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.

This information is provided without warranty of any kind. No liability for its use will be assumed by the publisher. It is provided purely as an historic document.
CASTING INVESTMENT
TECHNOLOGY AND TECHNIQUE

By: Richard D. Austin

There are a number of steps in the investment casting process. Each has its specific requirements and makes its own contribution to the overall effectiveness of the process. Obviously, the design or aesthetic expression in a piece of jewelry is put in place during the model making process. Much of the technical quality of the work comes from the methods involved in spruing, investing, and casting. In this article, we are going to focus on the investment and the investing process.

A properly invested casting will produce a high quality finish which is faithful to the original model but errors in the investing process can result in poor surface quality or other defects which can increase the amount of finishing that is required. In extreme cases, improperly investing castings may be of such poor quality that they cannot be salvaged.

The technical aspects of this discussion apply to casting operations of all sizes. However, the techniques and equipment described are particularly suited for individual craftsman or limited production casting operations. Achieving the best results from the investment casting
process requires consistency and attention to detail. The best technique for any given situation can only be developed based on a good understanding of the properties of the materials used.

Although the lost wax casting process has been in use for thousands of years, the plaster based investments are a relatively recent development. From the turn of the century to the present time there has been continuous development of the technique. New materials and better technical information have become available. This has created some confusion when older techniques are applied to modern materials. I hope that presenting some basic technical information will help you improve the quality of your work using whatever techniques and material you prefer.

**INVESTMENT - THE INGREDIENTS**

The best place to begin is with an understanding of what investment is. Most contemporary jewelry investments contain three basic ingredients:

1. **Gypsum** - The gypsum provides the structural base by the formation of a solid from the dry powder.

2. **Quartz** - The powdered quartz (silica) provides a cushion and structural support for the investment material.
3. Cristobalite - This form of silica is added to adjust the thermal expansion properties of the investment to compensate for metal contraction occurring during solidification.

In addition to the three primary constituents, other materials may be added in small amounts. Typical additives include: wetting agents which increase the flow of the investment and allow it to come in better physical contact with the surface of the model, defoaming agents which help prevent the formation of bubbles and assist in their removal from the slurry, and chemicals which control the setting time of the investment. Reducing agents may be added to reduce surface oxidation on the casting. Some information about the individual ingredients will help you understand how the investment reacts during handling.

Gypsum - Gypsum is a very common and widely distributed mineral. Chemically, it is a hydrated calcium sulphate, CaSO₄.2H₂O. Gypsum dehydrates when it is heated to approximately 190°C. Upon dehydration, it forms the hemihydrate 2CaSO₄·H₂O, which is the material used in gypsum plasters. The hemihydrate is called calcined gypsum, or plaster of paris.

When mixed with water, the hemihydrate converts back to the original hydrated calcium sulphate. During this reaction it
hardens into a solid mass through interlocking crystals. Theoretically, about 18% water (by weight) would be needed to complete this reaction but, in practice, excess water is required to insure that the reaction proceeds to completion and cracking doesn't occur. The excess water either evaporates during storage of the mold, or is eliminated during the burnout.

The rate of chemical reaction between the water and the plaster is influenced significantly by the amount of water present, the temperature, and the amount of agitation or mixing used to combine the materials. The way the investment is stored can also have an influence on the investment.

The dehydrated material is constantly looking for water to react with so that it can rehydrate. One source of water is the moisture in the air. If the investment is stored in an open container (particularly during the summer when the humidity is high), the investment will react with the water in the air and deteriorate. Each opening of the container allows a certain amount of moist air to enter. This can affect the investment in several ways. First of all, the reaction may proceed far enough to cause lumps in the material. If it reaches this point, throw the investment away. However, more subtle changes occur long before the investment deteriorates to this point. These changes show
in the working time in the investment. This will be discussed in more detail later, but it is important to remember that investment is a reactive material which should be kept as moisture free as practical.

Quartz/Cristobalite - A number of minerals occur which are represented by a single chemical structure but exist in two or more distinct physical structures. This is known as polymorphism. Carbon is a well known example existing as both graphite and diamond. There are several polymorphous forms of silica. Two of these are of importance in the preparation of investment. The first, is ordinary quartz and the second, is cristobalite. Both these materials have the same chemical form, SiO₂. However, they vary in physical properties. For purposes of this discussion, the principal difference is in thermal expansion. By using a combination of the two forms of silica in the investment, it is possible to tailor the thermal expansion properties of the investment mixture.

PHYSICAL CHARACTERISTICS

The precise characteristics of any investment relate primarily to the quantities of the three basic ingredients and, to a lesser degree, to the amount of water, physical treatment, and the presence of certain additives.

Many other factors can influence the properties in subtle
ways. These other factors will become apparent as we discuss individual factors relating to the casting process. Some of the key characteristics of any investment include:

1. Thermal Expansion Properties
2. Physical Strength
3. Air Permeability

One of the key areas of confusion seems to be the allowance which is required to produce a casting of a specific size. For example, many texts on jewelry casting suggest that a ring model be made a full size larger than the final ring. A good place to begin understanding the problem is to review the thermal expansion properties of the investment. With this basic property in mind, we will follow with a review of other factors which influence casting dimensions.

