Review and Evaluation of Metallic TRU Nuclear Waste Consolidation Methods

**D. R. Montgomery
J. F. Nesbitt**

August 1983

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**Pacific Northwest Laboratory
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ABSTRACT

A study was conducted by Pacific Northwest Laboratory to identify, evaluate, and rate consolidation methods that could reduce the volume of metallic wastes generated in a fuel reprocessing facility. Both compaction and melting techniques were rated, and each consolidation process was evaluated based on its feasibility for handling and processing the metallic wastes produced if the Barnwell Nuclear Fuel Plant were in operation. Vacuum coreless induction melting was rated as the best consolidation method for this application.

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SUMMARY

The U.S. Department of Energy (DOE) established the Commercial Waste Treatment Program (CWTP) to develop, demonstrate, and deploy waste treatment technology. In this report, viable methods are identified that could consolidate the volume of metallic wastes generated in a fuel reprocessing facility.

The purpose of this study is to identify, evaluate, and rate processes that have been or could be used to reduce the volume of contaminated/irradiated metallic waste streams and to produce an acceptable waste form in a safe and cost-effective process. A technical comparative evaluation of various consolidation processes was conducted, and these processes were rated as to the feasibility and cost of producing a viable product from a remotely operated radioactive process facility.

Out of the wide variety of melting concepts and consolidation systems that might be applicable for consolidating metallic nuclear wastes, the following processes were selected for evaluation:

- Inductoslag melting
- rotating nonconsumable electrode melting
- plasma arc melting
- Electroslag melting with two nonconsumable electrodes
- vacuum coreless induction melting
- cold compaction.

Each process was evaluated and rated on the criteria of complexity of process, state and type of development required, safety, process requirements, and facility requirements. It was concluded that the vacuum coreless induction melting process is the most viable process to consolidate nuclear metallic wastes.

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INTRODUCTION

The safe disposal of nuclear wastes is essential for the continued use of nuclear energy in the United States and abroad. In the United States, the basic goal has been to develop and use waste forms and environments that strictly limit the amount of radioactivity that can ever reach the biosphere. In pursuing the nuclear waste management goal, it will be necessary to produce acceptable waste form products for several specific wastes using feasible and cost-effective processes. The waste form process includes the isolation or solidification of that particular waste, containment, transportation, and long-term storage or disposal.

Metallic wastes are generated when spent reactor fuel is reprocessed. The reprocessing of light-water reactor (LWR) fuels typically begins with the removal of the nonfuel-bearing nozzles and end fittings from the fuel bundle assembly. The remainder of the assembly (fuel pins or tubes, shrouds, spacers, and other structural members) is sheared or cut into short lengths so that the fuel can be leached out of the tubes in an acid dissolver. The residues from the acid leach process are identified as hulls and include the short lengths of the fuel tubes or cladding, the end fittings, and assorted springs, flow channels, and other metallic fuel bundle components. The hulls constitute ~13% of the total waste volume generated in a spent fuel reprocessing facility and ~80% of the total metallic waste volume (Anderson, Carr, and Mitchell 1982). These materials have a bulk density of ~1.1 kg/L; however, this density can be increased and the volume can be reduced by a factor of six using any one of several methods.

Other contaminated metallic waste streams that will also be generated in a spent fuel reprocessing facility consist of failed or obsolete process equipment and equipment scrap. With proper facilities to reduce the size of large pieces of failed equipment and scrap, it is anticipated that a volume reduction of 10:1 could be achieved if these metallic wastes were melted.

High-level general process trash (HLGPT) is a remotely handled transuranic (TRU) waste stream. If segregated, metallic components such as failed motors,

pumps, valves, pipes, tubing, and miscellaneous metal items could be consolidated to reduce their volume. Similar metallic items will also be present in the contact-handled TRU waste separated from low-level general process trash (LLGPT).

Transport and burial of radioactive wastes is expensive. Since a major portion of these costs is a direct function of volume, there is an obvious economic incentive for volume reduction. Thus, the cost to achieve the maximum feasible reduction in volume may be more than offset by reduced transportation and repository costs.

Nearly all wastes from a spent fuel reprocessing plant may be processed for either safety or economic reasons or both. The size and form of the waste could impact the federal repository, and repository acceptance criteria will impact the waste handling processes in a reprocessing plant. Consideration of both the reprocessing plant and the repository requirements and limitations will be mutually beneficial and will aid in the safe disposal of radioactive wastes by an overall cost-effective process.

The main objective of all waste immobilization programs is to contain the radionuclides until their activity has decreased to acceptable or allowable levels. The purpose of this study is to identify, evaluate, and rate processes that have been or could be used to 1) reduce the volume of contaminated/irradiated metallic wastes and 2) produce an acceptable waste form in a safe and cost-effective process. It specifically addresses the metallic wastes that are anticipated from the operation of the Barnwell Nuclear Fuel Plant (BNFP), Barnwell, South Carolina. Since it is neither practical nor desirable to develop several parallel process concepts to the level where any one could be applied in a production facility, it is the objective of this study to 1) perform a technical comparative evaluation of various consolidation processes and 2) rate these processes based on the feasibility and cost of producing a viable product from a remotely operated radioactive process facility.

The U.S. Department of Energy (DOE), through its Office of Nuclear Fuel Cycle, established the Commercial Waste Treatment Program (CWTP) at Pacific

Northwest Laboratory (PNL).^(a) The goal of the CWTP is to develop, demonstrate, and deploy waste treatment technology. One of its objectives is to establish acceptable waste forms for storage and disposal. The scope of this particular study is to identify, evaluate, and rate consolidation methods to reduce the volume of metallic wastes generated in a fuel reprocessing facility. It includes the feasibility of operating a production-scale process in a radioactive environment that requires remote operation and maintenance. Thus, this study pertains only to the technical and engineering aspects of the candidate methods in respect to their suitability as production-scale operations with radioactive process materials. It is also limited to consideration of only the metallic wastes produced in the operation of the BNFP.

The projected large costs for transportation and burial of radioactive wastes will be a direct function of volume and activity level; thus, it was considered to be beyond the scope of this program to include a no-treatment process (i.e., segregate, identify, and containerize). Methods and processes to decontaminate the subject metallic waste streams so that the resultant products are not contaminated or are in a lower classification (contact handled versus remote handled) were also not considered.

There are several methods that can be used to consolidate the wide range metallic wastes. Basically these methods can be grouped into two general categories: compaction and melting. Methods that have been used to consolidate metals include induction melting, electric arc melting, hot pressing, and cold compaction. Studies and research have been conducted by Allied-General Nuclear Services (AGNS) on handling and storing wastes generated in the operation of the BNFP. In earlier conceptual designs, mechanical or cold compaction processes were considered to reduce the volume of spent fuel hulls (AGNS 1978; Anderson et al. 1979). Based on continuing research conducted at PNL, another densification process--Inductoslag melting--was identified in a preconceptual design (Butcher et al. 1980).

^(a) Operated for DOE by Battelle Memorial Institute.

A wide variety of melting concepts or furnace types might apply for consolidating metallic nuclear wastes. The following 24 melting systems or types of furnaces have been or are being used in various industries and were selected for preliminary evaluation:

- Induction Melting

Induction	Melting material by means of an electric current that flows through the metal by electromagnetic induction.
Vacuum coreless induction	Melting by induction in a vacuum; coreless means that the induction coil surrounds the metal charge.
Cored induction	The induction coil is surrounded by molten metal.
Conventional air coreless induction	Melting by induction in an air atmosphere.
Continuous induction melting and casting	Melting by induction to supply a continuous stream of molten metal to the casting mold.
Crucible coreless induction	Melting by induction in a preformed free-standing crucible.
Crucible coreless induction lift-swing coil	The induction coil is lifted up and away from the crucible after melting.
Inductoslag	Induction melting in a segmented water-cooled copper crucible with a slag as thermal and electrical insulation.

- Electric Arc Melting

Electric arc	Melting by means of an electric arc generated between the electrode and the melting charge.
Mechanically rotated non-consumable electrode	Arc is generated on a mechanically rotated water-cooled electrode.
Magnetically rotated non-consumable electrode	Arc is magnetically rotated on a water-cooled electrode.
Carbon electrode	The single electrode is carbon or graphite.
Tungsten electrode	The single electrode is tungsten.

Consumable electrode	The single electrode is the material to be melted and is consumed.
Indirect arc	The charge is melted by radiant heat from the arc.
Direct carbon arc	Each of three vertical carbon electrodes are connected to one phase of a three-phase alternating current circuit. Melting is accomplished by the arc generated between the electrodes and the charge.
Indirect rocking arc furnace	The charge is melted by radiant heat from the arc, and the furnace is rocked during melting.
• <u>Plasma Arc Melting</u>	
Plasma arc	Melting by a plasma arc that is generated by ionizing a gas passing through an electric arc.
Hollow electrode	Gas passes through a hollow electrode and is then ionized in the arc formed between two electrodes or between an electrode and the charge.
Plasma induction	Melting by plasma arc; the molten pool is stirred by an induction coil.
• <u>Electron Beam Melting</u>	
	Melting by a beam of electrons produced by an electron emitter and targeted on the metal to be melted.
• <u>Electroslag Melting</u>	
	A preformed consumable electrode is melted through a slag bath into a water-cooled steel or copper mold. The electrode is melted by thermal conduction from the slag where heat is generated by resistance to the passage of electric current.
Electroslag melting with two nonconsumable electrodes	Explained in Appendix D.
• <u>Resistance Melting</u>	
	Melting by elements that are heated as a result of their resistance to the passage of electric current.

When the general requirements for selecting consolidation methods are reviewed, it becomes apparent that a melting system should be capable of operating in a contained atmosphere and should use a crucible made of material suitable for melting zirconium. These two criteria basically eliminate any melting system that incorporates an oxide refractory crucible or one that operates in an air atmosphere. Not being able to use an oxide refractory is probably the single most limiting factor in the selection of a potential melting system for the application considered in this document. Oxide refractories require routine maintenance such as patching and periodic replacement, which would be very time consuming due to the limited access and the remote maintenance dictated by the hot cell installation. The use of oxide refractories would also generate large amounts of secondary waste. Refractory systems would not allow the melting of zirconium and titanium due to the metal/crucible reaction.

These limitations removed a number of the above melting systems from further consideration. This elimination is supported in a previous study and rating done by Nelson on the melting of Zircaloy hulls and residual fuel bundle scrap (stainless, Inconel, etc.) (Nelson, Schlienger, and Tiesenhausen 1976).

Thus, the scope of this study was limited to the following melting systems that have the most potential for application to the remote consolidation of metallic nuclear wastes:

- Inductoslag melting
- rotating nonconsumable electrode melting
- plasma arc melting
- Electroslog melting with two nonconsumable electrodes
- vacuum coreless induction melting.

The cold compaction system that was developed at Barnwell for the consolidation of spent fuel hulls was also evaluated in this study. Thus, systems that fall into the two general consolidation categories are assessed and evaluated.

RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

The purpose of this study was to identify, evaluate, and rate consolidation methods or processes that could reduce the volume of metallic wastes and produce an acceptable and viable waste form in a safe and cost-effective remotely operated radioactive processing facility. Each process was evaluated based on its feasibility for handling and processing the metallic wastes produced in the operation of the BNFP.

The seven processes were evaluated based on the following criteria: complexity of process, state and type of development required, safety, process requirements, and facility requirements. The ratings and numerical values shown for each criteria are the results of independent evaluations made by individuals with a broad base of experience in radioactive waste processes, remote handling, remote process facility operation, and/or metal melting and casting. The numerical ratings for each process by principal criteria, a total rating for each, and its ranking based on its total numerical rating when compared with the other processes are presented in Table 1. More detailed summaries of the composite numerical ratings assigned to each process by the evaluators are included in Appendices A through F.

TABLE 1. Composite Rating Matrix for Consolidation Processes

	Inductoslag Melting (Ingot)	Inductoslag Melting (Casting)	Nonconsumable Electrode Melting	Plasma Arc Melting	Electroslag Melting	Vacuum Coreless Induction Melting	Cold Compaction
Appendix	A	A	B	C	D	E	F
Complexity of process	302	362	359	320	254	435	320
State and type of development	240	254	264	244	210	284	229
Safety	227	228	212	222	210	262	282
Process requirements	157	156	217	189	140	226	242
Facility requirements	210	190	195	192	202	240	168
Total rating	1136	1190	1247	1167	1016	1447	1241
Ranking	6	4	2	5	7	1	3

Vacuum coreless induction melting was rated as the best process to reduce the metallic wastes generated when spent reactor fuel is reprocessed. The other processes ranked in the following order: nonconsumable electrode melting, cold compaction, Inductoslag melting (casting mode), plasma arc melting, Inductoslag melting (ingot mode), and Electroslag melting.

The composite process ratings were very close for some of the criteria. The ratings for the nonconsumable electrode and cold compaction processes were essentially the same and there were less than 100 total rating points variance between the second and sixth processes. The basic advantages and disadvantages for the individual processes are noted below:

- Inductoslag melting (ingot and/or casting mode) - The number of ingots or pours that was assumed to be required due to the apparent limited diameter of the crucible had a definite negative impact on the rating of these melting methods. If larger diameter crucibles prove to be feasible, the Inductoslag process and the casting method in particular could be ranked much more favorably.
- nonconsumable electrode melting - This melting method ranked neither very high nor very low; thus, it received a good overall rating. The water source above the surface of the molten pool is a safety concern, and the complexity of the electrode may impact operations and maintenance in a remote hot cell installation.
- plasma arc melting - Ingot withdrawal is the only practical method for this process due to the limited molten pool depth, which adds to process complexity because both ingots and canisters must be handled.
- Electroslag melting - The need to produce ingots and to require several ingots to fill a given canister resulted in a generally low rating for this process.
- vacuum coreless induction melting - This process received very good overall ratings for all the criteria. Additional secondary wastes may be a concern because crucible liners need to be changed after a few heats.

- cold compaction - Although this process has fewer requirements than the various melting processes, it does require considerably more handling while the containers are being filled. This fact and the ~50% density of the compacted wastes detracted from its rating.

Since a full-scale remotely operated system to consolidate nuclear metallic waste by melting does not exist (at least in the United States), it is recommended that a large-scale cold mockup facility be established to refine and test the melting system recommended by this study prior to production operation. The mockup facility could also be used to test other similar equipment, and it would be a valuable tool for troubleshooting subsequent production problems.

BASES AND ASSUMPTIONS OF STUDY

All wastes from the BNFP will be processed through the waste processing center (WPC). This facility will house the processes and systems required to consolidate the various solid and liquid wastes. It will contain the processes and equipment required for the solidification of high-level liquid wastes (HLLW), volume reduction or compaction of fuel hulls and metallic wastes, volume reduction of HLGPT, volume reduction of LLGPT, and equipment volume reduction and decontamination as well as other waste processing functions. These processes will be arranged in the WPC so they can function independently. Feed streams, effluents, and final products will be integrated with the various processes and facilities in the remainder of the fuel reprocessing plant.

GENERIC ASSUMPTIONS AND BASES

- Commercial reprocessing will be done, and nuclear wastes will be transported by commercial carriers to and placed in federal repositories.
- Due to the projected costs of transporting and disposing of radioactive wastes and because of regulatory requirements, a spent fuel reprocessor will process the radioactive wastes. The processing will generally be of two types: 1) volume reduction of wastes to reduce costs (for example, compaction, cutting, or melting) and/or 2) changing the form of the wastes to meet general safety regulations (for example, solidification).
- Mechanical compaction or melting technology could be used to densify the fuel hulls and the metallic wastes generated in a spent fuel reprocessing plant.
- Facilities will be available to reduce the volume of large pieces of failed equipment to a size that can be consolidated.
- Nozzles and end fittings will not be segregated from other fuel bundle components as they are sheared.

- The consolidation process will yield a waste form product that is close to maximum theoretical density and that is of a shape and size that can be cost effectively contained, shipped, and placed in a federal repository.
- Although decontamination by smelting has potential, it was not considered in this study.

REGULATORY CONSIDERATIONS AND REQUIREMENTS

The WPC will be subject to licensing by the U.S. Nuclear Regulatory Commission (NRC); therefore, it will conform to applicable regulatory guides and criteria for fuel reprocessing plants and nuclear facilities. The facility will also be subject to the requirements of the National Environmental Policy Act (NEPA); and the facility and equipment must be in accordance with other federal, state, and local codes, regulations, and standards.

Contamination Control

The metallic consolidation process (MCP) will be designed to confine radioactive contamination within processing vessels by several methods:

- Areas of higher contamination potential will be isolated or separated from areas of lower contamination potential.
- Ventilation air will flow from areas of lower contamination potential to areas of higher contamination potential.
- Areas that could become contaminated will be designed to contain any spilled solutions or solids or to direct the flow of such spills to areas of higher contamination potential.

Radiological Protection

The MCP will be designed and operated so that personnel radiation exposure will be controlled to as low as reasonably achievable (ALARA) levels. Effluent releases from the process will be monitored for radionuclide content and processed in the WPC as required. The process facility will be capable of ceasing or containing the effluent flow under all normal conditions and all design-based accident conditions.

Process Safety Features

Process protection systems will assure that acceptable operating design limits are not exceeded and will detect potentially hazardous conditions and malfunctions. Should a potentially hazardous situation be detected, hazard-suppression systems will be automatically activated where practical.

Life of Process Equipment

The MCP will have a useful operation life of 30 yr and will be designed and constructed according to the following design considerations:

- Every component will be designed for maintenance or replacement taking into consideration its remote or nonremote operating environment and design-based accident scenarios.
- Every component will be designed, procured, fabricated, and operated in accordance with established quality assurance requirements.

Process Cell Requirements

All operations within the process cell will be performed remotely. Process cell operations will be performed and/or monitored from a central control room; however, control may be selectively exercised from local consoles that will be supplemented by viewing windows, closed circuit televisions, and/or periscopes. The control consoles will also be equipped with instrument systems to detect equipment malfunctions and fluctuations in the properties of the feed materials and the process. Routine adjustments and the rerouting of process materials will be done from the consoles. Other adjustments or malfunctions may be corrected using manipulators or other devices.

The process cell walls will be thick enough to reduce the radiation dose rate to ALARA levels. The cells will be lined with Type 304L stainless steel to aid in decontamination and decommissioning and to protect the walls from corrosive chemicals and vapors.

Equipment on process cell walls will be mounted on ears, yokes, or racks; and equipment on the floor of the cell will be mounted on guide racks or dunnages. The placement of equipment will depend on the equipment and how it can

be handled in the cell. The width and height of the cell will be determined by the size of the equipment and the remote-maintenance and remote-servicing requirements.

Television cameras will be strategically located to provide coverage for operating, inspecting, and repairing equipment. Floor and wall space will be provided in each process cell for storing tools and other maintenance equipment. Space will also be provided between the process equipment in the cell for handling equipment and for moving items.

General Equipment Requirements

Remote operations require that all process equipment and equipment for handling process materials be automated or mechanized and remotely operable. Process cell equipment will be designed for simplicity, reliability, and easy maintenance. The use of master-slave and electromechanical manipulators for the routine remote operation of process equipment will be minimized. Process cell equipment will be fabricated from materials that are resistant to corrosion, radiation damage, and processing conditions.

The modular process equipment will be installed and removed remotely using a crane hoist and/or manipulators or other devices. Equipment modules that are expected to fail within the lifetime of the facility will be remotely replaceable without removing other major equipment. The dimensions of the modules will be controlled. Alignment dowels, studs, and fixed mounting trunions will insure exact positioning of equipment and components.

Auxiliary equipment that will require contact maintenance (for example, feeders, welders, and mass spectrometers) will be located outside the cells if possible. Air locks, antibackflow devices, and block valves between the in-cell and out-of-cell equipment will insure safe operations.

Processing equipment surfaces normally exposed to process materials will be isolated from the cell environment to the extent practical. The contained areas will be maintained at pressures lower than those in the cell by connecting the contained areas to the ventilation or off-gas system. Process

equipment that may be exposed to internal pressures exceeding the capacity of the ventilation or off-gas system will be fitted with devices that permit the safe release of pressure to the cell.

Processing equipment will be designed to minimize the buildup of process material in the equipment. Equipment that is prone to internal buildup of material will be fitted with sensors to monitor buildup. Process equipment that may be exposed to internal fire and/or explosive gas mixtures will be fitted with monitoring instruments and suppression devices.

FUNCTIONAL CAPABILITIES

All radioactive metallic wastes from the BNFP will be processed through the MCP in the WPC. The MCP shall be capable of processing the nonfuel-bearing residues from the nitric acid leaching of chopped fuel assemblies that are assumed to have the following irradiation history:

Burnup	29,000 MWd/MTU
Spec. power	32.5 MW/MTU
Initial enrichment	2.8%
Reactor on-stream	80%
Age at reprocessing	3 yr

The reference fuel cladding is composed of the following major constituents:

<u>Element</u>	<u>kg/MTU</u>
Zirconium	283.0
Iron	17.1
Nickel	9.9
Chromium	7.0
Tin	4.1
Niobium	0.8
Cobalt	0.04
Other	<u>2.1</u>
Total	324.0

The metallic wastes segregated from HLGPT will also be contaminated with particulates from the spent fuel processing operation and are considered to contain radioactive isotopes in the same percentages as the fuel but in much

smaller quantities. This material and failed processing equipment and metallic scrap (primarily stainless steel) will also be processed through the MCP. The majority of failed equipment and scrap will be classified as noncontact TRU waste because of its level of contamination although there may also be some material in the contact TRU waste category.

PROCESS MATERIAL IDENTIFICATION

The following material will be processed through the MCP on an annual basis:

- noncontact TRU waste (greater than 50 mrem/h)
 - a) hulls - These materials constitute a high-volume waste representing ~22% of the original fuel bundle weight with a bulk density of ~1.1 kg/L. As recovered from the dissolver, these hardware residues represent ~325 kg/t of uranium and consist of 70 to 80 wt% Zircaloy, 12 to 22 wt% stainless steel, and 8 wt% Inconel.
 - b) failed process equipment and equipment scrap of varying size (mostly stainless steel)
 - c) HLGPT - If segregated, the metallics would consist of failed motors, valves, pipes, and assorted metallics plus some organics and ceramics.
- contact TRU waste (less than 50 mrem/h)
 - a) failed equipment, motors, pumps, pipes, valves, and tools plus organics and ceramics
 - b) LLGPT - If segregated, the metallics would include tools, tubing, valves, and assorted metallics plus some organics and ceramics.

Based on reports by Anderson, Carr, and Mitchell (1982) and Keeley (1977), the volume and weight of the various metals assumed to be generated in a 1500-MTU processing plant and processed in the MCP are shown in Table 2. Volume reduction ratios of 6:1 and 10:1 were assumed for hulls and other metallics, respectively.

TABLE 2. Annual MCP Metallic Throughput

Type of Waste	Amount Before Processing, ft^3	Amount After Melting, ft^3	Weight of Material, lb (kg)	Number of Canisters Produced ^(a)
Hulls	16,875	2,812	1,197,500 ^(b) (543,100)	112
Failed equipment	2,400	240	117,800 ^(b) (53,400)	10
HLGPT ^(c)	940	94	43,900 ^(d) (19,900)	3
LLGPT ^(c)	1,220	122	56,900 ^(d) (25,800)	4

(a) Full canister is 24 in. in diameter by 10 ft long (31.4 ft^3).

(b) Based on 0.237 lb/in.³ Zircaloy and 0.284 lb/in.³ steel.

(c) HLGPT - high-level general process trash; LLGPT - low-level general process trash. Mixed metals: stainless steel, carbon.

(d) Based on 0.270 lb/in.³ mixed metals.

