melting system, and recycling of argon atomizing gas. Handling overspray can be addressed with several different methods: 1) the deposition chamber can be sealed and the DU overspray can be oxidized in a controlled manner; 2) overspray from the process can be recycled back into the melt; and 3) overspray in the deposition chamber can be continuously purged with argon for the production of several shields and then overspray material can be oxidized on an as needed basis. 4) the overspray can be collected and inject as a powder back into the spray. Osprey currently uses this approach for injecting ceramics for metal composites.

Porosity in the deposit and resultant mechanical properties of the coating can be addressed once the system has been installed by adjusting the process parameters to minimize the porosity in the coating. The Osprey process is particularly adept at providing high density products. In fact, Osprey products are used for turbine rings in the aircraft industry because of their ability to produce defect free materials.

The size of the melting system needs to be determined since production rate and size of the argon gas recycling system are dependent on the amount DU material to be sprayed.

Because the Osprey process relies on a layer of semi-solid/semi-liquid material on the surface of the product being formed to produce the high density coatings, multi-atomizers will most likely be required for the large diameter cylinder and end plugs. This requirement is simply based on the fact that the semi-solid/semi-liquid layer will cool by the time it makes a 1 revolution. Osprey has the in-house capability and know-how to model the spray deposition process to determine the number of atomizers required for spraying DU. *A major benefit of the Osprey process is that the atomizer does not come into direct contact with liquid material; thereby, eliminating nozzle erosion and reaction problems.* The only portion of the Osprey system exposed to the liquid uranium would be the tundish feeding system. Because of the high reactivity of liquid uranium, the tundish will have to be fabricated from a material that resists reaction with liquid uranium. A suitable solution is to use graphite crucibles with an yttria coating that are easily removable. Based on operating experience at the Y-12 using the VIM furnaces, estimated time between yttria application will ensure the survival of tundish. If a batch mode of operation is selected as the ideal method to fabricate the DU products, the bottom pouring furnaces can pour directly into the atomizer and preclude the use of a tundish.

The last area of consideration for using the Osprey process is how to handle argon in the VIM furnaces. This will be accomplished using the same approach Howmet, Inc. uses in their argon filled VIM furnaces.

Figure 9. Current processing steps for producing wrought uranium.

5. ENGINEERING DEVELOPMENT PROGRAM -- TECHNICAL DESCRIPTION

5.1 Technical Issues

The engineering development required to use the Osprey process for the fabrication of large diameter gamma shields is presented below. As discussed previously, the following technical issues need to be addressed:

- Handling overspray from the process. Options include controlled oxidation in the deposition chamber after cylinder fabrication has been completed; recycling overspray into the liquid DU in the tundish; controlled oxidation in the deposition chamber after fabrication of several cylinders, or injecting the overspray powder back into the spray.
- Producing the DU cylinder with a single melt (30-60 ton system) vacuum melt furnace, sizing a vacuum furnace to complete the cylinder in four batch loads; or retrofitting the existing VIM furnaces at a DOE facility for single or multiple melts.
- Optimizing the process for a maximum deposit porosity of 1-2%. This would first be addressed through modeling of the deposition process and secondly through five or six optimization spray runs.

Because of the specialized application of the gamma shield, an important aspect of the engineering development program will be to identify and coordinate information between Spray Manufacturing Systems, Osprey, the Y-12 Plant, DOE, the MPC designer, and other parties involved in the inspection and/or development of equipment.

5.2 Technical Approach

The technical objectives of this proposal will be in a three phased approach. Phase I will be to demonstrate the capabilities of the Osprey process to spray high density materials using the surrogate alloy WFeC. This phase will quantify coating characteristics such as porosity and microhardness. Testing results will also provide operating information for the gas usage, deposition efficiency, and feasibility of spraying 1/4 inch thick coatings to build up to a 3 inch thickness using a batch process. The testing is to be conducted at the Osprey laboratory as a developmental program under a teaming agreement between Spray Manufacturing Systems, Inc. and Osprey Metals, LTD.

