LEVEL II

Report and Recommendations

to

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY
TECHNICAL ASSESSMENT OFFICE

on

# PLASMA PROCESSING SYSTEMS FOR THE MANUFACTURE OF REFRACTORY METALS AND THEIR ALLOYS FOR MILITARY NEEDS


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# EXECUTIVE SUMMARY AND RECOMMENDATIONS

This technology assessment report highlights the present status of industrial development and applications of plasma melting manufacturing technology in the Soviet Union, German Democratic Republic and Japan. The industrial experience gained in plasma technology application for the purposes of melting refractory metals and their alloys, electronic alloys, titanium and its alloys have demonstrated significant benefits in concrete terms of cost reduction, processing short cuts, processing schedule, labor component and energy consumption reductions.

Soviet plasma technology developments have reached a threshold that they possess the capabilities for the production of multi-phase refractory metal alloys with directional structures.

The US industry has no plasma melting systems in operation and none are planned for the foreseeable future.

Government impetus is required to convince the industry the merits and economics of plasma melting devices.

A feasibility demonstration program is recommended whose objective will be to establish a pilot scale plasma melting facility for the production of improved penetrators from refractory metal eutectic alloys with copper or uranium. A relatively modest program is envisaged that would span a time period of 8 to 10 months and an expenditure of not more than 180,000 dollars.

## INTRODUCTION

This study presents a comparative technical and economic analysis of the current, powder metallurgy, and an alternate, plasmarc processing, method of producing improved armor penetrator materials. This technology assessment effort was conducted in order to highlight industrial applications of plasma arc melting technology for the manufacture of refractory metals and their eutectic alloys. Primary focus of this survey is on potential military uses of plasma technology which could provide both strategic and economic advantages.

### Background

Armor penetrator materials are made out of hard materials. Cemented carbides are the hardest man-made metals next only to diamonds. Certain armor piercing bullet cores are made from cemented carbides of tungsten, tantalum, titanium, columbium held in a metal matrix such as cobalt or nickel. Basic research into the manufacture of cemented carbides has reached a point of "tailorability" that it is now possible to deliver any desired combination of properties in a component needed for a given application.

Meanwhile, armor materials have also improved with the advent of electroslag processing, matrix strengthening, thermo-mechanical processing, composite fabrication.

Therefore, improved penetrator materials are needed to overcome the advantages in strength and toughness improvement of armor materials. Reports of Soviet development of a plasma melting method for producing multi-phase alloys with directional structure have recently come to light. It is conceivable that this processing technique is being used in the USSR, for the economic and efficient production of improved penetrator materials.

In France there had been some exciting progress made in the development of solidification composite materials for high performance aircraft turbine blade application by a single metallurgical operation. In these new materials oriented grain complex superalloys are further reinforced by the addition of fibers. The fibers are made of MC type carbides, in particular tantalum monocarbide, which provides very high strength. Tantalum monocarbide fibers have tensile strength in excess of 15,000 MPA and their melting point is around 4000°K. An exceedingly interesting feature of these solidification composites is the formation of fibrous MC type carbide structure spontaneously during unidirectional solidification. The manufacturing concept of these solidification composites is based on the solidification of oriented eutectics. The technical challenge is to correctly establish a temperature gradient at the melt-solid interface and a rate of ingot solidification so as to obtain oriented structure comprising alternating lamellae or refractory carbide fibers embedded in a suitable alloy matrix. A plasma heat source is ideally suited for establishing the required temperature gradient and melt solidification speed for the above purpose.

For penetrators, the matrix could be refractory metal binary alloys with copper or uranium and the eutectic phase could be carbide of tungsten, molybdenum, tantalum or titanium.

The consolidation of refractory metals and their alloys can be done by one of three processing techniques - namely, powder metallurgy, vacuum arc melting, electron beam melting.

In the conventional powder metallurgy process, metal powders are consolidated by cold pressing and sintering or hot pressing. The limitations of this process have been mainly of size and difficulty in producing high density materials. The sintering process, which depends on solid-state diffusion of metal particles cannot distribute the alloying ingredients as uniformly and effectively as the melting process.

Consumable-electrode vacuum arc melting is a major means of producing refractory alloy ingots. Limitations of this process include the short residence time of the metal in the molten state and the moderate vacuums employed which do not refine the metal or improve alloy homogeneity. The cold mold causes deterioration of ingot surface qualtiy and reduced yield of ingot product.

The yield loss problem can be relieved to some extent by the use of mold liners of the same material as being melted. Today, the arc melting process remains as a valid production method.

The requirements of high purity ingots of refractory metals and their alloys have led to the application of the electron-beam melting process. This process is conducted under very high vacuum environment. The problem with electron beam (EB) melting is the amount of volatile materials contained in the feed stock. The extra-pure refractory metals and alloys manufacture is done by a duplex melting technique in which the feed stock for electron beam melting is prepared first by vacuum arc melting. Another procedure is to isolate the electron beam heat source from the melting chamber through the use of a special diaphragm. A particular drawback of electron beam melted alloys is their lower strength while they display an apparent gain in ductility.

Of the three processing methods described, the powder metallurgy technique is normally used for manufacturing refractory metals and their alloy components because of the great difficulties associated with melting, casting and subsequent hot working of such materials. Claims have been made by Soviet researchers that plasmarc melting process has solved several technical problems relative to the production of high melting metals, compounds, and multiphase alloys such as, intensification of refining reactions, alloying by components of plasma gas, directional solidification, productivity improvement, simplification of the processing euqipment, its maintenance and servicing.

In order to better appreciate the merits of plasma heat processing, it would be expedient to review briefly the conventional powder metallurgy method of producing cemented carbide components.

The major processing steps involved are as shown in the flow diagram, Figure 1.

A plant capable of producing approximately 6 metric tons per month of finished tungsten carbide or mixed refractory carbide shapes such as the penetrators will require provisions of building space, manufacturing equipment, personnel and operating capital and processing costs as outlined in Table I.

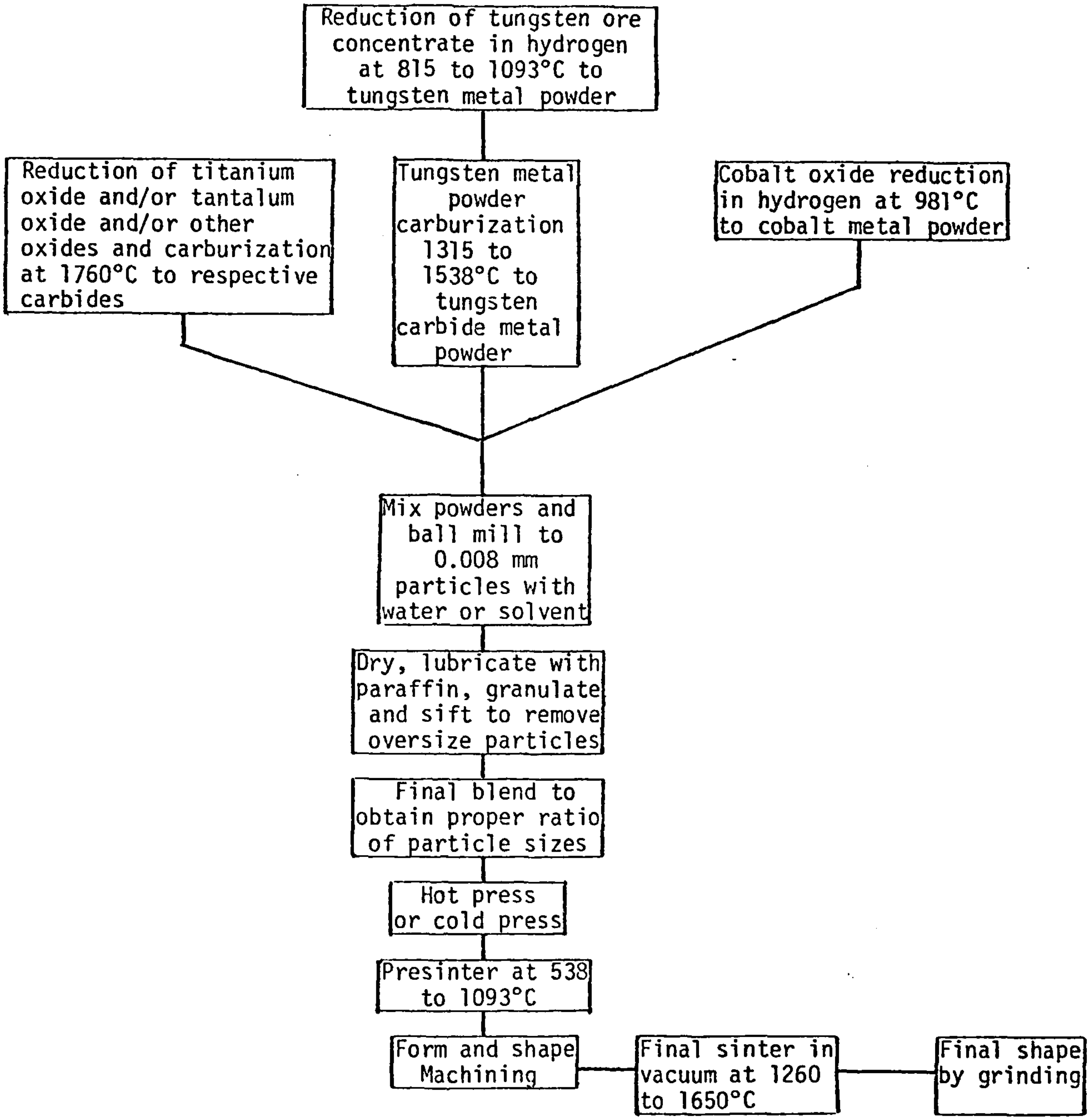



FIGURE 1 - Flow Diagram of Cemented Carbide Manufacture

# TABLE I - MANUFACTURING COST COMPARISON OF CEMENTED CARBIDES COMPONENT PRODUCTION BY POWDER METALLURGY VERSUS PLASMA MELTING