**THERMAL EXPANSION PROPERTIES**

Dental casting literature has numerous references to laboratory tests attempting to reconcile the physical properties of the investment to the final dimensions of the cast part. In my own reading, I have never found any research which can deal with all of the variables and I don't intend to try to do so in this article. However, a general understanding of thermal expansion properties of the investment and the various art metals should help shed some light on the problem.
Figure 1 illustrates the thermal expansion properties of two different investments (data courtesy of Kerr Manufacturing). The lower curve illustrates the expansion characteristics of an investment made from 20% plaster and 80% quartz powder. The upper curve is a cristobalite based investment. The nature of these two curves explains a number of characteristics of the investment. Most important, the addition of the cristobalite helps adjust for the contraction of the molded metal on cooling. This provides for more precise dimensional control of the final casting. A review of the expansion properties of the common jewelry metals will show now important this expansion factor is.

**Coefficient of Thermal Expansion** - The expansion or contraction of solids is generally expressed as a Coefficient of Thermal Expansion. Typically, this is measured in units per unit per degree centigrade. The unit of measurement is immaterial since the coefficient is a proportional measurement. It is important to note that the coefficient at room temperature will be different than the rate at 1000°F. However, the rate of expansion doesn't vary too widely in the range under consideration. An understanding of the approximate amount of expansion is what is important. Three of the common jewelry alloy constituents have the following coefficients of thermal expansion:

- Gold $13.20 \times 10^{-6}$
Copper $14.09 \times 10^{-6}$
Silver $17.04 \times 10^{-6}$

These coefficients are in the mid-range of most of the common metals and alloys. Some metals, such as platinum, will display less expansion while some of the bronze alloys will have considerably more. However, almost all of the common jewelry or art alloys will be somewhere in the range of 8 and $22 \times 10^{-6}$.

What this means is that for silver, a 1" bar of silver (coefficient of expansion of $17.04 \times 10^{-6}$), will expand 0.00001704" for each degree centigrade its temperature rises. The expansion effect is obviously rather small. However, it occurs over a wide range of temperature during the solidification process. If we assume that the average craft metal has a coefficient of thermal expansion of approximately $15 \times 10^{-6}$, and a melting point of about $800^\circ$ centigrade above room temperature, the results are significant. This means that our hypothetical metal will contract by a total of $800 \times 15 \times 10^{-6}$ inches per inch going from its solidification point to room temperature. This equals about 0.012" per inch, or a contraction of about 1.2%. You will note on the attached graph, that cristobalite investment contracts about 1.2% in the range of temperatures being considered. In essence, this means that the cristobalite investments will almost exactly offset the
contraction of most of the common jewelry metals and alloys. Even investments which expand only 0.8 or 0.9% during heating will compensate for a large part of the metal contraction on cooling.

In subsequent articles, we are going to discuss other physical properties of the investment material, the problems and procedures of investment mixing and debubbling, and finally, some of the key casting defects and how they can be corrected.
Figure 1 - A comparison of the thermal expansion curves of Kerr Cristobalite investment and ordinary quartz investment illustrates the way that investment properties can be adjusted (data courtesy of Kerr Manufacturing Co.).
In the previous article, we discussed the physical behavior of the investment in terms of thermal expansion. Two other properties are important:

1. Physical Strength
2. Permeability

Although the precise measurement of these properties is not important to the caster, they can have a major impact on casting success.

**Physical Strength** - The physical strength of a casting investment is a function of the formation of an interlocking matrix of crystals. These crystals encase the silica granules in a manner exactly analogous to the aggregate in ordinary concrete. The final properties of the investment relate to the proportion of the ingredients, their quality, and the treatment they receive during mixing and the subsequent reaction. All of these factors will be discussed in more detail under the specific directions for the investing process. It is important to realize that the physical strength of the investment will be decreased by improper handling. It might appear that maintaining the strength is of relatively minor importance. If the investment is never stressed to its limit, a 50% strength improvement seems meaningless.

However, most casting failure does not occur by catastrophic
destruction of the investment. Occasionally the back of a flask will blow out, but most casting failures are far more subtle. Decreased tensile and compressive strength of the investment can cause these failures. For example, if temperature cycling or model expansion stresses the surface of the mold, there may be surface damage to the investment, even though the stresses may not be great enough to cause total failure. Stress may also cause cracking, which shows up as fins or webs in the final casting. The investment mass may survive the casting process, and yet produce castings of poor quality. For these reasons, it is vitally important to achieve the optimum physical properties of the investment, even though they may not be required for the gross physical strength of the system.

**Permeability** - Permeability is the property of the material which allows air to escape from the mold cavity through the investment material. Permeability is a very fine scale porosity. Air can travel through pores much too fine for the metal. This is like holding mercury in a piece of cloth. Although the cloth is quite open, the surface tension in the mercury will keep it from flowing through. This is exactly analogous to what happens in the investment process. The porosity has to be fine enough to mold a smooth surface, and yet coarse enough to allow for easy and rapid flow of the air out of the mold. Permeability can be influenced by a number of factors, but the prime influence

Number-2
is the burnout cycle. Having considered the material properties let's go on to the details of the casting process.

General Directions - Some Rules

I have always been frustrated by the directions for investing. They often seem ambiguous and talking to casters doesn't seem to shed much light on the process. People told me I should modify or adjust the process all kinds of ways. I should use warm water, cold water, mix it hard, mix it hardly at all, and so on. Even among those who obtained a very high quality of work, there was considerable variation in practice. I've since discovered that this is not inconsistent with the basic technology involved. There are four fundamental rules which should be applied to the investment process:

1. Follow The Manufacturer's Directions
2. Mix The Ingredients In Proper Proportions
3. Use The Full Working Time Of The Investment
4. Be Consistent

Follow The Manufacturer's Directions - There is a classic piece of advice which will serve you well. "When in doubt, read and follow the directions." This is all that would need to be said if the manufacturer's were to provide clear, unambiguous instructions with their products. However, many products reach the user with no directions. This is a

Number-3
special problem when rock shops repackage investment.

