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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LOW COST INVESTMENT

Low melting temperature metals such as pewter can be satisfactorily cast in plastic molds. However, plastic molds are less suitable for high temperature casting or centrifugal casting. Within certain limitations, you may prepare your own investment. However, in my experience this is not worth the effort unless you are casting large sculptural objects.

The basic formulation is simple: 20% by weight of casting plastic and 80% by weight of 200 mesh silica. For each pound of this mixture, you will need 0.35 to 0.50 pounds of water. You will have to experiment to determine the precise amount of water required and the proper mixing cycle.

The properties of the investment may be modified by replacing part of the silica with fireclay. The substitution of the fireclay will generally change the amount of water required.

Remember that the absence of cristobalite changes the thermal properties of the investment. This will decrease dimensional control. On the plus side, the absence of the 400°F dimensional change makes it safer to cool the molds to room temperature for casting large objects and/or low melting alloys.
CASTING INVESTMENT

A clear understanding of the investment casting materials and processes will help insure optimum results. There are a wide range of technical considerations involved in the investment casting process. This chapter will focus on various aspects of investment application. We will begin with a discussion of investment materials. This will be followed by specific application techniques and some trouble-shooting suggestions.

The two most common types of casting investment are based on different chemical systems:
1. Calcium Sulphate
2. Ammonium Phosphate/Magnesium Oxide

The majority of commercial jewelry castings are made with calcium sulphate based systems. They provide a good balance of economy, workability and physical properties. The first portion of this discussion will be limited to calcium sulphate based systems. The information presented should not be applied to other investment systems.

The ingredients used in an investment formulation establish its basic properties. The calcium sulphate jewelry investments are composed primarily of:
Gypsum - Provides a structural base for the investment by the formation of a solid during the reaction between water and gypsum powder.

Quartz - Powdered quartz (silica) provides reinforcement for the investment material.

Cristobalite - A form of silica added to adjust the thermal expansion properties of the investment.

In addition, other materials may be added in small amounts:

Wetting Agents - Improve flow and insure intimate contact between the investment and the model.

Defoaming Agents - Minimize the development of bubbles in the mix.

Reducing Agents - Added to reduce surface oxidation on the castings.

Fibers - Improve structural properties.

Each of these materials will be considered in more detail. When heated to about 190°C, hydrated calcium sulphate (CaSO₄·2H₂O) dehydrates to form the hemihydrate (2CaSO₄·H₂O). The hemihydrate is referred to as plaster of paris or gypsum. This is a reversible reaction. When mixed with water, the hemihydrate reverts back to its original composition. During this reaction, a mass of interlocking crystals is formed. On a chemical basis, about 18% water (by weight) would be needed.
to complete the reaction. However, excess water is added to prevent cracking, to insure that the reaction proceeds to completion and to fully wet the surface of the fillers. The excess water is evaporated during the burnout. Two factors strongly influence the rate of the reaction between the water and gypsum:

. Proportions Of Water
. Temperature

Manufacturers generally recommend that variation in the amount of water be limited to $\pm 5\%$. Less water will shorten the setting time and more water will extend it. The $\pm 5\%$ change in water content will typically change the setting time by $\pm 30 - 45$ seconds. Increasing the water content will also cause a thinner mix.

Increasing temperature can significantly shorten investment setting time. Hold the shop and water temperature constant. If you experience seasonal temperature variations in your studio, it may be necessary to adjust your investment cycle.

Other variables also influence the rate of reaction. A key factor is the amount of moisture which is absorbed by the investment during storage (partial rehydration). An obvious source is the moisture in the air. If the investment is
stored in an open container, it will react with water in the
air and deteriorate. This can cause several problems. In the
worst case, the investment will harden and form lumps.
However, a number of more subtle changes occur before the
investment solidifies. The primary concern is the change in
working time of the investment. Moisture absorption will
increase investment work time and decrease final strength.

Two forms of silica are used in many contemporary investments.
A number of minerals exist which have a common chemical
structure but exist in two or more physical forms. This
characteristic is known as polymorphism. For example, carbon
can exist as graphite or diamond. There are several
polymorphous forms of silica. Two of these may be used in
investment materials. The first is ordinary quartz and the
second is cristobalite. Both have the same chemical form,
SiO₂, but they have dramatically different physical
properties. The specific property of interest is thermal
expansion. By using a proper proportion of the two forms of
silica, it is possible to tailor the thermal expansion
properties of the investment.