CRITERIA FOR METHOD SELECTION AND EVALUATION

Before any method can be considered as applicable to consolidate metallic wastes generated in a remotely operated and maintained production-scale fuel reprocessing facility, it must meet the following general requirements:

- capable of handling or melting all common metals and/or alloys including reactive metals such as zirconium with a limited metal/crucible reaction
- relatively simple to operate and maintain in a remote application
- relatively safe
- little or no secondary waste generation
- well-developed basic concept
- maximum containment of off gases and radionuclides
- atmosphere conducive to handling zirconium

- compatible with production throughput and product requirements
- system size and configurations compatible with facility limitations.

The following basic guidelines were also established for the evaluations:

- Other than product density and integrity before placing in a container, differences in the properties of the products are not to be considered a major factor in the assessment.
- Both process and equipment considerations are to be taken into account.
- Qualitative judgments are to be made as to the level and scope of development required to place the process in production in the remote mode.

The solidification processes that were identified in this report are described in Appendices A through F; they were considered and used as the bases of the comparisons. These data were supplemented by various publications, original manufacturers' data, and information available on the BNFP processes. An approach for engineering feasibility evaluation of processes to solidify nuclear high-level wastes (E. R. Johnson 1980) was used to develop the criteria shown in Table 3.

The principal ground rules for the processability analysis are summarized below:

- The solidification method must be capable of being designed for and operable using remote operation and maintenance techniques.
- All criteria for the safe handling of radioactive materials must be adhered to.
- The process must be capable of consolidating a variety of metals and/or alloys (including reactive metals) with an acceptable metal/crucible reaction.
- Ways and means to perform all process steps are to be at least envisioned. Undefined equipment required to perform a process step remotely shall be considered as a development item.

TABLE 3. Criteria for Process Evaluation

Complexity of Process

Material handling
Consolidation mode
Maintenance considerations and equipment reliability
Controls and operation
Adaptability to remote operation
Number of process steps
Feasibility for production
Feed limitations

State and Type of Development

Process
Equipment
Type of development
Scale of development
Development time required (from initiation of program)

Safety

Stability and atmosphere of process steps
Pyrophoricity, exothermic, and explosion considerations
Personnel radiation exposure

Process Requirements

Secondary wastes and off gases
Production capacity
Process additives and auxiliary materials
Process versatility and control
Quality assurance
Utilities (air, power, water, etc.)
Manpower

Facility Requirements

Noncontact facilities (remote)
Contact facilities (hands on)
Estimated capital cost

- Radioactive liquids or gases should be transferred at pressures negative to cell atmosphere.
- Each method must be capable of handling the applicable type and quantity of waste stream feed.

- Processing equipment should have built-in flexibility in size and operability to handle reasonable changes in waste stream composition or content.
- Services, power, and maintenance requirements are to be considered and shall be assessed if above or below a specified standard.
- Methods for accident recovery (for example, melt throughs or spills) must be defined.

EVALUATION METHOD

The rating system used for the analysis of these consolidation methods consisted of the five general categories:

- complexity of process
- state and type of development
- safety
- process requirements
- facility requirements.

Checkpoints or questions similar to those shown in Appendix G were then developed for each of the categories and used to compare the consolidation processes. This system met the objectives of having a rating system that was 1) quantifiable, 2) sufficiently comprehensive to delineate differences between the consolidation methods, and 3) simple and understandable.

The approach used in this study is similar to the approach used to evaluate candidate processes for the solidification of HLLW from irradiated fuel reprocessing^(a) and the approach used to evaluate various ways to coat high-level waste form particles (Oma et al. 1981). E. R. Johnson, Oma, and Nesbitt considered only the process feasibility, as does this report; the other two evaluations considered both process aspects and product characteristics.

The evaluation criteria, the scoring method, and the weighting factors were developed through a consensus process involving personnel with a broad base of experience in radioactive waste processes, remote facility operation, and metal melting and casting. The major criteria categories and the percent weighting that was used were:

<u>Criteria</u>	<u>Weighting %</u>
Complexity of process	30
State and type of development	20
Safety	20
Process requirements	15
Facility requirements	15
	<u>100</u>

(a) Stone, Goforth, and Smith 1979; E. R. Johnson 1980; Nesbitt and Treat 1980; Dunson et al. 1982)

The first criterion--complexity of process--represents the difficulty of operating a reliable process in a remote production facility. It is clearly the most crucial measure of the difficulty that may be involved in transforming a conceptual or pilot-plant operation to a successful remote production. An operation that can be conducted in a few steps, use equipment with the simplest and fewest moving parts, and be reliably monitored and controlled has the highest probability of success. Accordingly, the rating scales reflect higher values for simpler procedures and the weighting factor for this group of criteria (30%) is larger than that for any other group.

The state of development of the process and its equipment is important because the fewer unknowns present at any time will enhance the desirable outcome. The identification and magnitude of the required developmental efforts are important aspects in assessing the probability of future successful operations.

Safety will be, of course, a requisite of any process finally adopted. The safety rating is not so much an assessment of whether or not the process can be operated safely as it is an assessment of the degree of precaution that will be required in the design, construction, and operation to achieve the necessary safety.

Process requirements and facility requirements are a measure of the services required to support the process, the manpower to operate it, and the facilities required to house the operations. Thus, they provide a relative measure of required costs.

Each major category was divided into subcriteria, and the total weighting factor was distributed among the subcriteria. For each subcriterion, a rating scale from 1 to 10 was devised, and a set of qualitative descriptions was developed to define levels within each subcriterion and to serve as a uniform rating guide for all methods under consideration. The categories and their ratings are shown in Table 4. The process rating guide is presented in Appendix H.

TABLE 4. Criteria and Weighting Factors for Process Evaluation

	Factor Weighting	
	Sub	Total
<u>Complexity of Process</u>		60
Material Handling	5	
Consolidation Mode	5	
Maintenance Considerations and Equipment Reliability	12	
Controls and Operation	8	
Adaptability to Remote Operation	15	
Number of Process Steps	5	
Feasibility for Production	5	
Feed Limitations	5	
<u>State and Type of Development</u>		40
Process	5	
Equipment	10	
Type of Development	10	
Scale of Development	10	
Development Time Required (from initiation of program)	5	
<u>Safety</u>		40
Stability and Atmosphere of Process Steps	10	
Pyrophoricity, Exothermic, and Explosion Considerations	20	
Personnel Radiation Exposure	10	
<u>Process Requirements</u>		30
Secondary Wastes and Off Gases	5	
Production Capacity	4	
Process Additives and Auxiliary Materials	5	
Process Versatility and Control	5	
Quality Assurance	3	
Utilities (air, power, water, etc.)	3	
Manpower	5	
<u>Facility Requirements</u>		30
Noncontact Facilities (remote)	10	
Contact Facilities (hands-on)	10	
Estimated Capital Cost	10	

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APPENDIX A

INDUCTOSLAG MELTING

APPENDIX A

INDUCTOSLAG MELTING

INTRODUCTION

The Inductoslag melting process (Figure A.1) is basically a semicontinuous process that produces an ingot of metal using induction heating. Electric current, which is induced in the metal by a changing magnetic field, heats the metal and forms a molten metal pool. The melt is insulated from a segmented, water-cooled copper crucible by a layer of frozen slag. Melting takes place in a static one-third atmospheric pressure of helium or argon. For the ingot mode, a pool of molten metal and slag is melted on a "starting stub," and "charged metal" and flux is fed into the top of the crucible as the ingot is extracted out the bottom. The Inductoslag process can also be used in a casting mode (Figure A.2). In this adaptation, the crucible is tilted and the molten metal is poured into a mold after the desired batch size has been melted.

Calcium fluoride is used as the flux for metals with high melting points (for example, zirconium, chromium, and titanium). Mixtures of calcium fluoride and magnesium fluoride are used as the flux for metals with lower melting temperatures (for example, stainless steel, Inconel, and other iron-, nickel-, and cobalt-base alloys). Induction frequencies of 3 to 10 kHz are required for the Inductoslag melting process.

PROCESS DESCRIPTION

The scrap or waste metal feed materials are segregated from nonmetallic material, and they are cut so that the size and configuration of the individual pieces are compatible with the melter feed system and the size of the furnace crucible. The key component of the Inductoslag melting system is the unique segmented crucible design surrounded by an induction heating coil. The

FIGURE A.1. Inductoslag Melting Process - Ingot Mode

FIGURE A.2. Inductoslag Melting Process - Casting Mode

coaxial, water-cooled copper segments are covered by a refractory cement coating. The design and configuration of the furnace crucibles differ considerably for the ingot and casting modes.

Ingot Mode Operation

An isometric arrangement of an Inductoslag furnace and a schematic of how it produces an ingot of metal are shown in Figure A.3. A schematic of the furnace and a process flow diagram are depicted in Figure A.4 (Butcher et al. 1980). A metal starting stub^(a) is positioned on the water-cooled ingot withdrawal system in the crucible, and flux^(b) is added to the crucible on top of the starting stub. Metallics of a known composition^(c) are then transferred to and charged into the furnace charge hopper, and the furnace is evacuated to $\sim 1\text{-}\mu\text{m}$ vacuum and then backfilled to $\sim 1/3\text{-atm}$ argon. When the furnace power is turned on, the starting stub starts to heat and the existing flux melts by conduction. The molten flux flows down and around the annulus between the starting stub and the water-cooled crucible where it freezes and provides thermal and electrical insulation. As the power is increased, part of the metal starting stub melts and forms a molten pool of metal and molten flux around the top annulus of the molten pool. Metal is fed semicontinuously into the furnace crucible from the charge hopper via a feeder system, and additional flux is fed into the furnace as required. When the volume of molten metal reaches a predetermined height in the crucible, the withdrawal mechanism is activated and the ingot is withdrawn from the bottom of the crucible and cooled. This process is continued until the desired length of ingot is attained. After the ingot is removed from the furnace, the starting stub is removed and the adhering flux can be removed from the ingot and recycled. The ingot is placed in a container with a seal-welded lid, and the loaded canister is leak checked and decontaminated as appropriate before being placed in storage.

(a) The starting stub metal should be the same as or similar to the metal being processed.

(b) The composition of the flux will vary depending on the scrap metal being charged, i.e., CaF_2 for Zircaloy, $\text{CaF}_2 + \text{MgF}_2$ for stainless steel, etc.

(c) Scrap consists of: Zircaloy hulls; stainless steel end fittings, etc.; failed equipment (mostly stainless steel); metallics separated from HLGPT (all common alloys); metallics separated from LLGPT (all common alloys); and failed equipment (all common alloys).

FIGURE A.3. Conceptual Illustration of Inductoslag Melting Process - Ingot Mode

Casting Mode Operation

About one-third of the required flux charge^(a) is fed into the furnace and collected in the bottom of the crucible. The metal charge is fed into the furnace and crucible via the feeder system. The remaining two-thirds of the flux is then added on top of the metal charge. When the furnace power is turned on, the charge metal starts to heat and the flux melts by conduction. The molten flux forms a solidified layer between the crucible and the metal, which acts as a thermal and electrical insulator. As the power is increased, the metal charge melts. By tilting the crucible, the batch of molten metal can be poured into a mold (storage canister).

The melting and casting process is repeated until the canister is full. The filled canister is removed from the furnace and replaced by an empty canister. A lid is seal-welded on the loaded canister, and the canister is leak checked and decontaminated as appropriate before being placed in storage.

INGOT MODE PROCESS NEEDS AND REQUIREMENTS

The Inductoslag process using the ingot mode can consolidate and solidify the metallic wastes identified in the Process Material Identification section (p. 16). It will be required to produce an estimated 105 ingots (2 ft in diameter by 10 ft long) or equivalent in a maximum of 300 days/yr, and the facility could be operated 24 h/day. The canisters containing the consolidated process metallics must be suitable for remote handling and transport and compatible with long-term disposal in a geologic repository. The major remote process equipment that will be required is shown in Table A.1 (Butcher et al. 1980).

Furnace Feed

The process material (hulls and miscellaneous metallic components) will be remotely handled and moved to the furnace as shown in Figure A.5 (Butcher et al. 1980). A charge hopper with the capacity to hold up to 1 day's throughput (150 ft³ and 4600 kg) will be required above and close to the furnace. It

(a) The composition of the flux is determined by the metal being melted, i.e., CaF₂ for Zircaloy. The initial amount of flux required in the casting mode is ~8 wt% of the charge metal weight; ~2 wt% is required thereafter if the crucible skull is reused in subsequent heats.

TABLE A.1. Major Remote Equipment for Inductoslag Melting Process

<u>Equipment</u>	<u>Average Rate or Capacity</u>
Crane hoist	60 tons
Storage crane hoist	10 tons
Drum dumper crane and hoist	10 tons
Drum dumper	--
Charge hopper	--
Feeder	--
Melter	--
Ingot/canister handling system	--
Cooler	--
Canister welder	--
Canister leak test station	--
Canister decontamination station	--
Cell cranes and manipulators	--
Quench tower	38 kcal/h
Venturi scrubber	1059 l/s
De-entrainer	22.7 l
Steam vacuum jet	22 kg/h
Spray condenser	11,400 kcal/h
Scrubber recycle tank	1.4 m ³
Scrubber solution cooler	--
Off-gas heater	--
Off-gas primary filters	--
Ruthenium adsorbers	--
Off-gas reheaters	--
Final filters	--
Off-gas blowers	--
Scrubber solution air lift pot	--

NOTES:

1. MOVE HULLS CASK FROM TRUCK TO SHIELDED MATCH ON UPPER LEVEL VIA 60 TON CRANE HOIST
2. LOWER HULLS CONTAINER FROM INSIDE HULLS CASK TO HULLS MELTER FEED CELL VIA HOIST INSIDE OF HULLS CASK
3. MOVE HULLS CONTAINER TO HULLS FEED DUMPER VIA HULLS MELTER FEED CELL CRANE HOIST
4. USING REMOTE MANIPULATORS REMOVE LID, POSITION & FASTEN HOPPER ADAPTER
5. USING HULLS MELTER FEED CELL CRANE HOIST, TRANSFER HULLS CONTAINER CONTENTS TO HULLS FEED SH
6. REVERSE SEQUENCE OF OPS 1 TO 5 TO RETURN EMPTY HULLS CONTAINER TO HULLS CASK & HULLS CASK TO TRUCK
7. MELT HULLS IN INDUCTOSLAG MELTER AND MOVE MOLT TO INMOLT COOLER ON HULLS MELTER TURNTABLE, VIA HYDRAULIC LIFT CYLINDER #1
8. OBTAIN EMPTY REPOSITORY CONTAINER FROM STORAGE, INSERT EMPTY CONTAINER INTO HULLS MELTER CELL, DRAW EMPTY REPOSITORY CONTAINER TRANSFER DRAWER
9. MOVE EMPTY REPOSITORY CONTAINER TO BUILD AREA AND POSITION HOIST FOR THE HULLS MELTER CRANE HOIST
10. TRANSFER HULLS MOLT TO POSITION OVER HYDRAULIC LIFT CYLINDER #2 VIA HULLS MELTER TURNTABLE, LIFT TO HULLS MELTER CRANE HOIST, TRANSFER TO EMPTY REPOSITORY CONTAINER
11. PLACE HELIUM IMPREGNATED PUL & LID ON REPOSITORY CONTAINER VIA MASTER SLAVE MANIPULATOR & HULLS LID THICKER OVERPACK LIDS ON IN PLACE AND LEAK TEST
12. TRANSFER FULL SEALED REPOSITORY CONTAINER TO POSITION UNDER THE ROUGH DECON VESSEL VIA THE HULLS MELTER CRANE HOIST
13. USING DECONTAMINATION CELL CRANE HOIST, LIFT FULL REPOSITORY CONTAINER AND ROUGH DECON VESSEL, CLOSE VESSEL, POSITION MATCH, RELEASE CONTAINER AND DE VESSEL, REMOVE CRANE HOIST
14. CLOSE TOP LATCH OF HULLS DECON VESSEL, ACTIVATE VESSEL FOR DESIRED PERIOD OF TIME, DRAW VESSEL, OPEN TOP MATCH
15. USING DECON CELL CRANE HOIST, LIFT FULL REPOSITORY CONTAINER & TO THE DECONTAMINATION CELL, PLACE LID & REPOSITORY OVERPACK

FIGURE F4-2

NO.	REV.	ISSUED FOR CONSTRUCTION DESIGN	NO.	REV.	DATE	BY	CHKD.	APP.	APP.
1			1						
REFERENCE DESIGNS									
5300-B-5001	R/25								
5300-A-5001	R/23								
5300-A-5002	R/24								
ALLIED GENERAL NUCLEAR SERVICES									
BARNWELL NUCLEAR FUEL PLANT									
BARNWELL SOUTH CAROLINA									
AGNS DESIGN ENGINEERING DEPARTMENT									
2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36, 38, 40, 42, 44, 46, 48, 50, 52, 54, 56, 58, 60, 62, 64, 66, 68, 70, 72, 74, 76, 78, 80, 82, 84, 86, 88, 90, 92, 94, 96, 98, 100									
BARNWELL, S. C. 29032									
HULLS MELTER									
MECHANICAL SEQUENCE DIAGRAM									
REV.	NONE	DATE	3-25-68	DESIGN NO.	5300-B-5002	NAME	A		

FIGURE A.5. Inductoslag Melter Mechanical Sequence Diagram

is connected to the center cavity of the furnace with a system that will move the feed material (6 x 6 x 6 in. or less) into the furnace on a demand and controlled basis without voiding the atmospheric control of the furnace.

The charge hopper and furnace feed system (Figures A.3 and A.4) should be capable of feeding hulls and/or relatively small pieces of scrap metal into the furnace crucible. Rather than reducing all of the contaminated equipment and metal to these small pieces, it may be more economical to feed them into the furnace using a separate system (a bucket charge system). A second feed system could be incorporated into the design and operation of an Inductoslag ingot mode furnace.

The flux feed system is attached to the upper portion of the furnace. It introduces the required fluxes into the core of the furnace on a controlled and demand basis. Flux is supplied and fed from a series of hoppers that hold at least a 7-day supply of the required fluxes.

Furnace

An Inductoslag furnace similar to the ones shown in Figures A.3 or A.4 will be required. To produce an ingot 10 ft long and 1 ft in diameter (which is felt to be the maximum possible diameter) will require a furnace that is ~6 x 12 x 20 ft high. After the desired length ingot is produced, it can be withdrawn entirely from the crucible via the ingot withdrawal mechanism. The supported ingot can be rotated or moved to a position for transfer to an external station. After a new starting stub is inserted into the furnace, it is ready to melt and form another ingot.

Based on an engineering study, it has been assumed that it is feasible to make an ingot 1 ft in diameter by 10 ft long in a furnace cycle time of ~8 h (with a maximum instantaneous melt of ~150 kg). Thus, one Inductoslag furnace could produce three such ingots in 24 h, and it could process the estimated annual facility throughput in 157 days. About 464 ingots weighing an average of 1390 kg and canisters filled to 90% capacity would be produced. The 1-ft by 10-ft ingot will require handling and processing about four times more canisters than 2-ft diameter by 10-ft long ingots.

Ingot Transport and Encapsulation

The mechanical sequence diagram in Figure A.5 shows the steps and a tentative arrangement of an Inductoslag ingot melter and its material handling system. This system does not include the option of removing the starting stub from the ingot. However, the stub would not have to be removed if 1) it is made of process material in a separate step in the hot cells or 2) the reduced efficiency of a canister containing a starting stub made of nonprocess material is acceptable. Otherwise, an additional station to remove the starting stub from the ingot would be required between the melter and the canning station. If included, more space would be required and the equipment would have to be rearranged.

After the ingot is inserted into a canister, a lid is seal-welded in place by a remote welder.^(a) The canister is then checked for leaks. Either of two leak detection systems that have been used in remotely operated, radioactive processes can be utilized: helium detection or ultrasonic examination. Following leak detection, the canister can be decontaminated if required; or decontamination may be performed just prior to moving the canister from the process cell.

Although the welding and leak test stations are combined in Figure A.5, they could be separate. Combining stations reduces the number of times an ingot or canister must be moved and the size of the required processing facility. However, concentrating relatively complex or remotely operated equipment in a small area may be undesirable.

CASTING MODE PROCESS NEEDS AND REQUIREMENTS

The Inductoslag process using the casting mode will consolidate and solidify the metallic wastes identified in the Process Material Identification section (p. 15). It will be required to produce an estimated 116 fuel canisters (2 ft in diameter by 10 ft long and 90% full) or equivalent in 300 days or less, and the facility could be operated 24 h/day. The canisters containing

(a) Such a welder has been developed and demonstrated at Pacific Northwest Laboratory (PNL) (Treat et al. 1980).

the consolidated process metallics must be suitable for remote handling and transport and compatible with long-term disposal in a geologic repository. The major remote equipment that will be required is listed in Table A.1.

Furnace Feed

Provisions to introduce the process material to the furnace charge hopper could be the same as those identified for the ingot mode. A charge hopper with the capacity to hold up to 1 day's throughput (150 ft³ and 4600 kg) will be required above and close to the furnace. It is connected to the center cavity of the furnace with a system that will move the feed material (6 x 6 x 6 in. or less) into the furnace on a fast-feed and controlled basis without voiding the atmospheric control of the furnace.

For this process, an alternative to reducing all metallics to small pieces or requiring a second furnace charge system would be to load a predetermined amount of large scrap pieces into the bottom of an empty canister prior to its insertion into the furnace. This material would be covered and essentially surrounded with molten metal from subsequent batch pours.

The flux feed system is attached to the upper portion of the furnace. It introduces the required fluxes into the core of the furnace on a controlled and fast-feed basis. Flux is supplied and fed from a series of hoppers that hold at least a 7-day supply of the required fluxes.

Furnace

An Inductoslag furnace similar to the one shown in Figure A.6 will be required. To produce a casting in a canister 10 ft long by 2 ft in diameter will require a furnace that is ~6 x 12 x 24 ft high. Based on an engineering study, it has been projected that it would be feasible to fill a 2-ft diameter by 10-ft long canister 90% full in a furnace cycle time of ~66 h. This could be done by batch melting and pouring 55 melts of ~100 kg each. The maximum molten metal in the crucible at one time would be ~150 kg; thus, 116 canisters could be produced in ~321 days. Two furnaces would be required to process the projected facility throughput within the 300 working days.

FIGURE A.6. Conceptual Arrangement of Inductoslag Melt-and-Pour Furnace

Canister Handling and Transport

The system required to handle and transport the 6- to 7-ton canister will be similar to but somewhat less complicated than that required for smaller ingots and canisters. The canister handling system must be able to:

- bring an empty or partially filled canister to the furnace
- insert the empty or partially filled canister in the furnace
- remove the full canister from the furnace and contain it in a cooling station
- move the canister from the cooling station to the closure station
- move the closed canister to the leak detection station
- move the closed canister to the decontamination station if required

- move the decontaminated canister to storage or to the out-of-cell transfer station.

The canister cooling, closure, leak test, decontamination, and storage stations are all similar or identical to those stations identified for the ingot process.

FACILITY REQUIREMENTS

The overall requirements for a waste facility are generally similar for all the consolidation processes. Preliminary layouts of an Inductoslag furnace (ingot mode) without a starting stub removal station are shown in Figures A.5, A.7, and A.8 (Butcher et al. 1980). The overall facility requirements for the casting mode would be similar to but larger than those for the ingot mode if a second furnace is required to meet throughput needs. The canister handling steps would also be rearranged for the casting mode.

