Ancient Mexican bells: an empirical rediscovery of the casting process

by

Matthew Craig Neumann

Submitted to the Department of Materials Science and Engineering in Partial Fulfillment of the Requirements for the Degree of Bachelor of Science

at the Massachusetts Institute of Technology

June 1997

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Signature of Author.............

Department of Materials Science and Engineering

May 9, 1997

Certified by.................................................................

Samuel M. Allen
Professor of Physical Metallurgy
Thesis Supervisor

Certified by...................................................

Dorothy Hosler
Associate Professor of Archaeology and Ancient Technology
Thesis Supervisor

Accepted by.................................

David K. RoyランスChairman, Undergraduate Thesis Committee
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ABSTRACT

The majority of pre-Columbian Mesoamerican metal objects are not utilitarian, but
ceremonial. A large fraction of these objects are cast bells. The method of manufacture of
these bells is examined empirically, based on Sahagún's general description in his General
History of the Things of New Spain. A successful process for lost-wax casting using
native materials is described. Bells of down to 1.0 mm thickness are cast and illustrated.
Preliminary testing on effects of different alloys is reported.

Thesis Supervisor: Samuel M. Allen
Title: Professor of Physical Metallurgy
Thesis Supervisor: Dorothy Hosler
Title: Associate Professor of Archaeology and Ancient Technologies
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Acknowledgements

I would like to thank Professors Allen and Hosler both for providing the framework and funding for this research and for their assistance in the preparation of this document. This work could not have been done without Toby Bashaw’s advice and his willingness to freely share his experience and his time. Thanks are also due to Pat Kearny and Joe Adario for their technical assistance. Thanks to Ed Mc Cluney and Jeff Margolin for sharing their hands-on experience with ceramics. Special thanks are due to Elizabeth Krumm, for all the sketches and for much needed support and encouragement. Penultimately, thanks must go to Astrophe and Thisbe for their patience. Thanks finally to my parents for their support throughout my MIT experience.
I. Background and Introduction

Metallurgy was introduced to west Mexico around A.D. 700. This area was populated by a people who had already developed elaborate architectures, writing systems, and accurate astronomy and calendars. When the technology of metal working was brought in from the south, the primary focus of production was on elite and ceremonial goods such as large flat tweezers, hot worked open rings, and cast bells. Axes, awls, sewing needles and other tools were only a small fraction of items made from metal; the ancient Mexicans already had tools to perform tasks that these metal objects might duplicate (Hosler 1990). At one site in the north of the region, Amapa, nearly half of the objects excavated were small, lost-wax cast bells. The metal collection at the Regional Museum of Guadalajara consists of approximately 3200 pieces; 1934 of these objects are bells (Hosler 1994).

The metallurgical technology was developed in two distinct stages. The first, from about A.D. 800 to 1200/1300, was characterized by almost exclusive use of copper and production primarily of lost-wax cast bells. The second period, A.D. 1200/1300 to 1521, sees the exploration and exploitation of a wide variety of alloy systems involving copper, tin, arsenic, gold, and silver. Alloying technology was geared not toward alteration of mechanical properties but towards production of specific colors; hardness of bronze increases very little with compositions above 5% tin, but the color of the metal continues to change. Objects that have been analyzed show contents up to 23% tin or arsenic, concentrations much higher than those needed to effect mechanical properties (Hosler 1995).

Sounds and colors played a vital role in the production and use of metal objects in general and bells in particular. Collected ethnographic evidence indicates that the rattling and ringing sounds of bells were associated with fertility and regeneration as well as invocation of the protection of the gods in battle. Golden and silvery colors were associated with solar and lunar deities (Hosler 1995).

West Mexican metallurgical technology was destroyed with the coming of the
Spanish in the 16th century. What survives is an ethnographic account from 1555 by Fray Bernardino de Sahagún, his *General History of the Things of New Spain*. In one section of this work, he describes the native process of gold casting:

The craftsmen fashioned [and] designed objects by the use of charcoal [and clay molds] and beeswax [models] to cast gold and silver. With this [step] they made a beginning in their craft. To start with, he who presided distributed charcoal among them. First they had ground it, then they added it to, they mixed it with, a little potter's clay; this was the clay which served for ollas. Thus they made the charcoal [and clay mixture] into a paste, kneaded it, worked it with the hands into a cohesive mass, so that it would dry and harden.

And also they prepared it: in just the same manner [as tortillas] they made it into flat cakes, which they arranged in the sun; and others were likewise formed of clay which they set in the sun. In two days [these cakes] dried; they became firm, they hardened. When they had dried well, when they had hardened, then the charcoal [and clay core] was carved, sculptured, with a small metal blade

When the charcoal [core of the mold] had been prepared, designed, carved, then the beeswax was melted. It was mixed with white copal [a pine resin], so that it would [become firm and] harden well. Then it was purified, it was strained, so that its foreign matter, its dirt, the impure beeswax, could fall. And when the beeswax had been prepared, it was then flattened, rolled out, upon a flat stone with a round piece of wood. It was a very smooth, flat stone on which [the wax] was flattened [and] rolled.

When it was well flattened, just like a cobweb, nowhere of uneven thickness, then it was placed over the [carved] charcoal [and clay core]; the surface was covered with it. And carefully it was placed on the core; cautiously little pieces of wax were cut off or pared away. By this means a little wax entered hollows, cover eminences, filled depressions in places where the charcoal [and clay core] had been carved away. By means of a stick [or sliver of wood] they went making it adhere [to the core].

And when it was prepared, when everywhere the beeswax was placed, then a paste of powdered charcoal was spread on the surface of the beeswax. Well was the charcoal ground, pulverized; and a rather thick coating [of paste] was spread on the surface of beeswax.

And when it was so prepared, again a covering was placed over it, to wrap, to envelop completely the [thus far] completed work, in order for the gold to be cast. This covering was also of charcoal, also mixed with clay- not pulverized but relatively coarse (Sahagun 1959: 73-5).
The text then describes the actual melting and casting of the metal. This description was not written by one who has done the work himself, but was probably written by one who observed the process. When trying to follow these directions, it is evident that this description is not a rigorous step-by-step guide, but rather a push in the right direction. In order to produce replicas of the archaeological objects, more detailed information is needed.

The goal of this work was to gain insight into what parameters affected the work of the ancient Mexican smiths. Materials properties of molds and metals as well as design parameters of molds influenced processing and production. This research explores some design and materials variables and their effects on the casting process.

This research discovered a process that produced good replicas of the archaeological objects and was consistent with ethnographic and archaeological evidence for west Mexican metallurgy. The development of this process allows future production of multiple replicas of archaeological artifacts for testing that cannot be done on the artifacts themselves.