## POWDER METALLURGY ROUTE
(Representative Cost Estimation)

A. Building - 800 square meters area under a 5 meter high roof — Cost $500,000

B. Equipment
- Top loading scale - 1
- Ball mills - 3
- Carbide balls
- Mixers - 3
- Screening machine - 1
- Water heater - 1
- Naptha collector - 1
- Lab equipment
- Maintenance equipment
- Presses - 3
- Top loading scale - 1
- Dies for the press - 15
- Sintering furnace — Total Cost $1,200,000

C. Personnel
- Staff - 3 - one 8 hour shift operation
- Labor - 15 — Total Cost $ 300,000

The manufacturing cost estimate for 70 metric tons or 70,000,000 grams per year net yield of finished product:

| | |
|---|---|
| Equipment - 1,200,000 depreciated 5 year basis | $ 240,000 |
| Payroll | 300,000 |
| Building - 500,000 depreciated 10 year basis | 50,000 |
| Utilities, interest, taxes, and misc. | 50,000 |
| Total | $ 640,000 |

## PLASMA MELTING ROUTE
(Estimated)

A 6 metric tons per month production by the plasma melting technique will require 3 furnaces located in a small building, each furnace capable of producing 200 Kg of directionally solidified ingot metal per month.

The manufacturing cost estimate for 70 metric tons per year net yield of finished product:

| | |
|---|---|
| Equipment - 500,000 depreciated 5 year basis | $ 100,000 |
| Payroll | 100,000 |
| Building - 200,000 depreciated 10 year basis | 20,000 |
| Utilities, interest, taxes and miscellaneous | 80,000 |
| Total | $ 300,000 |

The manufacturing facility and manpower cost reduction via the plasma route are significant. However, the above economic analysis does not portray other advantages, which may be gained through the use of plasma processing. For example, it will be possible to use tungsten concentrate and oxides of other refractory metals or cheaper charge materials into the plasma system for simultaneous hydrogen reduction and fusion followed by solidification into the multi-phase alloy components. Evaluation of Soviet work indicates the possibility of realizing at least 22% savings in the average cost of blended powders. The production rate of 2000 Kg of ingot metal per each plasma furnace capable of casting 50 mm - 100 mm ingots weighing 30 Kg to 80 Kg is conservatively stated. A 200 Kg per day production from each plasma furnace can be easily realized. Taking into consideration all these factors, there are good prospects of reducing cost of plasma melted and cast penetrators by at least 50%, and the time schedule from 6 to 10 days for the powder metallurgy product to only 1 to 2 days.

Other factors not considered in the above discussion include technical improvements achievable through the manufacture and use of eutectic alloys of tungsten and other refractory metals. The potential application of plasma melting for the production of refractory carbide fiber reinforced turbine blades could be another outcome of a feasibility demonstration program for the manufacture of penetrators.

The Soviets are claiming that the plasmarc melting is an efficient method for producing cast multiphase alloys and eutectics alloys such as $W\text{-}W_2C$, $Nb\text{-}Nb_2C$. Eutectic composites of various types are of considerable interest as high strength and high temperature materials. In a eutectic composition, two or more phases are solidified simultaneously from the molten state under controlled thermal gradients and solidification rates. The directionally solidified eutectics display unusual material properties.

These are of considerable interest in the development of high density penetrators. For example, the large boundary area inherent in fine grain, directionally solidified eutectics may deflect crack propagation.

Plasma melting parameters offer wide range flexibility to control temperature gradient at liquid-solid interface, impurity content, ingot growth rate, crystallographic orientation, so as to develop special microstructures and material properties.

It is therefore feasible to obtain lamellar, parallel rod-like and colony formation types of structures in solidified eutectics. Some of these eutectic alloys could be of potential interest for improved penetrator applications.

Plasma heating has received considerable attention in many countries, as a viable and economic process for the synthesis of new materials.

Plasmarc Heat Source

The plasmarc heat source has substantial advantages over the conventional arc and other heat sources. Varying the composition and flow rate of the plasma forming gas and the degree of arc constriction, it is possible to control plasmarc temperature over a wide range and the concentration of the heat flow applied to a workpiece. The device which produces plasmarc is called the plasma gun or the plasma torch and the systems that supply electrical energy to the plasma torch are called power sources.

The heating of the charge in plasma arc primary melting and consumable electrode remelting systems is accomplished by the energy released in an arc discharge. The rate of energy transfer to the charge material from the plasmarc depends upon several parameters including the electric field applied, the intensity of the magnetic fields generated, charge of the particles, total current, the type of plasma gas used and its ionization potential, chemical reactivity and such other characteristics of the heat source and constituents of the charge material.

Transfer of the plasma heat energy takes place by the mechanisms of conduction, convection, radiation and diffusion. Conduction is through interparticle transfer from high to low temperature regions. Radiation travels in wave form and requires no medium. Convection depends upon mass density differences between the heated gas and the surrounding gas in the enclosure. Diffusion of heat is dependent upon the concentration of particulate species of gas and thermal gradients.

Plasma melting equipment and plasma heat sources used in the USSR, Eastern Europe and Japan are of diverse designs and processing capabilities. The western world has no industrial size plasma melting facility, although considerable research and development studies were performed during the sixties.

The essential features of plasma melting equipment is a sealed chamber which holds the melting receptacle, charge feeding system, ingot solidification system and sealed ports for the placement of plasma heat sources or torches.

Refining of metal in plasma furnaces is accomplished by one or a combination of following methods:

(a) Interaction between molten metal and gas phase.

(b) Vigorous mixing and exposure of molten metal to plasma temperature facilitating mass transfer of impurities and their removal at the gas-metal interface.

(c) Deoxidation of metal with hydrogen in the plasma.

(d) Refining with slags of required chemical reactivity.

Controlled rate solidification of the plasma melted metal progressively in a water cooled copper mold provides further opportunity for removal of inclusions, gases and shrinkage defects.

In plasma melting furnaces, argon is often used to protect the melt. Because of the low partial pressures of oxygen, nitrogen and hydrogen in the furnace atmosphere, these gaseous impurities are readily removed from the melt.

During plasma arc remelting, an increase of electrical power at a constant ingot growth rate does not deepen the molten metal pool. This is in marked contrast to remelting in vacuum arc and electroslag furnaces in which the molten metal deepens as the power delivered or temperature is increased. A shallow and flat molten metal pool in a water cooled copper mold facilitates the establishment of a uniform cross-sectional temperature gradient which will produce elongated grain structure parallel to the direction of ingot growth. Plasma heat promotes the formation of a homogeneous melt which is especially important in eutectic systems for the development of longitudinal reinforcing hard constituents or intermetallic compounds in a high strength alloy matrix. This concept is applicable for the manufacture of high density penetrators as well as significantly stronger gas turbine blade materials compared to multi-crystal directionally solidified alloys. The plasma furnace for this purpose will be a much simpler and lower capital investment manufacturing system than the electron beam or other types of melting and directional solidification systems.

Plasma Arc Characteristics

In the plasma torch, when an intense electric field is applied, the cathode is heated to high temperature and a gas passed around the heated electrode becomes partically ionized and electrically conductive. Electric current flows across the gap and the phenomenon of electric discharge occurs.

A feature of a gaseous conductor is continuous interchange of energy between electrons, ions and neutral particles. This interchange occurs through collision from disorderly movement of particles caused by heating.

At a pressure close to atmospheric or slightly above, the electrons lose part of their energy to the ions, neutral atoms and molecules in multiple collisions. This leads to the leveling of energy and temperature between all the particles of the plasma, i.e., thermodynamic equilibrium of plasma.

The operating principle of a plasma torch is based on the forced cooling and constriction of the arc column with steam, liquid or gas flow.

The plasma torch consists of an electrode which is in the form of a rod with a refractory tip attached to it as shown schematically in Figure 2. The electrode is fitted into a cylindrical chamber terminating into a copper nozzle with a hole coaxial with the electrode. The electrode and nozzle are both made of copper, and are water cooled. They are electrically insulated from each other with a spacer. The arc established between the electrode and the torch is forced through the nozzle by the working gas fed into the chamber. The anode spot of the arc moves on the inside wall of the nozzle passage whereas the arc column is firmly stabilized along the axis of the electrode and the torch.

In passing through the nozzle, part of the working gas is heated and ionized and emerges from the torch as the plasma jet. The outer layer of the gas flowing around the arc is relatively cool, and forms a thermal and electrical insulation between the plasma jet and the nozzle bore. The nozzle is thus prevented from rapid erosion. The density of the arc current in the plasma torch reaches 100 $A/mm^2$.

