From Clay to Ceramics and Ceramic Firing

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Clay objects must be dry before they can be fired. A good way to ensure that an object is dry is to feel it against your skin. If the object feels a little cool, it will probably still be moist even if it looks visually dry. If damp clay objects are fired, the steam coming out of the inside of the object may explode the object or cause cracks during firing. However, when drying earthenware, it must be remembered that the drying is done slowly and evenly enough that the shrinkage during drying does not cause the objects to warp or crack. The thicker the wall of the object is, the slower it must dry.

During the firing process, the clay transforms into ceramics. During firing, several different reactions take place, such as sintering, softening, and then eventually clay body melting if the firing temperature is too high. During firing, the free water is first removed from the clay, and then its crystal water, as the firing progresses. The particles of the clay body components melt together and form a new durable material.

Figure 1. Cearmic objects and schetches

1. Changes in ceramics caused by firing

Sintering is a key phenomenon in the ceramic process, which can also be called vitrifying. Sintering is a series of reactions in which part of the body melts at the same time as other parts only begin to adhere to each other. In connection with sintering, the total volume of the material decreases while the material becomes denser and stronger.

The sintered body is at its softest at peak firing temperatures and then the shape of the object tends to slump. For example, if an object is placed on a bent kiln shelf, it may warp during firing. When the body has softened, its internal stresses tend to be triggered, which causes distortions in the object, for example. This phenomenon is called clay memory. For example, clay memory can be seen at slip-cast seams that have been smoothed unnoticed before firing. However, after firing, the seams may emerge as the stress due to the direction of the settling particles relaxes. Similarly, changing the shape of the mouth of an object from oval to round is easily accomplished while the object is still wet, but during firing, due to the pulling caused by the clay particle memory, the mouth will probably return to a more oval shape.