This paper describes in detail each stage in the development of this process. Each casting attempt is presented chronologically with illustrations of the types of objects that resulted. Following this presentation is a discussion that details the optimal production methods that have been developed. It concludes with a discussion of avenues for future research.
II. Data and Results

A. First casting

Casting

I first attempted to replicate ancient bells using modern materials and methods. I chose plaster of paris to be the core and mold material and paraffin wax to shape the bell. The clappers were small collected stones, about 5 mm in diameter. Eight cores were made with plaster of paris (two parts powder to one part water), four of which had slightly more water in the mixture. The plaster was poured into 3.5 cm tall, 2.5 cm upper radius plastic creamer cups and the clappers were dropped into the plaster. After the plaster was dry, the cores were carved into roughly spherical forms with a knife (see figure 1(a)); the four cores with more water were denser and more difficult to carve. The cores were dipped in melted paraffin wax to create a uniform cover on the core. An opening for the mouth was carved at the base of the bell (see figure 1(b)). A suspension ring was added by heating the ring and the top of the bell form in an open flame and joining the two softened pieces. A 1 cm diameter sprue was added to the top of the ring and a 5 mm diameter vent was added to the side of the bell (see figure 1(c)).

![Figure 1](image.png)

FIGURE 1 (a): Plaster of paris core. (b) Core surrounded with wax. (c) Wax shape with suspension ring, vent and sprue added. This wax form is then immersed in plaster of paris in a tin can.
This wax form was immersed in a tin can (diameter 6 cm) containing wet plaster of paris. When the plaster had dried, a pouring cup was carved above the sprue to guide the metal into the sprue and prevent it from flowing to block the vent from above.

The wax was melted out in a Thermolyne drying oven; this leaves a hollow cavity in the mold in the shape of the bell. The mold was inverted over a collection tray, heated quickly to 110 degrees Celsius, and held at that temperature for three hours. No further heat treatment was done. The molds were allowed to cool to room temperature.

One hundred and eighty grams of copper (C11000, alloy 110; 99.90% pure copper) was melted in a ceramic crucible over a forced-air bituminous coal fire. To create a 10 wt% bronze alloy, 20 grams of 20 mesh tin was added to the melt. The crucible was lifted with curved forge tongs and the bronze poured into one mold. The crucible was put back into the fire to allow the metal to remelt. The mold was cooled next to an open window while the remaining molds were cast. The plaster of paris cooled enough to allow the mold to be broken open in two hours.

**Results**

As the metal was poured into the molds, smoke issued from the vent and the metal entering the sprue bubbled. When the cooled molds were opened, it was evident that the metal had not filled the entire cavity (see figure 2). Object 1 is a good example of the shapes resulting from this casting.

![Diagram](image)

**FIGURE 2:** Two views of object 1, an example of the bells from the first casting with wax burnout at 110 °C.
The surface of this object is smooth and brightly colored. The metal thickness is fairly uniform, about 0.6 mm.

I hypothesized that the wax had only partially burned out of the mold and that the smoke from the vent during the pour must have been the remaining wax burning. Those gases prevented the molten metal from filling the cavity before it froze. To prevent this from reoccurring, I decided to use a higher burnout temperature. The ASM Metals Handbook recommends drying temperatures from 120-260 °C, high temperature soaking from 175-870 °C for up to 72 hours, and a pre-pouring mold preheat temperature of 120 °C. It also warns that rapid heating can tend to crack the mold (1978, 243-4). This information was taken into account in the design of the heat treatment for the second casting (see table 1).

Another difficulty with this casting was the behavior of the metal during each pour. It solidified rapidly and irregularly as it was poured, with a semisolid and non-uniform texture. To ensure a uniform metal composition and regular behavior, it was decided that a uniform bronze alloy be produced. 3450 grams of copper was melted in an induction furnace and 345 grams of 20 and 30 mesh tin was added. The turbulence induced in the metal by the magnetic fields was assumed to have mixed the metal to a uniform composition. This 9.1 wt% tin bronze was poured into a steel mold. A section of this ingot was removed for the second casting.

B. Second casting

Casting

I prepared five cores with stone clappers. The dry cores were carved to shape and covered with paraffin wax by dipping the core into a container of molten wax. A mouth was cut out and suspension rings were added, as were sprues and vents. All sprue and vent configurations were identical (as in figure 1, the 1 cm diameter sprue was through the suspension ring and the 5 mm diameter vent atop the bell next to the ring). The molds
dried overnight, then the wax was burned out at 100 degrees Celsius for three hours. The molds were moved to a high temperature furnace (Lindberg model 808/847) and heated to 150 degrees at one degree per minute. They were held there for 16 hours and then heated to 650 degrees at less than one degree per minute. They were held at the high temperature for six hours. Thus, heat treatment can be summarized as in Table 1:

<table>
<thead>
<tr>
<th>Melt-out temperature</th>
<th>length (hours)</th>
<th>first hold temperature (° C)</th>
<th>length (hours)</th>
<th>ramp rate (°C/min)</th>
<th>second hold temperature (° C)</th>
<th>length (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>3.0</td>
<td>150</td>
<td>17</td>
<td>0.92</td>
<td>650</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Table 1: Heat treatment for molds in second casting.

The molds were cooled to room temperature for pouring. The metal was melted in a ceramic crucible in a forced-air coal fire and poured into the molds. Each mold required approximately 150 grams of metal to fill.

**Results**

The molds appeared to fill well, with the metal rising from the cavity to the vent. However, all five resulting figures resembled the incomplete bells of the first casting (see figure 2). All of these bells were melted down and the metal used in later castings.

There was no visible smoking as there had been in the first casting. I hypothesized that the metal could not force the air out of the entire cavity; the metal could only infiltrate to a certain amount after which it froze. Upon consultation with Toby Bashaw, a blacksmith with experience in plaster casting, I decided that a more porous material than plaster of paris might allow some gas to leave the cavity through the mold. Subsequent molds and cores were constructed with sand added to the plaster of paris mixture to create a more porous medium.
C. Third casting

Casting

Plaster of paris with sand (two parts powder, one part sand, one part water) was poured into five 3.5 cm tall, 2.5 cm upper radius plastic creamer cups and stone clappers added. The dry cores were carved with a knife and dipped in melted paraffin wax to create a uniform layer of wax on the core. Suspension rings were added, as were 1 cm diameter sprues and 5 mm diameter vents. All sprue and vent configurations were identical, as pictured in figure 1. Molds were allowed to dry overnight. The heat treatment of the molds is summarized in table 2.

<table>
<thead>
<tr>
<th>Melt-out temperature (°C)</th>
<th>length (hours)</th>
<th>first hold temperature (°C)</th>
<th>length (hours)</th>
<th>ramp rate (°C/min)</th>
<th>second hold temperature (°C)</th>
<th>length (hours)</th>
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<tbody>
<tr>
<td>110</td>
<td>3.0</td>
<td>150</td>
<td>16</td>
<td>0.92</td>
<td>650</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Table 2: Heat treatment for molds in third casting.

The molds were cooled to room temperature for pouring. The metal was melted in a ceramic crucible in a forced-air coal fire and poured into the molds.

Results

The metal remained fluid throughout the pour and came out the vents. When the cool molds were opened, however, the objects were incomplete, as pictured in figure 3.

![Diagram](image)

FIGURE 3: object 2, an example of the bells from the third casting with high heat treatment and sand and plaster construction. Note voids in the center of each side.
All five objects were similarly shaped, with voids in the center similar to those in object 2 (figure 3). Maximum wall thickness was 1.2 mm, at the mouth, and minimum thickness was 0.7 mm. Object 2 was saved and the remaining objects were melted down and used in later castings.

