

**THE HOBBYIST'S GUIDE
TO CASTING METAL**

2ND EDITION

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Acknowledgments

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Disclaimer

Many of the activities described in this book are very dangerous. I make an attempt to point out some specific safety precautions as they come up, but there is no way I can point out every conceivable danger. I'm not a professional foundryman, scientist, or engineer, just a hobbyist—so there may be dangers that I don't even know about. For that matter, any advice I give could be wrong or even dangerous in certain situations. I can't be held responsible for any harm that comes to person or property as a result of following my advice or using any of the information in this book. Remember, the extremely high temperatures that liquid metal can reach are more than enough to send you to the hospital or kill you, or to set fire to anything nearby (like your house). Other activities, like welding or machining, present their own very serious dangers.

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Introduction

The first question a beginner to the hobby of metalcasting might ask is, Why cast metal? Casters that have been with the hobby a while have already answered this question for themselves, of course, and they are likely to have a multitude of personal reasons for their own involvement in the hobby.

Utility of Metalcasting

Machinists will find the casting of metal invaluable for creating blanks and rough parts, as it is much easier and cheaper in most cases to cast a rough part and finish machine it than it is to machine the same part from solid. With care, machine turnings can be recycled by re-casting, and salvaged scrap metal and failed parts can be melted to produce new parts, drastically reducing the need to buy expensive stock. For many parts, also, casting to rough shape will save a large amount of machining time and tool wear compared to machining from stock. Indeed, casting and machining are complementary pursuits to such a level that I would regard a hobby machine shop without the ability to cast parts crippled in its pursuits and abilities.

Sculptural artists may find their expression in cast metal, as the casting is permanent but relatively easily formed from a sculpted pattern in wax, modeling clay, or wood. Art studios exist that will professionally produce castings from an artist's original, but these services are universally expensive and perhaps out of the reach of the non-professional artist. Furthermore, much greater control over the process is achievable by doing the entire process yourself.

For the experimenter, casting metal will be an interesting and challenging intellectual pursuit, drawing upon skills in a wide variety of fields. Casting at the hobby level provides especially interesting problems to solve due to the budgetary and other constraints not present in an industrial setting. The solutions to these casting problems often blend technology developed thousands of years ago with technology developed in the modern world to provide a manageable approach to processes usually reserved for heavy industry.

It is also possible for the entrepreneur to make a living, or at least some spending money, casting metal in a small home-built foundry. A commercial enterprise will require higher quality and more consistency than most hobby operations achieve, but this can be done if the income stream from casting offsets some of the money spent on better equipment.

Perhaps most fundamentally, casting metal is a way to make things. As an additive process, it nicely complements many subtractive processes such as machining and sculpting, and it

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is a valuable tool for any metalworker, artist, or artisan. Anyone who derives enjoyment from the act of creation will find enjoyment in the hobby of metalcasting.

The Basics

The next question a beginner might ask is, How do I cast metal? The technical details of this question are covered collectively by the rest of this book, but it is perhaps appropriate to make some general notes here.

In order to cast metal, you first need to have metal, a way to melt the metal, and a mold to put it in when it's melted. Getting the metal is relatively simple—it can come from collected scrap, or it can be purchased in ingot form from various suppliers.

To melt metal, you need some form of furnace. Crucible furnaces (the type covered in most detail by this book) use a vessel to contain the metal, and a furnace to heat the vessel up to the metal's melting point. Crucibles can be bought or made, and can be made of metal or ceramic.

Direct-melting furnaces, in contrast to crucible furnaces, have a place in the furnace (called a hearth) that holds the molten metal. Reverberatory furnaces are designed such that hot combustion gases (from a burner or the burning of solid fuel) make multiple passes above the hearth before being exhausted, improving efficiency. Cupolas allow the metal to fall through a bed of burning solid fuel, melting on the way down and collecting in the hearth until the furnace is tapped and the charge is emptied. Other types of furnaces, like arc furnaces, have a crucible-like hearth and apply heat directly to the metal through various means. Direct-melting furnaces may pour metal directly into molds, or into a ladle (similar to a crucible) that is then carried to the molds.

Molds can be made in many different ways. Sand molds will be discussed in detail in this book, and the basic sand molding process is to place a pattern in the shape of the casting into a specially-designed box (flask) and compress special molding sand around it on all sides. The sand takes the shape of the pattern, the pattern is removed from the mold (usually the mold is made in multiple parts to accommodate this), and the metal is poured in. The mold is destroyed in extracting the casting, but the sand can be reused.

These processes are extremely simple, as you can see. However, making crucibles and furnaces that can survive the temperatures required to melt certain metals can be challenging, and the other requirements (thermal shock resistance, good insulative ability, and so on) implicit in making the process practical will make the process even more difficult. In short, while casting metal is not in itself difficult, casting metal *well* is.

That being said, just because there is an enormous body of research already done on metalcasting does not mean that there is no room for innovation. While a practiced amateur is capable of getting good results from good equipment, the mark of a true expert is getting

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good results from bad equipment. So don't let the apparent requirements of metalcasting daunt you. People figured out how to cast metal successfully thousands of years ago, without the benefit of 5,000 years worth of information about the subject, and you can do it too.

Metalcasting is a very old process, dating back almost to the very beginning of civilization. Early castings were commonly made using variants of greensand casting processes, as well as investment and permanent mold processes. The Industrial Revolution created a huge demand for cast parts, and spurred on developments in casting technology. Nowadays, industrial casting using machine-made sand molds, high-pressure high-speed die casting machines, and technically advanced ceramic shell processes are commonplace. Still, the basis of most casting methods has not changed much if at all in the past 5,000 years, and the techniques work as well now as they did then.

Older technology is often advantageous to the hobbyist, because it tends to be cheap and readily accessible. That being said, modern technology can be of use. There's no need to build a hand-cranked bellows to supply air to your charcoal furnace when the blower from an old vacuum cleaner will do as well.

You will not find bleeding edge developments in casting technology in this book. Indeed, there is nothing particularly novel about the methods used in most hobby casting. Instead, the purpose of this book is to provide a guide, as close to comprehensive as possible, which details every step of the casting process. More importantly, I have tried where I can to explain some of the science at work behind the scenes. Many other hobby casting tutorials provide a set of detailed step-by-step instructions for doing things a certain way, but they rarely explain the reasoning behind those decisions. This tends to leave the beginner blindly following instructions, and if anything goes wrong he is helpless to correct it.

The science at work behind even simple casting processes is extremely complex, so this book provides no more than an overview. There is enough information available about most of the topics in this book to write a doctoral thesis about each one (that isn't to say I know enough to write a doctoral thesis about each one!) and still have only skimmed the surface.

Personal History

My introduction into hobby metalcasting, like many other hobbyists, occurred when I was in the middle of a project and trying to make a part I couldn't buy. I needed a set of gears duplicated, so I decided I would try to cast them. (I later learned that gears of that size wouldn't be possible to cast using any hobby technique I had access to at the time, but that doesn't matter.) In figuring out how I'd cast the gears, I learned more and more about the hobby, and decided to start experimenting with casting metal. The gears, and the project they went to, were quickly forgotten.

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I made plenty of mistakes and false starts when I was trying to learn how to cast metal. I was following what I'd seen other hobbyists do, but each person seemed to do things in a different way, and I didn't know which way was best. Many of the things I tried didn't work at all, or worked very poorly. Still, enough worked to show me what was possible with the hobby, and I pursued it fervently.

My first furnaces were both solid-fuel. This was messy, and the blowers that provided air were very loud. Neither of them were well-insulated, so they were expensive to run. I didn't have a good casting area or any greensand, so I was using the lost-foam method and casting over concrete. The foam burnt off and made the sand stink like melted plastic, and with every pour (though I didn't know at the time), I was taking a chance on having a steam explosion if enough metal hit the concrete. Still, I was casting things, and though none of my early castings were particularly good, they showed promise.

Then, I decided to upgrade. I got some commercial refractory (dense refractory, because I didn't know any better) and built a large furnace with it as a hotface and perlite for insulation. I spent a while fiddling with different waste oil burners, but none of them worked well enough to use in a furnace, so I eventually converted to propane. Furthermore, I had built too big, and I couldn't use this big furnace for the kinds of castings I really wanted to do. It took so much time and fuel to get it hot that I had to melt a lot of metal to justify the fuel costs, and I didn't have either enough molding sand to use that much metal, or a way to move it safely when molten. The big furnace sat unused for a year while I melted using a much smaller furnace made of perlite stuck together with some leftover refractory.

That small furnace eventually got destroyed by high temperatures and mechanical damage, so I built another one of similar size with ceramic wool and a clay/foam hotface. This furnace was also fragile, because I put too much foam in the hotface, but it worked very well for high-temperature, efficient melts. I also started using the big furnace at about the same time, and though it wasn't very efficient, it worked well for large melts and breaking down scrap.

The new furnace, while fragile, was well-insulated and more temperature-tolerant than anything I had made before. I used it for quite a while melting aluminum, copper alloys, and iron before a crucible failure flooded it with metal and destroyed it.

Then, I built the furnace detailed in this book. In building, I have attempted to incorporate all the lessons I've learned in my previous designs as well as the things I've learned about the science behind metalcasting and refractory ceramics, and I believe the results have paid off. It is a very capable design, built to fit commercial #4 and #6 crucibles as well as homemade steel ones of common sizes, efficient and well-insulated, and capable of sustained operation at iron temperatures without damage.

Section I

Safety

Casting metal is serious business, and very dangerous. Even when using proper safety gear, and observing all necessary precautions, serious accidents can still occur. Lack of proper safety gear, unsafe surroundings, or unsafe procedure increase both the likelihood and severity of accidents.

Safety Gear

The proper safety gear is *necessary*, but not *sufficient*, to ensure a safe casting environment. On the other hand, safety gear that is not suitable to protect against the hazards being faced may actually be worse than no safety equipment at all, because it provides an illusion of protection that does not actually exist. It is also possible to have too much safety gear—properly used safety gear should never restrict movement or vision, and no amount of safety gear is a substitute for prudence.

Clothing

When casting or working with hot materials, always wear cotton or wool clothing. Synthetics can melt and burn vigorously when exposed to high temperatures, whereas cotton only smolders and wool tends to self-extinguish. Wear long sleeves and long pants with a minimum of holes, and leather work boots with thick soles. Keep the boots laced loosely so you can take them off in a hurry if metal gets inside. Commercial foundry boots often have Velcro fasteners instead of laces, the point again being quick removal. Shorts and open-toed shoes (or worse, bare feet) are a recipe for disaster.

In industrial foundries, workers wear heavy fireproof aluminized chaps, aprons, jackets, and gloves to protect against both radiant heat and molten metal splash. Such an outfit would be ideal for the hobbyist as well, but a full set of safety gear can cost hundreds or thousands of dollars. Welding safety gear is typically leather, and while it will not protect against pounds of liquid metal (such as in a crucible failure), it will help considerably against smaller splashes. A full outfit will cover the front of the body from head to toe (except for the face, which I'll get to later), and costs between thirty and sixty dollars.

Gloves deserve special mention. Ordinary leather work gloves are too thin, and synthetic gloves are worse than nothing at all. Leather welding gloves are heat-resistant to a degree (typically for short contact with surfaces up to 400°F), and are what many beginners use.

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Intense radiant heat (such as when melting iron) or prolonged exposure to furnace exhaust can either burn the gloves and damage them permanently, or heat up the insides enough to cause burns to the wearer's fingers. They are, however, excellent for lower-temperature operations like pouring aluminum and general foundry work, and they are very cheap, between \$3 and \$12 a pair.

Real foundry gloves are much more expensive, between \$30 and \$80 a pair, and most of the materials they are made out of (woven ceramic fiber such as Zetex[®]) are not nearly as resistant to mechanical damage as leather. They are, however, much more heat resistant—the ceramic outer lining does not burn or melt under any normal circumstances, and they are typically several times better-insulated than welding gloves. They can be obtained in several different types, some designed for harsh mechanical conditions (typically aramid fiber such as Kevlar[®] or Nomex[®] instead of ceramic fiber) with a lower maximum temperature, some designed for maximum protection against hot objects (woven ceramic fiber, possibly with a double palm or extra insulation), and some designed for protection against radiant heat (aluminized gloves—be warned that contact with extremely hot objects can damage the aluminum coating).

Eye Protection

A full-face shield is necessary for metalcasting to protect against splashes of molten metal. Commercial foundry shields are often wire mesh, which has the advantage of not melting easily in hot environments compared to common polycarbonate face shields. Other types are made of tempered safety glass. For the hobbyist, a polycarbonate shield should be acceptable. Polycarbonate reflects infrared light quite well, so it will take a fair amount of hot furnace gas to melt the shield—it is unlikely to melt from radiant heat alone in a hobby situation.

A face shield does not offer complete eye protection—a pair of glasses (shatterproof polycarbonate lenses only) or safety goggles should be worn underneath. Side shields are strongly recommended. Safety goggles alone are not suitable either, since they do not protect the rest of the face.

Shaded lenses are necessary for iron melting, and recommended for bronze and copper melting, due to the volume of light released, and the increasing intensity of dangerous ultraviolet light at those higher temperatures. Sunglasses offer only marginal safety—ANSI No. 3 to No. 5 shaded lenses should be used. Oxyfuel welding goggles are of the correct shade and commonly available, but tend to dangerously block out peripheral vision. A tinted face shield, or face shield with flip-down tinted visor, is a superior solution. These may be a bit hard to find, and should sell for \$10 to \$25. When using a tinted face shield, the work area must be well-lit or movement becomes hazardous. Arc welding lenses (including the auto-dark variety, which can be triggered at random by a hot furnace or melt) are much too dark and should never be used.

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Respiratory Protection

Propane and electric furnaces are extremely clean by themselves, and of all common metals, only a handful emit harmful fumes when melted, so a good portion of hobby melters can forgo respiratory protection. Waste motor oil can produce small amounts of vaporized lead (from the bearings in engines), most waste oil burners tend to produce smoke on start-up, and solid fuels produce particulate ash. (All fuels except for electric still produce carbon dioxide (CO₂), so ventilation is important for all furnace setups.) These hazards can be dealt with by staying away from and upwind of the source, and by melting outside where there is plenty of ventilation.

More severe hazards come from the metals being melted. Zinc, when overheated (as in zinc-bearing copper alloys), boils and reacts with oxygen to produce zinc oxide smoke. This can produce an unpleasant condition known as zinc fume fever. Zinc fume fever is highly unpleasant, but generally not dangerous, and zinc does not accumulate in the body, so this respiratory hazard can be avoided by using a cover slag on bronze melts and staying away from the distinctive white smoke and metallic smell. Filter cartridges with P95 or P100 particulate ratings, when properly used with a suitable respirator, are effective in removing zinc fume from the air.

Lead and cadmium, when overheated, produce extremely toxic metal vapors. Not just any respirator cartridge is effective in filtering out these vapors—only cartridges with P100 particulate filters remove a sufficient percentage of the contaminants to be safe. The primary defense for the hobbyist is to limit exposure by keeping melts short and the temperature as cool as possible. Small children are much more susceptible to heavy-metals poisoning than adults, and should be kept far away from any area where lead is melted or worked. See “Lead” under “Special Precautions” for more information.

Contact with siliceous refractory in its dry powder form, silica-based parting dusts, or dry powdered clay also constitutes a respiratory hazard. Keep these materials cleaned up—careless spills on the floor can release microscopic particles of silica every time they are disturbed. Some of the smallest particles may stay in the air for hours. Silica, unlike asbestos, is not carcinogenic, but long-term exposure does cause a highly unpleasant cumulative disease known as silicosis. Again, cartridges with P100 particulate filters are necessary to remove high concentrations of these materials from the air. Nuisance dust masks are not even slightly effective, and are actually worse than useless because they provide an illusion of protection that does not actually exist.

The fumes from lost foam casting, or melting dirty, oily, or painted scrap, are usually fairly toxic and should be filtered out with an OSHA-approved organic vapor respirator. Chlorine-based degassing products release gaseous hydrochloric acid (HCl) and chlorine gas, and should be protected against with a respirator cartridge rated for these two gases. Combination cartridge filters are often available that are rated for organic vapors as well as reactive gases such as HCl and chlorine, and come with a P100 particulate filter attached.

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Note that disposable paper masks are only suitable for nuisance dusts such as sawdust—fine particles of silica and smoke particles are small enough to pass right through the masks. Not all respirator cartridges are created equal—don't assume it will protect you unless it's specifically rated for the hazards you need it to guard against.

Special Precautions

In addition to the hazards inherent in all metalcasting, certain metals present additional hazards that require special treatment.

Lead

Everybody knows that lead is toxic, and that eating it or breathing its dust is a bad thing. But how bad is it? It turns out that ingestion of lead is unlikely to cause harm in adults (only a small portion of ingested lead is retained by the body), but small children are more likely to retain lead, and it does them more harm. The primary spread of lead contamination is through contact: picking it up on the hands. Ordinary soap does not do an adequate job of removing lead contamination; a mild acid such as vinegar should be used in addition to a thorough hand washing with normal soap, especially before activities like preparing food for small children. Lead can also be spread through secondary contact; e.g. door handles.

Lead vapors are also a concern when melting lead. Not all respirator cartridges can screen out lead vapor; respirator cartridges rated for metal fume (P100 particulate rating) are more expensive, but a good idea. In any circumstances, the lead should not be overheated or kept molten for longer than necessary, and it should always be melted outside.

Lead dust is a concern when sawing or filing lead. A cold chisel is preferred, but if sawing or filing is necessary, use a blade with large teeth and go slowly, with adequate lubricant, to create large chips instead of dust. (Fortunately, lead generally makes chips instead of dust.) Lead should not be sanded without proper dust-collection equipment. The lead chips should be cleaned up and disposed of, not left lying around.

Lead dross is also a hazardous material, even more so because it is in powder instead of lump form. It is difficult to dispose of legally, and should be kept in labeled, sealed containers to prevent contamination.

Zinc

Zinc, unlike lead, is not harmful at room temperature. It does, however, have a low boiling point of 1665°F, so it should not be overheated when melting. Since its melting temperature is much lower, at 788°F, heating to the boiling point is difficult to do accidentally. The real danger comes when melting bronze with zinc in it, because the

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melting temperature of the bronze is greater than the boiling point of zinc. The zinc vapor, when exposed to the air, immediately burns into white zinc oxide smoke. Inhaling this smoke is not generally lethal, and has little potential for long-term damage, but can cause a highly unpleasant acute condition known as metal fume fever. Glassy slags should be used where possible when melting bronze to keep zinc vapor to a minimum, and the melting should always be done with excellent ventilation. Zinc fume has a characteristic smell, and the white smoke is often visible, so the best course of action is to simply stay away from it.

Magnesium

Magnesium is quite dangerous due to its high reactivity and its similarity to aluminum. Magnesium burns in air, water, and even the carbon dioxide used in common fire extinguishers. It can also react with sand, so even burying it in sand won't put it out (and, indeed, any moisture in the sand can cause a dangerous explosion, more so than an ordinary steam explosion, from the magnesium, sand, and water reacting to release a highly explosive mixture of hydrogen and silane (SiH_4) gases). The only sure-fire way to put out a magnesium fire is with inert gas such as argon or sulfur hexafluoride. Since most hobbyists don't have the equipment to extinguish a magnesium fire, the best thing to do is not let it get lit to start with. (If you plan on melting and casting magnesium, you should have the equipment to deal with a fire.)

The best cure in this case is prevention: learning to distinguish magnesium from aluminum. Magnesium is about 36% less dense than aluminum, and will fizz in a mild acid such as vinegar, while aluminum does not. If you do end up with a magnesium fire, the best thing to do is to stand back and let it burn out. It may destroy your crucible and even your furnace, but you're likely to get injured if you try to move a crucible of burning magnesium. (If you get splashed with burning magnesium, it will keep burning as it eats its way into your body, since people have plenty of water in their bodies for it to react with.) Magnesium oxide smoke can also cause metal fume fever (see entry on zinc above).

High-Temperature Metals

High-temperature metals present a different hazard than the toxicity hazards covered in the rest of this section. The primary difference with regards to safe practice between melting a low-temperature metal like aluminum and melting a high-temperature metal like iron is the intensity of the radiation emitted by the melt. Radiation increases as the fourth power of temperature, all other things being equal, and radiation from a constant source falls off as the cube of distance. That means that doubling the temperature of the source of radiation (a crucible, for example) and keeping the size and other characteristics the same, will cause the radiation to be 16 times as intense at the same distance, twice as intense if the hotter source is twice as distant as the cooler one, and the same intensity if the hotter source is $2^{4/3}$, or approximately 2.52, times as far away as the cooler one.

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In practice, this means that tools and practices used safely with low-temperature metals often have to be modified to be used safely with high-temperature metals. The radiation from a small crucible of aluminum is barely noticeable with suitable safety gear at a distance of approximately one foot, but the same size crucible of iron can put out enough radiation to char and burn leather welding gloves in the time it takes to complete a pour. It is therefore necessary to either use more temperature-tolerant gloves or longer tools, or both, with iron. Very large melts of high-temperature metals present the hazards of flash igniting clothing that gets too close, and of causing heatstroke or radiant burns, so aluminized safety gear designed to reflect the bulk of radiant heat will be necessary in these conditions. Usually, hobby-scale enterprises do not generate more molten metal than can be handled safely without this exotic equipment, but a very ambitious large-scale project must accommodate the increased hazards of dealing with large amounts of molten material.

An associated hazard that comes with high temperatures is dangerous visible and ultraviolet radiation. Fortunately, black body thermal radiation (as generated by hot objects) expends most of its energy in the infrared spectrum at all but the highest temperatures, but the spectrum of light shifts toward the visible and ultraviolet as temperature increases, in addition to the increased output of radiant energy that occurs as the temperature increases. See “Eye Protection” above for specific recommendations for shaded lenses.

Safe Foundry Practice

Safe practices are the most important aspect of safety. No safety gear can protect perfectly, so it is far better to prevent accidents than to rely on defensive measures to guard against them.

Steam Explosions

Steam explosions deserve special notice, because they are some of the most dangerous accidents, and some of the most common. Any time water comes in contact with molten metal, the water will flash to steam, expanding around 1,600 times in volume almost instantly. This can easily throw metal, ranging from small droplets to fist-sized globs, tens of feet in any direction. Steam explosions are most dangerous when confined against a nonporous surface, such as a wet ingot mold. This creates a mortar of sorts, launching the metal forcefully. A damp concrete surface (or even a dry concrete surface, if the amount of spilled metal is large enough to force out chemically bound water) is another candidate for severe explosions, which can also launch bits of hot concrete as the surface spalls. Damp dirt or grass is usually porous enough to dissipate generated steam, and sand is extremely porous, so even very wet sand will result in at most minor spattering. A sand bed is a good idea for fire-prevention reasons as well, but it is the best surface for preventing steam explosions.

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Steam explosions can also occur if damp tools, scrap, or flux is added to the melt. If the moisture stays on top of the melt, the metal is not thrown upwards, and any droplets of metal are small. If the moisture is submerged, however, it can throw the entire crucible full of metal out of the furnace. Scrap with recesses or cavities that can hold water, grease, or oil are usually the causes of such explosions—always preheat scrap before shoving it under the surface of the melt, especially if it might be wet. Certain fluxes (containing calcium or magnesium chlorides, usually) are hygroscopic and thus likely to contain water when put on the melt. Avoid these if possible—they are dangerous to use for this reason. If using them is necessary, preheat them before adding to the melt, and never shove them under the surface or stir them into the melt until you are sure all water is gone.

Even if a surface appears dry, it can still have chemically bound water. Common culprits are the hydrates in concrete and hydrated rust on steel tools and molds. These release water vapor more slowly and less energetically than liquid water, but they can still be very dangerous. A general rule is to preheat ingot molds where possible, and store permanent (usually steel) molds and tools in a dry area. If a permanent mold has gotten wet, it must be preheated before being used again.

Crucible Care

Only the best and most expensive safety gear can protect against significant amounts of spilled metal, and even top-quality stuff will have trouble preventing serious injury if you dump a crucible full of metal on your feet. Therefore, the best course of action is to prevent spills in the first place. Part of that is taking care of your crucibles.

Steel crucibles should be preheated to a cherry red before using to prevent them being dissolved by the metal. If your crucibles have a brazed joint (such as on a propane tank crucible), it is a good idea to weld over the joint, just in case. Soup can crucibles are naturally unsafe (too thin to be used safely), and if used, should never be used more than once. Steel crucibles for bronze and copper need to be at least schedule 40 pipe or equivalent to prevent deforming from the much higher heat. Never use a crucible that has eroded to much thinner than its original thickness, and always test for soundness before each melt.

Ceramic crucibles, except for silicon carbide (SiC), which does not absorb water, must be preheated at 200°F for 30 minutes before each use to get rid of any water that could crack or stress fracture the crucible. They should be evenly supported by their base block, and tools should always fit well around the middle (never the rim) of the crucible. Never lift a ceramic crucible with pliers, or use a crucible that is visibly cracked, has been dropped from a significant height, or otherwise abused. The empty crucible should “ring” somewhat when tapped—a dull “thunk” indicates stress fractures. (No crucible will ring like a piece of metal, and some varieties of crucible ring more than others, but the difference in tone between a cracked and sound crucible is perceptible. Experience is valuable here.)

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Some crucibles, usually clay-graphite crucibles, should be annealed periodically by heating empty to a bright orange heat, to relieve accumulated thermal stress. Consult manufacturer literature for exact procedures, which may vary.

Never leave a heel to solidify in the bottom of the crucible or wedge scrap in tightly—thermal expansion will crack the crucible. Also, endeavor not to freeze the melt by adding scrap too quickly, and be gentle when skimming slag and poking the melt. If in doubt, don't use a crucible that might be damaged—a new one may be expensive, but it's worth the cost if it saves a trip to the emergency room.

General Safety Rules

Keep a clean melting area, with a short, clear path between the furnace and molds. You don't want to trip while carrying a crucible full of metal. Also, keep a good footing and don't try to move a crucible that is too heavy. Hold the crucible away from your feet, so if it spills or fails, it won't spill on you. Always have your wits about you when casting—it's not something you want to be doing tired, distracted, or inebriated. Also, cast either outside or with a dedicated high-volume fume hood and fireproof casting area indoors. Outside is strongly recommended—a safe indoor casting area could cost thousands of dollars.

Keep flammable items well away from the casting area. If you're using solid fuel, be aware that sparks can travel a long way, so don't fire up if your area is particularly dry. Keep a bag of dry sand around to put out wooden flasks and such—you don't want to be spraying water on molten metal. A class ABC fire extinguisher should be kept on hand for oil fires if you're using waste oil or kerosene, and a class D if you're melting magnesium. Keep propane hoses out of the way of hot stuff (watch where the radiant heat from your lid is going), and shield them from heat and hot spatters where possible. Don't leave hot things where you might walk, or sooner or later, you'll step on one.

Most importantly, use common sense. I can't possibly foresee all the dangers you'll face, and neither can you—act prudently in all situations, and the danger will be minimized. Even if you're as safe as humanly possible, though, metalcasting is still a very dangerous hobby. Don't make it more dangerous than it has to be.

Section II

Melting and Casting Practices

This section details various practices and techniques necessary for melting and casting different metals, and the behavior of different metals and casting processes. This section provides only an overview of each subject; while enough to get the beginner started, it is by no means intended to be comprehensive.

Judging Temperature

Measurement of temperature is critical to the metalcaster, both in correctly firing refractory and in ensuring that molten metals are at a correct pouring temperature. As a general rule, metal that is too cold will result in a partially filled mold or loss of surface detail; metal that is too hot may cause sand to stick to the surface of the casting (in sandcasting); and problems with entrained gas and volatile metals boiling out of the alloy can also manifest themselves.

Temperature by Color

Judging the temperature of an object by observing the color of its glow is a very low-tech and inaccurate method, but it finds a great deal of use in a hobby setting. Obviously, the object must be glowing visibly for this method to work; the properties of the glowing surface and amount of ambient light also factor in to the perceived glow. The best surface to view is a dark matte surface, such as the outside of an oxidized iron crucible. A closed object with a small hole for viewing (such as a closed furnace) also provides an acceptable surface to view, more or less regardless of the properties of the surface inside the closed object.

Ideally, all glowing surfaces would be viewed in total darkness, but more practically, they should be viewed in the same lighting conditions, such as in the shade on a sunlit day, for consistency. Viewing in full sun tends to wash out even the higher temperatures, as does viewing a light or shiny surface (the reflective surface of molten aluminum is difficult to see glow, even when the crucible is glowing brightly), so these conditions should be avoided. An estimation of the temperature corresponding to each color is as follows (assuming a matte black surface in the shade in daytime):

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Color	Degrees Fahrenheit	Degrees Celsius
Faint red (barely visible, depending on conditions)	900-1200	500-650
Dark red	1200-1400	650-750
Bright red	1400-1600	750-870
Orange	1600-1800	870-980
Yellow	1800-2000	980-1100
Yellow-white	2000-2300	1100-1260
White (yellow through a #5 shaded lens)	2300-2600	1260-1430
Blinding white (point where shaded lenses are necessary; white through a #5 shaded lens)	2600	1430

Optical Pyrometry

An optical pyrometer is essentially a device for judging temperature by color, albeit far more accurately than the human eye. The fundamental structure of the device is a dark tube with an incandescent bulb in it. The filament's temperature is controlled by a potentiometer, so that its glow can be matched visually to the glow of an object viewed through the tube. The device can be calibrated with the melting temperatures of various pure metals, and then used to determine temperature in the visual range (greater than 1000°F in most circumstances).

Pyrometric Cones

Cones are devices used in ceramics to judge, not absolute temperature, but heat work, which is a function of time and temperature, and is necessary to determine how pottery is fired. Thus, a cone does not correspond to an absolute single temperature, but rather a range of temperatures depending on the heating rate and time spent “soaking” at that temperature. Cones are numbered sequentially, with 1, 2, etc. getting progressively hotter. Cones cooler than 1 are designated by prepending a zero, with cone 01, 02, etc. getting progressively cooler. A cone indicates its temperature by bending from the heat; when the cone has bent a full ninety degrees, that indicates the heat work corresponding to that cone has been reached.

In ceramics, cone 02 is considered low fire, cone 6 medium fire, and cone 10 high fire. Most commercial ceramics kilns go no higher than cone 10 or 12. An un-fluxed clay-based refractory should be fired to cone 18 to 20, and a good refractory clay should have a PCE (pyrometric cone equivalent, the amount of heat work at which a cone made from only that clay would bend appropriately) around cone 35.

A generic cone chart is available in Appendix 8, and more accurate ones should be readily available from the manufacturers of the specific cones you're using, but more importantly for the hobbyist are some rules of thumb.

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Given reasonable rates of heating, cone 1 represents about 2100°F, cone 10 2350°F, and cone 18 2800°F. I recommend a 30-minute soak at 2800°F to fire any un-fluxed clay-based refractory. This provides good sintering without unduly wasting fuel. Slightly over- or under-firing will not damage the refractory. Too much over-firing will mostly waste fuel; with the temperatures that most foundry burners are capable of reaching (no more than 3000°F except under exceptional circumstances), it is impossible to vitrify an un-fluxed refractory. Under-firing will produce a weak product, and this error may not be possible to fix with a second firing, so erring on the side of too much heat is a good idea.

Casting Processes

Different casting processes generally have very different applications and uses. While sandcasting and lost foam casting are beginner-friendly processes that are commonly used at the hobby level, hobbyists with different requirements may also wish to pursue investment or ceramic shell, or even permanent mold processes, none of which are out of reach for a dedicated and skilled hobbyist.

Sandcasting

Sandcasting, described in Section III, is one of the most common types of casting for hobbyists. The general process is to ram a mixture of sand and a binder around a pattern in one or more parts, remove the pattern, re-assemble the mold, and pour metal in. The mold is destroyed after a single use, but the pattern can be used to make many molds, and in most types of sandcasting, the sand is reusable with some reconditioning. Sandcasting is useful for anything from individual parts to short production runs of hundreds or thousands, though production at a reasonable pace requires a considerable amount of molding and sand-processing apparatus. Sandcasting is generally used in industry for high-temperature metals like bronze and iron that would destroy permanent molds.

Greensand

Greensand is bonded with clay and water. The bond is the weakest of all the bonded sand types, but greensand is cheap to make, the binder is relatively available, and if correctly made and processed, can handle high-temperature casts like iron for a very long time without “wearing out.”

Oil-Bonded Sand

Oil-bonded sand produces less mold gas (allowing for finer sand grain size and thus a better surface finish) and produces a stronger bond than greensand, but the organo-bentonite binder, binding oils, and catalysts are specialty products and tend to be expensive. Also, the molds produce hazardous oil smoke when poured, and the sand may “wear” quickly when used for iron and similar high-temperature applications. The sand requires more intensive mulling to recondition, and is impractical to recondition without machinery.

Resin-Bonded Sand

This includes sand bonded by sodium silicate and gassed with CO₂, and sand bonded by various commercial resins such as the brand name Furan. The bond is the strongest of all the sand types, and is often used for cores inside greensand molds, where the shapes must withstand additional handling. It is also useful for complex molds or those that need to tolerate rough handling. The resins often make very little mold gas compared to the other two sandcasting processes. The molds often have to undergo an additional process, such as gassing, baking, or curing over time, and while the sand can be ground up and reused, the binder is a consumable.

Lost Foam

This process uses a consumable pattern made of polystyrene foam, which is either buried in loose sand or rammed into a heavily vented greensand mold (termed the “full mold” process), and the mold is poured with the pattern in place. Since the pattern is destroyed after a single casting, this method is not readily adaptable to production. It is, however, very simple for the beginner to use. Some hobbyists have created foam-carving CNC mills for producing precise patterns, but this is a slow and expensive process not suitable for large production runs. Polystyrene foam can be inflated inside a machined mold to produce ready-made patterns, but this takes a fair amount of equipment and is generally out of reach of the hobbyist. Correct pouring speed is critical for a good casting, but the slower travel of the metal through the mold produces castings that in many cases have superior mechanical properties. The process produces large amounts of harmful smoke. Unlike traditional sandcasting processes, it can readily accommodate undercuts and shapes that would be difficult to mold in a way such that the pattern is removable.

Lost Wax

Lost wax processes produce castings of impeccable dimensional tolerance, comparable only to die casting, and though the process is slow and takes quite a bit of material and equipment, is the industry standard for production of precision castings in metals that cannot be used with permanent molds, such as bronze, iron, and various exotic alloys. The process is not generally suitable for a hobbyist without a source of income from his hobby, because the equipment is much more expensive than for sandcasting processes. The basic process is that a wax pattern is formed to shape, either by injecting into a mold made of silicone rubber or machined from aluminum, or carved by hand, and then cast into or coated with an investment ceramic. The mold is burned out in a kiln, and the wax pattern is lost. Once the mold is filled with metal, it is destroyed to extract the casting. Unlike traditional sandcasting processes, it can readily accommodate undercuts and shapes that would be difficult to mold in a way such that the pattern is removable.

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Investment Casting

Investment casting is the standard for production of jewelry and dental castings because of the high level of detail and suitability for one-off castings. Often, small parts are centrifugally cast, or cast with pressure or vacuum assist. Specialty investment materials are used in industry, but a mixture of equal parts plaster of Paris and silica flour can be used for aluminum and cooler metals. (Centrifugal or pressure assist may cause this homemade recipe to fail catastrophically—commercial products should be used in these demanding circumstances.) The investment ceramics must be de-waxed slowly, and then slowly burnt out to at least the temperature of the metal entering the mold, so this process is not suitable for fast production. The molds are poured hot, preventing cold shuts in small sections, but the slow cooling resulting from the large thermal mass of the mold often causes inferior mechanical properties.

