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Selection of a Melting Furnace for Consolidation of Nuclear Fuel Hulls

R. G. Nelson
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December 1976

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Battelle
Pacific Northwest Laboratories

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SELECTION OF A MELTING FURNACE
FOR CONSOLIDATION OF NUCLEAR FUEL HULLS

by

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SELECTION OF A MELTING FURNACE FOR CONSOLIDATION OF NUCLEAR FUEL HULLS

INTRODUCTION

In current light water reactor (LWR) fuel reprocessing technology, fuel bundles are sheared in short lengths for acid leaching of the fuel pellets. The residues from the acid leach include short lengths of fuel cladding, massive end fittings, fuel spacer grids, assorted springs, guide thimbles, and flow channels. These residues constitute a high volume waste, amounting in weight to about 22% of the fuel bundle. Without densification they constitute a substantially higher volume than the high level transuranic (TRU) calcines or glasses. These materials have a bulk density of about 1.1 kg/l. Densification by melting will reduce the volume by a factor of 6. As recovered from the dissolver, these hardware residues represent about 325 kg/tonne of uranium, and consist of 70 to 80 wt% Zircaloy, 12 to 22 wt% stainless steel (SS), and 8 wt% Inconel.

Stainless steel and Inconel are usually melted in ceramic (MgO) crucibles. However, because of Zircaloy's high melting point (1850°C) and reactivity, it must be protected from the atmosphere and melted in water-cooled crucibles. The development of "cold-crucible" or "cold-mold" melting has been advanced in recent years through the necessity to produce large quantities of titanium, zirconium, and other reactive and refractory metals. This technology has also been applied to the remelting of steel in tonnage quantities. It is, therefore, logical to consider cold-crucible melting as a method for volume reduction of nuclear fuel hulls. With proper sorting and precleaning such a process could produce metal of suitable quality for refabrication and reuse.

It is the purpose of this paper to define the selection and design criteria for a cold-crucible melting system for fuel hull consolidation, and to present appraisals of the cold-crucible processes that are available.

It is hoped that the analysis presented here will assist others who are contemplating the melting of specialty metal scrap.

MELT STOCK DESCRIPTION⁽¹⁾

Fuel bundles are made up of the components shown in Table 1. These assemblies are chopped into lengths varying from 2.5 to 13 cm long. The largest pieces are the 304 Stainless Steel end-fittings which are castings either 21.4 or 13.4 cm square with a maximum section thickness of ~0.64 cm. The materials have been neutron-irradiated, are highly radioactive, and have a corrosion product layer of 50 μ thick in locations of maximum corrosion. Impurities circulating in the reactor deposit on fuel surfaces and can contain transuranics if the coolant is contaminated with uranium or plutonium from fuel ruptures. The internal surface of the Zircaloy-clad fuel develops an oxide layer of a few microns in thickness. The (U, Pu)O₂ fuel has been observed to adhere and possibly react with this oxide layer. Residual (U, Pu)O₂ associated with the fuel cladding after leaching are usually estimated as less than 0.1 wt% of the uranium charged.

SELECTION AND DESIGN CRITERIA

GENERAL

The melting system shall be of a cold-crucible type capable of producing 90 to 130 kg per 8 hour day in a diameter range of 7.5 to 15 cm. Single melted ingots are to be made directly from fuel hulls without an electrode preparation step.

The operations of furnace preparation, charging, melting, stripping, cleaning, and maintenance must be performed remotely from the operating floor of a nuclear hot cell.

TABLE 1. Fuel Design Specifications⁽²⁾

	PWR (Diablo-Canyon-1)	BWR (Browns Ferry-1)
Assembly Arrangement	15 x 15 Rods	7 x 7 Rods
Number of Rods Per Assembly	204	49
Spacer Material	Inconel 718	Zircaloy-4
Number of Spacers Per Assembly	9	7
Assembly Dimensions	21.4 cm x 21.4 cm	13.4 cm x 13.4 cm
Number of Control Rod Guides	20	--
Material of Rod Guides	304 Stainless Steel	--
End Fitting Material	304 Stainless Steel	304 Stainless Steel
Uranium Oxide Per Assembly	519 kg	220 kg
Rod Diameter, OD	1.07 cm	1.43 cm
Rod Diameter, ID	0.95 cm	1.27 cm
Rod Length	376 cm	406 cm
Fuel Column Length	366 cm	366 cm
External Spring Material	--	Inconel-X
Cladding Material	Zircaloy	Zircaloy-2
Assemblies/MTU	2.19	5.15

Design considerations shall be based on the remelting of the Zirconium base materials; however, the ability of the furnace to remelt stainless steel, Inconel, and mixtures of these three should also be considered.

Hot cell space shall be kept at a minimum consistent with operation and serviceability.

Overall design shall be consistent with a high quality zirconium remelting practice that results in low oxygen, hydrogen, and nitrogen pickup.

It is anticipated that the melting stock in most cases will be cleaned prior to charging; however, the melting furnace should be capable of melting material with oxidized films as thick as 50 μ .

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It is anticipated that the vacuum system could frequently be exhausted to the atmosphere after suitable filtration. However, a closed-loop recirculating cover gas system should be considered as an alternative to gas storage and disposal.

COOLING SYSTEM

The cooling system should be a closed-loop type with adequate capacity, incorporating devices for adding make-up coolant and corrosion inhibiting chemicals. The construction materials should be such that heat transfer will be maximized and corrosion minimized.

SAFETY ANALYSIS

Safe operation and maintenance should be a prime consideration during all phases of equipment selection. Mechanical and electrical interlocking devices should be specified and recommended for use in the event of operator or component and systems failures. Safety systems redundancy, audible and visual alarms, administrative controls, and coolant-melt interaction should be considered.

PROCESS APPRAISALS

INTRODUCTION

Ten basic cold-wall melting systems have been evaluated in an attempt to establish the most suitable systems for the consolidation of nuclear fuel hulls. In this evaluation a primary consideration is the ability of the melting process to make a single-melt ingot that is suitable for remanufacturing into useful hardware. The ten melting systems considered are listed below.

1. INDUCTOSLAG
2. PLASMA
3. MECHANICAL ROTATING NONCONSUMABLE ELECTRODE
4. ARC MAGNETICALLY ROTATED NONCONSUMABLE ELECTRODE
5. CARBON ELECTRODE
6. TUNGSTEN ELECTRODE
7. CONSUMABLE ELECTRODE
8. ELECTRON BEAM
9. HOLLOW ELECTRODE
10. INDIRECT ARC

For an overview of the ten systems, a chart condensing information and evaluations from the individual appraisals is provided in the Appendix.