These castings showed that the metal failed to completely fill the cavities. The location of the voids in the bells seemed to indicate that air was trapped in the cavity that prevented the metal from filling the cavity. I hypothesized that addition of more vents to the wax form would allow air to escape completely and the bell would thus be fully formed. In addition, it was hypothesized that if the molds were hot at the time of the pour, the metal would take longer to freeze and thus would have more time to fill the mold and let air escape.

D. Fourth casting

Casting

I prepared three cores with the sand and plaster mixture. In order to minimize variations between castings, I chose at this point to use uniform clappers in each casting; I acquired a supply of commercially produced onyx beads four millimeters in diameter which I used in subsequent castings. The wax forming the bell, suspension ring, sprue, and vents was paraffin and formed as in the first three castings (see figure 1). Each bell shape had two vents added, near the top and on opposite sides (see figure 4 for configuration).

The molds were inverted and heated after they had dried for one hour. This rapid heating was done so that the wax would be melted out before the water was removed from the plaster. This would prevent the wax from being absorbed into the mold and releasing gases as it burned when the metal is poured. Heat treatment is summarized in table 3.
<table>
<thead>
<tr>
<th>Melt-out temperature</th>
<th>length</th>
<th>first hold temperature</th>
<th>length</th>
<th>ramp rate</th>
<th>second hold temperature</th>
<th>length</th>
</tr>
</thead>
<tbody>
<tr>
<td>(°C)</td>
<td>(hours)</td>
<td>(°C)</td>
<td>(hours)</td>
<td>(°C/min)</td>
<td>(°C)</td>
<td>(hours)</td>
</tr>
<tr>
<td>160</td>
<td>3.0</td>
<td>150</td>
<td>17</td>
<td>0.92</td>
<td>650</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Table 3: Heat treatment for molds in fourth casting.

The molds were cooled to 215 degrees for pouring. The metal was melted in a ceramic crucible in a forced-air coal fire and poured into the molds.

**Results**

The molds appeared to fill well, with metal appearing at the end of each vent. The cool molds were opened and the bells taken out. The objects were again incomplete but had smaller voids than those from the third casting (see figure 4).

![Diagram of Object 3 and Object 4](image)

**FIGURE 4** (a and b): objects 3 and 4, examples of bells from the fourth casting with dual venting. Vent and sprue locations are in dotted lines. Voids tend to appear at the bottom of the bell and near the top, next to the sprue and vents.

The surface of these objects was rough, resembling the surface of the cooled metal atop the sprue. The maximum thickness of these objects was 2 mm and the minimum 0.6 mm. The third bell was similarly shaped, and was melted down and the metal used in later castings.
Because all three bells had voids at the base and at the top of the bells, I decided to test whether venting closer to the base would lead to a full and successful casting. For the next casting, however, I decided to test whether indeed the incomplete bells were formed as they were due to lack of adequate venting. I determined to use a different bell shape and test two different venting configurations.

E. Fifth casting

Casting

This casting was a test to confirm results obtained so far and to verify that the previous castings were not incomplete due to their particular spherical shapes. One bell was unvented and the other had only one vent, like the first three castings. In this casting, I also explored the use of a different type of wax.

I decided to change from paraffin wax to beeswax for the shaping material. Paraffin wax requires a large container of molten wax in which to dip cores and the wax hardens quickly. It is therefore difficult to control bell thickness, and suspension rings, vents and sprues are not easy to add. Beeswax can be made malleable through heating with warm water and through hand-working; I rolled the wax into a flat shape and pressed it around the bell. This change in materials made construction of the bell shapes more efficient and moved the process closer to Sahagún’s description (see page 8).

Two sand and plaster cores with onyx bead clappers were prepared and shaped. These shapes were not spherical or ovoid, but had sharper corners at the base (see figure 5). The cores were surrounded with beeswax and immersed in plaster of paris. After the molds had dried one hour, I began the heat treatment summarized in table 4.
<table>
<thead>
<tr>
<th>Melt-out temperature</th>
<th>length</th>
<th>first hold temperature</th>
<th>length</th>
<th>ramp rate</th>
<th>second hold temperature</th>
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</tr>
</thead>
<tbody>
<tr>
<td>(° C)</td>
<td>(hours)</td>
<td>(° C)</td>
<td>(hours)</td>
<td>(° C/min)</td>
<td>(° C)</td>
<td>(hours)</td>
</tr>
<tr>
<td>160</td>
<td>3.0</td>
<td>190</td>
<td>17</td>
<td>0.92</td>
<td>650</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Table 4: Heat treatment for molds in fifth casting.

The molds were cooled to 250 degrees for pouring. The metal was melted in a ceramic crucible in a forced-air coal fire and poured into the molds.

**Results**

The molds appeared to fill well, with metal appearing at the end of the vent. The cool molds were opened and the bells taken out.

![Diagram of mold](image)

**FIGURE 5:** object 5, the only bell from fifth casting, with plaster of paris and sand mold and a single vent.

The unvented bell failed to fill at all, with the metal freezing in the sprue. The object with one vent is shown in figure 5. The surface of this bell was smooth and showed small lines, presumably where small cracks had formed in the plaster mold during heat treatment. Maximum wall thickness was 1.1 mm and minimum thickness was 0.4 mm. Although the bell shape was significantly different than all bells cast earlier, the cavity-filling behavior was similar.
It was clear that venting was a significant variable in this casting process, more important than object shape. I decided that the next casting would have multiple vents in areas that were likely to have voids; this would allow air to escape and metal to fill the entire cavity.

F. Sixth casting

Casting

One sand and plaster core with an onyx bead clapper was prepared, shaped, and coated with beeswax. This bell shape had a sprue in the side where voids had formed in previous objects (all other objects had sprues through the suspension ring). It had a vent through the suspension ring, and three other vents, two near the base and one opposite the sprue (see figure 6). Heat treatment is summarized in table 5.

<table>
<thead>
<tr>
<th>Melt-out temperature</th>
<th>length</th>
<th>first hold temperature</th>
<th>length</th>
<th>ramp rate</th>
<th>second hold temperature</th>
<th>length</th>
</tr>
</thead>
<tbody>
<tr>
<td>(° C)</td>
<td>(hours)</td>
<td>(° C)</td>
<td>(hours)</td>
<td>(°C/min)</td>
<td>(° C)</td>
<td>(hours)</td>
</tr>
<tr>
<td>150</td>
<td>3.0</td>
<td>190</td>
<td>17</td>
<td>0.92</td>
<td>650</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Table 5: Heat treatment for mold in sixth casting.

The mold was allowed to cool to 250 degrees for pouring. The metal was melted in a ceramic crucible in a forced-air coal fire and poured into the molds.

Results

The mold appeared to fill well, with metal appearing at the end of every vent. The
cool mold was opened and the bell taken out.

FIGURE 6: Object 6, the only bell from sixth casting with extensive venting and a side sprue. The incomplete areas resemble those from the third casting.

Though this mold had vents in areas where voids tended to form in earlier castings, object 6 still had gaps and voids (see figure 6). The surface was smooth and free from lines. Maximum wall thickness was 1.5 mm and minimum thickness was 0.5 mm. This object had a mouth filled with a thin layer of metal; this indicates that the joint between the plaster core and the plaster of the outer mold failed some time late in the pour; had the joint failed early, before most of the cavity was filled and cooling, the core would have been pushed up and the mouth covered by a thick layer.