Ceramic Shell Casting

This process is an industry standard for casting of high-temperature metals with high precision. The wax pattern is alternately dipped in specialty ceramic slurries and ground fused silica or zirconia to build up a strong, thermal shock resistant ceramic shell. This shell is then burnt out as quickly as possible to prevent the expanding wax from cracking the mold, and poured hot. The slurries required must be stirred constantly to prevent settling, and the dipping process can take weeks, so it is a process not well-suited to low volumes of castings. (The exceptions are art casting studios, where the high value and high finish requirements make it worthwhile to maintain slurry batches in between customers.) Since the castings cool faster due to the thin mold, mechanical properties are often superior to those of investment casting.

Permanent Mold Casting

In permanent mold casting, a mold is made that is designed to be disassembled and reused after every casting. Hobbyists have had success with steel or graphite permanent molds for short production runs, but in industry, permanent mold casting is almost entirely restricted to pressure die casting. Dimensional tolerance is excellent, but the molds tend to trap air mixed in with the metal, so mechanical properties are often poor. This process is best suited for large-scale production runs of tens of thousands of parts, ranging in size from less than an ounce to several pounds apiece. Because there is considerable labor and expense involved in making the casting die, this process is often well out of reach of the hobbyist. Like sandcasting, the castings are restricted by the requirements of draft, though draft can be a degree or less instead of the two to five degrees required by sandcasting.

Identifying Scrap

A small casting business will need reliable metal properties and will probably want to buy ingots of a known alloy, but the average hobbyist will not want to spend the money on

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metal, and may have a difficult time finding a source. Thus, collecting scrap is the lifeblood of a hobby casting operation.

The first test for scrap is by easily visible properties: average density, metal color if visible, and magnetism. A magnet is a valuable test tool: typically, steel is worthless as scrap, so that can be discarded right away. The most valuable scrap is copper and its alloys (excepting a rare find of precious metals or other valuables), and the most useful to the hobbyist is likely to be aluminum. Aluminum is readily distinguishable by its much lower density, and copper alloys by their color (which is rarely painted over). Generally, any nonmagnetic metal scrap is worth picking up and carrying back to headquarters for further investigation.

Separating lighter alloys is critical. An advisable test is to file clean a small portion of an object and drip some white vinegar on it: magnesium will fizz and aluminum will not react. Accidentally getting magnesium in an aluminum melt is dangerous and can easily destroy a furnace. Pure magnesium is worth selling for scrap if you have enough to make it worthwhile, or breaking into smaller pieces and playing with if you know how to do so safely. Very few casters will want to cast with it.

Distinguishing between aluminum, zinc, and the various alloys thereof is trickier. Density is a good test: zinc and zinc-heavy alloys are considerably heavier than aluminum. Breaking off a small shaving and heating it is another good test: zinc melts several hundred degrees cooler than aluminum, and if heated hot enough, will produce characteristic zinc oxide smoke.

Copper and bronzes are very easy to distinguish by their characteristic color. Filing the surface clean will allow you to get a good look at the true color: the redder it is, the more copper and the less alloying agents. Heating a small chip somewhat past melting point will allow you to test for zinc with the presence of zinc oxide smoke. Be careful: brasses and bronzes can potentially have some very nasty alloying agents, like lead and beryllium, that will produce toxic dross and/or harmful vapors when melted. Identifying a specific copper alloy is very difficult: a better test will be to cast with it and see if you like its properties. Electrolytic purity copper is sorted out by purpose rather than property: electrical wires and plumbing pipes will generally be very pure. Most other things are likely alloys, because pure copper is more difficult to process and more expensive.

Lead is very easy to tell apart by its extremely high density and softness. It is rare to find in large, usable quantity (lead-acid batteries are quite difficult and dangerous to disassemble, so it's better to leave this source to professional recyclers) because of its toxicity and regulations on its disposal.

Residential scrap sources are unlikely to contain any metals that have not yet been identified, but industrial sources may. A piece of nonmagnetic "mystery metal" that is none of the usual suspects could be fairly valuable: a high-grade stainless steel or a rarer metal.

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Now that scrap has been roughly sorted, aluminum scrap in particular should be sorted into cast alloys and wrought alloys. Any source that is a casting (automotive parts, etc.) will be a high-silicon alloy that will cast well. Other metal will have poorer casting and mechanical properties.

Melting Procedures for Common Metals

Different metals have very different characteristics and require different practices to melt successfully. Following is an overview of the procedures to follow when melting some of the metals most commonly encountered by hobbyists.

Aluminum

Aluminum is the bread-and-butter casting metal of most hobbyists. It combines easy availability with good casting and machining properties, low melting temperature, high strength, and light weight. Still, this metal has its own unique casting problems.

In particular, aluminum has a significant solubility for hydrogen gas in the liquid state. This gas, if introduced to the melt (usually by contamination from hydrocarbons in a reducing furnace atmosphere or from water or oil on scrap), and if not removed, will exit the metal upon solidification and lead to gas defects. The way to remove it is to either agitate the melt while displacing the gas, or introduce a reactive chemical that will remove it as a compound. Generally, this involves bubbling gas through the melt from a special tool. Inert gases, like nitrogen and argon, are introduced from a tank of the compressed gas and function only to agitate the melt, but reactive gases like chlorine can be sourced from a solid degassing compound that decomposes and produces gas when exposed to the heat of the melt.

Sodium and calcium hypochlorites (NaOCl and Ca(OCl)_2 , commonly sold as “pool shock”) will both source chlorine in this manner. Approximately a quarter teaspoon (1ml) of the granules will suffice per five pounds of melt. The degassing tool should be a small chamber that contains the granules (which can be packaged in aluminum foil for convenience) with many small holes for the gas to escape. This tool is plunged to the bottom of the melt and stirred until the chlorine gas bubbles up. Bubbles coming up should be small, approximately pea-sized. Hydrogen in the melt will be removed by the agitation and reaction with chlorine to form hydrochloric acid (HCl) gas. Chlorine gas and HCl gas are both highly toxic, so wear a respirator and have adequate ventilation when degassing. Aluminum chloride is unstable at aluminum melting temperatures, so the chlorine will not react with aluminum, but it will remove some magnesium from the alloy (as magnesium chloride, MgCl_2) if magnesium is present.

Arguably the best cure for gas defects is prevention. Run with a neutral or slightly oxidizing atmosphere and avoid painted or dirty scrap. Leaving a melt molten for longer than necessary, stirring it excessively, or overheating can also aggravate gas problems.

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Chloride salt fluxes have fairly high solubility of steam, which will source hydrogen and cause gas problems. It's best to flux as late as possible with most alloys to avoid this. Clean melts can often get away with no flux at all if good melt practices are followed, so the benefits of good practice are compounded.

In addition to gas problems, many extrusion alloys of aluminum suffer from hot tearing. This is caused by aluminum's hot shortness, combined with the comparatively high shrinkage of these alloys. Poor mold design may be one culprit, but the ideal solution is to switch to a silicon-bearing casting alloy, which will not suffer from this problem due to its low shrinkage, and will also have much higher fluidity.

Finally, aluminum dissolves iron. The iron does not benefit the alloy; in most cases the aluminum becomes brittle and harder to machine. Furthermore, it can easily dissolve right through an unprotected steel crucible. Steel crucibles and tools should be heated empty to a red heat before use, to build up a protective layer of iron oxide. This oxide layer will last longer if the aluminum is not fluxed, or fluxed lightly, and if the layer is not disturbed. For casting applications which need purity, consider using ceramic crucibles to avoid the problem entirely.

The recommended flux for aluminum is a mixture of sodium chloride and potassium chloride, 50:50 by volume, or 66% potassium chloride by mass. It should be melted together before use. Most applications will need no more than a teaspoon of flux per five pounds, added only a few seconds before skimming. A cover flux can be used to melt thin scrap, but dealing with thin scrap (e.g. soda cans) in the first place is generally not recommended considering the availability of much better scrap sources. Sand can be added to soak up excess flux, as it is quite runny when molten.

Aluminum can be tested for correct pouring temperature with the following test: Stir the melt with a cold 1/4" diameter steel rod, oxidized to prevent dissolution. If there are no submerged solid chunks of metal and the metal slips off the rod instead of adhering in a skin of solidified aluminum, the melt is ready to pour. This test is only a guideline; experience is a better judge of correct temperature, and a good pyrometer is still more accurate.

Copper and Copper Alloys

Copper alloys cover a wide range of casting characteristics, as brasses and bronzes are extremely diverse in terms of composition. In general, copper alloys tend to be more difficult to cast than aluminum due to the higher temperatures required and the wide variability of behavior of alloys derived from scrap sources.

Pure copper is a fairly nonreactive metal, and can in fact be cast reasonably well with no special procedures, if care is taken to follow good melt practice. Copper dissolves oxygen in much the same way as aluminum dissolves hydrogen, so it benefits strongly from a

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reducing atmosphere. Running a furnace in heavy reduction wastes fuel, so an alternate way of maintaining reduction is to add charcoal as a cover on the crucible, and run the furnace neutrally or with light reduction. Copper also dissolves iron (though unlike aluminum, there are a fair number of copper alloys that benefit from dissolved iron) and the temperatures required for casting are high enough to call into question the structural integrity of steel crucibles, so ceramic crucibles are strongly preferred. Bear in mind that many types of ceramic crucible, unless glazed, are porous to burner gases, and this can lead to oxidation and dissolved gas in the melt even if the top of the crucible has a charcoal cover, if the furnace atmosphere is too oxidizing.

The most common way to remove dissolved oxygen from copper is to introduce a reactive metal to carry it away as dross. Copper phosphorous or lithium are used if the copper must be kept pure; the addition of a few percent zinc will serve as well, creating a low-alloy brass. Aluminum in aluminum bronzes serves the same purpose as well, but aluminum bronzes can be quite tricky to cast.

Fluxes for copper alloys are usually glassy in nature; borax is a powerful flux that can be used on all alloys containing no aluminum or more reactive metals, and can be used quite sparingly (one teaspoon/5ml or less per fifteen pounds of melt) in combination with a charcoal cover. For drossier alloys and alloys containing zinc, which boils off, a glassy cover slag may be desired. This will typically be a soda-lime fluxed aluminosilicate, though it can also contain boron if not used for aluminum bronzes. The slag is not treated like an ordinary addition of flux; it is maintained throughout the melt and not skimmed off, and during the pour is held back with a tool so that the metal underneath stays protected throughout the entire process. This pouring operation usually requires three hands to do effectively; nevertheless, the slag offers benefits in protecting the metal and minimizing loss of volatile zinc. Glassy cover slags can be used multiple times. All glassy fluxes attack ceramic crucibles vigorously, and the viscous glassy variety may tend to attach to the crucible wall and resist efforts at removal. Copper phosphorous, being a deoxidizing agent, also functions as a flux for pure copper. It will not generally deal with heavy dross from zinc-bearing or aluminum-bearing copper alloys.

Many copper alloys present a respiratory hazard when melting. Zinc, lead, cadmium, and beryllium are notable hazards that may be present and will produce harmful fumes when melted. It is always advisable to wear a proper respirator when working with a copper alloy not known to be safe. Slags and dross containing lead, cadmium, or beryllium oxides are also toxic and need to be disposed of properly.

Zinc within a copper alloy can also provide a gauge of pouring temperature. For a given high-zinc alloy, there will be a temperature where the amount of evolved smoke noticeably increases. This temperature varies with the amount of zinc in the alloy, approximately indicating an appropriate pouring temperature for the alloy. Again, experience is a valuable judge here.

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In order to add zinc to a copper alloy safely and effectively, it must be preheated above the melt to nearly its melting temperature, then thrust to the bottom of the melt and stirred in vigorously. Simply adding it to the top of the melt will cause it to boil on contact, and very little zinc will actually end up dissolving.

Iron

Iron is often considered the holy grail of hobby casting technology, because its high melting point puts it near or above the limits of what most hobby foundries can achieve. That being said, iron is quite easy to work with if the high temperatures, and materials to tolerate them, are available.

Cast iron scrap is cheap and fairly easy to obtain; scrap structural steel is completely different, with a higher melting point and generally very poor casting properties. In general, it is best to avoid steel. Gray iron is the most common type: it is brittle and dark gray if broken. It has excellent damping characteristics and machinability, making it ideal for the construction of machine tools. White iron is gray iron cooled too quickly for graphite flakes to form, and it is not easy to machine, though it is very resistant to abrasion. The addition of ferrosilicon may be needed for a casting to harden as gray iron instead of white iron, especially if the casting has thin sections which cool quickly. Commonly, a sample wedge is poured and broken; if the tip forms white iron, ferrosilicon is added. Reheating the castings to about 1800°F (980°C) and letting them cool slowly will also turn white iron into gray iron, and this method may be more accessible to the hobbyist than obtaining ferrosilicon from a foundry supplier. Conversely, white iron can be purposely created by placing a heatsink (known as a “chill”) in the mold to cool the iron more quickly in that area.

Annealing white iron even more slowly, over a period of days, can create malleable iron, which as the name implies, is malleable rather than brittle. The addition of a small amount of magnesium to a cast iron melt will create ductile iron, another way to get around the brittle nature of cast iron.

Cast iron generally has low shrinkage and excellent fluidity, so risers and gates can be kept smaller than for aluminum. The use of a ceramic crucible is of course necessary, and the temperatures reached by melting cast iron will damage or destroy furnace linings that contain non-refractory ingredients. In general, refractories rated to 3000°F or higher, or homemade ceramic compositions without significant amounts of fluxes, are necessary. Iron takes a lot of fuel to melt, in general, because the melting temperature is very close to the maximum achievable temperature for air-breathing foundry burners, so furnace efficiency is poor. Good insulation and hotter fuels like waste oil pay big dividends for iron melts. Iron generally does not suffer from gas problems, so keep the flame as neutral as possible for maximum heat output.

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Iron will oxidize, so a charcoal cover can be used to lower losses. Iron oxide is a flux, so the metal will be somewhat self-fluxing; still, other fluxes may be needed. Fluoride fluxes are typical, and glassy fluxes can also be used. A cover flux is not necessary. All of these fluxes will attack ceramic crucibles and furnace linings vigorously, especially given the high temperatures involved. Iron tends to leave an unremovable coating of its oxide on ceramic surfaces it comes in contact with, which will flux the ceramic over time.

Zinc and Potmetal

Zinc and various zinc-aluminum alloys (referred to as “potmetal”) behave much like aluminum in many ways. Certain potmetal alloys have excellent fluidity and strength comparable to low-alloy steel. Given the low melting point of zinc-rich alloys, potmetal is often even easier to work with than aluminum. Unfortunately, its industrial uses are mostly constrained to die castings, so its prevalence as scrap is much less than aluminum.

The low melting point makes fluxing somewhat more difficult, as the salt fluxes that work with aluminum alloys will not melt when used to flux zinc alloys. Salt fluxes containing magnesium or calcium chlorides (see Appendix 3) have low enough melting points, but these salts are strongly hygroscopic, and that presents a danger of steam explosion. The flux should be stored in an airtight container and preheated before every use. Organic fluxes can also be used, but these will usually boil quite vigorously at zinc temperatures, so caution is needed in their use.

Zinc, like aluminum, dissolves iron, so the same precautions are needed to protect melts from contamination. Zinc does not form a passivating oxide layer as well as aluminum does, but the temperatures involved are lower, so oxidation is not an enormous concern. The furnace atmosphere should be kept neutral.

Zinc has a low boiling point of 1665°F (907°C), and it will produce distinctive white zinc oxide smoke if overheated to boiling. Unlike in zinc-containing brasses, zinc and potmetal alloys melt well below this temperature, so there should never be a respiratory hazard when melting zinc. Still, the possibility of overheating does exist and should be guarded against.

Lead and Tin

Lead and tin melt at temperatures low enough not to require an actual furnace to cast, instead requiring only a hotplate or camp stove to achieve the desired temperature. A furnace will be more efficient, but the temperatures involved are low enough that the loss of efficiency does not necessarily translate into large fuel costs. Unfortunately, tin is relatively expensive, lead is toxic, and both are quite soft, so lead and tin castings tend only to be useful for specialized applications like weights and poured bearings.

Both lead and tin are quite dense, lead especially so, which when combined with the good fluidity of both and of certain lead-tin alloys produces castings with excellent detail. This

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density can cause problems, however, especially in lost-foam processes, where hydrostatic pressure can distort the unbonded sand. In greensand casting, extra care must be taken to weight the mold adequately. The buoyant pressure exerted by lead (density 10.66 g/cc liquid) on sand (approx. 1.8 g/cc for rammed molding sand) is roughly fifteen times that exerted by aluminum (2.38 g/cc liquid), so the effects of increased density cannot be ignored.

Lead and tin are best fluxed with organic fluxes. Commercial petroleum-based pipe soldering fluxes (which may additionally contain zinc chloride) work well, as do many other organic preparations. Both metals are relatively nonreactive, and do not oxidize aggressively at their pouring temperatures.

Neither lead nor tin dissolve iron or have problems with dissolved gases, though both will dissolve copper. Lead and zinc are immiscible, though tin and zinc alloy well, and such alloys are used as solders for aluminum.

Tin is quite safe to melt, but lead is toxic and produces small amounts of lead vapor when in the molten state. This amount of vapor increases as temperature rises, so it is important not to overheat lead and its alloys, and to always wear an appropriate (P100 particulate) respirator when melting lead. Dross from lead alloys also contains toxic lead compounds and may be difficult to dispose of in an environmentally friendly fashion. It should be stored in a sealed, labeled container like any other toxic substance.

Working with lead also contaminates clothes and gear. The low levels of lead contamination may or may not be harmful to adults (if you do a lot of lead melting, it would be wise to test for lead levels on a regular basis), but poses significant danger to young children. Children accumulate lead much more readily than adults, and may also expose themselves more because of a lack of understanding of practices that limit the spread of lead contamination. It is a good idea to keep lead-working tools and crucibles separate from other foundry gear and safely stored. Even molding sand may pick up a low level of lead contamination.

Metalcasting on a Budget

Like most hobbies, metalcasting requires a bit of financial outlay. The old adage “time, money, quality—pick two” applies in full force. There are certain expenditures which are unavoidable or foolish to skimp on, whereas there are other areas in which an investment of skilled work can save quite a bit of money.

Safety

If there's one thing that deserves a financial outlay, it's safety gear. Even so, the expense need not be overwhelming. For most melting, a set of welding leathers (including leather welding gloves) will be adequate, on top of leather work boots and cotton or wool clothes,

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and a face shield. These items (except for the face shield) can be had secondhand or at discounted prices quite easily. A frugal caster might spend only \$30 to \$50 on a full set of safety gear. The need for a respirator can be done away with by only melting outside and avoiding toxic metals such as lead, and using a parting dust that is not a respiratory hazard (such as talcum powder or most commercial parting dusts). Casting iron or handling large quantities of metal will require more expensive safety gear designed for the metalcasting industry, and these items can run into the hundreds of dollars.

Metal Sources

A frugal caster shouldn't need to invest anything but time in order to obtain plenty of stock for casting. Aluminum is commonly sourced from residential trash (particularly old lawnmowers), copper and brass can occasionally be found free where plumbing is being redone, lead can be collected as wheel weights from tire service centers, and there are many other sources which an imaginative caster will be able to find. If all else fails, scrap prices for most metals are relatively affordable, and castings can be recycled with very little loss.

Equipment

Making or improvising foundry equipment instead of buying it represents a substantial financial savings. Most foundry equipment is relatively simple, but the market for it is small and relatively exclusive, so prices are high. Attention must be paid to the safety of the finished product at all times, but generally speaking, making safe foundry equipment is not difficult.

If you have access to a welder, all you need to make most tools (skimmers, lifting tongs, charging tongs, etc.) is a source of stock or scrap steel. If you cannot weld, it may take a bit more ingenuity to fabricate good tools. Slip-joint pliers work well as a substitute for most types of tongs (except that they can't be used to safely lift ceramic crucibles). Riveting can be used as a substitute for welding in many situations and requires no more than a hammer and suitable working surface, drill, and some malleable stock (for cold riveting). A metalcasting furnace can be used as a forge for hot riveting operations. Riveting takes only a modest amount of skill, but it is very slow. It is, however, cheaper and more permanent than bolting parts together.

Burner parts can get expensive, so if you can make parts out of scrap instead of having to buy plumbing parts from the hardware store, you can save some money. Be warned (especially depending on the type of burner you're making) that there is usually a fairly large time expenditure associated with this.

Blowers for solid fuel and waste oil burners can be had free from old vacuum cleaners and electric leaf blowers, and these blowers are generally as good as anything you could purchase. A cheap router control will allow adjustment of airflow, or for even less money (if you can stand the noise), an adjustable waste gate can be used to bleed off excess air.

Furnaces

A furnace is usually the single biggest investment that the hobby will require. To obtain high performance, it is almost necessary to spend some money. Still, there are ways to save.

Fuel

The type of fuel that you choose will dramatically influence both the amount of time you spend and the cost of your furnace. Solid fuel, the most common type for beginning casters, can use the cheapest furnace designs but is often (unless you have a free source of wood or coal) the most expensive fuel per pound of metal melted. It leaves behind ash, requiring messy, unpleasant work to clean up after a melting session.

Propane is very clean and very easy to use, but it is expensive. The cost of the tank, hose, high-pressure regulator, and burner fittings will likely total at least \$80-\$100, and the fuel itself is also expensive. The high cost of fuel necessitates spending extra money to make the furnace more efficient, especially so at higher temperatures, which propane struggles to reach. Natural gas may be slightly cheaper than propane, but is otherwise similar.

Waste oil is more difficult to burn cleanly than propane or solid fuels, but the fuel itself is free, and the flame temperature is higher, which makes the melting of higher-temperature metals easier and quicker. Furnaces can sacrifice a little efficiency without significant cost, but they must be built with high-temperature materials to survive the oil flame's extreme temperature, so they are usually not cheaper to build than propane furnaces. Building the burner may be a significant cost in terms of both money and time, depending heavily on the particular design.

Electric resistance heating is the cleanest of all and usually cheaper per pound of melt than propane and solid fuels. However, the low maximum power input (limited by the breaker or fuse on the circuit the furnace is plugged into) necessitates the most efficient and thus most expensive designs, and the elements are costly as well. The cost of high-temperature elements usually makes resistance melting above aluminum temperatures impractical.

Electric arc and induction furnaces can achieve very high temperatures, but the design of the furnace and electrical control units is well beyond the scope of this book, and these methods are generally not economical for melting on a budget.

Refractory

Some refractory materials are more expensive than others. Sometimes this expense is justified; sometimes not. More importantly, sometimes a perceived cost-cutting substitution can turn out to be a false economy.

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Non-refractory ingredients like Portland cement should be avoided in any furnace expected to last longer than one or two melts. There is no economy to be had in using cheap materials if they don't work. If you must construct a furnace out of non-refractory materials, save yourself the trouble of buying unsuitable materials and dig a hole in the ground instead. Even then, there will be no economy to be had in terms of fuel usage, as such a furnace is guaranteed to be wasteful. Still, it can provide some valuable experimentation time for the beginning caster.

Perlite is a fairly cheap insulator, as are diatomaceous earth and vermiculite. If your furnace is expected to see only low temperatures (primarily melts of aluminum and white metals), then by all means, use these cheap insulators. If you intend to do brass or iron work, you will save more in the long run by using materials that can survive the heat.

Clay-sand mixtures appear to be the best option for the budgeting hobbyist—the materials involved are quite cheap (between one half and one sixth the price of common commercial refractories) while also, in most cases, tolerating the highest temperatures that naturally aspirated burners can produce. Insulation can be cheaply added to whatever extent needed in the form of polystyrene foam beads, which burn out and leave air pockets.

However, there are two hidden costs which most hobbyists do not figure into their calculations: time, and firing costs. Homemade ceramics can be quite labor-intensive, particularly for the raw beginner. Unlike with a commercial product, there are no definitive instruction manuals. More crucially, there is a wealth of available advice, of which at least some is misleading, incomplete, or simply false. One of the many purposes of this book is to create an instruction manual for exactly this situation; however, you will still find no definitively accepted recipe for homemade ceramic refractory, but rather recipes that have been tested and found to work under most circumstances, along with some basic grounding on the science of ceramics so you can figure out how to modify them to suit your needs. Ceramics is an extremely broad and deep field; there exist people whose professional lives have been dedicated to the study of a tiny subset of the mechanisms at work when something like our furnace is fired.

So, be prepared to make some mistakes and have some failures. Be prepared to patch cracks as they form, to compensate for shrinkage that was more or less than you anticipated, to start over with a new recipe if the one you're using just refuses to work out. In the green state, clay mixes can be re-wetted and reclaimed (though separating such a mix into its individual components is highly impractical), so the primary loss will be of time.

More importantly in terms of budget issues, if you fire a ceramic only to discover after firing that something didn't work right, the fuel used in that firing (if you're using propane, often more costly than the materials that were fired) is gone forever. The ruined refractory can possibly be reused in the next mix as grog, but firing costs can add up very quickly to more than the total cost of commercial refractory after several failures.

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In my personal estimation, the real value of homemade ceramic refractories is not budgetary at all; rather, with the use of more refined mixes (with the substitution of expensive calcined alumina and kyanite for cheap quartz sand, homemade ceramics lose much of their budgetary advantages), properties can be achieved that are considerably superior to that of many commercial refractories. Furthermore, those properties are almost infinitely customizable. Finally, the learning process involved in making a homemade ceramic work is invaluable—if you want to learn about ceramics. If you wish to skip straight to casting metal, it may be more wise to simply buy commercial and have done.

Even among commercial refractories, there are still budgeting choices. In particular, ceramic wool is worthy of mention. It is the most effective insulator in common refractory use, so using it will save considerably on fuel; also, its cost per unit volume is not high compared with many other commercial materials. The only disadvantage is that it requires protection.

Commercial dense and insulating castables, unless intended for a specialized application, are generally also relatively cheap. Insulating castables are generally adequate in terms of mechanical properties, and will save fuel as well as filling substantially more volume per unit weight. Dense castables are only for use in the most abusive of situations.

Insulating and dense firebrick also deserve a mention precisely because they are not budgeting choices. Commercial kilns have fuel costs as well, and those are passed on to the consumer of fired products. Insulating firebrick also has additional costs associated with it due to its easily-damaged nature requiring more protection during shipment. These refractory products may be convenient, but will generally cost about twice as much per unit volume as comparable castable products.

Mold Making

Of all the mold-making processes in existence, two stand out as budgeting choices: lost foam and water-bonded greensand. Lost foam requires only loose sand to start, which can be recycled virtually indefinitely. There will be some start-up costs associated with respiratory protection, but these are not unreasonable and a good respirator has many other uses. The foam will be a recurring cost to the process, but it can be had cheaply or even for free if scavenged from foam packaging.

Lost foam, however, unless set up with a computer-controlled (CNC) foam mill or molds to expand foam into (both of which are expensive), is not good for producing many parts of the same type. Water-bonded greensand is superior in this regard, as the patterns are reusable, and it is also very cheap. The requirements are sand, bentonite clay, and some molding tools. Flasks can be built out of scrap lumber, sprue and riser patterns out of PVC pipe or disposable cups filled with concrete, and most other molding tools can be fashioned out of old silverware or sheetmetal. A good rammer is perhaps the exception; it is easy

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enough to cast one out of aluminum, or turn one from wood if you have access to a lathe. A power rammer can be made by modifying a cheap air chisel.

Both of these processes have much poorer tolerances than investment, ceramic shell, or permanent mold processes, yet the latter processes are much more expensive.

Section III

Sand Molding

Sand molding is one of the most approachable and low-cost methods of creating molds for metalcasting. It is also a very versatile process, being suitable for any volume of production between unique parts and runs of several thousand pieces, and suitable for almost any metal that is commercially cast. Detail is not as high as in some other processes, but with fine sand, correctly mixed, it will be more than acceptable for the majority of hobby applications.

Sand

The simplest of all possible sand molds is a hole or depression in sandy soil. If the soil is sandy enough to resist the hot metal, dry enough to avoid steam explosions, and wet enough with enough binders to maintain its shape, then the metal will accurately take the shape of the depression.

Pouring metal into sandy soil is undoubtedly how the process of sand molding was developed by our primitive ancestors, but it is not a controllable enough process to make much use of in modern casting. Instead of using naturally occurring sand, we need to make our own with desirable properties that can be controlled and maintained. The process is simple for water-bonded sands, which are the most accessible variety for most hobbyists. (Oil bonded and resin bonded sands achieve the same thing in principle, using more complex binders for improved properties.)

To make any molding sand, the first step is to get good sand. Clean white silica sand of approximately 70-90 mesh is a good starting point. Most hardware stores sell a sieved and cleaned “play sand” that will work adequately, though a foundry sand will generally have a finer and more useful gradation of mesh sizes. Olivine sand will also work, and it is usually green or black. The grains should be sharp, not rounded, and the sand should not contain rocks or debris.

This sand now needs a binder. For water-bonded greensand, the binder will be bentonite clay, approximately 10% by weight. Bentonite is available in high purity from ceramics suppliers and in bulk amounts from well drillers and some farm supply stores. Some types of cat litter are bentonite chips, but these will have to be ground into powder before use. A coffee grinder works well, if slowly.

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Adding more clay will increase the sand's strength but decrease its porosity, leading to gas defects in extreme cases. Adding less clay will lower the strength but make the sand more porous. 10% is what I prefer, but it is possible to get away with as little as 6%. As long as the sand molds well, less clay is generally better.

The clay and sand will not become greensand without the addition of water. Water should be added slowly to the blended clay and sand, and thoroughly mulled in until the sand feels uniformly damp (but not sticky) and forms a cohesive ball instead of crumbling when squeezed. It takes time for the clay to absorb water, and mulling action is necessary to distribute the clay evenly (but excessive mulling will “wear out” the sand by rounding off the grains, reducing porosity and strength). Sand generally improves dramatically if it is left to sit overnight after mulling in a sealed container, and the sand will continue to improve even more for several weeks after it was first made, as long as the moisture level is maintained.

Too much water in the sand increases the amount of porosity necessary to prevent gas defects and will cause the sand to stick to things. (Dramatically too much water can even cause metal to shoot back out the sprue of the mold from the steam generated! A mold that does this will never produce a usable casting, so it is best to retreat for safety's sake until the metal has cooled.) Too little water will cause the sand to abrade away and lose strength, eventually crumbling. A sand mold can be dried after molding without a loss of strength, but the drying will cause shrinkage, which can lead to gap run-outs and problems with dimensional tolerance. It is generally better instead to use properly conditioned sand and to pour molds as soon as they are made.

Mulling

Sand can be mulled by hand with acceptable results, but it is a labor-intensive process that falls short of the results a machine can achieve. Commercial mullers of a size that is practical for hobbyists are occasionally available at affordable prices from industrial equipment auctions and from the vocational departments of schools. A muller is a simple machine, so building one is quite straightforward and within the means and skills of most hobbyists.

Mulling action needs to mix the sand thoroughly, to compress it like it would be when rammed into a mold, and to fluff the sand and break up chunks to prepare it for use. A typical muller, as shown in Figure III-1, consists of a pair of wheels rotating inside a metal drum to compress the sand and crush lumps, and one or more plows to fluff the sand and funnel it from the walls and center of the drum into the path of the wheels. Plows shaped to smear the sand against the drum can be used in place of or in addition to wheels, particularly in smaller mullers where the force required to drive this action is not impractically high. The muller also needs a trapdoor in the bottom which can be opened to unload a batch of sand.

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The wheels need to exert a significant amount of force on the sand to be effective; this can be achieved by making them heavy or (commonly with smaller designs that would be too light to mull effectively using weight alone) using springs to force them into the sand. Both the wheels and the plow(s) need to be able to move to accommodate sand lumps and varying loads without damage to the machine. All metal surfaces exposed to the abrasive action of the sand, particularly the plow(s) and the bottom of the drum, should be fairly heavy steel for long life.

The mulling assembly can be driven from above by a simple shaft, or from below using a nested-pipe arrangement to keep sand out of the drivetrain. The assembly should spin at between 25 and 75 RPM, and will need extremely high torque, so a robust drivetrain is required. Belts and pulleys can be used as part of the speed reduction and for small mullers, but a muller of any size needs a sturdy gearbox for the final drive. Belts will tend to slip at such high torques.

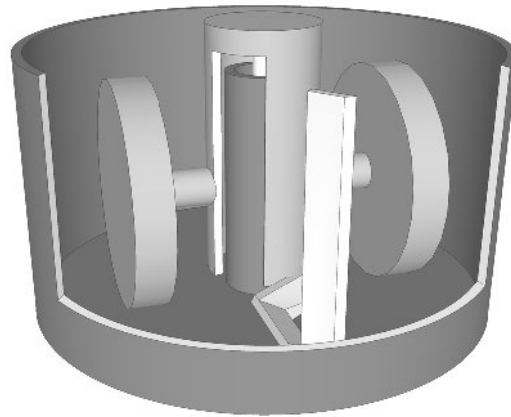


Figure III-1: Cutaway view of a basic muller

Required torque varies quite a bit based on design, but a torque of 100 ft-lb should generally be adequate to mull a 50 pound batch of sand. Processing time varies depending on the muller's rotational speed, design, and the condition of the sand, but one batch generally takes about five minutes. With a speed of 50 RPM and assuming 95% drivetrain efficiency, a 1 horsepower motor will be adequate for this size muller. More power will certainly harm nothing (unless it exceeds the structural limits of the mulling apparatus!) and will allow the muller to “power through” difficult, lumpy sand without jamming or stalling. **Note that even a small muller produces enough torque to overpower a human caught in the device, and mullers usually run open with no safety guards on the mulling apparatus. Entanglement of body parts in the machine is a serious danger and can have fatal consequences. Have a cut-off switch readily accessible and follow good shop safety practices when working with the muller.**

To mull sand by hand, it is necessary to duplicate the action of the muller. A garden hoe and a wheelbarrow work well to process the sand. The sand should be alternately smeared against the side of the container, chopped to break up lumps, and mixed around. Hand-mulling sand is physically intensive work, and trying to process too much at once will quickly sap your strength. The sand can also be mulled by alternately sandwiching it between sheets of tough plastic and walking over it or rolling a vehicle over it, then stirring and raking it around. This method poses a risk of contaminating the sand with dirt and other foreign matter, however.

Pattern Making

There are three critical parts to know about before making a pattern to be molded and cast in sand. First is something called the “parting line.” The seam between the cope (top half of the mold) and drag (bottom half of the mold) is the parting line, and the pattern's widest portion must sit at the parting line.

Often, you will want to make “split patterns.” This is basically a pattern that is in two halves that meet at the parting line. Alignment pins are installed in the halves. There are ways, however, to cast three-dimensional objects without a split pattern. Patterns with a flat side can be molded only in one half of the flask. If the pattern's projection is small or shallow, it can be molded with a board designed to accommodate it (known as a “follow board”), or molded normally and the sand carved down to the parting line (known as “coping down”).