1. INDUCTOSLAG

Inductoslag melting is a development of the U.S. Bureau of Mines located in Albany, Oregon, and consists of induction melting in a segmented water-cooled copper crucible. The system was developed for the melting of reactive metal scrap and requires the use of a high purity slag such as calcium fluoride. To date, this equipment has produced ingots of titanium and zirconium⁽³⁾ up to 12.7 cm in diameter and to 107 cm in length at power levels up to 100 kW. We feel that all of these parameters can be expanded without any major problems. The characteristics of this melting system are as follows:

A. Power

The power supply for the existing system is 450 volts ac at 10,000 hertz and a current of approximately 220 amperes. The induction power supply is a motor generator type; however, there is no reason to believe that solid state systems could not be used.

B. Vacuum Pressure Requirements

The best results to date have been obtained by evacuating the furnace chamber and back-filling with helium or argon to approximately 240 torr. This pressure is maintained during melting, and since the pressure is below atmospheric pressure, it is necessary that the furnace chamber be vacuum-tight to minimize contamination of the melt.

C. Material Feed

Material feed in the Inductoslag system can be accomplished by vibratory or rotary drum feeder. Since there is no obstruction above the melt, the feeding of a variety of scrap material is feasible, as long as care is taken not to damage the crucible with large or heavy scrap.

D. Pool Configuration

From all data available, it is apparent that fairly deep pool configurations can be obtained, and the equipment has been successfully adapted to casting operations.

E. Casting Modes

The Inductoslag unit should be capable of producing cold-wall ingots by either withdrawal, skull casting, or static-mold melting procedures.

F. Production Capacity

The present equipment appears to have a possible production rate of approximately 0.45 kg per 1.5 kW-hr. However, it is possible that the power efficiency would improve significantly when larger crucibles and power supplies are used.

G. Mechanical Complexities

The complexity of this melting system is primarily related to the design and configuration of the crucible. Although the crucible is more complicated and perhaps more fragile than the other cold-wall crucibles being discussed in this survey, it should be pointed out that there is no complicated electrode or electrode suspension system required. The overall simplicity of the system is quite desirable.

H. Maintenance Considerations

Extended production experience is not available, but considering the overall requirements of the equipment, maintenance should be quite favorable when compared to other cold-wall melting systems.

I. Controls

The controls for this equipment are not difficult, and no problem is foreseen in incorporating the proper remote operation and control requirements for such a system.

J. Hot Cell Adaptability

A primary consideration for hot cell adaptability is the handling and recycling of residue slag which will be approximately 4% by weight of the ingots being produced.

K. Safety

Safety considerations for this equipment are essentially the same ones required when melting any reactive metal in a cold-wall system under a vacuum or reduced pressure.

L. State-of-the-Art

A great deal of development work in pilot plant melting has been conducted at the Bureau of Mines. The system's feasibility has certainly been demonstrated, and we feel that scaling up, if required, would not be a major problem.

M. Ingot Quality

The surface quality of the ingot is excellent, and on a single-melt basis is perhaps as good or better than any other cold-wall system being compared, especially as related to withdrawal melting. Chemical properties indicate that there may be some increase in interstitial contamination, but under controlled melting conditions this problem is not prohibitive.

N. Cleanup Requirements

Slag residues may present added cleanup requirements; other cleanup considerations are minimal. However, when the skull casting mode is used, the problems related to splatter and cleanup of pouring lips, etc., must also be considered.

Evaluation

In conclusion, the advantages of the Inductoslag melting system are a clean melt with a minimum of splash and splatter in the withdrawal or static-mold mode of casting. The geometry of the equipment provides maximum room for feeding of material, and the resultant single-melt ingot is of excellent quality.

Some of the disadvantages are a relatively low production rate and the problems of slag handling, recycling, and disposal. Occasionally some problems may be encountered with bridging, depending again upon the size and density of the feed stock. However, bridging problems can be minimized by a supplemental heating source if required.

2. PLASMA

Plasma melting is considered to operate best at one atmosphere of argon. It has basically been used for melting of nickel-base alloys, titanium, zirconium, and a variety of other metals with the same or lower melting ranges. Plasma torches up to several megawatts capacity have been used for a number of melting and nonmelting applications, but actual production applications have been slow in developing. One reason for the slow development of production applications is the nonvacuum aspect of the equipment and the related expense of plasma-melting gas systems. The following parameters apply to equipment which has been successfully used for cold-wall melting applications:

A. Power

A dc powered torch of Linde design has been used at continuing power levels of 600 kW. Power is supplied by a well regulated dc power supply having a working output of 200 volts at 3000 amperes. An open circuit dc voltage on the order of 350 volts is desirable with a high frequency starter for initiating a pilot arc prior to transferring the arc to the melting material.

B. Vacuum Pressure Requirements

The Plasma torch does not operate well under low pressure or vacuum conditions. As pressure is reduced below atmospheric, the arc column becomes more diffused and less effective in transferring heat to the melt. The system operates best at atmospheric pressure or above; in normal practice the furnace chamber is evacuated and back-filled with argon since the torch requires approximately 570 l/min of argon when operating at 600 kW.

C. Material Feed

Material feed to the plasma furnace can be accomplished by either a vibratory or rotary (kiln) type feeder. The torch can be mounted in a ball-and-socket vacuum tight joint to facilitate feeding and to enable the direction of heat to areas where it is most required. Under normal

conditions an arc length of 20 to 30 cm is maintained. Arc length is a function of voltage, amperage, and gas flow.

D. Pool Configuration

The pool configuration resulting from the plasma melt is flat and shallow. In a 36-cm diameter cold-wall melt, the pool profile is pie-pan in shape with a depth of not more than 2 inches. This effect is caused by the soft arc or spreading effect of the plasma when it strikes the molten pool.

E. Casting Modes

Because of the shallow pool configuration, the only practical mode of casting with a plasma torch and a cold-wall crucible is to form ingots by withdrawal from a water-cooled copper sleeve.

F. Production Capacity

Melt rates with the withdrawal casting mode have been about 1 lb per kW-hr, which is certainly acceptable for the consolidation of fuel hulls. The cleanliness of material does not necessarily affect the production rate; however, large quantities of volatile matter can cause some splatter and complications when introduced to the molten metal pool.