If the hypothesis were true that production of a whole bell relied only on extensive venting, then this bell should have been complete. This result indicates that there is a variable other than venting preventing complete filling of the void. In the next casting therefore I located the sprue at the base to test whether introducing the metal from a different location in the cavity would allow the metal to fill the space completely.

G. Seventh casting

Casting

One sand and plaster core with an onyx bead clapper was prepared, shaped, and
coated with beeswax. This small, round bell had a sprue that entered at the base of the object and four vents (see figure 7). Vents and sprue were narrow (4 mm diameter); a plastic straw, coated with petroleum jelly, was used to make a channel in the plaster. Using a solid form for the sprue and vents ensured uniform construction and was easier to attach to the bell form than wax vents. The straws were removed before the wax was melted out. Heat treatment is summarized in table 6.

<table>
<thead>
<tr>
<th>Melt-out temperature</th>
<th>length (°C)</th>
<th>first hold temperature (°C)</th>
<th>length (hours)</th>
<th>ramp rate (°C/min)</th>
<th>second hold temperature (°C)</th>
<th>length (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>3.0</td>
<td>190</td>
<td>17</td>
<td>1.0</td>
<td>650</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Table 6: Heat treatment for molds in seventh casting.

The mold was allowed to cool to 250 degrees for pouring. The metal was melted in a ceramic crucible in a forced-air coal fire and poured into the molds.

**Results**

The mold appeared to fill well, with metal appearing at the end of three of the four vents. The cool mold was opened and the bell taken out.

**FIGURE 7:** Object 7, the only bell from the seventh casting, with four vents and a bottom sprue. The bell is incomplete as in previous castings. Note the 4.0 mm diameter vents and sprue obtained by using plastic straws as a form.
This object was also incomplete. The surface was rough, resembling the surface of the cooled metal atop the sprue. Maximum wall thickness was 2.0 mm and minimum thickness was 1.0 mm. There was a large void in the object directly above the sprue and a small void (7.0 mm diameter) across from the sprue (see figure 7).

The presence of multiple vents in the plaster of paris mold did not allow a complete bell to be cast. In order to fill the cavity completely, some other factor needed to be taken into account. It was decided that heat treatments would be varied while sprue and vent configuration remained uniform.

**H. Eighth Casting**

**Casting**

Seven sand and plaster cores were prepared with onyx bead clappers. Beeswax was pressed around the cores and mouths were cut from the base. Suspension rings were added to the top and the vent added to the suspension ring. The sprues were uniform tapered cylinders seven centimeters tall with an upper radius of 1.25 cm and lower radius of 0.5 cm. The sprues were added to the bell form with a cylinder of hot beeswax of the same diameter as the base of the sprue (see figure 8).

![Diagram](image)

**FIGURE 8:** (a) Plaster of paris and sand core (b) core surrounded with wax (c) Wax shape with suspension ring, vent, and tapered sprue added.
The forms were immersed in 8 cm radius tin cans full of plaster and sand mixture to a depth that allowed about two centimeters of the sprue to protrude. Heat treatment is summarized in table 7.

<table>
<thead>
<tr>
<th>Mold number</th>
<th>Melt-out temperature</th>
<th>length</th>
<th>first hold temperature</th>
<th>length</th>
<th>ramp rate</th>
<th>second hold temperature</th>
<th>length</th>
<th>pouring temperature</th>
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<tr>
<td>8, 9</td>
<td>150</td>
<td>3.0</td>
<td>150</td>
<td>10</td>
<td>1.0</td>
<td>1000</td>
<td>8.0</td>
<td>1000</td>
</tr>
<tr>
<td>10, 11</td>
<td>150</td>
<td>3.0</td>
<td>150</td>
<td>10</td>
<td>1.0</td>
<td>850</td>
<td>8.0</td>
<td>850</td>
</tr>
<tr>
<td>12, 13, 14</td>
<td>150</td>
<td>3.0</td>
<td>150</td>
<td>10</td>
<td>1.0</td>
<td>850</td>
<td>8.0</td>
<td>500</td>
</tr>
</tbody>
</table>

Table 7: Heat treatment for molds in eighth casting.

The metal was melted in a ceramic crucible in a charcoal forced-air fire and poured into the molds.

**Results**

The pour went smoothly, with metal appearing at the vents of all molds except 11 and 12. The molds were all cooled and the bells taken out. Figure 9 shows four of the objects in the state in which they were removed from the molds (sprues and vents attached, no polishing or smoothing). Figure 10 shows sketches of objects 8 and 13 as they would appear cleaned and photos of cleaned artifacts 9, 10, and 14.

![Figure 9](image-url)  
(a) Object 8  
(b) Object 11  
(c) Object 12  
(d) Object 13

FIGURE 9 (a-d): Uncleaned objects 8, 11, 12, and 13, from plaster of paris molds with varying heat treatments (see text for details). Flashing in (a) and (d) indicates a crack in the mold prior to pouring. Form of (b) indicates failure at the core-mold joint. (c) demonstrates catastrophic failure due to severe mold cracking. All photographs are to same scale.
FIGURE 10 (a-e): objects 8, 9, 10, 13, and 14, from plaster of paris molds with varying heat treatments (see text for details). All objects are presented with sprue locations at the base and on the outside of each pair of images (i.e., for Side 1, sprue was on left, for Side 2 sprue was on right).

The flashing on objects 8 and 13 and the nature of 12 (figure 9 (a), (d), and (c)) indicated that the mold cracked during the heating process or upon removal from the furnace. The form of object 11 was due to the joint at the mouth of the bell failing; the metal then floated the detached core up to the top of the cavity and pinched off the metal flow. Objects 13 and 14 had a thin layer of metal across their mouths; this indicated that the joint failed as it had in object 12, but after enough metal had filled the cavity and solidified to prevent the core from floating upwards.

This exhausted the 10% tin bronze that had been prepared in the induction furnace. Subsequent castings were done with a commercially purchased 11 wt% tin bronze (C90700; 89% Cu-11% Sn).

Because most of the bells were nearly complete, it was apparent that the large, tapered sprue, the high mold heat treatment, and the high temperature at the pour were what was required to make the plaster of paris system viable. There was no significant difference
between the molds that had been heated to different high temperatures; the lowest heat
treatment seems to be adequate (850 °C maximum temperature for eight hours; see table 7).
Some molds from each high heat temperature cracked but most filled almost completely.

Since the variations in mold construction and preparation seemed to have nearly
made the plaster of paris system viable, I decided to test materials closer to those described
in Sahagún's text and like those available to the ancient Mexicans.