The second thing you have to know about is “draft.” Draft, as shown in Figure III-2, is where side portions of the pattern have an angle that allows you to safely withdraw the pattern from the sand mold without disturbing the sand. Draft is very important. Having completely vertical sides makes it very difficult to remove the pattern. In some parts, however, this may be unavoidable. Usually the best solution is to design the pattern with draft, and then machine the part to have its 90° angle afterward.

The opposite of draft is an “undercut,” which for obvious reasons is impossible to mold in sand in a simple two part mold. Again, draft can be added and the part can be machined to finished dimensions afterward. This is usually a better solution than adding additional mold complexity to accommodate the undercut.

For some sand molds, you may need to use a three or more part flask, where there is an extra piece between the cope and drag. That extra piece would be called a “cheek.”

The third thing to know about is shrinkage. Metal shrinks when it cools, and different metals shrink at different rates. To further complicate the matter, different alloys of the same type of metal shrink at different rates. Also, you may have to make parts larger still to allow machining of the part afterward. This needs to be kept in mind when designing the pattern.

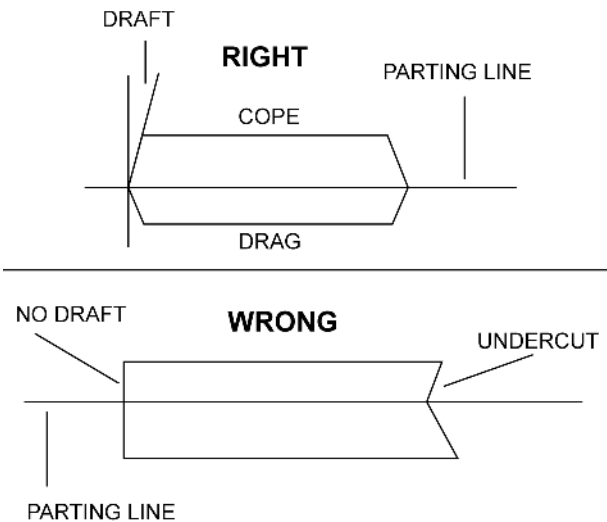


Figure III-2: Illustration of correct and incorrect draft

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Patterns for sand molds are best made of metal or wood. Wood patterns should be coated in a good coating of polyurethane, varnish, or lacquer to protect them, and keep them from absorbing moisture from the sand. This coating can be skipped for a one-off pattern, but molding is made more difficult by the lack of a smoothly finished surface.

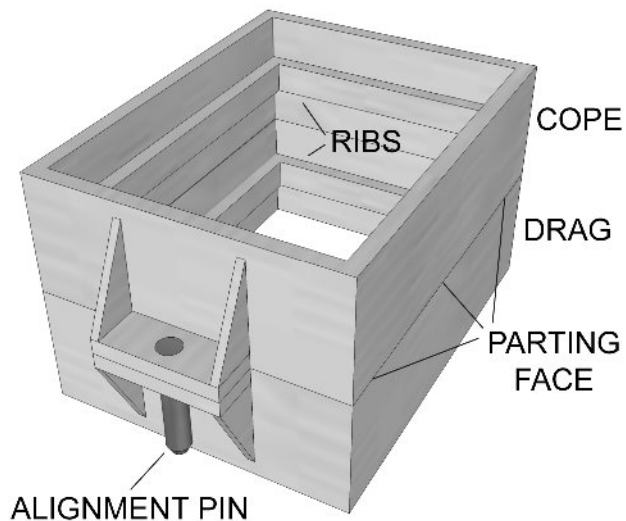
You don't have to be a good woodworker to make good patterns. Epoxy, wood putty, and anything else can be used to fix your mistakes, as long as the final surface is smooth and finished.

Molding Tools

In order to make molds, some tools and equipment are needed. The primary equipment consists of one or more flasks, some molding boards, a rammer, sprue cutters or sprue and riser patterns, a vent wire, and a knife or small trowel to cut gates and pouring wells, and clean up edges. An applicator for parting dust, some clean paintbrushes of various sizes to touch up edges and spread parting dust around, and a source of compressed air to blow out molds, are also handy, and various small pieces of sheetmetal can be bent into custom tools for a specific purpose. For large molds, the flasks may need to be lifted and rolled with a mechanical hoisting apparatus.

Flasks

Flasks are the most fundamental tool, and often the most consumable. Figure III-3 shows the different parts of a typical flask. The easiest material to make flasks out of is wood, but wooden flasks get charred every time metal is spilled on them, and they will eventually lose their accuracy or strength and have to be replaced. Wooden flasks can also get charred bits of wood and splinters in the sand, which can cause casting defects if they end up embedded in the inner surface of a mold.



Cast aluminum or welded steel flasks are superior from a durability perspective, but both are more expensive and labor-intensive to make, and they can also be very heavy, which makes it more difficult to roll over larger molds and to smoothly align and close a mold.

Either way, a flask needs to have alignment pins that are accurate, can be opened smoothly, and can only be assembled in one direction. This foolproof design keeps molds from being

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ruined due to operator error—if your flask design is symmetrical, it is surprisingly easy to accidentally put the cope on backward! There are many ways to build alignment pins, but the longer the pins are, the easier it will be to guide a mold to close evenly. The protruding portions of the pins are usually kept in the cope so the drag can be molded parting face down without a molding board cut to fit between the pins.

Large flasks (12"x12" and larger) also need something on the inside of the flask for the sand to grip. Smaller flasks usually have enough friction between the flask sides and the sand not to need anything more than a smooth side, but adding in something for the sand to grip is still a good idea that will save the hassle of cope fall-outs, especially if your sand has poor bond.

One common way to give the inside of the flask some grip is to add some ribs, which are easily nailed into a wooden flask. The problem with ribs is that they take up space inside the flask that could be used for patterns, and they make ramming the edges more difficult. Welded steel flasks often have lips or flanges on the edges to hold the sand in, and cast or wooden flasks can use grooves instead of ribs. For wooden flasks, especially smaller ones, my favorite technique is to drill a number of large, shallow holes in the inner face of the flask. This is quicker and easier to do than routing grooves or attaching ribs, and it is quite effective.

Very large flasks (typically 16"x16" or larger), especially large shallow flasks, may need supporting ribs running across the flask to give the sand more area to hold to. These can have grooves or holes of their own to give them more grip. Too many supporting ribs makes the flask hard to ram and reduces the available space for patterns, but large expanses of sand will need the support.

A useful addition to any flask, but particularly big flasks, is a way to clamp it together at the parting face, both for rolling over and during pouring to avoid a gap run-out due to hydrostatic pressure. If there is no way to clamp the flask, it will need to be weighted for pouring.

Flasks need to be big enough to accommodate the patterns that will be molded. Generally, at least 2" of sand is needed at the top and bottom of the pattern, and 1" around the edges. Large or unusually-shaped patterns may require a custom flask. An 8" by 8" and 12" by 12" snap flask, both with 4" deep cope and drag, will accommodate most hobbyists' castings, and custom flasks can be made as they are required.

A snap flask is a flask that can be taken off the finished mold and reused, so multiple molds can be made at one time with only one flask. Commercial snap flasks have hinges in one corner and a latch at the opposite corner, allowing them to be quickly and easily removed from a mold. This design can be duplicated, or for a simpler but less effective snap flask, the flask can be assembled out of wood with opposite corners held together by a single

large wood screw. This design has a limited lifetime and lower accuracy than a hinged flask, but it is cheap and quick to make.

Rammers

A rammer is a tool used to compress the sand into the flask, and of the remaining tools, it is likely to be the most difficult one to make. Most hand rammers have two ends: a blunt end for ramming large expanses of sand, and a pointed end (referred to as a “peen”) to compress sand next to patterns and around and under crevices. Figure III-4 shows a simple design for a double-ended hand rammer. Turned from approx. 2” diameter hardwood stock, or cast lost-foam style in aluminum, it makes a good rammer for small flasks and as a supplement for a larger air rammer. If you intend to ram large flasks entirely by hand, you will want a hand rammer with a larger face in addition to this one.

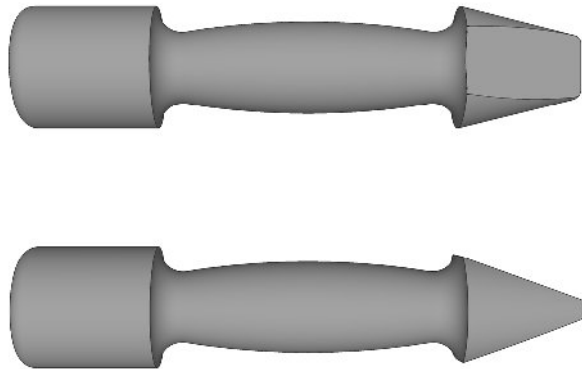


Figure III-4: Simple hand rammer

An air rammer, as seen in Figure III-5, is an invaluable tool for ramming big molds quickly. I have gone through several iterations of the same basic air rammer design based on an inexpensive air chisel, and found them all to work well. The ramming surface needs to be strong, as the vibration and repeated impacts exert a surprising amount of force. This one uses a 3” square of 1/4” thick steel plate welded to a chisel shank. The square surface allows the tool to ram into the corners of flasks, but is orientation-sensitive, whereas with a round ramming surface, the chisel can rotate freely without affecting the ramming.



Figure III-5: Air rammer

Even with an air rammer, you will also need a hand rammer like the one in Figure III-4 to get into small places and ram sand around delicate areas of patterns. An air rammer is only good for ramming large flat expanses of sand; it is far from a precise instrument.

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Other Tools

Molding boards are used to support the patterns during ramming, and they can be as simple as squares of plywood cut to size. I would recommend keeping them this simple, so they can be modified as needed for protruding patterns and so forth without any large associated cost. If the alignment pins of your flasks are long enough and of the appropriate shape (usually cylindrical so they can mate with drilled holes), it will be easy enough to modify a molding board to interface with these pins and attach patterns to it for a quickly-assembled matchplate.

Of the other tools needed, a surprising number of them can be made from old, discarded silverware. A few old butter knives and spoons can be used as is or bent into shapes to cut gates and runners, scoop out pouring cups and sprue wells, smooth down lifted edges, cope down to the parting line, and so forth. If silverware is not up to the task, a piece of sheetmetal usually will be.

Sprue and riser patterns can be made from PVC pipe, which even though it has no draft, makes an adequate pattern. Larger risers can be made from disposable cups filled with concrete or plaster of Paris, or even molding sand for temporary usage. Sprue cutters can be made from thin-walled electrical (EMT) conduit or copper plumbing pipe.

Any stiff wire can be used for a vent wire. For best results, the end of the wire should be tapered slightly into a dull point, which will narrow the vent's connection with the pattern and make it easier to break off at the surface. A sharp point on the wire will make dents in the pattern.

Parting dust can be applied by pouring it in an old sock or small bag, and shaking the bag to let the dust fall onto the pattern. A shaker bottle, like the ones baby powder comes in, is also effective. Once the parting is applied, it can be spread around, and any excess dusted off, with a dry paintbrush. A compressed-air blowgun is a convenient tool to have for removing dust and debris from the bottom of a mold cavity, but the same work can be done with a paintbrush and a sheet of paper or metal to sweep debris onto. Any method of applying parting dust will be dusty, so take suitable respiratory precautions.

Mold Design

Now that we have sand and tools, we need to put them to use. Extremely simple molds can be made by simply ramming sand around a flat-backed pattern, creating an open depression to accept metal. This kind of mold is good for making ingots, but most usable castings cannot tolerate the irregular top surface created by an open-face mold. To eliminate that surface, the mold needs to be enclosed.

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Figure III-6 illustrates the necessary parts of a basic casting. Metal is poured through a sprue into a well to catch debris, and from there it flows through a runner and a gate into the casting. The gate is designed so the metal enters near the bottom of the casting, allowing it to rise smoothly from the bottom instead of splashing turbulently in from the top. Turbulent metal flow can mix air bubbles into the metal, tends to wash sand into the mold, and provides a greater surface area for the metal to become oxidized. Also note that the design of the runner and gate skim off impurities from both top and bottom, instead of flowing straight into the casting.

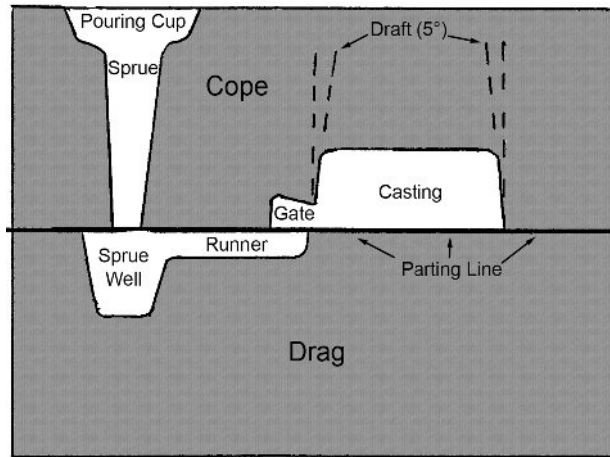


Figure III-6: Basic casting

The casting is given a positive draft of five degrees, which is fairly generous and will make for easy molding. Skilled molders can use patterns with only one or two degrees of draft in most places, especially for such a simple casting. The gate, runner, sprue, and sprue well can be molded with patterns as well, or carved into the sand after the mold is pulled apart. If patterns are used, these non-critical pieces should be given very generous draft for easy molding.

Note how the top corners of the casting are rounded, while the bottom corners as the casting meets the parting line are not rounded. Any edges cast in the mold itself must be rounded if an outside edge or filleted if an inside edge, to avoid fragile corners that will break off and wash away. As with draft, more rounding and filleting makes for easier molding.

This particular casting is a large, solid chunk much like an ingot. In general, a casting like this would need a generous riser as well as the elements pictured to prevent shrinkage. Figure III-7 shows some possible placements for risers. Risers work by holding large amounts of metal in a single piece of thick section, solidifying only after the casting has finished solidification and feeding more metal in as the casting shrinks. The riser will often have shrink defects, but that is of no consequence. This casting has three risers, which is generally excessive: one

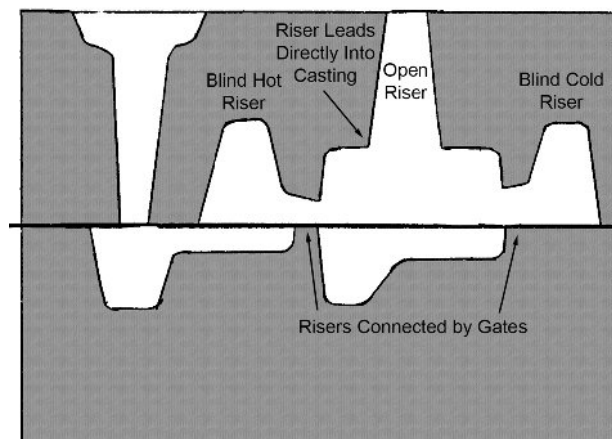


Figure III-7: Casting with risers

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or two will do unless there are far-separated parts of thick section that need separate risering.

In general, risers need to be placed adjacent to the thickest part of a casting, which will itself act as a riser for the thin parts of the casting. These risers need to be considerably larger than the section thickness in that area, but more importantly, the riser needs to be gated to the casting with a gate no smaller than the section thickness, otherwise the gate will freeze and prevent the riser from functioning. Risers may be attached directly to the casting, which leaves no narrowed channel to freeze. Blind risers will generally stay hot longer, because they are insulated within the hot sand, but an open riser will act as a vent for gases and provide a handy indicator of when the mold is full. Small “vent risers” are often used for this purpose, and they are usually made small enough as to have no effect on the casting's shrinkage. Note that risers can also be placed in the drag, but they must be blind, or the mold will not hold metal!

Large risers are often difficult to cut off a finished casting and leave large areas in need of finish work, so there are obvious advantages to keeping risering small or nonexistent. In industry, there are types of riser sleeves to place into the mold, allowing risers to be made smaller. Insulating riser sleeves are formed shapes in an insulating material that help risers retain heat. Homemade insulating riser sleeves can be made with scraps of ceramic fiber blanket pinned to the inside of the riser cavity in the mold. Exothermic riser sleeves are designed to burn away upon contact with the molten metal, actively heating the riser and thus keeping it liquid longer. Risers fed directly from the sprue (“hot risers”) also generally contain hotter metal than risers fed through the casting (“cold risers”), so do not need to be as large for the same effect.

Figure III-7 also has an extra detail: part of the casting is in the cope and part is in the drag. Most castings will require construction like this. In this case, the easiest way to make this feature is to split the pattern along the parting line. Another way to make the feature is to make one side of the mold normally (whether it's the cope or drag depends on whether the mold will be double roll or single roll), carve down to the correct parting line (“coping out”), and mold the other side normally. A temporary cope or drag (“odd side”) can also be molded up to support the pattern at the parting line while the other side of the mold is made, then the temporary mold is shaken out and remade permanently. Small protrusions can often be tamped into a blank mold section (usually the drag) up to the parting line, or a molding board can be modified to accommodate the protrusion.

Figure III-8 shows another way to get around the problem of thick sections. Most castings do not need to be solid, and in fact much is gained in terms of labor and material savings when castings are made as near finished shape as possible.

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The addition of a simple greensand core occupies the center of the casting, displacing the bulk of the metal and reducing section thickness to a level where little or no risering is necessary. This style of core can be molded as part of the drag (in which case the cope would be molded first to create a double-roll mold), or it can be molded as a separate piece that is placed in the mold before closing up to pour.

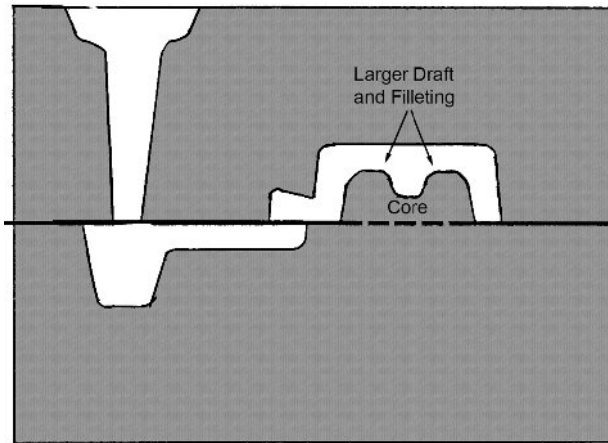


Figure III-8: Casting with simple greensand core

Most cores will stay put by virtue of their own weight, but heavier metals or very small cores may require the addition of a steel wire or nail to prevent the core from shifting or floating to the top of the mold. Loose cores cannot be suspended from the cope at all, and it is generally considered bad practice to suspend an attached core from the cope unless the mold design necessitates it. The large hanging weight of the core will be more fragile than a core sitting on the drag, and may require wires for reinforcement.

Note that the core has more draft and larger fillets than the outside of the mold. This is particularly important if the core is molded as part of the cope or drag: an easy release will prevent it from breaking off when the pattern is pulled. With a separate core box, less draft and smaller fillets can usually be tolerated.

It is usually advisable to “key” a loose core to the mold with some sort of protrusion, which will keep the core from shifting and aid in placing it correctly.

Cores in the drag can be prone to gas problems, because the inverted cup of molten metal will not allow generated gas to escape upwards or sideways without causing defects. Always vent cores thoroughly.

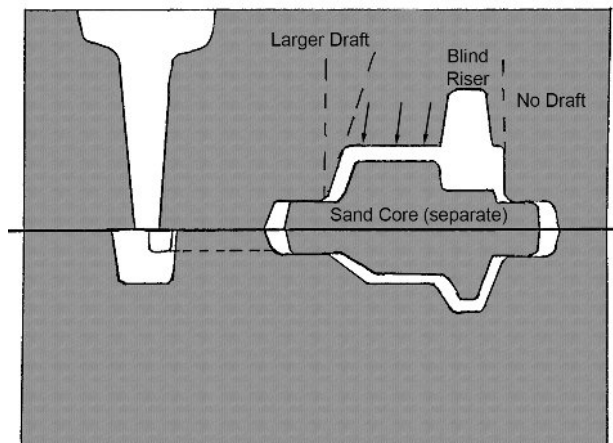


Figure III-9: Casting with loose bonded-sand core

Figure III-9 shows a more complex type of core. This style of core is used to create hollow castings and more complex shapes. The core in this case cannot be molded with the cope or drag; it must be made in a separate core box. For many applications, the strength of greensand will be inadequate and the core will need

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to be made of cured bonded sand. This type of sand also generally creates less mold gas, so it can reduce gas problems that would otherwise occur with a nearly-enclosed core. The sand can be bonded with a commercial resin, sodium silicate, or a baked organic binder such as sugar. In all cases, a curing process is necessary and the core sand is not reusable without adding more binder. Unless the volume of cores is great, the used core sand can usually be mulled into the greensand without consequence.

Cores of this style sit in special protrusions in the mold, called “core prints.” The core prints have to be sufficient to support the core and prevent it shifting. In cases where the core needs more support than prints can provide in the spaces available for them, small pieces of metal can be used to support the core. These are called “chaplets” and are designed to fuse with the incoming metal, so they must be of the same or a compatible alloy and thin enough to melt when the casting is poured.

Cores cannot be too strong or they will cause hot tearing as the metal in the casting contracts around the core. Certain alloys of aluminum are particularly susceptible to this, because aluminum suffers from hot shortness. Therefore, the core material must be strong in its dry state at room temperature, but must crumble relatively easily once exposed to hot metal. This crumbling is also useful for extracting the core: a core that stays solid can be very difficult to extract from tight spaces, and the abrasive sand will damage machine tools if not removed.

This mold contains another feature: one side of the mold cavity in the cope has no draft at all. A larger draft on the other side allows the pattern to be extracted by drawing it at an angle. Even slight negative drafts are possible to mold with this technique, if the draft on the other side is made large enough. The casting also has a small blind riser over the thickest section.

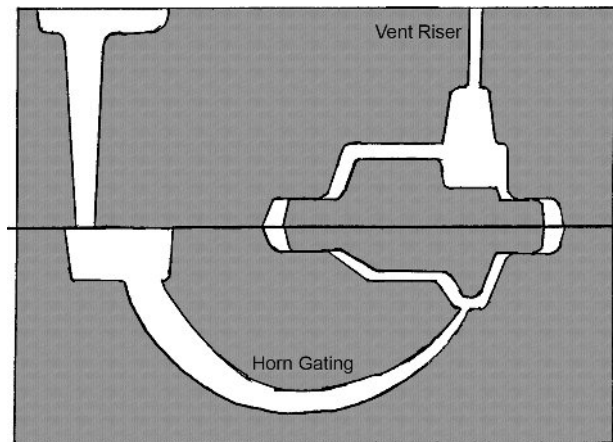


Figure III-10: Casting with horn gating

This particular example is suitable for discussion of an advanced gating method: horn gating. In Figure III-10, instead of a conventional runner on the surface of the cope or drag, a long curved horn is molded in the drag to feed the casting at its lowest point. This type of gating allows for good debris filtering of the incoming metal and very low turbulence. It is typically used for certain bronze alloys that readily form dross in air. The smooth bottom-filling of the mold prevents turbulence that would cause more dross to form, and the curving path of the metal skims off any dross that finds its way into the mold.

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In order to make horn gating, it is necessary to have a horn, with constant curvature and sufficient draft along its length to be pulled out of the mold along the curved channel it forms. The complexity horn gating adds to a mold means that it is generally not used unless necessary.

Also note that this mold has an additional vent riser on top of the preexisting blind riser. An arrangement like this saves the extra metal needed to extend the riser all the way to the mold surface and keeps the riser's metal more thoroughly insulated, while at the same time providing the same venting and fill indication of an open riser.

Figure III-11 shows a more complex mold: a teacup on a saucer, with a spoon in the cup. This is a traditional test of molding ability, and is a very tricky mold to create.

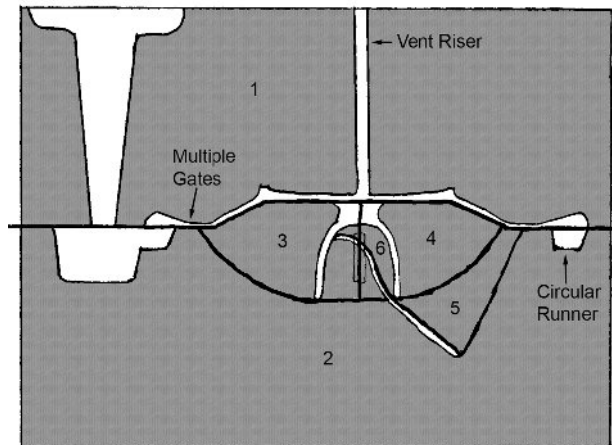


Figure III-11: Cup with saucer and spoon

The thin sections require the use of a fluid alloy and multiple gating points. In this example, a circular runner rings the saucer, with perhaps six evenly spaced gates filling the saucer from all sides. A vent riser in the center of the saucer reduces backpressure and allows the mold to fill more readily.

The outside of the cup is molded with two loose greensand cores, labeled (3) and (4) on the diagram, that are split at the vertical parting line of the handle and diametrically opposite on the other side. A third small core may be necessary if the handle does not have simple draft in this direction. The spoon is supported on the outside of the cup by another core (5) that rests on the teacup cores. To form the inside of the cup, there is a small core (6) under the spoon, and the rest of the cup is formed as part of the drag (2). Again, more cores may be needed if the cup does not have simple draft. Sometimes, a cube of sugar is added onto the spoon, which would require yet another core.

In usual molding practice, this mold would be started with the cope (1), perhaps with some sand to support the underside of the saucer. A full fledged odd side is not necessary. Then, the cope would be rolled over and the parting face cleaned up. A small amount of coping down may be necessary to free the rim of the saucer. If the sprue is formed by a molded pin instead of cut, the sprue pin would be left in the cope. Then, cores (3) and (4) would be formed freehand, making sure they have correct draft. Core (6) would come next, then (5). Finally, the drag (2) would be formed and the mold rolled a second time, then opened. At this point, the gating, sprue, and vent riser would be cut, and the mold vented. The saucer would be lifted out, followed by cores (3) and (4) and the cup, as one unit. The cup could

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then be extracted from the cores. (5) and (6) would follow separately, then the spoon would be extracted. The cores would be reassembled in reverse order in the mold, the cope put on, and it would be ready to pour.

Molding Practice

There are a great number of ways to mold different patterns in sand, and choosing the correct sprues, runners, risers, and gates, and the correct orientation of a complex pattern is part science and part art form. Even experienced molders are sometimes unsure how to sprue a complex mold; the standard procedure in those cases is to pour a test piece, examining the casting afterward to see how the metal flowed and how the flow can be improved. Most of the knowledge necessary to do this is gained from experience, but the basics can be taught.



Figure III-12: Patterns in the cope

The series of photos accompanying this section are of a fairly simple mold of a pair of pulleys. In molding parlance, they are both molded in the drag, for an easy single-roll mold and less chance of a failed casting in the case of a gap run-out. This is particularly important in this case, since the flask is just a little bit too small for these patterns, and the patterns are dangerously close to the edge, and to each other. Those narrow gaps between the patterns and the edge are hard to ram properly, and they can easily spring a leak and pour molten metal out the side of the mold.

To start making the mold, the patterns are laid on the molding board and covered with parting dust, as seen in Figure III-12. A light coat of sand is sprinkled on and patted into crevices by hand, then a heavier layer (about an inch and a half) is dumped in and rammed, as seen in Figure III-13. After ramming the entire mold with the blunt end of the rammer, the peen (pointy end) is used to ram sand around the edges of the flask, and in gaps between the patterns. After the first layer is rammed by hand, the rest of the flask is rammed with a pneumatic rammer (the



Figure III-13: Beginning to ram

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one shown in Figure III-14 is a modified air chisel). This part can be done by hand as well, but the power tool is much faster. The flask is struck off level and vented with a thin wire poked into the sand down to the pattern, then flipped over. Parting dust is applied, the sprue and riser are placed, and the cope is rammed much like the drag. It too is struck off level and vented, then the sprue and riser forms are pulled out. A pouring cup (like a funnel in the sand) is carved for the sprue, and the top edges of the riser are rounded off to prevent them breaking and falling in the mold.



Figure III-14: Finishing the ramming

(A note about parting dust: I use silica flour, which works well but is a significant respiratory hazard—wear a respirator! Other materials, such as talcum powder, chalk, or graphite dust, may work to greater or lesser degrees and present greater or lesser respiratory hazards. Commercial parting dust is a high-temperature plastic flour that is biologically inert, but it may also be expensive or hard to get. Any parting dust that absorbs water is unlikely to work well, and may cause casting defects.)

Then, the flask is opened and the patterns are pulled out. Gates (and, if necessary, runners) are carved, as is a well below the sprue to trap sand washed into the mold. This well should extend below the level of the gate so debris does not get washed into the mold.

Note how, in Figure III-15, the smaller pulley is fed from the larger one instead of directly from the sprue. Placing them so close together forced there to be a connection between the two, which can also serve as a gate. It would be better molding practice to move them apart (in a bigger flask) and gate each one directly from the sprue. Also note the dark patch at the far side of the big pulley. This is a little extra sand added to a loose edge to prevent a leak from forming there.

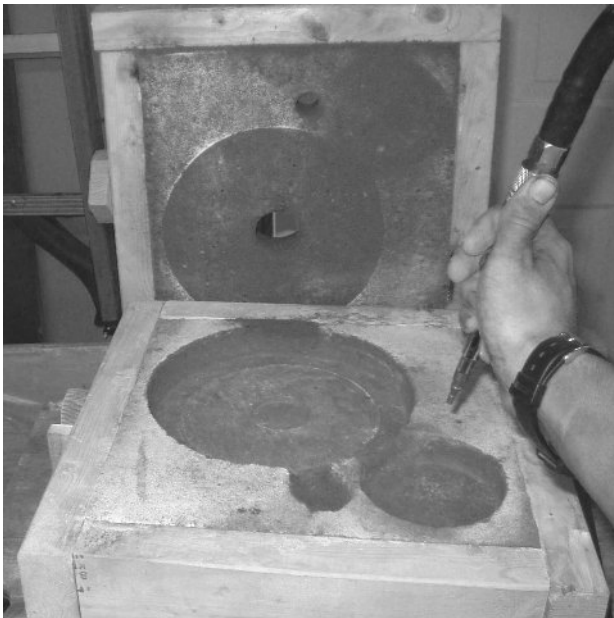


Figure III-15: Blowing dust out of the open mold

Now is the time to push down any loose edges and clean up any details. After the mold cavity is suitable, any dust is blown

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out (either with an air compressor and nozzle or with a hand-powered air pump or bellows—blowing dust out by mouth is a good way to inhale it) and the mold is closed up. It will be weighted before being poured, to prevent hydrostatic pressure from pushing the cope up and forcing metal out the gap. If the casting was formed in the cope, such a gap run-out would ruin it; this casting in the drag could conceivably turn out anyway. Casting in the cope, however, washes less sand into the mold and provides a smoother fill because the metal is rising up from below instead of pouring in from the side.

Section IV

Furnaces, Crucibles, and Fuel

This section details some of the background information necessary to design and build melting and casting equipment, to select the correct type of equipment and the correct process for a given application, and to understand how the equipment works. More detail on many of these subjects is provided in later chapters, but this section provides a basis for understanding the later information.

Furnaces

Furnaces, regardless of their type, need a few attributes to function properly. The first is refractoriness, or the ability to withstand heat. The second is insulative ability. While the first two are arguably the most important attributes of a successful furnace, attributes such as mechanical strength and flux resistance become important in some designs. Thermal mass is also an important consideration in furnaces that undergo a lot of cycling between room temperature and operating temperature.

Refractoriness

Refractory is, after all, named after its defining attribute: its resistance to heat. Some homebrew refractories, however, aren't very refractory. Commercial refractories are rated by the temperature at which they incur damage, most pure clays such as fireclay, ball clay, and kaolin are suitable for well over 3000°F, and common homebrew ingredients like perlite often start melting over a wide range, anywhere from 1600°F to 2200°F, depending on the properties of the individual batch. Non-refractory ingredients like Portland cement melt considerably lower, and worse, they can flux the entire mixture, turning your furnace into a puddle of goo.

Since puddles of goo don't generally make good furnaces, it is important that the heat resistance of your chosen refractory is adequate to survive all conditions in the furnace without being damaged. The maximum temperature present in your furnace is not the temperature of whatever you're melting; it's usually wherever a burner (or other heat source) impinges on the furnace wall, and it can reach temperatures several hundred degrees higher than the melt, depending on the power of the heat source and the ability of the melt to carry heat away from that area. Generally speaking, if the furnace heats up slowly, and the heat source is evenly distributed, the peak temperature in the furnace will be very close to the average temperature. A pottery kiln, for example, should be able to fire

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pottery to very near the limits of the refractory without damage around the burners or heating elements. Conversely, if the furnace heats up quickly, and the heat source is concentrated, then peak temperatures could reach as much as twice the average temperature.

Insulative Ability

Refractoriness is only part of the equation for a good furnace. Tungsten, for example, is highly refractory, but it doesn't make a great furnace because it acts as a heat sink, wasting large amounts of energy. A good furnace should keep the heat in, and that's where insulation comes in.

Air is a great insulator, but not if it can move around, forming convection currents. Most successful insulation, therefore, traps air in tiny pockets. The material that the insulation is made of should also be fairly insulative, but it won't be nearly as effective as the air it's keeping trapped. Therefore, the best insulators are light, fluffy materials with lots of air in them, such as the commercial insulating wool sold for kiln insulation (think fiberglass insulation, only it's designed to take high temperatures). A similar effect can be achieved by adding something burnable (like sawdust or finely shredded polystyrene foam) to your clay-based or castable refractory. When fired, the bits of material burn out, creating little air pockets. Commercial foaming agents essentially do the same thing, trapping lots of little gas bubbles.

Commercial castable refractories usually come in two varieties: insulating and non-insulating. The insulating variety will be lighter and weaker than the non-insulating variety, which is very dense and hard to withstand lots of mechanical abuse. Typically, the insulating variety is mechanically strong enough for homebrew furnaces, and should therefore be chosen over the non-insulating variety due to its greater insulative ability.

Thermal Mass

Thermal mass isn't a big consideration in commercial furnaces that run continuously for long periods of time, but it's very important in homemade furnaces that get cycled up and down a lot. The problem is simple: Before your furnace can heat anything else up, it has to heat itself up first. If your furnace has a lot of material to absorb the heat, it's going to take a lot of time and energy to get hot, even if relatively little heat escapes outside of it. When it's done melting whatever it's supposed to melt, all that energy put in to getting it hot gets lost as the hot furnace cools off.

Minimizing thermal mass is relatively easy to do. Materials that have lots of air in them have very little thermal mass, as well as being good insulators. Heavy, dense materials have lots of thermal mass and are best avoided under most circumstances. A rough rule of thumb is the material's density: Light furnaces are much better than heavy ones, as far as thermal mass goes.

Hotfaces

So far, I've only talked about furnaces made with a single material. Unfortunately, materials that are light and fluffy (good insulators with low thermal mass) aren't usually very durable. Materials that are hard, strong, and temperature-resistant are usually heavy and dense, with mediocre insulative abilities. A hotface is the easy way to get the best of both worlds, and is typically used for two reasons: to protect a highly insulative but weak material from mechanical abuse or chemical attack (e.g. fluxes), or to protect a highly insulative but not-terribly-refractory material from the hottest parts of the furnace's interior, such as the burner's flame. Hotfaces can also be used to stretch the budget, by protecting cheap insulation (like perlite) with a more temperature-tolerant but expensive material.

