Chapter 2
Melting and Casting of Uranium

Edward B. Ripley

Abstract The art of melting and casting uranium is a fascinating subject. Uranium, which is anisotropic and allotropic, reacts readily with oxygen. When methods to melt and cast uranium are considered, those unique behaviors need to be taken into account. The proven methods that will be covered in this chapter are vacuum induction melting (VIM), vacuum arc remelt (VAR), and microwave (MW) melting and casting. Each of these methods has been demonstrated through hundreds of castings to deliver consistent and reproducible results. A thorough understanding of these methods is essential when work is being done with any reactive metal or alloy system.

Keywords Vacuum induction melting • VIM • Vacuum arc remelt • VAR • Microwave • MW • Uranium • Melting • Casting • Ohmic heating • Reactive metal • Batch process • Dissolved gas • Inert atmosphere • Vacuum • Mold • Coating • Electrode • Crucible • Insulation

2.1 Introduction

Casting molten uranium into a useable form that meets dimensional, mechanical, and chemical specifications presents a number of challenges. The first of these challenges is thermal. In order to obtain a sound casting, a certain amount of additional heat, commonly referred to as *superheat*, has to be supplied to the molten metal. Superheat is the difference between the melting temperature and the pouring temperature. Uranium melts at 1,132 °C [1]. If the molten metal is to pour and fill the mold well, the mold should be hot (800–1,000 °C is ideal) and the metal needs

E.B. Ripley (✉)
Y-12 National Security Complex, 1 Bear Creek Road, MS #8097, Oak Ridge, TN 37831, USA
e-mail: ripleyeb@y12.doe.gov

J.S. Morrell and M.J. Jackson (eds.), *Uranium Processing and Properties*,
DOI 10.1007/978-1-4614-7591-0_2,

Table 2.1 Variations in phase change upon heating and cooling

	Temperature (C°)		
	Heating	Cooling	Average
Melt point (0.3)	1,131.85	1,132.15	1,132
$\beta \rightarrow \gamma$ (5.4)	774.7	769.3	772
$\alpha \rightarrow \beta$ (9.4)	672.7	663.3	668

to be approximately 1,350–1,450 °C. This will ensure that the metal does not start to solidify before it fills the mold [2].

The second challenge is chemical. Since uranium is chemically reactive, anything that comes in contact with the molten uranium is a potential source for contamination. This includes the crucible, mold, and foundry hardware as well as the chamber atmosphere.

Third, thermodynamic challenges exist because many deleterious reactions become more thermodynamically favorable at high temperatures. Since uranium is anisotropic (having properties that are different depending on grain orientation) and allotropic (having three distinct temperature-dependent solid phases), it presents some unique challenges as it changes from its room-temperature form to its molten state.

The allotrope α-uranium has an orthorhombic structure with four atoms per unit cell. This is the structure of uranium at room temperature. For α-uranium, the dimensions are as follows: $a = 2.85$ Å, $b = 5.87$ Å, and $c = 4.95$ Å. The first phase transformation is the $\alpha \rightarrow \beta$ phase transformation, which occurs at 668 °C. The structure of β-uranium is tetragonal with 30 atoms per unit cell. For β-uranium, the dimensions are as follows: $a = 10.76$ Å and $b = 5.66$ Å. The second phase transformation is the $\beta \rightarrow \gamma$ phase transformation, which occurs at 772 °C. Having a body-centered cubic structure with two atoms per unit cell, γ-uranium has the dimension of $a = 3.52$ Å. Uranium melts and undergoes the final phase transformation from $\gamma \rightarrow$ liquid at 1,132 °C (Table 2.1).

For ultrahigh-purity uranium, the phase changes differ between heating and cooling. The magnitudes have been verified from literature; however, the average values have been adjusted to correspond with generally accepted values.

From a practical point of view, these differences in temperature are beyond most people's ability to accurately measure. The concept that the temperatures may vary slightly from the heating and cooling cycles is academically interesting. As these phase changes occur, the number of atoms per unit cell changes and the size of the unit cells also changes. These allotropic transformations manifest themselves as dimensional changes. When room-temperature α-uranium is heated and melted, it goes through three distinct transformations, but what is often more important are the transformations that occur during the solidification of molten metal within the mold.

Uranium and its alloys, as highly reactive metals, have unique requirements for processing in order to achieve an acceptable end product. Three casting methods have been demonstrated to consistently produce satisfactory results. These are vacuum induction melting (VIM), vacuum arc remelt (VAR), and microwave (MW).

2.2 Vacuum Induction Melting

Vacuum induction melting (VIM) is the oldest and currently the most widely accepted method of melting and casting reactive metals such as uranium, titanium, and many of the modern superalloys. This melting and casting technique is an extension of induction heating. The basic principles of induction were independently conceived by Michael Faraday and Joseph Henry in 1831. Since Faraday was first to publish, he is generally given credit for the discoveries that make induction melting possible. Induction heating occurs when an electrically conducting object, like a graphite crucible, is placed in a coil and a high-frequency alternating current (AC) is applied to the coil. The coil is usually made of copper and is cooled internally with water or gas. When the AC current passes through the coil, these electromagnetic fields generate eddy currents in the graphite crucible, and the resistance to these changing fields leads to heating. This is often referred to as Joule, or ohmic, heating. The metal inside the crucible is heated by both the hot crucible (by conduction) and induction field. After the metal is melted, the induction field stirs the metal and leads to improved homogeneity and uniformity in the melt.

Uranium reacts with many gaseous species and atmospheres at high temperature, and a vacuum or inert environment is generally employed. An additional benefit of casting in a casting chamber or enclosure is that this helps contain any contamination and reduce potential exposure to personnel. It is widely accepted that a vacuum aids in the removal of dissolved gases.

Uranium is highly reactive with most refractory materials, and the crucible is routinely coated with a paint or wash that is resistant to reaction by molten uranium. In addition, all of the foundry hardware, such as molds, pour rods, filters, and launders, needs to be either inert in molten uranium or thoroughly coated with a protective refractory paint or wash. Some experimental results suggest that the coating of all surfaces, not just those in contact with the molten uranium, can reduce the pickup of carbon, which can enter through the gas phase. It is important to pick coatings or paints that are thermally and thermodynamically stable with molten uranium at several hundred degrees above the melt temperature of 1,132 °C. This is because the metal needs to be completely molten and supplied with enough superheat to decrease the viscosity to a point at which the metal flows quickly and smoothly through the pouring mechanism and into the mold.

2.3 Overview of VIM Technology

Electromagnetic induction is at the heart of VIM. Electromagnetic induction is an incredible phenomenon that has found use in a number of applications. To better understand VIM, it is important to have at least a rudimentary understanding of induction. Induction is used in both the generation of electricity and the conversion

Fig. 2.1 Example of a large bottom-loading vacuum induction casting line. Stack loading and unloading occur on this first floor, and the furnace is operated from the second floor

of electricity into motion. *Faraday's law of induction* dates back to the 1830s and is the basic law governing the behavior of electromagnetism. Faraday's law is applicable to a closed-circuit conductor and states: "The induced electromotive force (EMF) in a closed circuit is equal to the time rate of change of the magnetic flux through the circuit." The converse is also true: "The EMF generated is proportional to the rate of change of the magnetic flux." Therefore, if a stationary conductor is placed in a changing magnetic field, electrical current will be induced in the conductor. This can cause circulating flows of electrons in the conductor called Foucault currents, or eddy currents. These fields have inductance and can also induce magnetic fields. Because there is an inherent resistance to these rapidly changing fields, the eddy currents generate heat in the form of Joule, or ohmic, heating [3] (Fig. 2.1).

VIM offers a number of advantages in the melting and casting of reactive metals:

- Ease of operation
- Precise control of material chemistry (achieved through small batches)
- Low losses to oxidation due to vacuum processing
- Reduction of any high-vapor-pressure contaminants
- Precise temperature control
- Removal of dissolved gases

As a heating technology, induction heating is very efficient; nearly every watt of electrical power supplied to the coil is converted into heat. Changing the frequency can directly affect the depth of penetration of the heating. Varying the frequency and power characteristics to the coil can also aid in melt stirring and homogenization. When thick cross sections of components are heated or when materials are heated in an electrically conductive crucible, a lower frequency in the range of 5–30 Hz is used. An application of 60-Hz three-phase power can effectively stir the contents of the molten crucible. The depth of penetration decreases as the frequency increases. The depth of penetration from 100 to 400 Hz is very shallow in the metal. If the frequencies are 480 Hz or higher, only microscopic parts and skin effects or surface heating occurs [4, 5].

Because the VIM process occurs under a vacuum, it is ideally suited to the processing of reactive metals and metals that have strong affinities for certain gases like oxygen. For this reason, VIM is widely used in the production of specialized and high-performance alloys, including nickel-based superalloys, stainless steels for nuclear applications, cobalt-based alloys for medical applications, high-purity alloys, and magnetic alloys. This is also why the VIM process is particularly well suited for the melting and casting of uranium, where material quality and contamination by impurities is a paramount concern.