Off-Gas System

The off-gas system cools the gases generated during the melting operation and filters out any particulates or volatile fission products that may come from the furnace system. As identified by Anderson, Carr, and Mitchell (1982), the gas from the melter passes through a quench tower to remove process heat and to condense water vapor and then moves to a venturi scrubber for particulate removal. Off gas from the venturi scrubber passes through a de-entrainer and a vacuum jet into a spray condenser. The off gas, which consists primarily of noncondensable gases and residual particulates, is then heated and passed through a prefilter, a single high-efficiency particulate air (HEPA) filter, a ruthenium absorber bed, a reheater, and two stages of HEPA filters in series. The off gas is then exhausted into the waste processing center (WPC) gaseous effluent system or through blowers and out a stack. A flow diagram of the off-gas system is shown in Figure A.4 and its throughput is summarized below:

<u>Effluent</u>	<u>Flow Rate</u>
Gases (a)	30 m ³ /min
Particulates (b)	4.0 kg/h

(a) From furnace at 600°C and 1/3 atm.

(b) Metal fumes contaminated with radioisotopes.

Secondary Wastes Requiring Processing

Nonradioactive solid and liquid wastes will be handled in supporting systems. Wastes that will require processing for either of the Inductoslag melting furnace processes are listed below:

<u>Material</u>	<u>Amount</u>
Nonradioactive cooling water	1000 g/min
Process wastes	10 kg/h
Ventilation flow	500 m ³ /min

Utilities, Services, and Materials

Estimates of the normally required utilities, services, and materials that will be needed for either of the Inductoslag melting processes are summarized in Table A.2.

TABLE A.2. Utilities, Services, and Materials
for Inductoslag Melting Process

<u>Item</u>	<u>Capacity</u>	<u>Average Rate</u>	<u>Amount/Year</u>
Electricity	1200 kW, 3 kHz	900 kW	
Water	1800 g/min	1200 g/min	
Air	750 m ³ /min	500 m ³ /min	
Steam	15 kg/min	2 kg/min	6,500 kg
Flux			13,000 kg
Canisters	1 ft dia x 10 ft long		470 each
	2 ft dia x 10 ft long		120 each
He sources			500 or 150 each
Argon			2300 m ³ (ingot)
			600 m ³ (cast)

FIGURE A.7. Lower Elevations of Preliminary Layout for Inductoslag Furnace System

ASSESSMENT DISCUSSION

Inductoslag - Ingot Mode (Reference Process)

Based on the present state of the art of the Inductoslag furnace and its mode of operation, it has been assumed that the maximum crucible diameter will be ~1 ft. This limitation directly and indirectly impacts the feasibility of using this process to consolidate metallic wastes. It adds to the complexity of the process, and a larger number of small canisters would be produced. Because the subsequent costs for transportation and geological storage are based primarily on the number of units, these costs could be up to four times greater than those for canisters from another process. The numerical ratings assigned to the Inductoslag ingot mode process by the individual evaluators are shown in Tables A.3, A.4, and A.5 (see p. A.32). The criteria are discussed below.

Complexity of Process

Due to the projected limitation on crucible and ingot diameter (1 ft), the Inductoslag process involves more process steps and the handling of more canisters than the other processes. The separation and recycling of starting stubs and fluxes also complicate the process. The equipment required, its complexity, reliability, and maintenance considerations are considered to be better than normal for a remote process of this type. Remote operation and maintenance of this equipment, however, will not be without some problems.

Process controls are viewed as state of the art, and most have a reasonable allowable operating range. No special problems are anticipated in adapting this process to remote operation, and the crucible diameter is the only limiting factor for larger scale production use.

Material Handling. The initial material handling consists of transporting the feed materials to the WPC in shielded and sealed containers. Individual containers must be removed from the casks and put into process cells for storage or introduction into the consolidation process. This portion of the material handling is assumed to be essentially identical or at least very similar for all consolidation processes.

For this process, the individual containers are opened remotely and the process material is dumped into the process feed hopper. The material is then automatically fed into the furnace on a demand basis. A starting stub must be remotely inserted and positioned in the furnace, but the ingot will be withdrawn automatically. Remote operational in-cell equipment will also be required to cool the ingot so that it can be removed from the furnace. It may also be necessary to remove the starting stub and the adhering flux. Remote equipment will also be necessary to insert the ingot into a canister.

Other remote equipment will be required to seal, leak test, decontaminate, and transport the canister. This equipment will be identical or at least very similar for all consolidation processes. The remote recycling of starting stubs and flux material is anticipated.

Consolidation Mode. The Inductoslag melting process will be performed in a controlled atmosphere and pressure, and it will require water cooling. Mechanisms will be required for the controlled feeding of the process material and fluxes and the controlled withdrawal of the ingot while maintaining the required atmosphere.

Maintenance Considerations and Equipment Reliability. The interior of the furnace will be designed for decontamination by washdown, vacuuming, or similar methods. The coil and crucible assembly and mechanisms for ingot withdrawal, metal feed, and flux feed will all be replaceable as modules. The overall reliability of this melting system is relatively high with the weakest point being the segmented crucible. If a heavy piece of feed metal struck the segmented side wall of the crucible, it could knock the crucible out of alignment and allow molten metal to run out past the solidified portion of the ingot and into the area below. A heavy sharp piece of metal feed could puncture one or

more segments and cause a water leak. The interior of the furnace will be accessible for checking, cleaning, and removing modules.

Remotely operated in-cell equipment will be required to maintain and replace process equipment (cranes, manipulators, and robotics). Provisions must also be made for the maintenance and/or removal of the crane maintenance room, shielded areas, out-of-cell cranes, and cell cover blocks. Special tools, adapters, jigs, and fixtures will be required in the hot cell for maintenance and replacement activities; and extra cell space must be provided. Visual access to all areas in the cells is important; viewing windows, periscopes, and closed circuit television will be provided.

Controls and Operation. The controls for this furnace and its operation are complex but straightforward. Once melting is initiated, the power setting to the coil requires very little monitoring. The metal feed control allows the operator maximum flexibility in the amount of material in the crucible at any given time. The flux feeder operates the same as the charge feeder. Withdrawal of the ingot is easy although it must be coordinated with metal feed rates and melting times and temperatures.

The operational steps and controls required to supply the feed materials to the furnace and to handle the ingots and the canisters produced are all essentially batch-type operations. Each will require state-of-the-art controls whose sequence and timing will have to be coordinated.

Adaptability to Remote Operation. A laboratory-scale Inductoslag furnace with a 4-in. diameter crucible was operated remotely during ~60 heats at PNL. Internal operations were viewed on monitors on the console, which was 15 ft from the furnace. All feeding and ingot withdrawal was also remotely operated from the console. Although this furnace was designed for use in a semihot cell, it has only been operated in the laboratory; and no remote maintenance or replacement activities have been required or performed. With adequate design and testing time, no special problems are anticipated for a production-size furnace in a fully remote operational mode. All other remotely operated equipment (with the exception of radiation-resistant and decontaminable robotic devices) will be similar to adaptations of current applications.

Number of Process Steps. From the time the metal is loaded into the charge hopper until a canister is filled, at least 11 individual process steps will be required. Initial and final steps are batch-type operations, but the melting of the process material is essentially a continuous process.

Feasibility for Production. All steps in the internal operation of the Inductoslag furnace have been performed from remote consoles; thus, they are viable for production. The time required to remove and process a number of ingots remotely would appear to be compatible with the furnace cycle times. The ingot/canister processing steps that are not automatically sequenced and that require the operation and sequencing of a variety of remote mechanical equipment could be the limiting throughput factor. However, all are feasible for application in a remote production facility.

Feed Limitations. The diameter and size of the crucible along with the ability of the feed mechanisms to handle a range of sizes will set the maximum dimensions and weight of the feed material. A maximum individual size of 6 x 6 x 6 in. and a weight of 60 lb have been assumed for this process. However, if there are any pieces of feed material that weigh more than 4 or 5 lb or are much larger in any dimension than the fuel hulls, their entry into the crucible or molten batch of metal will have to be controlled. Thus, a second feed system will be required. These larger items, which constitute ~13% of the annual plant throughput, could be fed into the furnace using charge buckets.

State and Type of Development

Experimental and developmental work on Inductoslag furnaces for use in nuclear applications has been ongoing since 1975. Considerable laboratory-scale and cold pilot-scale work and process runs have been made; basic operating parameters, modes, and controls are well defined. Operating parameters and supporting system requirements for a 3X scale-up need to be determined, and the remote operation and maintenance of a production-scale furnace needs to be demonstrated.

Process and/or Equipment. From 1975 to the present, Inductoslag ingot furnace developments have included:

- development of the melting process and equipment by the U.S. Bureau of Mines (USBM) at Albany, Oregon
- evaluation of Inductoslag melting by PNL for consolidation of Zircaloy hulls at the USBM, Albany, Oregon
- design and fabrication of prototype furnace for PNL by Retech, Inc., Ukiah, California
- prototype furnace delivered in 1977 and installed in 1978
- hands-on furnace operation from 1978 to the present; ~60 heats have been conducted including ~30 heats of Zircaloy cladding, 10 of stainless steel, and 20 of titanium alloys; two segments of the crucible have been replaced and it has been realigned once
- valuable design and operating information has been gained that is applicable to future designs or remote applications.

Type and Scale of Development. Developments that will be required prior to actual hot cell operation of an Inductoslag furnace include:

- investigate the capability of Inductoslag melting on a variety of metals
- determine off-gas temperatures and the system to adequately process the contaminated off gases and particulates
- develop and test remote cleaning of sight glasses
- develop and demonstrate the capability of the system to clean the inside of the furnace remotely
- demonstrate remote operation and reliability of large-scale Inductoslag furnace
- identify means to remove and replace the furnace and components remotely
- demonstrate the remote handling of ingots and containers.

Development Time Required. The required design, fabrication, and testing could be done in a period of 24 months.

Safety

Two primary hazards are associated with the Inductoslag melting system in addition to the normal concerns regarding the processing of radioactive material:

- A water leak in the crucible during the melting of zirconium could result in a steam expansion and a simultaneous reaction of the molten metal and water, forming hydrogen. Explosive mixtures of hydrogen and air could be released to the surrounding area or cell.
- Finely divided metallic residues that deposit on interior melt chamber surfaces during normal melting (especially zirconium) are a potential fire hazard when the furnace chamber is opened or air is introduced.

Other potential hazards (crucible failure, spills, etc.) are common to conventional melting of metals. Although the molten metal in this furnace can be up to 1900°C, its volume is relatively small (155 kg). If a water leak ever developed in the crucible, the chances of water being trapped under the molten metal are not very likely due to the size and open bottom design of the crucible.

Since all radioactive material will be processed in shielded hot cells and devices designed for that purpose, the amount of excess radiation exposure will be a function of equipment maintenance and replacement, process accidents, or equipment failures.

Process Requirements

Less process off gases that require treatment will be generated for this melting process than for most others; however, it will require the addition of flux material and a greater number of canisters than the other processes. Although a wide mixture of metals can be safely melted, different metals and nonmetallics will have to be controlled to assure the structural and handling integrity of the ingot. Unless it is possible to use larger diameter crucibles to make bigger ingots, the production capacity of this furnace concept is limited.

Secondary Wastes and Off Gases. As with any melting system, this process will produce off gases that will require treatment. Residue consisting of condensed metallics, slag, and flux will be deposited on the furnace interior.

These and other miscellaneous wastes, cooling water, and process cell ventilation air will require handling and/or treatment.

Production Capacity. Based on the present state of the art, the Inducto-slag ingot mode of operation is limited to ~1-ft diameter ingots. The throughput capacity of a furnace is limited by this factor as well as other more typical factors such as melting rate, available space, and required material handling steps.

Process Additives and Auxiliary Materials/Utilities. This process requires the addition of flux chemicals patterned to the metals to be melted (4 wt%). The power and cooling required per unit of metal throughput are average for melting processes. Gas addition and atmospheric control volumes are about the same as for most melting processes.

Process Versatility and Control. This process will melt a wide variety of metals and, within the limits imposed by the off-gas system, some combustible and nonmetallic materials. The type and amounts of these nonmetallic feed materials would be limited by the need to assure the integrity of the ingot until it could be placed in a canister. To be certain that an ingot is in one piece and suitable for loading into a canister will be a definite quality control checkpoint for this process.

Manpower. Furnace operations are primarily automated and will not require as many personnel as required for the material handling operations to feed the furnace and process the ingots.

Facility Requirements

The facility required to house and support this Inductoslag furnace will be a typical one for highly radioactive processes where both chemical and mechanical processes are involved at multilevels in the building. Thus, it will be considered as the reference facility for evaluation purposes.

Inductoslag - Casting Mode

The assumed 1-ft crucible diameter limit adversely impacts the cost-effective use of this process for this application. It adds to the equipment required and to the cost of operation. The numerical ratings assigned to the Inductoslag casting mode process by the individual evaluators are shown in Tables A.6 through A.9 (see p. A.35). The criteria are discussed below.

Complexity of Process

The projected crucible diameter puts a severe limit on batch size that results in a high number of process steps and requires more time. To meet time constraints, two furnaces would be required, which will add to the complexity of the feed and canister handling systems. Remote operation and maintenance of the required equipment can be expected to provide some problems. Process controls are straightforward, and no special problems are expected if this process is applied remotely.

Material Handling. The steps and processes required to bring the process materials into the facility and feed them into the furnace are the same as those identified for the reference process. Less in-cell handling equipment will be required than for the reference process because there are no starting stubs to be separated from the ingot and recycled nor is there any flux to be removed from the ingot and recycled. The canister is loaded in the furnace and there are no ingots to be moved or transported outside a canister. About one-fourth as many canisters will need to be handled and transported as compared with the reference process.

Consolidation Mode. Batches of molten metal are poured into a canister in the furnace. Otherwise, the consolidation mode is the same as for the reference process.

Maintenance Considerations and Equipment Reliability. The equipment for this melting system is somewhat more reliable than the equipment for the reference system because its furnace crucible is not as vulnerable. The tilt-and-pour mechanism is somewhat less complicated and more reliable than the ingot withdrawal system. Since there is no need for equipment to separate the

starting stub, remove the slag or flux from the ingot, recycle the fluxes and starting stubs, and handle ingots, there will be fewer maintenance requirements than for the reference process.

Controls and Operation. The controls and operation will be very similar to those for the reference process. More batch operations will be required per canister in the furnace, but no ingots and fewer canisters will be produced that require handling.

Adaptability to Remote Operation. Based on experience with laboratory-scale Inductoslag furnaces and consideration of the required process steps and equipment, it is felt that the casting mode of operation would be more applicable to remote operation than the reference ingot process.

Number of Process Steps. Approximately 60 individual furnace steps (mostly short-term batch operations) will be required to fill one large canister after the feed material is loaded in the hoppers. However, 64 steps are required to fill and complete the processing of one canister--the same as that required to process an equal amount of material in the reference process (four 1-ft diameter canisters).

Feasibility for Production. As with the reference process, all phases of the Inductoslag furnace are considered viable for production. However, due to the time required to fill a canister with small batch pours, the furnace capacity will no doubt be the determining throughput factor; and two furnaces may be required to meet production demands.

Feed Limitations. As with the reference process, material larger or heavier than the hulls can only be introduced into the crucible or molten metal pool by closely controlled means. However, rather than a second feed system for this furnace, the larger and heavier pieces of material could be placed in an empty canister prior to its insertion into the furnace. Processing 13% of the facilities throughput in this manner should reduce the overall process requirements of time, power, etc., without any additional complexity.

State and Type of Development

Process and/or Equipment. The state of the development for the casting Inductoslag furnace is the same as for the ingot Inductoslag furnace.

Type and Scale of Development and Time Required. These items are the same as those of the reference process.

Safety

Potential process upsets or considerations that may create safety hazards are the same for this process as for the reference process.

Process Requirements

This mode of operation will require more flux but fewer canisters than the reference process. It has more latitude on process feed materials because the material is cast into a canister. The need for two furnaces to process the required throughput complicates the material handling equipment requirements. If larger diameter crucibles (up to 2-ft diameter) are found to be feasible, a one-furnace operation would provide extra capacity.

Secondary Wastes and Off Gases. Constituents and annual amounts generated will be the same as for the reference process.

Production Capacity. As with the reference process, a 1-ft diameter crucible is considered maximum; the maximum depth of the crucible is ~1.5 times the diameter. These factors limit the capacity and the throughput of an Inductoslag furnace, and two furnaces will be required to meet the projected throughputs and rates.

Process Additives and Auxiliary Materials/Utilities. This process will require about two times more flux feed than the reference process because none of the flux is recycled. Fewer canisters, helium sources, weld material, and about one-third the argon gas will be needed; otherwise, process needs are the same as for the reference process.

Process Versatility and Control. Like the reference process, this process will handle and melt a wide range of metals and mixtures. Because this material is cast inside a canister, a wider range of metal mixes, batches, and foreign materials could be processed without imposing a potential quality control problem of ingot or casting integrity.

Manpower. Due to a longer furnace cycle than the reference process, two furnaces will be required and the process will be run about the same number of days/year as the reference process (160 versus 157 days).

Facility Requirements

The facility required to enclose and support this process with two furnaces will be larger than that identified for the reference process or facility. It is estimated that the required hot cell space would be 1.25 times larger and the supporting facilities would be 1.1 times larger than those of the reference process. Installation would also be more complex than that of the reference process because of the two furnaces and their process feed and removal system requirements.

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TABLE A.3. Inductoslag Ingot Mode System Evaluation - Evaluator A

	Factor Weighting		Rating Assigned	
	Sub	Total	Sub	Total
<u>Complexity of Process</u>		60		373
Material Handling	5		15	
Consolidation Mode	5		40	
Maintenance Considerations and Equipment Reliability	12		72	
Controls and Operation	8		56	
Adaptability to Remote Operation	15		105	
Number of Process Steps	5		25	
Feasibility for Production	5		35	
Feed Limitations	5		25	
<u>State and Type of Development</u>		40		275
Process	5		30	
Equipment	10		80	
Type of Development	10		50	
Scale of Development	10		70	
Development Time Required (from initiation of program)	5		45	
<u>Safety</u>		40		330
Stability and Atmospheric of Process Steps	10		90	
Pyrophoricity, Exothermic, and Explosion Considerations	20		160	
Personnel Radiation Exposure	10		80	
<u>Process Requirements</u>		30		139
Secondary Wastes and Off Gases	5		25	
Production Capacity	4		24	
Process Additives and Auxiliary Materials	5		15	
Process Versatility and Control	5		20	
Quality Assurance	3		15	
Utilities (air, power, water, etc.)	3		15	
Manpower	5		25	
<u>Facility Requirements</u>		30		210
Noncontact Facilities (remote)	10		80	
Contact Facilities (hands-on)	10		80	
Estimated Capital Cost	10		50	
<u>Total</u>				1327

TABLE A.4. Inductoslag Ingot Mode System Evaluation - Evaluator B

	Factor Weighting		Rating Assigned	
	Sub	Total	Sub	Total
<u>Complexity of Process</u>		60		304
Material Handling	5		15	
Consolidation Mode	5		35	
Maintenance Considerations and Equipment Reliability	12		60	
Controls and Operation	8		64	
Adaptability to Remote Operation	15		75	
Number of Process Steps	5		15	
Feasibility for Production	5		20	
Feed Limitations	5		20	
<u>State and Type of Development</u>		40		225
Process	5		25	
Equipment	10		70	
Type of Development	10		50	
Scale of Development	10		40	
Development Time Required (from initiation of program)	5		40	
<u>Safety</u>		40		200
Stability and Atmosphere of Process Steps	10		70	
Pyrophoricity, Exothermic, and Explosion Considerations	20		100	
Personnel Radiation Exposure	10		30	
<u>Process Requirements</u>		30		160
Secondary Wastes and Off Gases	5		25	
Production Capacity	4		20	
Process Additives and Auxiliary Materials	5		40	
Process Versatility and Control	5		30	
Quality Assurance	3		15	
Utilities (air, power, water, etc.)	3		15	
Manpower	5		15	
<u>Facility Requirements</u>		30		190
Noncontact Facilities (remote)	10		60	
Contact Facilities (hands-on)	10		80	
Estimated Capital Cost	10		50	
<u>Total</u>				1079

TABLE A.5. Inductoslag Ingot Mode System Evaluation - Evaluator D

	Factor Weighting		Rating Assigned	
	Sub	Total	Sub	Total
<u>Complexity of Process</u>		60		228
Material Handling	5		15	
Consolidation Mode	5		15	
Maintenance Considerations and Equipment Reliability	12		48	
Controls and Operation	8		40	
Adaptability to Remote Operation	15		45	
Number of Process Steps	5		15	
Feasibility for Production	5		30	
Feed Limitations	5		20	
<u>State and Type of Development</u>		40		220
Process	5		30	
Equipment	10		50	
Type of Development	10		50	
Scale of Development	10		50	
Development Time Required (from initiation of program)	5		40	
<u>Safety</u>		40		150
Stability and Atmosphere of Process Steps	10		80	
Pyrophoricity, Exothermic, and Explosion Considerations	20		40	
Personnel Radiation Exposure	10		30	
<u>Process Requirements</u>		30		172
Secondary Wastes and Off Gases	5		25	
Production Capacity	4		20	
Process Additives and Auxiliary Materials	5		40	
Process Versatility and Control	5		30	
Quality Assurance	3		9	
Utilities (air, power, water, etc.)	3		15	
Manpower	5		25	
<u>Facility Requirements</u>		30		230
Noncontact Facilities (remote)	10		80	
Contact Facilities (hands-on)	10		100	
Estimated Capital Cost	10		50	
<u>Total</u>				1000

TABLE A.6. Inductoslag Casting Mode System Evaluation - Evaluator A

	Factor Weighting		Rating Assigned	
	Sub	Total	Sub	Total
<u>Complexity of Process</u>		60		448
Material Handling	5		45	
Consolidation Mode	5		40	
Maintenance Considerations and Equipment Reliability	12		84	
Controls and Operation	8		64	
Adaptability to Remote Operation	15		120	
Number of Process Steps	5		20	
Feasibility for Production	5		30	
Feed Limitations	5		45	
<u>State and Type of Development</u>		40		295
Process	5		30	
Equipment	10		80	
Type of Development	10		60	
Scale of Development	10		80	
Development Time Required (from initiation of program)	5		45	
<u>Safety</u>		40		300
Stability and Atmosphere of Process Steps	10		90	
Pyrophoricity, Exothermic, and Explosion Considerations	20		120	
Personnel Radiation Exposure	10		90	
<u>Process Requirements</u>		30		162
Secondary Wastes and Off Gases	5		25	
Production Capacity	4		12	
Process Additives and Auxiliary Materials	5		30	
Process Versatility and Control	5		25	
Quality Assurance	3		30	
Utilities (air, power, water, etc.)	3		15	
Manpower	5		25	
<u>Facility Requirements</u>		30		150
Noncontact Facilities (remote)	10		60	
Contact Facilities (hands-on)	10		60	
Estimated Capital Cost	10		30	
<u>Total</u>				1355

TABLE A.7. Inductoslag Casting Mode System Evaluation - Evaluator B

	Factor Weighting		Rating Assigned	
	Sub	Total	Sub	Total
<u>Complexity of Process</u>		60		314
Material Handling	5		20	
Consolidation Mode	5		35	
Maintenance Considerations and Equipment Reliability	12		60	
Controls and Operation	8		64	
Adaptability to Remote Operation	15		75	
Number of Process Steps	5		10	
Feasibility for Production	5		25	
Feed Limitations	5		25	
<u>State and Type of Development</u>		40		230
Process	5		30	
Equipment	10		70	
Type of Development	10		50	
Scale of Development	10		40	
Development Time Required (from initiation of program)	5		40	
<u>Safety</u>		40		220
Stability and Atmosphere of Process Steps	10		90	
Pyrophoricity, Exothermic, and Explosion Considerations	20		100	
Personnel Radiation Exposure	10		30	
<u>Process Requirements</u>		30		113
Secondary Wastes and Off Gases	5		25	
Production Capacity	4		4	
Process Additives and Auxiliary Materials	5		25	
Process Versatility and Control	5		25	
Quality Assurance	3		12	
Utilities (air, power, water, etc.)	3		12	
Manpower	5		10	
<u>Facility Requirements</u>		30		250
Noncontact Facilities (remote)	10		100	
Contact Facilities (hands-on)	10		100	
Estimated Capital Cost	10		50	
<u>Total</u>				1127

