Richard Austin (1936-1990) was a metalsmith and author, with several hundred articles to his credit.

After his death I was given custody of an extensive collection of manuscript material-mostly on the technical issues of metalworking.

This text represents the first effort to organize the material—an attempt merely to group the files by topic. None of this is finished, and the text makes reference to illustrations that were never done—illustrations which were stored separately in any case, making it extremely difficult to bring the parts together.

It is unlikely that I will ever be able to spend the time to sort this all out. But it seemed a shame to let these articles languish unread by those who might benefit from them in some small way. So I have decided to release them in their roughly sorted form in the hopes that someone may find them useful.

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PRODUCTIVITY

If you are an independent bench worker, you are constantly pressured by three significant constraints: productivity, quality and cost. For the most part, improvements in quality (given any particular materials) come from spending more time on the work or being more skillful. Goldsmithing, like any other activity which requires significant eye-hand motor coordination, improves with experience. The work flow becomes smoother, better organized, and there is less wasted motion. Setting aside these considerations, there is considerable productivity improvement which can be gained through "tricks of the trade". These are short cuts or techniques which allow you to achieve any particular result in a minimum amount of time.

I have always preferred the quality appearance of three-piece pin sets using a riveted joint. Although they are a little harder to adjust and rivet shut, I think they have a better appearance and, more important, it allows you to set the tension in the pin stem more precisely. A properly adjusted pin should not pop open, even if the clasp is not closed. Achieving this kind of alignment demands that you have a very tight hinge in the pin, and this can only be accomplished with
a riveted joint.

When you're working alone, this can be something of a problem since using an upset rivet seems to require three hands: one to hold the work, one to hold the punch and one to hold the hammer. Alternately, you can use a mechanical hammer, but the appearance is still marginal, the work is a little slow and, what's worse, it tends to bounce around and sometimes mark the work, requiring more finishing. The technique which I'll describe here is very quick and seldom puts any marks at all on the work. Basically, this requires a special tool to set the traditional tapered pin in the hinge joint.

Begin by purchasing an inexpensive pair of jeweler's pliers. These can be square or needle-nosed, depending on the basic shape of the tip. The first step is to use a dental cut-off blade to put a notch in one side of the pliers. This notch should be about three/thirty-seconds (3/32s) of an inch deep and have the same width as the major dimension of the pin stems which you will be setting.

Tapered pins can be made very quickly with your flexible shaft machine. File a small vee notch in the side of the bench pin and put a short piece of wire in the chuck. The diameter of the wire should be slightly larger than the final pin
required. Rotate the wire slowly and bring it to a long taper with the smooth mil file.

Slip the tapered pin into the joint and make any adjustments on the pin stem. It can be bent from side to side slightly or up or down to provide the required amount of tension. When you're satisfied that everything is properly adjusted, simply use the pliers to drive the tapered pin into the joint. The small end should emerge through the notch in the pliers. Typically, I use a long pin and there is a little something left over on both ends. The excess is cut off both sides with an ordinary diagonal cutter. The rough joint can be quickly smoothed by pinching it deep in the throat of a pair of jeweler's pliers. A final buffing and the appearance is usually excellent. The joint is tight and yet it can be removed if necessary.
SCULPTURE

Although the primary focus of this text is small, art metal objects, many of the same techniques can also be used to produce larger, sculptural objects. However, some adaptation will be required. The most obvious difference in the two classes is one of scale. The problem of scale manifests itself in several ways. First, large objects are usually poured castings. No mechanical assistance is used to force the metal into the mold. This means that the arrangements of gates, vents and risers must be used. In this sense, large investment casting relates more closely to conventional foundry practice. The second problem for small studios is often that of melting the metal. If bronze is used, relatively elaborate melting apparatus will be required for the larger melts. Alternately, low melting alloys such as pewter may be used. The large scale may also require special burnout arrangements. Finally, cost may dictate the use of lower cost materials.

In the case of the smaller metal objects, I would strongly recommend that you use top quality commercial investment. Their superior properties provide excellent results. However, at some size economics may favor producing your own casting investment. The basic _______ requirements to produce a
satisfactory sculptural casting are simple. A mixture of 80%, 200 mesh silica in 20% molding plaster can be used. The material can be calibrated by the same directions indicated in Chapter 9. There will be a number of nominal differences between this homemade material and commercial casting investment.

For most applications, the most notable change will be increased shrinkage due to the absence of cristobalite. The absence of cristobalite makes the investment less susceptible to cracking during cooling. Since much of the casting may be at or near room temperature, _____ is a benefit compared to jewelry investments. Note that most sculptural investment contains little or no cristobalite.

A gravity feed, poured casting, does not provide enough pressure to insure that the air will be forced out through the pours in the investment. Figure 71 illustrates a typical sprue and vent arrangement for larger castings. On the positive side, the vent system prevents many of the problems of incomplete burnout since makeshift burnout arrangements may require the margin of safety to prevent disappointment. Since the air does not have to go out through the investment material, incomplete burnout may represent less of a problem. Note, however, that the cavity must be fully cleared and that
the presence of carbon on the surface of the mold may cause interactions with the metal during pour.
Wetting Agents - Traditional casting practice calls for the use of a wetting agent to insure good contact between the investment and the model. Classical literature reference suggests the use of material such as peroxide and green soap. More recently, a number of commercial materials have become available. These are basically sold in two types, one for vacuum casting and one for vibratory investment, the primary difference being that the material sold for vacuum investment applications have less tendency to foam. The use and application of the wetting agents is an area of enormous controversy among casters. Which agent is best, how it should be applied and how long it should sit before investment are all issues of debate. Fortunately, this is gradually becoming a non-issue. Companies such as Kerr Manufacturing have begun to add wetting agents directly to their investment. These wetting agents work well enough to eliminate the need for material to be applied to the model. As a practical matter, at this point using a wetting agent may actually decrease surface quality if it's improperly applied. I would strongly suggest that you use an investment material containing a wetting agent and do not use any material on the models. There are some other benefits which accrue from this approach. First of all, it eliminates a whole area of uncertainty and, second, it means that you can invest very quickly after spruing. There is really nothing to wait for.

It should be noted that the use of silicone rubber molds or
silicone mold releases make the surface of the model considerably more hydrophobic. This can be seen if you attempt to apply wetting agents to the surface. Silicone-contaminated surfaces do not wet out even with the wetting agents. Although it may not at first seem obvious, the use of wetting agents with silicones is probably counterproductive since it does tend to bead up and concentrate in a heavier layer in certain areas of the casting. This is precisely the situation which we do not wish to encounter. Even in the case of highly hydrophobic surfaces, it's better to let the wetting agent in the investment do its work.

In addition to being hydrophobic, wax models often tend to develop a significant static charge, particularly in lower humidity conditions. This static attracts all kinds of contaminants, the most serious probably being wax dust from fabricating operations. It's not too hard to believe that having this contamination in the casting system is a bad idea. If you encounter situations where you seem to be getting various kinds of surface contamination, this can be eliminated by a quick rinse in a strong detergent solution followed by cold water. After the model is dried, you may proceed normally.
**Surface Discoloration** - Gross overheating the investment will free sulphur compounds which are available to react with the metal surface during the casting process. This kind of discoloration is very deep and persistent. It will be very difficult to remove by pickling and may require extended abrasion. Unfortunately, there is a more subtle problem which occurs. At any temperature, when the mold is placed in the flask, the contact area on the surface of the investment will be heated to the temperature of the metal. This heat transfer doesn't last very long. As the metal cools, the investment drops below the critical temperature and everything is under control. However, note that the higher the temperature of the investment at the time of casting, the deeper this affected surface area will become and the slower the metal will drop in temperature. This means that if you cast into a very hot mold, even though it's below the critical temperature of the investment, a significant depth of the investment will be affected. This kind of effect can be observed if you carefully section the investment or trim it away after casting. There will be a discolored zone near the metal.
The process of preparing individual wax models is inherently dusty and dirty. The shop area will become contaminated with wax dust and scraps. The wax models also tend to accumulate a static charge. When you combine these two problems you have a formula for failure. A simple cleaning will eliminate most of this problem. After the models have been sprued (but before they are attached to the sprue base) they can be washed. Simply dip the models in a strong household cleaner (ammonia or
INDUCTION MELTING FURNACE

A comprehensive presentation on the use of induction heating in the jewelry craft would include the following:

1. **Technical Background** - The basics of how induction melting works and its advantages (or disadvantages) in application would need to be discussed. Additionally, any safety aspects of the use of the equipment should be considered. This would be followed by a more detailed description of the actual Kerr equipment used.