In fairness to the manufacturer's, it is difficult to describe all of the system variables. Also, the bulk of these materials are sold into manufacturing operations where the technology is understood. Another source of information is the dealer who sells the product. However, in my experience, many dealers are misinformed and a lot of the products are sold by mail. I have found that most of the larger suppliers are quite helpful if you write and ask for specific directions for one of their products. Finally, I hope that this article will shed some light on the issue.

Mix The Ingredients In Proper Proportions - The investment mixing process is a chemical reaction just as surely as the chemical reactions we all remember from high school chemistry laboratory. Investment and water should be measured very carefully. Mixing investment by feel or eye is absolutely inappropriate and will usually lead to periodic if not consistent problems.

Use The Full Working Time Of The Investment - It is possible to change the investment working time. However, the investment process must use up the working time. Investing too soon is one of the principle mistakes which leads to poor detail or surface quality. In the extreme cases, it leads to channeling (water marks), which can dramatically
increase the clean up work on a casting, or make it completely useless.

**Be Consistent** - Whatever practices you develop, and however you choose to modify the investment process to suit your own requirements, consistency is the ultimate requirement. Without consistency, there will be no way to correct your faults or to even understand any difficulties which you encounter.

**Work Time**

The process of investing a model requires a number of steps. In future articles we will discuss each step in detail. However, the best way to deal with these individual issues is to treat them in the context of the reaction which occurs when the water and investment are mixed together. The parameters of this reaction are expressed in terms of "Work Time".

It always seems a little difficult to describe the work time of investment. Changes in the investment begin to occur immediately after the water is added to the powder. Although the reaction proceeds quickly, the appearance changes are subtle until the moment when the investment begins to set.

Number-5
The setting time is established by working backward from what is called the frost or gloss-off time. If you observe a mix of investment carefully, after about ten to fifteen minutes there will be a sudden change in the surface appearance. The gloss-off time is the time when water begins to disappear from the investment surface. Gloss-off occurs one to two minutes after the "setting" time of the investment.

If the investment glosses off at eleven minutes, the setting time is about nine minutes. At the setting time the viscosity of the mix will increase rapidly. This means that the model must be imbedded and debubbled within nine minutes after the initial mixing period. The work time and setting time establish the boundaries or limits of the casting process. The work time of a typical jewelry investment is illustrated in Figure 2. The actual work time may vary widely.

Although the investment appears to set quite suddenly, the reaction process begins the moment the investment and water combine, and it continues for some hours after setting. This is the reason it is difficult to "eyeball" the measurement of ingredients. The viscosity at the start of the mix will be different than at the time the investment is poured. With this basic concept in mind, let's examine the steps of the investment process.
Figure 2. The investment work time is a key parameter in designing a specific investing procedure.
The adjustment of work time is one of the key quality control elements in the manufacture of jewelry investment. Any given brand and grade of investment can be manufactured consistently, so there is no reason to expect that work time should vary significantly with any given material. It is important to note that a number of factors can change the work time after the investment is manufactured. The key factor is moisture absorption during storage. Investment should be purchased in quantities which can be used within a few months, and it should be stored in air tight (moisture proof) containers.

The treatment of the investment during use can change the work time considerably. Variations in the amount of water, mixing time and other subtle factors may change the work time slightly in any given application. The major influence on work time is temperature. Since climatic conditions vary, and many shops are not particularly well air conditioned, application temperature may vary as much as 20°F. Temperature is also a control factor which the operator can change. In industrial processes, where speed may be important, the work time is sometimes shortened by the use of warm water. The work time may be adjusted to a period of as little as five minutes by this approach. For limited production work, there is little advantage in trying to save four or five minutes on a batch of investment. However, in a commercial operation, this may be a
significant savings.

I would recommend that you conduct a few experiments to establish the work time for the investment which you use.

Up to this point we have discussed the material properties of the investment and the general considerations in developing an investment cycle. The next step will be to consider the process in further detail.

**Investing Steps**

The process of investing a model requires a number of steps. These include:

1. Material Preparation
2. Measurement of Ingredients
3. Mixing and Debubblizing
4. Flask Fill
5. Debubblizing the Flask
6. Cure
7. Storage
8. Burnout

Each step contributes to the success of the casting process. Unfortunately, "Popular Wisdom" and literature references will suggest different "Best Ways" to perform each step. After we have reviewed the variables and alternatives in each step we will be able to describe a specific investment cycle for both vacuum and non-vacuum procedures.
1. Material Preparation - The first step is to treat the properly sprued model with the correct wetting agent. Wetting agents, or surfactants (surface active agents) may be introduced to the investment or applied to the wax.

There are two different types of wetting agents which are applied to the wax depending on whether the system is to be vacuumed or treated by vibratory methods. Usually, the wetting agent is applied to the wax and allowed to dry for fifteen minutes or more. It is important to follow the manufacturer's directions.

Modern investment formulations often contain wetting agents. Many professional casters also add wetting agents to their investment mixes. This increasing use of surfactants creates a potential problem. Many surfactants function better in combination. For example, two different surfactants combined, may be more potent than either one individually. A third material may further improve performance. However, as more and more materials are combined, the system may become less effective. If you're encountering difficulties in surface quality or texture, a good place to begin is to remove all the surfactants from your system. Next, experiment by adding them back one at a time. Using an investment containing wetting agents, it is possible to get perfectly adequate castings with no surfactants applied to the wax.