Figure 1 illustrates the thermal expansion properties of two
investments. One is based entirely on quartz (30%) and
calcium sulphate (20%). The other is a mixture of quartz,
calcium sulphate and cristobalite. The chart indicates that the cristobalite based investment will expand about 1.2% as it is heated from room temperature to 300°C. In the same range, the quartz investment will expand approximately 0.5%. You will notice that the expansion curve of the cristobalite investment has a very sharp break. This corresponds to the silica inversion point at 232°C (450°F). At about 300°C, the investment stops expanding to any significant degree. This sudden change in expansion properties causes cracking if the investment is cooled below the inversion point.

Typical alloys of gold, copper and silver all contract roughly the same amount as the investment when cooling from solidification to room temperature. This means that the investment expands enough to compensate for the contraction of the metal during cooling. Older literature often suggests the use of compensation for contraction. In many cases, the descriptions deal with materials which did not incorporate cristobalite. Modern cristobalite investments need very little or no compensation for expansion. Figures 2 and 3 will help put this in perspective. The ring model and the test bars were fabricated from acrylic plastic. This allowed precise measurement. The photographs and subsequent measurement show that very little contraction occurred. The test bars contracted 0.71% and 0.86%. After sanding (400
grit) and polishing, the ring was only slightly smaller than the original model.

Many apparent cases of shrinkage are actually caused by poor measurement. Most waxes are flexible. A ring model may stretch as much as a size during measurement, and it's easy to build a wax bezel with a snap fit. The cast metal is not flexible, and what appears to be a case of shrinkage is simply poor measurement. Note that masters for wax injection do require compensation due to wax shrinkage during the injection process. The shrinkage of wax during injection may be as much as 4%.

In order to illustrate this higher level of shrinkage, I've included photos from an actual production shank. Figure 29a shows the size of the original master. 29b is the size of a cast and finished ring shank made from a wax injected in the rubber mold prepared from the original master. You will note that in this case, there is a significant degree of shrinkage.

The physical strength of the investment is obviously important. During solidification, an interlocking matrix of crystals forms around the filler material. The final physical strength of the investment is affected by the proportion of ingredients, storage conditions and the method of mixing the
investment. The physical strength of the investment may be significantly decreased by improper handling. The importance of physical strength may not be obvious. There is a wide margin of safety in the process, and cases of catastrophic failure are rare. However, more subtle factors may be at work. Diminished investment strength may degrade the surface quality as the investment spalls or is eroded during the metal fill. Any loose material ends up somewhere in the casting. Poor strength can also generate fins or webs on the casting. The fact that the investment survives the casting process does not mean that it developed its full strength or was properly applied.

A study of the investment application process immediately discloses two basic problems. First, the literature seems to be inconsistent. Second, actual shop practice varies widely. Many casting operations produce excellent results with procedures at variance with the manufacturer's directions. The principle problem with the literature is straightforward. It accumulated over a period of years, and materials have changed. Almost invariably, no reference is made to specific investment material. Is it calcium sulphate based or phosphate based? Does it contain cristobalite? Even the brand is seldom mentioned. This means that the literature is filled with references to different materials with different
working properties. It should come as no surprise that any specific recommendations are difficult to apply.

Variations in contemporary practice can be understood in terms of specific applications. The investment process is flexible. Within certain parameters, you can modify the process to fit your own shop situation. The following information will help you to tailor your shop procedures to insure consistent results.

Two basic system properties must be considered:

1. Viscosity
2. Work Time

The viscosity of the system is the physical property which changes most dramatically during the investment process. Viscosity relates to the flow properties of a slurry or solution. Honey is more viscous than water. This property of the system is important when suspended solids are present. Particulate matter will settle quickly in a low viscosity system and more slowly from a high viscosity system. The formulation of the investment itself is influenced by these characteristics. The investment must be thin enough to flow into every detail of the master model. On the other hand, it must be thick enough to suspend the particulate fillers in the
system. Settling of the suspended solids is one of the key causes of casting defects.