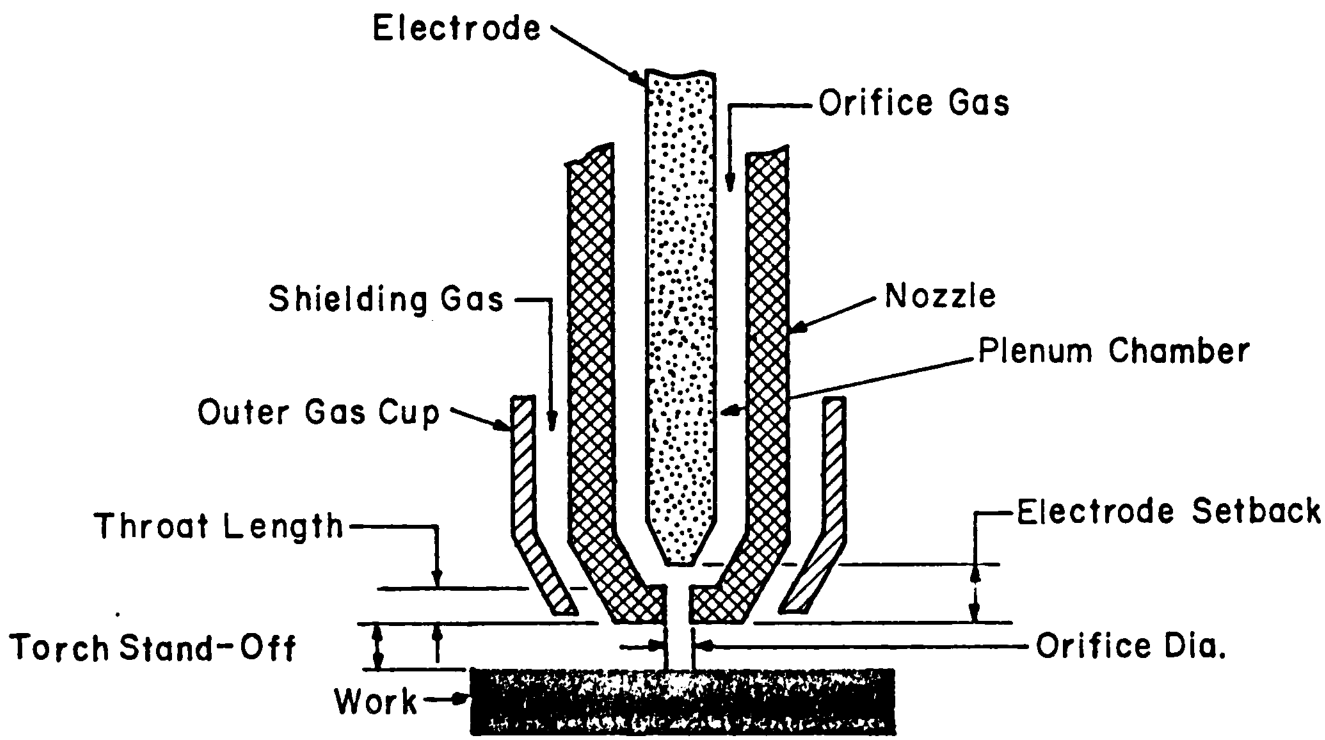



FIGURE 2. Schematic of a Plasma Torch Showing Essential Components.

A plasmarc is a converter of electrical energy into heat. It is therefore characterized by both electric parameters and thermal parameters. There is a complex interrelationship between the electrical and thermal parameters.

Plasma Torches for Metallurgical Applications

Plasma torches intended for various metallurgical operations should meet a number of general requirements.

The transferred arc plasma can be graphically represented as shown in Figure 3.

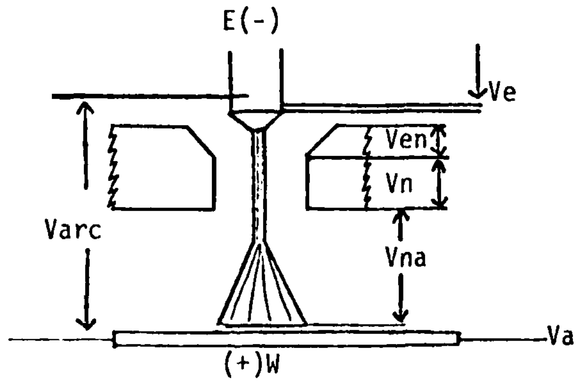



FIGURE 3. Graphical Representation of Arc Plasma

The arc voltage is the sum of drops of voltage across the various sections.

Ve = cathode drop
Va = anode drop

The cathode voltage drop with tungsten (W) cathode varies from 5 V to 8 V depending upon the current and the degree of arc constriction and from 10 V to 12 V with zirconium (Zr) cathode. The anode voltage drop is normally 5 to 6 V. Thus the plasma arc voltage is essentially dependent on the field intensity and on the length of the zones making up the total arc column.

For the transferred arc D.C. plasma, the current density can be approximated by the relationship

$$Jn = k \frac{4Iarc}{\pi d_n^2} \text{ A/cm}^2$$

where space factor k = 0.6 to 0.9 (factor of nozzle passage following the plasma)

$$\text{conductivity of plasma} = \frac{j_n}{E_n} \text{ 1/ohm·cm}$$
$$= f(T)$$

The plasma arc voltage depends on the torch design, arc current, composition and flow rate of the working gas and on the distance from the torch tip to the workpiece. To determine the range of operating voltages of plasma torches of a given type, a set of volt-ampere curves should be plotted; each for a monotonic gas and flow rate, length and unchanged basic dimensions of the working components of the torch.

The electric power of the arc almost entirely turns into heat and this heat is dissipated in the electrode, nozzle, the environment around the plasmarc and the workpiece.

The heat flux flow to the turngsten cathode is about 3.5 to 4.0 watts and the zirconium cathode 5.0 to 7.0 watts per each ampere of arc current. The power liberated by the electronic current ($I^2R$ drop) at the anode is approximately 10 watts per each ampere of arc current.

The heat lost to components of the plasma torch is more difficult to determine.

The effective efficiency of heating the workpiece (metallic charge) by transferred arc plasma varies from 70 to 80%. Melting is performed by transferred arc plasma torches of several kiloamperes capability. The arc voltage depends upon the composition and flow rate of gas and the arc length. It can vary from 80 to 600 V. Consumption of power in the process of melting is almost the same as in conventional arc furnaces.

Compared to VAR and ESR, PAR is more versatile and the bath temperature can be more precisely controlled through manipulation of the geometric and electric parameters of the plasma arc. The melting of the electrode and ingot withdrawal can also be independently controlled with greater precision. The uniform heating of the bath helps obtain a flat shape of molten metal pool which provides for high quality of the solidified ingot, i.e., ensures high density, homogeneity and directional crystallization of the ingot along its vertical axis.

Gas recirculation is possible in a closed system.

Plasma Torch Design and Operational Requirements

1) The torch should be of simple design, easy to manufacture, operate and repair. It is especially important to provide for easy assembly, dismantling for replacement of worn parts such as the cathode and nozzle.
2) The torch should be of economical and rugged design, must operate with minimum of cooling water, working gas and heat losses.
3) The torch should be safe to operate, must start and restart easily and operate with stability at the required range of power input. To satisfy this requirement, there should be a definite relationship between the electrode diameter, nozzle bore, nozzle length, and the gap between the electrode and the nozzle.
4) The elements subjected to the most intense heat must withstand prolonged thermal load, provide adequate service life.

5) Good insulation (thermal and electrical) must be provided between the electrode holder and the nozzle so that it withstands the maximum voltage appearing across the arc gap during arc striking and extinction. For the arc excited with the oscillator, the voltage is 2 to 5 Kv in the frequency range of 0.3 to 1 MHz.

The plasma torch should also meet a number of specific requirements peculiar to each design. Plasma torches used for melting must be fully shielded to prevent water leaks into the melt and electrical shorts with the chamber.

Plasma torches can be generally classified as follows:

The first step in designing a plasma system is to represent schematically the heating torch. This involves selection of a cooling system, electrodes, plasma gas, electrical parameters, method of plasma arc stabilization and electrode spot recovered. Plasma torches may be divided into two groups:

(a) by the type of arc (1) transferred arc or (2) non-transferred arc

(b) by the system of cooling of the electrode and the nozzle

  (1) air cooled - low current 300 - 400 A

  (2) water cooled - high current

(c) by the method of arc stabilization

  (1) gas - simplest - most often used

  (2) water - high temperature capability

  (3) magnetic - least efficient

(d) by the type of the electrode-cathode, rod-cathode, distributed cathode

(e) by the plasma forming medium

(f) by the type of current

Metal working plasma torches used a rod type cathode

(1) expendable - graphite

(2) gas shielded - tungsten rod load 15 - 20 A/mm$^2$

(3) film shielded

Operating features of tungsten electrode have been improved with small additions of thorium or lanthanum oxide (1.5 to 2%). Th added electrodes are slightly radioactive - therefore lanthanum added systems have become popular. These additions increase the recrystallization temperature of tungsten by about 600°K.

The film protected cathode is developed for use with oxygen containing gases. It is made out of zirconium or zirconium alloy embedded in a copper casing.

Plasma Power Sources

Current variations due to a change in the arc voltage are undesirable in metal working plasma torches. This means instability of melting. Arc voltage variations should be associated with the working gas flow rate, gas composition and arc adjustment. The current variation should be only in response to change in power level. Otherwise, it will render the plasma heating process unstable.

The external characteristic of power sources for plasma torches should be steep or vertical. Current fluctuations due to external influences are not tolerated.

Thyristor controlled power sources have found increasing applications as plasma torch power sources. The thyristor connected to an A.C. circuit is disabled in both directions. As soon as a momentary pulse is applied, it instantly opens in the "straight" direction. The average rectified current can be adjusted by changing the thyristor opening phase angle with respect to the feeding voltage sine curve.

At high power, the thyristor rectifiers excel the choke-type rectifiers more and more in their power and weight characteristics and in speed of operation.

The secondaries of the power source should have ability to supply open circuit voltages in the range 100 to 600 V.

## Plasma Arc Melting Furnaces

Plasma arc melting furnaces can be grouped into four specific types:

a. Single crystal production and multiphase alloy directional solidification installations.
b. Refractory lined primary melting furnaces.
c. Cold crucible consumable electrode remelting furnaces.
d. Sponge and powdered alloy melting and cold crucible ingot solidification systems.

### a. Production of Single Crystals and Multiphase Alloys by Plasma Heat Application

Plasma heat application for the production of single crystals of refractory metals, certain high melting carbides and directionally solidified high melting eutectic alloys has been intensively studied at the A. A. Baikov Institute of Metallurgy, Moscow, USSR. Pertinent reports of these studies are available in Soviet technical literature cited in a book entitled "Plasma Processes in Metallurgy" which is available as JPRS Report 61321 from the National Technical Information Service, Springfield, Virginia.