The chamber, generally water cooled, is evacuated by a series of vacuum pumps to quickly reduce the pressure inside. In a typical system, there will be pass-through areas where the power for such items as the induction coil, thermocouples, and instrumentation needs to be connected from the outside of the chamber to sensors and equipment inside the furnace. The chamber needs to be sufficiently leak tight so that it can be pumped down to operating pressures, generally on the order of 1×10^{-3} Torr, and so it can pass a leak rate test. The test consists of pulling a vacuum, securing the vacuum pumps, and allowing the chamber to sit for some predetermined period of time with little or no increase in pressure.

An additional consideration is the choice of vacuum pumps, specifically the use of the oilless variety. When an ultimate vacuum for a vacuum pump is reached, a slight back streaming of oil into the chamber will start to occur. It is important that no matter which vacuum system is selected, a leak rate check is part of the precasting inspection. This is crucial because with a sufficiently large vacuum system, any leakage into the system can be overcome. When this happens, the establishment of a good vacuum will still be evident, but the partial pressure of oxygen will be higher than the chamber pressure would indicate. The gauge can appear to be holding and maintaining a good vacuum that would be required for production of high-purity reactive metals. However, the in-leaking atmosphere can still contain oxygen, nitrogen, hydrogen, and other gases in sufficient quantities to contaminate the molten metal.

Inside the casting chamber is an induction coil, which is really the heart of the VIM system. The coil generally consists of several turns of copper tubing, which carries a high-frequency alternating current. The coil is usually placed as close as practical to the crucible and charge or to the material to be heated or melted. An insulating layer may exist between the coil and the crucible to provide thermal and electrical isolation. The alternating current that passes through the coil produces eddy currents in the conductive materials within the crucible, either causing them to heat and melt or directly heating the crucible to melt the metal.

The crucible containing the metal charge is placed inside the coil. If one were to imagine the field lines the coil created, it would be readily apparent that the field lines are most concentrated on the coil's interior. That is not to say that the field is only on the inside, simply that the field intensity is highest on the coil's interior. The part of the field that is outside the coil's interior is commonly referred to as the *stray field*. This stray field can also heat the furnace walls and ancillary equipment if they are too close to the coil. The induction coil is generally water cooled to prevent overheating [6, 7].

Overheating is bad for a number of reasons, not the least of which is that the resistivity of a metal increases as a function of temperature, and this higher resistivity exacerbates the heating of the coil. Designs have been built in which primary and secondary cooling loops with a heat exchanger or in which the system's coil is gas cooled or even solid metal. For melting, the coil is generally a multi-turn design with insulating spacers to maintain the interval between the energized coils. And some type of support structure is included to allow each turn of the coil to be held in relative position within the chamber with respect to the crucible mold and furnace hardware. Many articles and even books have been dedicated to coil design, so there is no need for further elaboration here. The coil needs to be carefully designed by an expert in order to ensure the most efficient transfer of energy from the power supply to the crucible and to the metal [8, 9].

A recent improvement in VIM induction coils is the addition of flux concentrators. These take some of the stray field that would spread around the outside of the induction coil and redistribute it into the interior, where that energy can be used to heat and melt the charge. When a number of flux concentrators are placed on the outside of the induction coil with the open slot directed toward the crucible and charge, practically all of the coil's current flows near the surface, which faces the load. This improves the coil-to-workpiece magnetic coupling and results in dramatically increased coil efficiency. This improvement in coupling can be directly translated into a reduction in the power required to melt the charge and can also result in lower coil temperatures and drastically improved coil life. If flux concentrators are to be added to an existing coil, it is important to note that the impedance of the coil can be much different. It is important to ensure that the coil properly matches the power supply after the flux concentrators have been applied. With multi-turn coils, care needs to be exercised because the voltage across the coil turns can be significant, and the potential for developing a short-circuit path exists if the coil turns are not electrically isolated with insulation (Fig. 2.2).

The ideal crucible and mold material for VIM would be chemically inert to molten uranium; would have good thermal conductivity, a low coefficient of thermal expansion, high-temperature toughness, and thermal shock resistance; and could heat rapidly in an induction field (or be transparent to allow the direct heating of the charge material). These properties allow the crucible and mold to heat and cool rapidly.

Chemical inertness reduces the amount of contaminants in the melt from the crucible and mold. One often overlooked aspect of this is the outer surface of the mold. Although only the inside of the crucible and mold comes in contact with

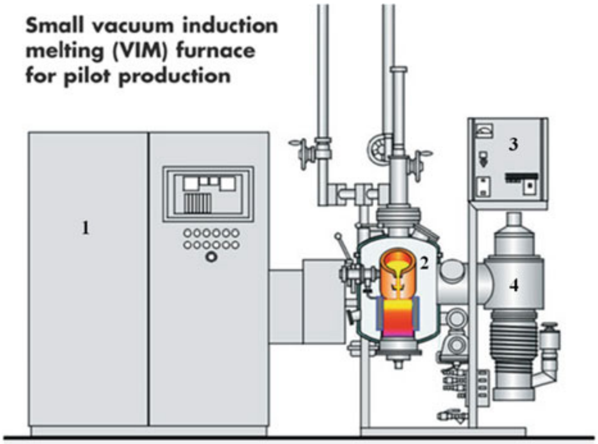

Fig. 2.2 This is a schematic of a small tilt pouring VIM caster for pilot-scale castings showing (1) power supply, (2) chamber with crucible and mold, (3) control panel, and (4) vacuum system

the molten metal, interactions with moisture and thermal breakdown products in the crucible and mold can react with the melt through the gas phase. While coatings are routinely used to protect the inside of the crucible and mold, it is common for the outside of the crucible and molds to be overlooked as a potential source for chemical contamination through the gas phase. Graphite is commonly used as crucible and mold material because graphite has excellent thermal properties, it is inexpensive, it machines easily to tight tolerances, it has high resistivity in an electrical conductor, and it readily accepts coatings. Because graphite reacts rapidly with molten uranium, isolation of the metal from the crucible and mold is critical if graphite is used. It is also important to preheat the graphite before coating to ensure that moisture and volatile organic compounds are reduced or eliminated (Figs. 2.3 and 2.4) [4–8].

It is important to choose a mold coating on the basis of the purity requirements of the finished product and the presence of alloying elements. Typically, metal oxide ceramics in a suspension with a binder are used as mold coatings. Although commercially available mold coatings may work for some applications, quite often, process-specific mold coatings have to be formulated. This is often a case of trial and error. Some candidate materials include yttrium oxide, zirconium oxide, magnesium oxide, erbium oxide, or combinations thereof. No single one is perfect. For example, magnesium oxide does react with molten uranium to a slight extent and results in contamination of the melt and increased oxidation of the metal. Zirconium oxide can present explosion hazards in casting cleanup if pickling of the metal is required (Fig. 2.5) [10–12].

Erbium oxide is prohibitively expensive and does not create a particularly durable mold coating. Yttrium oxide applies well and is relatively durable. However, yttrium oxide does dissolve slightly, and after a number of runs, contaminations by yttrium may build up in a product over time. Combinations like magnesium zirconate perform well when applied by brush but perform best when applied by flame spraying [6].

Fig. 2.3 VIM caster showing (1) power supply, (2) chamber (with crucible and mold inside), (3) control panel, and (4) vacuum system

Fig. 2.4 This is a VIM coil used in a tilt pour system for casting of reactive metals

Because of costs involved with some of these ceramic materials, coating of the noncontact areas (the outside of the mold, for instance) can be accomplished with less expensive coatings such as aluminum oxide, which work well for this purpose but would be unacceptable for use on the inside of the crucible or mold. Another important consideration is the choice of binders because a binder that burns off can often be a source of carbon contamination. It is also important to apply the correct amount of mold wash because an excessive amount of coating can cause it to spall

Fig. 2.5 This is the coil that was shown in Fig. 2.4 installed in a system. The molten metal in the crucible is a surrogate for this demonstration

off and result in contamination; conversely, a coating that is too thin or that has pinholes can cause contamination as well [5].

Casting atmosphere is a key factor to achieving acceptable metal yield and meeting desired chemical specifications. *Vacuum induction melting*, by definition, is performed in a vacuum. Typical evacuation of the furnace consists of using a roughing pump to reduce the pressure to approximately 1.5 mmHg. To then decrease the pressure to 25 μm, a turbomolecular pump, diffusion pump, cryogenic pump, or similar system is employed. While the metal is being melted, these low pressures are maintained. To outgas the metal before casting, the metal should be raised above the melt temperature with an additional 50–200 °C of superheat to allow for efficient outgassing. Key to metal quality is to limit in-leakage and to eliminate contamination of the atmosphere as a result of off-gassing from molds, stack components, and materials of furnace construction. Atmospheric levels of moisture that are present in graphite and insulation can react with stack and mold components, resulting in oxidation of metal. Increased levels of carbon, hydrogen, and other contaminants in the casting can be a result of transport into the melt through the gas phase.