I. Clay testing

A clay core must hold its shape when carved but be soft or brittle enough to be
broken out from the inside of a cast bell. In order to determine how charcoal affects fired
clay properties, I made twenty-seven clay (white stoneware clay provided by the Miller clay
company, New York) spheres with nine different and increasing amounts of pulverized
charcoal (see table 8). Clay amounts are presented in cubic centimeters; the clay was
measured this way to avoid any variations in weight between samples of clay with different
moisture contents. Sixteen cubic centimeters was measured out by rolling a slab of clay
2.5 cm thick and cutting 2.5 cm cubes from the slab. The heat treatment for the clay-
charcoal mixture is presented in table 9.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Clay (cm³)</th>
<th>Charcoal (grams)</th>
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<tbody>
<tr>
<td>1</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
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<td>4</td>
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<td>5</td>
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<td>12</td>
</tr>
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<td>6</td>
<td>16</td>
<td>28</td>
</tr>
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<td>7</td>
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</tr>
<tr>
<td>9</td>
<td>16</td>
<td>76</td>
</tr>
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Table 8: Clay and charcoal mixture ratios for test spheres.
<table>
<thead>
<tr>
<th>Ramp rate (°C/min)</th>
<th>First hold temperature (°C)</th>
<th>length (hours)</th>
<th>ramp rate (°C/min)</th>
<th>Second hold temperature (°C)</th>
<th>length (hours)</th>
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<tr>
<td>0.17</td>
<td>100</td>
<td>10</td>
<td>4.17</td>
<td>1150</td>
<td>0.33</td>
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</tbody>
</table>

Table 9: Heat treatment for clay and charcoal test spheres.

**Results**

The first six sets all had smooth, white surfaces. The next three sets had rougher surfaces that grew progressively darker and more pitted. When all the spheres were broken open, it could be seen that the charcoal segregated to the center during the heating process. The outer parts of each sphere were identical in density and color to the pure white clay, except in the highest coal content samples, where the outer region became pitted and extremely brittle (see figure 12(d)). With increasing amounts of charcoal, the area at the center grew darker and softer. At the highest charcoal content, 70% of the interior was of a grey, crumbly texture with a relatively smooth outer shell that fractured under moderate pressure. From these tests it was decided to use a high charcoal content for the core of the mold so as to facilitate removal of the material from the cast bell. For the mold itself, pure clay was chosen so as to maximize surface smoothness of the bell and minimize the chances of mold fracture or breakage.

**J. Ninth Casting**

**Casting**

Seven cores were formed from a mixture of white clay and charcoal, sixteen cubic centimeters of clay with 72 grams of pulverized charcoal. The clay was measured by rolling a slab 2.5 cm wide and cutting 2.5 cm cubes. The cores were dried one hour under a heat lamp and were rotated several times. Beeswax was pressed around the cores, a mouth cut out, and a suspension ring, vent, and sprue were added. The vent was atop the suspension ring and the sprues were uniform tapered cylinders seven centimeters tall with an upper radius of 1.25 centimeters and lower radius of 0.5 centimeters. The sprues were
added to the bell form with a small cylinder of hot beeswax of the same diameter as the base of the sprue. Small pieces of white clay were pressed around the bell form, gradually surrounding it. The clay and charcoal mixture, visible through the cut-out mouth area, was scored and wetted to ensure a good bond with the white clay. The clay was built up around the wax form to a mold shape that stood on its own and had small catch basins to collect metal emerging from the vent and spilled around the sprue (see figure 11).

Figure 11: A completed clay mold. This photograph is of a mold already poured; note the catch cups by both the vent and the sprue. The mold is 10 cm x 10 cm x 6 cm.

These molds were allowed to dry slowly over several days. High temperature heat treatment is summarized in table 10.

<table>
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<tr>
<th>Ramp rate (°C/min)</th>
<th>first hold temperature (° C)</th>
<th>length (hours)</th>
<th>ramp rate (° C/min)</th>
<th>second hold temperature (° C)</th>
<th>length (hours)</th>
</tr>
</thead>
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<tr>
<td>0.1</td>
<td>100</td>
<td>17</td>
<td>1.25</td>
<td>1100</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 10: Heat treatment for clay molds in ninth casting.

Molds were kept at the high temperature for the pour. It was observed that the clay molds, incandescent when removed from the furnace at 1100 degrees, continued to glow bright red on the interior of the mold as the metal was being prepared to pour. Small pieces of commercial 11% tin bronze were melted in a ceramic crucible in a forced-air coal fire and
poured into the molds. Each mold required about 200 grams of metal to fill. The molds were allowed to cool gradually next to the fire.

**Results**

The pour went smoothly, except for mold 20. With this mold, metal failed to appear at the vent and did not fill the sprue; upon closer examination, it was seen that the base of the mold had cracked and the metal was spilling out. Figure 12 illustrates several of the objects in the state in which they were removed from the mold. Figure 13 shows sketches of objects as they would appear cleaned and photographs of some cleaned objects.

![Image of objects with measurements](image)

(a) Object 16    (b) Object 17    (c) Object 19    (d) Object 20    (e) Object 21

**FIGURE 12** (a-e): Uncleaned objects 16, 17, 19, 20, and 21, from clay molds with uniform heat treatments and sprue and vent configurations. Object 20 demonstrates catastrophic failure of the mold, with a large crack at the base that allowed most of the metal to flow out of the mold. Visible here is the core material, showing the texture of the fired and cast sample. Objects 16, 17, 19, and 21 are pictured to the same scale.

![Image of objects with measurements](image)

Side 1    Side 2  
(a) Object 15  

Side 1    Side 2  
(b) Object 16  

Side 1    Side 2  
(c) Object 17  

Side 1    Side 2  
(d) Object 18  

Side 1    Side 2  
(e) Object 19  

Side 1    Side 2  
(f) Object 21

**FIGURE 13** (a-g): objects 15, 16, 17, 18, 19 and 21, from clay molds with uniform heat treatments and identical sprue and vent configuration. Sketches of objects 16, 17, 19 and 21 have been presented to make clear details obscured by flashing on the uncleaned forms (see figure 12). All objects are presented with sprue locations on the outside of each pair (i.e., for Side 1, sprue was on left, for Side 2, sprue was on right).
Objects 15, 19, and 21 had some flashing on the outer surface of the bell (see figure 12). Objects 15, 16, 18, and 19 had flashing on the interior. Object 19 also had some flashing in the mouth, indicating that the clay-charcoal and clay joint failed after most of the cavity had been filled. The exterior flashing was likely due to a poor joint between two different pieces of clay that had been pressed onto the bell. The interior flashing was likely due to cracking in the core from rapid drying.

The surfaces were smooth and showed clearly fingerprints left from the wax-pressing stage. The maximum thickness (measured at the mouth) was 3.5 mm and the minimum thickness (measured at the mouth) was 2.0 mm (aside from the void in object 19). Appendix A presents wall thicknesses for each bell individually.

Since all the bells were complete (except for object 20), this process and material system was judged a success. It was decided to perform another casting to test the effects of wall thickness and metal composition.

K. Tenth Casting

Casting

Nine cores were formed from a mixture of white clay and charcoal, sixteen cubic centimeters of clay with 72 grams of pulverized charcoal. The cores dried one hour under a heat lamp and rotated several times. Beeswax was pressed around the cores; three bells were the same thickness as the bells from the ninth casting, 3 mm, and six were formed to be thinner, 1 mm. Mouths were cut out, and a suspension ring, vent, and sprue were added. The vent was atop the suspension ring and the sprues were uniform tapered cylinders seven centimeters tall with an upper radius of 1.25 cm and lower radius of 0.5 cm. The sprues were added to the bell form with a small cylinder of hot beeswax of the same diameter as the base of the sprue. White clay was pressed around the bell wax. The clay and charcoal mixture, visible through the cut-out mouth area, was scored and wetted to ensure a good bond with the white clay. The clay was built up around the wax form to a mold shape that stood on its own and had small catch basins to collect metal emerging from the vent and spilled around the sprue (see figure 11).