Phase II is the design, fabrication, and installation of an intermediate Osprey spray plant in a DOE facility, (such as the Y-12 facility). This intermediate facility will be designed to spray intermediate diameter cylinders for the transportation cask and end plug disks for the MPC. The reason for this approach is to minimize the engineering required to demonstrate the process for spraying DU. Phase II work will provide the needed information to control the process for DU spraying and will also test controlled oxidation of overspray. Testing will also be conducted for reheating and spraying DU on material previously sprayed. While testing is being conducted during Phase II, engineering design work can begin for Phase III work.

Phase III work involves the design for an Osprey plant so that a licensed commercial manufacturer can produce the large diameter cylinder shields and end plug disks for the MPC.

5.3 Technical Development Tasks

The following tasks identify the direction of the Phase I, II, and III work associated with producing a system to fabricate cylindrical gamma shields for the transportation cask and large diameter end plugs for the MPC.

PHASE I:

Task 1. *Osprey Demonstration of Spraying High Density Materials*

A detailed program for the production of tubes formed from WFeC alloy (or other high density material) will be developed to characterize the metallurgical properties of high density as-sprayed material.

Task 2. *Prepare Final Report for Spraying High Density Materials*

A final report from the investigations of Task 1 will be prepared and would include experimental procedure, testing results, and operating parameters for spraying high density materials.

Task 3. *Conceptual Design*

A conceptual design of the proposed system will be provided and includes design issues for handling overspray, recycled argon, multi-atomizers, melt size, and sizing and manipulation.

PHASE II:

Task 4. *Design, Fabrication, and Installation of Osprey System at the Y-12 Plant for Thermally Spraying Intermediate Sized Cylinders and Large Diameter End Plugs for the MPC*

Functional requirements for the system will be identified and preliminary and final designs provided. Engineering drawings will be provided as well as design reviews. Equipment would be fabricated for a system to spray intermediate sized diameter cylinders for the transportation cask and end plugs for the MPC. Equipment will include the argon recycle system, deposition chamber, vacuum melt induction furnace, part manipulator, and atomizing nozzle and tundish. The entire plant will be designed to accommodate spraying large diameter cylinders in Phase III. Installation would be coordinated with personnel from the Y-12 and would use existing melt furnaces.

PHASE III:

Task 5. *Design of an Osprey System for Thermally Spraying Large Diameter Cylinders and End Plugs for the MPC*

Functional requirements for the commercial capability to spray large cylinders and end

plugs will be identified and preliminary and final designs will be provided. Engineering drawings will be provided as well as design reviews. Based on the results of the Phase II (Intermediate Facility possibly at the Y-12), equipment would be designed and would include: an argon recycle system, deposition chamber, vacuum melt induction furnace, and atomizing nozzle and tundish. Furnace sizing and process operation will be dependent on the results of the design review's and Intermediate facility testing.

6. ENGINEERING DEVELOPMENT PROGRAM COST AND SCHEDULE

The following schedule is submitted for Tasks I, II, and III. Engineering development costs will

include technical and management activities to spray the surrogate sample preform at the Osprey facility and to conduct a preliminary design study for the process application, including plant layout and full cost estimate. This work is estimated at \$500,000 and would take approximately 10 months to complete.

7. PROCESS ECONOMICS

Costs for implementation of the process include plant design, construction, start-up, operations and license and royalty fees are provided to establish estimated costs for the gamma shielding produced using the Osprey process.