The plasma arc single crystal growing equipment features are as shown schematically in Figure 4. The growth of a single crystal begins with fusing of the end plane of a seed crystal by the plasma jet. Argon-helium (Ar-He) and argon-hydrogen (Ar-$H_2$) mixtures are the most suitable plasma gases for growing refractory metal single crystals. Molten metal required to grow the single crystal is supplied in the form of droplets by fusing-off corresponding metal compacted electrodes of 3-10 mm diameter in the plasma furnace. There are a number of ways of deploying the plasma heat source and the consumable electrodes in the plasma furnace. The arrangement shown in Figure 4 has been found to be quite satisfactory for growing up to 50 mm diameter single crystals of tungsten and molybdenum.

The seed crystal mounted on a shaft as shown in Figure 4 is gradually withdrawn as the deposited molten metal begins to solidify in the water cooled copper mold. The shaft and the seed can be rotated at a speed from 1 to 100 r.p.m. The crystallization front at the base of the metal pool is maintained at a constant level in the mold. Metal is refined both in the bath as well as in the plasma jet during its detachment from the electrode and its free fall. The plasma jet serves as a protective medium, despite the use of hydrogen for metal refining purpose. Instead of the consumable electrode, it is possible to use sponge or powder as the metallic charge in the plasma crystal growing apparatus. Soviet researchers have noted that the use of hydrogen in the plasma gas is desirable. It permits the use of lower cost refractory metal compounds rather than pure metal as feed material. This also results in the reduction of total energy used. The Soviet reports stress the

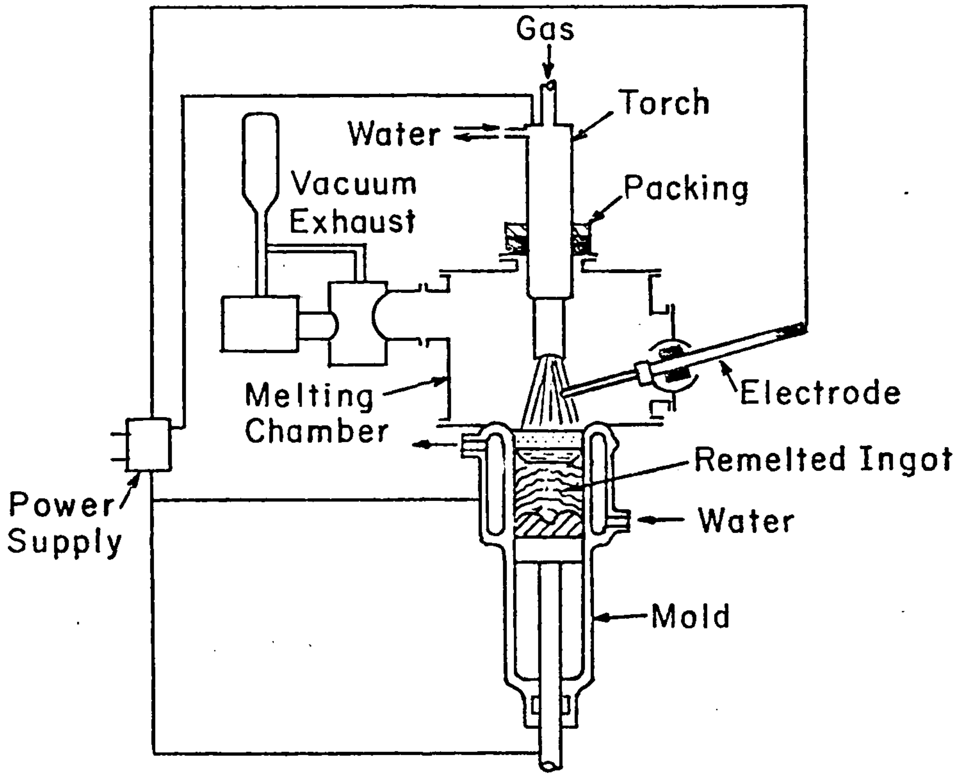



FIGURE 4. Schematic of a Plasma Arc Single Crystal Growing System

simplicity, safety and relatively small investment cost of their plasma system for the manufacture of single crystals of high-melting metals.

A further development of the plasma single crystal production development in the USSR has led to the introduction of a novel system for the manufacture of tungsten, molybdenum and rhenium single crystals having tubular and plate-like profiles. Details of this new development are sketchy at this time. However, many types of scanning subsystems for plasma heat distribution, temperature gradient control, the curvature control of the crystallization front have been developed in an effort to improve the plasma single crystal growing process.

The possibility of using carbon containing gases, such as $CO_2$, $CH_4$, natural gas as a component of plasma generating gas has led to the development of processes for the manufacture of single crystals high-melting carbides (NbC, TiC, HfC, TaC) and also directionally solidified multiphase eutectic alloys. These innovations should be of great interest to the manufacturers of penetrator materials and fiber reinforced turbine blades, having combination of physical and mechanical properties unattainable through alternate processing methods.

The productivity of a plasma crystal growing system is claimed by the Soviets to be significantly higher than that by the electron beam melting and ingot solidification system. It is also stated that plasmarc remelting is economically competitive with vacuum arc remelting and furthermore, the plasma remelting equipment itself is simpler in design and operation than the vacuum arc and electron beam remelting equipment.

b. Refractory Lined Primary Melting Plasma Furnaces

This group includes melting devices which resemble the conventional electric arc furnace and induction melting furnace. A plasma melting furnace introduced in 1962 by Linde Division of Union Carbide Corporation had a single plasma burner in the furnace roof. Figure 5 shows the design features of this furnace with a maximum charge capacity of around 1 metric ton. Electrical power from the direct-current plasma burner was transferred to a water-cooled copper electrode fitted into the furnace hearth. The charge placed on the hearth was rendered molten by the intense heat of the argon plasma arc. An argon cover was maintained over the melt. To insure chemical and temperature uniformity in the metal bath, and also to aid rapid melt-down, the furnace was equipped with two stirring coils connected to the bottom electrode. The interaction of the magnetic field from these coils with that generated by the plasma arc resulted in gentle stirring of the molten metal. The chemical and physical properties of low-alloy steels, superalloys, and bearing steels melted in the Linde furnace were claimed to be equal to those of vacuum melted alloys (e.g., oxygen content of 8 to 25 ppm, hydrogen 1 to 2 ppm and nitrogen 10 to 30 ppm).

The use of plasma arc primary melting furnaces of 6 ton, 10 ton and 30 ton capacity for melting nickel alloy and high alloy steel scrap in the German Democratic Republic (East Germany) has been reported by Lachner, et al (1), Fiedler, et al (2) and Mueller (3). These furnaces are lined with rammed chrome-magnesite refractory and the walls and roof are lined with chrome-magnesite bricks. Heating of the charge is done by three or four direct-current plasma burners normally located in the

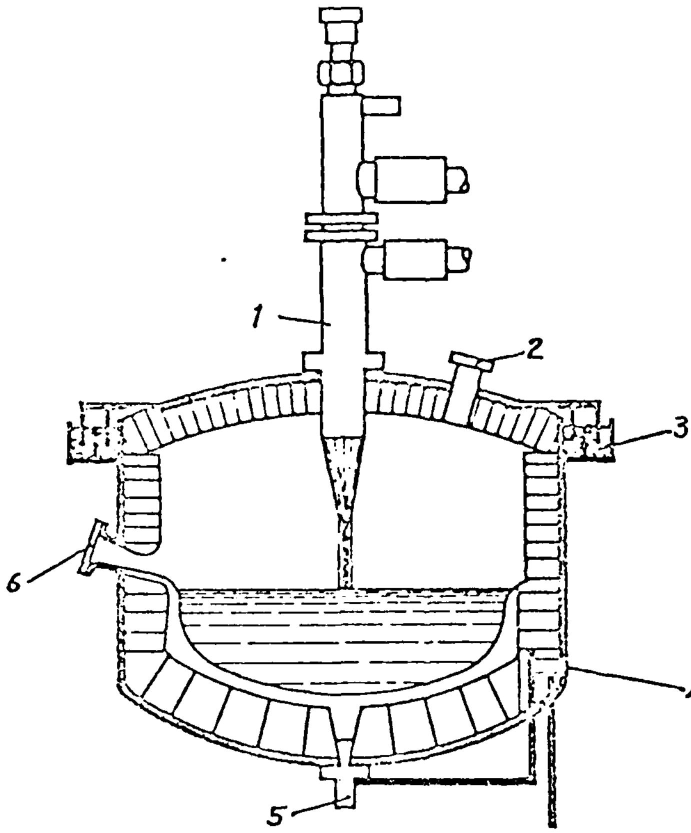



Figure 5. Linde Plasma Arc Melting Furnace(8).
1 = Plasma Torch, 2 = Viewing Port, 3 = Sand Seal
4 = Stirring Coil, 5 = Bottom Electrode, 6 = Tapping Spout

sidewall of the furnace. The plasma torches developed have current capability up to 9 KA at voltages in the range 100 to 600 volts. A schematic of the GDR plasma melting furnace is shown in Figure 6.

Their specifications of the 6 ton, 10 ton and 30 ton plasma melting furnaces are presented in Table 2. The plasma heat sources generate temperatures in the melting containment well over 15,000°C compared to the maximum temperature of about 3500°C attained in conventional electric arc furnaces operated with graphite electrodes.