G. Mechanical Complexities

The Plasma torch being discussed consists of a fairly sophisticated copper electrode and nozzle which require electrical isolation from each other and the furnace body. Both the nozzle and electrode have high velocity water passages and are fairly complex as presently designed. However, it is anticipated that the torch design can be considerably simplified.

H. Maintenance Considerations

The primary maintenance considerations are related to replacement of the torch nozzle or electrode. In tests which have been conducted, it is expected that a nozzle and electrode life in the range of 40 operating hours is feasible. If it becomes necessary to disassemble the Plasma torch, there are many "O" ring joints and critical components which must be

properly handled and aligned. As presently constructed, the torch may be somewhat difficult to maintain under hot cell conditions.

I. Controls

No major problems are seen in the control requirements for plasma melting. Electrode positioning, power supply controls, and gas flow should present no problems.

J. Hot Cell Adaptability

Because of the complexity of the torch itself, the system's major drawback in hot cell adaptability would be the difficulty of maintenance. It is felt that a complete redesign of the existing torch would be necessary for hot cell application on a production basis.

K. Safety Considerations

It is felt that the Plasma torch would be as safe a melting instrument as any cold-wall melting system being considered.

L. State-of-the-Art

Plasma torches have been used for a variety of applications at power levels up to 50 MW. However, plasma applications in the melting of metals have been limited to torches of approximately 3 MW capacity.

M. Ingot Quality

The quality of cold-wall plasma ingots has been fair. To date, most ingots which have been produced in withdrawal-type molds have shown evidence of considerable surface laps and folds which must be conditioned prior to further processing.

N. Cleanup Requirements

Minimum furnace cleanup is required following plasma melting. Plasma melts are usually quiet and have a minimum of splatter and splashing. No problem is encountered with bridging, and most of the residue are condensable materials left on the furnace walls.

Evaluation

The primary advantages of a plasma system are the soft heat of the plasma arc and the lack of splatter and splash. Another advantage is that high vacuums are not required, thus a minimum amount of leak-checking is needed.

The disadvantages are that a high quantity of plasma gas is required and that a great deal of the plasma heat is convected to the furnace walls. There is no doubt that a gas recycling system should be considered for a sustained production system.

3. MECHANICAL ROTATING NONCONSUMABLE ELECTRODE

The Mechanical Rotating Nonconsumable Electrode process has been in use for the production of titanium since 1970. The furnaces using this system are capable of melting titanium at rates of up to 450 kg/hr, producing ingots with weights up to 4500 kg. This type of melting system is capable of accommodating feed stock containing some volatiles, and is therefore not adversely affected by moderate gas loads.

The electrode assembly consists of a non-rotating ram which is capable of movement in the X, Y and Z directions. The electrode itself physically rotates in the center of this assembly at a speed of ~250 rpm. The whole assembly is inclined at an angle of about 20° from the vertical. During operation the arc-generating surface constantly changes, keeping the heat input to the anode spot on the electrode to a minimal time interval. This allows sufficient cooling to keep the electrode from being eroded.

The characteristics of a typical melt system using this type of electrode are as follows:

A. Power

The rotated nonconsumable electrode is powered by a high amperage, low voltage, dc power supply. For the melt rates mentioned above, a typical power supply would consist of a unit or units having an output of up to 20,000 amperes at 50 to 70 volts. In general, power supplies of the thyristor type have been used because of their superior response characteristics.

B. Vacuum Pressure Requirements

To date, most of the melting in furnace systems using the mechanical rotating electrode has been done at pressures of argon in the 5 to 20 Torr range. There are, however, no fundamental reasons for not melting at either higher or lower pressures. Because of the partial vacuum involved, the furnace feeding and casting chambers must be constructed for vacuum service so that the melt will not become contaminated.

C. Material Feed

A variety of material feed systems have been used. The most common ones in use today are the inclined tube and rotary drum feeder. Vibratory feeders, if designed for vacuum service, are also useable. Scrap pieces as large as 15 cm³ have been fed, using both the inclined tube and rotary drum feeder. In feeding large and heavy pieces of scrap, care must be taken not to damage the electrode or the crucible. The only limitations on the size of feed material are dictated by the design of the feeding system and the size of the crucible in which the melting takes place.

D. Pool Configuration

The pool configuration is very dependent on the type of crucible used (i.e., withdrawal or tilt-pour), the power employed, and the rate of feeding. Rather deep and wide pools can be established during steady state conditions and when melting is done at the upper end of the power range. In withdrawal melting, where the bottom cooling effects are much lower than with a skull-type crucible, pool depths on the order of one ingot diameter can be readily achieved.

E. Casting Modes

This process has been used in the direct withdrawal, pour withdrawal, and skull casting modes.

F. Production Capacity

Present production-size units require in the range of 0.7 to 1.0 kW-hr per lb. This difference is a function of the crucible size and also depends on whether the equipment uses the withdrawal or tilt-pour mode of casting.

G. Mechanical Complexities

The most complex and critical mechanical part of the whole melting assembly is the rotating electrode and its surrounding structure. The equipment's long production history has led to a substantial amount of refinement which has minimized the structure's complexity.

H. Maintenance Considerations

Maintenance of this melting system should be comparable with other types of cold-wall melting systems. Changes made in the system because of production experience have helped to substantially reduce the amount of maintenance that was originally required. The rotating tip itself is very robust and can easily be replaced if needed, even under hot cell conditions.

I. Controls

The controls for this melting system are easily adaptable to remote operation. With the experience gained during the manufacture and startup of other production-size furnaces of this type, the control modifications required are expected to be fairly minor.

J. Hot Cell Adaptability

This melting system should be quite adaptable to hot cell melting. The only problems would be the vacuum requirements (not severe) and the seals required in the rotating electrode itself. Because of the low voltages involved, power feed-through insulation, etc., would present no major problem.

K. Safety

Safety considerations for all of these types of cold-wall melting systems are expected to be similar. In all cases there is a danger of electric shock, and all of these systems should be treated with considerations dictated by safe industrial practice.

L. State-of-the-Art

At present there are mechanical rotating nonconsumable electrode melting systems in operation both in the United States and Europe. Large tonnages of reactive metals have been processed using this system, and it has proven to be a viable melting technique for the applications used.

M. Ingot Quality

Because of the various methods available for the production of ingots by this melting system, the quality of the final ingot is primarily a function of the production method. In direct withdrawal melting, the cleanliness of the feed material will also influence the ingot quality. In the skull casting of reactive metals, however, complete homogenization occurs during the melt cycle, and ingots having excellent surface quality can be cast, providing the mold capacity is equal to or less than the crucible capacity.