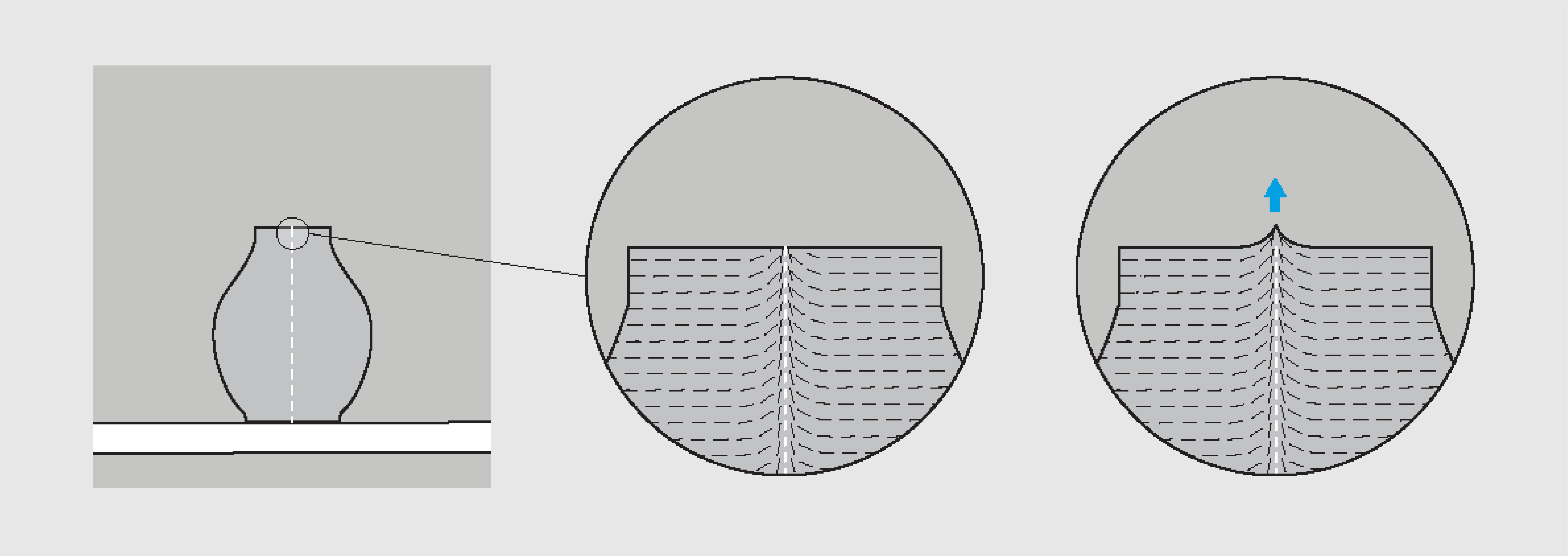


Figure 2. Clay memory: the finished slip-cast seam reappears during firing

If the firing temperature exceeds the sintering temperature of the clay body, the clay body begins to melt. The melting body turns into a soft, semi-solid mass into which bubbles begin to form from the gaseous constituents. At this point, the object loses its shape and eventually melts completely onto the kiln shelf, which can cause great damage to the kiln.

As the temperature in the furnace rises, the volume of the pottery increases. This phenomenon is called thermal expansion. As the temperature decreases, the volume of the materials decreases correspondingly. In the making of ceramics, this is particularly important in the coordination of the body and the glaze, since the glaze, when cooled, is subjected to either compressive or tensile stress in relation to the body beneath. The thermal expansion of the glaze should be less than that of the body because the glazes withstand the compressive stress better, in other words, the body should shrink more than the glaze during cooling.

The change in size after firing compared to the dry size of an object is called firing shrinkage. The denser the fired clay body, the more it shrinks. The shrinkage of a stoneware clay body is usually about 13%, slightly more with porcelain (14-16%) and considerably less with porous red clay. Changes during firing are taken into account in the design and making phase of the ceramic artefact. The fired product is also lighter than the unfired, because in addition to the removal of free water, organic matter and crystal water evaporate.

Firing temperatures of different clay bodies:

- Porcelain: 1200-1400 °C
- Stoneware clays: 1150-1300 °C
- Low firing clays (earthenware, earthenware and red clays): 1000-1100 °C

Figure 3. Post-firing changes, such as firing shrinkage, are seen when the unfired and vitrified fired pitcher are compared. Pitcher by Nathalie Lautenbacher

2. Progression of firing in stages

When firing ceramics, the heat is directed as evenly as possible into the kiln space. Too rapid a rise in heat can, at worst, cause the object to break. The relative slowness and uniformity of the heat rise ensures that the clay particles can adhere to each other and partially melt while the necessary crystal changes take place in the body.

Raw firing is started slowly, especially if the objects are thick and there is reason to suspect that they are still slightly moist. The thicker the object, the slower the initial firing necessary. In glazing, firing can be started faster if the objects have been bisqued. Correspondingly, the final firing is slowed down so that the glaze melts well. Finally, the heat is held at the peak firing temperature to ensure that the heat is evenly distributed throughout the furnace. After soaking, the kiln is allowed to cool at its own pace. Depending on the size of the objects placed in the kiln and the clay type used, the cooling of the kiln can be accelerated by cracking the lid open at 300 °C. The kiln can usually be opened when the temperature is below 200 °C. Opening the kiln when cooled protects the kiln from heat shock and prolongs the life of the kiln.

Below is a brief description of the important firing temperatures and chemical changes that occur in ceramics during the firing process. Understanding these steps will help you avoid common problems that occur during firing, such as cracks in an object caused by too rapid a rise in temperature.

Changes during firing in a porcelain body with a sintering temperature of 1200 °C:

1. 100-200 °C: Free water is removed.

2. 450-600 °C: Chemically bound crystal water is removed. Kaolin is converted to metakaolin and significantly increases the porosity of the clay body.

3. 573 °C (approx.): Change in crystal form of quartz from alpha to beta.

4. 300-700 °C: Impurities such as organic matter burn out.

5. 980 °C: Metakaolin turns into spinel and releases finely divided and fusible quartz.

6. 1050-1100 °C: The spinel begins to turn into a mullite, at the same time the feldspar begins to melt and its volume decreases. This is the beginning of the formation of glass material. The fine quartz released during the formation of mullite begins to melt into a glass material and dissolves the free quartz. Feldspar also dissolves quartz, but not yet alumina (Al_2O_3).

7. 1200 °C: The feldspar has completely melted and the glass material continues to spread. Porosity is greatly reduced.

8. 1200 °C: The body contains mostly glass with mullite crystals and pores. Overfiring has the effect that the porosity of the clay body begins to increase due to gas formation.