Number-9
It should also be noted that surfactants are often tailored or specialized to particular applications. The fact that a particular additive works for a kind of wax or a particular manufacturing situation does not mean that it represents a universal solution.

In addition to the wax surface, the water used to mix the investment also needs some preparation. You may have noticed that if you run cold water from the tap, small bubbles will form on the inside of the glass. The change in pressure releases the air trapped in the water. Also, the tap water is usually below room temperature. Investment should be mixed with water which has been allowed to sit at room temperature for a few hours.

2. Measurement of Ingredients — My preference is to measure the investment by weight and the water by volume. However, since some individual craftsmen and small shops are reluctant to invest in a scale, I will describe a system for measuring investment by volume. If you are going to measure investment by volume, the key is to be absolutely consistent. The following method will allow you to achieve a reasonable level of reproducibility.

A set of ordinary kitchen measuring cups are a good size for this application. In order to calibrate the system you will need access to an accurate scale. A range of 0–400
grams would be about right if one cup is the largest size you will be measuring.

When you receive a barrel of investment, it will have been handled and vibrated until it is very hard and compact. The first step is to loosen up the investment. Use a spatula or scoop to turn over the top portion of the investment until it will pour freely.

Calibration begins by weighing each measure (cup) while it is clean and empty. This weight (the tare weight) should be recorded. Next, each cup is weighed full of investment powder. Begin by filling the cup to overflowing, then settle it uniformly. A good way to do this is to tap the cup three or four times. Finally, use a straight edge to slice off the investment absolutely level. Weight the cup and the investment and subtract the weight of the cup to determine the weight of the contents. Repeat this procedure four to six times for each container.

You will note that there are small variations in the weight of investment measured. Average all the weights for all the measurements and use this for your standard investment weight. When you return to your own shop, follow the identical procedure and assume the calibration weight for the investment. You will find that a one-third to one-half cup measure of investment is an excellent unit for the small

Number-11
Kerr spatulator.

It is important to remember that if you change brand or type of investment, the system must be calibrated for each new material. It is a good idea to recheck your system from time to time just to make sure you are consistent. Although this is not the best way to proceed, it is certainly more accurate than any "eyeball" system.

The problems of a limited production shop or the individual artist/craftsman may be somewhat specialized. For example, a commercial shop may cast a very large number of flasks of a given size but they may use a limited number of sizes. I've visited commercial shops that do the vast majority of their casting in only two or three sizes of flasks. At last count I had about 50 different flask sizes in my studio. This creates a good deal of confusion in measuring up the investment, balancing the casting equipment and so on. A few simple steps can help organize the situation.

I always work with investment on a cubic centimeter basis. I have established that one cubic centimeter of mixed investment requires about 1.4 grams of dry investment powder (Kerr Satin Cast 20). You can check this yourself by taking a known quantity of the investment which you use (by weight), adding the appropriate amount of water, mixing it, and pouring it in a graduated cylinder. Measure the volume

Number-12
and then rinse it out before it sets up. Once you have this measurement, you can calculate how much investment to weigh out by calculating the volume of the flask.

If you are a little rusty on your high school math, remember that the volume of a cylinder is its area times its height. To calculate the volume of a flask begin by measuring the inside diameter and height of the flask (I always work in centimeters). Then

$$\text{Volume} = 3.1416 \times \frac{\text{diameter}}{2} \times \frac{\text{diameter}}{2} \times \text{height}$$

If you work in centimeters your answer will come out in cubic centimeters. For example, if your flask were 5 centimeters in diameter and 40 centimeters high

$$\text{Volume} = 3.1416 \times 2.5 \times 2.5 \times 40 = 785\text{cc}$$

To mix investment for this flask I would begin with at least 785 x 1.4 = 1099 grams of investment. In order to avoid recalculating, I have stamped the appropriate volume on the flasks in my shop. I usually round the numbers upward. In our example case, I would probably mark the flask as 790cc.

3. Mixing and Debubbling – Although the investment process can be accomplished entirely by manual means, there are three pieces of equipment which are commonly used to improve
productivity and quality.

1. Spatulators
2. Vibrators
3. Vacuum Systems

Before discussing their application, let me describe them individually.

Spatulators - A spatulator is a mixing device which uses a wiping motion to blend the investment. This action minimizes air entrapment and removes bubbles introduced during initial mixing. Large commercial spatulators are available for production work. For the individual craftsman, the most practical spatulators are the small, hand-cranked devices developed for the dental industry. In the jewelry trade, the only one which is widely available is sold by Kerr Manufacturing Company. This is illustrated in Figure 1. This product currently has a suggested list price of about $64. I would consider it a good investment in quality casting for any shop which does not have vacuum equipment. It should be recognized that this product was developed for small batches of investment, and it has inherent capacity limitations.

This spatulator becomes much less efficient (at bubble removal) as it is filled to the top. From a practical viewpoint, you should only fill it about 2/3 cubic full.
In spite of its small size, this spatulator, combined with a vibrator can provide excellent results on small investment batches. I have successfully cast several thousand pieces of jewelry using the vibrator/spatulator system. However, the small hand spatulator is not suitable for large flasks or production casting.

**Vibrators** - A vibrator can be used to debubblize the mix, or help to flow the investment around the wax model. There are a number of vibrators available commercially. One of these is illustrated in Figure 2. It is useful if the vibrator has several intensity settings. However, for a small shop this is not an absolute requirement. A number of makeshift systems can also be used to vibrate the investment.