Whatever you do, DO NOT make a hotface three inches thick, unless your furnace is thirty feet tall and you drop tons of scrap into it on a regular basis. Hotfaces should be as thin as you can make them and still have them fulfill their function. This goes back to the previous discussion of thermal mass. Your insulation is behind your hotface, so the hotface has to heat up and cool down with every furnace cycling. If the hotface is thick enough that the back side of it is still relatively cool by the time you're done melting, the insulation isn't doing anything.

Crucible Furnaces

Crucible furnaces are the most common type for hobby metalcasters. The only special design qualification for a crucible furnace is that it needs to fit a crucible. Instead of first building the furnace, then trying to find or make a crucible to fit it, I strongly recommend that you have a functional crucible on hand when you start designing your furnace. You should also be able to easily buy or make more crucibles of the same size. This will save a lot of trouble down the road, and since the furnace is designed to fit the crucible, it will run more efficiently and take less material than one that is too big. (One that is too small won't fit the crucible at all, and trying to enlarge a furnace after construction is more or less a gesture of futility.) This seems obvious, but many beginners try to build the furnace first, then have a hard time getting a crucible to fit it.

Also make sure to consider how you're going to get the crucible in and out of the furnace. Whatever lifting apparatus the crucible is designed to use should be able to lift the crucible out of the furnace without scraping against the walls or running into obstructions. Again, this is something you should think about before you build.

Furnace Shape

Crucible furnaces are usually shaped in a rough cylinder, with the lid being a flat disk that rests on top. Alternatively, the lid can have a recess to allow the crucible to extend above the sides of the furnace (for easier lifting), or the furnace can be built in three parts, with

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the walls lifted off the base to grab the crucible from the side. Furnaces should not generally be built in a “top hat” configuration, with the top and sides lifted as one piece off the base. The reason for this is that removing the side walls from around the crucible will cause it to cool quickly, so this should not be done for charging the crucible or skimming dross. The additional lid in the three-part design allows access to the top of the crucible without lifting the walls.

Lid Lifting

Lid lifting mechanisms can vary from the extremely simple (a pair of handles, suitable only if the lid is light enough to move easily) to the very complex (a system of slides and winches, usually used for very large and heavy three-piece furnaces). In between these two extremes, there are various types of pivots used for lids of moderate weight. Whatever the design, it should be easy to operate, robust enough not to wobble, and the hot side of the lid should not point toward a person operating the lid lifting mechanism, or in front of the furnace toward a person skimming dross. The lid can radiate a fair amount of heat (especially if it is large), and can make moving around the furnace uncomfortable or dangerous. It should also never point at fuel lines or electrical connections.

Solid-Fuel Crucible Furnaces

Many beginning metalcasters start by building a solid-fuel crucible furnace, because it offers arguably the quickest and cheapest way to get into the hobby. The primary reason is that solid fuel doesn't take any special apparatus to burn. All it requires is a source of air. Solid-fuel furnaces can reach high temperatures without using specialized refractories because the fuel provides some degree of insulation for itself. Many beginning furnaces use only a thin steel shell (e.g. a coffee can) or a terra cotta flowerpot (both poor insulators and not particularly robust), and they function acceptably well because the fuel in contact with the edges of the furnace never gets as hot as the fuel in the direct air blast.

The most primitive solid-fuel furnace is simply a wood or charcoal fire on the ground or in a fire pit, and such a fire can melt white metals and aluminum with ease. Fuel consumption is greatly reduced, however, if the fuel is contained within a proper furnace and forced air provided for a hotter burn.

Tuyere Placement

Solid fuel gets hottest when it is provided with adequate air for combustion. This will happen near the tuyere, where air enters the furnace. A tangential tuyere, as in a furnace designed to use a burner, will not provide an even heat; the wall that the air blast is directed toward will heat up, and the rest of the furnace (including the crucible) will stay cold. The best tuyere placement for an even heat is directly below the crucible, pointing up, but this creates problems in the event of a crucible failure, as metal will drain down into the tuyere.

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A solution might be to put a drain hole in the pipe leading to the blower, covered by a meltable or burnable plug such as aluminum foil or duct tape. A tuyere pointing directly at the side of the crucible may also provide a sufficiently even heat. A grate can be used to distribute the air evenly, but such a grate will be prone to oxidation.

Fuel Placement

Unlike in other crucible furnaces, solid-fuel furnaces do not use plinths. Instead, the crucible sits directly on a bed of fuel. This bed should be at least half the crucible diameter thick around the outside of the crucible, and somewhat thicker below the crucible. The crucible should be buried up to its rim in fuel. (Nestling the crucible back into a burning fuel bed after a pour is somewhat difficult; the undertaking is aided by thick gloves and long-handled pliers.) For maximum temperature, the entire fuel bed should be burning evenly. Fresh fuel should be added evenly around the top, no more than one layer thick at once. Fuel pieces should be big enough to allow free passage of air, but small enough to provide good contact with the crucible.

Air Blast

Hair driers, vacuum cleaners, and leaf blowers are often conscripted to provide the necessary air blast to run a solid-fuel furnace. The first of these may not provide enough air, while the latter two often provide too much. A shutter of some kind, either to vent excess air or to restrict the blower's intake, should be used to control the air blast. Excessive air can rapidly oxidize the bottoms of steel crucibles, creating failures often mistaken for melting. Too much air also wastes fuel.

Efficiency

Solid fuel tends to self-insulate, so good furnace insulation is less important with these furnaces than with other types of furnaces. Fuel usage can be greatly reduced, however, by a furnace that is the proper size and shape. Using extra fuel in place of a proper container is relatively costly, as the fuel burns whether it's melting metal or not. A well-built furnace with a proper lid can also save a good deal of fuel, as compared to one with little or no insulation. Well-built furnaces also tend to last longer, as well. Keep in mind that the refractory must be mechanically strong and relatively resistant to fluxing (ash is a flux) to handle solid fuel over a long lifespan.

A good deal of fuel can also be saved if combustion is halted at the end of a melt. The easiest way to do this is to cut off the air supply, which may not be effective if the furnace leaks. An alternative is to shovel out the hot coals and quench them, but this is a hot and messy job. Water should never be sprayed into the furnace unless the intent is to crack the refractory into small pieces. Regardless of the method, ash should be removed before the next firing. Coals will burn better if the ash isn't plugging the tuyere and taking up space, and there's less of a respiratory hazard when the blower is turned on.

Propane-Fueled Crucible Furnaces

Crucible furnaces that are heated with a gaseous-fuel burner (predominantly propane, but also natural gas) all share certain design requirements. One is the tuyere placement. The tuyere should be placed so that the outer edge is tangential with the inner wall of the furnace, and the vertical center line of the tuyere should be even with the bottom of the crucible.

Rules of Thumb

Since gaseous fuels are among the most expensive fuel sources, furnaces using these fuels should be as efficient as possible. One of the most important ways to increase efficiency is to size the furnace correctly.

- For every cubic foot of enclosed space inside the furnace, the burner should output approximately 100,000 to 200,000 BTU/hr.
- The vent hole diameter should be from 1/3 to 1/4 the inside diameter of your furnace, or 2 to 3 times the inside diameter of the tuyere.
- The walls of the furnace should be as close as possible to the crucible (with adequate room to operate the crucible lifting mechanism, of course), but the gap between the crucible and furnace walls should never be narrower than 3/4 the burner tube diameter.
- The gap between the top of the crucible and the furnace lid should have approximately the same area as the vent hole for maximum efficiency. If the lid and crucible lip are flat parallel surfaces, a gap of the correct area will be 1/4 the vent hole diameter.
- The plinth should be no taller than twice the tuyere diameter.
- The tuyere diameter should be about 1.4 times the burner tube inside diameter. If the burner has a working flare, use the largest inside diameter of the flare.
- The furnace wall thickness should be about a quarter the furnace's inside diameter for adequate insulation.

Oil-Fueled Crucible Furnaces

The burning of waste cooking or motor oil is advantageous to the hobbyist with a limited budget, as it is usually a free or very inexpensive fuel, but the additional requirements of dealing with a liquid, hard-to-burn fuel often necessitate a considerably more complex burner design than required by gaseous or solid fuels. There exist almost as many different oilburner designs as there are hobbyists in the field, and many of the burners tend to be cantankerous and highly tailored to a single, unique setup. Building a working oilburner is beyond the scope of this manual, but I will briefly touch on the furnace requirements for successful oil combustion.

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The general layout of an oil-burning crucible furnace is similar to that of a propane-fired furnace, with a tangential tuyere, lid, and vent hole above the crucible. The furnace needs to have more space for free airflow than with a propane furnace, as oilburners are generally more sensitive to backpressure. This means a larger tuyere, more space around and above the crucible, and larger vent hole. The combustion of an oilburner tends to happen in the furnace as much as in the burner, and tends to be more violent than with gaseous fuels, so a hard, durable hotface is advisable. With free fuel, efficiency is somewhat less of a concern, and denser, more durable refractories can be used. Oil combustion can easily get hotter than the best propane burner designs, so refractory, especially in the burner itself or in the tuyere region, should be rated to at least 3000°F. For iron melting or other high-temperature use, the higher temperature of an oil flame will lead to considerably quicker and more fuel-efficient melts, so the additional complexity is well worth considering.

Electric Crucible Furnaces

Electricity is a clean way to melt, and generally less expensive and more readily available than other fuel sources. Unless a high-amperage dedicated circuit is available, however, the power output will be low, leading to slower melts than with other fuels. Elements capable of high-temperature melting are quite expensive, so resistive electric melting is best reserved for aluminum and white metals instead of the higher-melting metals. The vagaries of element selection, and the intricacies of induction and arc furnaces and other exotic types of melting equipment are again beyond the scope of this manual, but the furnaces required for electric resistance melting are quite simple.

Again, standard furnace rules of thumb apply with electric furnaces. The major differences are the absence of a tuyere and vent hole, and the presence of grooves or other supports for electrical elements. Not all ceramics are electrical insulators at high temperatures; high-alumina ceramics generally perform well, whereas high-silica ceramics may lead to leakage currents through the refractory. The addition of a removable plug in the furnace lid for charging and skimming dross is advisable and will increase efficiency compared to removing the entire lid for these operations. Finally, the generally slower melting of electrical furnaces means that adequate insulation is vital. Insulation is generally thicker on electric furnaces than on other varieties.

Making Crucibles

Because crucibles are commonly quite expensive when bought commercially, many hobbyists make their own, at least when starting out. Crucibles can create a very dangerous situation when they fail, so it is worth taking some time to explore how to make crucibles that can safely hold molten metal without failing.

SECTION IV: FURNACES, CRUCIBLES, AND FUEL

Steel Crucibles

Steel crucibles are adequate for the melting of aluminum and white metals, and more foolproof for the beginner to use than commercial ceramic crucibles. A good size of crucible for the beginner is about 4" diameter and 6" tall, which will hold about five pounds of aluminum. I use disposable 1-lb propane canisters as a convenient size of crucible. (Safety note—the propane must be completely bled out of the nearly-empty tank by depressing the valve until no audible hiss is heard. For extra safety, it's recommended that you also unscrew the valve and fill the tank with water to displace the propane before cutting the tank.) These crucibles generally last about 10-20 melts apiece. For a longer-lasting crucible, you can screw a pipe cap onto a pipe nipple, or weld a piece of plate onto a steel pipe. The heavier the crucible, though, the more fuel it will waste and the longer it will take to heat up.

Steel crucibles are fairly simple to make from scratch if you have a welder and the skill to use it, and not difficult to make if you don't have a welder. One simple crucible is a black iron pipe nipple with a pipe cap screwed to the bottom. This is not an ideal crucible, because the heavy pipe cap takes a lot of energy to heat up, and large-diameter pipe nipples and caps tend to be expensive. The crucible is functional, however, and can be moved with a large pair of slip-joint pliers (if the weight of crucible and metal is less than five pounds, for safety reasons), or bolts can be put in the top to make lifting pegs.

A better crucible design is a steel pipe with a round piece of steel sheet welded on the bottom, and lifting and pouring lugs welded on. The pipe and sheet do not need to be exceptionally thick for most uses; 16 gauge metal is adequate for crucibles holding up to 5 pounds of aluminum, and 10 gauge metal is adequate for up to a 40-lb capacity crucible. The exception to that rule is a steel crucible designed for high-temperature use. Generally, aluminum temperatures are the hottest that steel crucibles should be used for, but a thick-walled crucible (schedule 40 pipe, at least) can be used for melting small amounts of brass or bronze (under 10 lbs). Obviously, for these crucibles to work at all, the weld has to be sound. It does not have to be completely water-tight; molten metals have a very high surface tension. However, any leaks larger than pinholes must be fixed, and the weld must be of sound enough bond that it will not catastrophically fail.

All steel crucibles, and any other tools that will contact the melt, should be preheated to a red heat before coming in contact with the melt. This will build up a layer of iron oxide that will keep the steel of the crucible from dissolving in the melt. Iron is quite soluble in aluminum and zinc (an uncoated crucible will dissolve through in a melt or two), and the contaminated metal will generally have poorer physical properties. Fluxes will interfere with this oxide layer and shorten crucible life somewhat, especially powerful fluxes at high temperatures. Salt fluxes generally do not have severe effects on the protective oxide layer, but if left on the crucible and stored in humid air, they will rust the crucible severely. It is a good idea to store all foundry tools in a dry area.

Ceramic Crucibles

Anyone can buy ceramic crucibles from a foundry supplier, and for the dedicated or professional caster, it makes sense to purchase commercial crucibles. Commercial ceramic crucibles are made from precisely-engineered materials and fired to a very high temperature for a very long time—a firing schedule that it would be impractical to duplicate on a hobby scale. The result is a product that is expensive, but of higher and more consistent quality than anything the hobbyist can practically reproduce. Making your own crucibles is possible, but the time and effort invested, and the lower performance of the completed materials, makes the process only worthwhile for the dedicated experimenter or the caster that needs unusual shapes or unusual material properties. Crucible-making is also a valuable learning experience, in which the final product may be secondary to the knowledge and experience gained.

Materials

Commercial crucibles are generally made from graphite and clay, or silicon carbide. In the case of clay-graphite crucibles, a long soak at extremely high temperature allows silicon carbide crystals to form in concentrations of approximately 20% of the crucible's mass, strengthening the crucible and allowing it to survive more severe thermal shock. The fuel requirements for such a firing are well out of the practical range of possibility for hobbyists, so other methods are required. Many of the strongest and densest refractories make good crucibles as well, possibly with the addition of thermally conductive grog to speed equalization of temperature. It is extremely important to thoroughly test homemade crucibles before relying on them to hold molten metal, as crucible failures can be very dangerous.

Good clay-based crucibles can be made using ceramic recipes and working techniques similar to those used to build a furnace hotface, as detailed in Section V. Still, crucibles have different requirements than furnaces and some parts of the process must be modified.

In contrast to furnace linings, crucibles need to be thermally conductive in order to transfer heat to the melt, and to reduce the thermal stress applied when a crucible is heated rapidly. Adding thermally conductive grog such as silicon carbide or graphite will increase the thermal conductivity, but these materials are usually expensive. Alumina and mullite are also fairly thermally conductive, so a densely sintered high-alumina ceramic will be a good second-best choice. Density is key—the more porous the material, the weaker and more insulative it will be. Unfortunately, the best way to achieve a densely sintered ceramic is to fire it longer and hotter, which is also expensive. Crucibles should not be made vitreous, because vitrification will excessively reduce thermal shock resistance.

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Construction

Slip casting is a good choice for making crucibles, as it produces a dense homogeneous product with a uniform repeatable cross-section and wall thickness. Plastic formed crucibles are also acceptable if great care is taken to de-air the plastic clay. Rammed crucibles are less dense than other varieties and have a greater likelihood of defects if rammed by hand, so I do not recommend using ramming mixes when making crucibles.

When making furnace linings, cracks are acceptable and to some degree even expected. Crucible making must have much more stringent quality control. Any crucible that cracks during any point in the process should never be used to hold metal, regardless of whether or not it was patched. The reason for this is that patching clay creates a moisture gradient, which creates stress concentrations and weak spots in the dried and fired product. Furthermore, if some of your crucibles are being lost to drying cracks with no obvious cause, it is likely that some other crucibles are being stressed but not cracking, which means these crucibles are weak and ready to fail. It is possible to fix this by creating an environment (known as a “damp box”) to store the crucibles in where they can be dried slowly and evenly without setting up stresses that could cause later failure.

In addition to making crucibles out of clay-based ceramic, it is possible to make crucibles out of commercial dense castable refractory, possibly with some added materials for increased thermal conductivity. As with clay-based ceramic crucibles, thoroughly test all materials and methods to ensure the product is sound before entrusting the crucibles with molten metal.

Propane

Propane is a very common fuel to use for melting, as it is extremely convenient and easy to use. It is expensive and cannot reach the temperatures of some other fuels, but it does not produce ash or smoke, requires only a simple burner design, and is easy to precisely meter and adjust fuel mixture. For this reason, propane is one of the best fuels to use for firing ceramics, something that any hobbyist who builds a furnace or makes crucibles out of clay-based ceramic will need to do.

Supply and Fittings

Most hobbyists get their propane from 20-lb refillable propane “barbecue” tanks or similar portable tanks. Some may have a large stationary propane tank available. This tank ensures plentiful supply, but it may also have a low-pressure regulator permanently plumbed in. Naturally-aspirated burners require high-pressure variable regulators. A minimum of 10 pounds per square inch (PSI) is needed for foundry use, and 30 to 60 PSI is preferable. Such regulators can be obtained from various specialty propane suppliers, but they are very different from the low-pressure, typically non-adjustable regulators that come with barbecue grills and in most propane hookup kits found in hardware stores.

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Most regulators also have a flow-limiting device (a small orifice, not unlike the orifice of a foundry burner). This is a valuable safety feature, especially at the high pressures that naturally-aspirated foundry burners use, but if your burner is especially large, it may exceed the capacity of the flow limiter at high pressure. The solution, if the flow limiter is removable, is to increase the size of the orifice to a value that will produce somewhat above the maximum required propane flow. Do not remove the limiter entirely or disable it by drilling it out to a very large size. If the limiter is integral to the regulator, the regulator will have to be replaced with a higher-capacity version.

When dealing with very large propane flows, the capacity of the tank to supply enough propane without icing over becomes an issue. The higher the required pressure, the warmer the tank must stay to maintain it, and the higher the flow, the more prone the tank is to cooling off. Tanks can be immersed in room-temperature or warm water (never use water above 120°F, nor any type of flame heating or other heat source that exceeds 120°F or provides a means of ignition) to increase their temperatures, but there is still a practical limit on capacity. A propane flow that will empty the tank in two hours is the maximum practical flow on that size of tank, even with a water bath. For a 20-lb barbecue tank, that flow equates to approximately 350,000 BTU per hour, which is large by most hobby standards. For a 1-lb disposable tank, this value is approximately 21,000 BTU/hr, which equates to a small burner in the 3/8" to 1/2" range at moderate pressure.

Tanks that have been used heavily enough to create condensation, or that have been submerged in a water bath, should be dried off immediately to prevent rust. Not only will suppliers refuse to fill a heavily rusted tank, many will also refuse to fill a tank that has been repainted (in case the paint is hiding structural damage to the tank), so any chips or scrapes in the paint must stay and be protected from rust manually. Tanks obtained at exchange stations are generally in poor shape compared to those that have been purchased new and taken care of, and tank exchanges are generally more pricey than fill stations, so endeavor to find a local fill station if you plan on using a lot of propane.

Most foundry burners are connected to their tanks by a standard propane fitting (POL fitting) that adapts the tank to the regulator, then the regulator with optional pressure gauge (highly recommended for kiln firing and other low-pressure applications), and then a flexible propane hose that connects to the burner-side plumbing with a 3/8" flare fitting. The POL fitting-to-tank connection does not need thread sealant, nor should the flare fitting if properly tightened, but the pipe thread fittings on the regulator and gauge, and any pipe-thread plumbing on the burner, require a thread sealant. Either use PTFE tape or PTFE-containing pipe dope, never non-PTFE imitation pipe tape. Pipe dope tends to seal more readily than tape, but is messier to remove and replace if disassembly is necessary. Always check for leaks with soapy water every time a connection is assembled. Burner-side valves are of limited utility when there is only one burner per system, but are necessary when multiple burners are manifolded onto a single regulator.

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The flexible propane hose is easy to burn through with a droplet of metal or a hot tool, so keep the section near the furnace shielded with sheet metal, and keep hot objects away from it. Permanent installations (such as a bench supply of propane or a supply line run from a stationary tank) should be assembled out of soldered copper, leak-tested galvanized steel pipe, or soft copper line with flare fittings. Never run liquid propane or propane that is at tank pressure or not protected by a flow limiter through a soft line. Hard lines are far more resistant to damage from hot objects or puncture, and these high-volume propane applications have the potential to be extremely dangerous in the event of a line breach. Also, do not connect copper or brass fittings to iron in a permanent application without an electrical isolator—otherwise galvanic corrosion will cause the joint to leak over time.

Burners

The burner detailed later in this section is a naturally-aspirated venturi burner, based on the Reil family of burners. Burners of this same general design display remarkable stability over a broad range of pressures, outclassing other simple burner designs, and unlike forced-air burners, they need no blower or separate power supply, making them simple, inexpensive, and portable. Of course, there are many designs for gas-fueled burners, but a detailed description of their construction is beyond the scope of this tutorial. Of note are forced-air burners, which can burn low-pressure natural gas and other fuels delivered at much less than 1 PSI, something naturally-aspirated burners cannot practically or efficiently do.

Anatomy

Naturally aspirated propane burners are simple devices with no moving parts, but it still helps to know some terminology.

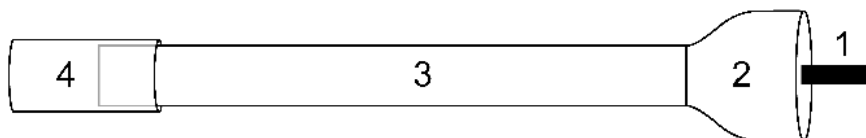


Figure IV-1: Diagram of propane burner parts

Starting from the rear of the burner in Figure IV-1, the fuel gas supply (1) enters the burner, where it terminates in a small hole known as the orifice. The pressurized gas blows into the venturi (2), drawing in combustion air with it. On some burners, a choke (not pictured) is added to the inlet of the venturi to control the amount of air mixing with the fuel. The fuel and air mix and stabilize in the burner tube (3), and burn inside the flare (4), which has a pressure step between it and the burner tube to hold the flame. In a furnace, the inside of the tuyere is commonly made to act as a burner's flare, as a steel flare would melt or oxidize over time, damaging the refractory from the fluxing action of the oxide. When the burner is being used in free air, a steel or iron flare is needed to hold the flame.

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Construction

The burner detailed here has a bore of 1/2" (nominal), and a practical output between approximately 7,000 and 74,000 BTU/hr. This design can be scaled up or down as needed, as long as the proportions between the various parts are kept roughly the same. Here are some rough ratios in the sizes of the components:

The venturi inside diameter (ID) should be from 1.4 to 1.7 times the burner ID.

The burner ID should be 20 to 30 times the orifice diameter.

The burner tube should be roughly 10 times as long as its ID.

The flare length should be about 1.5 times as long as the ID.

The materials needed are as follows:

- 6" long x 1/2" (nom.) dia. black iron pipe
- 1/2" x 3/4" (nom.) black iron pipe reducer
- 0.025" (nom.) MIG welding contact tip
- 3/8" x 3/8" x 2" square steel stock
- 3/8" male flare plug (or other fitting that fits the end of your propane hose)
- 1/2" black iron straight pipe coupling or 2" x 4" piece of steel sheet (18 to 28 ga.)

Start by laying out an accurate center line on the 3/4" side of the pipe reducer. Then measure 3/16" on each side of that center line to create a bar 3/8" across. Cut, grind, or mill out the material inside this bar 3/8" deep, so the 3/8" square stock fits snugly and flush with the surface of the reducer. Cut the stock to length and braze or weld it in place. (Brazing is preferred because welding cast iron to mild steel makes for a poor joint; however, this joint will not be under severe mechanical stress.) Epoxy can also be used if care is taken not to expose the joint to excessive heat. Next, accurately lay out and drill a 1/4" hole through the

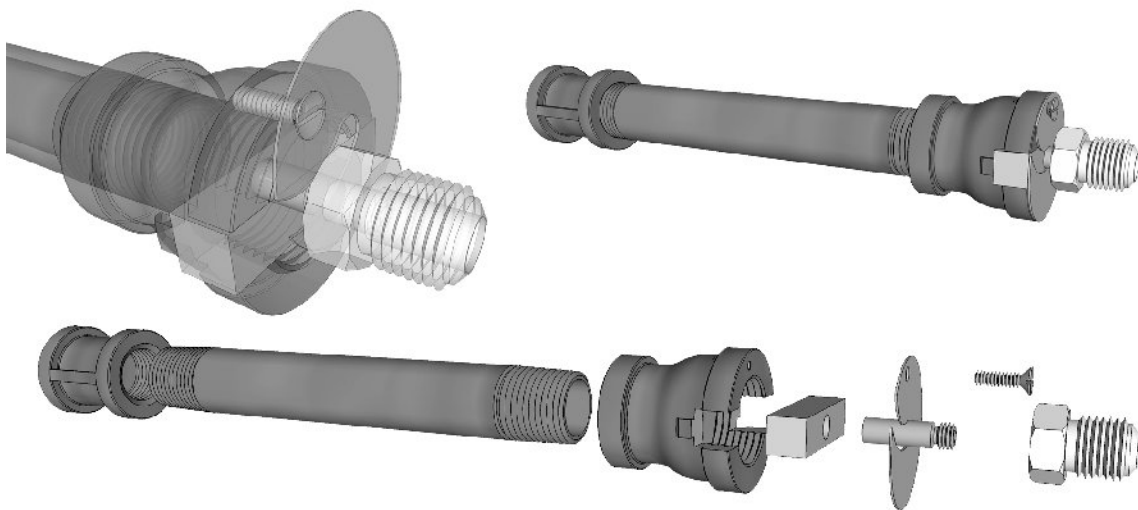


Figure IV-2: 1/2" burner assembled and exploded views

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center of the bar so that it points down the burner tube when the burner is assembled. (You may need a different size hole if your MIG contact tip is not 1/4" diameter.) The accuracy of this step is critical—if the jet is misaligned, the burner will not burn correctly. A drill press (or, better yet, a lathe) is the recommended tool, but you can hand-drill the hole if you pay meticulous attention to detail. Figure IV-2 shows how the burner parts fit together when correctly assembled.

After the hole is drilled, insert the MIG contact tip so the threaded end is pointing away from the burner, and the smooth end is flush with the far side of the 3/8" square stock. If the fit is reasonably loose, braze it in (be careful to keep the brass and flux well away from the orifice hole; if the hole becomes clogged with copper oxides, a few drops of muriatic acid will clean it out). Again, epoxy can be used in low-heat applications. The stronger joint made by brazing will make the burner more mechanically durable. If the fit is tight enough to preclude assembly by hand, an interference fit achieved by heating up the bar stock until the hole expands to fit the tip, then cooling to shrink the hole around the tip, will be adequate. If your tip is not within a few thousandths of an inch of 1/4", you will have to drill a different size hole in the crossbar. Now, drill a 1/4" hole in the plug end of the flare plug, slide it on the threaded end of the tip, and soft solder or epoxy it in position. It's a good idea to leave about a 1/4" gap between the crossbar and flare plug so you can make a swiveling choke later if you want.

If you have elected to make a flare out of the cast iron pipe reducer, grind or machine the threads out of one end. The object here is to make a smooth, round, straight-walled inner surface that is concentric with but bigger than the burner tube. You may want to screw the burner tube into the flare for reference—the flare should be ground or machined all the way back to the end of the burner tube.

If you have elected to make a flare out of the sheet metal, just wrap it smoothly around the pipe. You can hold it on with a pipe clamp or tighten up the wraps so spring pressure holds it still. You can experiment with the overhang over the end of the pipe, but start at about 1".

A side note on tapered flares: The taper, as far as I'm aware, produces no discernible benefit, and probably actually hurts burner performance compared to the sharp pressure "step" at the end of the burner tube. Why? Because when propane (or anything, for that matter) burns, the flame front travels at a specific speed. The design objective for a burner is to make sure that the gas within the mixing tube is traveling faster than the flame front (otherwise it'll burn in the tube), and the gas within the flare is traveling slower than the flame front (otherwise the flame front is outside of the burner, which doesn't work very well since once that gas starts mixing with ambient air, the fuel mixture shifts toward the lean end of the spectrum and the flame goes out).

A smooth taper between too fast and too slow means that if the speed of gas going through the burner changes (with an operating pressure or choke adjustment), then the flame front

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moves around. At the ends of the pressure range, the front is very close to either the end of the flare or the end of the burner tube, and a bit of turbulence could "bump" it over the line. A sharp step creates lots of turbulence (which means an easier time burning in that particular spot) instead of the smooth laminar flow of a tapered design, and holds the flame front still, so it's less susceptible to this kind of instability.

Now, screw the burner together, hook up the propane, and test it for leaks. If you built it well, it should fire right up and burn neutrally. If you have to choke the flame slightly, you can do it with a bit of masking tape or build an adjustable choke (good for kiln burners) out of sheet metal.

Adjustable Choke

The layout pictured in Figure IV-3 gives a choke for 3/4" pipe size burners using a 1" pipe size venturi opening, and Figure IV-2 shows the operation of the installed choke. It can be scaled up or down based on the same principle.

To lay out this choke, start by making a diagram of the venturi end of the burner. Find the center (point A in the diagram) and scribe a circle (1) equidistant from the inside and outside walls of the venturi. This circle will determine the center of the choke's pivot, which needs to be in metal wide enough on both sides to tap for a pivot screw. Then measure 1/8" down from the top of the crossbar where it intersects the inside wall of the venturi. This creates another point (B). With your compass on the same setting as it was for circle (1), swing an arc (2) centered on (B). The intersection of these arcs (C) is the pivot point of the choke. You can swing another arc (3) using the same setting to check accuracy—it should intersect both points (A) and (B). Also mark out arcs (4) and (5), 1/8" on either side of (3). These form the clearance path for the propane injector orifice. Make this path slightly larger than nominal so it will clear the orifice without needing to be perfectly made. Mark a 1/4" diameter circle centered at (A) to round off the end of the clearance path, and layout is complete. With this layout method, the clearance slot for the orifice will always fall directly over the crossbar, allowing the choke to close off airflow completely.

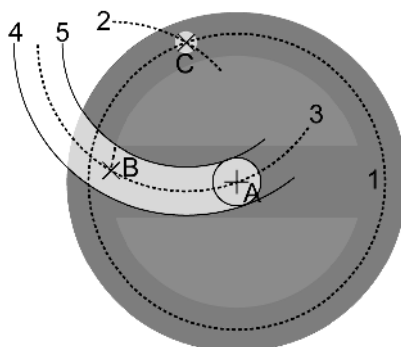


Figure IV-3: Choke for 3/4" pipe burner

Construction is simple: cut the choke out of sheet metal, drill a hole for the pivot, and mark and drill a similar hole on the venturi. Tap this hole for a screw to act as a pivot, snug the screw down so the choke can turn but is held in its setting by friction, and apply a chemical

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threadlocker to the screw's threads so it doesn't unscrew when the choke is moved. This adjustable choke is generally not necessary for a foundry burner, because the choke only needs to be adjusted below approximately 5 PSI, but it is very nice for a kiln burner, which will often need to be choked off at a range of mixtures for very low heat settings.

Tuning

Most burners made to the dimensions specified should burn neutrally, but very small burners may tend to run slightly rich because the crossbar takes up too much room in the venturi (unfortunately, the fix for this is to make the crossbar smaller, which is difficult to do after the burner is built), and larger burners may tend to run lean because the crossbar takes up less room in the venturi. This is easily fixed by choking the burner. Very large burners may need to be choked a bit to light easily.

A burner running neutrally produces a flame much like that of a blowtorch, with a bright blue inner cone and a fainter blue outer cone. As air is reduced and the flame gets richer, the flame will shift color from blue to blue-green, then green, and will eventually start to curve upwards and burn with less noise. The inner cone will also lengthen and blend with the outer cone. A very rich flame is bright yellow, leaves soot on surfaces, and rises almost straight up. This is termed a “lazy flame.”

As air is increased from a neutral flame, the inner cone gets shorter and brighter, and the outer cone gets fainter and shifts from blue to a purplish color. Too lean, and the burner blows out or refuses to light. If a propane burner is proving difficult to light, the first thing to do is choke it and make sure the problem is not caused by a lean mixture.

Because it is generally easier for the beginner to tell a rich flame from a neutral flame than a lean flame from a neutral flame, the best way to find a burner's neutral setting is to start with an obviously rich flame and open the choke gradually until the last tinge of blue-green disappears from the flame and it becomes entirely blue. This is a neutral flame. Bear in mind that backpressure, such as that caused by a furnace, tends to make the mixture slightly richer, so the choke may need to be opened some for furnace use. The burner will also get leaner at high pressures, as the efficiency of the venturi increases, and richer at low pressures. At very low pressures (less than 1 PSI, generally), the burner may need to be choked down to produce a very rich flame in order to prevent burning in the tube. Kiln firings are often started with a small lazy flame that looks like a candle flame—the term for this is “candling.”

Generally, a neutral flame should be maintained for melting and other operations. It heats the most efficiently and can achieve the highest furnace temperatures. A slightly lean flame will produce extra dross and can damage steel and clay-graphite crucibles and certain refractories over time, but will prevent or reduce hydrogen gas dissolving in the melt. A slightly rich flame will protect steel crucibles and certain refractories, but will damage others (silicon carbide and various nichrome materials prefer a lean atmosphere), and will

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reduce dross at the expense of dissolving more hydrogen gas in the melt. The flame should not be allowed to become very rich (except for producing certain effects on pottery) or very lean; such activities waste fuel and can damage refractories severely.

Section V

Refractory

In order to be able to melt metal, it is necessary to have furnaces and crucibles that can tolerate the heat. Refractory comes in many different forms, each with different applications, benefits, and drawbacks.

Commercial Refractory Products

Commercial refractory products come in a wide variety of cements, mortars, textures, and preformed shapes to meet the needs of commercial and industrial foundries and other high-temperature manufacturing applications of all types. These products may be slightly difficult to obtain in small quantities, and are usually somewhat expensive, but they are formulated to perform superbly in their given applications, and will provide a consistent high level of performance without the difficulty associated with formulating homemade ceramic recipes. The difficulty in using commercial products generally lies in selecting the correct product for a given application, as hobby melting and casting is often very different from similar processes done in an industrial setting.

Castable Refractories

Castable refractories are generally composed of aluminosilicate grog and insulative material bound by calcium aluminate cement. Other formulations exist for specialty applications, such as zirconia and pure silica-based refractories, phosphate binders, and so forth, but the basic calcium aluminate refractory is what will be most commonly used for hobby applications.

Dense Castables

Dense castables are designed to line the insides of large industrial furnaces and ladles, where tons of scrap are dumped in at a time, the walls may see direct metal contact and corrosive fluxes, and the furnaces are designed to run eight to ten hours a day for years without repair or patching. A large industrial scrap melter might have a three to four inch thick hotface of dense castable in front of a foot or more of insulating castable or insulating firebrick. If you're thinking this is a bit excessive for the average hobbyist, you're absolutely right. Dense castables have very little utility in a large majority of homemade furnaces, because their high density and low insulating value wastes enormous amounts of fuel and slows melts considerably.