(Jylhä-Vuorio, 2003)

The crystal change of quartz or quartz inversion takes place in the firing of raw materials and glazing, both as the temperature rises and when the furnace cools down to about 573 °C. The structure of the quartz crystal changes from alpha to beta as the temperature rises and at the same time expands, as the temperature decreases, the quartz crystals in turn shrink. These changes cause stresses in the clay body and therefore too rapid a firing program can cause cracking in the object. (Zakin & Bartolovic, 2015)

Cristobalite is a specific crystallized form of silica that occurs naturally in some clays (red clays and some stoneware) when fired at temperatures above about 1150 °C. The crystals shrink rapidly at 220 °C (about 3%) and can cause cracks in the object. Therefore, the kiln should only be opened at temperatures below 200 °C, especially when firing such clays. (Zakin & Bartolovic, 2015)

Figure 4. Coquillages by Nathalie Lautenbacher

2.1 Measurement of firing temperature

Temperature sensors are installed near the inner walls of the kilns, which measure the temperature of the kiln air flowing past them. A more accurate temperature can be found using ceramic thermometers, or pyrometric cones, as their composition is designed to melt at certain temperatures and they react to firing in the same way as clay and glaze.

The cones are numbered per cone according to the temperature at which the cone bends. Cones of three adjacent temperature ranges, for example cones 6,7 and 8, are placed on the kiln shelf in an angled position, approximately every couple of centimeters. The numbers correspond to a certain temperature and when this temperature is reached the cone bends forward. The kiln temperature is deduced from the melting position of the cones (see Figure 3). The evenness of the firing can be viewed when the cones are placed in the furnace at different heights.