**Vacuum Systems** - For larger individual flasks, or production work, there is no substitute for a vacuum system. Vacuum debubblizing will help ensure high quality and productivity. There are a number of commercial vacuum systems available. The Kerr machine which I use is illustrated in Figure 3. The smaller vacuum systems are relatively simple, consisting of a bell jar mounted on some kind of a table, which is connected to a vacuum pump. Various kinds of valving and metering are included to operate the system.

In any system, you need a way to determine if you have sufficient vacuum. The quickest way to tell is to put a

Number-15
small dish of room temperature water under the bell jar. Decrease the pressure, and see if the vacuum will boil the water at room temperature. If the vacuum system will boil water, you have sufficient vacuum for the investment purposes. A good quality commercial vacuum pump should bring room temperature water to a boil in about 30-60 seconds.

If you want to build your own system, laboratory supply houses sell vacuum pumps. Using one of these pumps, it is possible to put together your own vacuum system. However, you won't save much money unless you can pick up a used pump.

Although it is safe to experiment with building your own vacuum systems, you should never use a makeshift bell jar or vacuum chamber. The bell jar and baseplate must be of top quality and structurally able to support the air pressure when the chamber is brought to a full vacuum. Do not use makeshift or homemade vacuum chambers. Purchase good quality parts from a reputable laboratory supplier. The specifics of the vacuum process will be discussed as a part of the investment sequence.

**Mixing** - When the proper amounts of investment and water have been measured, and the model has been sprued and treated with a wetting agent, the next step is mixing. The
measured water should be placed in the mixing bowl and the investment added slowly with constant stirring. If you are going to use a vacuum system to debubble the investment, the bowl used should have a volume of about two and one-half times that of the investment mix to allow for the "rise" of the mix.

When the ingredients are combined, the clock begins to run. You have about nine minutes to complete the process.

If you are going to use a spatulator for mixing, the material should be hand mixed and vibrated briefly before mixing with the spatulator. If you are going to use the vacuum, simply proceed with the mix. Mixing should continue for two and one-half minutes. If you mix by hand, use a steady, smooth motion which does not whip air into the investment mix. An ordinary cooking wisk, such as the one illustrated in Figure 4, will help provide a smooth, consistent mix. The full mixing time is necessary to ensure the maximum structural strength of the investment. Proper mixing can significantly increase the structural strength of the investment. This helps minimize casting defects or blowouts during the casting process. Whatever mixing procedure you choose to use, apply it consistently for the same length of time to every investment batch.
The speed of the vacuuming process relates to the nature of the equipment, the size and number of castings and so on. However, the process usually proceeds quickly. Once the bell jar is in place, and the vacuum is turned on, it takes approximately 30 seconds for the investment to rise. This rising has been described as being like the rising of dough. It is characterized by the presence of a large number of small bubbles. This rising process lasts for perhaps 10-15 seconds, then the investment will collapse back down. Vacuuming should proceed for approximately 10 more seconds after the collapse. This means that in my system, the vacuuming is completed in roughly 50 seconds. When calculating the investment cycle I usually provide 60 seconds for vacuuming. Generally speaking, the reaction is much more vigorous during the first vacuuming. This is because the bubbles introduced during the mixing process have not been cleared. It is important to be sure that your mixing bowl is not too full. If there is considerable air present in the mix, it may expand as much as two and one-half times its original volume before it collapses. During the second vacuuming cycle the rise will be much less.

If you observe the system carefully, you will note that the action of the investment changes after the collapse. When the investment is initially rising, there is a pattern of a very large number of small bubbles. These are caused by the
expansion of air bubbles within the system. After the collapse they become much less numerous, and much larger. The investment tends to splatter and the reaction becomes very vigorous. At this point, you are simply boiling the water out of the investment and no further benefit is achieved by continuing the process. The 10 seconds after collapse is sufficient for bubble removal.

4. Flask Fill - As in many other parts of the investment process, literature and individual shop practice vary widely. There are suggestions that you begin by dipping the model in investment before it is put in the flask, that you fill the flask with investment and then place the model, and so on. However, the majority of practices fall into one of two basic methods. For most volume production, the flask is filled by pouring the investment down the side so that it runs down the wall and fills the space from the bottom upward. This tends to push the air out of any small cracks or crevices ahead of the rising investment. This may or may not be done while the flask is being vibrated. In any event, the flask can be filled quickly by this method.

The alternate is to introduce the investment to the fine detail of the model before the bulk of the material is poured around it. In cases where there is a very high degree of surface detail which can trap small air bubbles, painting the model with investment may improve casting
quality. When I have a finely detailed model, I usually take a small artist's brush and paint the model, trying to force the investment to the bottom of all of the surface texture. The investment can be painted on and blown or shaken with a vibrator until you feel that you have perfectly covered the surface. I often examine the surface with a binocular magnifier to be sure that it is fully wetted before proceeding. After this treatment, the investment is added by pouring down the side of the flask until it is full.

Another approach can be used to precoat the model. The model is placed in the flask, but before the investment is added to fill the cavity, a teaspoon or two is poured over the model while the flask is being vibrated. This is allowed to run completely off the surface of the model. All that should remain is a very light, thin film of watery investment. This seems to help wash off any excess wetting agents, and coat the surface with investment. After this step, I proceed by quickly filling the flask by the method described above.

5. Debubbling the Flask - The debubbling of the invested flask proceeds exactly as the debubbling of the bowl of investment. However, you will notice a couple of significant differences. First of all, there will be far less rise at this stage. The investment may only rise a
quarter of an inch or so before it collapses and begins to boil. As we stated previously, there is no advantage from continuing to boil the investment under vacuum. After the investment has risen and collapsed, ten seconds of additional vacuuming should be adequate.