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Most refractories, once fired, are made of aluminosilicates that have very similar density and thermal properties to each other, so as a crude estimate, one could say that the insulative value of a refractory is directly proportional to the amount of air trapped within the ceramic, or inversely proportional to the refractory's bulk density. In other words, less dense refractories insulate better than more dense refractories, and they also heat up faster, so they make furnaces more efficient. Dense castables range between 120 and 180 lbs/ft³, some of the most dense refractories available. For a reference, most fired clay ceramics range between 100 and 160 lbs/ft³, unless insulative material has been added.

Dense castables do have limited use in the hobby world, as a super-duty hotface for direct-melting reverberatory furnaces and large-volume scrap melters. They are nearly immune to fluxes and mechanical abuse, so they should be used only where this type of treatment makes them most practical. A hotface of 1/2" is sufficient for a furnace of 12" to 16" bore, which makes an exceptional hybrid crucible furnace and scrap melter. The hotface can also be made freestanding and the area behind it backfilled with loose insulation, such as perlite, diatomaceous earth, or bulk ceramic fiber, which has the potential to lower construction costs.

Dense castables can be made much more attractive to the hobby caster by adding air pockets in the form of a foaming agent or burnable materials. They are typically made with a low percentage of binder to other ingredients, so they will be able to accept less additives than clay-based refractories, but the trade-off is the lack of shrinkage and favorable firing schedule that clay-based products lack. Since different brands and types of castable have different formulations, it may take some experimenting to determine the maximum allowable amount of additives before strength becomes unacceptably low. The coarse grog may also be screened out of the castable to increase the amount of additives the mix can hold, or to create a brushable coating for ceramic fiber or steel crucibles. Some mixes will work better for this than others.

Insulating Castables

Insulating castables are quite sturdy compared to the fragile matrix left behind when a clay/foam refractory is fired, but not as strong as dense castables or dense fired ceramics. They have a density of 50 to 80 lbs/ft³, so insulation is good enough to build a monolithic furnace with the roles of both insulation and hotface taken up by an insulating castable, but a furnace built this way will still be markedly less efficient than what can be achieved with a dedicated hotface and insulation layer. They are strong enough to use as a hotface in front of a more fragile insulation, though they are less durable and flux resistant than dense castables. Burnable materials may also be added to increase insulation at the cost of strength. Again, different formulations will accept different amounts of material.

In industrial applications, insulating castables are generally used solely as a backing layer, never in contact with direct flame or furnace contents. They are, however, suitable for

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molten metal contact and direct flame contact on the timescales that most hobbyists require. Life will be shorter than that desired in industry, but not a concern for hobbyists.

Working With Castable

Castables are generally considerably more forgiving to fire than clay, and do not shrink significantly on drying or firing, so they can usually be used to patch cracks with reasonable success, and shrinkage does not have to be compensated for in furnace design.

Water-based (calcium aluminate) castables, unless a specific amount of water is given on the bag or in the data sheet, should be mixed so that a lump of the material held in the hand will flatten and sag, but not run through the fingers. It should be able to be tossed up in the air one foot without crumbling (too dry) or splattering (too wet).

For castable refractories that use phosphate binders or other formulations, the mixing and installation instructions will vary depending on the manufacturer, and should be stated in product literature available from the manufacturer. It is worthwhile obtaining any available product literature for your specific castable, because such literature will contain mixing, firing, and usage instructions more suitable for that product than any generic instructions found here. That being said, the product literature will necessarily specify conservative drying and firing schedules to ensure the success of large, thick-section industrial refractory pieces, and it is usually possible to considerably exceed the recommended drying and firing rates for smaller hobby applications without any catastrophic failure.

Working with mixed castable is much like working with concrete, in that it is poured and vibrated into place instead of being rammed or formed in a plastic state like clay. Like concrete, molds having small section thickness will be difficult to fill. This poses a problem for small efficient furnaces: a 1/4" section thickness is extremely hard to cast in a single piece. There are possible workarounds to this, such as making a mold in two pieces that is filled with castable and then closed to force the material into the proper thickness. In any case, be diligent to avoid trapping air bubbles, which can cause cracks and spalling during firing.

Wet castable can usually be cast or bonded onto cured castable (fired or unfired) if the surface it is bonding to is rough enough for good mechanical contact and dampened beforehand to ensure that the curing castable does not lose water too quickly to the porous surface of the cured castable. If the mechanical contact between the surfaces is intimate enough (on the order of the space between individual particles of the unfired castable), the surfaces will sinter together on firing. Because such a joint may only partially sinter, it is advisable to avoid designs that require such joints to take large shear or tensile loads. If a stronger bond is necessary, there exist commercial mortars designed to securely bond fired ceramic surfaces together.

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Like concrete, calcium aluminate castables cure through a chemical hydration process, gaining strength over time. Unlike concrete, castable in the cured but unfired state is generally not very strong, and because the castable needs to be dry before firing, wetting the curing castable surface, as commonly done for concrete, will significantly lengthen the drying and curing process with no benefit. Castables rely on the sintering process for their final strength, therefore the curing process does not have to proceed to completion to yield a mechanically sound product.

Once fired, castables are typically very strong and very tough. Insulating castables will have lower strength due to the presence of insulating grog, but dense castables are commonly much stronger than common concrete. Cutting or chiseling castable after firing is possible, but it will be a very difficult and very labor-intensive process, and is not recommended.

Suitable forms for castable include anything that will not hinder curing by absorbing water, and can be removed from the cured castable. My preference is polystyrene foam sheet, which is cheaply available in various thicknesses (as insulation for houses), easy to shape, and can readily be burnt out before or during firing. Nonporous forms on all sides of the castable will retard drying, so if the castable is damp but cured, remove the forms and allow to dry before firing.

Care is needed when casting a castable product against other refractory surfaces. The binder of castable may absorb into insulating firebrick or ceramic wool if cast directly onto the surface, leaving the grog in the castable inadequately bound. For insulating firebrick, unless the brick is extremely porous, wetting the surface of the brick before casting should be enough to ensure bonding between the two without adversely affecting the castable. If the brick is intended to stay separate from the castable (which will make replacing the hotface without damaging the insulation much easier), or when working with ceramic wool, place a thin sheet of plastic between the two. This will burn out during firing, and in the meantime, it will keep the castable from absorbing into the insulating layer.

Castable can be fired much faster than clay-based ceramics, but it should still be fired relatively slowly. As a general rule, wait until the castable is bone dry before firing, and if you notice water or steam exiting the castable during firing, slow down or stop the heating until the water disappears. Make an attempt to fire near the maximum operating temperature (without exceeding it!) for approximately thirty minutes to ensure maximum strength. If the castable is underfired, this can typically be fixed with a second firing and no adverse effects, unlike clay-based ceramics which will often be weak enough to crack or disintegrate if handled when severely underfired.

Do not apply any coating to the castable surface before firing. Rigidizers and reflective coatings tend to seal the refractory surface, which will cause spalling during firing as the water in the unfired castable cannot escape.

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Mortars and Rammable Refractories

Some commercial refractory cements, instead of being castable refractories designed to be poured like cement, are mixed in a rammable or plastic formulation that can be manipulated like clay, or a mortar that is designed to join firebricks and patch cracks. Commercial “fireplace cement” is a product that may or may not work in a hobby setting, but it is designed (as the name would seem to indicate) for fireplaces, not industrial furnaces or other high-refractory applications. Many of these rammable refractories are fairly specialized products, and except for crack-patching mortar, these products are not commonly very useful in a hobby context.

Firebricks

Firebricks are composed of pre-fired ceramics, commonly clay-based, in a selection of standard shapes and sizes. Because the bricks are fired by the manufacturer, they cost significantly more than commercial products that have not been fired, but they are also a simple and quick way to make a furnace or kiln. Insulating firebricks can easily be carved to shape, and firebrick furnaces can be disassembled or rearranged easily without damaging the components.

Dense Firebrick

Dense firebrick is used in industrial applications similarly to dense castable, and is not terribly useful for hobbyist furnaces. It can be used to make plinth blocks, to support the bottom of a furnace under the crucible, and similar applications, but it should not be used in a furnace lining unless the furnace is a very large direct-melter that would benefit from the square shape of the bricks. The bricks are typically between 100 and 160 lbs/ft³.

Insulating Firebrick

Insulating firebrick is quite expensive, but tends to be a better insulator than insulating castables, with typical density of 20-30 lbs/ft³. The bricks are very soft and easy to carve, so a furnace can be made out of bricks carved to shape and clamped together with no need for any mortar or firing stage. This is good for small furnaces, and the unmodified bricks can be rearranged to make impromptu furnaces and forges for heating oddly-shaped items. Flux resistance is low but higher than that of ceramic fiber. A coating of a reflective rigidizer or a thin hotface will improve flux resistance. Like insulating castable, it is typically only a backing material in industry.

Ceramic Fiber Products

Industrial applications of ceramic fiber materials (pressed boards, rope for door seals, fiber batts, and bulk fiber fill) are generally limited to kilns and ovens instead of furnaces, or if used in furnaces, protected by dense and insulating castables. The materials are quite

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fragile compared to castable refractories, and have almost zero flux resistance, but are far more insulating than other industrial products. With proper protection, they are invaluable materials to hobbyists.

Ceramic fiber products are sold in varying densities, but the most common is 8 lbs/ft³. For comparison, ceramic/foam refractory with a ratio of 1 part ceramic to 4 parts foam has a density of approximately 15-30 lbs/ft³.

Due to the fibers' fragility, and the respiratory hazard they present, they should be coated with something for any furnace operation. A commercial rigidizer, or a thin brushed-on coating of clay slip, will mitigate the respiratory hazard and offer some measure of flux resistance. A thin hotface made of clay-based ceramic or insulating castable will further protect the fibers, particularly from mechanical damage. Furnaces made in this manner represent the pinnacle of hobbyist furnace efficiency, and ceramic fiber materials are much easier to work than clay-based products. They do present a significant respiratory hazard when being installed, similar to that of fiberglass house insulation. The fibers cannot support more than their own weight, so some support structure will be needed to support a crucible, and additional supports will be needed for a hotface of any substantial thickness.

Ceramic fiber products are somewhat expensive as a raw material compared to clay and foam, but once firing costs and labor are figured in, they become attractive to the hobbyist with limited time. They are also flexible instead of brittle, so they are more resistant to mechanical damage than fragile fired clay/foam insulation.

Rigidizers and Reflective Coatings

The primary purpose of rigidizers is to form a stiff coating on ceramic wool, preventing stray fibers from becoming airborne and increasing the wool's durability. Many rigidizers serve a dual purpose as highly reflective coatings, which can improve furnace efficiency 25-30% by minimizing radiant heat loss. (At high temperatures, radiation, not convection, is the primary means of heat transfer.)

ITC-100, made by International Technical Ceramics, is the most well-known rigidizer and reflective coating for ceramic wool. The product is very expensive, but will pay for itself in saved fuel with heavy use. It also reduces the operating temperature of the refractory somewhat by reflecting a large portion of radiant heat, allowing the furnace to run at higher temperatures without damage.

Refractory clay slip is suitable for a rigidizer, but does not possess any better reflective properties than the raw ceramic fiber, so efficiency gains will be minimal or nonexistent. On the other hand, clay slip is much cheaper than an ITC product. Other brands of rigidizers may offer performance similar to that of ITC-100 at an intermediate cost. Castable with the grog sieved out, mixed to a paintable consistency, is also suitable for a rigidizer and performs similarly to clay slip.

Clay-Bonded Refractory Ceramics

The only option for a hobbyist that needs high temperature tolerance in a refractory but does not want to use commercial products is to blend a refractory ceramic from base ingredients. The most accessible source for many of these ingredients is a ceramics supplier, because many of the same ingredients are used in artistic and industrial pottery. This generally limits homemade ceramics to clay-bonded types; calcium aluminate and phosphate-based binders as used in commercial recipes are typically much more expensive and difficult to obtain than clays. Pressure or organic bonding processes as used in some industrial processes are typically out of reach of the hobbyist as well, because these either require much higher firing temperatures or high-pressure machinery to compact the refractory.

Ceramic Chemistry Overview

In order to be able to design and formulate a ceramic recipe for a specific application, a basic knowledge of the chemistry at work is required. Ceramic chemistry is a very complex subject, but even a basic understanding can be helpful to the hobbyist.

Understanding Phase Diagrams

Phase diagrams typically display the phase-change (change between solid and liquid, and sometimes gas) behavior of a single substance over varying pressures and temperatures, or the behavior of two or more substances over either varying pressure or varying temperature. In ceramics and casting-related work, the most common type of phase diagram is the binary diagram with varying temperature. Phase diagrams of ternary and higher-order systems can be found (and can be quite useful for complex ceramic interactions), but can be quite difficult to interpret. Also, phase diagrams are typically made directly from experimental, not theoretical, data, so finding a diagram of a particular complex system may be difficult or impossible.

The phase diagram in Figure V-1 is a fairly basic binary diagram, with the relative concentrations by weight of the two fictional substances A and B displayed on the X-axis (some diagrams may use mole fraction instead of weight or mass) and the temperature in degrees Celsius displayed on the Y-axis. There is a third fictional substance, substance C, which is a crystal that forms with approximately 38% of substance A and 62% of substance B. (This is a fairly simple diagram with only one such

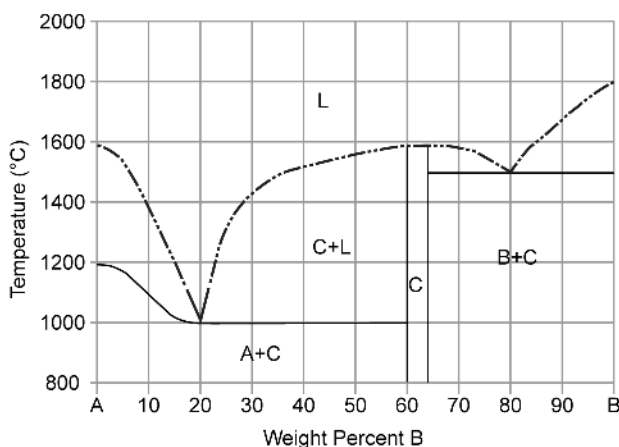


Figure V-1: Example phase diagram

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crystal phase—some materials have quite a few, and the formation of those crystals often depends on time as well as temperature.)

The solid line indicates the solidus of the material, the temperature below which none of the material is melted. Since the crystalline form C is favored, as much C forms as possible, and the rest of the material is substance A or substance B, depending on what is “left over,” so to speak. Keep in mind that except in circumstances of carefully controlled crystal growth, crystals of C will be evenly distributed within the material down to the microscopic level.

The dashed line indicates the liquidus of the material. Below the liquidus line, the material is in a “slushy state” with solid crystals of C distributed in a liquid matrix of either A or B (depending on which one is in excess). Above the line, all of the material is molten. Where the liquidus and solidus lines touch is termed an eutectic point, which will represent the lowest liquidus temperature of a given composition. Note also that where the composition forms only C, the solidus is about 100 degrees higher than at any other point on the diagram. If making a refractory with materials A and B, this concentration would yield the highest solidus, and thus the most temperature-tolerant refractory. If attempting to flux refractory material B by adding A, the eutectic at 80% A and 20% B would yield the lowest liquidus point, but would use a relatively high concentration of flux. The eutectic at 20% A and 80% B uses less of material A, but also requires a higher temperature to reach the melting point.

Importance of the Material Source of Ceramic Ingredients

If attempting to make and fire a sintered ceramic, eutectic points are generally avoided. The gap between solidus and liquidus is where liquid-phase sintering takes place, and if the liquidus is reached during firing, ware will collapse. Rapid changes between solid and liquid are rarely desirable in firing ceramics. Note that particle size and material composition plays a part in the sintering of ceramics in addition to the properties gathered from chemistry alone. For example, in liquid phase sintering, no melting will take place below the lowest eutectic consisting of no more than two materials in the ceramic composition, even if there are more complex eutectics that have lower melting points. (“Material” here is distinct from the actual content of the substance—each separate bag of powder, be it a clay, a pure oxide, or a complex pre-melted blend of fluxes, is one material.) The reason for this is simple: no more than two different types of particles will touch each other at the exact same point, so no higher-order liquid phases can form without first having an initial liquid phase to dissolve the materials together. Thus, in ceramics applications, the material source of an oxide (or other compound) is as important in the initial firing as its concentration. Also, particle size plays a role: larger particles take more time at temperature to dissolve, which equates to firing at a higher cone.

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Fluxes

Fluxes are of great importance to both the metalcaster and the ceramist. In casting metal, the primary use of a flux is to remove oxides from the melt, thus allowing the metal to flow easier and preventing those oxides from finding their way into a casting. In conventional ceramics, fluxes are used to reduce the melting point of clay bodies and glazes, allowing them to be fired more easily. In the kind of high-temperature ceramics that refractory-making falls under, an understanding of where fluxes are found is important, so those materials can be avoided in the recipe. Generally, for a refractory, the flux content should be as low as possible.

Acidic, Basic, and Neutral Refractories

Even among refractory materials, there are circumstances where a material can act as a flux. For example, silica and magnesia both have extremely high melting points, but a combination of the two will melt at a much lower temperature. The reason has to do with the refractory's pH.

Silica, along with siliceous clays and zirconia, is an acidic refractory. Magnesia, calcia, and dolomite are basic refractories. Alumina, mullite, silicon carbide, and carbon are neutral. More generally, any metal oxide of the form RO_2 is acidic, any of the form R_2O_3 is neutral, and any of the form RO or R_2O is basic. Mixing acidic and basic refractories will cause them to flux one another; mixing basic and neutral refractories or acidic and neutral refractories will do the same to a lesser extent. A refractory containing only elements of one group is likely to have a melting point no less than the lowest-melting member of that group. (Generally, aluminosilicates that are neutral or slightly acidic are used in most refractories, since many of the basic refractories react with water, atmospheric carbon dioxide, or other common substances at room temperature, and some of them can be quite caustic.)

Classification of Fluxes

Fluxes can be sorted into three broad categories: organic fluxes, salt fluxes, and glassy fluxes.

Organic fluxes, such as rosin and beeswax, melt and boil at low temperatures and are suitable only for the fluxing of white metals. Because these fluxes have very low melting points, they can be used to flux lower-temperature metals where many inorganic fluxes would stay solid and do no good.

Common salt fluxes are the chlorides and fluorides of sodium, potassium, magnesium, and calcium. Of these, the chloride fluxes (either singly or in an eutectic blend) are mostly suitable for the melting of aluminum and magnesium. (Magnesium is a very light metal and floats on most fluxes; therefore a cover of inert gas, or gas-producing slag like sulfur, is

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needed to keep the metal from burning in air.) Certain eutectic mixtures of the chloride salts melt at low enough temperatures to flux the higher-melting white metals, such as zinc. Also, certain transition metal chlorides, such as zinc chloride, can be used for the fluxing of white metals. Chloride salts have high vapor pressures when molten, and thus evaporate too quickly to be useful in fluxing bronze and higher-melting materials.

Fluoride fluxes (the principal one being fluorite, CaF_2) have higher melting points and vapor pressures, and are primarily useful for the fluxing of high-melting point materials such as iron and silicon. They have a somewhat more viscous nature, as compared to the extremely fluid chloride salts, and can be used successfully as semi-glassy fluxes with the addition of silica. They attack aluminosilicate refractories and crucibles vigorously, especially at high temperatures.

Glassy fluxes are composed of oxides, mostly the basic oxides from groups I and II (lithium, sodium, potassium, magnesium, and calcium), which can form low-melting eutectics with each other and silica. A notable exception is boron oxide, B_2O_3 , a powerful and relatively low-temperature flux as well as a glass former. Silica and alumina are used as glass formers in these fluxes, both forming eutectics with the fluxing oxides and producing a viscous, molten glass structure for the fluxes to cover the melt with. Glassy fluxes are the go-to fluxes for copper and its alloys, both because the melting ranges can be adjusted to a suitable temperature and because the viscous glass cover dramatically reduces the boiling out of zinc from the alloy. Glassy fluxes can be re-used for multiple melts, unlike the other fluxes which tend to get discarded with the dross. They are also the fluxes that play roles in the firing of ceramics. Glassy fluxes attack aluminosilicate materials vigorously, and over-use of these fluxes dramatically shortens the life of ceramic crucibles. (Note that B_2O_3 reacts with aluminum and several other metals, and is thus unsuitable for use with them despite its low melting point.)

Shrinkage

Reliance on clay as a refractory binder presents a problem: clay shrinks, once as it dries and then again as it is fired. Not only does this shrinkage present problems with the dimensional tolerances of fired refractory pieces, it also provides a mechanism through which cracks can form. If the ceramic piece is dried or heated unevenly, different parts will shrink at different rates, creating stresses which either weaken the material or crack it. Much of the difficulty in formulating and working with a homemade refractory ceramic lies in overcoming the problem of shrinkage.

Causes of Shrinkage

Clays are composed of microscopic (on the order of 1 micrometer in diameter) particles that suspend in water. This interaction between the clay and water is what gives clay its plasticity, and also what causes it to shrink when dried. As water leaves the clay body, the particles move closer to fill the space taken up by the water, causing a macroscopic effect

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of uniform shrinkage. Non-clay materials (sand, shredded foam beads, grog) are not bound by the water: they are held in place by the clay matrix around them and follow the movement of the clay. Therefore, only clay contributes to the drying shrinkage of a clay body, and adding non-clay materials will reduce the aggregate shrinkage proportionally. (Be warned that some materials which expand upon absorbing water, such as sawdust, can create unpredictable, undesirable effects on drying. That's one reason why I prefer foam: it absorbs a minimal amount of water and does not swell.)

The mechanism by which shrinkage occurs on firing is different. When a ceramic (whether clay-based or not) is fired, the high temperature corresponds to a higher average movement of the atoms that make up the individual particles. If the temperature is high enough and the particles small enough, the atoms start to move into adjacent particles where they touch. This is termed diffusion bonding, or solid-phase sintering. As the particles move into each other, center-to-center distance decreases and macroscopic shrinkage is observed. Note that this effect occurs where particles touch: the larger the particles, the fewer points of contact there are. Therefore, under the same firing conditions, identical materials will shrink less, bond less firmly, and have higher fired porosity if the particle size is larger. Clays typically have very small particles compared to other materials (200 mesh corresponds to a particle diameter of roughly 120 micrometers), so while non-clay materials do contribute to firing shrinkage, clay materials contribute to a much greater degree in the vast majority of cases. Also note that the particles must be in contact for diffusion bonding to occur. Particles simply poured into a container as powder will only form the occasional inter-particle bond. Instead, the contact must be facilitated by using plastic clay to surround the particles with clay particles, or using very high pressure to press the powder into a cohesive shape.

There is also a second mechanism by which particles can sinter together. When fluxing materials diffuse into the refractory particles around them, an eutectic is often formed which is liquid at the firing temperature. This fluxing liquid will start to dissolve more refractory and flux as long as the firing temperature is kept hot enough for it to remain liquid, until either all flux is exhausted and the composition of the liquid phase contains enough refractory that it becomes a solid again at the firing temperature, or until enough refractory is dissolved that the piece collapses under its own weight and starts behaving like a liquid. It is worth bearing in mind that this second approach constitutes failure of the refractory, and that the liquid phase typically speeds up diffusion considerably over solid-phase processes. Even with large particles of flux, if the total flux composition is too high, the refractory will fail over time as the liquid phase re-melts with every use and dissolves more and more of the solid refractory structure.

This potential for failure, however, does not mean that fluxes are necessarily bad. Liquid-phase sintered ceramics tend to be stronger and denser, and fire faster, than equivalent (or as equivalent as possible for purposes of comparison) diffusion-bonded materials. The flip side of this coin is that the vitreous solidified liquid phase tends to make the ceramic more brittle, and thus more susceptible to thermal shock (not to mention the fact that many fluxes have high coefficients of thermal expansion) than diffusion bonded materials. For high

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temperature metal-melting applications, flux content needs to be kept very low and individual fluxes need to be chosen carefully.

Reducing Shrinkage

Shrinkage should be minimized in refractory ceramics for two reasons: one, because high shrinkage requires a much more even, and therefore slow, drying and firing in order to avoid cracking or warping of ware; and two, because high shrinkage will change the final dimensions of the piece, often unpredictably with the low-tolerance firing procedures common in the hobby world.

The first step towards minimizing shrinkage is to minimize clay content. Clay blends for pottery-making commonly contain 50% raw clay or more. This gives these blends high plasticity for wheel throwing and other forming methods, but also requires difficult drying and firing methods, and even so, it would be extremely difficult to produce a furnace wall of 2" to 3" section thickness with one of these clays and have it dry without cracking. Thin pieces are more easily dried evenly, and most pottery is 1/2" thick or less.

For refractory use, low plasticity is usually acceptable, depending on the forming method used. In particular, ramming clay into a form requires almost no plasticity at all. Therefore, clay content can be as low as 5% or less (with highly plastic clays like bentonite), or between 15% and 35% for lower-plasticity clays like kaolins. Note that the plasticity of a clay is usually directly proportional to its contribution to shrinkage: bentonite has the smallest particle size, and typically shrinks enormously, but it is also highly plastic. Ball clays are also highly plastic, though much less so than bentonite, and their shrinkage is correspondingly less. Fireclays typically have intermediate shrinkage and plasticity, and kaolins have the lowest shrinkage and lowest plasticity of all.

The second step toward minimizing shrinkage is to include a wide variation of different particle sizes. A good selection might include 25-50 mesh grog, 100 mesh kyanite, 200 mesh calcined alumina, kaolin (approx. 5000 mesh), and bentonite (approx. 50,000 mesh). This increases porosity, allowing for more even drying and reduced chances of spalling or steam explosions during firing, as well as providing a matrix of non-clay particles that is more resistant to size changes than a single non-clay particle size would be. In particular, the inclusion of fine (smaller than 200 mesh) non-clay particles drastically reduces the amount of clay required to bond large particles securely, by filling voids between the large particles that do not then have to be filled with clay for a secure bond.

Shredded foam is somewhat of a unique particle: its mesh size is enormous compared to many other ceramic ingredients (typically as coarse as 10 mesh), and it acts as a hard particle during drying but not during firing. Mixes that contain large amounts of foam will also require large amounts of clay to keep the mix plastic enough to be workable, but the addition of non-clay hard particles in various sizes will pay big dividends in preventing firing shrinkage, which would be extremely high with clay alone.

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Dealing With Shrinkage

Shrinkage can be minimized, but in the case of clay-based refractories, never completely eliminated. Therefore, what shrinkage remains must be dealt with.

The first step in dealing with shrinkage is to measure it. Firing a bar of your refractory composition in circumstances as close as possible to the conditions you will use to fire the actual piece is a standard way to measure shrinkage. For accuracy, make marks in the wet clay as far apart from each other as possible. The lines should be thin for accuracy but visible enough not to disappear during drying and firing. Then, measure the marks after complete drying and again after complete firing, and calculate the shrinkage.

You can then scale your ware to a size that will, when fired, end up correct. There will be some inaccuracy in measurement and some variation in shrinkage between firings, and even in the same firing, and as a result it is very difficult to make precise sintered ceramic parts with the relatively low level of process control typical of a hobby setup. The less total shrinkage there is, the less this variation matters.

If you are firing a furnace in situ, it will inevitably shrink away from its shell. There is little that can be done about this, even if shrinkage is known, because there is no way to compensate for it short of firing in a larger kiln and adding a correctly-sized shell later. My recommendation is to backfill with something like sand to hold the fired furnace stationary in its shell and support the fragile unfired outside, if this effect cannot be avoided through use of a different furnace design.

If you are using forms, they must be designed in a way so as to allow the clay to shrink naturally, else it will crack during drying. This means that all interior forms must be removable while the clay is still in its plastic state. A layer of newspaper can act as a release from forms to which the clay would otherwise adhere. Exterior forms can also cause problems if the clay sticks to them strongly, or if they inhibit drying, so it is best to avoid leaving any forms in place. Forms made of plaster are porous enough to allow clay to dry with the form in place, and the clay will not stick if the plaster is dry when used, so plaster exterior forms can be left in place.

Drying the clay slowly is critical to allow it to shrink without cracking, particularly with recipes that have high shrinkage and low porosity. Whereas some heavily-grogged refractory clay mixtures can be dried in open air or even force dried at elevated temperature, denser clay with higher shrinkage needs to be protected from open air. Moisture gradients tend to remain present once introduced, so keeping the clay from drying out in thin areas is critical. To do this, enclose the clay in plastic so it retains its natural moisture. Use a cloth draped over the clay to protect it from drips of condensation. Once the clay has had a chance to even out its moisture levels, it can be exposed to lower and lower levels of humidity until it is completely dry. Correctly drying large thick pieces of

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high-shrinkage materials can take weeks or months, which is why keeping shrinkage down is so critical.

If cracks do form, they can be patched. For clay that is still somewhat plastic, an application of clay slip will be sufficient to re-wet the surface of the crack so that new clay will adhere. Patching cracks with clay that is drier than normal will reduce the moisture gradient that you are introducing, but even so, the patch has a higher likelihood of splitting than its surroundings. Do not re-wet the crack with plain water, which can make the crack worse by re-hydrating the clay too quickly and too unevenly.

For clay which is bone dry, small cracks can be patched by wetting them with vinegar and rubbing dry clay (not pure clay, but the same mix as the rest of the body) into the crack. Large cracks will be very difficult to patch successfully, and will likely need several stages of patching with plastic clay as the patch shrinks away and reopens the crack.

Cracks that do not compromise the structural integrity of a furnace are not necessarily harmful: they can provide a path for heat to escape, but the furnace will still be functional with some cracking. In contrast, a crucible that is cracked, or has cracked during drying or firing, should *never* be used. Even if the crack is repaired, there still could be a weak point where the crack was, and the consequences of catastrophic failure are too dangerous to take the risk.

In dealing with shrinkage, kyanite deserves special mention. Kyanite is an aluminosilicate having equal parts by molarity of alumina and silica. More significantly, it has an unusually high density of approximately 3.6 g/cc. When heated to over 2000°F (1100°C), it begins to decompose into less dense mullite and silica, with a corresponding expansion of up to 13%. This decomposition happens much faster at higher temperatures, and ware must be fired to an extremely high cone for the decomposition to happen fully.

This expansion behavior allows kyanite to be added to mixes to counteract firing shrinkage, or even to create mixes that expand slightly on firing, for use in patching cracks in already-fired materials. Note that kyanite-bearing clay-bonded ceramics formulated to end up with zero shrinkage are not zero-shrinkage mixes. They are zero-net-shrinkage mixes, which means that shrinkage does still occur. This is important to remember because the greater the volume change, the slower the firing has to be to minimize stress. Kyanite has a particular crystalline shape that helps it combat drying shrinkage as well, and it is a relatively cheap source of alumina, so it can also be used to great advantage in many mixes that are not required to have zero net shrinkage.

Thermal Expansion

After shrinkage, thermal expansion is the second critical issue to deal with when formulating clay-based ceramics. Ceramics, by nature, are brittle, so the larger the volume change they experience when heated, the more likely they are to crack due to fast, uneven

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heating. Unlike shrinkage, which is a one-time change, thermal expansion happens every time the ceramic changes temperature. The changes are small compared to shrinkage changes, but they can still be significant enough to crack ceramics containing high-expansion materials.

Certain materials have high coefficients of thermal expansion and others have low coefficients of thermal expansion. For good thermal shock resistance, thermal expansion must be kept low. The table in Appendix 6 lists coefficients of linear expansion (COLE) for a selection of common fluxes and refractory materials. Over the broad temperature range that refractory ceramics experience, this COLE is not necessarily constant or even a linear function of temperature, but the table values can be used in a relative sense to compare the behaviors of different materials, and for approximate calculations with accuracy suitable for most hobbyists.

Silica deserves a special mention here. When amorphous (glassy), silica has an incredibly low COLE. Combined with its relatively high temperature tolerance, this makes it a good candidate for all sorts of exotic applications, and indeed “fused quartz” (not actually quartz at all!) glassware is the standard for many demanding refractory applications. Unfortunately, silica likes to crystallize, and the high purity and high temperatures needed to make amorphous silica ware make it very expensive.

As a crystal, silica takes many forms. At ordinary pressures, the common ones are α -quartz, β -quartz, tridymite, and cristobalite. (At higher pressures, many more types of crystal can form.) There are temperatures, dubbed transition points or inversion points, where one crystal form abruptly converts to the other. Since the different forms have different densities (see Appendix 6), this conversion creates an abrupt volume change. Different forms may be metastable outside their temperature range (for example, it's entirely possible to have cristobalite in room-temperature ware), and different crystals take different amounts of time to form (and may be promoted or inhibited by various impurities), so predicting the exact behavior of crystalline silica is extraordinarily complicated. Fortunately, it is not necessary.

The most important thing the hobbyist needs to know about crystalline silica is that it creates abrupt volume changes and therefore significantly decreases thermal shock resistance. Unfortunately, it is also by far the cheapest (in the form of sand) refractory ingredient that is readily available, and is a component of a great many other materials, such as clays.

One way to get rid of excess silica is to add fluxes and make it amorphous instead of crystalline. However, this presents two problems: one, that in order to make silica amorphous, it must be melted, and that melting temperature will set an upper bound on the operating temperature of the ware if the silica is present in any quantity; and two, that many common fluxes are quite high-expansion themselves. Furthermore, large amounts of

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silica may decide to crystallize on cooling anyway if the cooling is slow enough for crystals to re-form.

Another way to get rid of excess silica is to add alumina, forming mullite. Mullite has an excellent COE (not as good as amorphous silica, but far better than many other ceramics) and is highly refractory to boot. This approach is expensive, but worthwhile. Calcined alumina is expensive, and mullite has a high proportion of alumina, so the pure form must be added; and to form mullite and leave no silica behind, the ware must be fired to a very high cone. Large crystals of silica (sand grains and the like) will never form mullite, not with any reasonable firing schedule, so they cannot be added.

A third approach combines the two. The ware is formulated to create mullite (with some excess alumina to ensure complete conversion), with a small amount of low-expansion fluxes added to hold any residual silica in its glassy state. The fluxes will also speed the firing process by allowing a liquid phase to form, and the high amount of alumina will ensure the fluxes do not significantly lower the operating temperature of the ware.

If any glazes are used, they must match the thermal expansion of the ware as closely as possible over all temperatures. The glaze should expand slightly less than the ware to keep it under compression in the cooled state, where it will be stronger than if it was under tension. Refractory glazes will be very different in terms of composition than traditional pottery glazes, but the same rules apply. Note that glaze fit can have a substantial impact on the strength of the ware.

Formulation

Shrinkage and thermal expansion may be the two biggest issues when dealing with clay-based ceramics, but there are a host of other issues—plasticity, green strength, fired strength, refractoriness, and so forth.

Almost every application is unique, and different people will prefer a different balance of trade-offs that will make their mixture easier for them to work. That being said, here are some recipes which I have used before with success:

The first recipe is a simple one containing 30% calcined alumina, 65% kyanite, and 5% bentonite by mass. This has quite good plasticity, and the alumina content is quite high at slightly over 72% by mass (25% by mass being silica, and somewhat under 3% combined flux and LOI), just right for the slightly under 72% alumina content by mass needed for mullite. This recipe is suited for hard, strong ware, and is formed easily enough despite containing only a small amount of clay. It is plastic enough to accept up to twice its dry volume in foam. The result will be ware of moderate strength and moderate insulative ability, suitable for plinths and other such applications.