TABLE A.8. Inductoslag Casting Mode System Evaluation - Evaluator C

	Factor Weighting		Rating Assigned	
	Sub	Total	Sub	Total
<u>Complexity of Process</u>		60		415
Material Handling	5		25	
Consolidation Mode	5		50	
Maintenance Considerations and Equipment Reliability	12		96	
Controls and Operation	8		64	
Adaptability to Remote Operation	15		90	
Number of Process Steps	5		25	
Feasibility for Production	5		40	
Feed Limitations	5		25	
<u>State and Type of Development</u>		40		270
Process	5		20	
Equipment	10		80	
Type of Development	10		50	
Scale of Development	10		80	
Development Time Required (from initiation of program)	5		40	
<u>Safety</u>		40		240
Stability and Atmosphere of Process Steps	10		90	
Pyrophoricity, Exothermic, and Explosion Considerations	20		100	
Personnel Radiation Exposure	10		50	
<u>Process Requirements</u>		30		205
Secondary Wastes and Off Gases	5		25	
Production Capacity	4		20	
Process Additives and Auxiliary Materials	5		50	
Process Versatility and Control	5		40	
Quality Assurance	3		30	
Utilities (air, power, water, etc.)	3		25	
Manpower	5		25	
<u>Facility Requirements</u>		30		230
Noncontact Facilities (remote)	10		80	
Contact Facilities (hands-on)	10		100	
Estimated Capital Cost	10		50	
<u>Total</u>				1360

TABLE A.9. Inductoslag Casting Mode System Evaluation - Evaluator D

	Factor Weighting		Rating Assigned	
	Sub	Total	Sub	Total
<u>Complexity of Process</u>		60		272
Material Handling	5		25	
Consolidation Mode	5		15	
Maintenance Considerations and Equipment Reliability	12		72	
Controls and Operation	8		40	
Adaptability to Remote Operation	15		60	
Number of Process Steps	5		10	
Feasibility for Production	5		25	
Feed Limitations	5		25	
<u>State and Type of Development</u>		40		220
Process	5		30	
Equipment	10		50	
Type of Development	10		50	
Scale of Development	10		50	
Development Time Required (from initiation of program)	5		40	
<u>Safety</u>		40		150
Stability and Atmosphere of Process Steps	10		80	
Pyrophoricity, Exothermic, and Explosion Considerations	20		40	
Personnel Radiation Exposure	10		30	
<u>Process Requirements</u>		30		143
Secondary Wastes and Off Gases	5		25	
Production Capacity	4		20	
Process Additives and Auxiliary Materials	5		35	
Process Versatility and Control	5		30	
Quality Assurance	3		9	
Utilities (air, power, water, etc.)	3		9	
Manpower	5		15	
<u>Facility Requirements</u>		30		130
Noncontact Facilities (remote)	10		30	
Contact Facilities (hands-on)	10		80	
Estimated Capital Cost	10		20	
<u>Total</u>				915

APPENDIX B

NONCONSUMABLE ELECTRODE MELTING

APPENDIX B

NONCONSUMABLE ELECTRODE MELTING

INTRODUCTION

The nonconsumable electrode melting process can melt a variety of metals of various sizes without contamination from either the electrode or the crucible. Arc melting is achieved by a water-cooled electrode (Figure B.1). The heart of the system is the Rototrode® (Figure B.2); this rotating, current-conducting electrode is electrically and mechanically coupled to a nonconsumable arc-generating surface. The electrode functions without being consumed by the melting arc because of a phenomenon called "arc locking" and because of the ability of the arc-generating surface to be in continuous motion relative to the arc itself. Arc locking can be accomplished geometrically or magnetically, depending on the particular application. The electrode tip is removable and replaceable.

Furnace dc power is supplied by silicon-controlled rectifiers (SCRs) for efficient current regulation and response. A separately valved vacuum chamber allows continuous charging and controlled feeding of process materials. The melt chamber can be operated at vacuums in the micron range or at higher pressures. The arc position is controlled by a joint that allows remote manipulation in the x, y, and z axes. An electrohydraulic servo maintains arc voltage at a predetermined or programmed level. The electrode and melt pool are monitored.

PROCESS DESCRIPTION

This furnace can be operated with different material feeding modes, and it can be used to produce ingots or to cast molten metal into molds or canisters (Figure B.3). One such mode or operational scenario is depicted in Figure B.4. In this batch melting process, a drum containing process material is placed in

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FIGURE B.1. Nonconsumable Electrode Furnace

the crucible and melted. This step is repeated until the crucible is full or until the desired batch size is obtained. The batch is then cooled and removed from the crucible.

In another operational mode (Figure B.5), the process material is fed into the crucible on a continuous basis after the initial charge is melted. The batch of metal is then cooled and handled in the same way as in the first scenario.

FIGURE B.2. Rototrode Electrode for Nonconsumable Electrode Melting System

In the melt-and-pour mode of operation (Figure B.6), the process metal is fed into the furnace as in the previous scenario. However, when the desired melt size is obtained, it is poured into a mold or container. This batch process is repeated until the container is full.

FIGURE B.3. Operational Modes for Nonconsumable Electrode Furnace

In another mode of operation (Figure B.7), the process material is continuously fed from the charge hopper into the furnace crucible, and the solidified metal is withdrawn from the bottom of the crucible as one continuous ingot. An ingot of the desired diameter and length can be produced in one basic operation.

PROCESS NEEDS AND REQUIREMENTS

The nonconsumable electrode melting process will consolidate and solidify the metallic wastes identified in the Process Material Identification section (p. 16). It will be required to produce ~105 ingots (2 ft in diameter by 10 ft

FIGURE B.4. Batch Skull Melting by Adding 55-gal Drums of Metal

FIGURE B.5. Batch Skull Melting with Continuous Feeding

long) or equivalent in a maximum of 300 days, and the facility could be operated 24 h/day. The canisters containing the consolidated process metallics are to be suitable for remote handling and transport and compatible with long-term disposal in a geologic repository.

FIGURE B.6. Batch Skull Melting with Continuous Feeding; Melt Poured Into Canister

FIGURE B.7. Batch Skull Melting with Continuous Feeding; Ingot Withdrawn from Bottom

Furnace Feed

Provisions and equipment to remotely handle and move the process material (hulls and miscellaneous metallic components) to the furnace will be similar to those identified in Appendix A. Cranes and hoists will be used to handle shielded casks and drums of metal. Provisions to empty the drums into a charge hopper and/or charge the full drums into the furnace crucible will be required. No flux feed provisions will be required for this melting process.

Furnace

A view of a furnace concept developed and designed to melt contaminated materials is shown in Figure B.8 (Beitel and Schlipphacke 1978). The furnace contains a centrifugally cast chrome-copper crucible large enough to hold a 55-gal drum containing metal parts. All interior surfaces of the double-walled chamber slope downward; external connections are accessible for remote operation; and the electrode is the only moving part that extends through the vacuum chamber wall (Figure B.9).

The nonconsumable direct arc electrode is designed for a minimum of 40 h of operation at 750 kVA between tip replacement. The electrode is cooled by a high-pressure, closed loop, deionized water system. It is mounted to provide three-dimensional movement within the crucible with adequate travel to initiate an arc ~1 m above the crucible bottom (at the top of the scrap charge) and follow the molten pool to within 15 cm of the crucible bottom. During meltdown, a sweeping movement around the crucible is required to melt all scrap and yet prevent localized overheating.

A furnace designed for batch skull melting (Figures B.8 and B.9) could melt the projected annual facility throughput in 341 days. Batches of ~250 kg would be melted to form a 1000-kg ingot that would be cooled and removed from the furnace. Based on engineering studies, six such ingots could be made in 69 to 70 h. The six ingots would fill a 2-ft diameter by 10-ft long canister ~98% full; 118 canisters would be required for the annual facility throughput.

A furnace designed for batch skull melting with continuous feed as depicted in Figure B.5 could melt the annual facility throughput in ~152 days (see Figure B.10). In this process, the feed material is continuously fed into

FIGURE B.8. Nonconsumable Coldwall Furnace Assembly

FIGURE B.9. Nonconsumable Coldwall Furnace Melt Chamber Assembly

the crucible after the initial charge is melted. When an 1100-kg ingot is formed, it is cooled and removed from the furnace. It has been estimated that five of these ingots could be made in 31 to 32 h. Five ingots would fill a 2-ft diameter by 10-ft long canister 90% full; 117 canisters would be required for the annual facility throughput.

The furnace concept depicted by the flow diagram in Figure B.6 is illustrated in Figure B.11. It has been estimated that this skull melt-and-cast process could handle the annual facility throughput in 131 days. Feed material is continuously fed into the crucible after the initial charge is melted until ~1100 kg of metal has been melted. The crucible is then tilted and ~725 kg of

FIGURE B.10. Batch Skull Melting with Continuous Feeding

FIGURE B.11. Batch Skull Melting; Melt Poured Into Canister

metal is poured into a canister. Eight of these pours would fill a 2-ft diameter by 10-ft long canister 95% full in 28 to 29 h; 111 canisters would be produced annually.

It has been estimated that a furnace of the concept shown in Figure B.1 using the ingot withdrawal mode depicted in Figure B.7 could process the required annual throughput in 92 days. An ~5550-kg ingot could be produced every 19 to 20 h. This ingot would be sized so it could fill a 2-ft diameter by 10-ft long canister ~90% full; 116 canisters would be produced every year.

A furnace ~3 m in diameter and 7 m high would be required for the batch skull melting mode. It has been estimated that a furnace 3 x 5 x 7 m high would suffice for the batch skull melting and ingot withdrawal with a continuous feed scenario. A furnace 5 x 5 x 8 m high will be required for the skull melt-and-pour mode.

Ingot/Canister Handling and Transport

A cart mechanism such as that shown in Figure B.8 could be used for remote batch charging of the furnace and for removal of the ingot from the batch skull melting modes. However, the sequences, equipment, and arrangements identified in Appendix A for the processing of Inductoslag ingots and/or canisters will also be applicable and adaptable for any one of the operating scenarios of the nonconsumable electrode melting process.

FACILITY REQUIREMENTS

Since the size of a furnace for any one of the identified operational modes could be up to twice as large as the Inductoslag furnace, this process will require more hot cell and operational space than that identified in Appendix A.

Off-Gas System

The off-gas system will cool the gases generated during the melting operation and filter out any particulates or volatile fission products that may enter the system. The equipment will be similar to that identified for the Inductoslag process. The estimated flow rates and constituents of an off-gas system for this furnace and its hot cell are summarized below:

<u>Effluent</u>	<u>Flow Rate</u>
Gases (a)	85 m ³ /min
Particulates (b)	4.0 kg/h

(a) From furnace at 600°C and 1/3 atm.

(b) Metal fumes contaminated with radioisotopes.

Secondary Wastes Requiring Processing

Wastes from this melting system that will require processing are listed below:

<u>Material</u>	<u>Amount</u>
Nonradioactive cooling water	900 l/min
Process wastes	10 kg/h
Ventilation flow	600 m ³ /min

Utilities, Services, and Materials

Estimates of the normally required utilities, services, and materials that will be needed for this melting system are noted below and summarized in Table B.1.

Power Supply

The electrode power supply will consist of two systems each with a capacity of 7500 A at 70 V each, providing a nominal heating capacity of 500 kW. The power supply is a solid-state SCR unit.

Water-Cooling System

Water cooling will be applied to the crucible, chamber, electrode, and subsystems to prevent overheating. Because the projected duty cycle (power on) will be low (10%), once-through cooling will be adequate. A maximum flow rate of 900 l/min (230 gpm) will allow a maximum water temperature increase of 20°C. A closed loop water system could reduce the usage to 53 l/min (14 gpm) to cool the heat exchanger.

TABLE B.1. Utilities, Services, and Materials for Nonconsumable Electrode Melting Process

Item	Capacity	Average Rate	Amount/Year
Electricity	900 kW		
Water	1500 ℓ /min	1000 ℓ /min	
Air	850 m^3 /min	600 m^3 /min	
Steam	15 kg/min	2 kg/min	
Canisters	2 ft dia x 10 ft long		111, 117, 118, or 133
He sources			120, 130, 130, or 150
Argon		60 ℓ /min	12,000 m^3
Hydraulics	38 ℓ /min at 140 kg/cm^2		

Vacuum, Argon, and Air Systems

The pumping system shown in Figure B.12 will produce and maintain a base pressure of 1.0 Pa. Two parallel, two-stage pumping systems will each consist

FIGURE B.12. Vacuum Pumping System

of a mechanical booster pump and a compatible backing pump. An argon system with a capacity of ~60 l/min will be required to provide a flush stream past the viewing window and the insulator (Figure B.13). The air system provides for a fixed vacuum above background, if desired, and backfill capability. A 1400-l/s (3000-cfm) blower will provide a slightly negative pressure within the furnace chamber whenever the chamber is opened to prevent metallic dust (or finely divided oxides) from flowing into the room.

Viewing System

Visual observation of the direct arc and molten metal zone is required to control electrode movement in the x-y plane. Positioning in the z-plane during operation is servo-controlled from the arc voltage. The viewing system can be based on a video camera or passive optics, depending on final facility layout.

Jet Cleaner

When steel scrap is arc melted, as much as 2 wt% of the charge is vaporized or volatilized. In a vacuum, most of these fumes are deposited on the cold walls above the melt. This deposit is a poorly adherent, soot-like, finely divided metal powder. By initially coating the clean walls with a detergent film, the adhesive power of the metal particulates can be further reduced. A jet cleaner that can be operated with water or steam at pressures up to 30 MPa (4000 psi) will be used to clean the furnace interior. The nozzles spray in a three-dimensional pattern and can reach almost every internal chamber surface.

FIGURE B.13. Argon and Air System

ASSESSMENT DISCUSSION

Four operational scenarios or modes for the nonconsumable electrode furnace have been identified. Based on the estimated time required to process the annual throughput, the number of individual product packages produced, and handling and encapsulation requirements, it was determined that the melt-and-pour mode of operation (Figure B.6) would be evaluated. The numerical ratings assigned to the process by the individual evaluators are presented in Tables B.2 through B.5 (see p. B.20). The criteria are discussed below.

Complexity of Process

Equipment requirements, process control, and maintenance considerations indicate that the nonconsumable electrode melting furnace will be generally more rugged but will present more operational complexity and maintenance problems than the reference Inductoslag furnace.

Material Handling. The steps and processes required to bring the process materials into the facility and feed them into this furnace are the same as those identified for the reference process. Less in-cell handling equipment will be required for this process because there are no starting stubs to be separated from the ingot/casting and recycled or any flux to be recycled. Canisters will be loaded in the furnace, and no ingots will be moved or transported outside a canister. Fewer canisters will be handled and processed (about one-fourth as many as for the reference process).

Consolidation Mode. The nonconsumable electrode melting process provides a contamination-free heat source that can operate in a vacuum or at low positive pressures. Mechanisms are required to move the electrode in three planes, feed the process material, and pour the molten metal. All functions are performed in a controlled atmosphere.

Maintenance Considerations and Equipment Reliability. The overall reliability of the equipment required for this melting system is considered to be better than that of the reference Inductoslag system. Although the electrode and its system are quite involved (with the exception of the electrode tip), they have proved to be long lived in production. Tips will require changing after ~40 h of melting time. The crucible for this furnace is not as

vulnerable to damage as that of the reference process, and the tilt-and-pour mechanism is considered to be at least as reliable as the ingot withdrawal system. Less maintenance will be required for this system than for the reference process because less remote equipment is required.

Controls and Operation. The controls for and the operation of this furnace are more involved and complex than those for the reference furnace due to the type of electrode and the continual monitoring and manipulation that are required during the melting cycle. The metal feed will be similar to that of the reference process, but no flux feeding is required for this process. The tilt-and-pour operation is a batch-type process that must be initiated at a certain phase of the furnace cycle. Fewer furnace feed operations are needed because no fluxes are required. Since no uncased ingots and fewer canisters of material are produced by this process, fewer batch-type operations and controls are required after melting.

Adaptability to Remote Operation. Like most melting systems, this furnace concept has been remotely operated in industries other than nuclear. A furnace designed for nuclear application has been fabricated but has not been placed in operation (Figures B.8 and B.9). With an adequate development, design, and testing program, no special problems are anticipated in using a production-size furnace in the remote nuclear operational model.

Number of Process Steps. About 48 operations are involved in filling a canister with molten metal after the required feed material is loaded in the hoppers. Fewer operations are required in the complete processing of one canister for this process than for the reference process (54 versus 64).

Feasibility for Production. All steps in the internal operation of the nonconsumable electrode furnace have been performed on a production scale. Some adaptations will need to be identified and incorporated in a fully remote nuclear application (radiation resistance, decontamination, and remote maintenance and replacement considerations). One furnace and its supporting systems are deemed adequate and feasible for the intended production.

Feed Limitations. Material can be fed continuously or with controlled entry batches of at least 55-gal and 250 kg. Thus, two feed systems could be used to feed various sizes of material; large, heavy pieces of material could be placed in an empty canister prior to its insertion into the furnace.

State and Type of Development

Process and/or Equipment. Furnaces larger than the one required for this installation are in production operation in various industries. A furnace of a comparable size designed for use in a fully remote nuclear application has been fabricated but is not yet in operation (Beitel and Schlipphacke 1978).

Type and Scale of Development. Developments that will be required prior to actual hot cell operation of a nonconsumable electrode furnace include:

- investigate the capability of melting a variety of mixtures of metals
- determine off-gas temperatures and the system to adequately process the contaminated off gases and particulates
- test system(s) for the fully remote monitoring of the electrode and molten pool
- develop and demonstrate the remote cleaning of the inside of the furnace
- demonstrate remote operation and reliability of furnace
- identify means to remove and replace the furnace and components remotely
- demonstrate the removal and/or handling of crucible skull buildup
- demonstrate the remote handling of containers.

Development Time Required. The required design, fabrication, and testing could be done in a period of 30 months.

Safety

Three primary hazards are associated with the nonconsumable electrode melting system in addition to the normal concerns regarding the processing of radioactive material:

- A water leak in the crucible or furnace interior during the melting of zirconium could result in a steam expansion and a simultaneous reaction of the molten metal and water, forming hydrogen. Explosive mixtures of hydrogen and air could be released to the surrounding area or cell.
- As compared with the reference process, this furnace system has an added potential source of water contained in the electrode above the surface of the molten pool.
- Finely divided metallic residues that deposit on interior melt chamber surfaces during normal melting (especially zirconium) are a potential fire hazard when the furnace chamber is opened or air is introduced.

Other potential hazards (crucible failure, spills, etc.) are common to conventional melting of metals. For this process, it has been estimated that the maximum amount of molten metal would be ~1100 kg. Its temperature could be as high as 1900°C.

Since all radioactive material will be processed in shielded hot cells and devices designed for that purpose, the amount of excess radiation exposure will be a function of equipment maintenance and replacement, process accidents, or equipment failures.

Process Requirements

Secondary Wastes and Off Gases. The projected flow rates in this off-gas system will be about three times those in the reference process. Other requirements are essentially the same as for the reference process.

Production Capacity. One furnace is more than adequate to meet the projected throughput. This furnace concept could be expanded to handle significant throughput increases.

Process Additives and Auxiliary Materials/Utilities. No special fluxes or chemicals are required for this process. The water-cooling requirements per unit of metal throughput are less than the reference process by 15% to 20%.

However, this process will require about six times more argon than the reference process. The power required per kg of metal will be about the same as for the reference process.

Process Versatility and Control. Like the reference process, this process will handle and melt a wide range of metals and mixtures. Because this material is cast inside a container or canister, a wider range of metal mixes, batches, and foreign materials could be processed without imposing a potential quality control problem of ingot or casting integrity.

Manpower. Due to a shorter furnace cycle than the reference process, this process will run ~131 days/yr.

Facility Requirements

The facility required to enclose and support this process is estimated to be ~1.1 times bigger than that identified for the reference process or facility. However, the complexity of the equipment installation will be similar to that of the reference process.

REFERENCES

Beitel, G. A., and O. B. Schlipphacke. 1978. Vacuum Furnace Development Plan. Rockwell Hanford Operations, Richland, Washington.

TABLE B.2. Nonconsumable Electrode System Evaluation - Evaluator A

	Factor Weighting		Rating Assigned	
	Sub	Total	Sub	Total
<u>Complexity of Process</u>		60		339
Material Handling	5		45	
Consolidation Mode	5		25	
Maintenance Considerations and Equipment Reliability	12		84	
Controls and Operation	8		40	
Adaptability to Remote Operation	15		90	
Number of Process Steps	5		30	
Feasibility for Production	5		40	
Feed Limitations	5		45	
<u>State and Type of Development</u>		40		245
Process	5		35	
Equipment	10		50	
Type of Development	10		60	
Scale of Development	10		60	
Development Time Required (from initiation of program)	5		40	
<u>Safety</u>		40		250
Stability and Atmosphere of Process Steps	10		90	
Pyrophoricity, Exothermic, and Explosion Considerations	20		80	
Personnel Radiation Exposure	10		80	
<u>Process Requirements</u>		30		205
Secondary Wastes and Off Gases	5		15	
Production Capacity	4		24	
Process Additives and Auxiliary Materials	5		40	
Process Versatility and Control	5		35	
Quality Assurance	3		30	
Utilities (air, power, water, etc.)	3		21	
Manpower	5		40	
<u>Facility Requirements</u>		30		170
Noncontact Facilities (remote)	10		70	
Contact Facilities (hands-on)	10		60	
Estimated Capital Cost	10		40	
<u>Total</u>				1269

TABLE B.3. Nonconsumable Electrode System Evaluation - Evaluator B

	Factor Weighting		Rating Assigned	
	Sub	Total	Sub	Total
<u>Complexity of Process</u>		60		389
Material Handling	5		40	
Consolidation Mode	5		30	
Maintenance Considerations and Equipment Reliability	12		84	
Controls and Operation	8		40	
Adaptability to Remote Operation	15		75	
Number of Process Steps	5		30	
Feasibility for Production	5		30	
Feed Limitations	5		70	
<u>State and Type of Development</u>		40		270
Process	5		40	
Equipment	10		60	
Type of Development	10		70	
Scale of Development	10		60	
Development Time Required (from initiation of program)	5		40	
<u>Safety</u>		40		210
Stability and Atmosphere of Process Steps	10		70	
Pyrophoricity, Exothermic, and Explosion Considerations	20		100	
Personnel Radiation Exposure	10		40	
<u>Process Requirements</u>		30		210
Secondary Wastes and Off Gases	5		25	
Production Capacity	4		40	
Process Additives and Auxiliary Materials	5		45	
Process Versatility and Control	5		30	
Quality Assurance	3		18	
Utilities (air, power, water, etc.)	3		12	
Manpower	5		40	
<u>Facility Requirements</u>		30		180
Noncontact Facilities (remote)	10		70	
Contact Facilities (hands-on)	10		70	
Estimated Capital Cost	10		40	
<u>Total</u>				1269

TABLE B.4. Nonconsumable Electrode System Evaluation - Evaluator C

	<u>Factor Weighting</u>		<u>Rating Assigned</u>	
	<u>Sub</u>	<u>Total</u>	<u>Sub</u>	<u>Total</u>
<u>Complexity of Process</u>		60		390
Material Handling	5		25	
Consolidation Mode	5		50	
Maintenance Considerations and Equipment Reliability	12		60	
Controls and Operation	8		80	
Adaptability to Remote Operation	15		60	
Number of Process Steps	5		25	
Feasibility for Production	5		40	
Feed Limitations	5		50	
<u>State and Type of Development</u>		40		290
Process	5		40	
Equipment	10		60	
Type of Development	10		70	
Scale of Development	10		80	
Development Time Required (from initiation of program)	5		40	
<u>Safety</u>		40		240
Stability and Atmosphere of Process Steps	10		90	
Pyrophoricity, Exothermic, and Explosion Considerations	20		100	
Personnel Radiation Exposure	10		50	
<u>Process Requirements</u>		30		260
Secondary Wastes and Off Gases	5		25	
Production Capacity	4		40	
Process Additives and Auxiliary Materials	5		50	
Process Versatility and Control	5		50	
Quality Assurance	3		30	
Utilities (air, power, water, etc.)	3		15	
Manpower	5		50	
<u>Facility Requirements</u>		30		230
Noncontact Facilities (remote)	10		80	
Contact Facilities (hands-on)	10		100	
Estimated Capital Cost	10		50	
<u>Total</u>				1410

TABLE B.5. Nonconsumable Electrode System Evaluation - Evaluator D

	Factor Weighting		Rating Assigned	
	Sub	Total	Sub	Total
<u>Complexity of Process</u>		60		249
Material Handling	5		25	
Consolidation Mode	5		15	
Maintenance Considerations and Equipment Reliability	12		60	
Controls and Operation	8		24	
Adaptability to Remote Operation	15		45	
Number of Process Steps	5		15	
Feasibility for Production	5		30	
Feed Limitations	5		35	
<u>State and Type of Development</u>		40		250
Process	5		30	
Equipment	10		60	
Type of Development	10		60	
Scale of Development	10		60	
Development Time Required (from initiation of program)	5		40	
<u>Safety</u>		40		150
Stability and Atmosphere of Process Steps	10		80	
Pyrophoricity, Exothermic, and Explosion Considerations	20		40	
Personnel Radiation Exposure	10		30	
<u>Process Requirements</u>		30		192
Secondary Wastes and Off Gases	5		15	
Production Capacity	4		32	
Process Additives and Auxiliary Materials	5		45	
Process Versatility and Control	5		35	
Quality Assurance	3		15	
Utilities (air, power, water, etc.)	3		15	
Manpower	5		35	
<u>Facility Requirements</u>		30		200
Noncontact Facilities (remote)	10		60	
Contact Facilities (hands-on)	10		100	
Estimated Capital Cost	10		40	
<u>Total</u>				1041

APPENDIX C

PLASMA ARC MELTING

APPENDIX C

PLASMA ARC MELTING

INTRODUCTION

The plasma arc melting furnace (Figure C.1) uses an argon plasma arc torch to melt various metals and materials into a molten pool in a water-cooled hearth in an airtight chamber. After the molten pool is formed, a solidified ingot is withdrawn; melting and withdrawal are continued until the desired length is attained.