2. **Application** - The specific, appropriate applications for the equipment would include:

   A. Metal Alloying and Grain Preparation
   B. Poured Casting
   C. Vacuum Casting
   D. Centrifugal Casting

3. **Projects** - Potential projects to illustrate the article would include:

   A. Tuffa Stone Casting
   B. Carved Investment, Poured Casting
   C. Large Centrifugal Casting
   D. Grain Preparation from Scrap
SIZE ADJUSTMENT

In the first segment of this series, we saw how the thermal expansion properties of the investment and the metal influenced final part size. Confusion about the dimensional problem stems from a number of sources:

1. Materials and process have changed over a period of time.

2. There are various routes or steps which may be involved in preparing the master.

3. Misconceptions about the actual nature of the casting process.

Dental practice is one of the key areas of technical development of investment casting. In this case, impressions were made and masters prepared for various pieces of gold dental work. Obviously, these have to fit with a high degree of precision. In some cases, the wax is worked directly at body temperature and in most cases the wax undergoes a good deal of handling during the build-up and modeling process. In any event, the model wax is usually prepared at some temperature well above room temperature. The waxes themselves have a fairly significant degree of thermal expansion. See Figure 2. This means that as the wax is cooled from this elevated temperature to room
temperature, there is considerable shrinkage. Thus, the pattern is already smaller when it is ready to be invested than it was when it was prepared. Historically, various methods have been used to compensate for these changes. Obviously, the pattern could be warmed, or the investment itself could be modified in some way to compensate for this wax shrinkage. A good deal of the literature on sizing of patterns of models relates to the various techniques developed to deal with this problem.

A very similar situation prevails in the preparation of jewelry from waxes which are prepared in rubber models. Once the molten wax is injected in the mold and solidifies, it continues to shrink as it approaches room temperature. This shrinkage may be great enough to amount to as much as 3/4 of a ring size on a ring. In addition to this, some of the rubber mold making processes themselves produce a cavity which is slightly smaller than the original master. Again, the process is used, the materials involved, and their treatment all influence the degree of shrinkage in the mold cavity. In any event, this situation where a master is prepared, a rubber mold is taken, and waxes are injected, leads to a series of steps which introduce significant shrinkage into the system by the time the wax model is prepared. In both of these cases, the net result of the process of preparing the wax model yields a model which is slightly undersized. The casting process itself may also
change the size of the final piece of work. Again, the thermal expansion properties of the investment material and the coefficient of thermal expansion of the flask and the cast metal itself all can influence the final size of the finished piece. Modern investment materials, when selected for the appropriate applications, are designed to compensate for most of these problems that occur in casting. Specifically, the investments are designed to have thermal expansion properties which will compensate for or exactly offset the thermal contraction which occurs during cooling of the cast part. Thus, a properly run casting procedure will produce finished castings which are very nearly the same size as the master pattern used. Because subtle variations in every step of the work have an influence on the final size of the casting, it is probably best to do an experimental test bar to determine the casting characteristics of the system which you use. The following discussion will describe a system which you can use in your own casting process to test the precise characteristics of your own system.

First, let's begin by identifying the order of magnitude of the problem. A size 5 ring has an internal diameter of approximately 0.618". A size 6 ring has an internal diameter of 0.650". This represents approximately a one percent difference in diameter. That would mean that if the casting process allowed for the shrinkage of the ring by as
little as one percent, the rule of thumb suggesting a one size allowance would be correct. It is obvious that we are working with relatively small changes.

Several other factors can influence dimensional control. Let me give you a couple of specific examples. It is possible to prepare a wax mounting where the stone pops into place. The wax is quite elastic and it can stretch or deform slightly to make up for irregularities in shape, or simply being too small. Unfortunately, the final metal doesn't stretch at all and the metal will appear to have shrunk far more than it actually did. If you combine this stretching effect with the fact that there is a very small percentage of shrinkage, this means that tight stone seats in wax will be unmountable.

This measurement problem also operates with rings. If you would like to satisfy yourself on this, carve a wax ring shank and simply drop it onto a vertical ring mantle. Note where it stops. Then slowly force the model further up the ring mantle. If the wax is tough and the temperature warm, you may find that you can stretch it as much as a full size before it breaks. Stretching errors in size measurement can be extremely misleading when the final product is absolutely inflexible.

In my personal experience, if you are using modern
investment materials and careful processing, you need make no allowance for ring size in your castings. You will find that they will be every so slightly smaller than the original measurement. However, the difference is just about equal to what you'll grind out in an ordinary finishing operation. In this case, the shrinkage simply balances the metal which you will remove during final polishing.
CRUCIBLES

When I began making jewelry, I read an article which described casting crucibles as very fragile. Contrary to this, my own experience indicates that they are really very tough. I've never broken a crucible in my shop except when they have been dropped on the floor, or thrown out of a centrifugal casting machine. I have one crucible that has been used for more than 200 melts. Although it doesn't look like much, it is still going strong. In fairness to that old article, I suspect that modern crucibles are much tougher and more resistant to thermal shock than those of 20 to 40 years ago.

Crucibles are much tougher and many other elements of the casting process have changed. Historically, most literatures suggested that crucibles for centrifugal casting be lined with fresh asbestos paper for each use. Typically, a piece of asbestos would be cut to shape, moistened, and formed into the crucible. This would be dried in the oven, and casting would proceed.

Given the present knowledge of the health hazards associated with asbestos, this procedure has fallen into disfavor. Unfortunately, I'm not aware of any unsatisfactory synthetic replacement. There were several benefits to the use of an asbestos liner. After casting, there was always a residue
of discolored flux, and traces of metal particles on the asbestos. These were removed along with the liner, so that each cast was made in a clean crucible. Without a crucible liner, all of this residue will end up somewhere in your next melt. This suggests a number of the key factors in the casting methodology.

A good place to begin considering the problem is with a new crucible. New crucibles are often rather dirty, with bits of ceramic dust or small chips clinging to them. Obviously having this show up in a casting later isn't going to improve quality. I usually begin by washing the crucibles with plain water to rinse away any particulate matter. After they are rinsed, I allow them to dry overnight. The next time I'm doing a batch of castings, I put the crucible in the oven, after the preliminary burnout is complete. You don't want to put it in the oven too soon, since there is often soot floating around in the system. Usually after the oven is at 800 or 900 degrees, you can pop your crucible in and bring it to the final temperature along with the rest of the casting load.

When the flask is at temperature, remove it and place it on a ceramic brick on your benchtop. Then, using an acetylene torch to bring it up to dull heat, sprinkle the heated surface lightly with borax. Alternately apply the torch and borax until you've succeeded in achieving a uniform glaze.
Be sure to coat the cone shape are around the opening so that metal will not tend to stick there as you throw a casting. When the crucible is well glazed, it is ready to be used.

After you've used the crucible a few times, the system comes to some kind of equilibrium. The amount of flux which is retained on the surface of the crucible builds up to a certain thickness and stays there. The excess then flows over with the metal. What you end up with is a lot of flux on the base of each sprue bottom. As long as not too much flux is coming over, this doesn't seem to be a problem. This does mean that it is very important to pickle sprue buttons thoroughly and remove very last trace of this contaminated flux before the metal goes back into the next cycle. This would be important in any case, but it is particularly important when you don't have a liner present to hold any of the contaminates.