Molds were allowed to dry 12 hours at room temperature. Heat treatment is
summarized in table 11.

<table>
<thead>
<tr>
<th>Ramp rate</th>
<th>first hold temperature</th>
<th>length</th>
<th>ramp rate</th>
<th>second hold temperature</th>
<th>length</th>
</tr>
</thead>
<tbody>
<tr>
<td>(°C/min)</td>
<td>(° C)</td>
<td>(hours)</td>
<td>(° C/min)</td>
<td>(° C)</td>
<td>(hours)</td>
</tr>
<tr>
<td>0.07</td>
<td>100</td>
<td>17</td>
<td>1.0</td>
<td>1100</td>
<td>15</td>
</tr>
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</table>

Table 11: Heat treatment for molds in the tenth casting.

Molds were kept at the high temperature for pouring. Small pieces of copper were melted in a ceramic crucible in a charcoal forced-air fire and poured into six molds. Small pieces of commercially produced 11% tin bronze was melted in a ceramic crucible in a charcoal forced-air fire and poured into three molds. Each mold required about 200 grams of metal to fill. The molds were allowed to cool gradually next to the fire.

The copper was more difficult to pour; it required a longer time to melt and froze rapidly during pouring. The copper also formed a porous slag atop the molten metal that prevented use of the crucible for further pourings.

**Results**

The pour went smoothly, with metal appearing at the top of most vents. The cooled molds were broken open.

![Images of objects](image_url)

**FIGURE 14 (a-i):** Uncleaned objects 22-30, from clay molds with uniform heat treatments and configuration. Nearly all objects demonstrate dislocated sprues or vents (see text for discussion). All objects are to same scale.
FIGURE 15 (a-i): Objects 22-30, from clay molds with uniform heat treatments and identical sprue and vent configuration. Objects 22-27 were cast with pure copper, objects 28-30 with 11% tin bronze. All objects are presented with sprue locations at the base and on the outside of each pair of images (i.e., for Side 1, sprue was on left, for Side 2, sprue was on right).

The surface of these bells was smooth. Most of the bells had flashing on their outside surfaces. This is most likely due to small cracks in the clay mold where pieces of wet clay were pressed together. If the clay is not allowed to dry completely before any heating is done, a large piece such as these molds is likely to crack. Since the tenth casting was done in molds that were prepared and heated quickly, not allowed to sit for several days as were the molds from the ninth casting, every object exhibited flashing to some
degree. In addition, many bells are missing suspension rings and most sprues were slightly detached from the bell. The metal flowed through thin cracks in the mold to fill each cavity nearly completely. This detachment of sprue and suspension rings was likely due to the rapid drying of the molds; the clay contracted non-uniformly as some parts dried faster and forced parts of the wax form apart.

The bells that failed to fill all had thicknesses around one millimeter, both copper and bronze. The copper bells that had been formed to be thicker, objects 23, 24 and 27 (figure 14 (b), (c), and (f)), were all poured with copper and all filled successfully. The maximum bell thickness for this casting was 3 mm in copper and 2 mm in bronze. The minimum bell thickness was 1 mm in both bronze and copper.
III. Discussion

Early efforts at casting employed plaster of paris and plaster of paris mixed with sand, materials used today in small castings. The results of the first through seventh castings demonstrate the difficulty in producing fully formed bells or in reproducing achieved results. With a move to clay and a clay-charcoal mixture as described in Sahagún's text, production quality and reliability increased markedly.

Plaster molds

The best process for creation of lost wax cast bells in a plaster of paris system requires careful construction and a high heat treatment. Core and mold material should be made from a mixture with half as much sand as plaster powder. Cores can be difficult to carve, so a container close to the shape of the desired core should be chosen to dry a shape of plaster for carving. Carving of the core should be done before the plaster has set completely so that the material is easier to form. Detailed carving is difficult to produce on a plaster and sand core; a smooth surface is simplest.

Beeswax should be warmed with hot water and through hand working; it is possible that the addition of a material such as pine resin may make the wax more malleable. The wax should be rolled out into sheets of uniform thickness and pressed carefully onto the core surface, any excess wax being removed with a sharp tool. Bell walls as thin as 1.5 millimeters are likely to produce complete bells. The surface of the bell should be smoothed and then handled carefully; surface resolution will be good enough to make fingerprints visible on the bell.

A mouth appropriate to the size of the clapper should be carved cleanly at the base of the bell. The sprue can be as long as seven centimeters and most likely could be longer. A sprue entering the bottom of the bell is most likely to allow air from the cavity to escape through the vents. Venting should be done through the suspension ring and possibly also at a high point on the bell where holes are likely to form. Vents should be at least four
millimeters in diameter, although smaller vents may be adequate. The wax form should be carefully lowered into a wet, well-mixed sand and plaster liquid in a metal can form of at least ten centimeters diameter. The molds should begin heat treatment after having dried an hour; enough time to let the plaster harden but not long enough to allow much water to evaporate.

Heat treatment should bring an inverted mold from room temperature up to 100 degrees over about six hours and hold it at that temperature for eight hours. The mold should then be slowly heated to at least 850 degrees Celsius and held at that temperature for a further eight hours. Fast heat treatments risk producing cracks in the mold that lead to flashing or complete failure while short or low-temperature heating will risk incomplete filling of the cavity. The mold should be at the high temperature for the pour to ensure a complete fill before metal solidification.

Plaster of paris and sand molds can produce a good bell form. Their constituents have the advantage of being cheaper and easier to acquire than clay molds but plaster of paris cores are more difficult to form and the molds are less likely to succeed than clay molds.

**Clay molds**

The ideal process for production of these lost-wax cast bells is with a clay and clay-charcoal system similar to the one reported to have been used by ancient Mexican smiths. Cores should be prepared with 70 grams of pulverized charcoal in 16 cm³ of clay and dried slowly and completely. They can be formed to an approximate bell shape while still wet and decorative carving can be added at the that time or later when the clay is more firm. Cores with a more brittle texture, requiring less work to remove from a cast bell, could be formed by using a higher concentration of pulverized charcoal. Since clay loses its malleability with extremely high concentrations of charcoal, a slab of the material should be prepared and allowed to dry before shaping; this is closer the process described by Sahagún.
Beeswax should be heated with hot water and hand working and then rolled to a uniform thickness and pressed onto the bell. Surface resolution is high with the clay molds so the wax may be carved with detail but care must be taken when handling the wax form to avoid leaving fingerprints. The beeswax covering should be at least 1.5 millimeters thick to ensure complete filling of the bell shape, but walls that are thinner might succeed occasionally.