To accurately measure temperature in the metal casting range is difficult. In an ideal situation, the casting process would be tolerant enough of variations in temperature to handle errors of 0.5 % (50 °C per 1,000 °C) without any detrimental effects. In reality, however, many uranium casting processes require temperature control that is much more precise. The use of thermocouples is a good solution if they can be located in areas where the induction field does not affect them. In the range of 1,200–1,600 °C, thermocouples can be accurate to within 2–4 °C. It is important to understand where induction fields (including stray fields) are, and it

Fig. 2.6 Example of mold that has been coated to prevent contamination of the metal by the mold and to facilitate releasing the casting from the mold

still may be necessary to use shielding, twisted pairs, common mode, and differential mode filters to remove interference before the signal goes to the amplifier. Many systems have common mode suppression circuits, but they are usually effective only at lower frequencies. One strategy is to briefly switch off the induction field and allow the system to equilibrate for a few minutes to get a more accurate measurement. There are some convenient points where the accuracy of the measurements can be checked. At 668 °C, 772 °C, and 1,132 °C, there are thermal arrests caused by phase changes from $\alpha \rightarrow \beta$ (668 °C), $\beta \rightarrow \gamma$ (772 °C), and γ to molten (1,132 °C). At these temperatures, there will be a short thermal arrest or plateau at the phase change, where the temperature stops increasing and levels out, and then after, the phase change the temperature continues to increase. Knowing this, the operator can check the temperature measurements to ensure that they are accurate at these very important points. If they are accurate at these points, the operator can have a little more confidence in their accuracy at other temperatures (Fig. 2.6).

2.4 Optical Pyrometry

Noncontact optical pyrometry is an excellent method of measuring temperatures because electromagnetic, microwave, or induction fields do not affect it. Various types of optical temperature measurement systems exist. The two most common are the disappearing filament pyrometer and the photoscreenic wedge.

The *disappearing filament pyrometer* uses a filament that can be heated to known values by the introduction of a precise electrical current, which causes it to heat and glow. When the glowing filament in the viewfinder is placed over the hot object in the viewfinder, it will appear hotter (brighter) or colder (darker) than the object to be measured. The current in the filament is adjusted until it disappears when someone is looking at an object to determine its temperature, and at that point, the temperature is determined by looking at the corresponding current versus voltage scale, which typically just reads out directly as a temperature.

A *photoscreenic wedge pyrometer* allows the user to rotate a photoscreenic wedge ring on the housing of the pyrometer while viewing the target. A comparison of an outer ring and a spot inside the ring is adjusted until both are the same color. It should look like a single large spot as opposed to a ring with a spot inside it. Since the light viewed by the operator is monochromic, the readings are not affected by color sensitivities, so it is very easy to get an accurate measurement.

2.5 Infrared Thermometers

There is also a group of optical temperature measurement systems called infrared (IR) thermometers. To understand how these work, it is best to understand how heat works. As an object heats up, the molecules in the object start to vibrate. As the temperature increases, the molecules vibrate faster and faster. IR radiation is given off whenever an object has a temperature above absolute zero. The heat an object emits can be from three possible sources:

1. Heat is reflected off the surface of another object (such as a glowing body or light).
2. An object can transmit heat from its internal temperature.
3. An object can emit heat from its surface.

IR thermometers are designed to capture and quantify emitted heat energy, and it is important for the sake of accuracy that the reflected and transmitted heat energy is ignored and only the emitted heat energy is measured. Two objects that are at exactly the same temperature can appear to have vastly different temperatures, depending on the type and condition of their surface. To get an accurate reading from an object, an emissivity is determined and entered as a correction factor. The emissivity is a ratio of the radiant energy emitted by the surface of an object to the radiant energy emitted by a blackbody at the same temperature. In a single-color pyrometer, this emissivity factor has to be known and entered in manually, or a value is determined experimentally and entered.

One method of eliminating these errors is to use a pyrometer, which reads two colors or temperatures and compares the ratios of the peaks of these temperatures. Using Planck's law and solving for the emissivity, one can correct for emissivity of the material under test to get an accurate temperature measurement [14, 15].

One more consideration is the preparation of the charge material. For ease of handling, the material is usually broken or cut into pieces that are small enough to fit into the crucible. The broken metal should be cleaned of any existing oils or contaminants; this can be done by acid pickling or other cleaning methods. When clean metal is used at the start, the amount of oxide that will be retained in the crucible is reduced. Sometimes if there are heavily oxidized parts or very small parts, a tenacious oxide shell can trap or retain a portion of the molten uranium and make it unavailable for casting. This decreases the metal yield and reduces casting efficiency. Through adequate cleaning of the charge material, these issues can be avoided.

When the metal is molten in the crucible and centered above a heated mold, the final obstacle is to release the metal and allow it to flow into the mold. Several different methods of pouring are available, and all have their strengths and weaknesses:

- Tilt pour
- Rupture disk
- Friction disk
- Pull rod mechanism
- Ball end in cone
- Ball end in bell
- Dud melt

Tilt pour is quite simply a crucible that is equipped with a pour spout and positioned above the mold with a tilting mechanism so the metal can be poured from the crucible into the mold. The advantage of tilt pour is that it is simple, easily controllable, and predictable. The disadvantage is that it pours from the top, so the first part of the melt that enters the mold includes oxides and dross that are floating on the surface. This can allow contaminants to be trapped in the cast part. This method is rarely used for high-performance precision castings for this reason. One variation of this that does yield high-quality, sound casting is the centrifugal caster. Quality precision castings can be made if the crucible has a spout on the side and is positioned adjacent to a mold that is on its side and on an arm that can be spun quickly and maintain the centrifugal and centripetal forces on the casting while the molten metal solidifies. For most uranium applications, this is impractical. However, it is mentioned as a possibility that could yield sound quality parts.

The *rupture disk* is a small disk of carbon or ceramic that is fitted in the lowest part of the crucible. It is strategically weakened to break when struck with a pour rod. The pour rod generally has grooves to allow the metal to flow past the pour rod. It is also customary to have a small reservoir to trap the fragment to prevent it from becoming trapped in the casting or blocking the pour discharge hole. The advantages of the rupture disk are that it is simple, reliable, and inexpensive. The disadvantages are that the pour rod mechanism has to be lowered into the molten pool and can allow molten metal to freeze on the pour rod mechanism. This is often overcome by allowing the pour rod to be lowered into the molten metal and to soak for a few minutes to allow any frozen metal to remelt. The broken edges are exposed to molten metal, and there is the potential for contamination or entrapment of fragments. (Studies have been conducted, and as a practical matter, the chemistries using this method are statistically the same as those using other pour methods.)

A *friction disk* is similar to the rupture disc; however, the center portion of the disk is held in by friction, and the pour rod pushes it through. The friction disk can have a larger top to prevent it from dropping through. The advantages are that like the rupture disc, it is simple, reliable, and inexpensive. Since this method requires a tight friction fit to prevent a premature pour, when the mechanism is activated, it does tend to dislodge the mold wash and expose carbon and has the potential to dislodge fragments of mold wash, which can become entrapped in the casting [15].

Another method that has proved successful is the *pull rod mechanism*. Pull rods have to be held down in the molten metal because they are lighter than molten uranium. In cases such as this, the potential for a pre-pour exists, which will adversely affect the quality of the casting. If the crucible is equipped with a cone, and the pour rod has a ball end, the pour rod can be conveniently forced into the cone and there is no issue with getting the alignment perfect. Other arrangements such as taper in tapered hole, cone in cone, or tapered plug in round hole have all been tried but proved to require angular alignment, which is so precise that it is impractical. The ball end in cone is simple, reliable, reusable, and inexpensive. In hundreds of castings, it has proved to be a simple and effective method for pouring molten metal.

A slightly different variation on the ball end in cone is the ball end in bell. The bell-shaped hole in the crucible has an added advantage over the ball in cone in that it can be designed to allow for better flowing of the molten metal, a gentler and laminar flow, and less potential for erosion of the mold coating in the crucible. It also allows for shaping the pour spout to allow for more precise pouring. It has all of the advantages of the ball in cone with one exception: It does require designing and computer modeling to optimize the effects.

The last method is to merely allow the metal melt to resolidify in the crucible. This is commonly referred to as a *dud melt*. It can be used for consolidation and/or to create a billet to be further processed. In the strictest case, a dud melt is not a casting because it does not involve pouring of the molten metal. It can, however, be done so that the molten metal drips into a hot mold. This method is called *drip casting* and can be used for consolidation but generally does not yield high-quality casting. The advantage is that it is cheap, easy, and relatively foolproof.

2.6 Safety

When a VIM system is operated, a key aspect is safety. Because induction uses a high-voltage electrical source to induce a low-voltage high current in the charge metal, it is important to have electrical isolation between the charge, the coil, and components. Proper furnace design and casting procedures need to take into account personnel safety, training, and protective equipment and awareness of the hazards of molten metal, pyrophoric metals, and inert atmospheres, which can asphyxiate. Because of the electrical hazards involved, bath grounding as well as ground detection should be incorporated into the furnace design.

When personnel work near the coil, it should be de-energized and preferably locked out. Any metal that gets close to the direct induction field or the stray induction field will heat rapidly. There are cases of items such as steel-toed shoes, zippers, and wedding bands causing significant injuries to people who failed to secure the power to induction coils and inadvertently got too close to the induction fields.

2.7 Vacuum Arc Remelting

Vacuum arc remelting (VAR) is a process to melt metal to produce alloys and to produce high-purity feedstock for recasting. VAR is most often used to quickly melt uranium and other high-melting-temperature reactive metals and alloys. The process produces excellent homogeneity and high chemical purity. VAR is rarely used as a direct casting method but is commonly used to produce the starting alloys and charge materials. The VAR process is typically used for high-value metals because it requires additional processing steps in order to improve casting quality or to produce difficult-to-make specialty alloys.