When no crucible liner is used, it is particularly important to reserve each crucible for one kind of metal. Since one used crucible looks pretty much like another, some marking is required. The simplest way to mark them is to write on the bottom with an ordinary graphite pencil. This will last through a number of melts and is easy to renew from time to time.
There are several other kinds of crucibles which you may encounter during your work. Some comments on these might be useful. One common crucible is the graphite or carbon crucible which is used with various kinds of induction melting equipment. Although there are some reasons other than reduction for using a carbon crucible, the main reason for its application is to provide a reducing (oxygen free) atmosphere over the molten metal. This prevents the formation of metal oxides during the melting process. Since many of the induction melting furnaces require 15 or 20 minutes to bring the melt to heat, this is particularly important. A few notes should be made about the use of graphite crucibles.

First of all, they function by reacting with the oxygen over the metal and turning it into carbon dioxide. They do this by burning off their own surface. Although this burning is very slow, it is a mechanism for oxygen removal. This means that the act of creating a reducing atmosphere slowly consumes the crucible. Eventually the carbon crucible will be burned away. Since these crucibles are fairly expensive, anything you can do to maximize their life will be helpful.

First of all, no flux is used with the carbon crucible. This means that the surface must be clean, pure carbon. Since the crucible must consume itself burning away oxygen, anything you can do that would keep oxygen out of the system
will slow this process. To put it simply, don't peek inside the crucible during the melting process. Each time you open the crucible lid, a blast of fresh oxygen rich air is introduced into the crucible. The crucible must then consumer part of itself to remove this oxygen. The oftener you look inside a crucible, the more quickly it will burn up. If you're going to use an induction furnace, rely on the pyrometer and not visual observation to check the condition of the melt. One small trick which has been suggested to help the situation, is to introduce a little more reactive carbon into the system. For example, if you add a small piece of pure charcoal to each melt, it will be consumed more rapidly than the graphite (which is somewhat less reactive) and use up the oxygen first. Any carbon from the charcoal which is used up will not have to be burned off the surface of the crucible. It is also worth noting that the carbon crucibles are fairly fragile and if you drop it, will most assuredly break.
CASTING SAFETY

Professional welders and pipe smokers both have a clear understanding of the fact that materials such as cotton and wool are much more resistant to high temperatures than synthetic fabrics. If you look at the polyester suit worn by a pipe smoker you'll invariably find small burn holes. By the same token, it is very difficult to burn a small hole in a woolen suit. Almost all of the clothing worn by welders and foundry workers tend to be natural materials. The reason for this is really quite simple. Most of the synthetic fabrics melt at relatively low temperatures. This means that if they are struck with an ember from a pipe or a small droplet of molten metal, they melt instantly. This causes two real problems. First of all, the piece of metal or hot ember will go right through the material. Second, the melted fabric is adhesive and tends to transfer heat very rapidly. This means that the melted fabric can stick to your skin and burn it badly.

For this reason, you should wear cotton or woolen clothes when doing any metal casting. In spite of the fact that I have a shield for my centrifugal casting machine, from time to time small pieces of metal splash outside. On one occasion I had a crucible jump out of the carriage, strike the wall of the shield and fly across the room. In that particular case, my son was working with his back to the caster and received both a bruise and burn on his back. I can't emphasize too strongly that while you can protect yourself from the hazards
there are certain dangers inherent in the casting process.

In addition to wearing clothes of suitable material, other precautions are required. The key one is to protect your eyes and face. For those of you who wear eyeglasses, you should always purchase safety glasses for use in the shop. During the casting process, welding goggles are excellent to protect your eyes from the flying metal and also from the bright yellow flare of the melted metal. A good alternate is to use a full plastic face shield such as provided to many laboratory or foundry workers. Either of these can provide considerable protection to the face from either solid or molten metal flying out of the casting system.
INTRODUCTION:

The lost wax technique of metal casting has a long and respected history. Beautiful examples of such work are associated with ancient cultures in China, Egypt, Central and South America and Africa. Some of the early examples of lost wax casting are thousands of years old. By the time of the Renaissance, methods were well developed and were applied to very large statuary as well as small objects. The modern era of lost wax casting began around the turn of the century when this technique was applied to dentistry. The development and availability of professional dental casting equipment and supplies was a major factor in the growth of the jewelry hobby. The dental type equipment produces very high quality, reliable results. However, it is rather expensive for the average hobbist. Within the last few years a wide range of less expensive equipment has come on the market. This provides an ideal entry point for the beginning jewelry maker although the more serious worker will usually prefer the higher quality more expensive equipment. The jewelry hobby has matured into a reliable, rewarding activity that can provide relaxation and a full range of creative challenges for the participant.

Since contemporary casting is often done with models made from materials other than wax, we need a slightly different language to describe our work. Metal may be introduced into a mold under the pressure generated by gas pressure, vacuum, gravity or centrifugal force. The common element is the investment mold. For this reason I would like to use this nomenclature for the balance of this book. The investment casting process is one of the most versatile craft metal fabricating techniques available to the contemporary hobbist. Casting equipment
is available in a wide range of quality and price that can suit the newest beginner or the most accomplished professional goldsmith. The modern equipment can produce consistent and reliable results with a minimum of time and bother. However, no matter how much experience a craftsman has with the investment casting process, or how elaborate his equipment is, the mechanics of investment casting are at best a skilled craft. The creativity or art of jewelry making is achieved in the model making process. As a practical matter many skilled professional jewelry makers don't bother to cast their own work. They ship their models to a professional caster who may also completely finish the work.

From an artistic viewpoint model building is where the action is; however, the model making process can be very frustrating to the jewelry maker. Most of the literature references on model making for investment casting are limited to one or two techniques. Other than some preliminary general remarks, this book will not deal with the mechanics of the casting process. It is dedicated to presenting the widest possible range of techniques for model construction for the investment casting process. Obviously it is impossible to discuss every possible technique. However, I will present a range of approaches as well as a discussion of the basic requirements of the model building process. I hope that this approach will give you some new ideas and encourage you to experiment and develop your own skills and techniques. The first portion of this book will deal with modeling in wax. Roughly half of the total content will be devoted to other specialized techniques in model
construction. The use of plastics, wood, paper, plants and other materials will be covered. Mold making and other reproduction processes will also be discussed.

INVESTMENT CASTING:

In the early stages of the development of the casting process the models were made of beeswax, and the molds were made of clay. The wax was burned out and the clay was fired at the same time. This clay mold was then used to make the castings. Many of the objects were hollow since the wax was actually constructed over a clay core to provide a wax shell and thus, a hollow casting. Modern materials have simplified the process but the basic technique remains the same.

Although the model building process can be treated as a completely independent issue, the characteristics of the casting method will place certain limitations on the model building process. For this reason, I would like to begin with a summary of the characteristics of the investment casting process.

The investment casting process can be divided into four major operations. Each of these to some degree inter-relates with the others. These are:

1. Model Building
2. Investment
3. Burn-Out
4. Casting
In essence, investment casting models can be built from any material which does not react with or damage the mold, which is dimensionally stable, and which will burn out of the mold at a temperature which does not damage the investment. If we look at the various steps in the casting process the requirements for the model become obvious.

**Investment** - The investment process consists of placing the model within a steel cylinder and surrounding it with the investment material. Although there are various investment formulations, it is simplest to think of these as a mixture of calcium sulphate (plaster) and various fillers. One of the most common fillers is finely divided silica powder. Since the investment is mixed with water, it is important that the model be constructed of a material which will not dissolve or soften during the 9 or 10 minutes that is required for the investment to set.

In order to insure that the investment is in good contact with the model, various physical means are applied to remove any air bubbles in the investment. The two most common means are mechanical vibration and vacuum. Both of these apply stresses which can damage the model if it is too fragile.