PROCESS DESCRIPTION

The scrap metals or waste materials that will be fed into this melting process will be reduced in size as required for feeding into the hearth from a feed hopper. The scrap metals will be melted by a plasma arc torch positioned as shown in Figure C.1; the plasma arc can be directed and controlled in the x, y, and z axes. Because the plasma arc melting process is not conducive to the formation of deep molten pools in a water-cooled hearth or crucible, the ingot withdrawal mode is the most practical method.

PROCESS NEEDS AND REQUIREMENTS

The process will consolidate and solidify the metallic wastes identified in the Process Material Identification section (p. 16). It will be required to produce ~105 castings or full canisters (2 ft in diameter by 10 ft long) or equivalent in 300 days, and the facility could be operated 24 h/day. The canisters containing the consolidated process metallics are to be suitable for remote handling and transport and compatible with long-term disposal in a geologic repository. The major process equipment required will essentially be the same as that listed in Appendix A (Table A.1) with some differences in capacity.

FIGURE C.1. Plasma Arc Furnace

Furnace

It has been estimated that a plasma furnace similar to the one shown in Figure C.1 using the ingot withdrawal mode could process the required annual throughput in 92 days. An ingot containing ~5540 kg of metal could be produced every 19 h at a melting rate of ~400 kg/h. This ingot would fill a 2-ft diameter by 10-ft long canister ~90% full; 116 canisters would be produced every year. One furnace (3 x 5 x 8 m high) would handle the projected facility throughput.

Furnace Feed and Canister Handling

The systems required to move process material to and from this furnace are basically the same as those identified in Appendix A.

FACILITY REQUIREMENTS

The plasma arc melting system is about the same size as the nonconsumable electrode melting system and could be up to twice as large as either of the Inductoslag furnaces. Thus, a furnace of this process will require more hot cell space than that identified in Appendix A.

Off-Gas System

The estimated flow rates and constituents in the plasma arc melting off-gas system are listed below:

<u>Effluent</u>	<u>Flow Rate</u>
Gases (a)	90 m ³ /min
Particulates (b)	4 kg/h

(a) From Furnace at 300°C and 1 atm.

(b) Metal fumes contaminated with radioisotopes.

Except for the requirement to handle higher flow rates, the off-gas system and its components will be similar to those identified for the Inductoslag processes.

Secondary Wastes Requiring Processing

Wastes from the plasma arc melting system that will require processing are listed below:

<u>Material</u>	<u>Amount</u>
Nonradioactive cooling water	800 L/min
Process wastes	10 kg/h
Ventilation flow	500 m ³ /min

Utilities, Services, and Materials

Estimates of the normally required utilities, services, and materials that will be needed for this process are summarized in Table C.1.

TABLE C.1. Utilities, Services, and Materials
for Plasma Arc Melting Process

<u>Item</u>	<u>Capacity</u>	<u>Average Rate</u>	<u>Amount/Year</u>
Electricity (3500 A, 200 V)	700 kW	2.2 kWh/kg of metal	1,400,000 kWh
Water	1400 L/min	900 L/min	
Air	750 m ³ /min	500 m ³ /min	
Steam	15 kg/h	2 kg/h	
Canisters	2 ft dia x 10 ft long		116
He sources			130
Argon	0.12 m ³ /kg melted		80,000 m ³
Hydraulics	38 L/min at 140 kg/cm ²		

ASSESSMENT DISCUSSION

The numerical ratings assigned to the process by the individual evaluators are presented in Tables C.2 through C.5 (see p. C.8). The criteria are discussed below.

Complexity of Process

The plasma arc furnace is very similar in complexity and requirements to the nonconsumable electrode furnace. However, the need to handle both ingots and canisters adds to the complexity of the process.

Material Handling. Except for the handling of ingots, the steps and equipment required for this process are the same as those required for the non-consumable electrode process (Appendix B).

Consolidation Mode. The plasma arc melting process can melt a wide range of alloys and metals at high production rates in controlled atmospheres.

Maintenance Considerations and Equipment Reliability. The overall reliability of the process equipment is about the same as that of the nonconsumable electrode process. The electrodes and their systems are quite complicated, but production applications have shown them to be reliable and fairly long lived.

Overall maintenance requirements and considerations will be similar to those for the nonconsumable electrode process.

Controls and Operation. The controls for and the operation of this furnace will be comparable to the nonconsumable electrode furnace.

Adaptability to Remote Operation. Various types of plasma arc melting furnaces are being operated for the production of a variety of metal ingots. Recent efforts have been made on the use of plasma furnaces for melting and refining reactive metals and for reducing the volume of radioactive wastes. With an adequate development, design, and testing program, it is felt this concept could be used in a remote nuclear application.

Number of Process Steps. Only about 12 process steps are required to fill a canister after the feed material required is loaded in the hoppers. Approximately 17 steps are required for the complete processing of a canister.

Feasibility for Production. One plasma furnace and its supporting system are considered to be adequate and feasible for this application.

Feed Limitations. Limitations on furnace feeds are similar to those for the reference process (Appendix A).

State and Type of Development

Process and/or Equipment. Plasma furnaces larger than the one required for this application are in production operation. Since 1979, the Japanese have been investigating and conducting cold tests on laboratory-scale furnaces to reduce the volume and stabilize noncombustible solid wastes generated at nuclear power plants (Eguchi et al.).

Type and Scale of Development. Developments that will be required prior to actual hot cell operation of a plasma arc furnace include:

- investigate melting a variety of mixtures of metals
- determine off-gas temperatures and the system to adequately process the contaminated off gases and particulates
- develop system(s) for the fully remote monitoring of the electrodes and the molten pool

- develop and demonstrate systems to feed the furnace and to withdraw the ingots remotely
- demonstrate remote operation and reliability of a large-scale furnace
- identify means to remove and replace the furnace and components remotely
- demonstrate the remote handling of ingots and containers.

Development Time Required. The required design, fabrication, and testing could be done in a period of 36 months.

Safety

Two primary hazards are associated with the plasma arc melting system in addition to the normal concerns regarding the processing of radioactive material:

- A water leak in the crucible during melting of zirconium could result in a steam expansion and a simultaneous reaction of the molten metal and water, forming hydrogen. Explosive mixtures of hydrogen and air could be released to the surrounding area or cell.
- Finely divided metallic residues that deposit on interior melt chamber surfaces during normal melting (especially zirconium) are a potential fire hazard when the furnace chamber is opened or air is introduced.

Other potential hazards (crucible failure, spills, etc.) are common to conventional melting of metals. For this ingot process, it has been estimated that the maximum amount of molten metal would be ~300 kg. Its temperature could be as high as 1900°C.

Since all radioactive material will be processed in shielded hot cells and devices designed for that purpose, the amount of excess radiation exposure will be a function of equipment maintenance and replacement, process accidents, or equipment failures.

Process Requirements

Secondary Wastes and Off Gases. The projected flow rates in this off-gas system will be about three times those in the reference process (Appendix A).

Other requirements are essentially the same as for the reference process.

Production Capacity. One furnace is more than adequate to meet the projected throughput. For the current throughput, the furnace will operate only ~92 days/yr; thus, this furnace concept has the capability to handle significant throughput increases.

Process Additives and Auxiliary Materials/Utilities. No special fluxes or chemicals are required for this process. The power and water cooling requirements per unit of metal throughput are less than for the reference process by ~20%. However, this process will require about 40 times more gas than the reference process.

Process Versatility and Control. Like the reference process, this process will handle and melt a wide range of metals and mixtures that must be controlled to assure ingot integrity.

Manpower. Due to a shorter furnace cycle than the reference process, this process will only need to be run about 92 days/yr.

Facility Requirements

The facility required to enclose and support this process is anticipated to be ~1.1 times bigger than that identified for the reference process or facility. The complexity of the equipment will be similar.

REFERENCES

Beitel, G. A., and O. B. Schlipphacke. 1978. Vacuum Furnace Development Plan. Rockwell Hanford Operations, Richland, Washington.

Eguchi, I., et al. Processing of Nuclear Wastes by Plasma Arc Melting. Daido Steel Co., Ltd., Nagoya, Japan.

TABLE C.2. Plasma Arc System Evaluation - Evaluator A

	<u>Factor Weighting</u>		<u>Rating Assigned</u>	
	<u>Sub</u>	<u>Total</u>	<u>Sub</u>	<u>Total</u>
<u>Complexity of Process</u>		60		376
Material Handling	5		25	
Consolidation Mode	5		30	
Maintenance Considerations and Equipment Reliability	12		84	
Controls and Operation	8		32	
Adaptability to Remote Operation	15		90	
Number of Process Steps	5		45	
Feasibility for Production	5		40	
Feed Limitations	5		30	
<u>State and Type of Development</u>		40		220
Process	5		35	
Equipment	10		50	
Type of Development	10		50	
Scale of Development	10		50	
Development Time Required (from initiation of program)	5		35	
<u>Safety</u>		40		270
Stability and Atmosphere of Process Steps	10		90	
Pyrophoricity, Exothermic, and Explosion Considerations	20		120	
Personnel Radiation Exposure	10		60	
<u>Process Requirements</u>		30		176
Secondary Wastes and Off Gases	5		15	
Production Capacity	4		32	
Process Additives and Auxiliary Materials	5		35	
Process Versatility and Control	5		20	
Quality Assurance	3		15	
Utilities (air, power, water, etc.)	3		24	
Manpower	5		35	
<u>Facility Requirements</u>		30		170
Noncontact Facilities (remote)	10		70	
Contact Facilities (hands-on)	10		60	
Estimated Capital Cost	10		40	
<u>Total</u>				1212

TABLE C.3. Plasma Arc System Evaluation - Evaluator B

	<u>Factor Weighting</u>		<u>Rating Assigned</u>	
	<u>Sub</u>	<u>Total</u>	<u>Sub</u>	<u>Total</u>
<u>Complexity of Process</u>		60		302
Material Handling	5		20	
Consolidation Mode	5		25	
Maintenance Considerations and Equipment Reliability	12		72	
Controls and Operation	8		40	
Adaptability to Remote Operation	15		75	
Number of Process Steps	5		25	
Feasibility for Production	5		25	
Feed Limitations	5		20	
<u>State and Type of Development</u>		40		235
Process	5		35	
Equipment	10		50	
Type of Development	10		60	
Scale of Development	10		50	
Development Time Required (from initiation of program)	5		40	
<u>Safety</u>		40		235
Stability and Atmosphere of Process Steps	10		70	
Pyrophoricity, Exothermic, and Explosion Considerations	20		120	
Personnel Radiation Exposure	10		40	
<u>Process Requirements</u>		30		151
Secondary Wastes and Off Gases	5		5	
Production Capacity	4		40	
Process Additives and Auxiliary Materials	5		35	
Process Versatility and Control	5		25	
Quality Assurance	3		12	
Utilities (air, power, water, etc.)	3		9	
Manpower	5		25	
<u>Facility Requirements</u>		30		170
Noncontact Facilities (remote)	10		70	
Contact Facilities (hands-on)	10		70	
Estimated Capital Cost	10		30	
<u>Total</u>				1088

TABLE C.4. Plasma Arc System Evaluation - Evaluator C

	Factor Weighting		Rating Assigned	
	Sub	Total	Sub	Total
<u>Complexity of Process</u>		60		365
Material Handling	5		25	
Consolidation Mode	5		50	
Maintenance Considerations and Equipment Reliability	12		60	
Controls and Operation	8		80	
Adaptability to Remote Operation	15		60	
Number of Process Steps	5		25	
Feasibility for Production	5		40	
Feed Limitations	5		25	
<u>State and Type of Development</u>		40		310
Process	5		40	
Equipment	10		80	
Type of Development	10		70	
Scale of Development	10		80	
Development Time Required (from initiation of program)	5		40	
<u>Safety</u>		40		240
Stability and Atmosphere of Process Steps	10		90	
Pyrophoricity, Exothermic, and Explosion Considerations	20		100	
Personnel Radiation Exposure	10		50	
<u>Process Requirements</u>		30		245
Secondary Wastes and Off Gases	5		25	
Production Capacity	4		40	
Process Additives and Auxiliary Materials	5		50	
Process Versatility and Control	5		50	
Quality Assurance	3		15	
Utilities (air, power, water, etc.)	3		15	
Manpower	5		50	
<u>Facility Requirements</u>		30		230
Noncontact Facilities (remote)	10		80	
Contact Facilities (hands-on)	10		100	
Estimated Capital Cost	10		50	
<u>Total</u>				1390

TABLE C.5. Plasma Arc System Evaluation - Evaluator D

	<u>Factor Weighting</u>		<u>Rating Assigned</u>	
	<u>Sub</u>	<u>Total</u>	<u>Sub</u>	<u>Total</u>
<u>Complexity of Process</u>		60		239
Material Handling	5		20	
Consolidation Mode	5		20	
Maintenance Considerations	12		60	
Equipment and Reliability				
Controls and Operation	8		24	
Adaptability to Remote Operation	15		45	
Number of Process Steps	5		20	
Feasibility for Production	5		30	
Feed Limitations	5		20	
<u>State and Type of Development</u>		40		210
Process	5		25	
Equipment	10		50	
Type of Development	10		50	
Scale of Development	10		50	
Development Time Required (from initiation of program)	5		35	
<u>Safety</u>		40		150
Stability and Atmosphere of Process Steps	10		80	
Pyrophoricity, Exothermic, and Explosion Considerations	20		40	
Personnel Radiation Exposure	10		30	
<u>Process Requirements</u>		30		184
Secondary Wastes and Off Gases	5		15	
Production Capacity	4		32	
Process Additives and Auxiliary Materials	5		40	
Process Versatility and Control	5		30	
Quality Assurance	3		12	
Utilities (air, power, water, etc.)	3		15	
Manpower	5		40	
<u>Facility Requirements</u>		30		200
Noncontact Facilities (remote)	10		60	
Contact Facilities (hands-on)	10		100	
Estimated Capital Cost	10		40	
<u>Total</u>				983

APPENDIX D

ELECTROSLAG MELTING

APPENDIX D

ELECTROSLAG MELTING

INTRODUCTION

A process flow diagram of an Electroslag melting system for the solidification of plutonium-contaminated metallic wastes is shown in Figure D.1 (Ochiai et al. 1982). Electroslag process metal is melted in molten slag held in a joule-heated furnace. The furnace operates on the principle that the molten solution will conduct electricity, therefore making it possible to pass alternating current through electrodes on each side of the furnace to generate heat in the slag/metal mixture.

PROCESS DESCRIPTION

The Japanese are using water-cooled copper molds, and nonconsumable tungsten electrodes have been used. A mixture of $\text{CaO}/\text{Al}_2\text{O}_3/\text{B}_2\text{O}_3$ has been found to be a satisfactory slag material for the waste presently melted by the Japanese. However, this slag would not be appropriate for melting zirconium because the zirconium would reduce the oxide slag. Calcium fluoride or some similar non-oxide slag would have to be used. The stool-arc method has been determined to be the best for the initial slag melting.

FIGURE D.1. Process Flow Diagram of Electroslag Melting Process

Scrap metals to be fed into this process will have been reduced to a size that can be handled by the furnace feed mechanisms. The scrap metal is fed into the furnace and deposited by controlled means on top of the molten slag or mixture of metal/slag as shown in Figure D.2 (Ochiai et al. 1982). After melting, the metal gradually solidifies in the lower portion of the furnace mold.

An inert gas is required in the furnace to prevent oxidation of the electrodes, and the pressure in the furnace is kept at $\sim 1/3$ atmosphere. To permit the removal of the solidified ingot, the mold is divided into halves. Thus, the ingot and the solidified slag can be moved from the furnace and separated. The slag is crushed and recycled, and the ingot is placed in a container or canister.

PROCESS NEEDS AND REQUIREMENTS

The process will consolidate and solidify the metallic wastes identified in the Process Material Identification section (p. 16). It will be required to

PIECES OF METAL ARE DEPOSITED BETWEEN THE NON-
CONSUMABLE TUNGSTEN ELECTRODES AND MELTED

FIGURE D.2. Electroslag Melting Furnace

produce ~105 ingots (2 ft in diameter by 10 ft long) or equivalent in 300 days, and the facility could be operated 24 h/day. The canisters containing the consolidated process metallics are to be suitable for remote handling and transport and compatible with long-term disposal in a geologic repository. The major remote process equipment that will be required is listed in Table D.1.

TABLE D.1. Major Remote Equipment for Electroslag Melting Process

<u>Equipment</u>	<u>Capacity</u>
Crane hoist	60 tons
Storage crane hoist	10 tons
Drum dumper crane and hoist	10 tons
Drum dumper	--
Charge hopper	--
Feeder	--
Melter	--
Ingot/canister handling system	--
Cooler	--
Slag recycle system	--
Canister welder	--
Canister leak test station	--
Canister decontamination station	--
Cell cranes and manipulators	--
Quench tower	--
Venturi scrubber	--
De-entrainer	--
Steam vacuum jet	--
Spray condenser	--
Scrubber recycle tank	--
Scrubber solution cooler	--
Off-gas heater	--
Off-gas primary filters	--
Ruthenium absorbers	--
Off-gas reheaters	--
Final filters	--
Off-gas blowers	--
Scrubber solution air lift pot	--

Furnace Feed

Provisions and equipment similar to those shown in Figure A.5 will be required to handle and move the process feed material to the furnace. A charge hopper with the capacity to hold up to 1 day's throughput (150 ft³ and 4500 kg) will be required above and close to the furnace. It is connected to the center cavity of the furnace with a system that will move the feed material (6 x 6 x 6 in. or less) into the furnace on a demand and controlled basis without voiding the atmospheric control of the furnace. The slag feed system is also connected to the upper portion of the furnace. The system introduces the desired slag mixture into the furnace mold on a controlled and fast-feed basis. It is supplied and fed with new or recycled slag material.

Furnace

An Electroslag melting furnace similar to the one shown in Figure D.3 (Ochiai et al. 1982) will be required. Six 900-kg ingots would fill a 2-ft diameter by 10-ft long canister ~88% full. It has been estimated that these ingots could be produced in ~54 h; 119 canisters would be required for the annual facility throughput. A furnace ~8 x 12 x 18 ft high would be required.

FIGURE D.3. Electroslag Melting Furnace

Ingot and Canister Handling

The system required to close and handle canisters after they are filled will be the same as that identified in Appendix A for the processing of canisters. Recycling slag, handling ingots, and inserting ingots into a canister will require more equipment than identified in Appendix A.

FACILITY REQUIREMENTS

Since the projected size of an Electroslag furnace is similar to that estimated for an Inductoslag furnace, it is assumed that with some reconfiguration of the facility this furnace would fit into the basic facility arrangements shown in Figures A.5, A.7, and A.8. Due to the need to recycle flux and to handle and canisterize a number of small ingots, it has been estimated that this process would need a total hot cell volume ~1.25 times larger than that identified for the handling of ingots and canisters in Appendix A.

Off-Gas System

The estimated flow rates and constituents in the Electroslag melting off-gas system are listed below:

<u>Effluent</u>	<u>Flow Rate</u>
Gases (a)	90 m ³ /min
Particulates (b,c)	4.0 kg/h

(a) From furnace at 600°C and 1/3 atm.

(b) Metal fumes contaminated with radioisotopes.

(c) Also includes CaO, Al₂O₃, B₂O₃, and WO₃ particles (~0.42 g/Nm³).

Except for the requirement to handle higher flow rates, the system and its components will be similar to those identified for the Inductoslag processes.

Secondary Wastes Requiring Processing

Wastes from the Electroslag melting system that will require processing are listed below:

<u>Material</u>	<u>Amount</u>
Nonradioactive cooling water	1000 ℓ /min
Process wastes	10 kg/h
Ventilation flow	600 m^3 /min

Utilities, Services, and Materials

Estimates of the normally required utilities, services, and materials that will be required for the Electroslag melting system are indicated in Table D.2.

ASSESSMENT DISCUSSION

The numerical ratings assigned to the process by the individual evaluators are shown in Tables D.3 through D.6 (see p. D.11). The criteria are discussed below.

Complexity of Process

Due to the need to handle a large number of ingots and insert several into each canister, the material handling equipment will be very involved. Separating and recycling the slag also adds to the process complexity. Furnace operational and control requirements are more complex than those of the reference Inductoslag furnace.

TABLE D.2. Utilities, Services, and Materials
for Electroslag Melting Process

<u>Item</u>	<u>Capacity</u>	<u>Average Rate</u>	<u>Amount/Year</u>
Electricity	1200 kVA	960 kW	642,000 kW/h
Water	1800 ℓ /min	1200 ℓ /min	
Air	900 m^3 /min	600 m^3 /min	
Steam	15 kg/h	2 kg/h	
Slag: Ca_2O			6100 kg
Al_2O_3			6200 kg
B_2O_3			650 kg
Canisters	2 ft dia x 10 ft long		118
He sources			125
Argon			2300 m^3

Material Handling. The steps and equipment required for this process are more complex than those required for the reference process.