The VAR process uses a crucible (the anode), which is electrically conductive. A water-cooled copper crucible, for example, is commonly used. In addition, one or more central electrodes (the cathode) are used, which can be lowered into contact or close proximity with the material in the crucible. A vacuum of typically 1–100 mTorr (0.13–13 Pa) is established above the metal to be melted, and several kiloamperes of direct current are used to start an arc between the electrode and the metal in the crucible. From there, the arc is maintained to cause the metal to melt (Fig. 2.7) [4, 5, 11–13].

VAR has several advantages over other melting methods:

- Because the solidification rate of the molten metal can be controlled, the microstructure of the metal can be tightly controlled.
- Many impurities that have high vapor pressures are liberated from the melt, and the concentrations in the melt are lowered. Dissolved gases, which are generally considered deleterious to the metals and alloys, are quickly liberated from the metals.
- Centerline porosity and segregation are eliminated (Fig. 2.8).

2.8 Electrodes

Arc melting of uranium can use several different types of electrodes as the cathode. Traditionally, for uranium where minor contamination of tungsten is not an issue, solid tungsten or thoriated tungsten electrodes are used. These are generally

Fig. 2.7 Example of large VAR unit, which makes high-purity alloys for further processing

considered nonconsumable electrodes and can be used for many melt runs before replacement. A run would typically involve placing a small charge of metal into the crucible. With a strong negative electrical charge on the crucible and a strong positive electrical current on the cathode, the current needed to produce and maintain an arc in a vacuum. It is the arc that, when struck, provides the heat necessary to melt the charge metal. The process is akin to welding; as the metal is melted in the arc, the arc can be moved around to melt the whole surface. In some cases with the consumable electrodes, the arc is struck and the metal in the arc melts and falls to the molten surface of the billet. As the melting continues, the underlying metal solidifies, and the electrode is advanced toward the melt to keep it close enough to the surface to keep the arc going.

The vacuum atmosphere is established, and a current is applied to initiate an arc. The power is increased as the electrode is held above the melt and the electrode is advanced into the melting pool. When the entire amount of metal desired is molten, it is allowed to solidify. In a round-bottom crucible, the lower surface of the charge

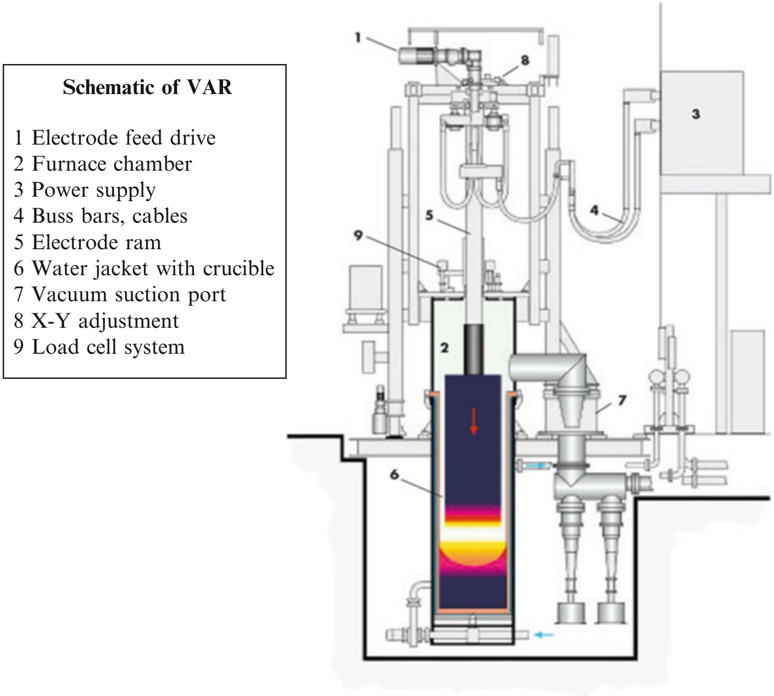

Fig. 2.8 VAR system showing major components

might not stay molten but form a crust or skull. The upper surface can be melted and form a relatively smooth surface. If the surface finish of the bottom of the ingot is unsatisfactory, it is not uncommon to flip the ingot and remelt the other side. This produces a fully melted and uniformly dense ingot that can then be used for feedstock. Small batches of material are generally processed because the surface finish is dependent on maintaining surface tension of the molten pool. Large metal charges can be problematic to keep fully molten, so generally the molten pool is allowed to cool and solidify, and then a new arc is established and additional metal is added to the top of the ingot and melted into it. Uranium and other refractory metals melt at lower temperatures than copper, so it stands to reason that a large quantity of molten uranium pouring into a copper crucible could damage the crucible as well as contaminate the melt. As a practical matter, this is avoided by cooling the crucible, even if it flash solidifies against the crucible after the metal melts, forming a protective coating or skull. The molten uranium can be kept molten and can be consolidated and homogenized without ever risking damage to the lower-melting-temperature copper crucible.

Alloys can also be produced the same way with high-temperature or difficult-to-alloy metals. One distinct advantage to this method is that any volatile contaminants are removed in this process. The arc can be controlled by its position relative to the center of the molten pool. Likewise, a magnetic field can also be used to help direct the arc toward the center of the molten pool. After the arc is struck, the power can be increased to enhance the melting speed. Generally, 200–300 A of current is enough to make a 2-in. ingot, whereas a 7-in. ingot might require 2,000 A of power at 15–30 V.

For high-purity alloys, consumable electrodes are generally used. These consist of making consolidated rods of uranium or alloy and feeding these into the molten pool. These rods can be cast or made up of consolidated metal turnings scrap or powder. This has the advantage of not adding any contaminants to the molten pool and improves purity further by removal of any volatile contaminants. Any of the previously mentioned techniques that use tungsten electrodes can be used with consumable electrodes with excellent results. Another approach is to have the electrode be able to swing in an arc and maintain a short interval from the crucible. This allows more metal to be melted and the metal to be mechanically mixed or stirred. The resulting ingot usually has a very rough bottom surface, which then is generally melted after the ingot is flipped. The consumable ingots can be welded together or may be secured in the cathode holder with a conductive collet. Sometimes it is desirable to cool the exterior of the collet to keep it from melting or forming a weld or eutectic bond with the electrode. Another approach is to make the electrode threaded and have a threaded cathode collet. When the cathode is too short to be used, a new one can be threaded on the end and the cathode pulled out to an appropriate length and fed in as needed.

2.9 The VAR Chamber

The VAR chamber is constructed so that a vacuum can be established, and the top and bottom are generally constructed so they can be electrically isolated and a strong electrical current can be applied. It is important to be able to observe the melt and to be able to control the distance from the crucible bottom and the relative position from the center to the edge. The bottom of the chamber, which functions as the crucible, should be cooled; water or other suitable cooling media, such as a molten salt or similar mixture, can be used. It is important to note that maintenance and inspection are critical with this type of system. If a leak were to develop and water were to be introduced into the molten metal, steam could develop and the potential for overpressurization or explosion could occur. Water may also represent a neutron moderation hazard for enriched uranium (Fig. 2.9).

It is a good idea to have an adequate vacuum system and have the ability to backfill with an inert gas. The use of gases like argon, which has a low electrical breakdown voltage and a high plasma potential, actually improves the performance of the VAR in melting the charge.

Fig. 2.9 VAR system showing major components for operation

2.10 Pyrometry and Temperature Measurement

Thermal measurement is not as critical with VAR as it is with VIM and microwave melting, because with VAR, usually only a portion of the charge is molten at a time. With nonconsumable electrodes, the metal is melted in small quantities and in small batches. With consumable electrodes, the electrode tip melts and drops into the molten top of the billet and forms the ever-growing billet. It is important to use closed-circuit cameras to view the melt or to have vacuum-tight windows to allow the direct viewing of the melting charge and allow manipulation of the electrode (Fig. 2.10).

Considerations for pyrometry are like those of VIM and microwave temperature measurement. Dual-color pyrometry or direct measurement with shielded thermocouples, neither of which will contaminate the melt, should be used. Since the pyrometry process generally has only part of the billet molten at any particular time, it will occur at a temperature very near 1,132 °C for uranium, and the molten portion is only about a hundred degrees above the melt point of higher melting alloys.