**Burn Out** - The elimination of the model from the investment material is brought about by raising the invested model to a temperature in the range of 900 F to 1400 F. Temperatures above this range may cause varying degrees of deterioration in the investment material depending on the time that the temperature is held. The flask is put in a furnace at a relatively low temperature and heated gradually. A series of steps occur during the burn-out. At first any material which can melt will simply run out the sprue opening and be consumed outside the
flask. If the model is made of some material which does not readily melt, then it must be totally consumed in place. If a wax model is used a part of the molten wax is absorbed into the pores of the investment material. This absorbed wax must be fully burned out to allow the air to move freely through the investment during the introduction of metal to the mold. In any case, the model is slowly raised to a temperature somewhere between 900 and 1300 degrees F and held there for a period of an hour or more. It's a good idea to always try for a maximum final temperature approximately 100 F below the manufacturer's recommended maximum. This allows a little leeway for hot spots or errors in temperature measurement. During this time the model should be totally eliminated from the cavity. Any residual ash or material left in the cavity may cause surface defects or other flaws in the cast metal. For those of you with a more technical orientation, it's probably worth noting that burn out is a misnomer for this process even though it is the commonly accepted term. Generally the idea of burning implies combustion, which is a chemical process, accompanied by the evolution of light and heat. In the case of the casting process, the burn out may be completely accomplished without meeting this criteria. A more accurate definition would probably be to describe the process as pyrolysis. Pyrolysis is a chemical change brought about by exposure to high temperature. In this case the pyrolysis proceeds in the presence of oxygen. Since most of the satisfactory investment materials contain a large amount of carbon (this is the primary residue after initial heating) the carbon simply combines with the oxygen in the air to form carbon dioxide gas which is gradually flushed out of the mold by normal convection.
This means is that any material which will undergo pyrolysis and combine cleanly with the oxygen in the air at temperatures within the range of the investment capability are satisfactory candidates for mold making materials.

Casting - The cast metal can be introduced into the mold cavity under a wide range of conditions. This can be simple gravity casting or a centrifugal or pressure casting, which can apply a great deal of pressure to force the metal into every detail of the mold. To a degree, the final casting process places limitations on the practical elements of mold building. There is no use in designing or constructing a mold with more detail than your casting process can effectively fill. For example, for those of you who are beginners, and would like to try some hand poured castings, it's important to keep your designs simple, clean & massive. Early examples of American Indian jewelry were typically cast in sand molds by pouring. To some extent this limited both the nature and style of the work, and helped establish the basic characteristics which we associate with in Indian jewelry. If you have access to more elaborate high pressure systems, almost any practical degree of detail can be put in the model.
Obviously the sprues and sprue buttons removed from a casting have considerable value for their precious metal content. Although they could be sold to a refiner as scrap, their economic value is much higher if they can be used in the next melt for casting. However, as removed from the casting the sprues and sprue bottoms are contaminated to a varying degree of flux and investment. Since the investment contains a significant amount of silver. Some jewelry workers recommend cleaning the metal with hydrofluoric acid. Hydrofluoric acid is an excellent solvent for the silver present on the metal but the authors are strongly opposed to the use of HF because of its very hazardous properties. Since HF is recommended for several craft processes it would be well to review its characteristics.

A far safer and completely satisfactory method for cleaning is recommended. The sprue materials should be thoroughly picked and then scrubbed with a brush to remove any remaining investment. The metal is then placed in a depression in a charcoal block and melted with a liberal covering of flux. (Borax - Boric Acid.) After cooling, the metal is picked and scrubbed again. The metal should be clean enough to use for future castings. Since the alloying elements in both gold and silver alloys are less noble than the gold or silver they will tend to form oxides faster than
the gold or silver. These oxides tend to dissolve into the flux leaving behind an alloy with a higher precious metal content. In order to maintain fairly constant composition in the finished work, it is a good practice to combine some new metal with the sprue pieces for casting.
The flask is the container which holds the mold material. It provides structural strength and maintains uniform dimensions. Stainless steel flasks are recommended since they are rust and corrosion resistant in the oven and ultimate water emersion. There are two basic types of flasks. The standard flask has a solid cylindrical wall and is used for centrifugal casting and vacuum-assisted casting. The perforated flasks have a number of holes in the wall and are used for vacuum-chamber casting. All flasks are available in various heights and diameters.

The flask size is determined by the size of your wax pattern. When placed inside the flask, the pattern should be centered so as to have a minimum of 3/8 of an inch from the sides and 1/2 inch from the top. Somewhat closer spacing may be used when casting single items in a small flask. Certainly these dimensions are appropriate for large trees.
FLASKS

The flask has a relatively simple role in the investment casting process. During investing, it simply provides a container for the liquid investment until it can solidify. In the actual burnout and casting process, it provides structural strength to reinforce or support the relatively fragile mold. In theory, you could dispense with the flask completely. Occasionally, I have someone invest a project in a paper cup. During burnout, the paper cup is destroyed and you have a block of investment to work with. I've successfully cast a number of these, although if you want to try this, you should use a considerably larger flask so there is a good mass of investment on all sides of the model. In any event, the flask is simply a device to reinforce or support the mold. In industrial practice the flask may be replaced by wire mesh.

We've discussed the thermal expansion properties of the investment materials extensively. Various materials have different expansion properties and this is certainly true of the stainless steel used in investment flasks. Since the stainless steel will expand or contract at a different rate than the investment undergoing temperature changes, this will tend to create certain stresses in the flask/mold system. Historically, the use of asbestos paper lining in the flasks was included to provide a certain cushioning
against the stresses which might be created. This tended to allow the investment to expand more freely and gave better dimensional control in all directions. Also, in theory the asbestos provided a more open channel for airflow toward the ends of the flask as the cavity fill.

In recent years, the health hazards associated with asbestos have essentially eliminated it from this process. There are certain synthetic materials provided by manufacturers such as Kerr which can be used to replace the asbestos flask liner. In my own practice, I simply invest the material directly onto the stainless flask. If you follow good dimensioning and process control processes, I've found that this gives you no difficulty with regard to dimensional tolerances, or airflow in the flask system. As an actual matter of practice, I simply stopped using asbestos in my shop one day and quite frankly, could detect no measurable difficulty as a result.

From time to time, I need special sizes or shapes of flasks which I don't have in my stock. In my experience, there are a number of perfectly adequate alternatives. For single use in large sizes, I've had moderately good success using tin cans as flasks. I've also used ordinary electrical conduit cut to various lengths. The tin cans only make it through burnout cycle, but I've used the ordinary steel flasks for as many as 100 burnouts. Perhaps the only caution when
using conduit is the fact that they are plated with various materials which may tend to burn off or vaporize. The first few burnouts should be made with very good ventilation, so you're not breathing any of the fumes from the plated metal. One of my students had access to a lot of copper tubing and tried using this for the flasks. Although the copper is very rust-proof at room temperature, it oxidizes very rapidly at high temperature. The copper flasks only survived a few burnout cycles. Plain, mild steel seems to survive much better. Also, if you have any access to any industrial grade steel tubing, this seems to work quite well. A trip to a refrigerator repair/maintenance shop may produce a number of odds and ends of metal tubing large enough for flasks.
FLUXING

As you heat a mass of metal the various constituents of the alloy will react with the oxygen in the air. Pure gold and silver oxidize very slowly but the copper in the karat golds and sterling oxidizes rather quickly. The oxides formed are impurities which affect the quality of the metal in various ways. Other impurities also tend to find their way into the system. These would include traces of investment (from sprue buttons) or bits of the crucible itself. The purpose of flux is really threefold. First, it forms a protective film on the metal that slows down the oxidation process. Second, it serves to dissolve or entrap the various impurities present. Finally, it may act as a reducing agent. Reducing agents reverse the process of oxidation and return the metal to its elemental form. The pure metal can redissolve into the melt and maintain the composition of the alloy.

Traditionally, Borax has been the recommended flux for jewelry casting. I have personally made several thousand successful castings with Borax or Borax combined with boric acid as the flux. However, Borax only serves two of the required functions. It forms a film to inhibit oxidation and it dissolves various impurities. It is not a reducing agent. The result is that the alloy content of your casting is slightly lowered. Copper is oxidized and then the oxides
are dissolved into the flux leaving less copper in the melt. Although this is not a serious problem, I would recommend that you use a commercial reducing type casting flux. They may also contain other compounds which help form a smooth, continuous film of the flux.