N. Cleanup Requirements

In hot cell operation where the moisture content of the air can be rigidly controlled, the cleanup requirements for this type of melt system are much less stringent than they are in high humidity environments. The melting operation produces a certain amount of splatter (this can be recycled without additional preparation) and causes volatiles to condense on the cold walls of the furnace chamber. When titanium or zirconium sponge is melted, these volatiles consist mainly of chlorides. What effect contamination by transuranic elements will have is a matter of conjecture.

Evaluation

In summary, the mechanical rotating nonconsumable electrode melting system has been used in production more extensively than any other type of new system. This has allowed appropriate refinement and redesigning of the equipment until it has become a relatively trouble-free production unit. Considering the difficulties of maintenance in hot cell environments, the production-proven reliability of this system is a great attraction. Another attraction of this system is its versatility.

4. ARC MAGNETICALLY ROTATED NONCONSUMABLE ELECTRODE

The arc magnetically rotated nonconsumable electrode melting process consists of a water-cooled, nonconsumable copper anode that incorporates a magnetic field coil in the extreme tip in order to cause rotation of the arc. Normally the electrode is not physically rotated, but because of problems that arise during the melting of larger pieces of scrap, one of the nonconsumable electrode installations in this country uses a physically rotating electrode. To date, this process has been used both with continuous-withdrawal systems and tilt-pour crucibles. Commercial-size remelt electrodes of titanium have been produced at melt rates of up to 400 kg/hr.

The characteristics of this melting system are as follows:

A. Power

The furnace is powered by a high amperage, low voltage dc power supply. For the melt rates mentioned above, a typical power supply would consist of a unit having an output of up to 13,000 amperes at 60 to 70 volts.

B. Vacuum Pressure Requirements

To date, most of the melting in furnace systems using the magnetically rotated arc has been done at pressures of argon either in the 5 to 20 torr range or in the 0.05 to 0.1 torr range. Because of the vacuums involved, the furnace feeding and casting chambers have to be constructed for vacuum service to avoid contamination of the melt.

C. Material Feed

A variety of material feed systems have been used. The most common ones in use today are the vibratory feeder and the rotary drum feeder. Scrap pieces as large as 15 cm³ have been fed using the rotary drum feeder. If the nonrotating electrode is used, using large pieces of scrap has caused a great many tip failures. Otherwise, the only limitations to the size of the feed material are dictated by the design of the feeding system and the size of the crucible in which the melting takes place.

D. Pool Configuration

The pool configuration is very dependent on the type of crucible used (i.e., withdrawal or tilt-pour), the power employed, and the rate of feeding. Rather deep and wide pools can be established during steady state conditions and when melting is done at the upper end of the power range. In withdrawal melting, where the bottom cooling effects are much lower than with a skull-type crucible, pool depths on the order of one ingot diameter can be readily achieved.

E. Casting Modes

These melting furnaces have been used in the direct withdrawal and skull casting modes.

F. Production Capacity

Present production-size units require in the range of 1.5 to 2.2 kW-hr/kg. This difference is a function of the crucible size and also depends on whether the equipment uses the withdrawal or tilt-pour mode of casting.

G. Mechanical Complexities

The most complex mechanical part of the whole melting system is the electrode tip and its surrounding support structure. Because of the magnetic field coil which is placed inside the tip, assembly is somewhat difficult and critical.

H. Maintenance and Considerations

Except for the expected difficulties in the replacement of the electrode tip itself, maintenance of the melting system should be comparable with other types of cold-wall systems.

I. Controls

The controls for this melting system are easily adaptable to remote operation. With the experience gained during the manufacture and startup of other production-size furnaces of this type, the control modifications required are expected to be fairly minor.

J. Hot Cell Adaptability

The only problem areas expected in adapting this process to hot cell operation would be the replacement of the electrode and the seals required for vacuum service. Power feed-through insulation, etc., would present no major problem because of the low voltages involved.

K. Safety

Safety considerations for all of these types of cold-wall melting systems are expected to be similar. In all cases there is a danger of electric shock, and all of these systems should be treated with considerations dictated by safe industrial practice.

L. State-of-the-Art

At present there are three of these melting systems in operation in the United States. Production quantities of titanium have been processed using this system and, except for the fragility of the electrode, it has proven to be a viable melting technique.

M. Ingot Quality

Because of the various methods available for the production of ingots by this melting system, the quality of the final ingot is primarily a function of the production method. In direct withdrawal melting the cleanliness of the feed material will also influence the ingot quality. In the skull melting of reactive metals, however, complete homogenization occurs during the melt cycle, and ingots having excellent surface quality can be cast, providing the mold capacity is equal to or less than the crucible capacity.

N. Cleanup Requirements

In hot cell operation where the moisture content of the air can be rigidly controlled, the cleanup requirements for this type of melt system are much less stringent than they are in high humidity environments. The melting operation produces a certain amount of splatter (this can be recycled without additional preparation) and causes volatiles to condense

on the cold walls of the furnace chamber. In the case where titanium or zirconium are melted, these volatiles consist mainly of chlorides. What effect contamination by transuranic elements will have is a matter of conjecture.

Evaluation

The arc magnetically rotated nonconsumable electrode has had proven exposure as a production tool in the melting and consolidation of reactive metals. Its power and melt rate capability are proven to enable handling of large quantities of metallic scrap. The system also has desirable versatility in melting mode application.

The disadvantages of this system are the complexity of the electrode tip structure as related to remote electrode maintenance and tip changing.

A field coil is also required around the crucible structure to permit proper arc control, which adds to the in-cell complexity of the equipment.

5. CARBON ELECTRODE

The carbon electrode or carbon arc system of melting in cold-wall melting was used to some extent in the early and mid-1950's in the production of titanium ingots. The overall equipment is very similar to a standard consumable arc furnace, except the consumable electrode is replaced by a graphite electrode. Melting was usually accomplished in crucibles no deeper than 180 cm with conventional dc power supplies. This system is not normally used today because of the continuing problem of carbon contamination. However, when in use, it was applied to melting both sponge and small sized scrap. The following parameters are characteristic of this equipment:

A. Power

Power for the carbon arc equipment is normally provided by a dc power supply having an open circuit voltage of 80 volts and an operating voltage of 40 volts at a current level of approximately 15,000 amperes.

B. Vacuum Pressure Requirements

Under most conditions the carbon electrode operates best in an atmosphere of argon. Melting pressures above and below one atmosphere could be used after completely vacuum-purging the furnace.