Fig. 2.10 This is an example of a process and over temperature pyrometer being used to control temperature. This configuration is for a microwave caster, but the equipment and setup are the same for microwave, VIM, and VAR

2.11 Microwave Melting Overview of Technology

Of the three melting and casting techniques discussed, microwave metal casting is the newest and the most obscure. Bulk metals do not readily couple directly with microwave energy at room temperatures. Since metals are electrically conductive, they readily reflect the incident energy. Microwave metal melting is counterintuitive, given common misconceptions about the behavior of metals in microwave fields. A few fundamental principles that make this possible follow:

In order to heat and melt bulk metals using microwaves, three basic ingredients are required: a multimode microwave cavity, a microwave-absorbing ceramic crucible, and a thermally insulating casket that is microwave transparent. The metal charge is placed in an open ceramic crucible, and the insulating casket is positioned to completely cover the open crucible. The casket and crucible assembly are then placed into a high-power multimode microwave cavity that can uniformly heat the crucible to the desired temperature. When microwave energy is applied to the cavity, the energy is strongly absorbed by the crucible. The metal charge in the crucible is quickly heated through radiation, conduction, and convection in the heated crucible. The thermally insulating casket increases the energy efficiency of the microwave system by trapping the heat generated in the crucible. In this way, metal objects that could not be directly heated by microwave energy can be melted easily and efficiently [14, 15]. Microwaves are preferentially absorbed by whatever absorbs them best. That might seem obvious, but remembering it can save a lot of frustrations when issues arise. If two items that absorb microwaves on their own and heat up readily are placed into the same chamber, whichever item absorbs the best will heat much more than the other. It is also possible that a very small component in the system might get superheated and the balance of the stack could remain cold. If there is arcing or a plasma formation

Fig. 2.11 View of a casting stack, crucible, and insulation. A lid will be added; no mold is used to melt and solidify a billet. This is called a dud melt

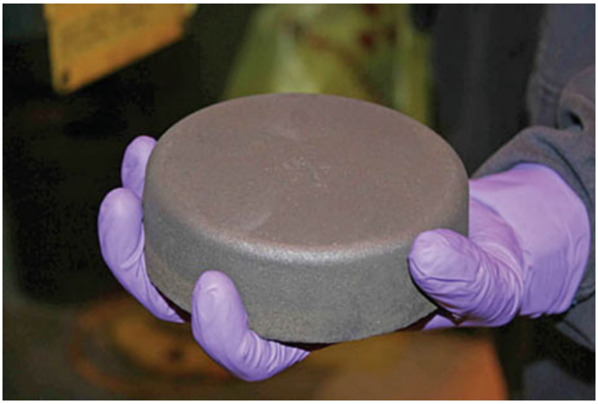

Fig. 2.12 This is an image of a microwave cast uranium billet

in the chamber, the arc or plasma may absorb essentially all of the energy, which could damage equipment while essentially no energy gets to the crucible or mold. As mentioned before, if this behavior is recalled when a problem arises, it might well save expensive equipment or hours of frustration (Figs. 2.11 and 2.12).

2.12 Theory

Metals are electrically conductive and as such microwave energy is readily reflected off the surface. There is a very minute depth to which microwaves penetrate, but for the most part, pieces of metal will not heat in a microwave directly to a temperature that would allow for melting and casting. In order to melt metal, a ceramic crucible is used, which couples (absorbs microwave energy) with the microwaves and converts microwaves into heat. To *suscept* also means to absorb microwaves to convert them into heat. A suscepting crucible is used to heat the metal from room temperature to about two-thirds of its melting point. This occurs by the ceramic crucible's dielectric absorption of microwaves. Dielectric constants, despite the name, are not constant with respect to temperature or electromagnetic frequency. As the temperature increases, the ceramic's ability to absorb microwaves enters into one of four possible scenarios. The ceramic:

- Is transparent to microwaves; it does not absorb microwaves and also does not heat up.
- Absorbs microwaves better as the temperature increases, making the ceramic hotter, which in turn increases its capacity to absorb microwaves. This behavior is called "thermal runaway." If these ceramics are used, applied power has to be decreased to control temperature as the temperature increases.
- Can decrease its ability to absorb microwaves as a function of temperature; so as the ceramic gets hot, it becomes increasingly more difficult to heat and will generally establish a plateau or suddenly drop in temperature once a critical temperature is reached.
- Does not start to absorb until a critical temperature is reached and then it starts to absorb increasingly better as the temperature increases.
- Heats in a linear fashion to the upper limit of what the system can handle with no change in absorption as a function of temperature. This behavior of linear heating is extremely rare (Fig. 2.13).

The crucible, which is coated to prevent reaction with the molten metal, is situated above the mold, which is usually made of graphite and is also coated to prevent reaction with the molten metal. The crucible and mold, which make up the casting stack, are enclosed in ceramic high-temperature insulation. This is referred to as the "casket," which is transparent to microwaves but does not allow heat generated inside the casket to escape. With this arrangement, microwaves in the chamber pass through the ceramic insulation and impinge on the crucible. If the microwaves hit the metal or graphite, they bounce off and continue to bounce around until they are absorbed by the crucible. The crucible heats and the metal inside is heated by conduction and convection. Since the heat generated inside the casket cannot escape, the temperature inside the casket rises quickly and heats the mold and pour rod as well as the metal. Since only what is inside the casket is heated, this process is a relatively simple and efficient method of melting metal. As the metal heats up, it starts to heat directly by ohmic heating mechanisms, and at elevated temperatures, many ceramics used for crucibles start to lose their ability to absorb, so an interesting phenomenon happens (Fig. 2.14).

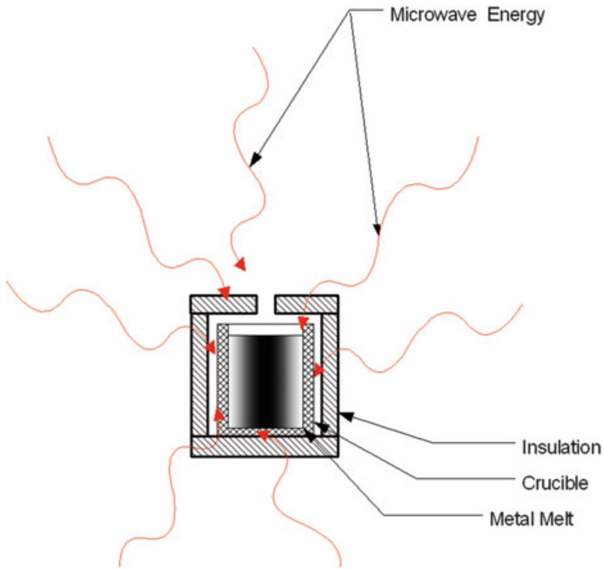

Fig. 2.13 Microwave energy can easily be transferred to metal shapes in a suscepting crucible

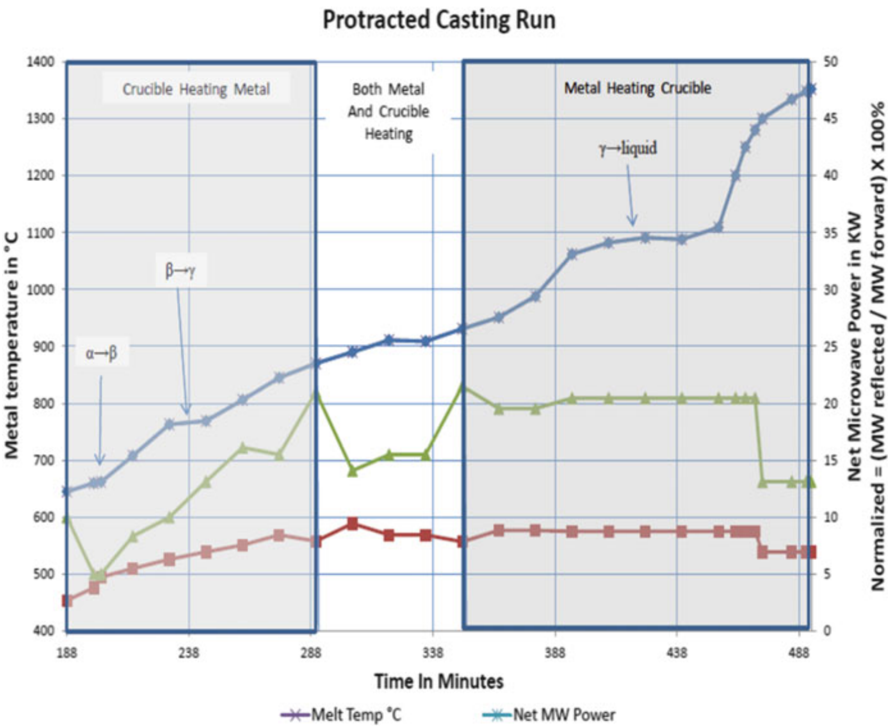

Fig. 2.14 Protracted casting run (extremely long slow casting run) to show temperature, microwave power, and regions where the crucible is the main absorber and where the metal is a better absorber

From room temperature to about two-thirds of the melting point, the crucible heats up and the metal and mold are heated by conduction and convection, so the crucible is the hottest thing in the system. At some point (which is different for every metal), the metal absorbs the microwaves and heats, and at that point, the metal is the hottest thing in the system. This has the advantage of putting the heat where it is needed and allowing for the most efficient application of power to supply the superheat required to cast the metal.

2.13 The Equipment and Setup

A microwave for melting and casting reactive metals in quantities of about 90 lb or less should have a chamber that is large enough to hold the casting stack and leave about a 9-in. space remaining on each side and at the top. The chamber should be microwave tight and have adequate viewing ports (which also prevent microwave leakage) to view the stack and to look down into the melt. It should be fitted with a vacuum roughing pump and be able to be backfilled with an inert gas (Fig. 2.15) [14, 15].

Since the chamber will be run under positive pressure, the vacuum is used to reduce the amount of inert gas required to establish an inert casting atmosphere. The microwave power source should be from 12 to 24 kW, with the understanding that the power is applied at a rate at which the stack absorbs the microwaves. Any extra power is simply wasted as reflected power or can overheat components like windows and waveguides, which could damage the system. The most commonly used frequency is 2.45 gHz.