When you apply the flux don't fall into the trap of believing that if a little is good a lot is better. Too much flux can make a mess out of your crucibles and if it gets into the mold cavity it will produce very bad surface texture problems. This possibility will also be treated in the chapter on spruing.
CASTING

PRESSURE CASTING

Air (or nitrogen) pressure is a very inexpensive and effective method of applying force to the molten metal. Although there are various opinions, pressures in the range of 60 psi per pressure casting are not unusual, and some people work at even higher pressures. This means that you can have four or five times as much working pressure as that which can be achieved with a vacuum. There is one major problem with all of the simpler pressure casting systems. The pressure casting system is set up to melt the metal in the sprue opening, or to melt it in another crucible and pour it in the sprue opening before the pressure cap is applied to the system. Even with the most nimble operator, there is a delay between the time that the heat is removed from the metal, the lid is closed, and the system is brought to full pressure. If the delay extends to even two or three seconds, this may significantly affect the chances of getting a good casting. If metal begins to flow into the sprue system, and solidify before the cavity is full, no amount of pressure will fill the mold.

This method also imposes strict limitations on the sprue configuration.
CASTING OXIDATION

Even if the casting process is conducted with great care the as cast sterling parts will typically have heavy oxide film. This film should be relatively easy to remove by pickling. However, this can lead to a curious problem at later stages of the finishing process. During the pickling process copper is removed from the surface. The copper being more reactive, it forms more oxide and is essentially leached out of the surface in the oxide form. This is analogous to the process used by primitive goldsmiths to enrich the surface of their low gold alloy jewelry by successive oxidizing and pickling the work. In any event, this enriched surface is not very thick and during buffing it will be removed from the high points on the jewelry. However, it will remain in the low recessed areas. This means that when the part is colored with chemicals, the rate of reaction will be different on different areas of the work and therefore, the coloring may vary considerably. Generally, a vigorous enough oxidation will take care of this. Also, if the piece is worked thoroughly with a bristle brush and tripoly, most of this thin film of high alloy material can be removed.
Under ordinary workshop conditions, with a torch melted metal system, there will be at least some oxidation of the metals in most jewelry alloys. Dealing with this oxidation takes several forms. The first and most obvious approach is to prevent the formation of metal oxides during melting. This can be accomplished in several different ways. The most common is to add a casting flux. Common borax will provide some degree of protection. As the borax melts, it forms a clear glassy film which protects the molten metal from oxygen. To a limited degree, this prevents the formation of oxides. Materials such as borax perform a second function. As quickly as the metal oxides form, they are dissolved into the borax, and therefore prevented from contaminating the metal melts. However, it's important to understand that the process removes the alloying constituents. The rate of this removal is directly related to the reactivity of the various alloying constituents. Metals such as zinc, which are very reactive with oxygen will tend to be removed quite quickly. In essence, you are refining the alloy and shifting its composition toward the most oxygen resistant components in the system.

Obviously, metal alloys represent very balanced combinations of constituents to provide specific material properties. Excessive loss of any of the constituents may change the characteristics of the alloy. In simple alloys, such as
copper and silver (sterling) this may not be a significant problem. However, with the more complex modern casting alloys, it may materially change the properties of the final metal.

Modern casting fluxes contain materials which do more than simply protect the metal surface. They are "reduction agents" which tend to reverse the reaction between oxygen and the metal present. This frees up the pure metal, which can back into solution.

This problem is often compounded by the fact that some of the constituents may have low melting points and simply volitilize away. For this reason, in larger industrial situations, the trace alloying constituents may be added after the melt is complete, and just before it's cast. This minimizes both the reaction with air, and vaporization of the alloying materials.
SHRINKAGE

Almost everyone involved with any form of metal casting is aware of the fact that a certain amount of shrinkage occurs during the solidification and cooling process. In various jewelry classes and books there are descriptions of how to adjust for this shrinkage in order to make sure that parts fit correctly. Different experiments are described telling about the amount of shrinkage which occurs under any particular set of circumstances in a laboratory experiment. Unfortunately, these only give general guidance to the jewelry maker. The difficulty is a wide range of factors influence the actual degree of shrinkage encountered. These include the specific alloys used, the various temperatures employed in both the metal melt and the investment and even the orientation inside the flask. A simple experiment can determine what your own specific shrinkage characteristics are for the process which you use.

The following is a description of an actual experiment performed on casting sterling silver slugs in satin cast investment. In order to provide a very accurate measurement, a hard, rigid model was desired. For this reason, two rods were prepared from acrylic plastic. These were roughly a quarter of an inch in diameter and just under one inch in length. This length was chosen because it would fit a small, curved flask and also because the standard opening of most precision micrometers only goes up to one inch. Two slugs were prepared as shown in the drawing and sprued on the same sprue former. One was
was positioned lengthwise to the flask and one crosswise. Very careful measurements were made of the plastic models and the parts were cast. After casting the parts were cleaned and measured again and the calculation of percentage shrinkage was made. This calculation is made as follows:

\[
\begin{array}{c}
0.986 \\
-0.979 \\
0.007 \\
\end{array}
\]

This means that the cast parts were approximately five thousandths of an inch shorter than the original models. Percentage shrinkage is calculated as follows:

\[
\begin{array}{c}
0.007 \\
\div 0.986 \\
\times 100 \\
= 0.5 \% \\
\end{array}
\]

This means that shrinkage was equal to roughly one half of one percent in this process. There are points in the casting operation where some precision is required. These are in casting the rings to a specific size and the preparation of the seats for stones. In both cases, a certain degree of precision is required. It's interesting to evaluate about what this level of shrinkage will do to change a ring size.

Ring sizes are actually established in a linear fashion. Any given size ring is 0.032 inches larger than the preceding size. For example, a size six ring has an inside diameter of 0.650 inches, while a size five ring has an inside diameter of 0.618 inches. If a model is prepared very precisely with an inside diameter of 0.650 inches and it were to be cast with
one half of one percent shrinkage, the final inside diameter would be 0.00325 inches smaller. This would mean that the final inside diameter was about 0.647 inches in diameter. On this basis, the ring would be less than six but greater than 5 and three quarter inches. Generally experience indicates that any significant degree of finishing would bring the ring back up to the full size six through ordinary removal of material. In order to demonstrate this, a series of rings were cast from carefully measured plastic models in sizes five six and seven the results of this test are described below.
To Flank Axis 0.8161 + 0.8093 = 0.7194

To Flank Axis 0.8275 + 0.8604 + 0.86%  

Satin cast 20
at .38 Water.
TIME TEMPERATURE RELATIONSHIPS

The literature seems a little bit vague on the matter of flask temperature, rate of rise and burnout times. I suspect that one reason for this is that there is no clear understanding of what's going on inside the flask when it's in the burnout oven. There is sort of a underlining assumption that the internal flask temperature is something pretty close to the oven, and that the flask will cool off when you pull it out. It seems to me from a surface to volume point of view that flasks behave quite differently according to their size. To the best of my knowledge no work has been done in this area. I would assume for example that a very large flask will tend to lag the oven temperature considerably during burnout, and it would remain much hotter for a longer period of time after it's removed from the oven.

There is another issue which I have never seen discussed in the literature. But it seems to me that during the de-watering stage at about 212°F the temperature of the flask would stop rising until all of the water is expelled. Based on these two considerations a hypothetical flask temperature versus oven temperature would probably look something like the one attached. What would be very useful is to develop some real insight about this situation. I suspect that the issue of burnout cycle would be considerably clearer if this were better understood.
INVESTMENT CASTING

The investment casting process has been one of the single most important factors in making the jewelry hobby the widespread and popular activity that it is today. With modern equipment and materials the process yields quick, sure, results for the beginners. At the same time the method is sufficiently versatile to provide a means for a wide range of artistic expression. For the adept craftsman there are a wide range specialized techniques that afford an opportunity to test anyone’s skills.