The moment that the investment and the water are combined, a chemical reaction begins. This reaction continues for an hour or more after the solidification of the investment. The viscosity of the investment mix changes almost constantly during the time between mixing and settling. If you measure this viscosity change, the requirements of the investment process become clearer. The top portion of Figure 4 illustrates the viscosity properties of an investment mix. The system starts out with a low viscosity which increases dramatically at the setting time. The rapid rise in viscosity is a very significant characteristic. It establishes the amount of time available to complete the investment process. This is known as the work time.

Many of the changes (such as viscosity) can only be measured under laboratory conditions. However, there is one characteristic of the investment mix which is easy to observe. This is referred to as the "gloss off". The gloss off is the transition from a slurry to a semi-solid.

I would recommend that you observe this phenomenon in your own studio. Following the manufacturer's instructions, prepare a
small batch of investment and pour it into an open container. Place the container under a bright light. Time the mix from the moment the water and investment are combined (the investment is added to the water). Initially, the investment mix has a wet, glossy appearance. After 9 - 13 minutes, you will see a change. In less than a minute, the appearance will change from wet and glossy to flat and dull. The investment has lost its gloss. Note the time when you can first observe this change. This is referred to as the gloss off time. This time period is very important in developing an investing cycle. If you refer to Figure 4, you will note that gloss off corresponds to a sudden increase in viscosity. Obviously, the investing process must be completed at some point in time before gloss off begins. In practice, all handling of the investment must be completed about 1 1/2 minutes before gloss off. The period of 1 1/2 minutes before gloss off is referred to as the setting time. The elapsed time from mixing to gloss off less 1 1/2 minutes is the work time. Work time is the amount of time available for processing.

With this information, a specific investing cycle can be established. Several elements must be considered. First, the chemical reaction between the water and calcium sulphate is influenced by mixing. The optimum properties of the investment are developed when mixing is continued for at least
3 minutes. The second element relates to the nature of the slurry. It is a combination of water and solids. If the investment is poured too soon, the solids will settle out. When this occurs, serious surface defects will be encountered. The optimum properties will be achieved when the material is thoroughly mixed and the pouring of the investment is done as close to the gloss off time as practical.

It should be noted that the gloss off time in investments with other chemical bases (such as phosphate investment) are more difficult to measure. In these cases, you must rely on the manufacturer's directions. Other investment systems may also be more sensitive to ambient conditions and/or exposure to moisture in the air. Calcium sulphate investment is more forgiving than most of the other materials available.

There are four key operations which must be accomplished during the working time. These must be integrated into an appropriate time schedule.

- Mixing
- Initial Vacuum
- Pouring
- Second Vacuum

**Mixing** - A minimum mixing time of 3 minutes is required to
develop the optimum physical properties of the investment. Shorter times may cause decreases in physical strength and attendant surface defects, break-out or webbing. Mixing may be performed with a spatulator, commercial mixer or by hand. An ordinary kitchen whisk works well for hand mixing small batches.

Initial Vacuum - Although spatulation and vibration may be used to replace the vacuum, the vacuum cycle is preferred. Depending on the size and capacity of your equipment, the vacuum cycle requires about 60 seconds. Roughly 45 - 50 seconds are required to fully evacuate the chamber. At this point, the investment will rise significantly. About 4 - 5 seconds after the rise, the investment will collapse and the character of the bubbling will change. At least 10 additional seconds of vacuuming should be applied. Over vacuuming may cause very small spherical nodules to form on the casting. No additional benefit is achieved by continuing to vacuum more than 10 seconds after the collapse.

Vacuum systems must be able to produce a low enough pressure in a short enough period of time to be effective. You can measure this fairly easily for yourself. Place a small container of room temperature water in the vacuum chamber and turn on the pump. The water should begin to boil in about 45
seconds. If this time extends much beyond a minute, the chamber is being evacuated too slowly. If the water doesn't boil, you're not pulling enough vacuum. In my own observation, vacuum pump maintenance is pretty bad in most jewelry shops. First of all, the oil in the pump should be changed about every six months if the pump is being used regularly. Also, the mounting plate gasket and base of the bell jar should be kept clean. Too much dirt can cause a slow leak which significantly degrades the performance of the vacuum equipment.