The microwave generator is made up of some key components. Although these industrial microwave generators are usually purchased as complete units, it is important to know what components are being used in the system. Key components

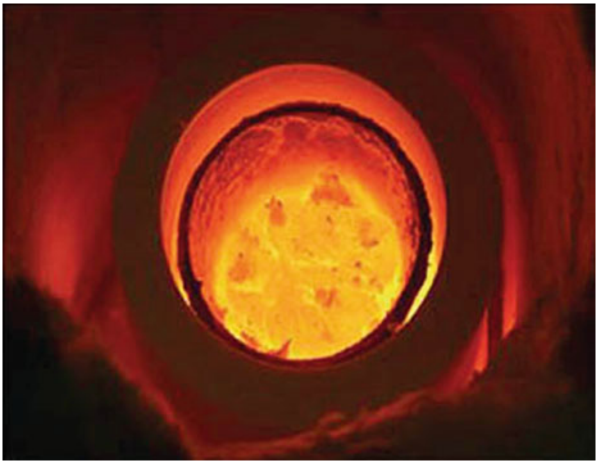

Fig. 2.15 Molten uranium metal; note the insulation casket and suscepting ceramic crucible

in the microwave generator are the power supply, the magnetron, and the isolator. Each of these components can profoundly affect the operation of the system. The complete microwave consists of a number of specialized components, and discussions of each follow.

2.14 Chamber or Applicator

The microwave chamber (also called an applicator) is a metal container that holds the casting stack and charge, and the microwaves are directed into it. Common types of applicators include front loading, drawer, or bottom loading; however, many application-specific chambers could be employed. The metal of construction is important; the losses due to absorption by the walls need to be minimized. Chambers like the one that Fig. 2.11 provides are constructed of aluminum, which has low wall losses and is inexpensive and easy to manufacture. Despite the low melting temperature of aluminum, such a chamber can be used to cast metals up to and including titanium (melting point 1,668 °C) without getting hot. This is because of the excellent insulating properties of the ceramic insulation used in the casket.

It is still a good idea to have thermocouples and thermal interlocks and cutoffs in case of crucible brake or casket damage. However, with proper care, these features will never be needed.

It is important to have some type of pour mechanism to release the molten metal into the mold. Commonly used pour mechanisms are the pull rod and rupture disk. Just as with the VIM, the choice is a matter of practicality and convenience. With the exception of the waveguides, any penetrations into the applicator need to be designed so that microwaves cannot inadvertently leak out. This can be done by incorporating a perforated metal screen like that used in a home microwave or by having a tube narrow enough and thin enough to prevent the microwave energy from escaping. The latter of these concepts is called "waveguide beyond cutoff." It needs to be capable of being evacuated and backfilled with an inert environment and of holding a modest pressure. In addition, it should be smooth walled with sound, smooth welds and be easily cleanable (Figs. 2.16, 2.17, and 2.18) [14, 15].

2.15 Power Supply

One of the key components in the microwave generator is the power supply. The different types of power supplies are described below.

Half-wave voltage doubler (common in home microwave ovens). This type of a power supply is the simplest and takes alternating current as an input and produces twice the voltage in direct current as the output. These are cheap and simple but

Fig. 2.16 Large front loading microwave chamber for casting high-temperature reactive metals

Fig. 2.17 These are uranium chips that are about to be cleaned, pressed, and dried before melting

Fig. 2.18 The solid oxide shells often referred to as *ghosts*, which are left in the crucible when the uranium is melted and poured into the mold

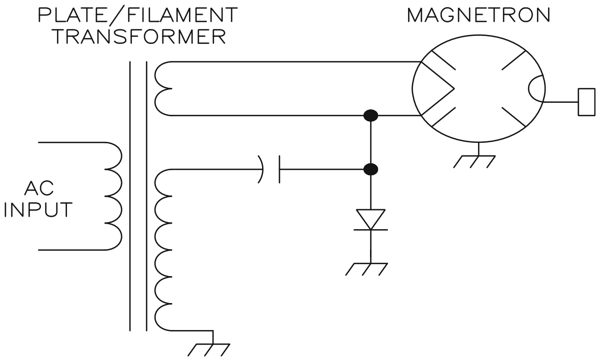

Fig. 2.19 A simplified schematic of a half-wave voltage doubler power supply

have limited duty life and performance. They have a fixed peak output and can be run as a pulsed duty power supply (Fig. 2.19).

Full-wave rectified (linear). This type of power supply takes AC current as its input and converts the whole wave form to an output of constant polarity. The performance of this type of power supply circuit is much better than the half-wave doubler, and it can be operated as a fixed-voltage or variable-voltage power supply. It is more complex and more expensive, but the cost is offset by much better performance and longer service life. These are the types of power supplies in the better industrial-quality microwave generators (Fig. 2.20).

Inverter (switch mode). This type of power supply is the most efficient of the three but suffers from the potential to cause noise problems if not adequately shielded. The advantages are that it can deliver variable output, in pulsed or continuous wave waveform; plus, it has unparalleled performance and runs significantly cooler than the other power supplies. However, it is more complex and more expensive, and it can suffer from shorter service life if it is used for extended periods of time.

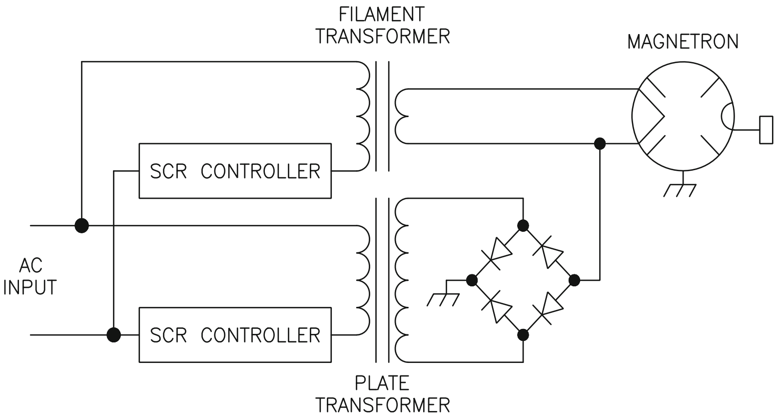

Fig. 2.20 Simplified schematic of a linear or full-wave rectified power supply circuit

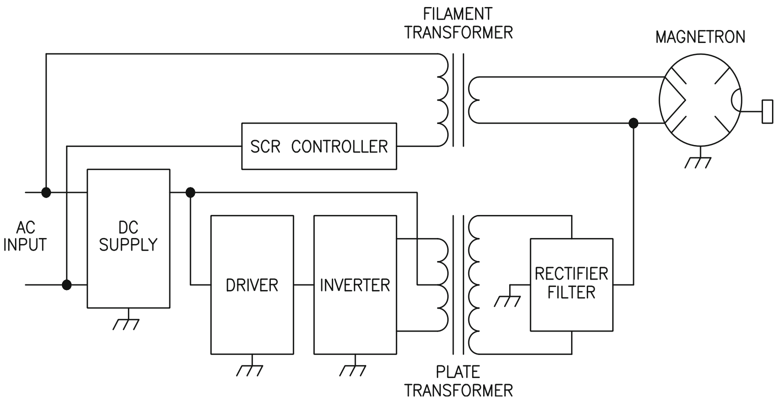

Fig. 2.21 Simplified schematic of a switch mode or inverter type of power supply

For most continuous industrial heating applications, the linear or full-wave rectified power supply is the best option because of its long service life, minimal complexity, and overall value (Fig. 2.21).

2.16 Magnetron

The theory of magnetron operation is based on the motion of electrons under the combined influence of electrical and magnetic fields. For the tube to operate, electrons must flow from the cathode to the anode. Two fundamental laws govern their trajectory:

1. The force exerted by an electrical field on an electron is proportional to the strength of the field. Electrons tend to move from a point of negative potential toward a positive potential. With no magnetic field present, there is a uniform and direct movement of the electrons in an electrical field from the negative cathode to the positive anode.
2. The force exerted on an electron in a magnetic field is at right angles to both the field itself and the path of the electron. The direction of the force is such that the electron proceeds to the anode in a curved rather than a direct path.

Permanent magnets are added above and below the tube structure. The tube is a cavity, which has a number of spaces. Around the rim of the tube is a series of cylindrical resonant cavities on its periphery. These cavities have a slit opening along the interior wall. The electron leaves the cathode and is attracted to the wall, but because of the magnetic bias applied, it cannot travel in a straight line to the wall but approaches the wall in a decaying spiral trajectory. As it does, it sets up a high-frequency resonant electromagnetic field in the cavity. This resonant frequency is determined by the size of the cavities. A small output coupling loop acts as an antenna and allows the electromagnetic waves to exit the tube through a launcher and enter the waveguide.