Consolidation Mode. The Electroslag melting process utilizes the joule-heating concept where electrical current passes through the slag/metal mixture located between two nonconsumable electrodes.

Maintenance Considerations and Equipment Reliability. The equipment required for this melting system is considered to be about as reliable as that of the reference system. The nonconsumable tungsten electrodes and their systems and life expectancy are more involved and shorter lived than comparable parts of the reference process, but the mold or crucible is not as vulnerable. Removing the ingots from the furnace, recycling slag, and filling the canisters with several ingots will require more equipment and introduce more maintenance concerns than the reference process.

Controls and Operation. The controls for and the operation of this process are considered to be more complex than those of the reference process.

Adaptability to Remote Operations. A pilot plant-scale furnace has been designed for operation in an a-tight glove box (Ochiai et al. 1982). Similar larger furnaces with consumable electrodes are being operated in various industries. After an adequate development, design, and testing program, it is felt this concept could be operated and maintained under fully remote nuclear applications.

Number of Process Steps. Approximately 43 process steps are required to fill one canister with ingots after the required feed material is loaded in the hoppers. The number of operations involved in the complete processing of one canister is less for this process than that required to process an equivalent amount of material in the reference process (48 versus 64).

Feasibility for Production. One Electroslag furnace and supporting system are deemed adequate and feasible for this application.

Feed Limitations. This furnace would have fewer feed limitations than the reference furnace.

State and Type of Development

Process and/or Equipment. Similar larger furnaces with consumable electrodes are in production operation in various industries. As noted above, a pilot-scale furnace has been designed for operation in a glove box.

Type and Scale of Development. Developments that will be required prior to actual hot cell operation of an Electroslag furnace include:

- investigate the capability of melting a variety of mixtures of metals including zirconium and determine what fluxes are required
- determine off-gas temperatures and the system to adequately process the contaminated off gases and particulates
- develop systems to remotely monitor furnace operation
- develop and demonstrate systems to feed the furnace remotely
- demonstrate remote operation and reliability of large-scale furnace
- identify means to remove and replace the furnace and components remotely
- demonstrate the remote handling of ingots and containers.

Development Time Required. The required design, fabrication, and testing could be done in a period of 36 months.

Safety

Two primary hazards are associated with the Electroslag melting system in addition to the normal concerns regarding the processing of radioactive materials:

- A water leak in the crucible during melting of zirconium could result in a steam expansion and a simultaneous reaction of the molten metal and water, forming hydrogen. Explosive mixtures of hydrogen and air could be released to the surrounding area or cell.
- Finely divided metallic residues that deposit on the interior melt chamber surfaces during normal melting (especially zirconium) are a potential fire hazard when the furnace chamber is opened or air is introduced.

Other potential hazards (crucible failure, spills, etc.) are common to conventional melting of metals. For this ingot process, it has been estimated that the maximum amount of molten metal at any time would be ~300 kg. Its temperature could be as high as 1900°C.

Since all radioactive material will be processed in shielded hot cells and devices designed for that purpose, the amount of excess radiation exposure would be a function of equipment maintenance and replacement, process accidents, or equipment failures.

Process Requirements

Secondary Wastes and Off Gases. The projected flow rates in this off-gas system will be about three times those of the reference process. Other requirements are essentially the same as those of the reference process.

Production Capacity. One furnace would appear to be adequate for the projected throughput; however, it would not be capable of handling any significant increases.

Process Additives and Auxiliary Materials/Utilities. Additional chemicals and fluxes are required for this process. The gas, power, and cooling water requirements are similar to those of the reference process.

Process Versatility and Control. This process will melt various metals with a wide melting range and/or mixtures. Within the limits imposed by an off-gas system, this process can be fed some combustible and nonmetallic materials. In addition, the type and amount of nonmetallic feed materials would be limited by the need to assure the integrity of the ingot until it can be placed in a canister. Ascertaining that an ingot is in one piece and suitable for loading into a canister will be a definite quality control checkpoint for this process.

Manpower. Due to a longer furnace cycle than the reference process, more operating manpower will be required. The process will be run ~268 days/yr.

Facility Requirements

The facility required to enclose and support this process will be somewhat larger than that identified for the reference process or facility. Equipment complexity will be similar.

REFERENCES

Ochiai, A., et al. 1982. "Treatment of Plutonium-Contaminated Metallic Wastes by Electroslag Melting Method." Presented at International Symposium on the Conditioning of Radioactive Wastes for Storage and Disposal, June 1982, Utrecht, The Netherlands.

TABLE D.3. Electroslag System Evaluation - Evaluator A

	<u>Factor Weighting</u>		<u>Rating Assigned</u>	
	<u>Sub</u>	<u>Total</u>	<u>Sub</u>	<u>Total</u>
<u>Complexity of Process</u>		60		331
Material Handling	5		10	
Consolidation Mode	5		35	
Maintenance Considerations and Equipment	12		48	
Reliability				
Controls and Operation	8		48	
Adaptability to Remote Operation	15		75	
Number of Process Steps	5		35	
Feasibility for Production	5		45	
Feed Limitations	5		35	
<u>State and Type of Development</u>		40		240
Process	5		35	
Equipment	10		70	
Type of Development	10		50	
Scale of Development	10		50	
Development Time Required (from initiation of program)	5		25	
<u>Safety</u>		40		240
Stability and Atmosphere of Process Steps	10		90	
Pyrophoricity, Exothermic, and Explosion Considerations	20		100	
Personnel Radiation Exposure	10		50	
<u>Process Requirements</u>		30		130
Secondary Wastes and Off Gases	5		15	
Production Capacity	4		20	
Process Additives and Auxiliary Materials	5		30	
Process Versatility and Control	5		20	
Quality Assurance	3		15	
Utilities (air, power, water, etc.)	3		15	
Manpower	5		15	
<u>Facility Requirements</u>		30		80
Noncontact Facilities (remote)	10		80	
Contact Facilities (hands-on)	10		50	
Estimated Capital Cost	10		50	
<u>Total</u>				1121

TABLE D.4. Electroslag System Evaluation - Evaluator B

	Factor Weighting		Rating Assigned	
	Sub	Total	Sub	Total
<u>Complexity of Process</u>		60		260
Material Handling	5		15	
Consolidation Mode	5		20	
Maintenance Considerations and Equipment Reliability	12		60	
Controls and Operation	8		40	
Adaptability to Remote Operation	15		60	
Number of Process Steps	5		20	
Feasibility for Production	5		25	
Feed Limitations	5		20	
<u>State and Type of Development</u>		40		230
Process	5		30	
Equipment	10		50	
Type of Development	10		60	
Scale of Development	10		50	
Development Time Required (from initiation of program)	5		40	
<u>Safety</u>		40		220
Stability and Atmosphere of Process Steps	10		70	
Pyrophoricity, Exothermic, and Explosion Considerations	20		100	
Personnel Radiation Exposure	10		50	
<u>Process Requirements</u>		30		134
Secondary Wastes and Off Gases	5		15	
Production Capacity	4		20	
Process Additives and Auxiliary Materials	5		30	
Process Versatility and Control	5		20	
Quality Assurance	3		12	
Utilities (air, power, water, etc.)	3		12	
Manpower	5		25	
<u>Facility Requirements</u>		30		190
Noncontact Facilities (remote)	10		70	
Contact Facilities (hands-on)	10		70	
Estimated Capital Cost	10		50	
<u>Total</u>				1034

TABLE D.5. Electroslag System Evaluation - Evaluator C

	Factor Weighting		Rating Assigned	
	Sub	Total	Sub	Total
<u>Complexity of Process</u>		60		228
• Material Handling	5		5	
Consolidation Mode	5		25	
Maintenance Considerations and Equipment Reliability	12		60	
• Controls and Operation	8		48	
Adaptability to Remote Operation	15		30	
Number of Process Steps	5		5	
Feasibility for Production	5		30	
Feed Limitations	5		25	
<u>State and Type of Development</u>		40		145
Process	5		20	
Equipment	10		20	
Type of Development	10		50	
Scale of Development	10		30	
Development Time Required (from initiation of program)	5		25	
<u>Safety</u>		40		240
Stability and Atmosphere of Process Steps	10		90	
Pyrophoricity, Exothermic, and Explosion Considerations	20		90	
Personnel Radiation Exposure	10		50	
<u>Process Requirements</u>		30		150
Secondary Wastes and Off Gases	5		5	
Production Capacity	4		20	
Process Additives and Auxiliary Materials	5		50	
Process Versatility and Control	5		40	
Quality Assurance	3		15	
Utilities (air, power, water, etc.)	3		15	
Manpower	5		5	
<u>Facility Requirements</u>		30		230
Noncontact Facilities (remote)	10		80	
Contact Facilities (hands-on)	10		100	
Estimated Capital Cost	10		50	
<u>Total</u>				993

TABLE D.6. Electroslag System Evaluation - Evaluator D

	<u>Factor Weighting</u>		<u>Rating Assigned</u>	
	<u>Sub</u>	<u>Total</u>	<u>Sub</u>	<u>Total</u>
<u>Complexity of Process</u>		60		198
Material Handling	5		10	
Consolidation Mode	5		15	
Maintenance Considerations and Equipment Reliability	12		36	
Controls and Operation	8		32	
Adaptability to Remote Operation	15		30	
Number of Process Steps	5		20	
Feasibility for Production	5		30	
Feed Limitations	5		25	
<u>State and Type of Development</u>		40		225
Process	5		30	
Equipment	10		60	
Type of Development	10		50	
Scale of Development	10		50	
Development Time Required (from initiation of program)	5		35	
<u>Safety</u>		40		140
Stability and Atmosphere of Process Steps	10		80	
Pyrophoricity, Exothermic, and Explosion Considerations	20		40	
Personnel Radiation Exposure	10		20	
<u>Process Requirements</u>		30		147
Secondary Wastes and Off Gases	5		15	
Production Capacity	4		28	
Process Additives and Auxiliary Materials	5		35	
Process Versatility and Control	5		30	
Quality Assurance	3		9	
Utilities (air, power, water, etc.)	3		15	
Manpower	5		15	
<u>Facility Requirements</u>		30		210
Noncontact Facilities (remote)	10		70	
Contact Facilities (hands-on)	10		100	
Estimated Capital Cost	10		40	
<u>Total</u>				920

APPENDIX E

VACUUM CORELESS INDUCTION MELTING

APPENDIX E

VACUUM CORELESS INDUCTION MELTING

INTRODUCTION

In the vacuum induction melting process, metals are melted by induction heating under a protective atmosphere and/or a vacuum. There are basically two types of induction furnaces: the core or channel-type furnace (Figure E.1) and the coreless or crucible furnace (Figure E.2) (Kotzin 1972). The high-frequency induction furnaces operate on the principle of an air-cored transformer with the charge representing the short-circuited secondary winding of a single-turn coil. High-frequency power is used to decrease the current penetration and increase the heating effect. Although both furnaces induce current into the metal to be melted, the number of coil designs, power sources, and frequencies used with these furnaces have shown that one type will work better than the other in many given melting situations.

FIGURE E.1. Cored Induction Furnace

FIGURE E.2. Coreless Induction Furnace

The coreless high-frequency furnace will be the only type considered for this application. It can be started with a cold charge, poured empty, and has a wider range capacity than the channel-type furnace. The coreless-type furnace imposes no theoretical limitation on capacity or kW rating.

Induction furnaces with melting capacities of ~500 to 2000 lb and larger normally use a rammed oxide refractory as the crucible. The reference metallic wastes include Zircaloy hulls that cannot be melted in an oxide refractory crucible because of the intense reactivity between molten zirconium and oxide refractories. However, past work has shown that Zircaloy hulls form a low melting eutectic mixture of zirconium with iron, nickel, and chromium; and they

can be melted in a graphite crucible (Nelson and Griggs 1976). A metal/crucible reaction still occurs, but the crucibles can be reused for an undetermined number of heats. The low melting eutectics occur at the approximate composition of the fuel bundle residues.

Other work (Westerman 1962) has shown that pure zirconium can be melted in graphite crucibles and held for 20 min at $\sim 2000^{\circ}\text{C}$ with a carbon pickup of 0.41 ± 0.05 wt%. Since this is the approximate saturation level of carbon in zirconium, it follows that multiple heats could be made and poured from a graphite crucible before the crucible would have to be replaced. The melting of stainless steel has shown that multiple heats can be made in clay/graphite crucibles without undue erosion or wear of the crucible. Thus, graphite crucibles would be used to melt Zircaloy hulls and/or eutectic mixtures of Zircaloy plus iron, nickel, and chrome. Clay/graphite crucibles would be used to melt stainless steel and nonferrous metals or alloys like copper and aluminum. The core or channel-type furnace is only applicable for the tilt-and-pour method of casting molten metal. The coreless or crucible furnace would be applicable for either pouring method. The bottom pour method is illustrated in Figure E.3; the tilt-and-pour method, in Figure E.4. In the bottom pour mode, furnace components such as the induction coil and the crucible will be replaceable as modules (Figure E.5).

PROCESS NEEDS AND REQUIREMENTS

With a melting rate of ~ 1400 kg/h and a maximum molten pool of metal of 1400 kg, this casting mode would require ~ 71 days to process 642,210 kg of metallic waste from a 1500-MTU/yr processing plant. About 118 canisters 90% full would be required. It is estimated that four heats would be made per crucible liner or one liner per canister. Assuming that the secondary waste liner weighs ~ 68 kg and an incineration reduction factor of at least 10:1, the crucible waste would be 900 kg/yr.

Furnace Feed and Canister Handling

The systems required to move process material to and from the vacuum melting furnace are basically the same as those identified in Appendix A. Process material could be fed to the top of the furnace using 55-gal barrels. Several

FIGURE E.3. Bottom Pour Stationary Crucible for Vacuum Induction Melting Process

FIGURE E.4. Tilt-and-Pour Method for Vacuum Induction Melting Process

FIGURE E.5. Induction Melting Coil and Crucible Modules

barrels could be fed without interrupting the furnace atmosphere, or bulk scrap could be side fed into the crucible from an air lock feeder system. This feeder system would hold enough metal to fill one or more canisters when melted. When feeding bulk metal pieces using the feeder chute, the maximum dimension should be 6 x 6 x 6 in. because of the danger of damaging the crucible or splashing an excessive amount of molten metal. For this reason, it may be prudent to segregate the metals by alloy and size and feed the hulls through the feeder system. Larger pieces could be charged into the crucible in a charging bucket or in 55-gal barrels. Another option would be to place the larger pieces in a canister and encapsulate them with molten metal poured from

the crucible. Obviously, the metal would have to be placed in the canister so that the molten metal penetrated the interstices and flowed around the pieces, effectively encapsulating them within the canister.

Furnace Operation

Enough scrap metal is charged to the feed hopper to fill the canister with solidified ingot. If 55-gal barrels of metal are to be used as the charge, an air locked charging system allows the charging of one barrel at a time to the crucible without interrupting the furnace atmosphere. The power to the induction coil is turned on, and the charge is fed and melted until ~1365 kg of metal is melted in the crucible. If the metal is poured by the bottom pour method, the chill block is lowered and swung to one side. The power to the small induction coil is activated; and the freeze plug and other frozen metal in the sprue area are melted, allowing the majority of molten metal to flow into the canister. This process is repeated three times before the canister is 90% full. If the tilt-and-pour method is issued, the metal would be poured into the canister by tilting the crucible and pouring the metal over the lip of the crucible.

FACILITY REQUIREMENTS

Since the size of the induction melter is similar to that of the Inducto-slag melters, it is assumed that this furnace would fit into the facility arrangements shown in Figures A.5, A.7, and A.8 with some rearrangement.

Off-Gas System

The estimated flow rates and constituents in the vacuum induction melting off-gas system are listed below:

<u>Effluent</u>	<u>Flow Rate</u>
Gases (a)	30 m ³ /min
Particulates (b)	4.0 kg/h

(a) From furnace at 600°C and 1/3 atm.

(b) Metal fumes contaminated with radioisotopes.

Secondary Wastes Requiring Processing

Wastes from the vacuum induction melting system that will require processing are listed below:

<u>Material</u>	<u>Amount</u>
Nonradioactive cooling water	1000 l/min
Process wastes	15 kg/h
Ventilation flow	500 m ³ /min

Utilities, Services, and Materials

Estimates of the normally required utilities, services, and materials that will be required for the vacuum induction melting system are indicated in Table E.1.

ASSESSMENT DISCUSSION

The numerical ratings assigned to the process by the individual evaluators are presented in Tables E.2 through E.5 (see p. E.12). The criteria are discussed below.

Complexity of Process

Material Handling. The equipment and the steps required to handle the various process materials are considered to be about the same as those required for the nonconsumable electrode process (Appendix B).

Consolidation Mode. As implied by its name, the vacuum coreless induction melting process melts metals under a protective atmosphere or vacuum by induction.

Maintenance Considerations and Equipment Reliability. The equipment required for this furnace system is anticipated to be more reliable than the equipment required for the reference system. The bottom pour mode requires less complicated equipment in the furnace, and lighter and less complex crucible and coil arrangements will suffice. Less equipment and maintenance will be required than for the reference system.

TABLE E.1. Utilities, Services, and Materials for
Vacuum Coreless Induction Melting Process

<u>Item</u>	<u>Capacity</u>	<u>Average Rate</u>	<u>Amount/Year</u>
Electricity	1000 kW	800 to 900 kW	
Water	1800 g/min	1200 g/min	
Air	750 m ³ /min	500 m ³ /min	
Steam	15 kg/h	2 kg/h	
Canisters	2 ft dia x 10 ft long		133
He sources			150
Crucible liners			140
Argon			2300 m ³

Controls and Operation. The operation of and controls for this process are deemed to be less complex than those for the reference process.

Adaptability to Remote Operations. Similar larger furnaces of this concept are common in the metal melting industry and could be adapted for and used in fully remote nuclear processes after an adequate development, design, and testing period.

Number of Process Steps. About 28 process steps that consist of four batches of continuous process steps are required to fill a canister with molten metal. For the complete processing of equivalent amounts of material, this process requires about half the process steps of the reference process.

Feasibility of Production. One furnace and its supporting equipment is deemed feasible for production with considerable surplus capabilities.

Feed Limitations. This furnace will have fewer feed limitations than the reference process and about the same limitations as the nonconsumable electrode furnace (Appendix B).

State and Type of Development

Process and/or Equipment. With the exception of the bottom pour crucible, furnaces of this or similar concepts are one of the major melting methods presently in operation in various industries.

Type and Scale of Development. Developments that will be required prior to actual hot cell operation of a vacuum coreless induction furnace include:

- investigate the capability of melting a variety of mixtures of metals
- determine off-gas temperatures and the system to adequately process the contaminated off gases and particulates
- develop and test systems to monitor furnace operation remotely
- develop and demonstrate systems to feed the furnace remotely
- determine the life of crucible materials
- test the reliability of the bottom pour method
- demonstrate the remote operation and reliability of a large-scale furnace
- identify the means to remove and replace the furnace and components remotely
- demonstrate the remote handling of containers.

Development Time Required. The required design, fabrication, and testing could be done in a period of 24 months.

Safety

Two primary hazards are associated with the induction melting system in addition to the normal concerns regarding the processing of radioactive material:

- A water leak could occur in the induction coil cooling system.
- Finely divided metallic residues that deposit on interior melt chamber surfaces during normal melting (especially zirconium) are a potential fire hazard when the furnace chamber is opened or air is introduced.

Other potential hazards (crucible failure, spills, etc.) are common to conventional melting of metals. For this ingot process, it has been estimated that

the maximum amount of molten metal would be ~1400 kg. Its temperature could be as high as 1900°C.

Since all radioactive material will be processed in shielded hot cells and devices designed for that purpose, the amount of excess radiation exposure will be a function of equipment maintenance and replacement, process accidents, or equipment failures.

Process Requirements

Secondary Wastes and Off Gases. Off-gas system requirements will be about the same as those of the reference process. The amount of process wastes may be greater than for the reference process due mainly to the use of crucible liners.

Production Capacity. One furnace can process the projected throughput with considerable excess capacity.

Process Additives and Auxiliary Materials/Utilities. Gas and water requirements are estimated to be about the same as for the reference process. Required power may be ~15% less. One consumable crucible liner per canister produced is anticipated.

Process Versatility and Control. Like the reference process, this process will handle and melt a wide range of metals and mixtures. Because this material is cast inside a container or canister, a wider range of metal mixes, batches, and foreign materials could be processed without imposing a potential quality control problem of ingot or casting integrity.

Manpower. Due to a shorter furnace cycle than the reference process, this process will only need to run ~71 days/year or less than one-half the time required for the reference process.

Facility Requirements

The facility required to enclose and support this process will be about the same as that identified for the reference process or facility; the equipment will be less complex.

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• Westerman, R. E. 1962. Investigation of Pyrolytic Graphite as Crucible Material for Zirconium Melting. HW-72998, General Electric, Hanford Atomic Products Operation, Richland, Washington.