There is one practice which I would like to point out here. Because the rise isn't too high, many casters simply fill the flask with investment to the top of the model. This leaves a little head space for the investment to expand. After investing, they "top off" the flask. Generally speaking, I think it is better (because you are working close to the end of the investment working time) to accomplish everything in one step. For this reason, I always use either rubber collars or masking tape (See Figure 5) to build up the flask to accommodate the expansion. This means that the investment rises into the flask or collar, collapses down, and no topping off is required.

6. Cure - Although the investment "sets" quite suddenly after about 12 minutes, its properties are not fully developed. The strength during this early period when the investment is solid but not fully reacted is usually referred to as "green strength". The green strength of the investment can be very important to the caster. The green strength of the material grows over a number of hours or
even days. If the investment is heated, it dries out. The moment the water is removed, the reaction stops as does the growth in strength. That means that you can arrest the investment at some condition where it has not developed its full physical properties by heating it too soon. This can easily decrease strength by as much as 50%. Again, this can lead to a number of casting defects or problems. One common problem associated with insufficient curing time is webbing or finning from stress on the investment.

Most instructions indicate that the investment is quite fragile during the early period of its cure (say less than one hour). Although the investment is fragile, this may be somewhat overstated. One reads directions indicating that the investment should not even be moved during the first hour. In my own experience, it is perfectly safe to move the invested flasks after 15-20 minutes. Generally speaking, after 40 minutes no damage is encountered from removing the sprue former.

It is critical that the model develop a high strength level before burnout begins. Since there is some variation in the development of green strength (depending on flask size), no firm rules can be given. However, even the smallest flask should cure for an hour and larger sizes should stand for 3-4 hours before burnout.

Number-22
7. Storage - The treatment of cured, invested models is probably an area where practice varies more widely than any other technical consideration in casting. Generally speaking, the manufacturers of investment recommend that invested models be stored damp. If the molds are allowed to dry out, they are to be remoistened before they are put into the burnout oven. However, many commercial shops simply invest the models and allow them to dry for varying amounts of time from a few hours to days or weeks.

When you talk to a commercial caster, you learn that the reason they process models quickly is that they don't want to have a large inventory of flasks tied up. Once the model is put in the flask, they like to get it cast, and get the flask back into circulation as quickly as possible. This cost of the inventory of flasks has led to use screen wire reinforcing of the investment to avoid the flask inventory. This way, finished models can be carried through the investment process, and inventoried for long periods of time. They can be cast the moment an order is received, and the supplier can get very rapid turn-around time.

From a technical viewpoint, I never know quite how to respond to these various approaches. When people tell me that the investment may break down in storage, I'm reminded of the fact that I've seen houses with plastered walls well over a hundred years old. On the other hand, I've seen
plastered walls that were a few weeks old that displayed various kinds of crystallization and faults. Obviously, when properly reacted and stored, the plaster need not undergo any significant deterioration over an extended period of time. On the other hand, why take a chance? I've done only limited experiments, but I've never been able to demonstrate a bad surface by investing the models, storing them for a week or two, and putting them in the oven dry (starting with a cold oven).

Another reason suggested for not pre-wetting the models is that it takes more energy to dry the water out, which comes out as time and energy cost. If the models are completely dried out at room temperature, they can rise more quickly to heat. It is intriguing to note that this may be the reason for some of the alleged defects associated with dry loading. The lack of water means that thermal shock is put on the model as it is heated rapidly from room temperature. The presence of the water would insure that the model comes to a temperature of 212°F. all the way through its thickness before the outside could rise appreciably in temperature.

It is worth noting that most of the common sprue waxes and the non-polyethylene waxes will be softened or melted at the boiling point of water. However, acrylic plastics and some of the polyethylene waxes may only soften at these temperatures and will remain in the mold cavity. In any
event, the temperature hold which occurs within the flask during the water elimination phase should effectively remove most of the wax present.

8. Burnout - The burnout of the invested model is the last step before the actual casting process. The parameters of the burnout cycle are limited by the physical nature of the investment and the requirement to remove all traces of the carbon residue from the pores of the invested mold.

The investment process is time/temperature dependent. The burnout of the carbon occurs more rapidly at a higher temperature. This means that a high temperature burnout accomplishes the same result in less time. The fundamental limitation of the process is the calcium sulphate. At a temperature of about 1350°F, the investment binder begins to break down. This can cause poor surface texture and the sulfur compounds which it liberates can react with the metal being cast.

The elimination of the wax or model takes place in two stages. As the investment temperature rises, the wax melts and a portion of it runs out of the sprue opening. However, a major portion of the melted wax is absorbed directly into the investment material. As the temperature continues to rise, the wax residue is carbonized within the investment pores. Although the mold cavity is actually empty very
early in the cycle, the flask is not ready for casting.

There is a possibility that residues in the cavity may react with the molten metal but the major problem is the fact that the carbon in the pores will prevent the air from leaving the mold cavity and interfere with the mold filling process.

The high temperature portion of the burnout eliminates the carbon residue. At the higher temperatures, the carbon reacts directly with oxygen in the air to form carbon monoxide and/or carbon dioxide. These are both gasses that find their way out of the mold. For this reaction to proceed, there must be some air available. When a very large number of models are being burned out at one time, it is helpful to leave the oven door ajar, an open vent in the oven (during the early portion of burnout) to provide some oxygen to burn up the carbon.