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For an insulating layer containing more foam, a recipe with much more clay is needed. This recipe contains 37% alumina, 10% kyanite, 39% kaolin, and 14% bentonite by mass. (Note that two clays are used for a wider distribution in particle sizes; also, adding too much bentonite raises flux levels dangerously high. Fortunately, most of the flux in bentonite is of the low-expansion variety, so adding a little bit extra isn't terribly harmful with these flux-resistant high-alumina recipes.) This recipe accepts up to four times its dry volume in foam, which is close to the practical limit of clay/foam insulation.

Alumina content is lower, at around 62% by mass. (30% silica, 1.5% fluxes, and 6.5% LOI). This is below the threshold needed to form pure mullite, but adding more alumina would either dilute the clay and lower green strength, or if the clay was increased to match, dilute the kyanite grog such that the mix would have poor drying properties. Enough mullite will form to consume up to 24% of the 30% silica, and of the 6% remaining silica, it is not unreasonable to expect that the 1.5% fluxes (20% fluxes from the viewpoint of the free silica) will keep the silica in the amorphous phase. Of course, the fluxes will not act only on the silica; the real world is rarely that convenient. Still, the amount of crystalline silica formed should be kept small enough that this recipe will still tolerate substantial thermal shock.

With so much foam, this recipe will have low plasticity and low fired strength, but that is the price to be paid for good insulative capacity. Mixes high in foam are best rammed instead of plastic formed, because the ramming process is more forgiving of low plasticity.

Preparing Clay

In order to turn ceramic ingredients into usable ware, they must first be properly mixed. Making clay is not as simple as adding water to the dry ingredients and stirring; doing so will produce a lumpy heterogeneous mixture with entrained air and poor working properties.

Mixing

The first step in preparing a clay mixture is to weigh out the dry ingredients. With the exception of light insulating materials like foam, ceramic ingredients are always measured by weight. The ingredients need to be measured accurately; a 0-2000g postal scale with at least 1g resolution works well for small to medium-sized batches. Always wear suitable (P100 particulate) respiratory protection when working with dry ceramic ingredients, particularly ingredients which contain fine silica or toxic oxides like chromia, and do the measuring and mixing in an area that can be easily cleaned of any spills of dry ingredients and ventilated of any dust produced during the mixing process.

After the ingredients are weighed, they must be mixed dry. This process produces a lot of dust when done in the open; I prefer to do it inside a sealed plastic bag. Pay special attention to any lumps in the dry mixes, and attempt to break those up as well as you can. If

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you have a fine mesh sieve, you can run the mixed dry ingredients through the sieve to break up any remaining lumps. If not, thorough dry mixing and later kneading and wedging will usually break them up. Make an effort to keep ceramic materials stored such that they cannot absorb atmospheric moisture, and they will not form lumps as readily.

After the dry mix is thoroughly blended, now is the time to add any shredded foam if the recipe calls for it, or dry paper pulp or reinforcing fibers. These should be blended dry before the water is added.

I prefer to add the correct amount of water to the sealed bag and mix everything together by kneading the bag from the outside. The alternative to this approach is to dump the dry ingredients into a mixing tub and add the water slowly while mixing it in. The bag contains the mess created by the wet clay, but it also makes the mixing more difficult. Either method will work, as long as the water is mixed in to the correct level of plasticity and evenly distributed throughout the clay.

Water used for making clay should be clean and clear at the very least. If your tap water has a high concentration of minerals, use distilled or deionized water instead. Particularly for slip casting, but also with other methods of forming, minerals and other foreign matter in the water can interfere with the clay's chemistry and produce undesirable effects ranging from cosmetic stains to increasing the fluxes in the clay or preventing a casting slip from deflocculating correctly.

Once the clay has been mixed with water, allowing it to sit and absorb the water will improve its working properties considerably. As little as an hour of aging will help, though a day or two will do more to ensure the clay has absorbed the water evenly. Working properties will continue to improve for several weeks of aging, though the increases become significantly less as time goes on. Keep clay sealed while aging, otherwise it will dry out.

Wedging and Kneading

After the clay is mixed and aged, it still must be homogenized and de-aired before it can be used for plastic forming. (Ramming mixes will need to be mulled like greensand, as their plasticity is too low to work normally.) Wedging is one process used to de-air and fully mix clay. The clay is worked on a sheet of heavy canvas to prevent sticking; as the canvas gets wet, clay will start to stick to it and the canvas will have to be dried before continuing.

The basic wedging process is as follows: First, cut the lump of clay in half. Pictured in Figure V-2 is a lump made from 4 kg of dry clay with approximately 1 kg of water added, which is a good amount to work at one time. Then, take one half and slam it down onto the table, and slam the other lump down on top, forcefully enough that it sticks. Keep repeating this process—the repeated impacts will force air to the surface, and the cutting and re-combining will homogenize the clay.

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Kneading is another process that accomplishes much the same thing as wedging. The kneading process is similar to kneading bread dough, but clay is much stiffer and more resilient than dough. As pictured in Figure V-3, first pull up on a lump of clay, placing it on its side. Then compress it downward while twisting it around. The object is not to fold it over on itself, which can trap air, but to repeatedly change its shape. The twisting motion ensures that the entire mass of clay is worked evenly.

Kneading requires more strength and skill than wedging, but it can also produce a better result. I prefer to combine both processes to ensure that the clay is well-worked and homogeneous.

Forming Methods

Forming clay-based ceramics is very different from pouring a castable refractory or assembling a structure with firebricks or ceramic wool. There are several different methods of forming well-suited to clay-based materials, and each one has different advantages and drawbacks. Fortunately for the hobbyist with a background in pottery, forming clay-based refractory ceramics is very similar to forming any other clay-based ceramic, and many of the same techniques are used.

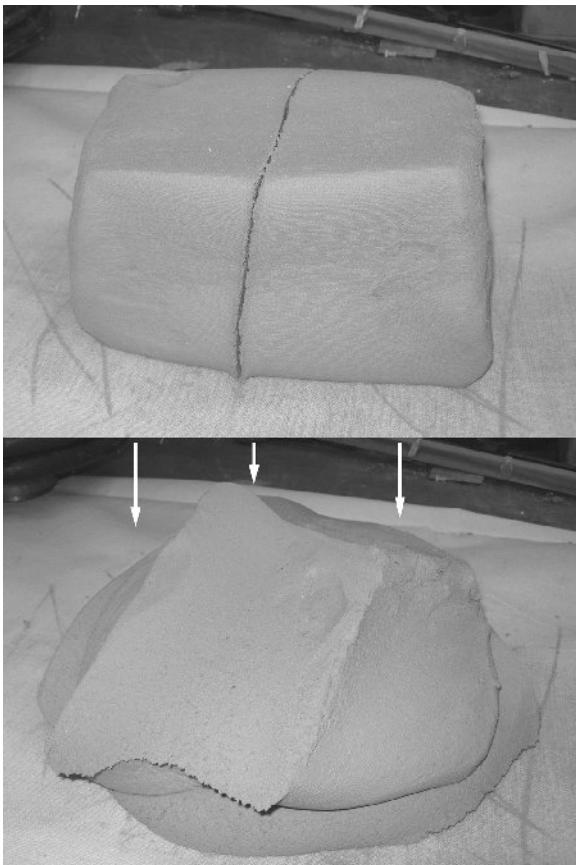


Figure V-2: Wedging

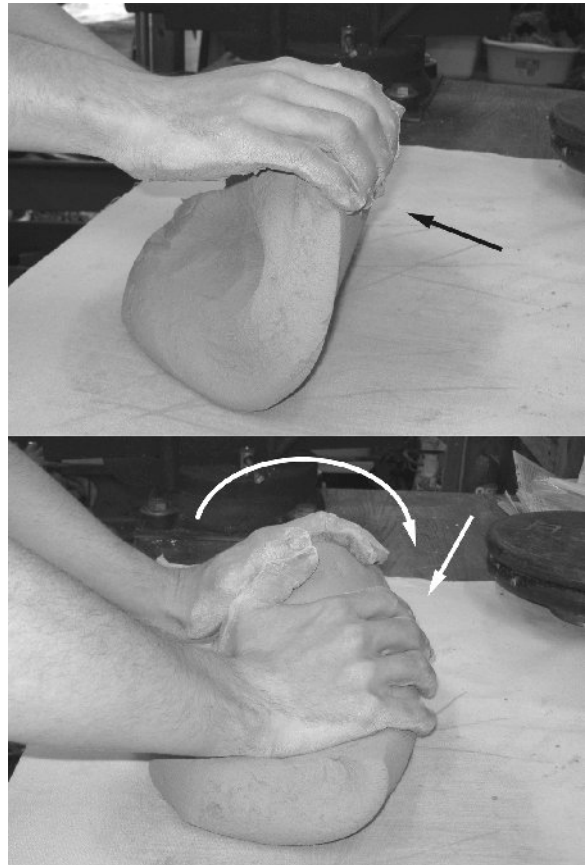


Figure V-3: Kneading

Slip Casting

Slip casting is a difficult method of forming, and comprehensive instruction is well beyond the scope of this tutorial, but this section will attempt to provide a basic understanding of the process. Slip casting provides excellent dimensional control and the densest possible product if done correctly, so its difficulty is well worthwhile for any hobbyist wishing to make many high-quality crucibles or similar ware. It is generally not a practical process for making something as large as an entire furnace or furnace hotface, though small hotfaces could be assembled from several slip-cast parts.

Simply adding water to a typical plastic ceramic composition until it makes a slip will result in a 60-70% water content, and extremely high shrinkage. For comparison, plastic-formed bodies contain 20-35% water. Therefore, a deflocculant must be added to prevent the clay from settling out of the slurry. Water content of as low as 30-35% can be achieved with this method. Sodium silicate is a common deflocculant—typically, about 0.2% of the mass of the dry clay is added to the appropriate amount of water, along with 0.2% to 0.3% soda ash, and the dry clay is slowly mixed into the water.

Casting slips cannot be mixed by hand or with a power drill; the slip, after being initially mixed, will require mixing for hours to stabilize its properties. The slip also becomes extremely viscous and heavy, so a powerful mixer is needed. A commercial mixer may sell new for \$600 or more, but they are relatively easy to make. Variable speed is a must; a dimmer-style router control can be used to control a universal motor out of a vacuum cleaner, circular saw, or router, or a variac can be used to control a much quieter induction motor. A 5-gallon bucket of slip will need at least 1/2 HP of mixing power, and the motor must be continuous duty. The business end of the mixer is a simple propeller assembly; they are available from ceramics suppliers, or they can be fabricated relatively easily.

To properly regulate a casting slip, it is necessary to test the slip's properties. Specific gravity can be measured with an accurate graduated cylinder and an accurate balance; acceptable values are between 1.7 and 1.9 g/cc. Viscosity can be measured in a relative manner by noting the setting of the speed control on the mixer compared to the amount of slip in the mixer, but these values will mean nothing until you gain experience working with the slip. A viscometer can be bought or made for the same purpose, and it will provide a much more consistent measurement.

An ideal casting slip will never settle out or separate, and will gel (thicken up and become pseudo-solid) after about an hour. If it settles out or gels in the mold, the casting will be ruined.

Slip casting molds are generally made from plaster, and must have slight draft. They can be made in one or more parts, just like greensand molds. For casting, the mold is filled with a suitable casting slip and left to stand for several minutes (fifteen minutes is reasonable, but the time will depend on thickness and dampness of the mold, and the properties of the slip),

SECTION V: REFRACTORY

then the excess slip is poured out to leave a solid coating on the inside of the mold. Once this dries to a plastic state (after about an hour for most items), it can be de-molded and the mold left to dry. The mold will dry in a half hour to an hour in a 170°F drying oven, or overnight in still air, depending of course on humidity level and the amount of moisture that needs to be removed.

The sodium silicate will eventually clog the pores in the plaster mold and ruin it; the mold should last for 20 to 100 casts.

Plastic Forming

Any ceramic recipe plastic enough to form can be used with plastic forming methods. Ware can be thrown on a potter's wheel (with some skill; the typical refractory recipes are difficult at best to throw) or constructed by hand like one would shape any ordinary clay. To learn about these methods, it would be wise to visit a local art ceramics studio or the art department of a local high school. Plastic forming methods are best taught in person, with examples.

Plastic forming will produce a product with low dimensional control and moderate density, and the product can easily crack if done incorrectly.

Ramming

Ramming recipes are mixed somewhat differently than plastic forming or slip casting recipes. A lower percentage of clay is allowable, and the amount of water can be lower than for plastic forming (except for mixes high in foam, which generally need all the plasticity they can get, and should be mixed with enough water to achieve peak plasticity), with a consistency much like greensand. The material is rammed, again much like greensand, between a pair of plaster or cement molds, and pressed out of the mold immediately. This produces a highly porous product with low density, which will be more resistant to thermal shock but less durable, and it will also conduct heat poorly. The porosity and low water content allows a fast drying cycle with low shrinkage, but failure to ram tightly enough will create weak spots that can easily lead to failure. Dimensional control is reasonable, and this procedure can potentially also be used to ram highly refractory materials with organic binders instead of clay to bind the material together. In this case, a hydraulic press may need to be used to ram tightly enough.

Firing

Firing is the operation that transforms a pile of fancy dirt into a usable ceramic product. It is also likely to be the limiting factor in production: fuel and equipment costs will generally be higher here than in other steps of the process, and it also consumes a significant amount of time and labor.

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To fire any ceramic, you need a kiln. Commercial pottery kilns typically have a maximum temperature of cone 6 to cone 10, which is adequate for decorative ware but unsuitable for refractory ceramics. A foundry furnace, built with commercial or homemade refractory that can tolerate at least 3000°F, can be used as an impromptu kiln, but a dedicated kiln should be made for any large operation. A properly-designed kiln will achieve a much more even and controllable temperature than a furnace designed for melting metal. The kiln should be able to fire to at least cone 18 in order to properly sinter un-fluxed refractories.

Certain furnace lining mixtures (those with good thermal shock resistance, low shrinkage, and high porosity, because firing in situ will never be as even as in a kiln) can be fired in place using the furnace's own burner. This has the advantage of drastically reducing fuel consumption compared to a kiln large enough to fire the entire furnace evenly, and also not requiring a large, expensive kiln to be constructed. On the other hand, it is impossible to fire more than a thin layer of the inside shell of the furnace in this manner. Ceramic near the outer walls will be unfired and perpetually fragile. If the insulation is of another variety (such as ceramic wool, for example), a hotface can be fully fired in this manner.

Ordinary firing practices apply for in-situ firing, with the additional note that extra effort should be made to protect the area where the burner flame impinges on the unfired wall of the furnace. Placing a piece of fired ceramic to block the direct flame will in most cases keep this area from heating so fast it crumbles. Clay/foam recipes are particularly susceptible to this crumbling effect, because the foam vaporizes at a relatively low temperature, and if placed in the direct flame path, the foam will vaporize vigorously and destroy the structure of the ceramic around it.

The key to any successful firing is firing slowly. Temperature should stay at or below 200°F until all water has left the ware, and from there, should rise no faster than 1000°F per hour. Half that rate is still considered a “fast” firing in the ceramic world. A controllable burner or set of burners is necessary to fire this slowly—the initial burner flame should be about the size of a candle flame, and from there, fuel pressure should be increased in increments of less than 1 PSI until the kiln reaches red heat, and any change should be given at least a half hour to take effect. At no point should the burner flame point directly at unfired ware, nor should ware sit directly on the bottom of a poorly-insulated kiln or furnace. There should be no visible gradation of heat across any individual piece of ware, and all the ware in the kiln should be fired to approximately the same temperature. Blocking the vent hole, especially when the burner is very low, will help the heat stay even—any gaps or holes in the refractory will create cool spots.

Once temperature is reached—a blinding white heat if you are firing without commercially-made pyrometric cones—it should be held for at least a half hour. Because the now-fired ware is fairly resistant to thermal shock, turning the burner off and blocking all exits to the kiln will be adequate for cooling. Decorative ware would generally be cooled more slowly, with the aid of the burner.

Section VI

Furnace Construction

There are many valid ways to build a furnace. Furnace design, like all design, is a set of trade-offs between desirable characteristics. The furnace detailed in this section is small in size, with low thermal mass and good insulation for quick, efficient melting, and constructed of highly refractory materials for the ability to withstand repeated melts of high-melting-point metals like iron. This is not the easiest, nor the cheapest furnace to build, but I have found that a furnace of this size and construction is capable of melting the metal for the vast majority of my casting work, and as is suitable for a furnace designed to be used often, it is also very economical to run.

In my opinion, while raw beginners can usually better be served by something low-tech and fairly inexpensive while they hone their skills and decide if this new hobby is worth a larger financial outlay, a furnace with capabilities comparable to this one ought to be what every experienced hobby caster uses. (Keep in mind, though, that the caster makes the tools, not the other way around! Having the best furnace in the world won't allow you to produce excellent or even passable work if you lack the essential skills to do so, and building those essential skills takes time and hard work.)

Design

This particular furnace, detailed in Figure VI-1, is designed to best fit commercial A4 and A6 crucibles, as well as steel crucibles made from disposable 1-lb propane tanks, for an approximate capacity of 5 lbs of aluminum or 15 lbs of iron. The design is fairly easily scaled up or down to accommodate different volumes of metal, though large increases in size will also require some design changes (for example, an additional support directly under the plinth to bear the weight of a much heavier crucible).

The basic furnace design is a light, thin-but-strong hotface of any suitable high-alumina ceramic backed by a generous insulating layer of high-temperature commercial ceramic fiber blanket, and all this wrapped by a metal shell of some sort.

This furnace has an 8" bore with 2" of ceramic fiber insulation on all sides. The hotface is 1/4" thick on the side wall, 1/2" thick on the bottom to support the weight of the crucible, and nonexistent on the lid, which only needs a coating of rigidizer or clay slip to seal the ceramic fiber. Ceramic fiber blanket is commonly sold in 1" and 2" thicknesses, and the rolls are typically 24" wide. A piece 40" long will suffice for the 2" material (if, for the

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sake of conserving material, a 1/2" sliver is cut out of the main 12" tall wrap of fiber for the 12 1/2" diameter lid; this missing sliver can be filled with a piece of scrap fiber and placed at the bottom of the furnace with no noticeable performance loss), and with considerably less scrap, a piece 60" long of the 1" material will be adequate.

With a 12" tall outside (14" including the lid), 2" of insulation under the floor, and a 1/2" hotface on the floor, chamber height is 9 1/2", which with a 2" plinth leaves 1" of space between the lid and the top of the crucible. A 2 1/2" diameter vent hole, correctly sized for the furnace's intended burner, only needs 5/8" between the lid and the top of the crucible, but the extra space allows for scrap to extend above the top of the crucible rim without impeding exhaust flow or damaging the lid.

The tuyere should be positioned vertically such that its center line is even with the top of the plinth, and horizontally on a tangential path such that the center line of the burner aims directly between the wall and the edge of the crucible. A 1/2" (nominal) pipe size propane Reil burner will be adequate for this furnace size at 20-60 PSI, or a 3/4" pipe size burner can be used for lower pressure propane supplies. An oilburner, depending on type, will probably need a tuyere that accepts at least 1" pipe.

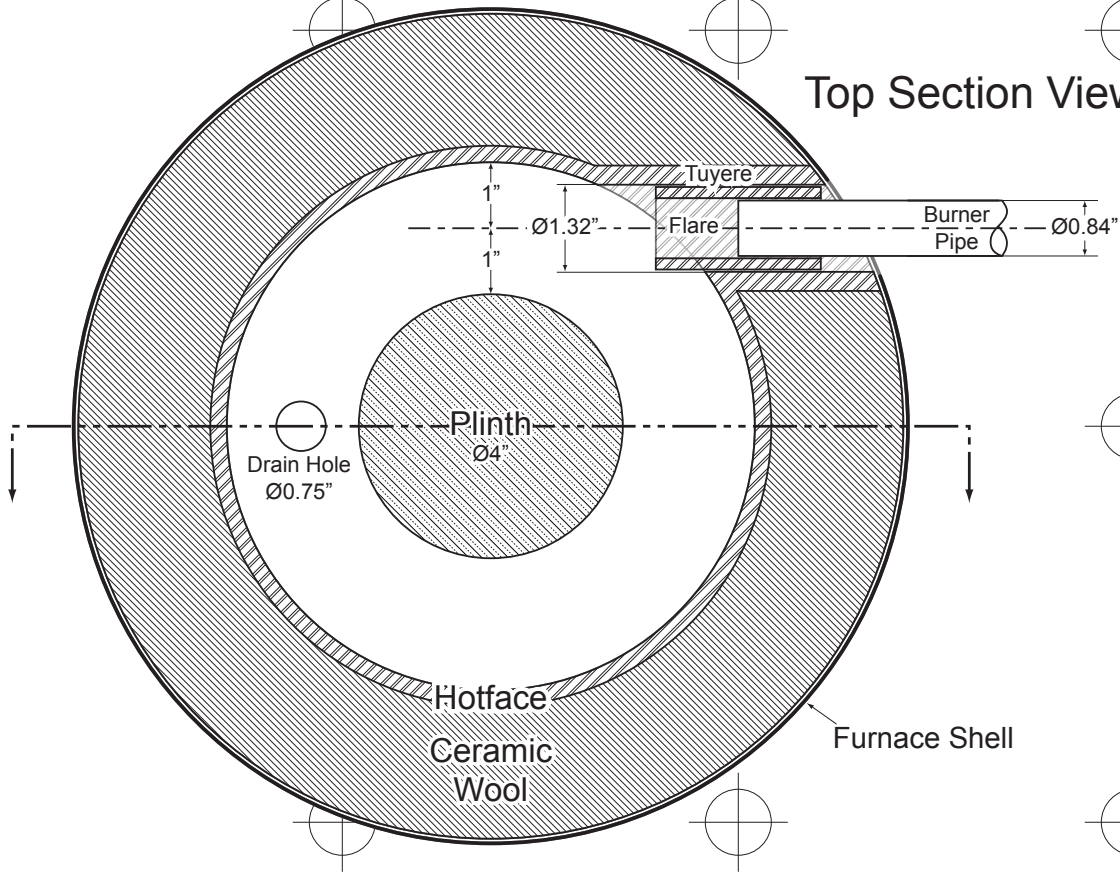
In either case, furnace design and construction is simpler if the furnace is designed to correctly fit only one size of burner. That way, a single flare can be molded directly into the clay lining the tuyere. To fit the tuyere to multiple sizes of burner, mold a ceramic flare having inner dimensions to fit the smaller burner size and outer dimensions to fit smoothly into the tuyere, and fire it with the furnace. This adds complexity to the design, and the gap between the tuyere and ceramic flare will inevitably leak some heat, but the added flexibility of a design that accepts multiple burner sizes (usually to switch between a propane burner and an oilburner) may be worthwhile. The furnace in Figure VI-1 accepts 1/2" pipe and 1" pipe sizes.

The furnace floor is supported by a strip of ceramic cemented to the bottom of the hotface wall, approximately 1/4" thick, which extends down with the rest of the hotface through the bottom insulation to the steel shell surrounding the furnace. This approach minimizes heat dissipation through the plinth and the bottom of the crucible, but also forces the bottom of the furnace to carry the entire weight of the crucible as a bending load, which is not ideal from a structural perspective. For heavier expected loads (e.g. if planning to melt lead) or larger furnaces, it would be better to add a central pillar of hotface material directly below the crucible, and compensate for the inevitable cold spot with a more insulating plinth. Some castable refractories may also have trouble with the bending loads that the edge-supported floor design places on the structure, though any properly-fired clay-based ceramic should have no trouble with the load at this scale.

Either way, it is critical to ensure that the floor is evenly supported over all its support points and secured in place with refractory mortar (if fired separately) or clay slip (while plastic), and that any vertical member supporting the floor is in turn evenly supported by



Top Section View



Side Section View

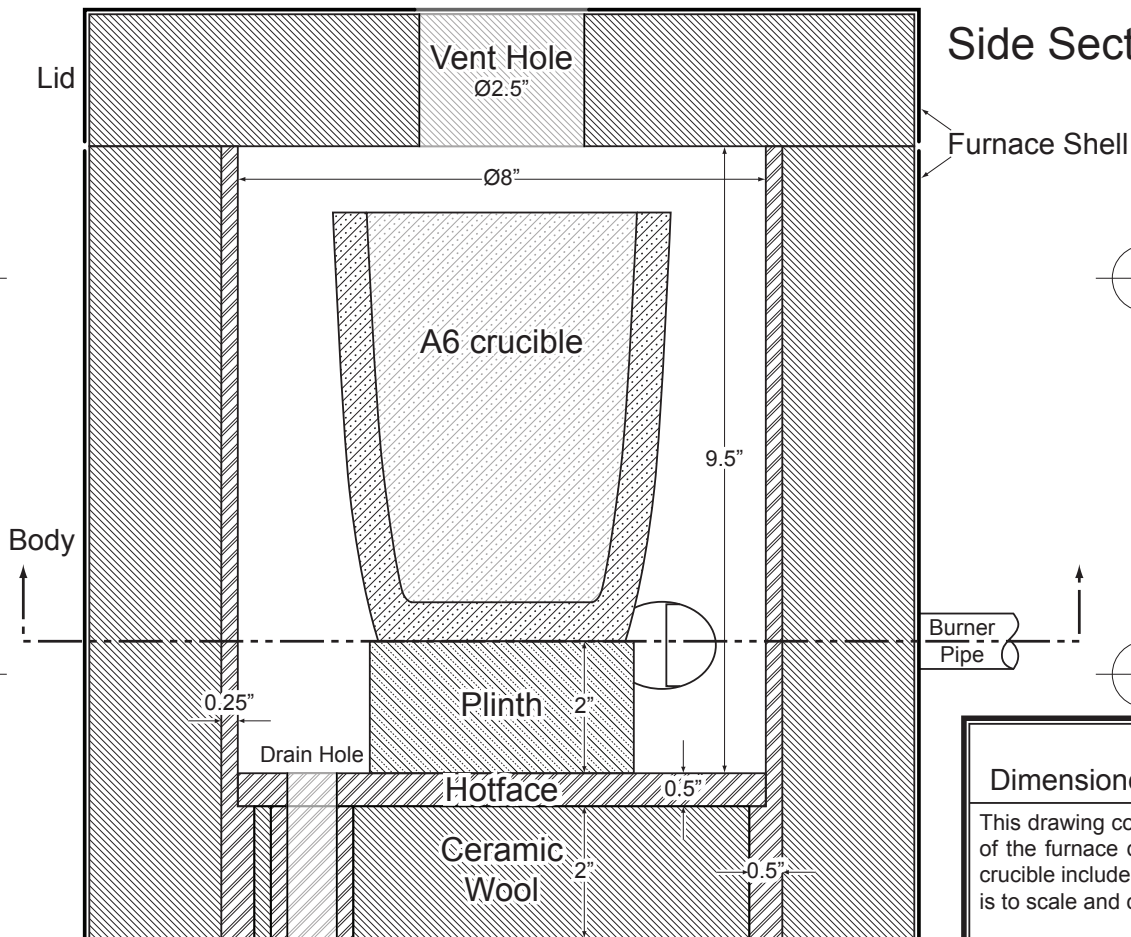


Figure VI-1:
Dimensioned scale section drawing
 This drawing contains top and side section views of the furnace detailed in Section VI, with an A6 crucible included for scale purposes. The drawing is to scale and can be used as such.
 This is the full (vector) version of the original drawing, scaled down to page size for inline viewing.

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the metal shell of the furnace (which needs to be stiff enough not to flex during movement and normal operation of the furnace). Concentrating loads at a single point or allowing the parts to wobble and scrape past one another is a sure-fire recipe for breakage.

The drainage hole is 3/4" in diameter (the smallest size I have found that will reliably stay open in the event of crucible failure), placed near the edge of the floor and roughly opposite the tuyere. Placing the hole right below the tuyere will cause a large amount of radiant heat loss, and placing it behind the tuyere (near, but in the direction opposite that of the flame swirl) may cause it to freeze up, because that part of the furnace will always be one of the coldest areas. Hence, a compromise.

The wool under the hole is cut somewhat larger and protected with a thin layer of clay plastered into the hole. All the same, it would be wise to avoid intentionally direct-melting in this furnace to keep from making a mess of the wool around the drain hole. Furnaces designed for direct-melting in addition to crucible operations will have thicker hotfaces and different locations of the burner and drain hole in order to be able to handle the molten metal without damage from accidents or undue wear.

Figure VI-1 presents the dimensions used for the furnace built during the writing of this section, but these dimensions need not be exactly followed. Working with clay is not generally a precise process, and the furnace can of course be adapted to the size needed for a particular application and the dimensions of raw materials on hand.

This furnace was built using 2" thick 2600°F rated Kaowool ceramic fiber blanket with a density of 8 lbs/ft³ for the insulation; plastic clay-based ceramic composed of 30% calcined alumina, 65% kyanite, and 5% bentonite by mass for the hotface, tuyere, and flare; a slip of the same ceramic painted over all exposed ceramic wool surfaces; and a rammed plinth of the same ceramic mixed with twice its dry volume in shredded foam beads.

The A6 crucible in Figure VI-1 is provided for scale purposes to demonstrate how a crucible should fit in a furnace. Less space can be left around the sides of the crucible without affecting the burner, but I prefer enough space to operate tongs without constantly scraping against the hotface and causing damage.

The lid lifting mechanism (a pair of handles is more than sufficient for a light ceramic wool lid of this size), legs for the furnace body, internal structure of the burner, and burner support pipe are not shown.

Construction

Once a furnace has been designed, the first step in construction is usually to build the furnace shell. A pre-made shell, like an empty 20lb or 30lb propane tank, or a metal 5-gallon bucket, will save some time, and in the case of the propane tanks, will provide a shell that is stiffer and more durable than what most people can easily fabricate.

SECTION VI: FURNACE CONSTRUCTION

Furnace Shell

The shell, needless to say, needs to not be flammable. A steel shell is ideal. The shell will get hot, so if you want it painted, high-temperature paint must be used. If the metal you use already has ordinary paint on it, be mindful that it will probably produce hazardous fumes on the first few uses, until the paint burns off. Galvanized metal is safe to use; the zinc coating may discolor or oxidize from the heat, but it should not get hot enough to burn off except for some small areas directly exposed to exhaust gases around the vent hole and the lid seal. Getting any kind of paint, even high-temperature paint, to stay on these areas will be difficult or impossible as well.

For furnaces much larger than the one detailed here, the shell needs to be strong enough to support the furnace's weight, and mobile as well; typically large furnaces are mounted on wheeled carts of some sort, and the shells are made of 30-gallon or 55-gallon drums. Smaller furnaces can get by with thinner shells; even common 26-gauge or 28-gauge sheetmetal sold for duct work will be adequate if the sheet is further supported with a framework of light structural steel. Thicker sheetmetal, in the neighborhood of 18 to 20 gauge, or thin metal with reinforcing corrugations rolled into it, will be self-supporting for these light furnaces. The objective is to provide a container that will not flex significantly when the furnace is moved, because if the container flexes, the refractory inside will be stressed, and may crack or weaken prematurely. Ceramic fiber blankets can also create hazardous dust when flexed.

Even in small shells, a particular point of importance is the burner support pipe, which must be sturdy enough that the weight of the burner and associated paraphernalia does not cause the shell to flex at the attachment point or cause the tip of the burner to put pressure on the refractory of the tuyere. This is easy to do for propane burners, which are relatively light, but an oilburner with an integrated blower may need a more elaborate support apparatus.

The furnace shell in larger furnaces will also have to support and provide attachment points for the lid-lifting mechanism. This is one reason to build lids out of rigidized ceramic fiber blanket: even for fairly large lids, it keeps the weight low enough so that the lid can be safely lifted by hand, and avoids the construction issues associated with suspending a heavy slab of refractory in the lid shell. Still, with larger lids, the ceramic fiber will have to be supported in some way. One approach is to hang it from the top of the lid with Kanthal wire or similar; fired ceramic buttons can be formed to support the fiber over a wider surface area and to protect the wire from the worst of the furnace atmosphere.

Insulation

Installing the insulation for this furnace is a very simple matter of cutting it to size and sliding it into the shell. That is one of the advantages of working with ceramic fiber blanket. Still, there are a few tricks to working with it successfully.

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Working with ceramic fiber blanket is much like working with fiberglass house insulation, only the former is denser and, of course, much more temperature-tolerant. The same handling precautions apply, however: Wear a respirator with a P100 particulate filter, long sleeves, and gloves. Make sure that the area you are working in can be ventilated to the outside easily: the hazardous microscopic particles of fiber that are produced during handling cannot be removed by sweeping, vacuuming, or ordinary air filtration (except with a HEPA filter); these operations simply cause them to become airborne. Exchanging that air will carry them outside where they can dissipate into the atmosphere or settle out and be trapped by water or wet surfaces. Also make sure your working surface is clean, so as to avoid contaminating the fiber with fluxes.

The fiber blanket can be cut easily with multiple passes from a sharp utility knife, as long as care is taken not to tear the material. However, transferring measurements from the furnace to the blanket is not as straightforward as it might seem. Rolling the blanket in a cylinder shape to form the lining of the furnace will stretch the outside and compress the inside, so neither the circumference of the furnace shell nor the circumference of the outside of the hotface will be the correct length to cut it. The easiest way to determine this length is to roll the uncut blanket up to the correct diameter and mark it, then cut a little long and trim to an exact fit. If your cut ends up too short, you can patch the mistake with a small sliver of scrap fiber.

Cutting circles is somewhat trickier, but all it requires is patience. For the large circles of the lid and furnace bottom, proceed as normal. For the small circles of the vent hole, drain hole, and tuyere, you may find it necessary to pluck out the partially cut center of the circle as the cut proceeds. Either way, be patient and avoid getting these holes too large, which will be difficult to fix later.

Ceramic fiber insulates best at its intended density, so compressing it only until it is its nominal thickness is ideal. The fiber is usually slightly thicker than nominal when new, and will compress easily to nominal thickness. Fluffing it or leaving gaps between the fiber and the hotface will allow convection currents to form in the airspace thus created, and compressing it into a space smaller than its nominal thickness will increase the conductivity through the ceramic itself.

If using a castable hotface that is to be cast into place, put a barrier of some sort between the fiber and the hotface. Otherwise, water and the binder from the castable can wick into the fiber, which will lower its insulative value, make salvaging the fiber very difficult if the hotface is ever badly damaged, and can cause the castable not to cure correctly. Plastic wrap is ideal for this barrier, as it is thin, leaves no ash, and is waterproof. For hotfaces that are plastic-formed into place, no barrier is necessary, though dampening the wool slightly will retard drying and reduce the likelihood of cracks. (Dampening more than the surface of the wool will retard drying too much, and the furnace will take a very long time before it is ready to fire.)

SECTION VI: FURNACE CONSTRUCTION

Hotface

Building and installing the hotface is by far the most difficult part of building a furnace like this one. There are several valid approaches, depending on what the hotface will be made of and how it will be fired. The furnace detailed here has a hotface of clay-bonded plastic-formed ceramic (specifically, using the first recipe presented in Section V), and it will be fired in place. I chose to roll out the hotface using slab-forming techniques that will be familiar to students of art ceramics, press it onto a stiff paper backing, and install it into the furnace while still plastic. This allows the joints between hotface sections to be as strong and uniform as possible, though it also allows the hotface pieces to deform during installation, and the result is not as dimensionally accurate as other methods.