C. Material Feed

Material feed would normally be accomplished with a vibratory or rotary drum feeder. It should be noted that electrode control would be by an automatic voltage controller similar to that used in consumable arc melting.

D. Pool Configuration

The pool configuration is sufficiently deep to permit skull casting. There have been some skull furnaces constructed that have incorporated carbon electrodes for their arc sources.

E. Casting Modes

Though withdrawal melting can be used with this equipment, skull casting and static casting have been the primary modes used in the past.

F. Production Capacity

The production capacity of carbon electrode equipment would be quite satisfactory for consolidating fuel element hulls. It is expected that the kW-hr per kg requirement would be at a 2-to-1 ratio or better.

G. Mechanical Complexities

The carbon electrode furnace would perhaps be as simple as any equipment under consideration, since the problems of electrode replacement and cooling are minimal.

H. Maintenance Considerations

Maintenance considerations should be quite favorable with this equipment because of its basic simplicity. The biggest problem would probably be the cleanup and disposal of the radioactively contaminated graphite electrodes after use.

I. Controls

The controls required for this equipment are fairly standard in the industry and basically the same as those used with consumable arc melting equipment.

J. Hot Cell Adaptability

The adaptability of the graphite electrode to hot cell applications is somewhat questionable. The problem of carbon contamination of the melt and radioactive contamination of the electrode appear to be major obstacles with this equipment.

K. Safety

Moderate voltage levels make the safety aspects of this system certainly acceptable in comparison with the other melting systems considered.

L. State-of-the-Art

There is in the industry a considerable amount of information on carbon electrode melting practices. For the most part, this system is not being used today because of the inherent problems of carbon contamination.

M. Ingot Quality

It is doubtful that the ingot quality from a single melt with this equipment would be acceptable, unless small ingots were to be cast by skull melting. Single-melt ingots produced statically or in a withdrawal crucible would probably require remelting prior to processing.

N. Cleanup Requirements

The primary cleanup requirements of this equipment involve splatter and carbonaceous deposits on the furnace walls. If the equipment were to be applied to static-mold melting, the overall cleanup requirements should be quite moderate.

Evaluation

The largest problems in considering the carbon electrode system for melting nuclear fuel hulls are the presence of carbon in the ingot and the decontamination or disposal of the electrodes.

5. TUNGSTEN ELECTRODE

The water-cooled tungsten electrode was used in the early days of reactive metals production and is still used as a lab tool in alloy studies and quality control procedures with a variety of metals. Some skull melting has been accomplished using water-cooled tungsten-tip electrodes, but there does remain the problems of tungsten contamination in the melt and a fairly high consumption rate for the electrode tip. The following parameters are characteristic of this equipment:

A. Power

Power for this equipment would best be provided by a dc rectifier having an open circuit voltage of approximately 80 volts, a working voltage of approximately 40 volts, and a current capability on the order of 15,000 amperes.

B. Vacuum Pressure Considerations

The nonconsumable tungsten electrode would operate best in one atmosphere of argon or the range from ~250 to 760 torr.

C. Material Feed

Material feed to the water-cooled tungsten electrode furnace could best be accomplished by a vibratory feeder or a rotary drum type feeder. We anticipate that the electrode would be pivotally mounted to enable manipulation of the arc zone as required within the melting crucible or sleeve.

D. Pool Configuration

We anticipate that the pool configuration could be moderately deep. However, there is not enough data on equipment of the scale being considered to be certain.

E. Casting Modes

We feel that the water-cooled tungsten electrode could be applied to withdrawal, skull, or static casting equipment.

F. Production Capacity

The production capacity of this equipment would probably be sufficient for the anticipated fuel hull consolidation requirement, but it would not rate as well as some of the other systems being considered.

G. Mechanical Complexities

Generally speaking, the equipment should be quite simple in design with the most complex considerations being limited to tip changing and electrode maintenance.

H. Maintenance Considerations

The primary maintenance considerations would be related to servicing the tungsten tip.

I. Controls

Controls required for this equipment would be relatively simple and no major problems are anticipated.

J. Hot Cell Adaptability

The equipment could be adaptable for hot cell operation. The major problems are electrode manipulation and tungsten contamination of the melt stock.

K. Safety

We anticipate that this equipment would be relatively safe for hot cell application, once empirical values for electrode life can be established.

L. State-of-the-Art

Although a great deal of water-cooled tungsten electrode melting is continually being accomplished, it is limited mostly to relatively low power and small melt requirements. A large scale production system is yet undeveloped. We feel that the metallurgical quality of the material would be somewhat endangered by high density tungsten inclusion.

M. Ingot Quality

It is doubtful that ingot quality suitable for direct processing of the material could be obtained from a single melt. We also anticipate that the possible frequency of tungsten inclusion would be extremely detrimental if the material is to be further worked or utilized.

N. Cleanup Requirements

Although data is not available on a production-size unit, we expect that cleanup requirements for this equipment would normally be quite simple.

Evaluation

There is an absence of data on the use of the tungsten electrode for melting reactive metals. There is also an early history of quality problems in attempts to produce titanium with such equipment. Considering these and contamination problems, the tungsten electrode melting system appears to have some definite shortcomings as a choice for the hot cell consolidation of nuclear fuel hulls.

7. CONSUMABLE ELECTRODE

Consumable electrode arc melting is probably the most widely used of cold-wall melting techniques. It has been utilized for static-mold ingot casting, withdrawal-type ingot casting, and skull casting. A variety of furnaces having production capacities from a few kilograms to ~20 tonnes and more have been used for melting for many years, in almost all phases of the metal industry. In considering direct consumable electrode melting of fuel hulls, it will either be necessary to form the hulls into an electrode by pressing, sintering, or premelting. Another approach is to use a wrought, consumable electrode while side-feeding quantities of hull scrap into the melt zone, thus consuming noncompactible material at some weight rate perhaps less than the consumable electrode consumption.

The following parameters are characteristic of this equipment:

A. Power

A power source for a medium-sized consumable installation would consist of a dc power supply having an open circuit voltage of 80 volts, an operating voltage of 40 volts, and a maximum current rating of approximately 15,000 amperes.

B. Vacuum Pressure Requirements

Depending upon electrode configuration and certain safety aspects, consumable melting is operated in an inert atmosphere from 10^{-3} torr to pressures above atmospheric. Under any conditions, the melt should take place in vacuum or an inert atmosphere.

C. Material Feed

In consumable melting at least 50% of the feed material must be in the form of a consumable electrode, properly adapted to an appropriate stinger and automatic drive system. Any material to be loose-fed would be best done by using a vibratory type feeder. There is no doubt that the combination of a consumable electrode with loose feeding can result in a difficult and erratic melt.