Principal advantages of plasma melting process over the electric arc furnace melting may be summarized as follows:

- higher recoveries of alloying constituents
- decreased total iron losses
- higher melting efficiency (lower energy consumption)
- elimination of carbon contamination of the melt from graphite electrodes
- possibility of alloying nitrogen through the gas atmosphere thereby saving nitrogen enriched ferro-alloys
- low dust and heat exposure for furnace crew
- low-noise operation
- no electrical spikes, surges or discontinuous loading on the power supply mains
- better control of refining reactions under a protective atmosphere with minimum slag constituents.

The GDR plasma furnaces have been in continuous, three shift, production operation for the past three years. The operation of the 10 ton plasma arc furnace, since 1972, has been claimed to be both economically and technically rewarding despite the fact that the melts were tapped and teemed under ambient conditions.

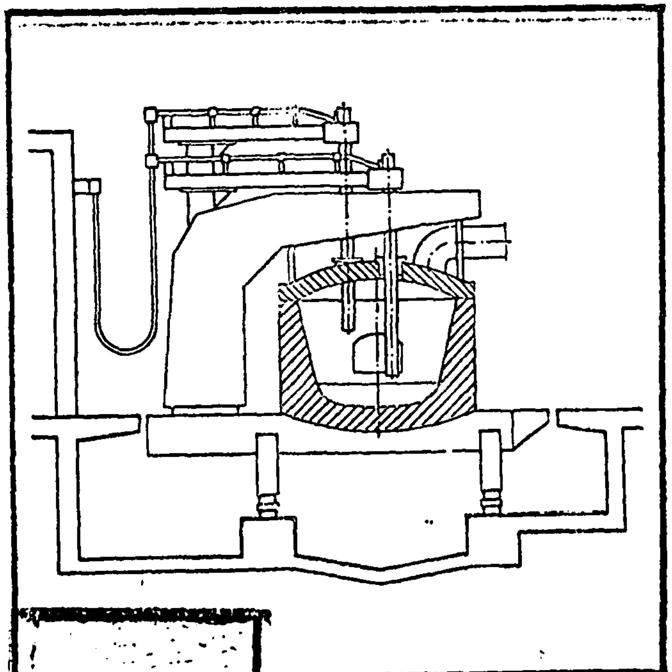
TABLE II - SPECIFICATIONS OF EAST GERMAN (GDR)
6 TON, 10 TON, 30 TON CAPACITY
PLASMA ARC PRIMARY MELTING FURNACES

| Characteristic | | Furnace Type | | |
|---|---|---|---|---|
| | | 6 | P 10 | P 30 |
| Nominal capacity | t | 6 | 15 | 30 |
| D. c. intensity | kW | 6600 | 9900 | 19800 |
| D. c. voltage | V | 660 | 550 | 660 |
| Power coefficient | cos | 0,96 | 0,96 | 0,96 |
| Feeder mains voltage | kV | 6 | 15 | 15 |
| Feeder mains Frequency | Hz | 50 | 50 | 50 |
| Argon consumption | $m^3/h$ | 20 | 24 | 60 |
| Cooling water consumption | | | | |
| chemically pure | $m^3/h$ | 25 | 30 | 50 |
| technically pure | $m^3/h$ | 50 | 60 | 100 |
| Melting-down capacity | t/h | 4 | 9 | 20 |
| Specific melting-down power consumption | kWh/t | 800 | 550 | 500 |

FIGURE 6. GDR Plasma Arc Primary Melting Furnace (right) Compared to Conventional Electric Arc Furnace (left)

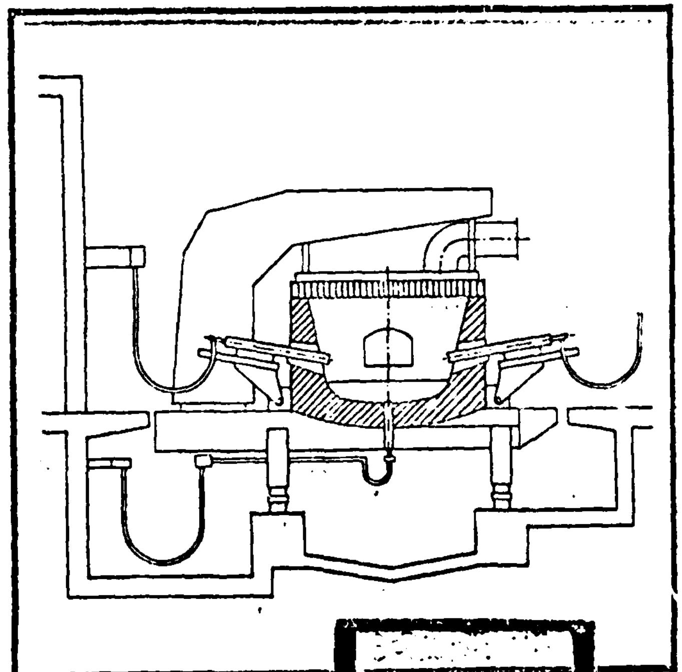
Conventional electric arc furnace

- Vertical graphite electrodes
- Heat transmission by conduction and radiation
- Maximum temperatures about 3.500°C



Plasma furnace

- Oblique or vertical plasma torches; bottom electrode
- Heat transmission by radiation and convection
- Maximum temperatures about 15.000°C



The 10 ton plasma furnace is powered by three plasma torches which are introduced in the furnace through the sidewall. They have both horizontal and vertical adjustment and the plasma arc length can be varied within wide limits. Each torch is connected to individual direct current power source.

Argon is used as principal plasma gas and its consumption per torch is approximately 8 $Nm^3$ per hour. The maximum adjustable amperage is 6 KA in a voltage range 200 to 600 V. The plasma arc transfer is accomplished through a water-cooled copper anode located in the bottom lining of the furnace hearth. The tungsten cathodes used in the plasma torch are either coated or alloyed with lanthanum which serves as an effective emitter. The present generation plasma torches used in the GDR plasma furnaces can also inject oxygen during melting of the charge. The use of oxygen has not been damaging to the life of the tungsten cathode in these plasma torches.

The GDR-30 ton plasma furnace is equipped with 4 plasma torches introduced in the furnace through the sidewall, as in the 10 ton unit. The furnace is equipped with a pivot cover. The hearth is banked with magnesite and the wall and cover are lined with chrome-magnesite bricks.

The plasma torches operate on argon gas at a voltage ranging from 150 to 660 V and the maximum current capabilities of each torch are 10 KA. The torch, in both the 10 ton and 30 ton furnace, can be replaced within 15 minutes without interrupted operation. It was observed that all four torches are used only during preliminary melting of the cold charge but the heat supplied by one torch is adequate during the refining period. The plasma arc is ignited without contact by the pilot arc feed and the oscillator.

An alarm system is used to protect the torch against short-circuiting with the furnace charge. In addition, the entire electrical control system is interlocked with cooling water flow, temperature control, and plasma gas control mechanisms. The furnace cover, charging door, tap hole and torch ducts are sealed to maintain a slight positive pressure of argon or the neutral atmosphere in the furnace during the melting of the charge.

It is claimed that the installed capacity of the 10 ton and the 30 ton plasma furnaces guarantees an annual production of at least 100,000 metric tons of high-quality and high-grade alloy steels.

High-alloy steels produced with scrap and ferro-alloy charge in the plasma furnaces have provided the yields of individual alloying ingredients as shown in Table 3 compared to those obtained in conventional electric furnaces. In particular, the total iron loss in plasma furnaces amounted to about 2%.

The recovery of the above alloying elements from the scrap is of special importance, not only because of the steadily depleting world metal resources, but also because of the gradually increasing world market price and high consumption of energy in their production.

The dissociation and ionization processes which occur in the plasma furnace permit nitrogen alloying through the gas phase for chromium-nickel and straight nickel alloy steels. This is more economical than the addition of high-nitrogen ferro-alloys.

The total specific energy consumption in the 10 ton plasma furnace is on the average less than 620 KWH per ton. This value is expected to reach, in the 30 ton plasma furnace, the minimum of 500-530 KWH per ton attained in UHP (ultra-high-power) electric arc furnaces.

TABLE III

RECOVERY (OR YIELDS) OF ALLOYING ELEMENTS IN PLASMA ARC MELTING AND ELECTRIC ARC FURNACE MELTING

| ELEMENTS | PLASMA ARC MELTING Per Cent | ELECTRIC ARC FURNACE Per Cent |
|---|---|---|
| Mn | 97 - 99 | 94 |
| Cr | 96 - 98 | 95 |
| Ni | 98 - 100 | 98 |
| Mo | 98 - 100 | 95 |
| Ti | 70 - 85 | 40 - 65 |
| W | 97 - 99 | 85 - 90 |

Plasma Induction Furnaces

The use of a combined induction melting furnace and a plasma heat source has provided an improved and more economical melting system which should be of interest to non-ferrous alloy manufacturers and the foundry industry.