The degree of rise which can be expected varies widely. Proper mixing procedures which minimize the air entrapment in the investment decrease the degree of rise during vacuuming. In my own experience, I have seen a volumetric expansion ranging from about 10% to about 300%. These very large expansion rates are usually associated with investments which contain other types of fillers, such as fire clay, which are porous and able to entrap significant volumes of air.

Pouring - Pouring a group of flasks usually required about 60 seconds. Some shops pour in two steps, first a partial fill and second a top off after vacuuming. This allows the investment to rise in the flask without overflowing. In my experience, topping off is probably not the best procedure.
It extends the cycle and sometimes comes too late. The head space at the end of the flask may not be sufficient to contain the investment during vacuuming, even when the investment barely covers the model. The use of a rubber or masking tape collar is preferred.

**Second Vacuum** - The second vacuuming step requires an additional 60 seconds. You will note that the rise of the investment on the second vacuum cycle will be much less than the rise during the first vacuuming.

If you add up the times involved, you will find that some excess time is available.

- Mixing 3 Minutes
- Initial Vacuum 1 Minute
- Pouring 1 Minute
- Second Vacuum 1 Minute
- 6 Minutes

Since a typical work time is in the range of 9 minutes, there are several alternate uses for this extra time. You may set the investment aside during this period. If you allow the investment to stand, it will be necessary to mix it briefly before pouring since the ingredients will tend to separate.
Alternately, you may continue to mix the investment until you have consumed the available time. In industrial processes using power mixing, this is the common procedure. Extended mixing times (within the work time) do not materially affect investment characteristics. In rare cases, it may be useful to paint the investment onto the surface of the model. This should only be considered when there are very deep, sharp recesses in the surface texture or when no vacuum is available. Some literature suggests that the model should be painted with investment (sometimes thinned investment) and then sprinkled with dry investment powder before the procedure continues. There is little reason to use this technique with contemporary materials and processes.

The open time available allows for other adjustments to the cycle. For example, the investment can be mixed with heated water to shorten the work time in high volume production. Other modifications can also be made if they are applied consistently and if they do not interfere with the basic working properties of the materials. By measuring the gloss off time, you can develop an individualized investment cycle.

The investment process cannot be treated as an independent operation. The design of the model, spruing, pre-treatment of the model surface, post-treatment after setting, and burnout
may have a dramatic influence on the result. Some other specific factors are important. Surfactants or wetting agents improve the contact between the investment and the waxy surface. Commercial solutions are available in two basic types, those which are formulated for use with vacuum systems and those for use with non-vacuum systems. There is another factor which may influence surfactant application. Many casters attempt to improve their results by adding additional wetting agents to the investment. A combination of too many wetting agents will actually be less effective. As time goes on, it is likely that there will be more wetting agents incorporated in the investment material and less emphasis on treating the model. If you wish to add surfactants to the investment, experiment carefully. Another factor may cause problems. Waxes cast in silicone rubber molds are very hydrophobic and are more subject to defects caused by poor wetting.

The reaction between the gypsum and water continues for an extended period of time after setting. During this period, the investment continues to cure and gain strength. Introduction of the flask into the furnace stops the reaction. If heating is started too soon, it will result in a significantly weaker mold. Small flasks should cure for at least 2 hours, and a cure time of 4 - 6 hours should be used.
for larger flasks. After the reaction is complete, any excess moisture will evaporate. There is no inherent problem with room temperature storage of the flask for an extended period of time. However, the flask should be remoistened before burnout. The moisture minimizes absorption of the wax into the investment and reduces thermal shock. The sprue former should be removed prior to rewetting so that the water will flush away any particles of investment which break loose when the sprue former is removed.

The basic objective of the burnout cycle is to remove the model from the cavity and then eliminate any carbon residue from the pores of the investment. This must be achieved without inducing any unnecessary stress to the mold. This means a slow temperature rise. Since the investment is an insulating material, the rate of rise must be controlled. One problem with the fiber insulated furnaces is the fact that they have a very high rate of temperature rise. They must be monitored carefully to avoid cracking the investment. The calcium sulphate begins to break down at about 1350°F. This breakdown may degrade the surface of the mold cavity and/or release decomposition products. These products contain sulfur, which reacts with the alloys present. If a brief pickling does not remove the discoloration, acid treatment or abrasion may be required. Since the torch flame may play into
the sprue opening, this effect is sometimes localized in the sprues or sections of the work directly adjacent to the sprues.