There are really two parts to the whole casting process: model preparation and casting. The primary emphasis of this book will be in the area of the casting process. I will be treating the more detailed aspects of model preparation in a separate work. This book will deal specifically with the investment casting process. It will deal with the basic character of the materials and their application. We will also review all of the commonly used methods for forcing metal into the investment world. What are the advantages and disadvantages of the various methods and what specific types of jewelry are they best suited for.
HYDROSTATIC PRESSURE

It's important to understand that the hydrostatic pressure is related strictly to the column height of fluid. If you look at Figure 42, the hydrostatic pressure at level X in all of the systems would be the same if all other factors such as gravity or acceleration were the same. The only difference the configuration can make is the volume of fluid which can past through the system at any given pressure, and at any given length of time. Since molten metal is an incompressable fluid the mechanics (dynamics) of the system are relatively simple.
This hydrostatic effect can be applied in very practical ways. In commercial production when a complex tree is used a number of different models may be cast at the same time in this case detailed models are placed at the “top” of the tree and simple pressure models are located at the bottom. This ensures that the maximum hydraulic force will be applied to the more detailed models.
CASTING PRESSURE

In order to properly evaluate or estimate the effectiveness of various types of castings, it is necessary to have a fundamental perception or understanding about how the various systems work. It is simplest to begin with the basic concept of a poured gravity fit casting. In essence, the situation is no different than pouring a glass of water. The liquid metal is poured into a mold until it reaches its own level. The only force operating on the metal to distribute it in the mold (or even keep it in the mold) is the force of gravity. To understand the nature and degree of this effect, a few comments on the basic hydrostatic force involved will be helpful.

Everyone knows that if you dive into the water and swim downward, you'll experience an increasing pressure. On a swimmer this is often felt in his ears. Everyone knows that at very great depths water pressure reaches enormous proportions. Since water weighs about 62.4 pounds per cubic foot, this means that the weight of water pressing down on one square foot at a depth of one foot, will equal 62.4 pounds or just a little bit less than one-half of one pound per square foot. This means that if we were to fill a pitcher one foot deep with water the pressure on the bottom of the vessel would be about one-half a pound per square inch. Obviously, the pressure would decrease on the vessel toward the top until it reached zero at the surface of the water. Exactly the same
situation prevails when metal is cast into a mold by pouring. If we were to structure a mold which would hold sterling silver to a depth of one foot, the same hydrostatic kind of pressure would apply. However, since silver has a specific gravity of about 10.5 (that is it is ten and one-half times as dense as water) the pressure will be ten and one-half times as great at the bottom. This means that the bottom of our cast object, the pressure would be about five pounds per square inch in a poured silver casting. If we use 14 karat yellow gold it would approach seven pounds per square inch.

Obviously, most precious metal castings are not that large or deep. A typical belt buckle and sprue system for a piece of indian jewelry might only be four inches deep. This means that when it is cast in silver the pressure at the bottom of the mold is hardly more than one pound per square inch. At this pressure, the viscosity of the molten metal may prevent it from flowing into all the details of the mold and cause either an incomplete casting or a casting lacking in detail. This problem led to a search for ways to increase the pressure applied to the metal in order to ensure that the mold will fill and that will accommodate fine detail. There are only two basic methods which have been applied to the problem:

1. Auxiliary Pressure
2. Centrifugal Force
**Auxiliary Pressure** - There are at least three commonly used methods to apply auxiliary pressure to force the metal into the mold cavity. These can generally be classed as:

1. Steam
2. Air
3. Vacuum

Various techniques have been used to generate steam pressure to assist the mold filling operation. The most common is simply to use an asbestos pad within a metal cap. The asbestos pad is moistened and it is forced down over the sprue opening after the melted metal is in place. The heat from the investment and the molten metal generates steam from the water and an increase in pressure in the space over the metal. This system has the obvious advantage of being very inexpensive. On the other hand, the sealing of the system is somewhat uncertain and the overall pressure applied is more or less indeterminate. At best, this is a fairly unreliable casting method. Although it can produce satisfactory results for an occasional piece which is simple in form and design, it is quite unsatisfactory for any significant production rate or any high quality jewelry.

**Air** - Rather than rely on the more or less uncontrolled creation of steam, air or nitrogen can be introduced to the system to provide a driving force for the metal. Basically a tightly fitting cap or seal is applied above the sprue area
and air or natural gas can be introduced from a regulated nitrogen cylinder, a compressed air flask, or even from a simple hand pump. In this case, pressures of 60 psi or more are practical. There are some limitations due to safety and general handling. However, it is certainly possible to apply a very high level of pressure to the metal and this can be done very quickly to ensure filling before the metal chills.

**Vacuum** - At first it may seem odd to include vacuum casting under the general heading of pressure casting, however if you think about it a moment, this is completely logical. At the surface of the earth all objects are surrounded by air and it presses in from all sides. This pressure is absolutely uniform and equal so there is no sense of the presence of the air. However, if a vacuum is created in a closed space the air outside the enclosure presses down just like the water example discussed previously. In this case, the total column of air in the earth's atmosphere has a sea level pressure of about 14.7 pounds per square inch or the equivalent of about 30 millimeters of mercury. This means that if the air can be totally evacuated from one side of a system, the effective pressure will be 14.7 psi. If the base of a flask can be attached to a vacuum system this means that effectively an air pressure of 14.7 psi can be applied to the open metal in the sprue. There are both advantages and disadvantages to this system. Obviously, one disadvantage is the pressure cannot exceed 14.7 psi. On the other hand, the mechanics of
operating such a system are very simple since the vacuum can be applied and maintained while the metal is introduced into the sprue area. This means a continuous pressure action against the metal with no delay while the system is closed or pressurized.
DEFECTS

There are a number of possible defects in any investment casting. Many of the defects can be caused by more than one factor or by some combinations of factors. However, the most common ones associated with the investment process are:

1. Water Trailing (Streaming)
2. Nodular Defects
3. Cracks and Fins

Each of these defects can be related to a casting process and particularly investment process almost directly. Probably water trailing and nodules are the ones most directly influenced by good or bad casting practice.

**Water Trailing (Streaming)** - I have used both the expressions water trailing and streaming because I have heard these used to describe this phenomenon in different publications. My suspicion is that the most commonly used expression is water trailing. Basically water trailing occurs when the investment is poured too soon. That is, it is not near enough to the end of the investment cycle. It seems to be particularly aggravated by excessive vibrations. The basic cause of water trailing is relatively straightforward. As we have stated elsewhere, the proportions of water in the investment exceed the absolute chemical requirements of the system. In essence, this means that over a period of time the investment can settle out with the water rising to the top and the particulate solids sinking to the bottom. When this occurs in the flask with a model present,
slight open channels are left against the surface of the model. These later fill with water and appear as fine, vertical, web-like ridges on the casting. Most commonly they will be observed on the backside of flat objects which are invested at an angle in the flask. The solution to this particular problem is to work closer to end of the open time on the investment and to minimize the vibration applied.

Nodules (Bubbles In The Investment) - This is probably the most common and widespread defect among amateur casters and particularly among people who do not have access to vacuum investing systems. Basically, small bubbles of air are trapped in the investment in contact with the model. The spheres of air result in hollow spots in the mold which fill with metal leaving the surface covered with any number of small spheres. It should be noted that if only a few small nodules are present, these can often be best removed with an engraving tool. If they are small and the contact point minimum, they can usually be removed and simply chipped off and the area repolished.

Cracks And Fins - The presence of cracks in the invested model at the end of the investment process, may or may not be visible. Obviously, a crack in the mold which connects with the pattern cavity will result in a web or fin forming a contact with the casting. In some cases this webbing may be very minimal in nature, in others it may be severe enough to cause rejection. The causes of cracks in the mold are perhaps more subtle than the
previous two defects and in proper proportion of investment to water, moving the mold before it is fully hardened, too rapid a burnout cycle, or dropping the mold, may all contribute to this problem. Further, some physical shapes (such as knife edges or sharp corners) tend to concentrate the stresses on the mold and encourage the formation of webs.
TECHNICAL EXPERIMENTS

The technical questions associated with the investment casting process are myriad. Common problems or questions that arise are:

. How much should one allow in sizing a ring model for casting shrinkage?
. How much flow back can be tolerated before an additional sprue is required to fill an area which is not directly in line with the casting flow?
. How thin a sheet section can I expect to cast?
. How small a diameter wire can I cast?

Unfortunately, there are no hard and fast rules for these problems. That there are many different answers in the literature all of which may be correct under various circumstances. One of the key elements of this textbook will be a series of experiments which will illustrate the general characteristics of these various technical problems. At the same time, there will be a brief description of how these can be applied to your own special casting problems. This means that you will be able to answer these questions for the specific materials, shop equipment and procedures used in your shop.