A mouth appropriate to the size of the clapper at the center of the core should be cleanly cut from the base of the bell. The sprue can be attached to the form with a channel as small as a three millimeter diameter cylinder or perhaps even smaller. The clay-charcoal core visible through the mouth cut should be scored and wetted to ensure a good joint with the core and the pure clay mold. Clay should be pressed onto the bell with small, wet pieces to encourage formation of a good seal that will prevent flashing and catastrophic failure. Clay pieces inherently have different water contents that lead them to dry at different rates and with different changes in volume. Care must be taken to allow the mold to dry slowly over several days so that the mold will dry uniformly and without cracks.

Heat treatment of the molds should follow that laid out in table 11; a slow ramp up to 100 degrees and a long hold at that temperature to allow all the water to leave the mold and then a faster ramp up to a calcining temperature. Molds should be at the highest temperature reached for pouring.

Results indicate little variation between the behavior of thin-walled castings when copper or bronze is used. Both tend to fill incompletely when wall thickness decreases beyond about 1.5 mm (see Appendix A for individual bell compositions, measurements, and heat treatment information).

Clapper materials observed by the author and reported in the literature include metal beads or drops, twisted metal pieces, pebbles, and clay twists. In the process of digging the fired clay and charcoal material out of the bell, the bead clapper from my experiments occasionally fractured and then fell out the mouth. This led me to the conclusion that the bell production process would be made simpler by the addition of a clapper after the bell is
cast. This could be done with a long piece of metal that is inserted in the mouth and twisted with a gripping tool, or with a long roll of clay that is pressed into a spherical shape inside the bell. Indeed, several archaeological bells appear to have clay clappers that could have been inserted after the casting of the bell. This bell with green clay clapper could be safely fired to at least 300 degrees Celsius to allow the clapper to be bisqued and made permanent.
IV. Conclusions

This research has shown that Sahagún’s description is essentially correct and has supplemented that description sufficiently to allow bells to be cast in the manner of the ancient Mexican smiths. It is clear that the use of materials closest to those available to the ancient Mexicans is the best method of reproducing these bells. Modern materials and methods introduce many unnecessary difficulties that hinder the process.

Sahagún’s text describes casting with a series of channels as well as from a crucible, presumably of clay. The process described herein could certainly be adapted to using a vessel to melt the metal that has a plug at the base. This plug could be removed when the metal is molten to fill a pre-heated mold through a channel.

Bell thicknesses of about 1.5 mm can be reliably produced using this process. Archaeological bells observed vary in thickness between about 0.6 mm and 1.7 mm. Production of bells approaching the very thinnest artifacts using the process developed here will likely require multiple castings to produce a single complete object. With further development and experience, this process should be able to be refined to a state that allows 0.6 mm wall thicknesses to be cast reliably.

Further research can be done on the objects themselves; now, for the first time, it will be possible to test a wide variety of bell shapes and alloy compositions both for successful casting and for acoustical properties of the bells themselves. Bells in all the varieties that appear in archaeological contexts should be reproduced to actual size. Different alloys can be used in these productions to determine whether some shapes are better suited to some alloys. The effects of size, shape, and alloy composition on acoustical properties can be directly measured. This testing will reveal why the Mexicans shaped bells as they did; by producing bell shapes that are not common in the archaeological record, archaeologists will gain insight into why certain alloys and geometries were preferred. If results indicate that materials or design properties do not significantly effect certain bell properties, archaeologists will know to look for explanations in ethnographic and cultural contexts.
References Cited


<table>
<thead>
<tr>
<th>Casting</th>
<th>Object</th>
<th>Figure in text</th>
<th>Fill (%)</th>
<th>Mold material</th>
<th>High temp (°C)</th>
<th>Temp for pour (°C)</th>
<th>Metal</th>
<th>Width at mouth (mm)</th>
<th>Sprue geometry</th>
<th>Vent geometry</th>
<th>Comments</th>
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<td>-</td>
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<td>Sprue through suspension ring</td>
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<td>-</td>
<td>-</td>
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<td>650</td>
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<td>-</td>
<td>Sprue through suspension ring</td>
<td>vent on top, near sprue</td>
<td></td>
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<td>0.7</td>
<td>Sprue through suspension ring</td>
<td>Two vents on opposite sides of bell</td>
</tr>
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<td>Sprue through suspension ring</td>
<td>Two vents on opposite sides of bell</td>
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<td>0.4</td>
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<td>vent on top, near sprue</td>
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<td>6</td>
<td>50</td>
<td>Plaster of paris and sand</td>
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<td>250</td>
<td>9.1 wt% Sn bronze</td>
<td>1.5</td>
<td>0.5</td>
<td>Sprue on top, near suspension ring</td>
<td>Four vents, two high and two low</td>
</tr>
<tr>
<td>Seventh</td>
<td>7</td>
<td>7</td>
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<td>9.1 wt% Sn bronze</td>
<td>1</td>
<td>1</td>
<td>Sprue comes in at base</td>
<td>Four vents, all near top</td>
</tr>
<tr>
<td>Eighth</td>
<td>8</td>
<td>9(a)</td>
<td>90</td>
<td>Plaster of paris and sand</td>
<td>1000</td>
<td>1000</td>
<td>9.1 wt% Sn bronze</td>
<td>1.5</td>
<td>0.7</td>
<td>Tapered sprue comes in at base</td>
<td>Vents and sprue were formed with a plastic straw</td>
</tr>
<tr>
<td>Eighth</td>
<td>9</td>
<td>10(b)</td>
<td>95</td>
<td>Plaster of paris and sand</td>
<td>1000</td>
<td>1000</td>
<td>9.1 wt% Sn bronze</td>
<td>1.7</td>
<td>1.5</td>
<td>Tapered sprue comes in at base</td>
<td>Vents through suspension ring</td>
</tr>
<tr>
<td>Eighth</td>
<td>10</td>
<td>10(c)</td>
<td>95</td>
<td>Plaster of paris and sand</td>
<td>850</td>
<td>850</td>
<td>9.1 wt% Sn bronze</td>
<td>2</td>
<td>2</td>
<td>Tapered sprue comes in at base</td>
<td>Vents through suspension ring</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Incomplete near mouth on same side as sprue</td>
<td></td>
</tr>
<tr>
<td>Ninth</td>
<td>11</td>
<td>9(b)</td>
<td>50</td>
<td>Plaster of paris and sand</td>
<td>850</td>
<td>850</td>
<td>9.1 wt% Sn bronze</td>
<td>-</td>
<td>-</td>
<td>Tapered sprue comes in at base</td>
<td>Bottom half filled, floated top half off the core</td>
</tr>
<tr>
<td>Ninth</td>
<td>12</td>
<td>9(c)</td>
<td>0</td>
<td>Plaster of paris and sand</td>
<td>850</td>
<td>500</td>
<td>9.1 wt% Sn bronze</td>
<td>-</td>
<td>-</td>
<td>Tapered sprue comes in at base</td>
<td>Bottom of mold cracked, metal flowed out</td>
</tr>
<tr>
<td>Ninth</td>
<td>13</td>
<td>9(d)</td>
<td>80</td>
<td>Plaster of paris and sand</td>
<td>850</td>
<td>500</td>
<td>9.1 wt% Sn bronze</td>
<td>2</td>
<td>2</td>
<td>Tapered sprue comes in at base</td>
<td>Large void next to and above sprue</td>
</tr>
<tr>
<td>Ninth</td>
<td>14</td>
<td>10(e)</td>
<td>95</td>
<td>Plaster of paris and sand</td>
<td>850</td>
<td>500</td>
<td>9.1 wt% Sn bronze</td>
<td>2</td>
<td>2</td>
<td>Tapered sprue comes in at base</td>
<td>Mouth covered, one hole (2 mm dia) near top, opposite sprue</td>
</tr>
<tr>
<td>Ninth</td>
<td>29</td>
<td>13(h)</td>
<td>75</td>
<td>Clay</td>
<td>1100</td>
<td>1100</td>
<td>11 wt% Sn bronze</td>
<td>1</td>
<td>1</td>
<td>Tapered sprue comes in at base</td>
<td>No ring, incomplete across from sprue</td>
</tr>
<tr>
<td>Ninth</td>
<td>30</td>
<td>13(i)</td>
<td>100</td>
<td>Clay</td>
<td>1100</td>
<td>1100</td>
<td>11 wt% Sn bronze</td>
<td>1</td>
<td>1</td>
<td>Tapered sprue comes in at base</td>
<td>Vent through suspension ring</td>
</tr>
</tbody>
</table>
### Appendix A (cont.): Table summarizing object pictures, completeness, heat treatments, thickness, and sprue and vent configurations.