D. Pool Configuration

Pool configuration in a straight consumable-type melt is generally quite deep, provided sufficient power is available. However, if side feed material is to be included, the chilling effect could appreciably reduce the size of the molten pool.

E. Casting Modes

It is possible with consumable arc melting to incorporate withdrawal, static, or skull casting procedures. However, it is anticipated that either skull casting or static melting would be most suitable for hot cell operation.

F. Production Capability

The production capability of consumable melting itself is quite high. However, the production advantage is considerably reduced when considering the requirement for preparation of electrodes, etc.

G. Mechanical Complexities

Although the actual melting equipment for this system would be quite simple in design and construction, the support equipment would be complex. This would involve primarily the remote-operated electrode preparation equipment and the necessary handling equipment for loading and unloading of the furnace.

H. Maintenance Considerations

Maintenance considerations would be somewhat complicated, not because of the actual melting furnace, but because of the equipment required to fabricate, prepare, load, and unload the furnace.

I. Controls

Controls for consumable arc equipment are well developed and very reliable under normal operating conditions.

J. Hot Cell Adaptability

Because of the limited potential for handling large quantities of loose scrap with the complex pre-preparation consumable melting, the consumable electrode does not appear to be the most desirable avenue for the consolidation of nuclear fuel hulls.

K. Safety

Although there have been some serious consumable furnace mishaps related to reactive metal melting, we feel that this system would be quite safe with the present day state-of-the-art, not considering the loose-feeding of scrap. However, when the loose-feeding of scrap is considered, we anticipate that certain safety hazards might be encountered with bridging and sidewall arcing.

L. State-of-the-Art

Consumable electrode melting is the most highly developed of all present day cold-wall melting systems.

M. Ingot Quality

It is doubtful that suitable ingot quality would normally be obtained from a single melt, except with skull melting, where small diameter ingots of acceptable quality could be produced.

N. Cleanup Requirements

Cleanup requirements from a straight consumable melt into a static crucible should normally not be too severe. However, when skull casting is considered, a certain percentage of splatter, lip residue, and related difficulties could impose considerable cleanup problems.

Evaluation

The consumable electrode as a tool for the consolidation of nuclear fuel hulls does not appear to be the most acceptable procedure to follow. This is primarily because of the difficult requirement of fabricating an electrode from nuclear fuel hulls. The cost of electrode fabrication can be reduced somewhat through the loose-feeding of scrap, but then potential safety hazards due to bridging and sidewall arcing are introduced.

8. ELECTRON BEAM

Electron Beam (E.B.) melting has been used for several years in the production of refractory metals. Its best known application has been in the melting of columbium and tantalum alloys, but it has been used on a large scale in the production of stainless steel and a variety of other materials. E.B. furnaces with total connected power on the order of 3 MW are in operation today. The E.B. furnace is capable of melting a variety of materials at melt rates approaching several tonnes per hr. However, cleanliness of feed material is important in obtaining good operation and production from E.B. melting equipment. The characteristics of the E.B. melting system are as follows:

A. Power

The E.B. furnace is powered by a high voltage dc power supply and usually incorporates two or three individual gun systems. A power supply for a typical furnace having a capacity to produce ingots from 30 to 36 cm in diameter would be rated at 18,000 to 20,000 volts dc and a current of approximately 30 amperes. The power supply is fairly sophisticated in design and requires considerable attention to safety, interlocks, cleanliness, and electronic maintenance.

B. Vacuum Pressure Requirements

The E.B. furnace is characteristically a high vacuum furnace, and best operating conditions are in the 10^{-4} torr range or lower. Of all the cold-wall systems being discussed, the E.B. furnace requires the most sophisticated vacuum system and the highest degree of in-furnace cleaning, especially in the area of the E.B. guns and high voltage power feed-throughs.

C. Material Feed

Material feed to E.B. furnaces can be accomplished by vertically hanging the material to be melted (and preferably rotating it) above the melt zone, thereby drip-melting the material into the pool. When considering the feeding of loose or small scrap, disposable-boat type feeders may be used by progressively pushing them over the lip of the crucible and allowing

the material to be melted and dripped into the molten pool. It is also possible to directly feed material into the molten pool by vibratory or rotary type feeders; however, if the materials are not completely clean, a great amount of sputtering and splashing may occur because of the furnace's low pressure. The melt rate is affected considerably if the material is not properly prepared or if the material should contain large quantities of hydrogen.

D. Pool Configuration

The pool configuration with a typical E.B. melt is quite shallow and flat. This is caused by a high degree of evaporative cooling at the pool surface, plus the spreading effect of the electron beam when a plasma is established above the pool area. Although people have attempted to use the E.B. furnace for skull casting, the results have not been particularly encouraging.

E. Casting Modes

E.B. melting is most adaptable to producing cold-wall ingots by the withdrawal technique. Skull casting or static melting procedures do not show much promise.

F. Production Capacity

E.B. melting equipment presently exists which is capable of producing metals in the tonnes-per-hr range. It is difficult to establish a kW-hr-per-Kg melt rate because melt rates vary considerably depending upon the cleanliness and chemical characteristics of the feed material. When considering extremely clean melt stock, high power efficiencies can be obtained.

G. Mechanical Complexities

The E.B. furnace is perhaps the most complex of all cold-wall melting systems being discussed. This is true for both the mechanical and electrical complexities of the E.B. gun system and the requirement for shielding guns from metal splatter and high pressure bursts. It is also necessary to provide appropriate protection for the high vacuum insulators and other equipment necessary for proper operation.

H. Maintenance Considerations

E.B. melting equipment requires the highest degree of competence in both electrical and mechanical maintenance. It also requires more detail and care in cleaning and assembling than the other cold-wall equipment under discussion.

I. Controls

The controls for E.B. equipment do not provide any prohibitive problems, and although it is somewhat more complex than other melting systems, there is no problem in accomplishing remote operation. It is, of course, necessary to isolate any high voltage meters, etc., from the operator.

J. Hot-Cell Adaptability

Because of overall complexity and the need for frequent cleaning and for high vacuum integrity, we do not recommend that the E.B. furnace be considered for melting radioactive materials. Characteristically, a large amount of vaporized matter condenses throughout the electron beam system, and when considering remote maintenance, we anticipate that some relatively major operating problems would be encountered.

K. Safety

Safety considerations for this equipment are essentially the same as other cold-wall systems, except for the added danger of high voltage dc. However, with proper shielding and interlocking, the high dc voltage would not prove to be a major problem.