All but one of these issues relates directly to the question of mold fill. The fundamental problem of mold fill relates
to a surface to volume relationship within the cavity. Since there is a significant temperature differential between the mold material and the molten metal (approximately 300 F.) the mold material starts to chill the surface of the metal as quickly as they come in contact. The secret of success is to ensure that the molten metal completely fills the cavity before it chills. Obviously, as the amount of surface area for heat transfer increases relative to the volume of metal, the rate of cooling or solidification increases. It's relatively easy to realize that the surface area of a piece of paper is very large with regard to its total mass or cross-sectional area. The surface area of a round rod is much smaller, relative to its mass or cross-sectional area. This means that although two models might have the same bulk volume, the large, thin area would chill much more rapidly than the cylindrical rod. This means that it's more difficult to fill a thin section, since it will tend to chill the metal very rapidly. The fill problem relates to a series of factors which include:

. Temperature differential between the metal and mold.
. Surface to volume relationships.
. Absolute temperature of the metal.
. Metal viscosity (can relate to temperature).
. Pressure applied by the molding process.
. The difficulty in removing air from the mold ahead of the metal.
FLOW-BACK EXPERIMENT

It's relatively easy to establish a flow back test in your own shop. Using this test, you can determine approximately how much flow back can be expected under varying conditions in the casting process. What's required is a special test model such as the one illustrated in Figure 32. If you would like to perform this test, begin by determining the maximum depth flask which your casting machine will accommodate, or the maximum which you normally would expect to use. When you have selected your flask length, take a standard sprue base and measure the actual available distance you have from the point of the sprue base to the end of the flask. Subtract whatever margin or allowance you use for the depth of investment, and you will have determined the total model height. Using this height or length, prepare a tapered sprue core as indicated in Figure 40. Keep the diameter quite large so that this basic core structure does not become a restricting element in the flow of molten metal into the details of the model. The example shown is approximately 3" long and tapers from 3/8" in diameter at the thick end to 1/8" in diameter at the thinnest end.

The next step is to cut a series of wax wires all to standard length. In this case, I used 1" wax wires of 10, 12, 14 and 16 gage. These short lengths of wire were attached to the central form at a uniform angle of about 45° pointing back toward the sprue base. Rows were placed about ½" apart, and 1 wire of
each diameter was used in each row. If you consider this experiment, you will see that each row farther and farther from the sprue base receives greater pressure from the metal, and should therefore fill more detail or finer wires to a greater distance. If you prepare a model such as this, you will get a good idea of how your own system functions. Obviously, of all the wires fill completely to the tip, you have more than sufficient pressure. However, there is a good chance that some of the finer wires which are close to the sprue base will not fill. The distance or degree to which they do fill is a good indicator of the kind of detail you can expect in your own spruing arrangements.

The flow back problem is obviously far less significant in the case of vacuum casting. As we have discussed in the general descriptions of the mechanics of casting, there are major pressure differences throughout the depth of the metal in the mold. One of the unique advantages of vacuum casting is that the difference in pressure between the surface of the metal and the deepest point in the casting may only be a few percent. In the case of centrifugal casting, the surface of the metal is at essentially a much lower pressure than that experienced at the far end of the model.
CASTING FAILURE

In addition to the problem of materials which won't burn out completely, other forms of casting failure occur from time to time. One popular concept about plastic model-making suggests that plastic tends to crack the molds. This would suggest that the plastics are more rigid and structurally stronger. The theory of the case suggests that as the material is heated the thermal expansion of the plastic puts stress on the mold and cracks it or degrades the surface. However, if you look at the structural strength of the plastics it tends to be in the same range or somewhat lower than the investment material. More important, the softening point of the plastic is low enough that the material should lose its structural strength well before it has expanded enough to put any real stress on the mold. Although I can't totally discount the possibility of cracking due to thermal stress, most of the flaws I've seen are related to the forms that were developed from large sheets of plastic and the casting process rather than from any structural problems related to thermal expansion.

From time to time I have encountered plastic materials which do seem to attack the mold itself. The texture or the surface of the mold is actually broken down during burn out. Given the enormous number of chemical additives and
the complexity of the chemical systems which might be present in plastic compounds, this shouldn't be any surprise. The calcium sulfate base in the casting investment is not chemically resistant. At any temperature some reaction between the chemicals present and the plastic of the investment material seems to be a logical and natural possibility. If you encounter a plastic which seems to be attacking the mold surface itself, don't be particularly surprised. Quite often this will be accompanied by discoloration of the investment material. Most of the bad failures I've seen were associated with a distinct yellow staining of the investment. I don't know what the chemical reaction is but it certainly seems to be real.
Safety, efficiency and machine life all demand that centrifugal costing equipment be carefully balanced. In cases where a single size of flask, crucible and melt are cost repetitively, this presents no problem. If these vary between casting setupd the equipment must be rebalanced. In production situations the time consumed may be significant. This extra labor can be minimized by grouping sizes and asting in order of ascending or descending weights.

In most situations the balancing will be conducted with a hot flask. Obviously, this increases the potential for accidents which may damage the flask or the worker. It’s important to emphasize that undue haste is not required. Tests indicate that the flasks cool quite slowly and the temperature variables introduced during balancing are not significant.
DEFECTS

Hard spots in the final casting may come from a number of sources. Common sources would relate to:

. Remelted Scrap
  
  Alloy Mixes - White Gold Into Yellow
  
  Foreign Material - Steel

. Crucible Fragments

. Investment Fragments

. Improper Alloy Procedures
  
  White Gold - Pockets of Nickel or Zinc
  
  Yellow Gold - Boron Bearing Alloy

Distortion often occurs when removing wax models from the rubber mold.

. Carelessness

. Complex Molds

. Improper Cutting
Anyone familiar with the casting process understands that there are an enormous variety of potential defects which can occur during the casting process. These may be related to a wide range of problems and in more subtle cases are subject to interpretation. For this reason we will deal with the problem of casting defects in two ways. Individual problems will be addressed in conjunction with the appropriate technology or technique. A reference guide for troubleshooting will summarize the common defects in the final chapter.

One of the difficult problems in correcting casting porosity is the fact that it is sometimes difficult to visually identify the precise nature of the defect involved. In some cases microscopic sectioning is the only way to identify the source of subtle problems. This is compounded by the fact that even in the same pattern the defect may not always be present. The issue is further compounded by the fact that different metals, investment and equipment all have slightly different characteristics. Consistency is your best hope for identifying and correcting most problems. If a fault is reproducible its far easier to correct.

Casting will generally be improved if the pressure remains on the metal until it is fully solidified. Motorized centrifugal casters and vacuum casting perform the best in this respect. A spring loaded centrifugal caster delivers its energy to the arm during the first two or three revolutions. After that, friction constantly slows the rotation.
The specific details of the application of the investment casting process are based largely on a rather complex set of empirical rules. The precise physical elements behind these rules are not always well understood. On the one hand, I suspect that I have seen every rule ever invented violated and a successful casting achieved. On the other hand, I have seen faultless technique fail. In a sense we are dealing with probabilities. The closer one adheres to the "rules", the higher the probability of success.
Positioning of the various elements within the flask may have a significant impact on the rate of cooling. In Figure 92, three plates are placed in a parallel pattern. In this case it is obvious that the center plate will cool more slowly. It might well have a higher probability of casting defects associated with slow cooling. Figure 93 illustrates a pattern which is more likely to promote uniformity between the three parts.
CASTING
MECHANICS

A number of casting books, some still in print, give elaborate and detailed directions on how to index the flask so that the cavity will be properly aligned during the casting procedure. Unfortunately they usually neglect to mention that these procedures apply to older, straight arm casters but not to modern, broken arm units. If you have a broken arm caster the rotational position of the flask is immaterial. The following discussion will help clarify the issue and may add some insight into the basic casting mechanics.

Thus far, we have considered the mechanical forces at work in a centrifugal system at a steady state condition (rotating at a constant speed). However, it is important to understand what happens during the first moments after rotation begins.