The objective in the introduction of plasma-induction furnaces is to overcome the limitations of conventional induction melting furnaces with regard to effective slag or gas refining treatments. Daido Steel Company in Japan has been instrumental in the development of plasma-induction furnaces. The present melting capacity of plasma-induction furnaces is limited to 5 tons because of undesirable electromagnetic interactions between the plasma and induction heating systems. However, the smaller capacity plasma-induction furnaces function satisfactorily, which are being used by manufacturers of non-ferrous alloy, magnetic, electronic, thermoelectric and resistance alloys. Successful desulfurization and oxygen content reduction to less than 20 ppm have been reported for this type of plasma assisted melting devices. This type of furnace has also been successfully used for the purification of titanium, chromium and silicon and for the melting of copper-beryllium alloys in batches up to 1.2 tons. A schematic diagram of the plasma-induction furnace and a picture of the installation are shown in Figures 7 and 8 respectively. For small scale production applications, this installation is ideally suited. The equipment cost and operating costs have been determined to be lower than that for a similar size vacuum induction melting installation. Plasma-induction furnaces can be designed in such a way that the induction heating provides 50 to 65 per cent of heat for

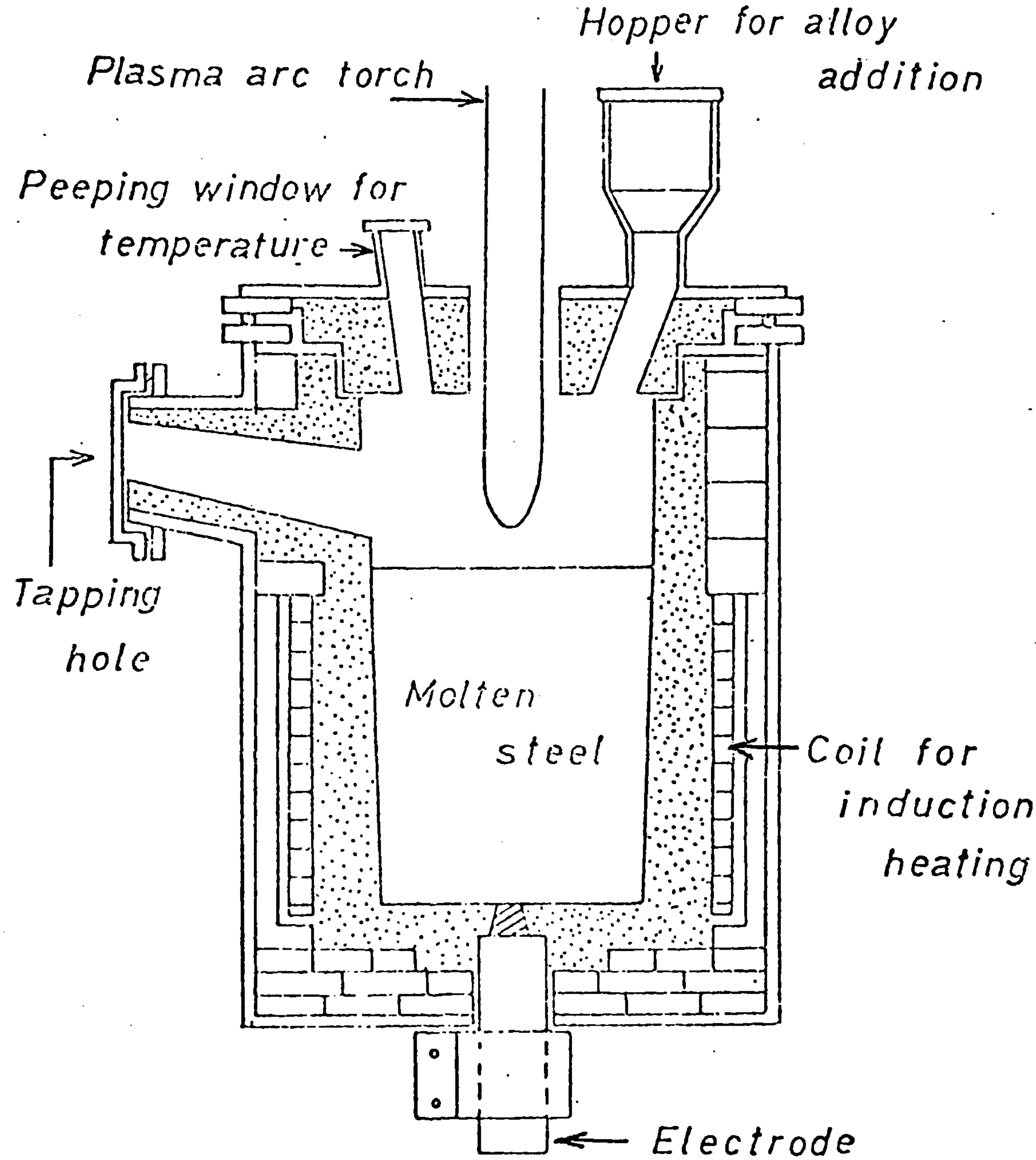



FIGURE 7. Design Features of a Plasma Induction Furnace (Daido Steel, Japan)

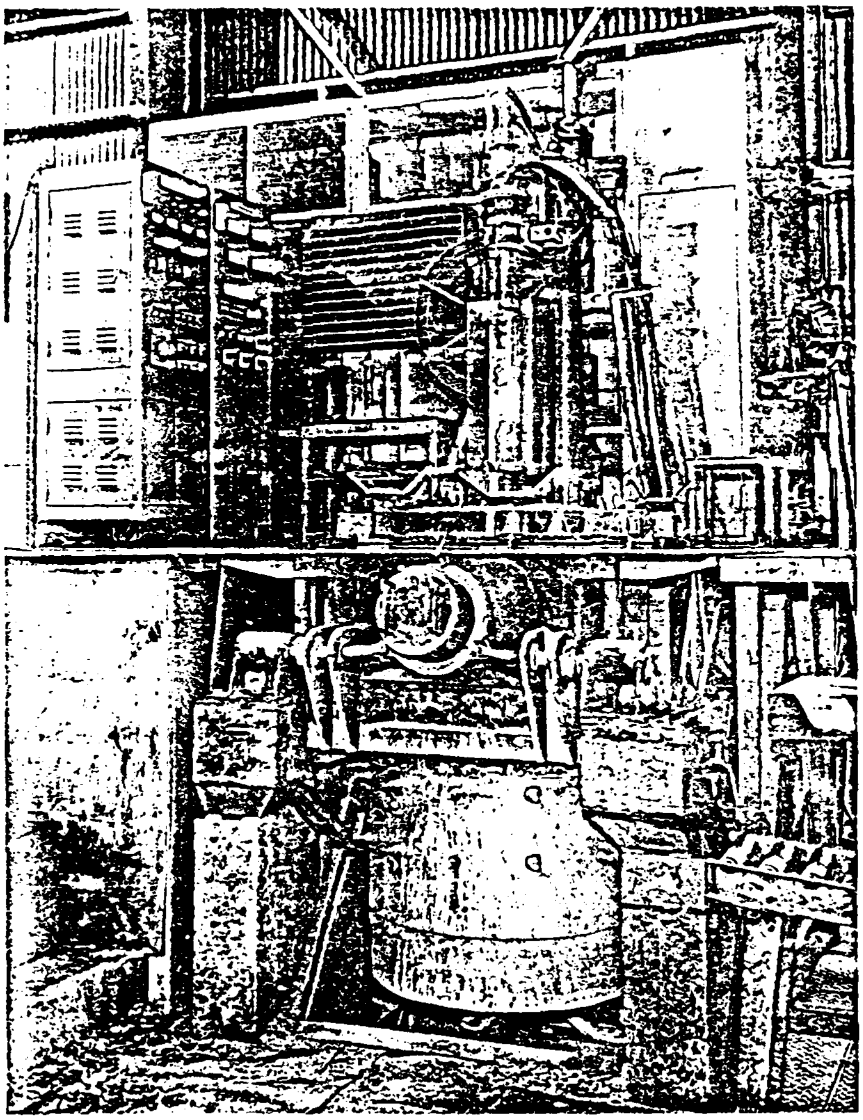


FIGURE 8. Photograph of a 2 Ton Plasma Induction Melting Furnace Installation
(Daido Steel, Japan)

the charge with the balance provided by the plasma arc. The plasma torch used is of the arc-transfer type. The electrode for transferring the arc is located in the furnace bottom as shown in Figure 7. Normal argon consumption in the plasma torch operating at 200 V at 200 amperes is around 5 to 7 cubic meters per hour.

The alloy recoveries reported for melting of a variety of stainless steels, superalloys, magnetic and electronic alloys is as follows:

| C | Si | Mn | Cr | Al | Ti | V | B | Nb |
|---|---|---|---|---|---|---|---|---|
| 100% | 99% | 98% | 100% | 96% | 95% | 100% | 95% | 97% |

The attractive features of plasma-induction furnace include, the achievement of vacuum quality (low oxygen, low hydrogen) alloy melts, deoxidation and desulfurization using highly basic slags and the possibility of producing ultra-low carbon stainless steels and superalloys having exceptional resistance to intergranular corrosion.

c. Cold Crucible Consumable Electrode Remelting Plasma Arc Furnaces

Plasma arc remelting furnaces are basically of similar design as the electron beam drip melting furnaces. The main features of Soviet plasma arc remelting (PAR) system with three or more plasma torches (also known as plasmatrons) are as shown schematically in Figure 9. In this arrangement, a consumable electrode is fed vertically down with a slow rotary motion with the electrode tip maintained in close proximity above the molten metal pool so as to make efficient use of radiant heat transfer from the plasma jets focused on the metal bath. Plasma heat penetration in the molten metal pool is very limited. The flexible and independent control of plasma heat permits achievement of any desired electrode melt rate and super heating of the bath. The shallow pool