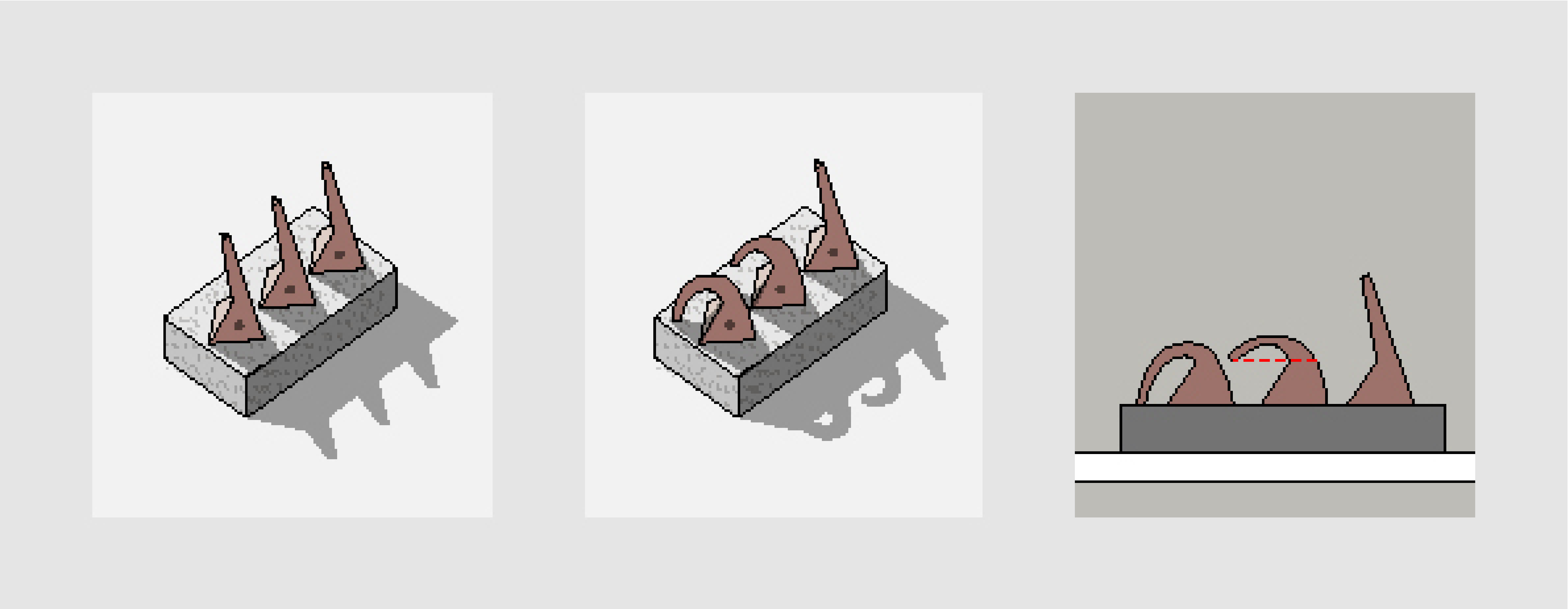
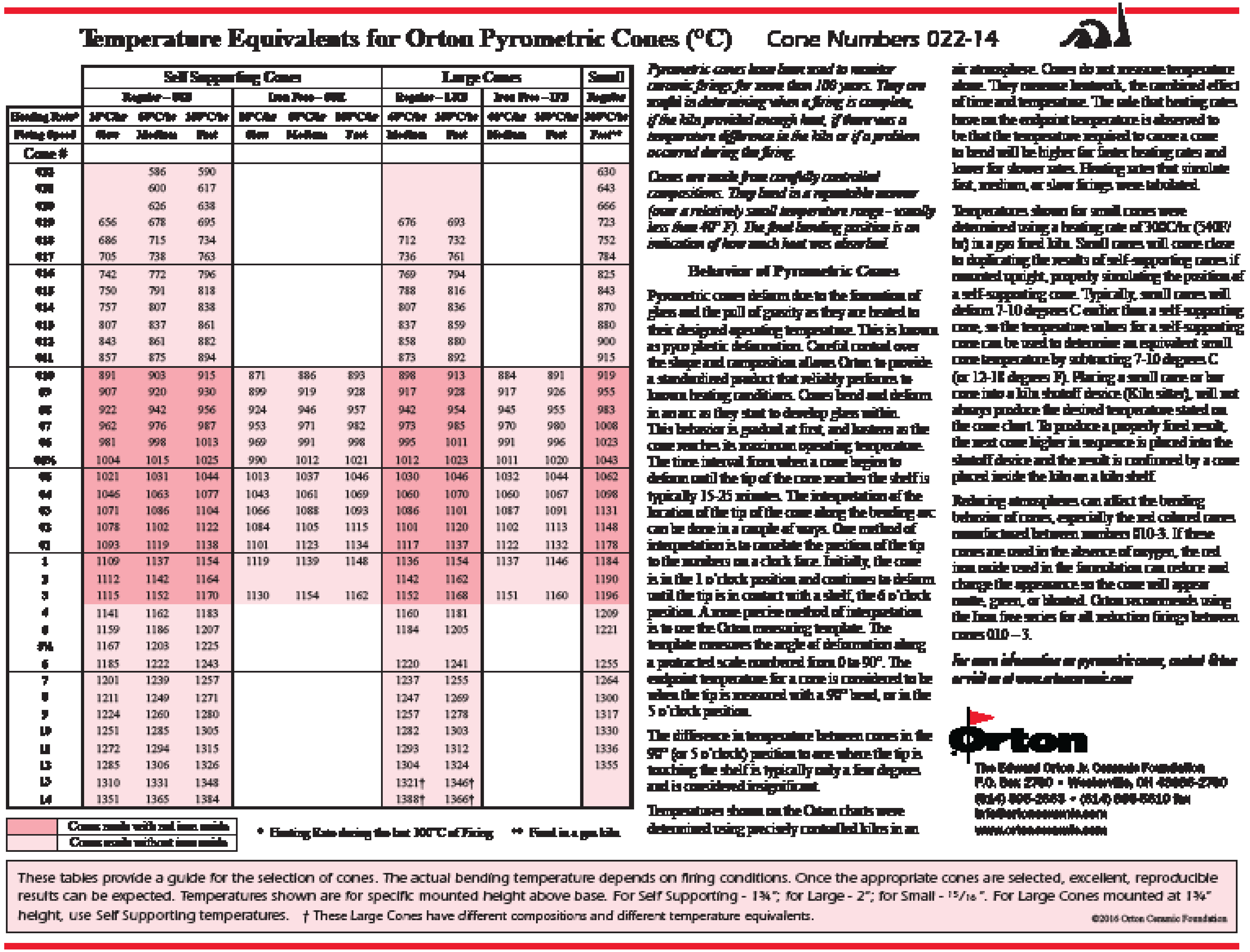