TABLE E.2. Coreless Induction System Evaluation - Evaluator A

	Factor Weighting		Rating Assigned	
	Sub	Total	Sub	Total
<u>Complexity of Process</u>		60		435
Material Handling	5		40	
Consolidation Mode	5		45	
Maintenance Considerations and Equipment Reliability	12		96	
Controls and Operation	8		64	
Adaptability to Remote Operation	15		60	
Number of Process Steps	5		40	
Feasibility for Production	5		45	
Feed Limitations	5		45	
<u>State and Type of Development</u>		40		265
Process	5		35	
Equipment	10		70	
Type of Development	10		60	
Scale of Development	10		60	
Development Time Required (from initiation of program)	5		40	
<u>Safety</u>		40		350
Stability and Atmosphere of Process Steps	10		90	
Pyrophoricity, Exothermic, and Explosion Considerations	20		160	
Personnel Radiation Exposure	10		100	
<u>Process Requirements</u>		30		219
Secondary Wastes and Off Gases	5		25	
Production Capacity	4		36	
Process Additives and Auxiliary Materials	5		30	
Process Versatility and Control	5		35	
Quality Assurance	3		30	
Utilities (air, power, water, etc.)	3		18	
Manpower	5		45	
<u>Facility Requirements</u>		30		220
Noncontact Facilities (remote)	10		80	
Contact Facilities (hands-on)	10		80	
Estimated Capital Cost	10		60	
<u>Total</u>				1489

TABLE E.3. Coreless Induction System Evaluation - Evaluator B

	Factor Weighting		Rating Assigned	
	Sub	Total	Sub	Total
<u>Complexity of Process</u>		60		515
Material Handling	5		40	
Consolidation Mode	5		50	
Maintenance Considerations and Equipment Reliability	12		120	
Controls and Operation	8		80	
Adaptability to Remote Operation	15		90	
Number of Process Steps	5		45	
Feasibility for Production	5		50	
Feed Limitations	5		40	
<u>State and Type of Development</u>		40		295
Process	5		40	
Equipment	10		60	
Type of Development	10		90	
Scale of Development	10		60	
Development Time Required (from initiation of program)	5		45	
<u>Safety</u>		40		310
Stability and Atmosphere of Process Steps	10		70	
Pyrophoricity, Exothermic, and Explosion Considerations	20		160	
Personnel Radiation Exposure	10		80	
<u>Process Requirements</u>		30		243
Secondary Wastes and Off Gases	5		15	
Production Capacity	4		40	
Process Additives and Auxiliary Materials	5		40	
Process Versatility and Control	5		50	
Quality Assurance	3		18	
Utilities (air, power, water, etc.)	3		30	
Manpower	5		50	
<u>Facility Requirements</u>		30		270
Noncontact Facilities (remote)	10		100	
Contact Facilities (hands-on)	10		100	
Estimated Capital Cost	10		70	
<u>Total</u>				1633

TABLE E.4. Coreless Induction System Evaluation - Evaluator C

	<u>Factor Weighting</u>		<u>Rating Assigned</u>	
	<u>Sub</u>	<u>Total</u>	<u>Sub</u>	<u>Total</u>
<u>Complexity of Process</u>		60		441
Material Handling	5		25	
Consolidation Mode	5		50	
Maintenance Considerations and Equipment Reliability	12		95	
Controls and Operation	8		80	
Adaptability to Remote Operation	15		90	
Number of Process Steps	5		50	
Feasibility for Production	5		50	
Feed Limitations	5		50	
<u>State and Type of Development</u>		40		335
Process	5		40	
Equipment	10		80	
Type of Development	10		90	
Scale of Development	10		80	
Development Time Required (from initiation of program)	5		45	
<u>Safety</u>		40		240
Stability and Atmosphere of Process Steps	10		90	
Pyrophoricity, Exothermic, and Explosion Considerations	20		100	
Personnel Radiation Exposure	10		50	
<u>Process Requirements</u>		30		240
Secondary Wastes and Off Gases	5		5	
Production Capacity	4		40	
Process Additives and Auxiliary Materials	5		50	
Process Versatility and Control	5		50	
Quality Assurance	3		30	
Utilities (air, power, water, etc.)	3		15	
Manpower	5		50	
<u>Facility Requirements</u>		30		230
Noncontact Facilities (remote)	10		80	
Contact Facilities (hands-on)	10		100	
Estimated Capital Cost	10		50	
<u>Total</u>				1536

TABLE E.5. Coreless Induction System Evaluation - Evaluator D

	Factor Weighting		Rating Assigned	
	Sub	Total	Sub	Total
<u>Complexity of Process</u>		60		300
Material Handling	5		25	
Consolidation Mode	5		25	
Maintenance Considerations and Equipment Reliability	12		72	
Controls and Operation	8		48	
Adaptability to Remote Operation	15		45	
Number of Process Steps	5		25	
Feasibility for Production	5		30	
Feed Limitations	5		30	
<u>State and Type of Development</u>		40		240
Process	5		30	
Equipment	10		60	
Type of Development	10		50	
Scale of Development	10		60	
Development Time Required (from initiation of program)	5		40	
<u>Safety</u>		40		150
Stability and Atmosphere of Process Steps	10		80	
Pyrophoricity, Exothermic, and Explosion Considerations	20		40	
Personnel Radiation Exposure	10		30	
<u>Process Requirements</u>		30		202
Secondary Wastes and Off Gases	5		20	
Production Capacity	4		36	
Process Additives and Auxiliary Materials	5		30	
Process Versatility and Control	5		35	
Quality Assurance	3		18	
Utilities (air, power, water, etc.)	3		18	
Manpower	5		45	
<u>Facility Requirements</u>		30		240
Noncontact Facilities (remote)	10		80	
Contact Facilities (hands-on)	10		100	
Estimated Capital Cost	10		60	
<u>Total</u>				1132

APPENDIX F

COLD COMPACTION

APPENDIX F

COLD COMPACTION

INTRODUCTION

Processes for reducing the volume of radioactive hulls and high-level general process trash (HLGPT) wastes by cold compaction have been identified by Allied-General Nuclear Services (AGNS) (1978) and Anderson et al. (1979). These processes were not intended to handle all the metallic wastes generated in a reprocessing facility--i.e., failed equipment and the metal in the low-level general process trash (LLGPT) or contact transuranic (TRU) waste. However, they were to be capable of handling all HLGPT (metallics, organics, ceramics, combustibles, etc.). Thus, the size and capacity of these processes are assumed to be capable of handling and consolidating all of the metallic wastes identified in the Process Material Identification section (p. 16).

PROCESS NEEDS AND REQUIREMENTS

The cold compaction process (Figure F.1) is basically a batch-type operation that consists of a number of mechanical operations and transfers and very minimal chemical processing or changes (Anderson et al. 1979). In addition, very little off gas is generated. The process utilizes a compactor (Figure F.2) in a vertical position (Anderson et al. 1979). It is designed for an 8-ft 11-in. stroke, 3000-psi cylinder pressure, 10,000-psi developed compaction pressure, and 4.5×10^6 lb total force.

Hull Compaction Operations (Anderson et al. 1979)

As depicted in Figure F.1, hulls are trucked to the facility in a hulls cask, which shields personnel from the high radiation levels within the container. The hulls container is assumed to be of AGNS design (44 in. in diameter by 8 ft high), and the containers are assumed to contain waste (mainly hulls) that has not had sand added at the Separations Facility. If sand were to be added, the compaction procedure would be the same except that the actual compacting step would be eliminated.

The cask is lifted by the 60-ton crane hoist and placed on top of the shielded hatch, which is in the ceiling of the compactor feed cell. The two-piece shielded hatch has a stepped opening to reduce radiation leakage and an electrically powered screw drive to open and close the hatch. The hatch door is an integral part of a fixture that mates to and supports the hulls transfer cask. The hulls container is lowered from inside the hulls cask to the shelf in the compactor feed cell via a captive hoist in the hulls cask. The hulls container is subsequently moved from the shelf to the hulls container storage cell using the 10-ton compactor feed cell crane hoist. The container is then moved to a storage position within the storage cell using the hulls container storage cell 10-ton crane hoist.

If the compactor is in operation, there may be no need to place the hulls container in storage. The container could be directly processed to the compaction step. The hulls storage area allows for a surge capacity to build up, which could be helpful, particularly during periods of plant maintenance or hulls transfer cask maintenance.

For the compaction process, a container is lifted from storage to the shelf area in the compactor feed cell. Using the compactor feed cell hoist, the container is lifted onto the dumper platform; and the lid is removed remotely using manipulators and in-cell tools. The container is securely fastened into the hulls dumper so that the adapter and the hulls hopper will mate and form a seal during dumping. This seal should substantially reduce the amount of contamination in the cell.

Using the compactor feed cell crane hoist, the platform and the attached hulls container are lifted above an upper pivot point and the hulls are dumped into the hopper. When the container is empty, it is detached from the dumper platform and the lid is remotely replaced. The empty container may be temporarily stored or it may be transferred out of the facility.

The hulls will be compacted into repository containers that are ~22 in. outside diameter by 8 ft long. Empty repository containers are obtained from the clean container storage with their lids lightly tack welded in place.

FIGURE F.1. Mechanical Sequence Diagram of Cold Compaction Process

Using the decontamination cell crane hoist (included in the solidification facility), an empty container is inserted into the compaction die through the rough decontamination vessel at Station 4.

The repository container moves to Station 3 on a trolley system that services compaction Stations 1 through 4. At Station 3, the friction welder/delidder is placed on top of the lid and remotely clamped in place. The tack welds holding the lid in place are cut, and the container lid ends are prepared for a later friction weld. The friction welder/delidder is raised from the container but retains the lid. The weld flashing scrap from the tack welds is removed by the friction welder/delidder, and the shavings from the weld preparation are deposited in the empty container.

The trolley moves the repository container to Station 2 where the container is lifted by the break cylinder. The container lifts the extension die from its normal storage position, and the hydraulic rotation cylinder is activated to rotate the container and extension die. This rotation releases the extension die from its support lugs. The break cylinder is retracted, leaving the extension die sitting on top of the compaction die with the repository container in the compaction die. The dies and repository container are moved to Station 1 by the trolley. The container is lifted by the lift cylinder, which in turn lifts the extension die that encompasses the chute end of the hulls hopper.

Using the chute valves, a measured amount of hulls or scrap metal is released from the hopper and drops into the repository container. When the desired combined level of loose and previously compacted material is obtained, the lift cylinder is retracted and the trolley moves to Station 2 for compaction. The hydraulic compaction is activated to compact the material. The trolley alternates between Stations 1 and 2, filling the container and compacting until the desired level of compacted material inside the container is obtained. It is expected that six to eight strokes (cycles) will be required to fill a repository container 80% to 90% full.

The repository container may have been press fitted into the compaction die during the compaction process. The hydraulic break cylinder is activated to push up on the lift plate where the container is sitting, causing the

repository container to break free from the compaction die. To remove the container from the die, it may be necessary to slightly taper the compaction die so that the top of the die is slightly larger than the bottom. The repository container may also be tapered so that the outer diameter is smaller at the bottom, thus allowing the container to break free from the compaction die when lifted from the bottom by the hydraulic break cylinder.

When the container breaks free from the compaction die, it will also physically lift the captive extension die. Using the hydraulic rotation cylinder, the extension die will be placed back on its support lugs for temporary storage (until the next container is to be filled and compacted). The break cylinder is retracted so the trolley can move to Station 3 for welding. A friction welder is activated to weld the lid on the repository container. Excessive weld flashing is removed from the container lid area and retained at Station 3 until the next empty repository container is positioned on the welder; the flashing is placed in the container.

The trolley with the repository container is moved to Station 4. Using the decontamination cell crane hoist, the full repository container is lifted into the rough decontamination station. The bottom of the vessel is closed by remote hydraulics (or a motor), and the container is released from the crane hoist. The crane hoist is lifted out of the way, and the upper hatch door to the rough decontamination vessel is closed. Decontamination solution is sprayed onto the container and drained from the sealed bottom of the station vessel. The upper hatch door is opened, and the crane hoist lifts the relatively clean repository container into the next cell.

Other Waste Compaction Operations (Anderson et al. 1979)

As indicated in Figure F.1, metallic scrap in HLGPT drums is brought to the compaction facility by truck in HLGPT casks. Individual casks are lifted by the 60-ton crane hoist to a position above the drum removal cell. At about the same time, a hulls container is placed below the HLGPT chute. The HLGPT drum cask is lowered through the drum removal cell shielded hatch using the drum cask boom hoist. Using the drum removal cell crane hoist, the cask lid is removed and a drum is lifted above and through the sliding hatch above the drum dumper cell. An individual drum is positioned in the drum dumper and secured

in place. The drum lid is removed using mechanical manipulators. The HLGPT chute plug is removed and the drum dumper is activated, which tilts the drum until the contents fall down the chute and into a waiting hulls container. The sequence is reversed to return an empty HLGPT drum to the cask and the cask to the truck.

The hulls cask, which has been filled with the metallic waste, sits in the hulls container storage cell (just as hulls waste would) awaiting compaction. The subsequent operations are identical to those described above.

Based on data reported by AGNS (1978) and adding the requirement of processing other metallics in addition to hulls, it has been projected that 300 canisters 2 ft in diameter by 8 ft long and filled to 90% capacity would be required each year. The contained metallics would be pressed to ~50% of their melted or cast densities. Two canisters per shift (six per day) could be produced; thus, the system would be in operation 50 days of the year.

Equipment Identification

The major equipment used in the compaction process and facility operations is identified in Table F.1 (Anderson et al. 1979).

FACILITY REQUIREMENTS

The facility will be constructed of normal density concrete. In general, most of the cell walls will be 42 in. thick. Overviews of the upper and lower levels of the facility are shown in Figures F.3 and F.4 (Anderson et al. 1979), and an isometric view of the compaction facility is shown in Figure F.5 (Anderson et al. 1979). Components of the facility are described in Table F.2 (Anderson et al. 1979).

Off-Gas System

Off gases from the compactor, the dumping device, and the remote welder pass through a venturi scrubber where the majority of the particulates are removed. The off gas is then cooled in the cooler-condenser, separated from the condensate in the separator, heated above its dew point in the reheater, and filtered through a roughing filter and a high-efficiency particulate air

TABLE F.1. Equipment Description for Cold Compaction Facility

Building Area	Quantity	Description	Material	Dimensions
Roof	1	60-ton crane	Carbon steel	22-in. span
	1	10-ton crane	Carbon steel	15-ft boom
	1	Pneumatic-operated roof plug	Concrete/stainless steel	60 in. dia x 41 in. thick
	1	Guillotine door (for hulls cask)	Concrete/stainless steel	6 ft x 12 ft x 42 in. thick
Drum removal cell	1	10-ton crane	Carbon steel	14-ft span
Drum dumper cell	1	Drum dumper ^(a)	Stainless steel	
	1	Floor plug	Concrete/stainless steel	36 in. dia x 42 in. thick
	1	Roof vent door ^(a)	Stainless steel	60 in. dia x 4 in. thick
Compactor feed cell	1	Hulls hopper and valves	Stainless steel	
	1	Hulls dumper and adaptor	Stainless steel	
	1	10-ton crane	Stainless steel	26-in. span
	1	Shielding door ^(a)	Concrete/stainless	30 ft x 16 ft
Operating gallery (elevation 268 ft)	1	Friction welder	Stainless steel	For 24-in. dia cylinders
			Stainless steel	
Hydraulic cylinder room (elevation 236 ft)	1	Lift cylinder	Stainless steel	
	1	Break cylinder	Stainless steel	
	1	Hydraulic rotation cylinder	Stainless steel	
Compaction cell	1	Extension die	Stainless steel	
	1	Compactor	Stainless steel	
	1	Compactor die assembly	Stainless steel	
	1	Compactor trolley	Stainless steel	
	1	Rough decontamination vessel	Stainless steel	
Hulls container storage cell	1	10-ton crane	Stainless steel	26-ft span
Mechanical equipment room	1	Hydraulic power package	Carbon steel	

(a) Remotely operated.

FIGURE F.3. Lower Level Building Layout for Cold Compaction Facility

SAFETY & SECURITY EQUIPMENT

- 1. FIBER BEAD AIR SAMPLER
- 2. AMBIENT AREA MONITOR
- 3. RETARDER & ALARM
- 4. ALARM ON EMERGENCY EXITS
- 5. TV SCANNER
- 6. EQUIP. MOTION DETECTOR

ISSUED FOR CONCEPTUAL DESIGN		DATE: 11/10/00	
PROJECT: BARRWELL NUCLEAR FUEL PLANT		SHEET: 403	
DESIGNED BY: BARRWELL		CHECKED BY: BARRWELL	
APPROVED BY: BARRWELL		DATE: 11/10/00	
PROJECT: BARRWELL NUCLEAR FUEL PLANT		SHEET: 403	
DESIGNED BY: BARRWELL		CHECKED BY: BARRWELL	
APPROVED BY: BARRWELL		DATE: 11/10/00	
PROJECT: BARRWELL NUCLEAR FUEL PLANT		SHEET: 403	
DESIGNED BY: BARRWELL		CHECKED BY: BARRWELL	
APPROVED BY: BARRWELL		DATE: 11/10/00	

FIGURE F.4. Upper Level Building Layout for Cold Compaction Facility

Using the decontamination cell crane hoist (included in the solidification facility), an empty container is inserted into the compaction die through the rough decontamination vessel at Station 4.

The repository container moves to Station 3 on a trolley system that services compaction Stations 1 through 4. At Station 3, the friction welder/delidder is placed on top of the lid and remotely clamped in place. The tack welds holding the lid in place are cut, and the container lid ends are prepared for a later friction weld. The friction welder/delidder is raised from the container but retains the lid. The weld flashing scrap from the tack welds is removed by the friction welder/delidder, and the shavings from the weld preparation are deposited in the empty container.

The trolley moves the repository container to Station 2 where the container is lifted by the break cylinder. The container lifts the extension die from its normal storage position, and the hydraulic rotation cylinder is activated to rotate the container and extension die. This rotation releases the extension die from its support lugs. The break cylinder is retracted, leaving the extension die sitting on top of the compaction die with the repository container in the compaction die. The dies and repository container are moved to Station 1 by the trolley. The container is lifted by the lift cylinder, which in turn lifts the extension die that encompasses the chute end of the hulls hopper.

Using the chute valves, a measured amount of hulls or scrap metal is released from the hopper and drops into the repository container. When the desired combined level of loose and previously compacted material is obtained, the lift cylinder is retracted and the trolley moves to Station 2 for compaction. The hydraulic compaction is activated to compact the material. The trolley alternates between Stations 1 and 2, filling the container and compacting until the desired level of compacted material inside the container is obtained. It is expected that six to eight strokes (cycles) will be required to fill a repository container 80% to 90% full.

The repository container may have been press fitted into the compaction die during the compaction process. The hydraulic break cylinder is activated to push up on the lift plate where the container is sitting, causing the

repository container to break free from the compaction die. To remove the container from the die, it may be necessary to slightly taper the compaction die so that the top of the die is slightly larger than the bottom. The repository container may also be tapered so that the outer diameter is smaller at the bottom, thus allowing the container to break free from the compaction die when lifted from the bottom by the hydraulic break cylinder.

When the container breaks free from the compaction die, it will also physically lift the captive extension die. Using the hydraulic rotation cylinder, the extension die will be placed back on its support lugs for temporary storage (until the next container is to be filled and compacted). The break cylinder is retracted so the trolley can move to Station 3 for welding. A friction welder is activated to weld the lid on the repository container. Excessive weld flashing is removed from the container lid area and retained at Station 3 until the next empty repository container is positioned on the welder; the flashing is placed in the container.

The trolley with the repository container is moved to Station 4. Using the decontamination cell crane hoist, the full repository container is lifted into the rough decontamination station. The bottom of the vessel is closed by remote hydraulics (or a motor), and the container is released from the crane hoist. The crane hoist is lifted out of the way, and the upper hatch door to the rough decontamination vessel is closed. Decontamination solution is sprayed onto the container and drained from the sealed bottom of the station vessel. The upper hatch door is opened, and the crane hoist lifts the relatively clean repository container into the next cell.

Other Waste Compaction Operations (Anderson et al. 1979)

As indicated in Figure F.1, metallic scrap in HLGPT drums is brought to the compaction facility by truck in HLGPT casks. Individual casks are lifted by the 60-ton crane hoist to a position above the drum removal cell. At about the same time, a hulls container is placed below the HLGPT chute. The HLGPT drum cask is lowered through the drum removal cell shielded hatch using the drum cask boom hoist. Using the drum removal cell crane hoist, the cask lid is removed and a drum is lifted above and through the sliding hatch above the drum dumper cell. An individual drum is positioned in the drum dumper and secured

in place. The drum lid is removed using mechanical manipulators. The HLGPT chute plug is removed and the drum dumper is activated, which tilts the drum until the contents fall down the chute and into a waiting hulls container. The sequence is reversed to return an empty HLGPT drum to the cask and the cask to the truck.

The hulls cask, which has been filled with the metallic waste, sits in the hulls container storage cell (just as hulls waste would) awaiting compaction. The subsequent operations are identical to those described above.

Based on data reported by AGNS (1978) and adding the requirement of processing other metallics in addition to hulls, it has been projected that 300 canisters 2 ft in diameter by 8 ft long and filled to 90% capacity would be required each year. The contained metallics would be pressed to ~50% of their melted or cast densities. Two canisters per shift (six per day) could be produced; thus, the system would be in operation 50 days of the year.

Equipment Identification

The major equipment used in the compaction process and facility operations is identified in Table F.1 (Anderson et al. 1979).

FACILITY REQUIREMENTS

The facility will be constructed of normal density concrete. In general, most of the cell walls will be 42 in. thick. Overviews of the upper and lower levels of the facility are shown in Figures F.3 and F.4 (Anderson et al. 1979), and an isometric view of the compaction facility is shown in Figure F.5 (Anderson et al. 1979). Components of the facility are described in Table F.2 (Anderson et al. 1979).

Off-Gas System

Off gases from the compactor, the dumping device, and the remote welder pass through a venturi scrubber where the majority of the particulates are removed. The off gas is then cooled in the cooler-condenser, separated from the condensate in the separator, heated above its dew point in the reheater, and filtered through a roughing filter and a high-efficiency particulate air

TABLE F.1. Equipment Description for Cold Compaction Facility

Building Area	Quantity	Description	Material	Dimensions
Roof	1	60-ton crane	Carbon steel	22-in. span
	1	10-ton crane	Carbon steel	15-ft boom
	1	Pneumatic-operated roof plug	Concrete/stainless steel	60 in. dia x 41 in. thick
	1	Guillotine door (for hulls cask)	Concrete/stainless steel	6 ft x 12 ft x 42 in. thick
Drum removal cell	1	10-ton crane	Carbon steel	14-ft span
Drum dumper cell	1	Drum dumper ^(a)	Stainless steel	
	1	Floor plug	Concrete/stainless steel	36 in. dia x 42 in. thick
	1	Roof vent door ^(a)	Stainless steel	60 in. dia x 4 in. thick
Compactor feed cell	1	Hulls hopper and valves	Stainless steel	
	1	Hulls dumper and adaptor	Stainless steel	
	1	10-ton crane	Stainless steel	26-in. span
	1	Shielding door ^(a)	Concrete/stainless	30 ft x 16 ft
Operating gallery (elevation 268 ft)	1	Friction welder	Stainless steel	For 24-in. dia cylinders
	1		Stainless steel	
Hydraulic cylinder room (elevation 236 ft)	1	Lift cylinder	Stainless steel	
	1	Break cylinder	Stainless steel	
	1	Hydraulic rotation cylinder	Stainless steel	
Compaction cell	1	Extension die	Stainless steel	
	1	Compactor	Stainless steel	
	1	Compactor die assembly	Stainless steel	
	1	Compactor trolley	Stainless steel	
	1	Rough decontamination vessel	Stainless steel	
Hulls container storage cell	1	10-ton crane	Stainless steel	26-ft span
Mechanical equipment room	1	Hydraulic power package	Carbon steel	

(a) Remotely operated.

FIGURE F.3. Lower Level Building Layout for Cold Compaction Facility

TABLE F.2. Cold Compaction Facility Description

<u>Building Area</u>	<u>Operational Mode</u>	<u>Maintenance Mode</u>	<u>Dimensions (LxWxH), ft</u>	<u>Volume, ft³</u>	<u>Floor</u>	<u>Walls</u>	<u>Sump</u>	<u>Fire Protection</u>
Roof	Contact	Contact	--	--	--	--	No	Sprinkler where required
Drum removal cell	Contact/remote	Contact	18 x 15.5 x 22	6,138	Epoxy	Epoxy	Yes	Sprinkler
Drum dumper cell	Remote	Contact	10 x 15.5 x 10	1,550	Epoxy	Epoxy	No	Sprinkler
Compactor feed cell	Remote	Remote	28.5 x 15 x 33	12,226	No floor	Epoxy	No	Halon
Operating gallery (elevation 268 ft)	Contact	Contact	--	--	Epoxy	Epoxy	No	Sprinkler
Hydraulic cylinder room	Contact	Contact	--	--	--	--	Yes	Sprinkler
Compaction cell	Remote	Remote	53 x 6 x 14	4,452	Stainless steel	Epoxy	Yes	Halon
Hulls container storage cell	Remote	Remote	60 x 28.5 x 22	37,620	Stainless steel	Epoxy	Yes	Halon
Mechanical equipment room	Contact	Contact	--	--	--	--	Yes	Sprinkler

(HEPA) filter. The filtered off gas passes through redundant fans and is released to the building exhaust system. Quantities and properties of the constituents entering the off-gas system are shown below:

Temperature, °C	60
Pressure, psia	14.5
Density, lb/ft ³	0.058
Flow, m ³ /min	2000
Flow, kg/h	4300
Flow, lb-mol/h air	320
Flow, lb-mol/h H ₂ O	9.3
mol% air	97
mol% water	2.8

Secondary Wastes Requiring Processing

Nonradioactive solid and liquid wastes will be handled in supporting systems. These and other wastes that may contain radioactive nuclides that will require processing prior to release are listed below:

<u>Material</u>	<u>Amount</u>
Nonradioactive cooling water	500 g/min
Process wastes	10 kg/h
Ventilation flow	500 m ³ /min

Utilities, Services, and Materials

Utilities, services, and materials that will be required for the compaction facility are summarized in Table F.3.