A good way to think about the process is to visualize holding a very full cup of coffee in your hand. You could move the cup straight up quite suddenly and there wouldn't be any problem. However, if you made a sudden sideways motion the coffee would spill over the side away from the direction of motion. The same thing happens with a straight arm caster. The initial force on the metal tends to force it over the edge of the crucible. This effect was countered by putting a very high back wall on the crucible to retain the metal during acceleration.
6) **Investment Casting Pewter** - The casting of pewter or other low melting alloys in silicone rubber molds is a fairly well understood process in the jewelry industry. However, for custom items, repairs are very limited production, investment casting in pewter can be a very valuable technique. However, the temperature inversion properties of conventional jewelry investment combined with a need for low temperature casting generally lead to poor results. However, there are specific materials and techniques which can be used to overcome these difficulties and provide fine quality pewter investment castings.
4) **Flow Back and Fill** - There is considerable misunderstanding about what kind of forms (particularly how fine) can be filled in the investment casting process. Also, there is some misunderstanding about the way flow back or flow against the centrifugal force may work. There are a series of very easy experiments which can be set up to determine the limits of the casting process in any specific situation. This particular article could probably be expanded to include some general experiments on dimensional control and tolerances, which would round out the caster's understanding of the way the metal flows and responds during the casting process. Perhaps more important, it would be a natural lead in to a second article, which would deal with the spruing process.
3) **Casting Mechanics** - The actual mechanics of centrifugal casting are surprisingly poorly understood. For example, many people don't even realize that increasing the turns on the casting machine does not increase the acceleration of the flask in a linear way. It is very useful for casters to understand the relationship between the degree of turns applied to the manual system, the weight of the flask and crucible, and the acceleration applied to the metal. Although this isn't important to the people who use large electric casting machines, it can be a very useful thing for smaller shops to understand.
MECHANICS

CENTRIFUGAL CASTING

The forces which act on the molten metal during the casting process are governed by the combined influence of a number of physical factors. Although it's not necessary to understand all of the basic physical principles involved, an overview of these various elements may be useful.

The fundamental concept involved in this problem is Newton's second law of motion, which states that the force transmitted to the skull by a falling apple will equal the mass of the apple times its acceleration. In equation form:

\[ f = ma \]

Acceleration is defined as the change in velocity in a given period of time. The key thing to recognize here is that the change in velocity may be in direction only and it is still acceleration.

Now if we look at the specific application of casting, we see that the mass in question is that of the melt. The force is that which is "driving" the molten metal into the mold. All that is left is to calculate the acceleration. Since the mold is on the end of an arm moving in a circle, then the
acceleration is a function of a directional velocity change that results in steady circular movement.

A few more equations to be accepted on faith:

\[ v = \frac{(2 \pi R)}{T} \]
Where \( R \) is the radius and \( T \) is the time of one revolution

\[ a = \frac{v^2}{R} \quad \text{and} \]

\[ T = \frac{1}{\text{rpm}} \]
Where rpm is the revolutions per min of the casting machine

Using the above equations in Newton's second law equation

\[ F = ma \]
and simplifying, we find:

\[ F = m \left( \frac{39.6R}{\text{rpm}} \right) \left( \text{rpm} \right) \]

The net is if you want to increase the force "driving" the metal into the mold, you can increase the length of radius arm or increase the rpm's. Increasing the radius increases the force in direct proportion. Increasing the rpm's increases the force by the square of the change.

The second element which influences the mechanics of centrifugal casting is the way force is applied to the system. Almost all casting machines are powered by coil springs or electric motors.
MOLD FILL

A number of factors influence the quality of detail which is achieved in casting. Obviously, the surface of the mold cannot carry all the detail which you wish to impart to the metal. However, since molten metal has a relatively high viscosity, the metal may not fill all of the fine detail. It will bring sharp corners, as indicated in Figure 26. The degree of pressure exerted on the molten metal is a major factor in casting success and the degree of detail achieved. It is not a surprise that a good deal of work has been done to increase the pressure on the molten metal during casting.

During the poured casting process, the pressure exerted on the metal is simply the hydraulic pressure created by the weight of the column of molten metal above the mold surface. For example, if the casting were poured in the configuration shown in Figure 16, the pressure on the metal would vary from nothing on the surface to the weight of the column of the metal at Point C. The pressure is more or less, depending on the weight or specific gravity of the metal and the height of the column. A one-foot-high column of lead would exert more pressure than a one-foot-high column of aluminum. Using the specific gravity of sterling silver, the pressure would range 0 psi at Point A to 0.361 psi at B, and to 0.722 psi at Point C.
The various mechanical casting apparatus are devices which can increase this pressure to appreciably higher levels. Vacuum casting represents a good example of how this enhancement can function. At sea level, the atmospheric pressure is approximately 14.7 pounds per square inch. If this pressure could be added to the hydraulic pressure in the metal system, a very significant increase would be accomplished. At any point in the atmosphere, an object is completely surrounded by air and, thus, the air operates to totally balance the pressure. If the air is evacuated or removed from some space, the surrounding air continues to supply the pressure.

Everyone knows that if you evacuate the air from an object such as a tin can, the surrounding pressure will actually collapse the can. Fundamentally, vacuum casting removes the air pressure from one end of the flask. The air continues to exert its full pressure at the sprue and, thus, it creates a differential between the casting cavity (which has been evacuated) and the sprue area. In effect, the pressure at Point C in our diagram is increased by over 20 times when a vacuum is applied to the end of the flask. The absolute amount of pressure which can be applied is limited to the maximum atmospheric pressure. One way to achieve even higher pressure is through the use of pressure casting.
Since an effective pressure of 14.7 psi is all that could be achieved, any pressure greater than that will represent a further improvement. Various kinds of systems have been developed over the years to apply gas pressure in the range of 20-60 psi. A 40 psi presence would yield a total pressure of 40.72 psi at Point C. This would represent an increase about 55 times over ordinary poured castings. This situation is illustrated in Figure 18.

These increases to pressure add significant strains to the mold. If the stress exceeds the load carrying capability of the mold, you will obviously experience break-out and all its attendant hazards. This is a well-known problem in the vacuum casting field and it presents an obvious limitation for pressure casting.

Even more significant with pressure casting is the difficulty of introducing the molten metal to the sprue area and enclosing the system while pressure is applied. Typical systems use the flask itself for a crucible in configurations such as that shown in Figure 19. After the metal is melted, it remains outside the sprue channel system by reasons of its viscosity. When the melt is fully molten, the lid is closed and pressure applied. This dramatic increase in pressure forces the metal through the channels into the mold. This
system requires a certain amount of care and, in manual systems, a good deal of dexterity. At the present time, pressure casting is relatively limited in its application in the jewelry field.

Steam casting is precisely analogous to pressure casting, with the only difference being the source of pressure itself. Rather than introducing air or nitrogen to the head space above the metal melt, the steam caster introduces a small amount of water. As the water vaporizes, it sharply increases the pressure in this enclosed space. Figure 20 illustrates an example of a steam casting situation. Although steam casting, at least in theory, can provide more than sufficient pressure, there are so many variables in the system that it is generally considered unreliable. One of the keys to successful steam casting is to achieve a good seal around the edge of the flask. Also, enough pressure must be applied to hold the seal intact until the casting is complete. The amount of molten metal, the quality of the deal, the volume of the head space over the metal, the amount of excess air in the system, and other variables all contribute to determining the amount of pressure applied. Since this is more or less out of control, results tend to be far more erratic than with other mechanical systems.
A wide range of systems have been employed to provide the vacuum system for vacuum casting. From a reliability standpoint, the commercial positive displacement vacuum systems are the best. However, if a sufficient reservoir is used, aspirating systems are also successful. The need for a vacuum reservoir is necessitated by the fact that the aspirating systems remove air rather slowly. One of the more curious kinds of vacuum system applied to limited jewelry production has been the steam systems. If a small amount of water is added to a closed system and brought to a boil, the chamber will become filled with steam. If the heat is removed and the chamber is sealed (don't seal it before the heat is removed), the chamber will cool and the water will condense. At this point, the water vapor is removed from the air, effectively creating a vacuum in the chamber. This vacuum reservoir can then be ducted to the casting set-up and used for vacuum casting.