Figure 5. Self-supporting cones before and after firing



Temperature Equivalents for Orton Pyrometric Cones (°C) Cone Numbers 022-14

	Self Supporting Cones						Large Cones				Small
	Regular – SSB			Iron Free – SSBF			Regular – LRB		Iron Free – LRBF		Regular
Heating Rate*	15°C/hr	60°C/hr	150°C/hr	15°C/hr	60°C/hr	150°C/hr	60°C/hr	150°C/hr	60°C/hr	150°C/hr	300°C/hr
Firing Speed	Slow	Medium	Fast	Slow	Medium	Fast	Medium	Fast	Medium	Fast	Fast**
Cone #											
022		586	590								630
021		600	617								643
020		626	638								666
019	656	678	695				676	693			723
018	686	715	734				712	732			752
017	705	738	763				736	761			784
016	742	772	796				769	794			825
015	750	791	818				788	816			843
014	757	807	838				807	836			870
013	807	837	861				837	859			880
012	843	861	882				858	880			900
011	857	875	894				873	892			915
010	891	903	915	871	886	893	898	913	884	891	919
09	907	920	930	899	919	928	917	928	917	926	955
08	922	942	956	924	946	957	942	954	945	955	983
07	962	976	987	953	971	982	973	985	970	980	1008
06	981	998	1013	969	991	998	995	1011	991	996	1023
05½	1004	1015	1025	990	1012	1021	1012	1023	1011	1020	1043
05	1021	1031	1044	1013	1037	1046	1030	1046	1032	1044	1062
04	1046	1063	1077	1043	1061	1069	1060	1070	1060	1067	1098
03	1071	1086	1104	1066	1088	1093	1086	1101	1087	1091	1131
02	1078	1102	1122	1084	1105	1115	1101	1120	1102	1113	1148
01	1093	1119	1138	1101	1123	1134	1117	1137	1122	1132	1178
1	1109	1137	1154	1119	1139	1148	1136	1154	1137	1146	1184
2	1112	1142	1164				1142	1162			1190
3	1115	1152	1170	1130	1154	1162	1152	1168	1151	1160	1196
4	1141	1162	1183				1160	1181			1209
5	1159	1186	1207				1184	1205			1221
5½	1167	1203	1225								
6	1185	1222	1243				1220	1241			1255
7	1201	1239	1257				1237	1255			1264
8	1211	1249	1271				1247	1269			1300
9	1224	1260	1280				1257	1278			1317
10	1251	1285	1305				1282	1303			1330
11	1272	1294	1315				1293	1312			1336
12	1285	1306	1326				1304	1324			1355
13	1310	1331	1348				1321†	1346†			
14	1351	1365	1384				1388†	1366†			

🟥	Cones made with red iron oxide
▨	Cones made without iron oxide

* Heating Rate during the last 100°C of Firing ** Fired in a gas kiln

Pyrometric cones have been used to monitor ceramic firings for more than 100 years. They are useful in determining when a firing is complete, if the kiln provided enough heat, if there was a temperature difference in the kiln or if a problem occurred during the firing.

Cones are made from carefully controlled compositions. They bend in a repeatable manner (over a relatively small temperature range – usually less than 40° F). The final bending position is an indication of how much heat was absorbed.

Behavior of Pyrometric Cones

Pyrometric cones deform due to the formation of glass and the pull of gravity as they are heated to their designed operating temperature. This is known as pyro plastic deformation. Careful control over the shape and composition allows Orton to provide a standardized product that reliably performs to known heating conditions. Cones bend and deform in an arc as they start to develop glass within. This behavior is gradual at first, and hastens as the cone reaches its maximum operating temperature. The time interval from when a cone begins to deform until the tip of the cone reaches the shelf is typically 15-25 minutes. The interpretation of the location of the tip of the cone along the bending arc can be done in a couple of ways. One method of interpretation is to correlate the position of the tip to the numbers on a clock face. Initially, the cone is in the 1 o'clock position and continues to deform until the tip is in contact with a shelf, the 6 o'clock position. A more precise method of interpretation is to use the Orton measuring template. The template measures the angle of deformation along a protracted scale numbered from 0 to 90°. The endpoint temperature for a cone is considered to be when the tip is measured with a 90° bend, or in the 5 o'clock position.