Most metal workers recognize the inherent dangers of molten metal and a spinning casting arm. However, there are some less obvious dangers in the process. A 10 inch bell jar has a surface area of approximately 1,000 square inches. This means that when it is evacuated, there is a total pressure of over 14,000 pounds on its surface. An implosion caused by a defective or damaged bell jar can be very dangerous. The typical investment materials contain as much as 80% silica. Long-term inhalation of the dust can lead to a lung disease known as silicosis. Good hygiene is very important. Keep your work area clean. If you are working in a casting shop or involved with handling of bulk investment, you should wear a suitable dust mask.

In my opinion, asbestos is the most serious health threat in the casting operation. The hazards of asbestos are treated in more detail in the chapter on Shop Safety.

If you wish to use a liner, Kerr Manufacturing and others offer asbestos substitutes. The use of asbestos crucible liners was recommended to promote metal purity and preserve
the crucible. Proper fluxing of the crucible is sufficient. However, you may experience flux build-up to the point where flux is carried into the mold cavity. This generally causes small, bright crystaline porosity on the casting surface. Proper sprue arrangement will generally minimize or eliminate this problem.

Before presenting specific trouble-shooting suggestions, there are some fundamental rules which you should always follow.

. When in doubt, read and follow directions. If you have no better information, follow the manufacturer's instructions faithfully.

. Weigh and measure the ingredients carefully.

. Develop an investing cycle which takes advantage of the full working time of the investment.

. No matter what cycle or process you select, be consistent.

Many casting defects may be caused by more than one problem. The preparation of the model, the use and application of the investment, burnout, metal alloy and melting can all have an impact on quality. However, to the extent that the investment relates to the visible defects in the casting, the following should be considered.

**Channeling** - The channeling (watermarks) defect which is
illustrated in the photograph can be caused by too much water in the investment, pouring too early in the investment cycle, or excess vibration during handling. Pattern size, shape and orientation in the flask may also contribute.

Fins - Finning or webbing can be caused by several factors. Improper investment proportions, rapid temperature rise in the burnout oven and/or cycling the mold below the cristobalite inversion point all tend to cause webbing. Placing the flask in the oven too soon or abusive handling may also cause fins.

Gross Nodules - Large, irregularly-shaped nodules on the casting usually means you have waited too long in the investment cycle to pour the material. The investment viscosity is so high that significant amounts of air are trapped, forming large cavities. An extreme case is illustrated in Figure 12.

Spherical Nodules - The majority of spherical nodules are caused by incomplete air removal from the investment. The solution is proper vacuuming and/or spatulation and vibration during the investment process. Very small nodules may occur if the material is vacuumed for too long. Failure to use an appropriate wetting agent may also be the problem. If your equipment lacks a reliable vacuum gauge, you may check the
vacuum level by placing a tumbler of room temperature water in the chamber. It should come to a boil about 1 to 1 1/2 minutes after the vacuum pump is started.

**Poor Surface Texture** - Poor surface texture can be caused by a wide range of factors. The excess use of wetting agents (they should be allowed to dry), improper burnout cycle, excessive water in the investment or reactions between the model material and the investment may degrade the surface. This last problem usually occurs with certain kinds of plastics. Natural organic materials cause poor surface texture if they absorb water. Improper model design, spruing, short cure time and rapid temperature rise may all cause surface defects. The use of an extended dewaxing cycle generally improves surface texture significantly.

**Surface Discoloration** - Overheating the investment will free sulfur compounds which react with the metal surface and may be very difficult to remove. Overheating also contributes to poor texture.

The quality of an investment casting is influenced by every step from the original design sketch to final buffing. In the case of production items cast from injected waxes, a modest level of reject castings is not a serious problem. However,
failures are extremely frustrating if you produce one-of-a-kind objects. In this case, all of the labor invested in model construction is lost if a casting fails. A clear understanding of investment properties and application can significantly decrease the risk of casting failure. Extra care will produce results which more than justify the extra effort.