2.17 Circulator or Isolator

One critical component for high-power microwave operation is the circulator, which consists of an isolator and a dummy load. The isolator is a piece of equipment that prevents microwaves from reentering the waveguide and damaging the magnetron. It is inserted between the magnetron (microwave generator) and the waveguides. It allows microwaves to pass through unimpeded in one direction, but when they enter in the opposite direction, they are redirected into either a solid-state load or a water load. The purpose of the dummy load is to absorb this excess energy and prevent microwaves from making it into the magnetron. Reflected microwave power causes excess heat and, ultimately, catastrophic damage to the magnetron.

The isolator works by establishing a strong magnetic field across the waveguide. Ferrites and magnets on top and bottom function to make sure that microwaves entering can follow only two basic rules: First, they can circle only in one direction, and second, they have to exit at the first possible opportunity. If one were to imagine the isolator as a roundabout with three roads, one road is an entrance, opposite it is an exit, and the third road is a dead end (dummy load). If a car were to enter this roundabout at the entrance, it moves with the direction of traffic and takes the first possible opportunity to leave the roundabout. This is the exit that leads to the applicator. Now, if the car tries to return via the exit, it moves in the direction of traffic and takes the first opportunity to exit, which in this case is a dead end (dummy load) and is absorbed. With this system in place, there is no danger of the magnetron's being damaged by reflected power (Fig. 2.22).

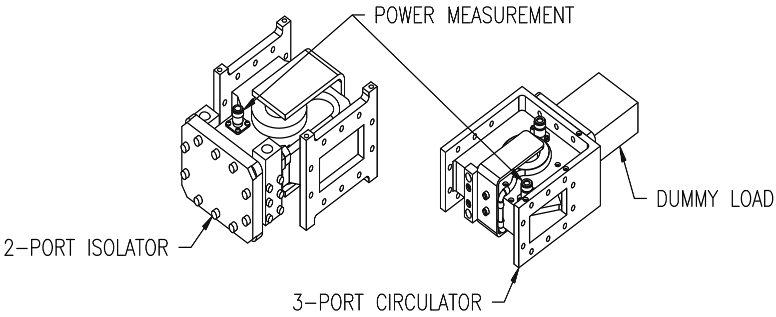

Fig. 2.22 A circulator and isolator showing coupler to give power measurement

2.18 Power Measurement Devices

When high-power microwave generators are used, there is great potential to put a lot of energy into a crucible and casting stack. Conversely, there is great potential to cause quick damage to equipment and components if they inadvertently receive too much microwave energy too quickly. It is the absorbed power that is important:

$$\text{Absorbed power} = \text{forward power} - \text{reflected power}$$

In order to know the absorbed power, it is critical to know the forward and reflected power. These measurements are made using one of several measurement devices. Each of these devices has a purpose, depending on what information is available from other sources.

Directional couplers measure power in one direction. It can be subject to error because it gives information only in one direction; it essentially ignores the power flowing in the opposite direction. A pair of directional couplers, which has one in each direction, is referred to as a dual coupler. This will allow a measurement in both the forward and reflected (rev) directions. The dual coupler reduces this error by showing power flow in both directions. Many times these will be used, even if there is forward or reflected power indications somewhere else in the system, because they can be placed strategically to give information at the point where it is desired.

The nondirectional couplers are inexpensive, but in order to be useful, they have to be placed where power flows in one direction only.

Finally, reflectometers cost more but can provide a lot more information than other types of power measurement devices. These are used to make complex impedance measurements. For most applications, reflectometers are overkill, and the information gathered is not required (Fig. 2.23).

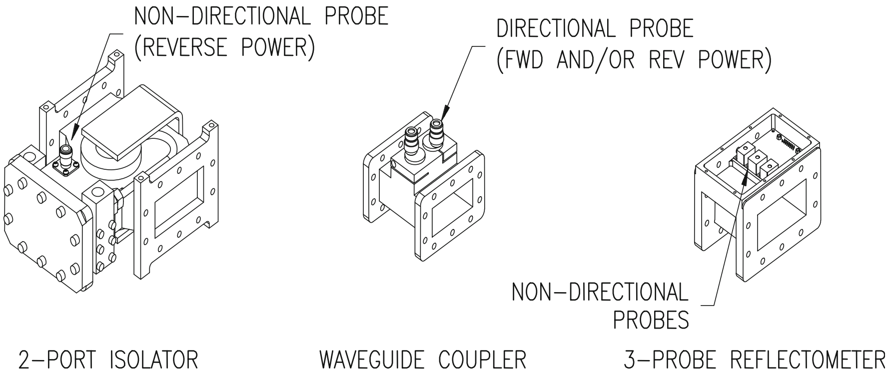

Fig. 2.23 Three different power measurement devices

2.19 Pyrometry

Pyrometry for microwave systems is essentially the same as was discussed for VIM. For microwave applications, the following items are preferred:

- Dual-color or multicolor.
- Small spot size with viewing port (or camera).
- Temperature range that spans the range of interest many times; several will have to be used for different parts of the run.
- Calibration of the pyrometer in accordance with the conditions under which it will be read. If shooting will be done through two windows—one that is a few inches away and at room temperature and the other that is a foot away at 500 °C—it is a good idea to duplicate this setup in the calibration.

Finally, one needs to pay attention to the temperature profile. If uranium is heated at a constant energy input, consistent heating that follows a smooth curve will more or less be achieved. With a few notable exceptions, thermal arrests will occur at 668, 772, and 1,132 °C because of phase changes. These will show up as small plateaus in the otherwise smooth curve. These can also be used to check the relative accuracy of the pyrometric measurements because these thermal arrests or plateaus have to occur, and always occur, at specific temperatures. Knowing this, one can correct for any systematic errors to gauge the temperature at any point with more precision and accuracy than would be possible by simply relying solely on the dual-color pyrometer.

2.20 Impedance-Matching Devices or Tuners

Impedance matching was originally developed for electrical engineering but is particularly applicable to high-power microwave applications. Simply stated, impedance matching maximizes the power transfer and minimizes the reflection from the load.

Several approaches can be used to accomplish this goal, including the following:

- Manual three-stub tuners
- Automatic stub tuners
- Fixed iris
- Internal wave matching structures

Manual three-stub tuners are a cost-effective way to maximize power application while minimizing reflection. The tuner has three stubs, which are effectively quarter-wave chokes. They move into or out of the waveguide and can eliminate part of the signal, which is likely to be reflected back into the waveguide. Typically the stubs will be turned to extend them into the waveguide while monitoring the change in reflected power. If the reflected power decreases, the stub is turned further into the waveguide. If the reflected power increases, it is withdrawn. This is performed in a systematic method, going from one tuner to the next, until the minimum reflected power is attained. Generally, this approach is adequate. However, it is possible the lowest reflected power that can be obtained by tuning the stubs in one combination might represent a local minima. But using a different combination may result in a lower overall reflected power. If it is critical to obtain the best possible impedance match, different combinations of tunings need to be tried, the positions noted (most tuners have a micrometer or a digital position indicator), and the absolute minima noted. These are inexpensive and effective methods of impedance matching.

Automatic stub tuners operate like the manual tuners but have a computerized program and built-in reflectometer, so multiple combinations of tunings are attempted, and the absolute minima is achieved in a matter of seconds rather than after laborious minutes of manual tuning. The system is constantly checking for standing wave measurements and adjusts accordingly. This is an expensive system but has the advantage of being able to adjust to constantly changing loads. It also relieves the operators of the responsibility of constantly adjusting for operating peak efficiency.

For a steady-state system where little systematic changes are observed, a cheaper alternative is to place an impedance-matching feature in the waveguide or to fit the window with an iris. These wave matching features do have to be determined by trial and error but are very inexpensive to employ. Typical shapes that are used interior to the waveguide are blocks of copper or aluminum that obstruct a portion of the waveguide from top to bottom, blocks of copper or aluminum that obstruct a portion of the waveguide from side to side, or pieces that block one or more corners. Another approach is to place a conductive metal sphere inside the waveguide on the bottom or top center wall. The position of this is important so it can be put in place, moved around until it is in the right spot, and then permanently installed. Finally, an iris or partial opening between the waveguide and the process chamber can be used. The iris generally blocks the top and/or bottom, left and/or right side, or one or more corners. If an iris or waveguide matching structure is used, no other impedance-matching feature should be used (e.g., manual or automatic stub tuners) (Fig. 2.24).