The difference in temperature between cones in the 90° (or 5 o'clock) position to one where the tip is touching the shelf is typically only a few degrees and is considered insignificant.

Temperatures shown on the Orton charts were determined using precisely controlled kilns in an air atmosphere. Cones do not measure temperature alone. They measure heatwork, the combined effect of time and temperature. The role that heating rates have on the endpoint temperature is observed to be that the temperature required to cause a cone to bend will be higher for faster heating rates and lower for slower rates. Heating rates that simulate fast, medium, or slow firings were tabulated.

Temperatures shown for small cones were determined using a heating rate of 300C/hr (540F/hr) in a gas fired kiln. Small cones will come close to duplicating the results of self-supporting cones if mounted upright, properly simulating the position of a self-supporting cone. Typically, small cones will deform 7-10 degrees C earlier than a self-supporting cone, so the temperature values for a self-supporting cone can be used to determine an equivalent small cone temperature by subtracting 7-10 degrees C (or 12-18 degrees F). Placing a small cone or bar cone into a kiln shutoff device (Kiln sitter), will not always produce the desired temperature stated on the cone chart. To produce a properly fired result, the next cone higher in sequence is placed into the shutoff device and the result is confirmed by a cone placed inside the kiln on a kiln shelf.

Reducing atmospheres can affect the bending behavior of cones, especially the red colored cones manufactured between numbers 010-3. If these cones are used in the absence of oxygen, the red iron oxide used in the formulation can reduce and change the appearance so the cone will appear mottle, green, or bloated. Orton recommends using the Iron free series for all reduction firings between cones 010 – 3.

For more information on pyrometric cones, contact Orton or visit us at www.ortonceramic.com

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These tables provide a guide for the selection of cones. The actual bending temperature depends on firing conditions. Once the appropriate cones are selected, excellent, reproducible results can be expected. Temperatures shown are for specific mounted height above base. For Self Supporting - 1¾"; for Large - 2"; for Small - ¹⁵⁄₁₆". For Large Cones mounted at 1¾" height, use Self Supporting temperatures. † These Large Cones have different compositions and different temperature equivalents.

Figure 6. Orton cone chart

3. Bisque firing and glazing firing

Bisque firing refers to the first firing of objects to a temperature of about 800-950 °C. The purpose of this firing is to make the objects durable enough to easily handle when glazing. The bisque fired body is porous and absorbs water from the glaze, whereby the glaze adheres to the surface of the object. In bisque firing, a slow start is important so that any free water left in the pores can evaporate away. Crystal water is also removed at the beginning of firing (400-650 °C). Firing should be slow so that all firing reactions have time to complete. Contaminants remaining in the clay body during bisque firing can cause vitrification defects when gassing during glaze firing.

For bisque firing, objects can be stacked together or even gently stacked on top of each other.