Other possible ways to install the hotface would be to support it on an inner form that could be extracted after it was in place, or to build the hotface in a self-standing manner (using coil-building techniques, perhaps) and construct the rest of the furnace around it. Constructing the completed hotface outside of the furnace also allows for the possibility of firing it separately. This takes much more fuel and requires access to a large kiln capable of high-temperature firing, but it will also produce a product that is much less stressed by the firing process, and can be fired faster and more completely. Still another option is to separately fire the hotface in sections and assemble the sections with refractory mortar, which will make the unfired pieces less delicate to construct and easier to fire evenly. If the hotface is cast or rammed from commercial products, it will most likely have to be made and cured in sections before assembly, because the forms would be too intricate to fill completely with such thin walls if made in a single piece.

Slab Rolling

There are three major pieces of clay to form for this furnace, and all of them can be easily made by rolling slabs. The three pieces are the furnace sidewall, which is 12" tall, roughly 26" long (it can be trimmed to fit during assembly), and 1/4" thick; the floor support strip, which is 2" tall to accommodate the 2" of insulation under the floor, the same length as the hotface sidewall, and also 1/4" thick; and the furnace floor, which is an 8" diameter circle 1/2" thick. The floor support strip is bonded to the bottom 2" of the hotface sidewall to create a 1/4" wide ledge to support the furnace floor. See Figure VI-1 for a visual representation of this layout.

In order to successfully roll slabs of clay, it is necessary to have sheets of heavy canvas or a similar heavy fabric that the slabs will not stick to, otherwise it will be impossible to manipulate the finished slabs once they are formed. The material must be dry or the clay will stick; as it is used, it will absorb water from the clay, eventually needing to be dried out before it can be used further. It is also important to watch for wrinkles in the material, which if not pulled taut will embed into the clay and make undesirable lines.

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One sheet of canvas should be laid out on a suitable working surface. I prefer to clamp or weight it in a stretched condition to avoid wrinkles and ensure that the sheet does not move during the rolling process. On this sheet, a lump of clay sufficient to form the desired size of slab is placed, and pounded flat. The rolling process will expand the clay in the direction of rolling, but very little expansion will occur perpendicular to the direction of rolling, so the raw slab must be of the correct width and shape to start. Figure VI-2 shows a raw slab of clay ready for rolling. Spacers are used to roll the slab to a uniform thickness; here, the spacers are 1/4" round steel rod. Anything smooth and of the correct height will work.



Figure VI-2: Clay ready for rolling

To roll the slab, lay another piece of canvas on top of it, and use a rolling pin or piece of rigid pipe to roll the clay flat, as shown in Figure VI-3. A large diameter roller will make this job easier, but in any case, multiple passes will be necessary to achieve final dimensions. Do not attempt to roll too much at once; it will merely take more effort and will not finish the job any faster. Rolling does take some physical exertion, and it is very easy to miss parts of the slab once the thickness becomes close to finished.

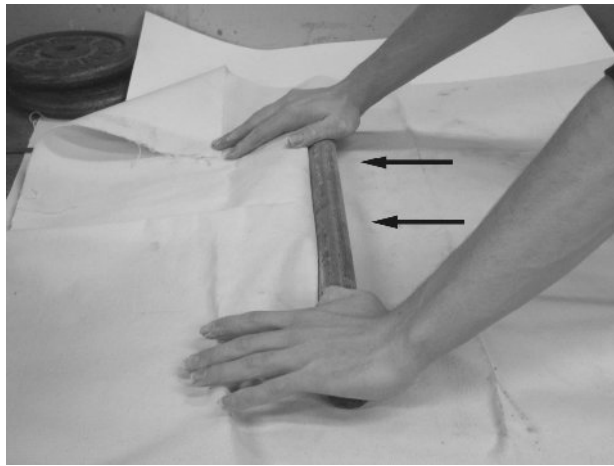


Figure VI-3: Slab rolling

Make several passes after you think you are finished to ensure the slab is truly of uniform thickness, then peel back the top canvas to make sure the slab is big enough. If the slab is not big enough (usually because a corner is rounded when it needs to be square), it is possible to add extra clay, but be very careful to make a secure bond and not to trap air bubbles in the process of doing so. It is better to recycle the too-short slab and start over with more clay.

Once the slab is rolled, it can easily be cut to size with a knife, and the unused edges can be recycled by kneading or wedging. For this build, I made a final roller pass to press a piece of stiff posterboard into the clay, and then cut around its edges as a template, as shown in Figure VI-4. The posterboard supports the clay slab during assembly of the furnace and will harmlessly burn out when the furnace is fired, but it also encourages cracks later by sticking to the clay and not allowing it to shrink as easily. Furthermore, the posterboard

SECTION VI: FURNACE CONSTRUCTION

will eventually absorb water from the clay and lose strength, so slabs with this type of backing need to be used soon after they are made.

To flip the finished slab without damage, slide a thin stiff board under the bottom sheet of canvas, and place another stiff board on top of the slab (with a sheet of canvas in between the top board and the clay if there is no posterboard to keep the clay from sticking). This assembly can then be inverted as a single piece, not unlike rolling a sand mold, and the bottom board and bottom canvas can then be removed.



Figure VI-4: Rolled slab for hotface sidewall

The other two pieces necessary for the build, the furnace floor and floor support strip, can be rolled in a similar manner.

The only difference is that the furnace floor is rolled 1/2" thick for structural strength, and neither of these pieces will benefit from a posterboard backing.

Assembly

After all the pieces are rolled, it is time to assemble them. The first step is to attach the floor support strip to the base of the hotface sidewall. The hotface sidewall is generously coated with clay slip (formed by adding water to the same clay-based mixture used for the rest of the furnace and stirring until the slip reaches the consistency of heavy cream), and the floor support strip is laid in place. Err on the side of too much slip rather than too little; too much will ooze out and can be wiped off, but too little slip will prevent a secure bond from forming and can trap air bubbles, leading to cracking later. If slip does not ooze from the joint, you have added too little. Gently but firmly press the floor support strip onto the hotface sidewall, working from the center to the edges to force out any air bubbles that may be trapped, and adjusting the position as you progress to keep the top edge of the strip straight and parallel with the top of the hotface.



Figure VI-5: Blending floor support strip into hotface sidewall

Once the strip is secured in place, blend the clay of the strip and hotface sidewall all around the joint with a suitable tool. I

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am using a commercial clay-working tool in Figure VI-5, but a suitable tool can be quickly made from an old knife or scrap of wood or metal. Once the clay is blended, smooth the joint. Take this opportunity to adhere a paper strip to the bottom of the completed furnace sidewall; otherwise, it will stick to the metal furnace shell later in the assembly process and greatly complicate the correct positioning of the furnace wall.

After the hotface sidewall is finished, it is time to form it into a cylinder and place it into the furnace. I chose to spiral it around a can for support, lower it in, and press it into position against the wall by hand. For a more dimensionally accurate product, a removable inner form of the correct dimensions will give better support and allow you to bond the edges of the hotface together from the outside before placing it into the furnace. As Figure VI-6 shows, the force required to position it correctly freehand leaves finger marks in the hotface wall. This is not of structural concern as long as the marks are not too deep.



Figure VI-6: Hotface sidewall installed in the furnace

Of more concern is the method used to bond the edges of the hotface sidewall together. However the hotface is installed, the posterboard (if any) must be stripped off these edges, the clay trimmed to fit with a slight amount of overlap, and slip generously applied to make a good joint. Then, the edges can be pressed together and blended thoroughly, and after the joint is smoothed, it will be strong.

After the sidewall is in, it is time to install the insulation for the bottom. In Figure VI-6, I have already placed the insulation in the furnace and lined the drain hole with clay of approximately 1/4" thickness. I did this freehand, checking for correct size with a 3/4" dowel, but a form can be used for a neater appearance.

Next, cut the opening for the tuyere. This can be precut before installing the hotface sidewall, but lining it up correctly with the shell may be a tricky process. I chose to cut it after the wall was installed. Make sure, if you are using the posterboard backing, that the paper does not interfere with the joint between the hotface sidewall and the tuyere lining. Again, I freehanded the tuyere lining, using a pipe of suitable size as a gauge, but this can also be done with a form. Use standard clay-working practice (slip and thorough blending) to join the tuyere lining with the sidewall.

Then, it is time to install the furnace floor. Measure the approximate location of the drain hole and precut the bottom to fit. Thoroughly coat the rim of the floor support strip and the

SECTION VI: FURNACE CONSTRUCTION

top edge of the drain hole coating with slip, and then drop the bottom in, ensuring that the orientation is correct. I did this step while the bottom was still plastic, which makes it easy to blend together with the sidewall and the top of the drain hole, but also allows it to bend easily.

The same thing can be accomplished by letting both pieces of clay dry to a “leather hard” state, in which the clay will bend slightly without cracking but is stiff enough to be handled without deforming. In this state, all connecting surfaces should be scored with the teeth of a comb or a coarse wire brush, everything coated in slip, and a small coil of plastic clay laid into the joint to fill any gaps. This technique also introduces a greater moisture differential across the joint, which will require more careful drying to prevent cracks. The advantage, of course, is that the floor will stay flat.



Figure VI-7: Furnace ready to dry

In either case, if there are any gaps between the sidewall and the furnace floor, fill them with plastic clay, and add enough extra to make a fillet reinforcing the junction.

The last step is to paint the exposed ceramic wool on the top of the furnace body and on the lid with clay slip, and the furnace is ready to dry. Figure VI-7 shows the completed furnace body before drying. The lid was coated with clay slip in the same way.

Drying

As with all clay-based materials, drying slowly and evenly is the key to drying without cracks. In particular, the top edges of the furnace, which are exposed to the atmosphere, will tend to dry out faster than the thicker, more protected bottom. For the initial stages of drying, it may be best to cover the furnace completely with plastic (use a towel or rag between the plastic and clay to keep condensed water from dripping on the clay and creating spots of uneven dampness) and allow the moisture levels to equalize. The furnace will dry slowly or not at all during this stage, but once the moisture levels are equalized, it can be dried faster without danger of cracking. If the furnace was put together with clay that initially had a homogeneous distribution of moisture, and did not dry too much during assembly, this step may not be necessary.

The difficulty of drying ware without cracks increases exponentially as the ware gets larger, so large furnaces may have to be made in sections for the drying process to be completed in a reasonable amount of time. However, fortunately, a crack in a furnace lining is not a fatal flaw, and can safely be patched. (Crucibles, on the other hand, must

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never be used once cracked, even if the crack is repaired before the crucible is fired. The danger of residual stresses causing the crack to re-open at the worst possible moment is too great.)

If cracks appear in the furnace lining while it is still plastic, they can be easily patched by the addition of more plastic clay, possibly with slip to exclude air and improve the bond. Cracks which appear during later stages of drying can also be patched this way, but as the newly added plastic clay will shrink away from the already-dried clay, the crack will tend to reopen. Patching a crack multiple times using this method will eventually either fix it permanently, or reduce it in width to a hairline crack that refuses to close. These hairline cracks can sometimes be filled by spreading vinegar on the crack and rubbing dry clay dust into it, but a stubborn crack will only be superficially concealed using this method, and will often reopen during firing.

Fortunately, even these cracks, and other cracks caused by firing shrinkage or thermal shock, can be patched. Unfortunately, the use of a heterogeneous crack-patching mixture will not restore the full strength and thermal shock resistance of the clay, so it is always better to patch cracks as soon as possible in the drying process.

I have had little success devising a clay-based crack-patching compound for fired ceramics. However, there are several commercial products that are designed to patch cracks, bond firebricks together, and so forth, that will work well.

The final stage of drying, if possible, should be conducted at higher than room temperature. There are many methods of accomplishing this, from leaving an incandescent light inside the closed furnace to using a hair dryer or heat gun to putting the entire furnace in an oven. Starting this stage of drying before initial room-temperature drying is complete, however, will almost always cause cracks. This final stage of drying can also be performed as the first stage of firing, but usually these alternative methods are more controllable than a foundry burner, and controllability matters most during the initial stages of firing when water vapor is leaving.

Firing

Firing a furnace from the inside out is a bit different from firing ceramics in a kiln. The principles are the same, in that slow even heat is needed to prevent firing shrinkage or thermal shock from destroying the piece, but actually applying this even heating is much more difficult. On the other hand, firing a furnace from the inside out has significant cost savings in that it requires no additional equipment and takes far less fuel than conventional firing methods.

The conventional tangential burner placement in a foundry furnace is not optimal for even heating of the furnace itself, so a special effort must be made to deal with the hot spot created by the burner. Placing a shard of fired refractory ceramic in front of the burner such

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that the flame impinges on the fired ceramic instead of the unfired furnace wall will help significantly.

Figure VI-8 shows the heat distribution around the tuyere of a furnace during firing. This picture was taken when the furnace walls were glowing a dull red. The shard of fired ceramic placed in front of the burner is glowing nearly white where the burner impinges, whereas the nearby wall is mostly protected from this area of excessive heat. The flare in this picture is a separate piece, made of the same ceramic and in the process of being fired (rather than being separately fired beforehand) as well. The flare temperature is higher than the temperature of the furnace body, but its heating is relatively even, and it is a much smaller piece, so it is less vulnerable to these relatively harsh conditions than the furnace wall. Note also that the furnace floor, almost always the coolest part of this type of furnace, is glowing significantly less brightly than the walls. This is unavoidable, but it clearly demonstrates why plinth blocks improve melting efficiency and why it is a bad idea to put ware directly on the floor of a kiln.

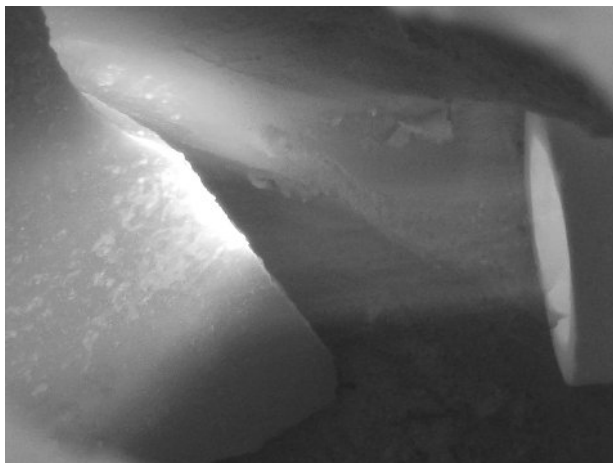


Figure VI-8: Heat distribution during in-place firing

After firing is over and the burner is shut off, it is a good idea to remove the burner and plug up the tuyere. This will allow the furnace to cool slower, decreasing the likelihood of cooling cracks, and will also prevent hot air from moving through the burner or heat from the furnace interior from conducting along the burner tube, both of which can damage burners built with soft solder, epoxy, or other temperature-sensitive materials. Likewise, it keeps heat away from the propane supply hose.

Section VII

Dictionary of Metalcasting Terms

A

Adiabatic flame temperature

A way of describing the “ideal” temperature of a flame, this is what a flame's temperature would be if it was burning neutrally and there was no heat loss to its surroundings. This is not the maximum possible temperature with some fuels (certain fuel mixtures that are not neutral can get somewhat hotter than the adiabatic temperature), but it's a safe assumption that with real world insulation, actual achievable temperatures will be several hundred degrees Celsius lower than the adiabatic temperature.

Air belt

A hollow "belt" around the outside of a cupola furnace which distributes the air draft amongst the cupola's multiple tuyeres.

Alloy

An alloy is a solid solution of two or more metals that have been melted together. Not all metals will alloy with each other: some react chemically (forming *intermetallics*), and others are mutually immiscible. Alloys are typically stronger, less ductile, melt at a lower temperature, and are less electrically conductive than the pure metals they are composed of.

Alumina

Alumina, Al_2O_3 , is the highly refractory oxide of aluminum metal. It is a common ingredient in refractory materials. Sapphires and rubies are primarily composed of alumina with various other impurities of metal oxides that give them their characteristic colors.

Annealing

Annealing a metal removes residual stresses caused by cold working, as well as allowing the grains (individual crystals) of the metal to realign themselves and grow larger. Annealing is done to make a metal that has been cold worked less brittle and more ductile, usually so more cold working can be done without causing cracks.

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B

Baked sand

Any molding sand formulation using a binder that has little or no green strength and must be baked or fired before casting. In these formulations, the binders are not reusable. There are some commercial binding resins that require a heating or activation step, but the most important binder for hobbyists is molasses, or a similar sugar mixture, which can be mixed with sand and baked in a household oven before casting. This formulation makes an excellent core, because the product has excellent strength after baking, but the high temperature of the molten metal destroys the bond and allows the core to collapse as the metal shrinks around it.

Ball clay

Ball clays are typically of high plasticity and reasonable purity. They are relatively high in silica, so they may be more sensitive to quartz inversions, but they are nearly as refractory as kaolins.

Bentone

A chemically-modified bentonite, it bonds with oil instead of water. Used in oil-bonded molding sands.

Bentonite

A clay, not used in large amounts in refractory formulations because it contains fluxes, but used in greensand since little is needed to give a high green strength. For most bentonites, about 10% by weight (the remainder being clean sharp sand) is suitable for greensand, whereas other clays may require 20-25%. There are two major types of bentonites, sodium (or western) bentonite, and calcium (or southern) bentonite, which is also called fuller's earth. There are also specialty white bentonites, which are specialty products and should not be used for greensand. Sodium bentonite is slightly more plastic than calcium, but both are suitable for greensand use.

Bod plug (also bott)

A clay-and-sand plug used to seal the tap hole of a cupola; it is chipped away with a pointed tool to allow the metal to exit the cupola. A similar arrangement can be used to direct-melt scrap in a burner-fired furnace, if care is taken to keep metal out of the burner.

Burnout

A term used to describe the initial stages of firing a ceramic containing combustible materials, which are literally burned out of the ceramic matrix. This stage must be undertaken very slowly to prevent combustion gases causing spalling or cracks.

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C

Calcination

Calcination is the act of *calcining*, or heating a substance to drive off chemically-bound water. Many substances, such as plaster of Paris and Portland cement, store water chemically as hydrates, and must be heated well above the boiling point of liquid water to break these chemical bonds and create the *anhydrous*, or water-free, version of the compound. See *hydrate*.

Castable

Short for “castable refractory,” it’s a commercial ready-made refractory material that is mixed and poured much like concrete.

Chaplet

A small piece of metal that is designed to support a core in a mold. The chaplet is placed in an area that will be filled with molten metal, and when the mold is poured, it fuses to the rest of the casting.

Cheek

Not always used, it is an extra flask piece inserted between the cope and drag of a sand mold to mold complex shapes. Many cheeks can be stacked if necessary.

Chill

A piece of metal inserted in a mold to produce faster localized cooling. Chills can be used on heavy sections to reduce the need for risering, or to alter the mechanical properties of the material in certain areas.

Clay-graphite

A material used to make commercial crucibles, typically made by mixing a high-quality clay with 30-40% of its weight in graphite. Organic binders, such as tar or pitch, may also be used. The crucibles are fired for a very long time at a very high temperature to promote formation of silicon carbide (SiC) crystals, which increase thermal shock resistance and strength. This firing schedule isn't feasible to duplicate on a small scale, so homemade clay-graphite crucibles will have no greater strength than their clay/grog cousins.

Coke

Essentially pure carbon, coke is to coal as charcoal is to wood. Used in iron melting and forge work, where the sulfur in coal would make the iron brittle. Coke produces a very hot fire and is denser than charcoal, so less refueling is needed.

COLE

An acronym for “coefficient of linear expansion,” this is a measure of how much a material changes size with changing temperature. COLE is usually approximated as a constant for a

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given material, even though it may change with temperature (which corresponds to nonlinear material expansion with temperature). Typical units are $\frac{10^{-6} m}{m(^{\circ}C)}$.

Cone

See *pyrometric cone*.

Cope

The top half of a greensand mold.

Coping down

When a pattern with an irregular parting line is molded, part of the line will be buried in sand. Coping down is the practice of carving out sand until the line is reached, creating a parting face that is not flat. When this is done, a large amount of draft should be used on the parting face so that the mold halves can separate easily.

Core

A piece of the mold that forms a cavity in the casting. Cores can be part of the mold, or they can be separate pieces that are placed in the mold. When cores are made separately, they are usually made with a stronger binder than the clay in greensand, so as to survive the extra handling required.

Core print

An indentation in a mold meant to receive the end of a separate core, so as to hold it in place when the metal is poured into the mold.

Crucible

The pot that holds molten metal. Common homemade crucibles are made of steel or various clay-based ceramics; commercially made ones are usually clay-bonded graphite or carbon-bonded silicon carbide.

Crucible furnace

A furnace which uses a crucible to hold the metal and can be fueled in many different ways. It works by heating up the crucible within the refractory-lined furnace and adding metal until the required amount is molten in the crucible. The crucible is then usually removed to pour, but some crucible furnaces are designed so the entire furnace tilts to pour metal, and the crucible is a permanent part of the furnace.

Cupola

A direct melting furnace designed to process large volumes of metal in many smaller batches. The basic operating principle of a cupola is a refractory tube with multiple tuyeres and a bed of fuel, typically coke. As charges of metal and coke are added, the metal melts, drips through the bed of fuel, and causes the fuel to float up higher. The metal is drained

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from the well by opening a plugged tap hole at the bottom of the furnace; typically, a cupola can melt a batch of metal every five to fifteen minutes. Cupolas take skill and a great deal of work to operate, but they melt very large amounts of metal. A 10" bore cupola can produce 300 to 500 pounds of cast iron per hour, requiring several tons of molding sand and an army of molders and attendants to keep up with the flow of metal.

D

Deflocculant

A deflocculant is a chemical that prevents a suspension or colloid from clumping together or settling out. For example, sodium silicate deflocculates clay particles by binding to them and making them repel each other, keeping them suspended in water at much lower water levels than would otherwise be required. See *flocculant*.

Degassing

Certain metals dissolve gas in their liquid state, such as aluminum, which dissolves hydrogen. If the gas is not removed, it will come out of solution upon solidification and create gas bubbles in the casting. There are two primary methods of removing gas: mechanical agitation and chemical reaction. Mechanical methods generally bubble an inert gas through the melt, releasing the dissolved gas much like shaking a soda would release carbon dioxide. Simply stirring the melt can remove some gas (often noticeable on heavily fluxed aluminum melts as little pops of flame when the melt is agitated—because salt fluxes dissolve steam readily, they promote hydrogen dissolution into the melt), but stirring alone rarely removes all of it, and can introduce other contaminants like iron. The other method, chemical reaction, adds a material to the melt with which the dissolved gas will react. In the case of aluminum, bubbling chlorine gas through the melt will remove hydrogen as HCl gas. In the case of copper, the additions of reactive lithium, zinc, phosphorous copper, or other deoxidizers will remove dissolved oxygen as a solid oxide.

Diatomaceous earth

Formed from the fossils of microscopic diatoms, diatomaceous earth is a highly porous silica-based material, and thus valuable as an insulating refractory. It is typically available as cat litter in pea-sized pieces. It can be somewhat more heat-tolerant than perlite, but does contain fluxes. Diatomaceous earth is also available in ground form (sold for pool filters) and can be used as a parting dust, but it carries with it an extreme risk of silicosis and should never be used without respiratory protection.

Die

A die is a block of durable material with a surface designed to form the shape of a part. Usually, dies are made so that two or more fit together, similar to the way a sand mold fits together, to create a mold for *die casting* or other processes such as *die stamping* or *die forging*. Dies are usually very expensive to make and only practical for production runs of thousands of parts.

SECTION VII: DICTIONARY OF METALCASTING TERMS

Draft

The slope of a pattern away from the parting face of a mold, so as to allow the pattern to be removed without damage to the sides of the mold.

Drag

The bottom half of a greensand mold.

Draw plate

A plate used when molding patterns with intricate edge details or no draft (e.g. a gear that would be cast with a finished tooth form). It has a cutout in the shape of the pattern to be pulled, and the pattern is pulled through the plate, keeping the sand at the edges of the pattern from breaking off.

Drift

The temperature rise between the measured temperature before pulling a melt and the maximum equilibrium temperature of the melt. The temperature rise is caused by the crucible being hotter than the part of the melt that is being measured. This is only an issue when temperature can be measured precisely in the first place, and occurs more with ceramic crucibles than metal ones due to their lower thermal conductivity.

Dross

Solid metal oxides and impurities within a melt (usually present as powder), which float to the surface and must be removed by skimming. See *slag*.

E

Eutectic

When two or more materials are melted together, the combined melting point of the two materials is often lower than that of either material by itself. The ratio of the different materials that yields the lowest melting point is known as an eutectic composition. Eutectics generally do not take effect until the materials have been melted together. When heating finely-powdered materials, such as when sintering ceramics, no melting will occur below the melting temperature of the lowest-melting binary eutectic. Once a liquid phase is present in the material, ternary and higher-order eutectics can form.

F

Fillet

A rounding-over of an inside corner on a part, usually accomplished in pattern work with a bead of wood putty or auto body putty. Fillets keep molds from having sharp, easily damaged edges and improve the strength of finished parts by avoiding the stress concentration created by a sharp corner. Pronounced "*fill-it*," not "*fih-lay*."

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Fireclay

Fireclays tend to be coarser, less pure clays than kaolins or ball clays, and have earned a bad name in the art ceramics world because of it. (Certain impurities, such as chunks of limestone, can spall in the kiln and destroy ware.) Commercial firebricks are typically made with a fireclay base. Fireclays are highly refractory, as are kaolins and ball clays.

Flash

A casting defect which forms as thin, foil-like metal at the parting line of the casting. It is formed as excess metal forces itself into any small gaps between the parts of the mold.

Flask

The box (usually made of wood) that supports the greensand during molding. Flasks have at least two parts: the cope and drag, possibly with one or more cheeks as well.

Flocculant

A flocculant does exactly the opposite of what a deflocculant does—encourages suspended particles to clump together into agglomerates called *flocs*. See *deflocculant*.

Flux

A material added to the crucible that usually melts at a lower temperature than the metal and floats on top of the liquid metal, for the purpose of separating metal oxides from the melt. Fluxes can be used to protect the metal from reacting with the outside air. Flux can also mean a material that melts at a fairly low temperature and helps melt things that normally melt at a higher temperature. For instance, fluxes are bad in refractories, because they tend to make the refractories melt at a lower temperature. A refractory material is said to be *flux resistant* if a large quantity of flux lowers the melting point of the material by only a small amount, or dissolves only a small portion of the refractory.

G

Gate

A channel carved between the sprue and casting.

Greensand

Contrary to its name, greensand is not green. The “green” part refers to the fact that it has not been fired. A typical homemade greensand would contain 90% by mass fine silica sand (such as “play sand” available at most hardware stores), 10% by mass bentonite clay, and just enough water to stick the sand together.

Green strength

This refers to a material's strength in the green, or unfired, state.

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Grog

A clay additive, usually bits of crushed fired clay, that adds abrasion resistance and thermal shock resistance, as well as reducing shrinkage on firing.

H

Heat capacity

Heat capacity is the measure of how much energy it takes to raise the temperature of a substance one degree. Specific heat capacity is heat capacity on a per mass basis—usually for one gram or one kilogram of the substance. Specific heat capacities are often listed as constants for a given material, though they in fact vary with temperature and pressure (and with the crystalline phase of a substance), and those variations cannot be neglected when the changes in temperature or pressure are very large. Commonly, reference values are taken at standard conditions of 25°C and 1 atmosphere, or similar conditions that approximate “room temperature.” In contrast, much of the interesting behavior of molten metals and refractory ceramics happens at over 1000°C, where the “room temperature” values are far from accurate. Typical units are $\frac{J}{g(^{\circ}C)}$.

Heat of fusion

Denoted as H_f , heat of fusion is a measure of how much energy it takes to turn a solid substance at its melting point into a liquid without raising its temperature. Typical units are $\frac{J}{g}$.

Heel

A small amount of molten metal in the bottom of the crucible, serving two primary purposes. First, it allows for lower losses in melting thin scrap because the scrap can be pushed under the melt surface before it has a chance to oxidize. A heel also improves thermal conduction from the crucible to the scrap, causing it to melt faster. Adding too much scrap to the heel at one time will freeze the heel and potentially crack a ceramic crucible.

Hotface

A hotface is a layer of comparatively strong, flux-resistant, highly refractory material used to line the inside of a furnace. Hotface materials are usually poor insulators by themselves, and are used to protect a more-fragile insulation layer from mechanical damage, fluxing, or extreme temperatures.

Hot shortness

At a certain temperature, some metals become hot short, where the metal crumbles and breaks up without actually melting. Different metals have different points of hot shortness. A dramatic example is aluminum, which loses its strength and crumbles at a temperature

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several hundred degrees cooler than its melting point. Other metals, like steel, instead become progressively more malleable until they melt.

Hot tearing

Hot tearing occurs during cooling of a casting, where the mold is strong enough to keep the casting from shrinking naturally, and the metal cracks or tears apart instead. This is most commonly seen with hot short metals and large, rigid coring, but it can happen in other molds as well. Generally a symptom of a mold or core material that retains too much strength after the casting is poured, it can be fixed in part by choosing an alloy with less shrinkage or higher hot strength, but if the underlying problem of the mold material is not fixed, the casting will still have residual stresses built up during cooling.

Hydrate

A chemical element or compound with water chemically bound to the compound. This water will exit the hydrate as steam upon *calcining* at a temperature that varies depending on the material, but is greater than the normal boiling point of water. Materials can have several different hydrates. For example, “alumina hydrate” could indicate $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ (gibbsite), $\text{Al}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$ (bauxite), or $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$ (diaspore). Most water-setting materials, such as Portland cement and plaster of Paris, use a calcined compound that combines with water to form a hydrate. This is important to casters because these materials can release that bound water, sometimes violently, if heated by contact with hot metal. See *calcination*.

Hygroscopic

Materials that are hygroscopic spontaneously absorb water from atmospheric moisture. Some materials, like calcium chloride, are so strongly hygroscopic that if left exposed to the atmosphere, will absorb enough water to turn from a dry material into a liquid solution.

I

Ingot

An ingot is a bar or block of a metal, usually of a specific alloy and of a standard size, that has been cast into a mold for future casting purposes. Ingots are made in order to consolidate scrap that is difficult to store or to use directly for casting, as an intermediate stage between processing impure scrap and using it for casting, and as overflow to deal with leftover metal from a casting session.

Investment

A plaster-like ceramic which is used to surround a wax pattern in lost wax investment casting.

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J

K

Kaolin

A pure, refractory clay with high alumina content but low plasticity.

L

Ladle

A container used to hold molten metal, sometimes made of metal lined with refractory instead of a solid piece of ceramic as is typical with commercial crucibles. Steel ladles are also used, mostly for white metals. The main difference from a crucible is that the metal isn't melted within the ladle; it is simply transferred to it from where the metal was melted, such as a cupola or reverberatory furnace, or a large crucible, for better control of a more manageable amount of metal.

LOI

LOI is an acronym that stands for "loss on ignition," or the sum total of volatiles and burnables in a ceramic material. Typically, the majority of LOI is chemically-bound water, with organic impurities and carbon dioxide from decomposing carbonates also contributing. Absorbed liquid water in plastic materials is not part of LOI, which is measured from the "bone dry" state of the material.

Lost wax casting

This involves surrounding a wax pattern in an investment compound which then sets around the wax. The wax pattern is then melted out (thus it is lost), forming a cavity within the investment material into which metal can be poured.

Lost foam casting

A sacrificial foam pattern is placed into loose sand, and metal is poured over the pattern, vaporizing it and replacing it with metal. The process can also be done in a thoroughly vented greensand mold, which is termed the full mold process.

M

Matchplate

A pattern or patterns mounted on a molding board, usually with gates and runners, and sometimes with risers and sprue, attached. Used to align the two halves of complex patterns, and in production situations to simplify the molding process. A matchplate can be cast by spacing apart the two halves of an ordinary mold with steel bars or similar.

Melt (noun)

A crucible of melted metal is often referred to collectively as a melt.

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Melt (verb)

When a substance changes from solid to liquid due to the addition of heat, it is said to melt. The physical process of melting is the same for metals as it is for substances like ice; the only difference is the temperature. Contrast *smelt*.

Mesh size

Mesh size is a method of classifying powdered or granular materials. A material that is 100 mesh, for example, would just barely pass through a sieve with 100 holes per inch. Mesh size numbers are identical to the numbered grits on sandpaper, which can be used as a reference for comparison.

Molding board

A board used under a flask, which supports the sand and pattern and creates the parting face of a mold. If the board is cut to accommodate a pattern, it is termed a follow board. If the board is used to support the sand in a flask that is already rammed, it is termed a bottom board.

Muller

A machine designed to properly mix greensand; it has a kneading action to remove lumps and even out the clay and water content. Mulling can be performed by hand, but it is laborious and the results are somewhat poorer than when done with a machine.

Mullite

An aluminosilicate that is hard, strong, and resistant to thermal shock. It has a very high melting point, and is a prime material for crucibles, hotfaces, and other high-temperature furnace apparatus. It can be made by firing a mixture of clay and calcined alumina such that the molar ratio is 3 parts alumina (Al_2O_3) to 2 parts silica (SiO_2).

N

Neutral

Conditions that are neutral are exactly balanced between oxidizing and reducing. Ideally, there would be neither free oxygen nor free fuel to react with anything. In practice, there will be a small amount of both. Neutral flames are blue in color and heat more efficiently than either oxidizing or reducing flames.

O

Oxide

An oxide is the compound produced when an elemental substance reacts with oxygen. Metal oxides are denoted by appending an -a suffix. For example, alumina is aluminum oxide (Al_2O_3), and silica is silicon dioxide (SiO_2). Most metals form oxides when exposed to air at

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high temperatures; in some cases, the oxides form a layer that protects the metal from further chemical attack.

Oxidizing

Conditions that are oxidizing contain an excess of oxygen and a lack of fuel. Materials that react with oxygen (such as graphite and many metals when molten) will oxidize in this environment. In the case of a melt, this forms undesirable dross. Materials such as nichrome, which rely on a protective outer skin of oxide to survive the furnace atmosphere, benefit from oxidizing conditions. An oxidizing flame reaches a higher color temperature than a neutral flame (becoming purple instead of blue), but the additional unused air or oxygen mixed in with the flame causes it to heat less effectively than a neutral flame. Very oxidizing flames will “blow out” and refuse to burn at all.

P

Parting dust

A material that is dusted on the parting face of a mold (and sometimes the pattern) to prevent sticking.

Parting face

The face where two parts of a mold separate. This is usually a flat plane, but does not have to be.

Parting line

The line on a pattern where the parting face is designed to go. All parts of the pattern should slope away from the parting line. The line is usually straight, but does not have to be.

Pattern

A piece, usually made of wood, that is in the shape of the final casting. The greensand (or other mold-making material) is rammed in place around it to create the mold.

Perlite

A volcanic material used in gardening, it can be added to refractory for insulative purposes. However, it lowers the refractory's melting point, as it contains fluxes. Shredded polystyrene foam is a superior alternative, providing the same or greater insulative benefit without the added fluxes.

Petrobond

A brand of oil bonded molding sand.