L. State-of-the-Art

E.B. melting has been well developed and perhaps has more technical input than any other vacuum melting system being considered. Plants of large tonnage scale are in operation both in the United States and eastern Germany, and for the melting and refining of certain refractory metals, it is the best and most advanced melting system available.

M. Ingot Quality

The surface quality of the E.B. ingot is largely dependent on feed material cleanliness and the method of material entry into the pool. The best ingot quality is obtained by remelting the electrodes which are hung vertically and rotated above the molten pool, resulting in a drip-melt with all material entering the pool in a molten state. When material is side-fed or cold-fed into the molten pool, it is very difficult to obtain an ingot with good sidewall quality.

N. Cleanup Requirements

Considering the high quantities of metal and volatile condensation which are normally deposited within the optical funnel of the E.B. melt, the cleaning problem is quite severe. Frequent and thorough cleanup is required to maintain desirable pressure and melting conditions because of the high vacuum requirements.

Evaluation

In evaluating the E.B. melting system, as applied to the consolidation of nuclear scrap, we feel that the E.B. melting system would not be desirable for the consolidation of radioactive metallic wastes because of its overall complexities and high vacuum requirements. There is no doubt that this is an excellent system for purity of product. However, because of the low pressure melting environment, it is also difficult to maintain metallurgical control of alloys having a variety of vapor pressures.

9. HOLLOW ELECTRODE

The hollow electrode melting system is in some respects related to plasma arc melting, except that melting can be conducted in a range from 5×10^{-3} to 0.5 torr. To date, the largest single electrode system used in the United States has a power rating of approximately 340 kW; however, this system has had an operating time of only ~60 hr. Conclusive data on many of its characteristics is not available, and the system has not been widely adapted to melting applications in the United States.

The following parameters are characteristic of this equipment:

A. Power

Power for this equipment is provided by a dc rectifier source having an open circuit voltage of approximately 150 volts and an operating voltage of 75 volts. Full load current of the equipment being discussed is on the order of 4500 amps. A high frequency starting unit is normally incorporated to initiate the arc.

B. Vacuum Pressure Requirements

The hollow electrode equipment can operate in a pressure range from 5×10^{-3} to 0.5 torr. Normal operating pressures are in the range from 5×10^{-2} to 0.1 torr. Since the hollow electrode usually consists of a closed-end tube, containing a center line gas aperture through which argon gas (the plasma carrier) is introduced to the arc zone, the vacuum for a given pumping system is limited by plasma gas throughput.

C. Material Feed

Material should normally be side-fed into the crucible by a vibratory or rotary drum feeder, depending upon the focusing coil configuration. The hollow electrode melting system requires a substantial magnetic focusing coil to concentrate the plasma beam within the confines of the melting crucible. It is felt that the presence of the magnetic focusing coil between the electrode and crucible may complicate the feeding of material. It should be pointed out that arc lengths from 20 to 90 cm have been obtained, although it is the opinion of the authors that the most efficient operation would result with shorter arc lengths.

D. Pool Configuration

Conclusive information about the pool depth is not available. However, the general characteristics of the melt apparatus indicate that the pool depth would be relatively shallow.

E. Casting Modes

Available information indicates that hollow electrode melting has been primarily performed with withdrawal casting operations. Operation in this mode is apparently quite satisfactory.

F. Production Capacity

The production capacity of this equipment is evidently a low kW-hr per Kg ratio. This assumption is made considering the requirement for tight magnetic focusing to direct the arc to the melt zone. Long plasma columns, especially in vacuum, have a tendency to be somewhat inefficient.

G. Mechanical Complexities

It is felt that the requirement for focusing coils in the proximity of the melt and concentric with the arc path presents some degree of complexity, both in the coil mounting and material feeding. Electrode changes and other requirements should not normally be prohibitive in considering application of this system; however, the maintenance and cleanup of the coils may prove difficult.

H. Maintenance Considerations

Though limited data makes it somewhat difficult to fully evaluate this requirement, we feel that the primary maintenance considerations for this equipment would be cleaning and maintaining the focusing coils and material feed equipment.

I. Controls

Controls for this equipment should not provide any major problems.

J. Hot Cell Adaptability

Focusing coils and restricted feeding clearance somewhat deter hot cell adaptability for this equipment. Again, lack of conclusive operating data clouds this determination.

K. Safety

Because of the moderate voltage levels, we feel that overall safety considerations for this equipment would certainly be as acceptable as any of the other systems being considered.

L. State-of-the-Art

Most of the hollow electrode melting conducted in the United States has been on a pilot plant or very limited production basis. For this reason, the state-of-the-art is not as well defined as most of the other melting systems being considered in this study.

M. Ingot Quality

It is doubtful that ingot quality from a single melt using this equipment would be acceptable for direct forging or processing. Observed surfaces of large ingots melted outside the United States substantiate this feeling.

N. Cleanup Requirements

Sufficient data from actual operations is not available. However, because of lower vacuum levels and other physical requirements of the system, some difficult cleanup problems are anticipated.

Evaluation

It is somewhat difficult to make a complete evaluation of the hollow electrode melting system because of the limited information available; however, the system's physical characteristics alone would indicate that it is probably not the most desirable approach for hot cell use.

10. INDIRECT ARC

Indirect arc melting systems have not been generally accepted in cold-wall melting practices, primarily because of their inherent low power efficiency and (in some cases) the possibility of melt contamination by electrode materials. Indirect arc melting equipment generally refers to equipment where the metal or molten pool is not used as a termination point for the arc. Examples of this equipment would be a nontransferred plasma arc torch (sometimes referred to as a gas heater) or the traditional rocker furnace using two horizontally opposed electrodes providing a high powered arc which both radiates and convects heat to the melt surface.

The following parameters are characteristic of indirect arc equipment:

A. Power

Power for this equipment can be provided either as single phase ac or dc at voltages in the range from 40 to 80 volts and an estimated 15,000 amperes for this particular application.

B. Vacuum Pressure Requirements

For the most part, the indirect arc system would require argon or another inert gas at atmospheric pressure or slightly higher.

C. Material Feed

Material feed could be accomplished by a vibratory or rotary drum feeder; however, under any feeding conditions the high percentage of radiated and convected heat could cause severe problems with the feeding mechanism.

D. Pool Configuration

There is no doubt that the pool configuration for this mode of melting under cold-wall conditions would be extremely shallow.

E. Casting Modes

The only practical casting mode with indirect arc equipment would be withdrawal.