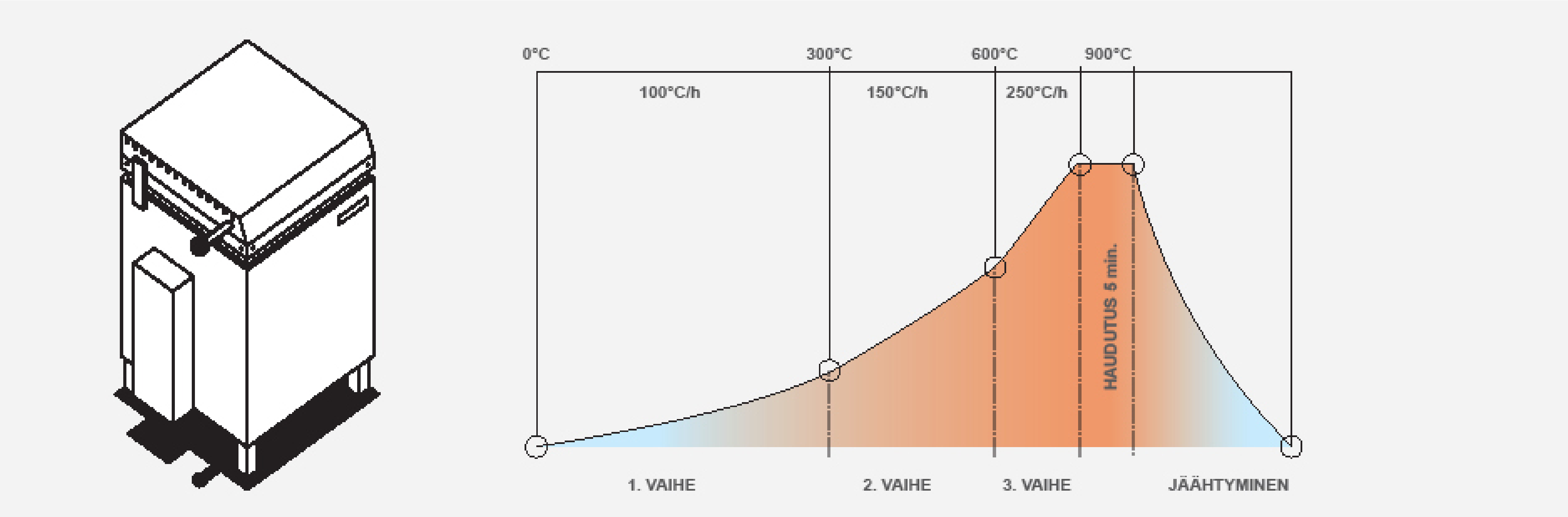

Figure 7. Bisque firing curve

In glaze firing, objects are fired to as high a temperature as the melting of the glaze requires. At the same time, the body is made to sinter in the desired manner into a suitably dense and durable object. The final glazing temperature varies depending on the clay type used and the glaze. A fast or slow heat rise program affects the melting of the glaze and some glazes require deceleration at different stages of firing. For example, in crystal glazes, the crystals grow in a cooling glaze, which is why the glaze firing is held at different cooling temperatures for several hours, depending on how large and what shape crystals are sought. (http://www.airihortling.fi/Lasite_ja_lasittaminen.pdf).

Before firing, the glaze is carefully wiped from the bottom of the bisque fired objects so that they do not stick to the kiln shelf. The objects are loaded in the kiln so that they do not touch each other.

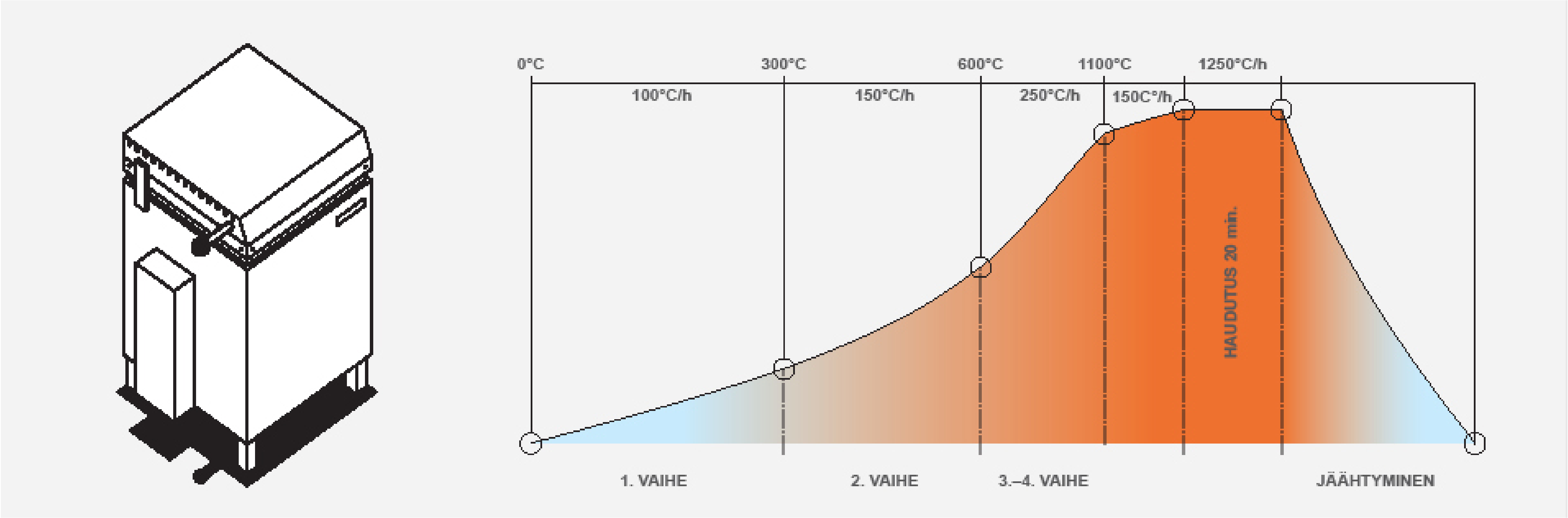

Figure 8. Glazing firing curve 1250 °C

4. Different firing methods

Before looking at different methods of firing ceramics, such as gas and electric firing, let's open up what firing atmospheres mean.