Although the investment is a very sturdy material, sudden changes in temperature can cause shock or cracking. Generally speaking, the flask should be introduced to the oven at a temperature of 300°F or less. The temperature rise from the initial starting temperature to 1000°F should proceed over a minimum time of one hour.

As a practical matter, the burnout of most materials, including the majority of plastics, can be accomplished at
1000°F if sufficient time is allowed. For this reason, unless you have a very large load, about all that is really required is to cycle small flasks to about 1200 or 1300°F and immediately let them drift back down to the casting temperature. Larger flasks require a longer time to come to temperature. For this reason, on small flasks, it may be just as well to allow them to burnout at 1000°F, so that only slight temperature adjustment is required at the end of the cycle. In any event, you should not cast into flasks which are operating at maximum burnout temperature.

There is another key area which causes some difficulty. These are the problems associated with cooling the mold to too low a temperature for whatever reason. For example, if you wish to investment cast pewter, you need to bring the mold back down to nearly room temperature. Alternately, if you should have an electrical failure during burnout, the molds may cool before they are cast. In any event, if the molds are cooled below about 400°F, the sudden changes in dimension are very likely to crack the molds and/or create a bad surface texture. Although I occasionally do pewter castings by cooling investment molds to room temperature (I've even discussed this in various articles), it is not a particularly good technique and I wouldn't recommend it as a general practice.
In the next installment we will review the investing cycle and conclude with a description of typical casting defects, their causes and cures.

We have described how to determine the work time of a casting investment and the steps which must be performed during that work time. Having evaluated these steps in terms of your own equipment, you can develop an investing schedule tailored to your own operations. I would like to describe two common systems. Let's begin by discussing vacuum investing.

The investment must be mixed for not less than two and one half minutes and the vacuuming cycle requires roughly 60 seconds for each vacuuming. There is one other time element to consider. I generally allow about 60 seconds for the actual process of pouring the investment in the flasks (assuming that there are several), and getting them set up on the vacuum table. With these time constraints in mind, we can describe a vacuum investing cycle in more detail. This is shown in Figure 1. Working from the 9 and one half minute work time, we need to allow about 60 seconds at the end of the cycle for vacuum and about 60 for pouring. This means that the final filling and finishing steps must begin about 7 and one half minutes after the cycle starts. Working from the front end, we need about 2 and one half minutes of mix, and a minute of vacuum, or about 3 and one
half minutes at the beginning of the cycle. This leaves about 4 minutes of time in the middle of the cycle which can be employed in different ways. As long as it is reasonably consistent, you have a number of options open to you. In my own case, I do one of two things during this time. I either let the investment sit undisturbed, or I pretreat the models by brushing with investment. I only brush the models when there is extensive surface detail which may not fill well. In my own case, I usually do nothing during this four minutes. In order to keep myself from rushing ahead, I sometimes read during this time period.

You have the opportunity to adjust your work cycle using this optional time yourself. One approach is to continue the mixing for the full 6 and one half minutes, then vacuum and pour immediately. This is a good approach as long as you are consistent. Any other combination of practices which meets the basic system requirements will be satisfactory.

If you do not use a vacuum cycle, you have even more lattitude in the timing. Basically, this frees up another couple of minutes which were tied up in the two vacuum cycles, and you now have as much as 5 and one half to 7 minutes of free time. I suspect that this is the reason that many amateur casters have so much difficulty with the problem of channeling. If you spatulate or hand mix the
investment for 2 or 3 minutes, there is a terrible temptation to rush on and pour the investment over the model. Actually, you should wait an additional 5 minutes before pouring. During this period of time, you can paint the model with investment, set up other shop operations, but you must not pour the investment too soon. Although it's probably not the best procedure, when a vacuum system isn't available, I often spatulate larger batches of investment by doing them in two or even three cycles. Since the spatulator won't hold too much investment, I use a large bowl and mix the investment for about a minute by hand; then I spatulate in batches. I can spatulate at least three batches during the waiting time. This is not quite as consistent, but I've achieved reasonable results this way. The key to success was stated at the beginning. You must be consistent, follow the manufacturer's directions, and use up the work time.

Defects

One of the frustrations of the casting process is the fact that it is not always possible to assign a cause to a defect you are encountering. I sat down one day and listed at least ten causes for casting porosity. Many of these, such as gas entrapment, turbulence, improper spruing, and flux impurities have little to do with the investment process. However, some investing defects can appear in this same general class of porosity. For example, an improper mix may

Number-30
weaken the investment and small pieces of material will come loose during casting. These bits of investment can be embedded almost anywhere in the casting and are rather difficult to tell from other kinds of porosity.

However, most of the specific defects which you can associate with the investment process are ones which I would call "surface imperfections". There are three classes of defects which are common in the casting process. These are:

1. Surface Nodules
2. Channeling
3. Poor Surface Texture

Each of these may present a different appearance in different situations but they're all so common as to seem the universal plagues of the caster.

1. Surface Nodules - There are two common types of nodules. The most common are small, spherical nodules which are attached to the surface of a casting. These are most likely to appear in corners or in recesses in the texture. Their cause and cure is fairly simple. These are air bubbles which attach themselves to the surface of the model. The source of these air bubbles is improper debubblizing of the mix, or careless filling of the flask. If you use a vacuum system and bring the material to a full vacuum, this particular kind of defect should be very rare. In
spatulator/vibratory investment systems, it is far more common. The spruing arrangement and the angle of the model in the flask may also contribute significantly to the problem. It is vitally important for the model to be set up so that rising bubbles don't get trapped anywhere in the system. With the manual systems, the use of investment painting will tend to minimize this problem. This is particularly true with deeply textured surfaces. Texture traps the bubbles. They can be broken down before the flask is filled.