F. Production Capacity

Since no production equipment of this type is known to be used for cold-wall melting, it is expected that the production capacity (kW/kg) would be the lowest of all melting systems being considered in this study.

G. Mechanical Complexities

The two-electrode system, the associated necessity for insulation, and the subsection of in-furnace components to high levels of heat would all involve some mechanical complexity. The equipment enabling a continuous production operation could become quite complex.

H. Maintenance Considerations

For the reasons mentioned above, we feel that the maintenance of a large production unit using a nontransferred or indirect arc could become a major consideration. This again is a determination that has been made in the absence of good operating data.

I. Controls

The controls involved with this equipment should not provide any major problems.

J. Hot Cell Adaptability

For the reasons listed in G and H above, along with an anticipated low efficiency and insufficient information on actual operation, it is felt that this equipment would not be adaptable to hot cell operations.

K. Safety

Because of moderate voltage requirements, the atmospheric pressure operation of this equipment, and the minimal possibility of having a credible failure by arc-through, it appears that the overall operation would be quite safe.

L. State-of-the-Art

Practically no information is available on indirect arc melting related to cold-wall melting.

M. Ingot Quality

Because of low power efficiencies and a rather minimal operating range above the melting temperatures of most scrap to be melted, we would not expect good ingot quality from this melting system.

N. Cleanup Requirements

Cleanup requirements with an indirect arc system would perhaps be very favorable in hot cell melting. Metal splatter and metal condensate should be kept to a minimum.

Evaluation

Considering the state-of-the-art, low efficiency, and many other anticipated shortcomings of an indirect arc melting system, it is recommended that such equipment not be considered at this time for consolidation of nuclear fuel element hulls.

CONCLUSIONS

It is the consensus of the authors that the following melting systems are the most desirable for possible adaptation to hot cell operation:

1. Inductoslag
2. Plasma
3. Mechanical Rotating Nonconsumable Electrode
4. Arc Magnetically Rotated Nonconsumable Electrode

If it were not for slag handling requirements, perhaps the Inductoslag system would be top candidate for providing a finished ingot for remanufacturing on a single-melt basis. The Inductoslag system appears to be especially desirable when considering ingots of 8-in. diameter or less.

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APPENDIX

OVERALL RATING CHART FOR THE TEN MELTING FURNACES BEING CONSIDERED FOR THE CONSOLIDATION OF NUCLEAR FUEL HULLS

The overall rating chart which follows has been assembled to aid in sensibly evaluating the ten cold wall systems for what would be some of the key considerations in hot cell operation.

Items F through M on this chart are rated on a point system as follows:

- 1 Excellent
- 2 Good
- 3 Fair
- 4 Poor

As a result, those systems having the lowest additive scores should be most desirable for hot cell considerations.

OVERALL RATING CHART FOR THE TEN MELTING FURNACES BEING CONSIDERED
FOR THE CONSOLIDATION OF NUCLEAR FUEL HULLS

Melting System	A		B	C	D	E	F	G	H	I	J	K	L	M	N	Total Rating Score	Remarks
	Power Volt	Amp	Vacuum Pressure	Material Feeding	Pool Configuration	Casting Modes	Production Capacity	Mechanical Complexities	Maintenance Considerations	Controls	Hot Cell Adaptability	Safety	State-of-the-Art	Ingot Quantity	Cleanup Requirements		
1. Inductoslag	450 10,000 Hz	220	250 torr Helium/Argon	Vibratory or Rotary Feeder	Deep	Withdrawal Skull Casting Static	3	2	2	2	2	2	2	1 1 1	1 3 1	17 19 17	Clean melt. Low production rate with good quality. Slag handling may be major drawback.
2. Plasma	200 dc	3,000	250 torr to 1 Atmosphere Argon	Vibratory or Rotary Feeder	Shallow	Withdrawal	2	3	3	2	3	2	2	3	1	21	Clean melt; soft heat; major problem is argon flow rate required and bad ingot surface.
3. MRNE (a)	40 dc	15,000	20x10 ⁻³ to 20 torr	Vibratory or Rotary Feeder	Deep	Withdrawal Skull Casting Static	1	3	3	2	2	2	1	2 1 2	2 3 2	18 18 18	Some splatter in melting. This is major drawback. Ingot surface good in casting; fair otherwise.
4. AMRNE (b)	50 dc	11,000	20x10 ⁻³ to 20 torr	Vibratory or Rotary Feeder	Deep	Withdrawal Skull Casting Static	1	4	3	2	3	2	1	2 1 2	2 3 2	20 20 20	Some splatter in melting - and complexity of tip. Ingot surface good in casting; fair otherwise.
5. Carbon Electrode	40 dc	15,000	1 Atmosphere Argon	Vibratory or Rotary Feeder	Deep	Withdrawal Skull Casting Static	2	2	2	2	4	2	1	3 3 3	2 2 2	20 20 20	Basically has problem of carbon contamination plus frail electrode.
6. Tungsten Electrode	40 dc		1 Atmosphere Argon	Vibratory or Rotary Feeder	Deep	Withdrawal Skull Casting Static	3	2	2	2	3	2	3	3 3 3	2 2 2	22 22 22	Problem of tungsten contamination plus problems in scaling up to high power levels.
7. Consumable Electrode	40 dc	15,000	10 ⁻² torr to 1 Atmosphere Argon	Electrode Drive	Deep	Withdrawal Skull Casting Static	3	4	3	2	4	2	1	2 1 1	2 3 2	23 23 22	Requirements for electrode preparation and handling are too much.
8. Electron Beam	20,000 dc	30	5x10 ⁻⁴ torr	Vibratory or Boat Feed	Shallow	Withdrawal	4	4	4	3	4	3	1	3	4	30	Too delicate. High voltage and clean melting practice required; high vacuum operation.
9. Hollow Electrode	75 dc	4,500	5x10 ⁻³ to 5x10 ⁻¹ torr	Vibratory or Boat Feed	Shallow	Withdrawal	4	3	4	3	4	2	4	3	4	31	Somewhat similar to above mentioned with focusing coil and other built in complexities.
10. Indirect Arc	40 dc	15,000	1 Atmosphere Argon	Vibratory or Rotary Feeder	Shallow	Withdrawal	4	3	3	3	4	2	4	3	4	30	Hard to control with cold-wall melting; inefficient plus good chance of tungsten contamination.

(a) Mechanical Rotating Nonconsumable Electrode
(b) Arc Magnetically Rotated Nonconsumable Electrode

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