The cost estimates provided in this section have been scaled up from a plant designed by Osprey, Mannesman Demag Huttentechnik, for ABB Calidus plant, for which a detailed design has been completed. The ABB plant will manufacture stainless and nickel-based alloy tubes up to 33 inches in diameter, with wall thicknesses of 4 inches. The total part weight will be 3 to 4 tons. The metal dispensing system for this plant has a capacity of 5 tons. The Osprey plant proposed herein is extrapolated from this unit and includes factors that take into account: 1) larger sized product, 2) the product is a clad or composite structure and 3) that spraying DU requires substantial increases in

product containment, which require added safety precautions be designed into the system. It should be noted that no review of this conceptual design has been provided by Y-12 personnel, which is considered a crucial ingredient for accurate estimating. Consequently, the cost estimates provided at this stage have a high level of uncertainty and are provided for scoping purposes only. Since the size of the melt system is unknown the processing rate of the system is variable; however, if a single melt system was used, an entire 58 ton cylindrical shield could be sprayed in 12 hours. Including required turn around time for cooling, part removal, DU reloading, and melting a complete large diameter gamma shield could be produced every two days.

7.1 Capitalization Costs

Capitalization costs include license and know-how fees, along with design, component and fabrication costs. Up-front license fees are approximately \$500,000. The gas atomizer and control system is estimated at \$2 to \$4 million; the spray chamber, complete with preforming mechanism, collector, product support rollers, exhaust gas treatment/recirculation (overspray powder) and associated control systems is estimated at \$9 to \$11 million. It is proposed to retrofit the existing vacuum melting/dispensing DU systems at a DOE facility. Cost estimates to accommodate these modifications have not been included in our estimate. A 15% design and project management fee should be added to the above costs.

7.2 Operational Costs

Operational costs include royalties, start-up costs (including on-site training and supervision of commissioning), manpower and annual maintenance costs. Royalties are specified to be 4 to 10% of the product selling price, with an annual minimum of \$120,000. Start-up costs included the normal equipment SO tests, plus approximately 10 test runs to fully commission the facility. It will require 5 to 10 runs to optimize the sprayed DU metallurgy for the tube preforms and 5 to 10 runs to qualify a procedure for spraying flat disks. The plant can be operated with 3 to 4 people. Annual maintenance costs are 5 to 10% of the total equipment costs. The estimated costs for on-site training and supervision of commissioning range from \$400,000 to \$500,000.

7.3 Cost Summary

In summary, the facility fixed costs through start-up are estimated to be between \$11.3 million and \$16 million, not including retrofit of the existing vacuum melting/dispensing system at a DOE facility. A level of uncertainty of 25% should be used on this upper number for budget purposes. This uncertainty factor allows for the number of safety issues and unspecified details that will arise during a preliminary design, and that is not accounted for within the scope of this study. Operational costs include royalties, energy, purge gases, materials (stainless material, preforms and DU) maintenance and staffing. These costs were not annualized or specified on a piece-part bases for this analysis, but were listed to give a ROM cost estimate for operation of the proposed plant.

APPENDIX A

OSPREY COMPANY BACKGROUND AND PROCESS APPLICATIONS

OSPREY COMPANY BACKGROUND AND PROCESS APPLICATIONS

In this Appendix, additional background on the Osprey Company and its development capabilities are summarized. A listing of Osprey process applications elucidating the process versatility and its commercial impact on metals production is also provided. The Appendix includes a listing of Osprey Process Preform production applications. The list emphasizes process acceptance in the metals producing industry worldwide which demonstrates its maturity in the commercial production of high-quality, stock and speciality metals.

Osprey Company Background

Osprey was formed in 1974 to develop and license the Osprey Preform Process and in 1977 diversified into the development of technology for the production of gas-atomized metal powders. Osprey Metal Ltd. is a wholly owned subsidiary of Sandvik AB, Sweden.

Osprey has three main business activities:

- Spray Forming Technology -- Technology for the manufacture of spray-formed products (i.e., performs), including tubes, billets, strip and plate in a wide range of alloys, metal matrix composites and coatings.
- Powder Technology -- Technology for the production of gas-atomized powders. This business line includes the licensing of technology, R&D and commercial production plants.
- Specialized Equipment -- Process and plant design for custom preform and powder production capabilities.