4.1. Firing Atmospheres

The firing atmosphere refers to the firing climate in the kiln during firing. The firing atmosphere is affected by the amount of oxygen in the furnace space, which in turn affects the appearance of both the clay body and the glaze.

Neutral firing means firing in which firing reactions take place to completion. In other words, firing consumes only the amount of oxygen used by the firing reaction in question. During neutral firing, the furnace is free of excess, free oxygen, and carbon monoxide (CO). In an electric kiln, the firing is usually neutral. Neutral fired glazes are typically brighter than reduction fired glazes, especially at lower temperatures.

Oxidation firing occurs when more air is introduced into the furnace than would be necessary for firing. Oxidation firing can be achieved by opening the kiln ventilation hatches or by opening the kiln door lid. As a result of oxidation firing, for example, copper oxide, which has already been reduced once, can be oxidized back to its original color.

Reduction firing is often done in a gas or wood kiln. The reduction is achieved when not enough oxygen is released into the burner housing for complete firing. This produces carbon monoxide (CO) in the furnace. Carbon monoxide tends to bind with another oxygen atom, and some metal oxides used in ceramics, in turn, can release oxygen atoms during firing. Reduction occurs when oxygen is removed from these compounds. In practice, the most visible change occurs in the coloring of ceramics: for example, brown iron oxide (Fe_2O_3) and changes to blue-green (FeO) during firing. Another easily reducing non-ferrous metal oxide is a greenish copper oxide that turns red during reducing firing. There are glazes designed for reduction firing, e.g. Celadon and Ox blood.

4.2 Firing Methods

Ceramic kilns are divided into two main types: gas and electric. The gas kiln is heated by firing fuel such as oil, gas or wood in the kiln or burners. In these kilns, the flames enter directly into the kiln space and are in direct contact with the objects being fired. Gas and wood kilns are particularly well suited for Reduction firing. The heat required in an electric kiln is generated when an electric current is directed to the electric heaters inside the kiln, called elements. The atmosphere of the electric kiln is neutral when the kiln space is closed. Oxidation firing is achieved when the kiln vents or door are cracked.

Raku is a Japanese firing method in which objects are lifted from a kiln at the peak temperature of firing and placed in a container containing combustible material (often sawdust). The smoke penetrates the pores of the hot body, staining it black. At the same time, many glaze colorants can be reduced. After smoking, the objects are rapidly cooled in a water vessel. Raku objects are characterized by cracks in the glass surface that occur during cooling due to thermal shock. Raku should only be fired by an experienced professional, as there are several dangerous steps involved in the firing.

Wood firing is the traditional and oldest method of firing ceramics, in which wood is used as fuel for the kiln. Wood firing requires a lot of time as logs are added to the firing chamber throughout the firing process. Firing generally takes 14-30 hours. During firing, the appearance of clay bodies and glazes is greatly affected by the flame and smoke formed in the kiln space, as well as the ash. Traces of flame form on the object and molten ash can glaze the surface of the unglazed object. In a wood kiln, clay bodys and glazes can also be reduced, so glazes from reduction firing such as Celadon and ox blood work well in wood firing.

In salt firing, moistened coarse salt, i.e. sodium chloride, is thrown into the furnace at the sintering temperature of the clay body, whereby the silica contained in the surface of the clay body reacts with sodium to form a glass coating. The glaze layers and thickens as the firing continues. The more times the salt is thrown, the thicker the glaze is formed. The method requires a kiln type in which a flame carries salt inside the furnace during firing. The temperature of the clay body depends on the firing temperature of the salt glaze, which must be at least 1100 °C, at which point the salt begins to evaporate. (http://www.airihortling.fi/Lasite_ja_lasittaminen.pdf).

Figure 9. Nuutti Fermentation Pot by Saara kantele

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Figure 10. Soil and Landscape by Chen Tzuyu