<table>
<thead>
<tr>
<th>Casting</th>
<th>Object Figure in text</th>
<th>Fill (%)</th>
<th>Mold Material</th>
<th>High Temp (°C)</th>
<th>Temp for pour (°C)</th>
<th>Metal</th>
<th>Width at mouth (mm)</th>
<th>Sprue geometry</th>
<th>Vent geometry</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ninth</td>
<td>15 13(a)</td>
<td>100</td>
<td>Clay</td>
<td>1100</td>
<td>1100</td>
<td>11 wt%</td>
<td>2</td>
<td>Tapered sprue comes in at base</td>
<td>Vent through suspension ring</td>
<td>Ring slightly detatched, flashing inside</td>
</tr>
<tr>
<td></td>
<td>16 12(a) and 13(b)</td>
<td>100</td>
<td>Clay</td>
<td>1100</td>
<td>1100</td>
<td>11 wt%</td>
<td>3.5</td>
<td>Tapered sprue comes in at base</td>
<td>Vent through suspension ring</td>
<td></td>
</tr>
<tr>
<td></td>
<td>17 12(b) and 13(c)</td>
<td>100</td>
<td>Clay</td>
<td>1100</td>
<td>1100</td>
<td>11 wt%</td>
<td>2.5</td>
<td>Tapered sprue comes in at base</td>
<td>Vent through suspension ring</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18 13(d)</td>
<td>100</td>
<td>Clay</td>
<td>1100</td>
<td>1100</td>
<td>11 wt%</td>
<td>3</td>
<td>Tapered sprue comes in at base</td>
<td>Vent through suspension ring</td>
<td>Flashing inside bell</td>
</tr>
<tr>
<td></td>
<td>19 12(c) and 13(e)</td>
<td>95</td>
<td>Clay</td>
<td>1100</td>
<td>1100</td>
<td>11 wt%</td>
<td>3</td>
<td>Tapered sprue comes in at base</td>
<td>Vent through suspension ring</td>
<td>Mouth filled, hole (2mm dia) on top, opposite sprue</td>
</tr>
<tr>
<td></td>
<td>20 12(d)</td>
<td>0</td>
<td>Clay</td>
<td>1100</td>
<td>1100</td>
<td>11 wt%</td>
<td>-</td>
<td>Tapered sprue comes in at base</td>
<td>Vent through suspension ring</td>
<td>Bottom of mold cracked, metal flowed out base</td>
</tr>
<tr>
<td></td>
<td>21 12(e) and 13(f)</td>
<td>100</td>
<td>Clay</td>
<td>1100</td>
<td>1100</td>
<td>11 wt%</td>
<td>2.5</td>
<td>Tapered sprue comes in at base</td>
<td>Vent through suspension ring</td>
<td></td>
</tr>
<tr>
<td>Tenth</td>
<td>22 14(a) and 15(a)</td>
<td>100</td>
<td>Clay</td>
<td>1100</td>
<td>1100</td>
<td>Cu</td>
<td>1.9</td>
<td>Tapered sprue comes in at base</td>
<td>Vent through suspension ring</td>
<td></td>
</tr>
<tr>
<td></td>
<td>23 14(b) and 15(b)</td>
<td>95</td>
<td>Clay</td>
<td>1100</td>
<td>1100</td>
<td>Cu</td>
<td>3</td>
<td>Tapered sprue comes in at base</td>
<td>Vent through suspension ring</td>
<td>Ring detached but filled through thin flashing</td>
</tr>
<tr>
<td></td>
<td>24 14(c) and 15(c)</td>
<td>95</td>
<td>Clay</td>
<td>1100</td>
<td>1100</td>
<td>Cu</td>
<td>3</td>
<td>Tapered sprue comes in at base</td>
<td>Vent through suspension ring</td>
<td>No ring, sprue detached, filled through flashing</td>
</tr>
<tr>
<td></td>
<td>25 14(d) and 15(d)</td>
<td>75</td>
<td>Clay</td>
<td>1100</td>
<td>1100</td>
<td>Cu</td>
<td>1.1</td>
<td>Tapered sprue comes in at base</td>
<td>Vent through suspension ring</td>
<td>No ring, incomplete across from sprue</td>
</tr>
<tr>
<td></td>
<td>26 14(e) and 15(e)</td>
<td>60</td>
<td>Clay</td>
<td>1100</td>
<td>1100</td>
<td>Cu</td>
<td>1.2</td>
<td>Tapered sprue comes in at base</td>
<td>Vent through suspension ring</td>
<td>Incomplete at top. sides. and above sprue on one side</td>
</tr>
<tr>
<td></td>
<td>27 14(f) and 15(f)</td>
<td>95</td>
<td>Clay</td>
<td>1100</td>
<td>1100</td>
<td>Cu</td>
<td>2.5</td>
<td>Tapered sprue comes in at base</td>
<td>Vent through suspension ring</td>
<td>Hole at very top, under ring</td>
</tr>
<tr>
<td></td>
<td>28 14(g) and 15(g)</td>
<td>100</td>
<td>Clay</td>
<td>1100</td>
<td>1100</td>
<td>11 wt%</td>
<td>2</td>
<td>Tapered sprue comes in at base</td>
<td>Vent through suspension ring</td>
<td></td>
</tr>
<tr>
<td></td>
<td>29 14(h) and 15(h)</td>
<td>75</td>
<td>Clay</td>
<td>1100</td>
<td>1100</td>
<td>11 wt%</td>
<td>1</td>
<td>Tapered sprue comes in at base</td>
<td>Vent through suspension ring</td>
<td>No ring, incomplete across from sprue</td>
</tr>
<tr>
<td></td>
<td>30 14(i) and 15(i)</td>
<td>100</td>
<td>Clay</td>
<td>1100</td>
<td>1100</td>
<td>11 wt%</td>
<td>1.2</td>
<td>Tapered sprue comes in at base</td>
<td>Vent through suspension ring</td>
<td></td>
</tr>
</tbody>
</table>

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