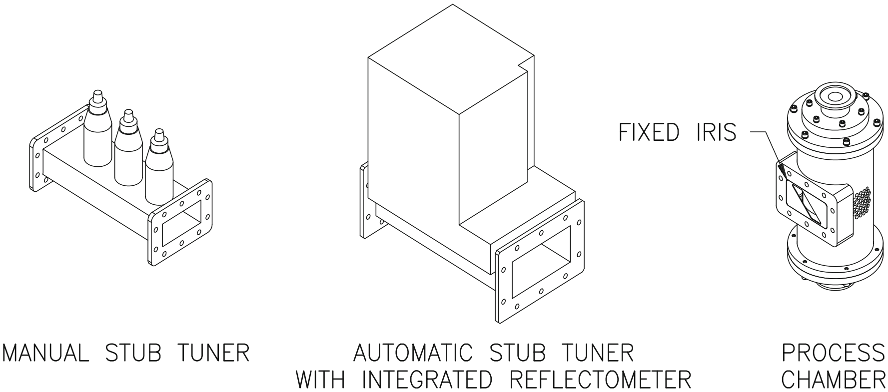

Fig. 2.24 Examples of impedance-matching features

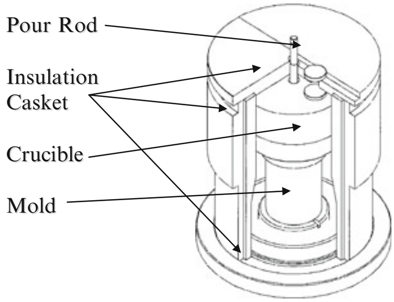

Fig. 2.25 Cutaway of the casting stack showing the crucible, mold, and insulation casket

2.21 Casket

The *casket* is the term used to refer to the thermally insulating structure around the casting stack. It is typically a rigid fiberboard of 80 % Al_2O_3 and 20 % SiO_2. It is important that it be transparent to microwaves at the frequency of interest and that it be able to withstand high temperatures. A good density range is nominally 30 lb/ft^3 and 85 % open porosity. These are general guidelines to be used as a starting point. The insulating casket could be made with completely different materials, providing it does two things: allows the microwaves to enter the stack unimpeded and does not allow heat to escape. This creates a superheated interior, which allows the metal to heat and melt (Fig. 2.25).

2.22 Casting Stack

The casting stack consists of the crucible, mold, and ancillary items such as the pour rod and windows. As discussed previously, the crucible is made of a ceramic, which couples with the microwaves. The mold is typically made of coated graphite, which can contain the molten metal without reacting with its chemistry. The pour rod is also typically coated graphite.

Of course, if the goal is simply melting and consolidation, a closed-bottom crucible with a slight draft angle on the side can be used. A crucible that is going to be used to pour molten metal should also be designed with a central hole for pouring (alternatively, a spout could be used for tilt pouring), a shallow taper on the sides, and a slight draft angle sloping from the sides of the crucible to the pour hole. With this general design, the metal can melt; when poured, the metal will flow out completely, and if no pour is made and the metal freezes in the crucible, it can be removed without sacrificing the crucible. If this were to occur, it is generally a good idea to break, shear, or otherwise reduce the metal in size before remelting. It could also be placed in a slightly larger crucible or even placed on its side before remelting. If the frozen metal is simply reheated in the same crucible without one of these things being done, as the metal heats, the expansion could crack the crucible and result in an unsuccessful pour or damage to the equipment. Of course, all of these components must be of criticality safe dimensions, and to reduce the potential for a criticality accident, the entire system must be evaluated if the metal to be cast is fissile, fertile, or fissionable.

2.23 Vacuum and Inert Gas Backfill System

Unlike VIM or VAR, the microwave is operated at slightly positive pressure with a small flow of gas, which is vented to remove any moisture and any gases that are given off by the insulation, crucible, or metal as they are heated. To achieve this, it is a good idea to pull a rough vacuum and then backfill with an inert gas. Positive pressure is key because when microwave power is applied to a gas at reduced pressure, the potential for creating a plasma is greatly increased. Some gases are less likely to produce a plasma, and as the pressure increases, the plasma potential decreases.

It is helpful to look at the Paschen discharge curves for the atmosphere desired for the casting operation in order to select a gas that is less likely to be a problem. It is also possible to bleed in a less reactive “quench” gas to reduce the plasma potential or to stop one when it forms. If a plasma forms, it is advisable to turn off the power completely for a few seconds and then turn it back on slowly. If a quench gas is used, it may alleviate any further problems.

If a plasma reoccurs, the addition of a higher plasma potential gas or a quenching blends like Ar 90 %, H_2 10 %, or N_2 or any other compatible high plasma potential gas. If the application of the quench gas is unsuccessful, simply turning

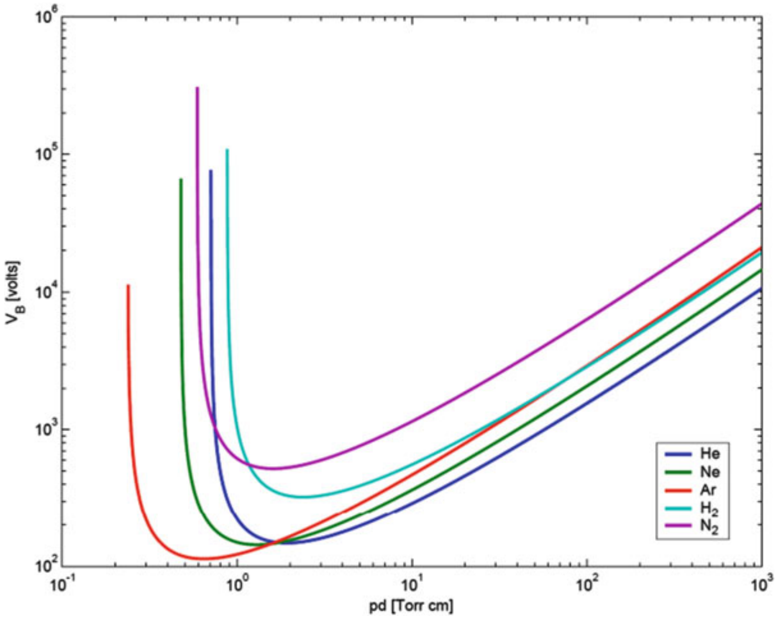

Fig. 2.26 Paschen discharge curve of several gases

the system off and back on might take care of the plasma problem as well. If plasma formation occurs, it is important to pay attention to the reflected power levels because plasma formation is often a symptom of excess power in the chamber. Only absorbed power is heating the crucible and metal, so reflected power is wasted and can lead to issues later (Fig. 2.26).

The Paschen discharge curve is an indicator of the relative plasma potential only. These curves were derived under a different set of conditions, so no direct mathematical correlation of microwave energy to a specific casting stack and the likelihood of plasma formation can be inferred. However, the relative behavior and pressure trends hold true in microwave applications.

2.24 Summary and Conclusion

When a method of heating and casting uranium or other reactive metals is being considered, a number of factors must be taken into account:

- Ease of operation
- Ease and cost of maintenance
- Ergonomics
- Contamination control
- Ultimate chemical requirements of final product
- Mechanical properties of cast material

- Size, shape and complexity of part, etc.
- Capital equipment cost
- Cost to operate
- Casting capacity and size of part
- Service life of equipment
- Number of castings per week

There is no off-the-shelf solution to the problems routinely encountered when casting uranium. Every alloy, charge size, part type, etc., will present unique challenges that will need to be addressed before entering the foundry. This information was intended to be a brief overview to make the reader aware of the current state of the various technologies and help them determine which options might best suit their needs.

Acknowledgements

Figure credits
Photos for Figs. 2.1, 2.7, 2.12, and 2.15 were taken by Brett Pate.
Photos for Fig. 2.6 were taken by Matt Marsicek.
Photos for Figs. 2.2, 2.3, 2.4, 2.5, 2.8, and 2.9 were provided by ALD Vacuum Technologies.
Figures 2.19, 2.20, 2.21, 2.22, 2.23, and 2.24 were provided by John Gerling.
Photos for Figs. 2.11, 2.14 2.16, 2.17, and 2.18 were provided by MS Technologies Inc.
Figures 2.13, 2.14, 2.25, and 2.26 were provided by the author.
Photo for Fig. 2.10 was taken by Hugo Huey.

References

1. Dahl A, Cleaves H (1949) The freezing point of uranium. J Res Natl Bur Stand 43:513–517
2. Baumrucker C, Warren B (1953) Unpublished information
3. Sadiku OMN (2007) Elements of electromagnetics, 4th edn. Oxford University Press, New York
4. Harrington C, Ruehle A (1959) Uranium production technology. D. Van Nostrand Co. Inc., Princeton, NJ
5. Patton F, Googan J, Griffith W (1963) Enriched uranium processing. The Macmillan Co., A Pergamon Press Book, New York
6. Wilkinson W (1962) Uranium metallurgy, vol I. Wiley, New York
7. Wilkinson W (1962) Uranium metallurgy, vol II. Wiley, New York
8. Wilhelm H (1942) The casting of uranium rods at Iowa State College. Internal publication (A-4045): Iowa
9. Holden A (1942) Physial metallurgy of uranium. Addison-Wesley, Reading, MA
10. Blumenthal B (1955) Melting of high purity uranium. University of Michigan Library Jan, 1952
11. Googan J, VanDermeer R, Koger J, Donnelly (1981) Metallurgical technology of uranium and uranium alloys vol. I. ASM American Society for Metals Press, OH
12. Googan J, VanDermeer R, Koger J, Donnelly (1981) Metallurgical technology of uranium and uranium alloys vol. II. ASM American Society for Metals Press, OH
13. Googan J, VanDermeer R, Koger J, Donnelly (1981) Metallurgical technology of uranium and uranium alloys vol III. ASM American Society for Metals Press, OH
14. Gupta M, Leong W, Eugene W (2007) Microwaves and metals. Wiley, Asia
15. Brooks K, Industrial-Scale Melting of Uranium Using Microwave Energy. Industrial Heating, February 8, 2011

http://www.springer.com/978-1-4614-7590-3

Uranium Processing and Properties
Morrell, J.S.; Jackson, M.J. (Eds.)
2013, X, 313 p., Hardcover
ISBN: 978-1-4614-7590-3