I rarely see gross nodules but occasionally, someone will wait a little too long to fill the flask, and the investment is too thick to flow into the surface detail of the model. Usually you can tell when this is happening and stop the investment process before the flask is filled. It is a lot easier to junk a batch of investment than it is a batch of castings.

2. Channeling - I probably see more channeling than any other problem of surface texture. It is particularly apparent in large, flat objects such as belt buckles and medallions. Channeling is caused by the flow pattern of the settling investment and rising water which can occur if the investment is mixed with too much water, is over-vibrated, or poured too soon. I recently conducted an experiment to see if I could create some channeling. Figure 2 is the back
of a medallion which was invested with an investment mix using about 10 percent too much water, poured after about five minutes, and vibrated extensively. If you want to know what channeling looks like, this is it. The riverbed pattern which grows more severe toward the top (away from the sprue) is a classic example of the channeling effect. Channeling may be so mild that you have to examine the work with a loop to see it. It is corrected by using the proper proportion of water to investment, by using the full work time, and by minimizing vibration.

3. Poor Surface Texture - Surface defects can be as much of a puzzle as casting porosity. Like porosity, they can occur from a broad range of causes. Some of these are not necessarily related to the investment process itself. For example, overheating during burnout and reactions between model making material and the mold may deteriorate the surface. Cooling of the flask below the 400° break point in the expansion curve can deteriorate texture since it tends to spall off the surface of the cavity. Investment related causes may be the storage and rewetting of the model before burnout, the rate of burnout, the proportions of the investment materials, and excess wetting agents. If you find yourself producing castings with consistently bad texture, your best hope is to be extremely consistent and modify one variable of the system at a time, until you learn what is wrong.
There is one additional type of surface defect that should be considered. Various kinds of surface discoloration may appear on the casting.

**Metal Discoloration** - A certain amount of surface discoloration is normal with sterling silver and the karat golds used in jewelry. However, if the discoloration persists after a normal pickle you may have one of several problems. Residue in the mold may be the culprit. This residue can be carbon from the wax which would be the result of incomplete burnout or it could be caused by incomestable material in the pattern. For example, some plastics have fillers or pigments which won't burn away. A second possible cause is overheating of the mold. The calcium sulfate in the investment begins to break down at around 1350°F. and the decomposition products will tend to discolor the metal.

You will sometimes experience discoloration of the casting just opposite the sprue. This is most common when the sprue is short and large. This seems to be the result of the contact of the hot gases from the torch flame being directed into the sprue opening. This is minimized by melting the metal before placing the flask in the cradle.

If there is no detail in the discolored area it can usually be ground out and polishing can proceed. Some references

Number-34
recommend boiling in nitric acid pickle or repeated heating in air followed by cooling in air and sulfuric acid pickle. Frankly, I would not recommend nitric acid or sulfuric acid pickle for the average shop. If you can't file or grind the color away, pickle for several hours in a hot (not boiling) solution of commercial solid pickling compound.

Safety
The spinning casting arm and a flying spray of molten metal are obvious hazards. These kinds of dangers are easy to see and everyone tends to protect themselves. However, there are more subtle and long term dangers in the casting process.

I recently calculated the surface area of the belljar on my vacuum system. This came out to be about 1000 square inches. When the chamber is evacuated there is a total pressure of over 14,000 pounds distributed over its surface. If it should break and implode, the results would certainly be spectacular. Use only a top quality belljar and never one which has been damaged.

As we have stated in a number of places in this article, the investment is composed of roughly 80 percent, finely powdered silica. Excessive inhalation of the dry investment powder could lead to a lung disease known as silicosis. This disease is historically associated with the mining
industry, where miners breathe rock dust. With normal care and handling, working with the investment should not generate enough dust to cause any problems. However, even in the smallest shop, good hygiene is important and you should work in a way which minimizes the amount of dust generated. Keep your work area cleaned up so that the investment dust does not become a part of the environment. If you are working continuously in a casting shop or are involved in the repackaging of bulk investment, you should wear a dust mask suitable for this application.

Asbestos is a far more serious threat. I would strongly recommend that you do not use asbestos for any shop operations. Alternate processes and materials produce adequate results. It is not worth the risk. This issue is worth a little further discussion.

**Asbestos Flask Liners** - By now most metalsmiths have received the message that asbestos is a significant health hazard in the shop. For the most part, it has been completely eliminated from the casting process. The reasons for the use of asbestos will help you understand the use of substitute materials and/or what to expect when asbestos flask liners are not used.

A typical investment might expand between 0.2% and 0.4% on setting. In dental practice, this expansion was part of the Number-36
compensation system required to make everything fit properly. Basically, the asbestos flask liner would act as a cushion to allow the investment to expand radially, in spite of the retaining effect of the steel flask.

When the investment is constrained, it is put under some strain and isn't allowed to expand. Since the investment can still expand to some degree lengthwise in the flask, there may be slight differences (directional) in the dimensional tolerances achieved in an investment casting made without the asbestos cushion. Sensitive tests indicate that this may indeed be the case. However, for purposes of jewelry casting, these effects are too small to be a significant problem.

The other alleged benefits, such as the ease of cleaning the flasks, were marginal anyway so I find no difficulty in doing my castings without using an asbestos flask liner. Those of you who did investing by the vibratory method, may have had the frustrating experience of the asbestos ring floating loose and moving against the casting. Even at best, this was not a particularly good system.