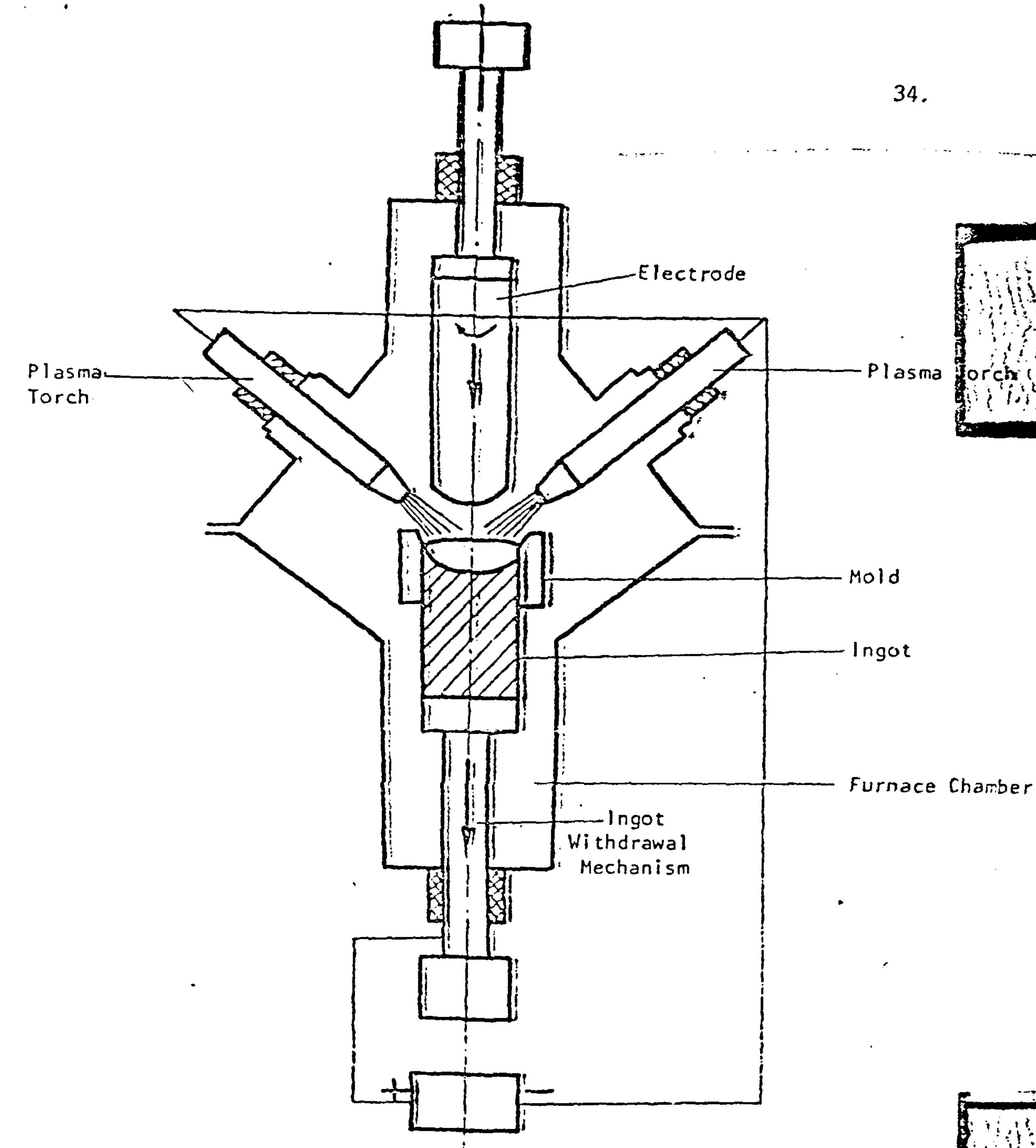



FIGURE 9. Schematic of a Plasma Arc Remelting (PAR) Furnace (Soviet Design - Paton Institute)

profiles obtainable can be effectively utilized to obtain segregation-free ingots of complex alloys. The ingots invariably contain uni-directionally solidified grain structure which is extremely useful for subsequent hot working by extrusion rolling, rotary forging and even using the metal in the cast condition.

Using collar molds of various geometrical shapes it is possible to develop simple and complex cast shapes of high melting and reactive metal alloys. The ingot or casting is solidified in the collar mold and the solidified segment is withdrawn continuously until the designed weight of the ingot is obtained. The radial arrangement of the plasma heat source facilitates spreading of the thermal load and precise regulation of molten metal temperature and the thermal gradient in the ingot for achieving directional solidification.

The melting stock in the plasma remelting furnace can also be introduced in the form of sponge, small pellets, powders and metallic concentrates from different sealed openings in the furnace chamber. Sponge and powders can be injected or otherwise introduced through feeder systems. Compacted electrodes of various shapes can be introduced either vertically or horizontally. The solidification system can be separated from the melting containment so as to avoid entrappment of solid particles in the ingot while using sponge or pellets.

Since plasma heat can be independetnly supplied to the charge and the crucible in furnaces operated with multi-torches, it is possible to cast ingots or components of different shapes and weights.

Despite the various advantages of plasma arc remelting systems, the metals industry in the USA has no such systems. This situation is due largely to the non-availability of integrated plasma melting manufacturing equipment and process economics data.

Soviet publications allude to the availability to four types of plasma melting furnaces to their industry. Table 4 provides specifications of models U-102, U-401, U-467 and U-600 plasma arc remelting installations. Figures 10 through 13 illustrate the schematics of these four Soviet plasma remelting furnaces. U-102 plasma furnace is used mostly for the production of noble metal electronic alloys and laboratory size ingots of various metals and alloys. The U-400 furnace is principally used for the production of titanium and its alloy ingots for the manufacture extruded tubes. Model U-467 is used for the remelting of precision alloys, titanium alloy slabs, heat resistant alloys, and high quality alloy steels. The group represented by U-600 plasma furnace is mostly used for remelting high nitrogen structural steels and bearing steels.

d. Sponge and Powdered Alloy Plasma Melting Systems Using Cold Crucible and Ingot Withdrawal

Sponge and powdered alloy plasma melting systems are mostly developmental at this time in the US and other countries. An exception, however, is a system in commercial operation at Nippon Stainless Steel in Japan for the production of titanium and titanium alloy slabs. This, however, is a plasma electron beam system with hollow cathode rather than pure plasma melting system. Ulvac Corporation in Japan is the developer of this six plasma electron beam melting system for one step melting, refining and casting of reactive metal slab ingots weighing up to 3 tons. This furnace is reportedly quite suitable for processing refractory metals,

TABLE IV

SPECIFICATIONS OF SOVIET PLASMA ARC REMELTING FURNACES

| Specifications | Plasma Furnace Models | | | |
|---|---|---|---|---|
| Model No. | UP-102 | U-400 | U-467 | U-600 |
| Maximum Weight of Ingot (steel) Kg | 50 | 400 | 400 | 5000 |
| Ingot Dimensions, mm | | | | |
| Diam. round | 125 | 150,250 | 100,150,200,250 | 250 |
| Section - squares | - | - | - | 450x450 |
| - slabs | - | - | 70x300 | - |
| Height | 500 | 1000 | 1200 | 2300 |
| Total Power of Plasma Torches KW | 160 | 300 | 360 | 1800 |
| Plasma Torch Working Current, amps | 500 | 750 | 1500 | 3000 |
| Plasma Gas Consumption l/min | 30-60 | 75-150 | 240-300 | 360-450 |
| Power Consumption KVA | 350 | 485 | 990 | 1980 |

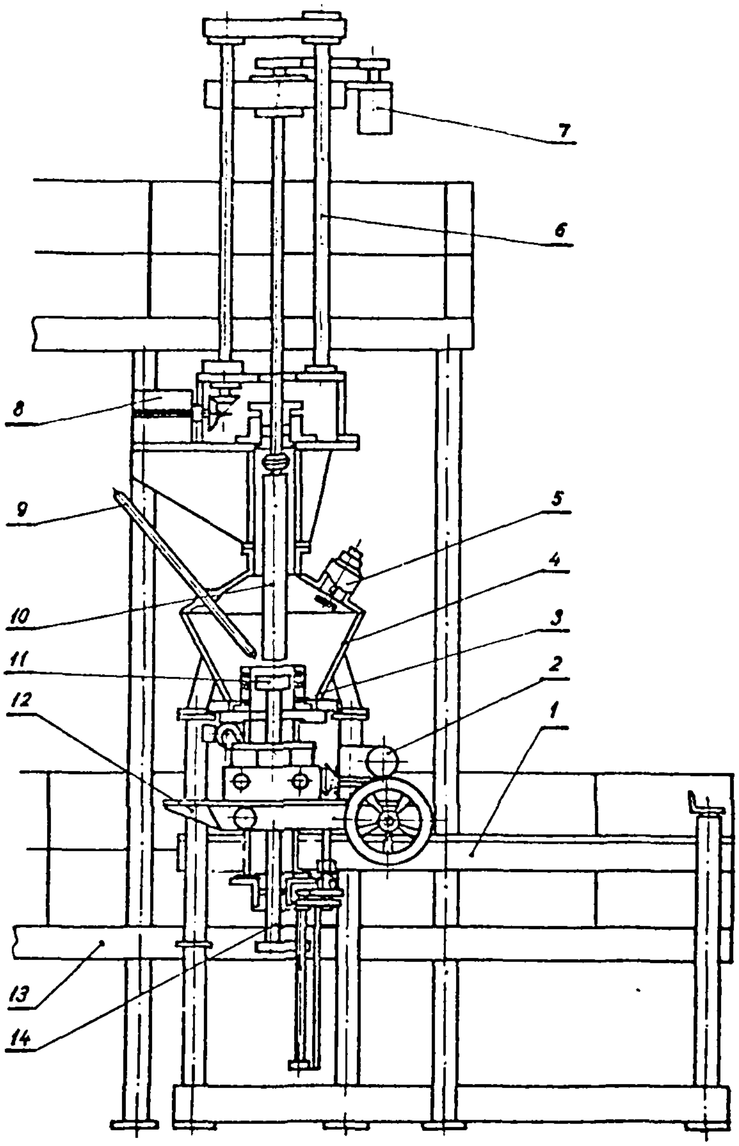



FIGURE 10. Schematic of Soviet Model U-102 Plasma Arc Remelting Furnace Used for the Production of Noble Metal Electronic Alloys - 50 Kg Round Ingots.
<u>Special Features:</u> 9-Plasma torch; 10-Electrode; 11-Ingot Withdrawal Ram.