ASSESSMENT DISCUSSION

Considering the limitations of size, pressure, and force, it has been projected that it is only feasible to fill a 2-ft diameter by 8-ft long canister

90% full of metal compacted to ~50% of its apparent density. Thus, more canisters will be produced than from most of the melting processes. The subsequent cost to transport and dispose of these canisters may eliminate the cold compaction process from further consideration. The numerical ratings assigned to the process by the individual evaluators are presented in Tables F.4 through F.7 (see p. F. 23). The criteria are discussed below.

Complexity of Process

More complex equipment is required to cold press the process material in canisters than for an electrical melt furnace. Although the equipment is complex, the process and its controls and operation are relatively simple. No heating or cooling are required, and the process requires no additional materials or recycling. Due to the complex mechanical equipment, there are concerns about satisfactory remote production. Maintenance modes and procedures for the equipment need to be identified and verified.

TABLE F.3. Utility, Services, and Materials for Cold Compaction Process

<u>Item</u>	<u>Capacity</u>	<u>Amount/Year</u>	<u>Remarks</u>
Essential air	3 m ³ /min		For breathing air
Utility air	2 m ³ /min		One air tool operating
Instrument air	1 m ³ /min		
Utility water	400 L/min		Cask washdown
Drinking water	200 L/min		One eyewash/safety shower operating
Electricity	100 kW		
Ventilation	750 m ³ /min		
Canisters	2 ft dia x 8 ft long	300	
He sources		325	

Material Handling. The steps and the equipment required to bring the process materials into the facility and put them into canisters are considered to be the same as those required to introduce the process material to the furnace in the reference process. The equipment required to seal, leak test, decontaminate, and transport the canisters will be about the same as that for the reference process. However, compaction does not require equipment to cool the canisters or to remove and recycle slag and starting stubs. Mechanisms to handle the canisters and to compact the process metals are much more involved than those required in the reference process to withdraw an ingot.

Consolidation Mode. Metal components are impacted and pressed by a metal ram moved by a hydraulic cylinder. The only heat induced into the compacted metal in this mode is that generated due to friction and mechanical forces. Mechanisms for feeding the process material are external to the consolidation station. The only atmospheric control required is to limit the spread of contamination.

Maintenance Considerations and Equipment Reliability. Other than the compactor instead of a furnace, the maintenance considerations will be about the same for this process as for the reference process. The compactor involves many mechanical functions that are performed in the normal atmosphere and temperatures. High pressures are required; thus, more maintenance will probably be required on a compactor than on a furnace although the reliability of the process may be comparable.

Controls and Operations. The controls for and the operation of the compactor will be less complicated than those for the reference furnace.

Adaptability to Remote Operations. Conceptual designs have been completed on at least two compactor concepts. With an adequate development, design, and testing program, a compactor concept could be finalized that would be operable and maintainable in a remote nuclear hot cell.

Number of Process Steps. From the time a batch of metal is ready to be dumped into a canister until the canister is full of compacted metal has been estimated to require 32 batch-type operations. A total of 38 operations are

required to complete the processing of one canister that contains ~1.5 times the metal of an ingot from the reference process or only ~40% of the material cast into a 2-ft diameter by 10-ft long canister.

• Feasibility for Production. One compactor and its supporting systems are deemed more than adequate and feasible for the intended operation.

• Feed Limitations. Feed material sizes will be limited by canister size and compactability. Thus, feed limitations will be at least as restrictive as those of the reference process.

State and Type of Development

Process and/or Equipment. Concepts and designs of compactors for this application have been developed (AGNS 1978; Anderson et al. 1979).

Type and Scale of Development. Developments that will be required before actual hot-cell operation of a cold compaction system include:

- develop the compactor concept, its controls, and monitoring systems
- demonstrate functional operation of large-scale compactor
- demonstrate remote operation and reliability of production-size compactor
- identify means to maintain compactor and components remotely
- demonstrate remote handling of canisters.

Development Time Required. Research, design, and testing could be performed in a period of 36 months.

Safety

The major safety concerns are fires (from the Zircaloy fines that occur as new nonoxidized surfaces are exposed during compaction) and the processing of radioactive material. Relatively high pressures and forces are involved in a few of the process steps. As with the reference process, all radioactive materials will be processed in shielded hot cells and devices designed for that purpose; therefore, the amount of excess radiation exposure will be a function of equipment maintenance and replacement or process accidents.

Process Requirements

Secondary Wastes and Off Gases. Less secondary waste will be produced by this process than by the reference process due to the lack of slag. Due to lower temperatures (60°C versus 600°C), fewer particulates, and less radioactivity, the off-gas system required for the compaction process is not as involved as that for any of the melting processes.

Production Capacity. One compactor can handle the projected throughput and has the capability of processing significant throughput increases.

Process Additions and Auxiliary Materials/Utilities. Basically no process additives are required, and the utilities (power and water) that are required are considerably less than those of any of the melting processes.

Process Versatility and Control. No high temperatures, vacuums, or inert atmospheres are required in the compaction process although it does require high pressures (3000 psi). The amount of nonmetallic feed is not limited, and ingot integrity is not a concern. Container integrity after compaction is a definite quality control checkpoint.

Manpower. Although the use of this process will result in a greater number of canisters being produced than all of the melting processes except the reference process, they can be produced in fewer days.

Facility Requirements

The facility required for this process will be larger than that identified for the reference process.

REFERENCES

- Allied-General Nuclear Services. 1978. Studies and Research Concerning BNFP: Storage and Handling of Wastes from Uranium Fuel Processing Alternatives. AGNS-1040-3.3-34, Barnwell, South Carolina.
- Anderson, K. J., et al. 1979. Studies and Research Concerning BNFP: Engineering Evaluations of Wastes Handling and Storage Facilities. AGNS-35900-4.2-26, Allied-General Nuclear Services, Barnwell, South Carolina.

TABLE F.4. Cold Compaction System Evaluation - Evaluator A

	Factor Weighting		Rating Assigned	
	Sub	Total	Sub	Total
<u>Complexity of Process</u>		60		315
Material Handling	5		25	
Consolidation Mode	5		30	
Maintenance Considerations and Equipment Reliability	12		48	
Controls and Operation	8		72	
Adaptability to Remote Operation	15		75	
Number of Process Steps	5		15	
Feasibility for Production	5		25	
Feed Limitations	5		25	
<u>State and Type of Development</u>		40		215
Process	5		40	
Equipment	10		40	
Type of Development	10		50	
Scale of Development	10		50	
Development Time Required (from initiation of program)	5		35	
<u>Safety</u>		40		320
Stability and Atmosphere of Process Steps	10		100	
Pyrophoricity, Exothermic, and Explosion Considerations	20		160	
Personnel Radiation Exposure	10		60	
<u>Process Requirements</u>		30		249
Secondary Wastes and Off Gases	5		40	
Production Capacity	4		40	
Process Additives and Auxiliary Materials	5		25	
Process Versatility and Control	5		45	
Quality Assurance	3		24	
Utilities (air, power, water, etc.)	3		30	
Manpower	5		45	
<u>Facility Requirements</u>		30		180
Noncontact Facilities (remote)	10		70	
Contact Facilities (hands-on)	10		60	
Estimated Capital Cost	10		50	
<u>Total</u>				1279

TABLE F.5. Cold Compaction System Evaluation - Evaluator B

	Factor Weighting		Rating Assigned	
	Sub	Total	Sub	Total
<u>Complexity of Process</u>		60		357
Material Handling	5		40	
Consolidation Mode	5		40	
Maintenance Considerations and Equipment Reliability	12		72	
Controls and Operation	8		40	
Adaptability to Remote Operation	15		75	
Number of Process Steps	5		25	
Feasibility for Production	5		40	
Feed Limitations	5		25	
<u>State and Type of Development</u>		40		260
Process	5		40	
Equipment	10		60	
Type of Development	10		70	
Scale of Development	10		50	
Development Time Required (from initiation of program)	5		40	
<u>Safety</u>		40		340
Stability and Atmosphere of Process Steps	10		100	
Pyrophoricity, Exothermic, and Explosion Considerations	20		160	
Personnel Radiation Exposure	10		80	
<u>Process Requirements</u>		30		245
Secondary Wastes and Off Gases	5		50	
Production Capacity	4		40	
Process Additives and Auxiliary Materials	5		50	
Process Versatility and Control	5		25	
Quality Assurance	3		15	
Utilities (air, power, water, etc.)	3		15	
Manpower	5		50	
<u>Facility Requirements</u>		30		130
Noncontact Facilities (remote)	10		50	
Contact Facilities (hands-on)	10		50	
Estimated Capital Cost	10		30	
<u>Total</u>				1332

TABLE F.6. Cold Compaction System Evaluation - Evaluator C

	Factor Weighting		Rating Assigned	
	Sub	Total	Sub	Total
<u>Complexity of Process</u>		60		344
Material Handling	5		25	
Consolidation Mode	5		25	
Maintenance Considerations and Equipment Reliability	12		60	
Controls and Operation	8		64	
Adaptability to Remote Operation	15		90	
Number of Process Steps	5		25	
Feasibility for Production	5		30	
Feed Limitations	5		25	
<u>State and Type of Development</u>		40		220
Process	5		20	
Equipment	10		60	
Type of Development	10		50	
Scale of Development	10		50	
Development Time Required (from initiation of program)	5		40	
<u>Safety</u>		40		250
Stability and Atmosphere of Process Steps	10		100	
Pyrophoricity, Exothermic, and Explosion Considerations	20		100	
Personnel Radiation Exposure	10		50	
<u>Process Requirements</u>		30		260
Secondary Wastes and Off Gases	5		50	
Production Capacity	4		40	
Process Additives and Auxiliary Materials	5		50	
Process Versatility and Control	5		40	
Quality Assurance	3		15	
Utilities (air, power, water, etc.)	3		15	
Manpower	5		50	
<u>Facility Requirements</u>		30		190
Noncontact Facilities (remote)	10		80	
Contact Facilities (hands-on)	10		100	
Estimated Capital Cost	10		10	
<u>Total</u>				1264

TABLE F.7. Cold Compaction System Evaluation - Evaluator D

	Factor Weighting		Rating Assigned	
	Sub	Total	Sub	Total
<u>Complexity of Process</u>		60		266
Material Handling	5		10	
Consolidation Mode	5		25	
Maintenance Considerations and Equipment Reliability	12		60	
Controls and Operation	8		56	
Adaptability to Remote Operation	15		45	
Number of Process Steps	5		15	
Feasibility for Production	5		30	
Feed Limitations	5		25	
<u>State and Type of Development</u>		40		220
Process	5		25	
Equipment	10		40	
Type of Development	10		60	
Scale of Development	10		60	
Development Time Required (from initiation of program)	5		35	
<u>Safety</u>		40		220
Stability and Atmosphere of Process Steps	10		70	
Pyrophoricity, Exothermic, and Explosion Considerations	20		100	
Personnel Radiation Exposure	10		50	
<u>Process Requirements</u>		30		213
Secondary Wastes and Off Gases	5		40	
Production Capacity	4		32	
Process Additives and Auxiliary Materials	5		50	
Process Versatility and Control	5		40	
Quality Assurance	3		6	
Utilities (air, power, water, etc.)	3		30	
Manpower	5		15	
<u>Facility Requirements</u>		30		170
Noncontact Facilities (remote)	10		40	
Contact Facilities (hands-on)	10		80	
Estimated Capital Cost	10		50	
<u>Total</u>				1089

APPENDIX G

EVALUATION CHECKLIST

APPENDIX G

EVALUATION CHECKLIST

Items similar to those identified in this appendix were used as a checklist to evaluate the consolidation methods or processes. The process information in Appendices A through F was used to establish basic characteristics. This information was integrated with the bases and assumptions identified in the text and supplemented by other sources and the knowledge of the authors and consultants to identify to the extent possible the relative requirements of each method or process.

COMPLEXITY OF PROCESS

- material handling aspects
 - How are process materials introduced to the system?
 - How are process materials removed from the system?
 - How are in-process transfers of radioactive materials made?
 - What is the magnitude of material recycling?
- method or process used for radioactive material consolidation
- equipment reliability and maintainability
 - number and type of mechanical components
 - number and type of electrical components
 - special features required for remote removal or maintenance
 - special features required for decontamination
 - size of equipment and components
 - time required for equipment/component replacement or maintenance
 - frequency of routine maintenance

- potential for trapment/absorption of process material
- ramifications of controls and operations
 - critical control parameters
 - magnitude and complexity of in-cell controls
 - utilization of closed circuit television
 - process reactions/conditions at each process step (time, temperature, pressure, etc.)
 - methods required to achieve remote control
 - in-process sampling needs and requirements
- adaptation to remote process
 - complexity of equipment/process
 - remote cell(s) arrangements and limitations
 - visual access required or attainable
- number and magnitude of process step or operation; continuous, batch, or combination
- remote production feasibility
 - magnitude of scale-up required
 - one or more parallel process lines
- feed limitations (maximum size, configuration, range of sizes, and configuration mixes).

STATE AND TYPE OF DEVELOPMENT OF EQUIPMENT/PROCESS REQUIRED

- use in remote radioactive applications
- adaptability of equipment to remote operation
- type and magnitude of development efforts required

- type and magnitude of development efforts that may improve anticipated equipment performance
- time and cost requirements for developmental efforts.

OVERALL SAFETY CONSIDERATIONS PERTINENT TO THE PROCESS AND EQUIPMENT

- routine releases of radioactive materials
- potential for elevated releases during process upsets
- potential for catastrophic releases due to process or equipment malfunction
- effects of process conditions (for example, temperature and pressure) on confinement of radioactive materials
- hazardous materials required in process (other than the process feed)
- explosive or potentially explosive materials required in process
- spread of radioactive materials.

OVERALL PROCESS REQUIREMENTS

- reagents, process additions, supplies
- services and utilities
- process latitudes and effects of feed variations
- process upsets and effects on product quality or recycle
- number of and qualifications for personnel
- number of shifts per day
- startup and shutdown ramifications.

OVERALL FACILITY REQUIREMENTS FOR RADIOACTIVE PROCESS OPERATIONS AND SUPPORTING EQUIPMENT AND SERVICES

- total shielded cell space required
- supporting facilities required
- complexity of mechanical operations required

- equipment redundancy required to meet scheduled throughputs
- use of cranes, master-slave manipulators, electromechanical manipulators, robotics, etc.

APPENDIX H

PROCESS RATING GUIDE

APPENDIX H

PROCESS RATING GUIDE

A list of descriptive statements was used to identify levels of merit for each criterion. Each criterion was assigned a value from 1 to 10; a high numerical value indicates high merit attributed to the process in respect to that criterion. For example, for the attribute of process complexity, the least complex process was accorded the highest merit. All ratings are subjective.

RATING OF THE PROCESS

The rating of each process is the summation of the products of criterion weight and ranking for all criteria. Appropriate comments are entered where necessary.

DESCRIPTIVE STATEMENTS

Complexity of Process

Material Handling. Material handling includes charging metals to the process, removing ingots and/or canisters, and recycling process material. The ratings consisted of:

- 10 - requires limited handling of charge materials and product
- 5 - requires moderate handling of charge materials and product
- 1 - requires substantial handling of charge materials and product.

Consolidation Mode. The consolidation ratings consisted of:

- 10 - process is simple and equipment is few in number
- 5 - process is simple but equipment is complicated
- 1 - both process and equipment are complicated.

Maintenance Considerations and Equipment Reliability. The ratings for this criterion consisted of:

- 10 - equipment is relatively simple or few in number
- 8 - nominal maintenance frequency and duration; components can be serviced or replaced easily and nominal maintenance is required
- 5 - equipment includes complex mechanical/electrical components in-cell with limited or restricted access
- 1 - equipment must be decontaminated and maintained in place.

Controls and Operation. The ratings for this criterion consisted of:

- 10 - minimal controls on material flow quantities and process conditions; process can accommodate wide variation in operating parameters
- 8 - straightforward controls on process conditions; process can accommodate variations in operating parameters
- 6 - numerous controls necessary; limited variation in operating parameters
- 4 - complex control required; close control of process is essential
- 1 - complex controls required; failure of control system can lead to serious upset condition or safety problem.

Adaptability of Equipment to Remote Operation. The following ratings were assigned to this criterion:

- 10 - equipment has been used in radioactive production operations
- 8 - equipment has been used in radioactive pilot-plant operations and performed satisfactorily
- 6 - equipment has been designed for remote operation but only tested in simulated remote operation
- 4 - equipment remotely operable and relatively uncomplicated
- 2 - equipment adaptable to remote operation
- 1 - questionable that equipment could be designed for remote operation or maintenance.

Number of Process Steps. The ratings for this category consisted of:

- 10 - small number of batch or continuous operations performed in automatic sequence
- 5 - nominal number of simple operations performed in semiautomatic process
- 1 - large number of complex operations performed on a step-to-step integrated bases.

Feasibility for Production . This criterion is basically an assessment of the probability of success of a development program of reasonable and prudent scale. The ratings consisted of:

- 10 - process and equipment are relatively simple; adaptation to large-scale use is clearly possible
- 8 - process and equipment are relatively simple but include one or more steps that may be questionable for long-term continuous operation
- 6 - process and equipment are moderately complex and include one or more steps that may be difficult for long-term continuous operation
- 4 - process includes one or more steps about which there is some doubt that scale-up to production operation will be practicable
- 1 - available information indicates that the process may not be feasible for production use.

Feed Limits. The following ratings were assigned to this category:

- 10 - process and equipment can handle a wide range of feed material sizes
- 5 - definite limits exist on the size of process material feeds
- 1 - size of process feed material is extremely limited.

State of Development

Process. This criterion was ranked as follows:

- 10 - demonstrated technology; routinely used in production-scale radiochemical operations
- 8 - demonstrated technology; production-scale operating experience with materials other than those involved in proposed application or extensive hot pilot-plant work on same types of materials
- 6 - extensive cold pilot-scale work with simulated products
- 4 - small pilot-scale work on individual process operations (non-radioactive)
- 1 - limited or no laboratory work.

Equipment. The ratings for this criterion included:

- 10 - equipment has been demonstrated in remote production operation
- 8 - equipment has been demonstrated in simulated nonradioactive remote operation
- 6 - equipment of standard commercial (nonradioactive use) design has been used in similar process; satisfactory performance
- 4 - equipment of standard commercial design must be modified to satisfy special process requirements
- 2 - no commercial equipment is available that will perform required function
- 1 - no experimental equipment is available that would serve the required purpose.

Type of Development. The development scale is sequential from 1 to 10; that is, a process rated at 4 implies that development states 1, 2, and 3 have been completed and 4 through 10 remain to be accomplished. In some cases (for example, where the process is reasonably simple, the equipment is uncomplicated, or there are extensive data on nonnuclear applications of the process and/or equipment), one or more of the identified development stages may be skipped.

The following ratings were assigned to this criterion:

- 10 - process requires only cold shakedown of full-scale facility;
i.e., available data would permit design of production-scale
hot facility
- 9 - limited hot pilot-plant work required to confirm process
limitations
- 7 - extensive hot pilot-plant work required to confirm process and
equipment design data
- 6 - radioactive equipment development required
- 5 - pilot-scale process development to establish equipment and pro-
cess scale-up factors
- 4 - nonradioactive equipment development
- 3 - process and equipment materials development
- 2 - small-scale hot cell process development
- 1 - nonradioactive laboratory process development.

Scale of Development. The following ratings were assigned to this
criterion:

- 10 - equipment has been developed; facilities available for radioac-
tive development work
- 8 - minimal radioactive facilities required to gather necessary
design data
- 6 - extensive hot pilot-plant facilities required; minimum
complexity
- 5 - extensive hot pilot-plant facilities required; complex process;
equipment design data available but scale-up information needed
- 3 - equipment and process data require remote operation verification

2 - considerable complex equipment to be designed and proven on nonradioactive basis

1 - no equipment design data available.

Development Time Required. The time required from the initiation of program was ranked as follows:

10 - 0 to 1 yr

9 - 1 to 2 yr

8 - 2 to 3 yr

5 - 4 to 5 yr

1 - more than 5 yr.

Safety Considerations

Stability and Atmosphere of Process Steps. The ratings for this criterion consisted of:

10 - process operates at temperatures of 1000°C or less and moderate pressures

9 - process operates at 1000 to 1900°C and subatmospheric pressures

7 - process operates at subatmospheric pressures and in excess of 1900°C

5 - process operates in excess of 1900°C with gas pressures at atmospheric or above

1 - process includes high pressure and high temperature (in excess of 1900°C).

Pyrophoricity, Explosive, and Exothermic Considerations. The following ratings were assigned:

10 - no steps provide potential for pyrophoric, exothermic, chemical process upsets, spills, or dispersions

5 - moderate potential exists for process material dispersion

1 - materials with high toxicity or with explosive potential required.

Personnel Radiation Exposure. Exposures include routine, accident, and maintenance operations and were ranked as follows:

- 10 - low potential for component failure and replacement
- 5 - moderate potential for major component failure due to error or other malfunctions
- 1 - life of major equipment components is potentially short.

Process Requirements

Secondary Wastes and Off Gases.

- 10 - wastes and off gases are less than those of reference process
- 5 - wastes and off gases are essentially the same as those of the reference process
- 1 - wastes and off gases are significantly greater than reference process.

Production Capacity.

- 10 - one reasonably sized production line capable of processing the required throughput with excess capacity
- 5 - long process period required for unit throughput or no excess capacity
- 1 - multiple or large-size equipment required to process throughput.

Process Additives and Auxiliary Materials.

- 10 - requires minimum additives of moderate cost
- 7 - requires large quantities at moderate cost
- 4 - requires limited quantities at high cost
- 1 - requires large quantities at high cost.

Process Versatility and Control.

- 10 - process capable of accepting substantial variations in feed composition and process conditions

- 8 - process moderately susceptible to effects of variations in feed composition
- 6 - process requires moderately tight control of process conditions
- 4 - process requires tailoring of reactants/additives for each batch of feed
- 3 - process requires very tight control of process conditions
- 1 - process may not be capable of being controlled so as to produce the desired product.

Quality Assurance.

- 10 - simple process; minimum quality control problems
- 5 - product quality controlled through control of input materials quantity and composition
- 1 - product quality can be determined only by evaluation of finished product.

Utilities.

- 10 - process additives, supplies, utilities, and services are less than those of the reference process
- 5 - requirements about the same as for the reference process
- 1 - requirements considerably more than for the reference process.

Manpower.

- 10 - requires considerably less manpower/yr than reference process
- 5 - requires essentially the same manpower/yr than reference process
- 1 - requires significantly more manpower/yr than reference process.

Facility Requirements

Facility requirements include structures (evaluated as volume), equipment (evaluated as number of items and complexity of installation), special maintenance facilities, and process auxiliaries (evaluated as number of items and complexity of installation).

Radioactive Facilities.

- 10 - facility requirements are less than those of the reference process
- 8 - shielded cell requirements are similar to the reference process; no complex installations
- 4 - shielded cell requirements greater than for reference process; some complex installations required
- 1 - significantly greater shielded space requirements; many complex equipment installations required.

Nonradioactive Facilities.

- 10 - facility requirements not materially different from the reference process
- 5 - facility requirements significantly greater than for reference process but of a commonly used industrial character
- 1 - extensive facilities for material storage and preparation required outside of process cells; high temperature or possibly toxic materials must be provided to process.

Estimated Capital Costs

- 10 - costs are considerably less than those of the reference process
- 5 - costs are about the same as those of the reference process
- 1 - costs are considerably higher than those of the reference process.

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