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Plastic

A material that is capable of deforming and holding its new shape without losing strength. The more plastic a material is, the more it can be deformed without losing strength (tearing or cracking) during the move. Silly Putty, for instance, is a very plastic material.

Plinth

A brick or block that the crucible sits on. It holds the crucible off the furnace floor, allowing the burner's flame to circulate beneath it and reducing heat loss through the floor of the furnace.

Pouring basin

An area at the top of a sprue, into which the metal is poured. It is usually tapered downward toward the sprue, and a volume of metal can accumulate in the basin to supply the casting as it shrinks on cooling. Risers may have a similar "basin" on top to supply the cooling casting. Large pouring basins can be molded in a separate small flask half to act as a funnel. This is helpful for pouring with large crucibles or other scenarios where pouring accurately is difficult, but metal should be poured directly down the sprue when possible to minimize the amount of sand that washes into the mold.

Pyrometer

A type of instrument used to measure high temperatures. Optical and infrared pyrometers use visible or infrared radiation to measure temperature, whereas thermocouples use a junction of dissimilar metals to measure temperature with a type of thermoelectric effect.

Pyrometric cone

A device used in ceramics to determine the amount of heat work that has occurred in a particular environment. Cones themselves usually consist of slanted cone-shaped wedges (though some can be bars or rods) of fluxed ceramic materials with a known softening point. When the cone is heated such that it bends until the top portion is horizontal, that cone number is said to be reached.

Pyrometric cone equivalent (PCE)

The pyrometric cone that bends at the same amount of heat work that a pure sample of a given ceramic material (often a clay) would bend. Also used to describe the amount of heat work itself. This is a good guideline for the failure point of a refractory material. Clays considered "refractory" have a PCE of 30 or greater.

Q

Quartz

A crystalline form of silica, it is a hard and strong mineral, but undergoes dramatic changes in volume at specific temperatures (dubbed "quartz inversions"). Refractory containing

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quartz is more susceptible to thermal shock than refractory containing only mullite crystals and alumina. See *silica*.

R

Ramming

The act of compacting a material with a hard, blunt object. Greensand is rammed into molds, and the amount of compaction used is critical to the integrity and surface detail of the mold. Likewise, some refractories are rammed into place in furnace bodies.

Reducing

Conditions that are reducing contain a lack of oxygen and a surplus of fuel. Reducing conditions inhibit oxidation of a melt, but the presence of hydrogen from unburned fuel can create problems with dissolved gas in a melt. Reducing flames are cooler than neutral flames, burning green instead of blue. An extremely reducing flame (typically one with no air or oxygen added to the stream of fuel) is characterized by a smoky yellow flame that rises almost straight up from its source instead of blowing forward. This is termed a *lazy flame*.

Refractory

Refractory materials are characterized by extreme resistance to heat. While many materials are refractory, those most useful to the hobbyist must also be relatively cheap, relatively insulative (for furnaces), and relatively chemically inert, among other requirements.

Reil burner

Possibly the most common type of naturally aspirated propane foundry burner, this burner uses a venturi to draw in air from the back of the burner, and is an excellent performer over a wide range of pressures. It will operate at a minimum pressure of around 1/4 PSI, and a maximum of greater than 60 PSI. The design was pioneered by Ron Reil, and many other metalcasters have made variations or modifications to the same general operating principle. Most commercial naturally-aspirated burners (including the gas injectors on barbecue grills) operate using the same venturi principle and basic construction.

Reverberatory furnace

A type of direct melting furnace, which can be powered directly with gas or liquid fuel, or the hot combustion gases from solid fuel. It is lined with refractory and has a depression in the refractory to hold the metal in place of a crucible.

Riddle

A coarse sieve which can be used to break up lumps in molding sand when making molds.

Riser

A mass of metal connected to the casting, designed to supply it with extra molten metal as it shrinks. Risers can be connected through gates, similarly to sprues, or they can lead directly

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into the casting. If a riser is between the sprue and casting, it is referred to as a hot riser; if on the other side of the casting, it is a cold riser. Risers are often open to the air to help vent gases from the mold; a riser specifically for this purpose is sometimes called a vent riser or chimney riser. A riser that is not open to the air is a blind riser or shrink bob.

Roll-over

The act of turning a flask over to ram the other half, roll-overs are usually performed with top and bottom boards securely in place so as not to stress the sand.

Round

The inverse of a fillet, rounds are rounded-over outside corners. Like fillets, they are used on patterns to improve molding and in finished parts to avoid the stress concentrations created by a sharp corner.

Runner

A channel, generally longer and wider than a gate, that is designed to feed metal to multiple castings, or into different areas of the same casting simultaneously.

S

Sand

Everybody knows what sand is, but there is a lot of information about sand that the hobby caster needs to know. Suitable refractory sands contain mostly silica (quartz) or olivine. Clean silica sand is very white (red or brown colors indicate iron contamination), and olivine is green to black. Coral sand, or the sand produced by the weathering of shells, is largely composed of limestone and is not suitable for any foundry uses. This sand is also very white. Good foundry sand is relatively fine (90 mesh is ideal for molding sand; 75 mesh is suitable), and sharp. “Sharp” in the context of sand means that the grains are angular instead of rounded, giving the sand better green strength and higher porosity.

Sandcasting

Involves the use of oil or water bonded molding sands to create a mold into which metal is then poured.

Shrinkage

The amount that a material shrinks when it is cooled. This usually refers to how much the cast part shrinks upon solidifying and cooling.

Shrink bob

Also referred to as a blind riser, this is a mass of metal connected to the casting, designed to supply it with extra molten metal as it shrinks. See *riser*.

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Silica

Silica (SiO_2) is a common refractory mineral and the oxide of silicon metal. Its crystalline form is called *quartz*, and is what most types of sand are made of. *Amorphous* or *fused* silica lacks the inversions characteristic of the crystalline quartz, and is extremely resistant to thermal shock, but also unlikely to be available to the hobbyist. See *quartz*.

Silicon carbide

Silicon carbide (SiC) is a highly refractory material used for crucibles. It has high thermal and electrical conductivity for a nonmetal, making it suitable for resistance heating elements and high-temperature items like crucibles, but not for furnace linings. It is extremely thermal shock resistant, but is unsuitable for iron melting because the metal dissolves it.

Sintering

Sintering happens when unfired ceramics are heated to near their melting point. The fine particles of clay bond to each other, filling in gaps and creating a strong but porous structure. If the ceramic particles melt, the material is fused instead of sintered, and the resulting product is glassy.

Slag

Slag is the liquid (usually fluxed) impurities and oxides from a melt. The term has a meaning very similar to *dross*, which refers to solid impurities. When melting certain metals (brasses in particular), fluxes and glass-forming ingredients are often added to intentionally produce a thick slag layer on top of the melt, protecting it from oxidation and keeping volatile metals (namely zinc) from boiling off, as well as fluxing the melt. This layer can also be referred to as a cover flux. See *dross*.

Slip

Slip is a clay-based slurry, used to aid in the bonding of clay pieces by excluding air and wetting the surfaces. It can also be used to seal the fibers of ceramic wool. Specially formulated slips can be cast in water-absorbing molds, in a process known as *slip casting*.

Smelt

To smelt a metal means to refine it from ore. Contrary to popular use, it is not a synonym for “melt” as applied to metal. Contrast *melt* (*verb*).

Snap flask

A flask built with a hinge at one corner and a latch at the opposite corner, so that at the end of the molding process, the flask can be removed and reused on another mold.

Sodium silicate

Sodium silicates are a group of compounds, often collectively referred to as “water glass,” that are used to bind some refractories and molding sands, and as deflocculants in clay slips. When sodium silicate reacts with CO_2 , either in the air or supplied from a gas cylinder, it

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produces silica and soda ash by the reactions $\text{Na}_2\text{SiO}_3 + \text{CO}_2 \rightarrow \text{SiO}_2 + \text{Na}_2\text{CO}_3$ and $\text{Na}_4\text{SiO}_4 + 2\text{CO}_2 \rightarrow \text{SiO}_2 + 2\text{Na}_2\text{CO}_3$. When the bonded product is heated, the Na_2CO_3 decomposes into Na_2O (soda ash, a flux) and CO_2 , which is released. Thus, the result is a refractory bonded by a fluxed glass mixture. Depending on the composition of the refractory and the ratio of binder to filler, the entire mix can liquid-phase sinter into a highly refractory material in which the flux content is of little significance. Bound molding sands do not need to be pre-fired before use (the silica is present as a binder before firing, and the evolved CO_2 is of little consequence in porous bonded sand). When the sodium silicate is used as a deflocculant, its creation of a flux in the mix is again of little consequence; however, the reaction between sodium silicate and CO_2 in air means that the slip should be stored in a sealed container and air not mixed in during the stirring process. Adding dry slip-cast pieces to a batch of slip will require some extra sodium silicate for similar reasons.

Spalling

Spalls are chips or flakes of material. Trapped or chemically bound water in concrete, plaster, house bricks, clay and uncured commercial refractory will turn to steam when sufficiently heated. If heated too quickly this will result in immense increases in localized stress within the material, which may result in material failure and spalls breaking away with explosive force.

Specific heat capacity

See *heat capacity*.

Sprue

This is the inlet through which metal is poured into the mold. Sprues can be formed with a pattern, or cut with a hollow sprue cutter. A piece of thin-walled pipe makes a very serviceable sprue cutter.

Stripper plate

See *draw plate*.

Sweep molding

A sand mold making process whereby, instead of a conventional positive pattern being made and molded in the normal manner, a sectional profile of the pattern is made and swept along the sand to form the contours of the mold. Commonly used for large surfaces of revolution where a conventional pattern would require large amounts of time and material to make, but the technique can also be used to make any shape consisting of one or more regular profiles that can be repeatedly swept out using a guide. Because the sweep mold-making process requires additional time and skill for each mold, this process is only appropriate in special circumstances for production runs of any significant volume.

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T

Tap hole

The "spout" of a cupola; it is below the lowest level of metal in the cupola well, so that when opened (by breaking the bod plug used to seal it) all the metal inside flows out into the waiting ladle. It may be resealed with a fresh bod while there is metal still inside if the ladle becomes full. The drain hole of a crucible furnace can be moved to the side to act as a tap hole for direct-melting scrap.

Thermal conductivity

As the name indicates, thermal conductivity is a measure of how easily heat can pass through materials. Good insulators need very low thermal conductivity. Typical units are $\frac{W}{m K}$.

Thermal shock

This phenomenon happens when a material changes temperature rapidly. Thermal shock can easily shatter brittle glassy materials, but more loosely bound sintered ceramics are resistant to it. Metals are generally malleable enough to be virtually immune to thermal shock.

Tuyere

The entry point for the burner flame on furnaces with burners, or the air draft on solid-fuel furnaces. It is pronounced "*tweer*."

U

Upwind

A style of naturally-aspirated propane burner, this burner relies on air holes between the gas jet and flame to draw in combustion air. The turbulence created by this method of air delivery makes the burner unstable at low pressures, though it may be more stable at very high pressures (greater than 50 PSI) due to the better mixing provided by that turbulence. The burner generally does not burn well below 15 PSI. Designed by Lionel Oliver.

Ursutz

A waste oil burner consisting of a metal shell lined with refractory to provide a combustion chamber, with an outlet for the hot burning gases to enter the furnace. Also known as a "hot box" style burner. Because primary combustion happens in a separate, smaller chamber, efficiency is lower, but the burner heats up more quickly than a burner that relies on a hot furnace chamber to maintain combustion. Pioneered by Lionel Oliver.

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V

Venting

This involves providing holes in something so that gases such as water vapor can exit freely without building up and causing cracking. Sand molds are vented by thrusting a wire into the sand around the mold cavity; lost wax molds can be vented by attaching thin sticks of wax to the wax pattern, which also melt out to leave a "chimney" that allows gases to escape. Rammable and plastic refractories can be vented similarly to sand molds by thrusting a wire into them. This makes it easier for water vapor to exit the refractory on firing, reducing the likelihood of cracking.

Venturi

A venturi is a device consisting of two tubes of differing sizes, connected by a smooth taper (ideally a bell curve). As a fluid flows through the tubes, a pressure difference is set up (the small tube has a lower pressure and the large tube has a higher pressure) due to the effects of Bernoulli's principle. This is used to practical effect in naturally aspirated foundry burners, where the flow of fuel gas sets up a pressure differential and draws in combustion air from the atmosphere.

Vitreous

Vitreous substances are glassy and fully fused. Refractories should be sintered instead of vitreous; the loose sintered structure is more resistant to thermal shock than a vitreous structure. If refractory vitrifies in use, it has gotten too hot.

W

Waste oil

A foundry fuel that is usually free but difficult to burn, waste oil (WO) comes from two main sources. The first, waste vegetable oil (WVO), comes from fast food restaurants and your last fish fry. The second, waste motor oil (WMO), comes from the local mechanic and your last oil change. Be careful about burning used brake fluid, transmission fluid, etc., as it may have chlorinated oils that release toxic fumes. WMO may also potentially contain trace amounts of heavy metals (lead especially, from bearings in engines) that vaporize when burnt.

White metal

Any of a class of metals with melting points below the temperature required to emit visible light. Lead, tin, and zinc are common examples.

Woodgas

Woodgas is the volatile vapor formed as wood is heated. This consists of water vapor and various organic fractions, including hydrogen, methane, and carbon monoxide. Woodgas can be produced and burned, using special apparatus, to fire a foundry in much the same way as

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an oilburner is used. Some of the production methods produce charcoal as a secondary product; some burn the charcoal to fuel woodgas production.

Wrought

Wrought parts are cast into billets and hot or cold worked (extruded, rolled, forged, drawn, etc.) into final shape, instead of being cast to near final shape. Alloys intended to be wrought instead of cast typically have poor casting properties but higher malleability and ductility to enable processing. Virtually all stock shapes are wrought, not cast.

XYZ

APPENDICES

Appendices

Appendix 1: Temperatures by Color

Color	Degrees Fahrenheit	Degrees Celsius
Faint red (barely visible, depending on conditions)	900-1200	500-650
Dark red	1200-1400	650-750
Bright red	1400-1600	750-870
Orange	1600-1800	870-980
Yellow	1800-2000	980-1100
Yellow-white	2000-2300	1100-1260
White (yellow through a #5 shaded lens)	2300-2600	1260-1430
Blinding white (point where shaded lenses are necessary; white through a #5 shaded lens)	2600	1430

Appendix 2: Melting Points and Pouring Temperatures of Various Materials

Melting points given for alloys are approximations only and depend on the composition of the alloy. Pouring temperatures are given as guidelines and can be varied to vary casting properties.

Material	Degrees Fahrenheit		Degrees Celsius	
	Melting Point	Pouring Temp.	Melting Point	Pouring Temp.
Tin	450	500	232	260
Lead	622	700	328	370
Zinc	787	850	419	455
Aluminum Alloy	1180	1350	640	730
Pure Aluminum	1220	1380	660	750
Yellow Brass	1680	1950	915	1070
Copper	1982	2200	1083	1200
Cast Iron	2200	2450	1200	1350
Pure Iron	2800	2920	1538	1605
Pure Silica	3002	--	1650	--
Mullite	3360	--	1850	--
Pure Alumina	3730	--	2054	--
Silicon Carbide	4946	--	2730	--
Carbon (graphite)	6442 (sublimates)	--	3550	--

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Appendix 3: Table of Common Foundry Fluxes

Melting points for some entries are approximate, depending on exact composition.

Common Name	Flux Composition (% by mass)	Melting Point		Classification	Suitable Metals
		°F	°C		
Beeswax	$C_{15}H_{31}COOC_{30}H_{61}$	145	63	Organic	White metals
Rosin	$C_{19}H_{29}COOH$	210-250	100-120	Organic	White metals
Zinc chloride	$ZnCl_2$	527	275	Salt	White metals
Potassium, magnesium, sodium chlorides	$KCl-MgCl_2-NaCl$ (18.6-59.5-21.9)	745	396	Salt eutectic	White metals, aluminum, magnesium
Magnesium, sodium chlorides	$MgCl_2-NaCl$ (56.1-43.9)	806	430	Salt eutectic	Zinc, aluminum, magnesium
Calcium, potassium, sodium chlorides	$CaCl_2-KCl-NaCl$ (50-7.25-42.75)	869	465	Salt eutectic	Zinc, aluminum, magnesium
Boric oxide, borax	B_2O_3	896	480	Glassy	Copper alloys
Calcium, sodium chlorides	$CaCl_2-NaCl$ (55-45)	914	490	Salt eutectic	Zinc, aluminum, magnesium
Potassium, sodium chlorides	$KCl-NaCl$ (67-33)	1216	658	Salt eutectic	Aluminum, magnesium
"Diet" salt	KCl	1429	776	Salt	Aluminum
Table salt	$NaCl$	1474	801	Salt	Aluminum
Soda-lime glass	$SiO_2-Na_2O-CaO-MgO$ (73-14-9-4)	1500	815	Glassy	Copper alloys
Limestone	$CaCO_3 + SiO_2$	2450	1340	Glassy	Ferrous alloys
Fluorite	CaF_2	2555	1402	Salt	Ferrous alloys

Appendix 4: Flame Temperatures and Energy Densities of Selected Fuels

Fuel	Chemical Composition	Adiabatic Flame Temperature				Energy Density	
		Air (°F)	Air (°C)	Oxygen (°F)	Oxygen (°C)	BTU/lb	J/g
Propane	C_3H_8	3600	1980	4580	2530	21800	50600
Natural Gas	CH_4	3540	1950	5020	2770	18500	43000
MAPP Gas	C_3H_4	3650	2010	5300	2930	21000	48800
Acetylene	C_2H_2	4530	2500	5610	3100	21500	50000
Oil	$C_{30}H_{62}$	4000	2200	???	???	17900	41600
Charcoal/Coke	C	3800	2090	???	???	12400	28800
Bituminous Coal	$C + C_xH_y$	3730	2060	???	???	13500	31400
Dry Wood	$(C_6H_{10}O_5)_n$	3580	1970	???	???	6400	14900

APPENDICES

Appendix 5: Composition of Selected Aluminum Alloys

Alloy Number:	6061	2024	7075	3004	356	443	4032	2618	A535
Composition (%)									
Aluminum (Al)	97.90	95.90	93.37	97.80	91.13	94.20	85.00	93.70	92.82
Magnesium (Mg)	1.00	1.50	2.50	1.00	0.32	-	1.00	1.60	7.00
Copper (Cu)	0.28	4.35	1.60	-	0.25	0.60	0.90	2.30	-
Silicon (Si)	0.60	0.50	-	-	7.00	5.20	12.20	0.18	-
Iron (Fe)	-	0.50	0.50	-	0.60	-	-	1.10	-
Manganese (Mn)	-	0.60	0.30	1.20	-	-	-	-	0.18
Zinc (Zn)	-	0.25	5.60	-	0.35	-	-	-	-
Chromium (Cr)	0.20	0.10	0.23	-	-	-	-	-	-
Nickel (Ni)	-	-	-	-	-	-	0.90	1.00	-
Titanium (Ti)	-	0.15	-	-	-	-	-	0.07	-

Alloy Number	Description
6061	Very common, usually extruded. What most extruded scrap is made of. Average to good machinability and average to poor castability.
2024	High-strength wrought aircraft alloy. Good fatigue resistance, susceptible to corrosion. Average machinability and average to poor castability.
7075	Another high-strength wrought alloy. More corrosion resistance than 2024 and good machinability. Average to poor castability.
3004	Soda can alloy. Ductile for good rolling and forming characteristics. High shrinkage and poor castability.
356	The bread-and-butter sandcasting alloy. What a good portion of cast scrap is made of. Superb castability and good machinability, though abrasive to tools.
443	Simple sandcasting alloy. Good castability and machinability, only moderate strength.
4032	Forged silicon-bearing piston alloy. Decent castability, brittle but extremely strong and abrasion-resistant.
2618	Another piston alloy, very strong and much less brittle than 4032, but harder to work.
A535	This alloy has excellent machinability and does not need heat treatment to reach full strength. Very dimensionally stable, and good castability.

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Appendix 6: Thermodynamic Data for Selected Materials

COLE stands for Coefficient of Linear Expansion

SHC stands for Specific Heat Capacity

H_f stands for Heat of Fusion

TC stands for Thermal Conductivity

When two values are listed, the first value is for the material at room temperature (approx. 20°C) and the second value is for the material at high temperature (approx. 1100°C). If only one value is listed, it will be most accurate near room temperature. While the coefficients of linear expansion and specific heat capacities of various materials are often not even close to linear, a linear interpolation between the high and low values provided should yield results accurate enough for the average hobbyist.

For some of the more obscure thermodynamic data in this table, different sources reported wildly inconsistent values. This table is an assemblage of the best data I could find; however, it may have errors. Use the data below as a guideline only. (In particular, the expansion behavior of crystalline silica is extremely complex, and depends on heating rates and many other factors. A simple number cannot accurately describe its behavior.)

Material	Density (g/cc)	COLE (10 ⁻⁶ /°C)	SHC (J/g°C)	H _f (J/g)	TC (W/m K)	Transition Temp (°C)
Al ₂ O ₃	3.96	5.5/10.1	0.753/1.247	1092.6	46.0	—
B ₂ O ₃	2.55	2.5	???	352.8	???	—
CaO	3.34	11.7	???	1426.6	???	—
Fe ₂ O ₃	5.25	9.2/10.4	???	???	???	—
K ₂ O	2.35	26.2	???	???	???	—
Li ₂ O	2.01	5.4	???	???	???	—
MgO	3.58	12.8	???	1910.5	???	—
Na ₂ O	2.27	30.7	???	774.5	???	—
SiO ₂ (amorphous)	2.20	0.40/0.45	0.670/0.750	159.8	1.7	—
SiO ₂ (α-quartz)	2.65	8.1/18.9	0.742/1.381	159.8	1.7	573 (to β-quartz)
SiO ₂ (β-quartz)	2.53	8.1/18.9	0.742/1.381	159.8	1.7	867 (to tridymite)
SiO ₂ (tridymite)	2.30	8.1/18.9	1.123/1.181	159.8	1.7	1470 (to cristobalite)
SiO ₂ (cristobalite)	2.33	8.1/18.9	1.185/1.211	159.8	1.7	stable above 1470
Mullite	2.80	5.0/5.3	0.950	???	3.5	—
SiC	3.10	4.0	0.670	???	125.6/77.5	—
Graphite	2.25	4.3	0.708	???	24.0	—
Aluminum	2.70	22.1/27.4	0.900	386.9	210.0	—
Copper	8.93	16.7/24.8	0.385	204.8	398/357	—
Zinc	7.10	29.7	0.390	110.0	112.2	—
Tin	5.77	23.8/40.3	0.213	59.5	62.8/32.6	—
Lead	11.34	29.2	0.129/0.139	24.1	33.0	—
Brass	8.47	20.3	0.380	160.0	116.0	—

APPENDICES

Appendix 7: Properties of Selected Refractory Materials

SHC stands for Specific Heat Capacity

TC stands for Thermal Conductivity

Firing cost is computed using propane at \$1/lb, and is for a furnace lining that is fired in place. Firing in a kiln will cost roughly three times as much, depending on the form factor of the ware and the design of the kiln.

Many of these properties are approximations or typical values: commercial products come in a wide range of densities, temperature tolerances, etc., and there is unavoidably some variation in the properties of homemade ceramics, even when made from the same recipe. In particular, costs will vary widely depending on the source of the ingredients, and will change over time.

Densities given are bulk density for a fired product, not homogeneous material density.

Material	Density		Mat'l Cost \$/cu. ft.	Firing Cost \$/cu. ft.	Total Cost \$/cu. ft.	SHC (J/g°C)
	lbs/cu. ft.	g/cc				
Dense Castable	150	2.40	\$90	\$4	\$94	0.85
Dense Castable/Foam 1:3	50	0.80	\$27	\$5	\$32	0.85
Insulating Castable	80	1.28	\$48	\$4	\$52	0.75
Insulating Castable/Foam 1:3	27	0.43	\$17	\$5	\$22	0.75
Dense Firebrick	140	2.24	\$135	\$0	\$135	0.75
Insulating Firebrick	30	0.48	\$135	\$0	\$135	0.75
Ceramic Fiber Blanket	8	0.13	\$40	\$0	\$40	0.72
Dry Sand	94	1.50	\$7	\$0	\$7	0.74
Loose Perlite	6	0.10	\$24	\$0	\$24	0.74
Clay/Sand 1:3	100	1.60	\$12	\$11	\$23	0.74
Clay/Sand/Foam 1:1:8	20	0.32	\$8	\$13	\$21	0.74
Mullite (sintered)	120	1.92	\$84	\$11	\$95	0.95
Mullite/Foam 1:4	24	0.38	\$22	\$13	\$34	0.95
Material	Max Temp.		Flux Resistance	Mechanical Durability	Ease of Use	TC (W/m K)
	°F	°C				
Dense Castable	3000	1650	Very Good	Very Good	Very Easy	1.30
Dense Castable/Foam 1:3	3000	1650	Good	Poor	Easy	0.43
Insulating Castable	2800	1540	Good	Good	Very Easy	0.53
Insulating Castable/Foam 1:3	2800	1540	Good	Very Poor	Easy	0.18
Dense Firebrick	3100	1700	Very Good	Very Good	Easy	1.20
Insulating Firebrick	2800	1540	Poor	Moderate	Easy	0.26
Ceramic Fiber Blanket	2600	1420	Very Poor	Poor	Easy	0.08
Dry Sand	2800	1540	Moderate	--	Easy	0.50
Loose Perlite	1700	930	Very Poor	--	Easy	0.16
Clay/Sand 1:3	2800	1540	Moderate	Good	Moderate	0.80
Clay/Sand/Foam 1:1:8	2800	1540	Poor	Very Poor	Very Difficult	0.16
Mullite (sintered)	3200	1760	Excellent	Very Good	Difficult	1.30
Mullite/Foam 1:4	3200	1760	Very Good	Very Poor	Very Difficult	0.26

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Appendix 8: Pyrometric Cone Chart

Pyrometric cones read slightly differently between different brands and types of cone, and many of the values on this table are extrapolated because cones in that particular heat range are not commonly tested for those heating rates. This table is accurate enough for general reference, but a data sheet from the manufacturer of the cones you plan to use will be much more accurate.

Cone	Heating Rate (degrees per hour)									
	27 °F	15 °C	110 °F	60 °C	270 °F	150 °C	500 °F	280 °C	1000 °F	560 °C
022	1017	565	1055	586	1062	590	1145	636	1324	736
021	1044	580	1080	600	1111	617	1194	663	1373	763
020	1093	607	1127	626	1148	638	1232	684	1411	784
019	1181	656	1220	678	1251	695	1334	741	1513	841
018	1235	686	1287	715	1321	734	1404	780	1584	880
017	1269	705	1328	738	1373	763	1457	809	1636	909
016	1336	742	1390	772	1433	796	1516	842	1695	942
015	1350	750	1424	791	1472	818	1556	864	1735	964
014	1363	757	1453	807	1508	838	1592	884	1771	984
013	1453	807	1507	837	1550	861	1633	907	1812	1007
012	1517	843	1550	861	1588	882	1671	928	1850	1028
011	1543	857	1575	875	1609	894	1692	940	1872	1040
010	1604	891	1625	903	1647	915	1730	961	1909	1061
09	1633	907	1656	920	1674	930	1757	976	1936	1076
08	1660	922	1696	942	1721	956	1804	1002	1983	1102
07	1732	962	1757	976	1777	987	1860	1033	2039	1133
06	1766	981	1796	998	1823	1013	1907	1059	2086	1159
05	1838	1021	1856	1031	1879	1044	1962	1090	2142	1190
04	1883	1046	1913	1063	1939	1077	2022	1123	2201	1223
03	1928	1071	1955	1086	1987	1104	2070	1150	2250	1250
02	1940	1078	1984	1102	2020	1122	2103	1168	2282	1268
01	1967	1093	2014	1119	2048	1138	2132	1184	2311	1284
1	1996	1109	2047	1137	2077	1154	2160	1200	2340	1300
2	2002	1112	2056	1142	2095	1164	2178	1210	2358	1310
3	2007	1115	2074	1152	2106	1170	2189	1216	2368	1316
4	2054	1141	2092	1162	2129	1183	2213	1229	2392	1329
5	2086	1159	2135	1186	2173	1207	2256	1253	2435	1353
6	2133	1185	2200	1222	2237	1243	2321	1289	2500	1389
7	2162	1201	2230	1239	2263	1257	2346	1303	2525	1403
8	2180	1211	2248	1249	2288	1271	2371	1317	2550	1417
9	2203	1224	2268	1260	2304	1280	2387	1326	2566	1426
10	2252	1251	2313	1285	2349	1305	2432	1351	2611	1451
11	2290	1272	2329	1294	2367	1315	2450	1361	2629	1461
12	2313	1285	2351	1306	2387	1326	2470	1372	2649	1472
	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C
	27	15	110	60	270	150	500	280	1000	560

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Cone	Heating Rate (degrees per hour)									
	27 °F	15 °C	110 °F	60 °C	270 °F	150 °C	500 °F	280 °C	1000 °F	560 °C
13	2367	1315	2396	1331	2426	1348	2510	1394	2689	1494
14	2428	1349	2457	1365	2491	1384	2574	1430	2754	1530
15	2522	1401	2551	1417	2570	1428	2654	1474	2833	1574
16	2594	1441	2623	1457	2655	1475	2738	1521	2917	1621
17	2633	1463	2662	1479	2677	1487	2760	1533	2939	1633
18	2675	1486	2704	1502	2714	1508	2798	1554	2977	1654
19	2711	1506	2740	1522	2754	1530	2837	1576	3016	1676
20	2750	1528	2779	1544	2792	1551	2875	1597	3054	1697
21	2790	1550	2819	1566	2828	1571	2911	1617	3090	1717
22	2810	1561	2839	1577	2847	1582	2930	1628	3109	1727
23	2830	1572	2858	1588	2866	1592	2949	1638	3128	1738
24	2839	1577	2867	1593	2887	1604	2970	1650	3150	1750
25	2848	1582	2876	1598	2900	1611	2992	1662	3163	1757
26	2857	1587	2885	1603	2918	1621	3001	1667	3180	1767
27	2866	1592	2894	1608	2952	1640	3035	1686	3214	1786
28	2876	1598	2905	1614	2963	1646	3046	1692	3225	1792
29	2900	1611	2929	1627	2986	1659	3069	1705	3249	1805
30	2911	1617	2939	1633	2997	1665	3080	1711	3259	1811
31	2943	1635	2972	1651	3029	1683	3113	1729	3292	1829
32	3004	1669	3033	1685	3091	1717	3174	1763	3353	1863
33	3051	1695	3080	1711	3137	1743	3221	1789	3400	1889
34	3087	1715	3116	1731	3173	1763	3257	1809	3436	1909
35	3127	1737	3155	1753	3213	1785	3296	1831	3475	1931
36	3161	1756	3190	1772	3247	1804	3330	1850	3510	1950
37	3190	1772	3218	1788	3276	1820	3359	1866	3538	1966
38	3244	1802	3272	1818	3330	1850	3413	1896	3592	1996
39	3271	1817	3299	1833	3357	1865	3440	1911	3619	2011
40	3307	1837	3335	1853	3393	1885	3476	1931	3655	2031
41	3460	1922	3488	1938	3546	1970	3629	2016	3808	2116
42	3541	1967	3569	1983	3627	2015	3710	2061	3889	2161
	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C
	27	15	110	60	270	150	500	280	1000	560

Data from the Edward Orton, Jr. Ceramic Foundation. <<http://www.ortonceramic.com>>

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Appendix 9: Formulas and Unit Conversions

Unit Conversions									
1	inch	=	2.54	centimeter	1	centimeter	=	0.394	inch
1	foot	=	0.3048	meter	1	meter	=	3.281	foot
1	fluid ounce	=	29.57	milliliter	1	milliliter	=	0.03382	fluid ounce
1	pound	=	0.4536	kilogram	1	kilogram	=	2.205	pound
1	ounce	=	28.35	gram	1	gram	=	0.03527	ounce
1	troy ounce	=	31.10	gram	1	gram	=	0.03215	troy ounce
1	BTU	=	1055.0	joule	1	joule	=	0.000948	BTU
1	BTU/hour	=	0.2931	watt	1	watt	=	3.412	BTU/hour
1	horsepower	=	745.7	watt	1	watt	=	0.001341	horsepower
1	US penny	=	2.5	gram	1	gram	=	0.40	US penny
1	US nickel	=	5.0	gram	1	gram	=	0.20	US nickel

Metric Prefixes			
p	pico	10 ⁻¹²	trillionth
n	nano	10 ⁻⁹	billionth
μ	micro	10 ⁻⁶	millionth
m	milli	10 ⁻³	thousandth
c	centi	10 ⁻²	hundredth
k	kilo	10 ³	thousand
M	mega	10 ⁶	million
G	giga	10 ⁹	billion
T	tera	10 ¹²	trillion

Metric Unit Relations			
1	watt	=	1 joule/second
1	cm ³ of water	=	1 gram

Temperature			
		To convert from °F to °C:	Subtract 32 then divide by 1.8
		To convert from °C to °F:	Multiply by 1.8 then add 32
		To convert from °C to Kelvin:	Add 273.18

Imperial Unit Relations									
1	gallon	=	4	quart	1	quart	=	0.25	gallon
1	gallon	=	8	pint	1	pint	=	0.125	gallon
1	gallon	=	16	cup	1	cup	=	0.0625	gallon
1	gallon	=	128	fluid ounce	1	fluid ounce	=	0.0078125	gallon
1	pound	=	16	ounce	1	ounce	=	0.0625	pound
1	pound	=	14.58	troy ounce	1	ounce	=	0.0759	troy lb
1	troy lb	=	12	troy ounce	1	troy ounce	=	0.0686	pound
1	troy lb	=	13.17	ounce	1	troy ounce	=	0.0833	troy lb
1	fl. ounce of water	=	1	ounce					

Area	
Rectangle, Parallelogram	$A = bh$
Trapezoid	$A = \frac{b_1 + b_2}{2} h$
Triangle	$A = \frac{1}{2} bh$
Circle	$A = \pi r^2$
Annulus	$A = \pi (R^2 - r^2)$
Circumference	
Circle	$C = 2\pi r$
Polygon	$C = \sum s_1 + s_2 + \dots$

Surface Area	
Cylinder	$S = 2A_{base} + Ch$
Annular cylinder	$S = 2A_{base} + (C_1 + C_2) h$
Cone	$S = A_{base} + \pi r \sqrt{h^2 + r^2}$
Sphere	$S = 4\pi r^2$
Volume	
Prism	$V = A_{base} h$
Cone, pyramid	$V = \frac{1}{3} A_{base} h$
Sphere	$V = \frac{4}{3} \pi r^3$

Appendix 10: Patternmakers' Rulers

Patternmakers' rulers are special rulers with the shrinkage of the metal already taken into account. These rulers are somewhat of a relic nowadays, as computers make it easy to calculate shrinkage and apply it manually. Still, they may come in handy for simple layout tasks, and are generally easier to deal with for whole-number measurements (which end up as odd decimal values on an ordinary ruler). The shrinkage values used here are for typical alloys; aluminum in particular has a large variance in shrinkage between cast and wrought alloys. Computer graphics programs make it relatively easy to make a custom ruler for a particular alloy by scaling a ruler graphic to the desired size.