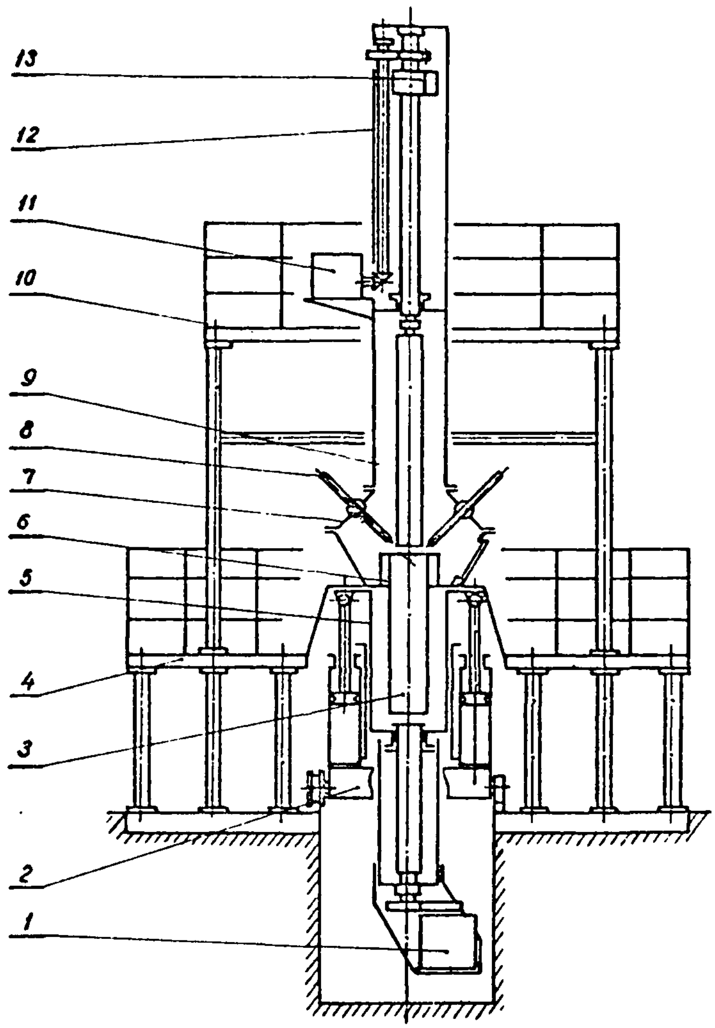



FIGURE 11. Schematic of a Soviet Model U-400 Plasma Arc Remelting System for Titanium and Titanium Alloys 400 Kg Round Ingots. Special Features: 1-Ingot Withdrawal Ram; 3-Ingot; 5-Ingot Containment; 6-Collar Mold; 7-Plasma Torches; 8-Electrode Chamber; 10-electrode; 12-Electrode ram.

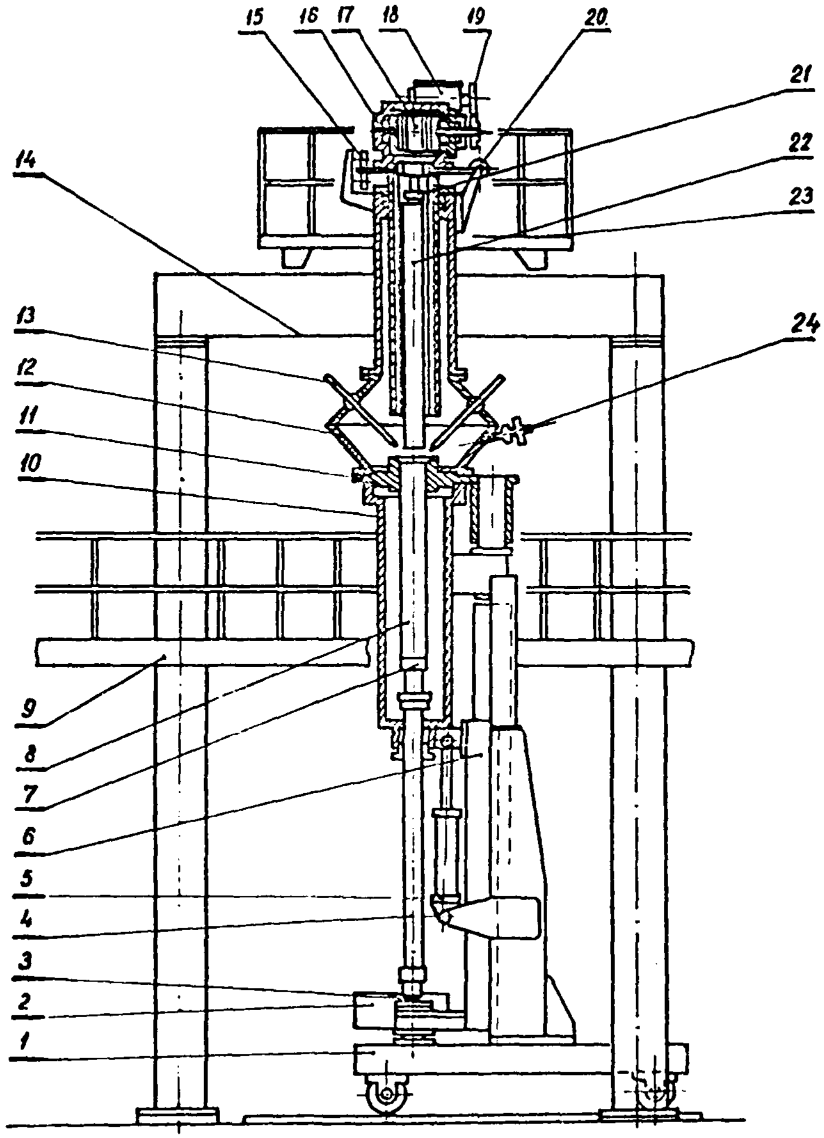



FIGURE 12. Schematic of a Soviet Model U-467 Plasma Arc Remelting Production System for Precision Alloys, Titanium Alloys and Super Alloy Round and Slab 400 Kg Ingots.
Essential Features: 1-Ingot Roller Stool; 3-Bottom Electrode; 4-Ingot Withdrawal Ram; 8-Ingot; 11-Collar Mold; 12-Furnace Chamber; 13-Plasma Torches; 22-Electrode; 18-Electrode Feed Mechanism.

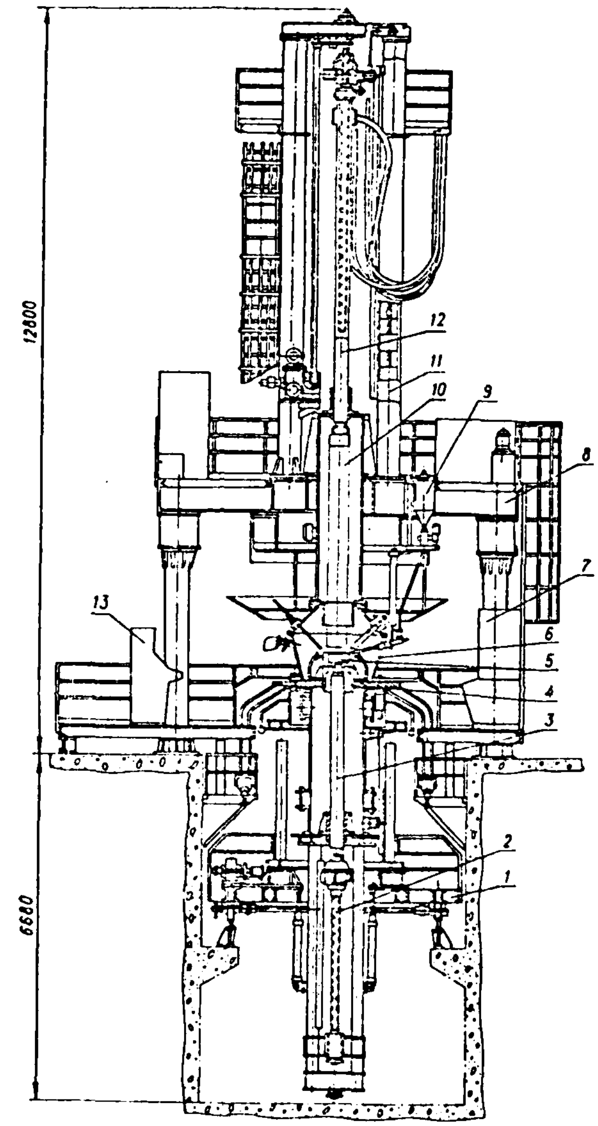



FIGURE 13. Schematic of a Soviet Model U-600 Plasma Arc Remelting Production System for Round and Square 5000 Kg Ingots of Bearing Steels and High Nitrogen Alloy Steels.
Essential Features: 2-Ingot Withdrawal Ram; 3-Ingot; 4-Mold; 6-Furnace Enclosure; 10-Electrode; 12-Electrode Feed System.

such as, tungsten, molybdenum and tantalum. The features and operating details of the furnace have been adequately described in several reports (4,5).

The prospects of plasma arc heat application for the consolidation of superalloy and titanium scrap into electrodes suitable for consumable remelting using either plasma arc remelting systems or other remelting systems appear promising. However, developmental work in this area is lacking because of non-availability of pilot scale equipment. Also, the previous work conducted to demonstrate the feasibility and technical merits of such an approach clearly indicated the need of multi-torch plasma melting systems rather than one powered by a single MW or higher power capability plasma torch.

## Future Outlook

The outlook for future development of plasma heating, reduction, melting and single crystal growing devices appears quite promising. The Soviet, GDR and Japanese plasma melting systems are worthy of particular note and study. The economics of these systems require intensive evaluation.

A modest beginning in the US for industrial application of plasma melting system could occur with a program involving feasibility demonstration of producing high density penetrators of W-Cu, W-U and high melting eutectic alloys of $W\text{-}W_2C$ and $Hf\text{-}Hf_2C$.