Osprey spray-forming development activities are conducted at one of its own five plants explicitly used for: 1) Internal process/product development; 2) conduct of development contracts for customers; and for 3) demonstrating Osprey process operation. Each of these plants offers unique capabilities as outlined below:

- Horizontal Billet Production -- Capabilities of this pilot plant includes a 660 lb capacity, air melting furnace that is used to produce spray-formed billets up to 10 inches in diameter and 47.2 inches long, at deposition rates of 110 lb/min for high-speed steels and copper alloys.
- Compound Bar/Tue Production -- Capabilities of this pilot plan includes the cladding of a round bar up to 60 inches and 3.9 inches in diameter with high-speed steel. Capabilities include the production of spray-deposited tubes and compound material tubes.
- Non-Reactive Alloys Process Development -- The primary function of this plant is for sample production. Small billet and tubular shaped preforms can be produced in the weight range of 22 to 66 lbs, in a wide variety of materials, including copper alloys, stainless steels, high-speed steels, superalloys, Stellites, hastelloys, intermetallics, etc.

Particulate reinforced composites, e.g., MMCs, can also be produced in a wide combination of metal matrices and particulate fillers.

- Light Alloys Process Development -- Alloys which are potentially explosive in the powder form are processed in this plant. Aluminum and magnesium alloys and MMC preforms can be produced in billet or tubular form in the weight range of 6.6-55 lb are spray-formed.
- Reactive Alloys Process development -- This plant is mainly used for processing reactive alloys, such as magnesium and titanium alloys.

Commercial Applications of the Osprey Preform Process

The Osprey Preform process has been successfully adapted for the production of large spray-formed products. Existing commercial plants exist that produce billets weighing 4400 lb, 17.7 inches in diameter, and 100 inches in length. Deposition flow rates are as high as 132 lb/min. Commercial tube and ring production capabilities exist for diameters of 32 inches and lengths up to 315 inches. Material deposition rates at these facilities range from 88 to 176 lb/min.

Process versatility includes demonstrated commercial capabilities to produce a broad range of aluminum alloys for aircraft applications, copper alloys and composites, numerous hard to produce special high alloy steels, superalloys such as inconels, nimonics, hastelloys, Stellites and intermetallics, also for aircraft service.

A listing of Osprey Preform Process licences is provided below. This list provides a view on the depth of application and wide base of acceptance for commercial production of metals that this process has matured to.

Special Steels

Sandvik Steel, Sweden; Sumitomo Heavy Industries Foundries and Forgings, Japan; Sumitomo Heavy Industries, Japan; Kobe Steel, Japan; CRM, Belgium; Forded Rolls Ltd., United Kingdom; British Rollmakers Corp., United Kingdom; Special Melter Products, United Kingdom; DDS, Denmark; US Navy Sub-Licence, United States.

Superalloys

General Electric, United States; Teledyne Allvac, United States; Howmet, United States.

Aluminum Alloys

PEAK, Germany; SLM, Japan; Pechiney, France; Alcoa, United States.

Copper Alloys

Wieland, Germany; SWISSMETALWORKS, Switzerland.

Research Institutes

US Navy, United States (two plants); Drexel University, United States; RIST, Korea; Rautarukki/Oulu University, Finland.

Distribution

Custom Spray Technologies, Inc.

Watson, Lloyd

Department of Energy-Headquarters

Dionisio, M. C. (2)

Johnson, A. B.

Department of Energy-Oak Ridge

Harness, J. L.

Moore, J.O.

Lockheed Martin Energy Systems

Beck, D. E.

Churnetski, S. R. (2)

Coates, C. W.

Derrington, S. B.

Heck, J. L.

Lee, A. K./DOE-OSTI

Malinauskas, A. P.

Thompson, J. E.

Y-12 Central Files

Montec Spray Manufacturing Systems

Tierney, J. C.

MSE, Inc.

Glovan, R. J. (3)