# A Discussion of Flameware

## *George J Chechopoulos explains Flameware clay body and glaze formulation*

FLAMEWARE CLAY BODIES AND GLAZES WILL WITHSTAND SUDDEN CHANGES in temperature if properly designed for use in the oven and on stove-top burners. The common cone 10 stoneware clay bodies used by potters today will most likely fail (break) when subjected to thermal shock in the oven because tensile stresses in the ware will exceed the strength of the clay body and glaze. Having said that, I understand that there are stoneware clay bodies that are recommended for use in the oven but they all come with their own special precautionary use instructions that are usually more than the typical household cook would care to deal with on a daily basis. Also, stoneware clay bodies are never recommended for direct stove top use or quick changes of temperature. In order to properly understand the concept of Flameware pottery design and formulation, we first need to understand the physical changes that stoneware clay bodies undergo when fired in the kiln.

### QUARTZ INVERSION:

Stoneware clay bodies and glazes are typically the standard material of choice of the potter for producing functional pottery. When fired in the kiln, quartz crystals in the stoneware clay bodies change from alpha to beta quartz at 573ºC (1063ºF) and expand suddenly. Although this expansion is not visible to the human eye, if the rise in temperature is too rapid through this phase, the pottery can break in the firing. According to Ron Roy, Ceramic Consultant, on the way up in temperature the rim of pots will heat up before the foot, causing compression. Therefore, passing quickly through this phase on the way up, may not cause breakage. The expansion is reversed on cooling at the same temperature but this time 'dunting' will occur if the temperature is cooling too rapidly because the foot of the pot, in contact with the hot shelf, goes through this inversion phase later than the rim (now in tension), causing a rim crack . This phase of expansion and contraction is called 'quartz inversion'.

### CRISTOBALITE INVERSION

Once most available stoneware clay bodies reach the stoneware temperature range (cone 8 to 10), micro fine silica in the clay body forms cristobalite (a form of silica) from silica that did not become part of the glossy structure of the clay. Upon cooling, the stoneware clay body again

*Left: Fig 1: **Photo of cone packs used at top and bottom kiln spy holes for the 15th firing of the Marrowstone Pottery 32 cu/ft downdraft kiln.***
*Right: Fig 2: **A small bowl thrown for testing from the first small batch of Flameware clay mixed for the experiment.** Clay body 2F and Glaze #15 shown.*
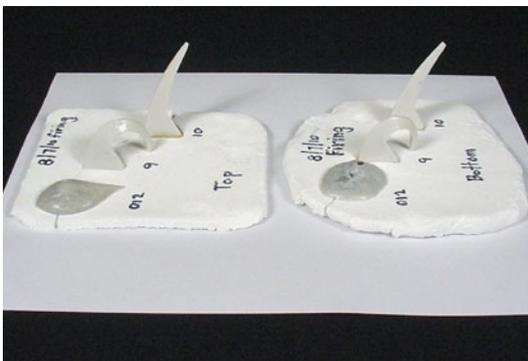
contracts between 177°C and 204°C (350°F and 400°F). For clay bodies that are the exception to this rule, see Peter Sohngen's article entitled, "Cristobalite: The Hump, New Data on Silica at Cone Ten" in *Studio Potter*, Volume 28 #1.

Once cristobalite is formed, the clay body expands upon heating and contracts upon cooling suddenly at that temperature range and will break if the rise or drop in temperature is too great. This phase of expansion and contraction is called 'cristobalite inversion' and is one of the main reasons why most commonly available stoneware clay bodies are not suitable for cooking within the oven, let alone, on the burner.

## THERMAL SHOCK THEORY:

Thermal shock is the most important consideration when formulating a Flameware clay body. There are several physical properties of a material involved in the prediction as to whether or not it can withstand thermal shock but, of all, the only variable that can be controlled by the potter is thermal expansion. A common method of describing thermal expansion of a material is by calculating its Coefficient of Thermal Expansion (CTE) also known as the Alpha Coefficient of Thermal Expansion (ACE). The CTE is the distance that any material expands or contracts per unit of length (typically in inches) per one degree of temperature (typically in centigrade).

The CTE or ACE values are calculated to the $10^{-6}$ in./C decimal place which is the same as Parts Per Million (PPM). So, as you can see, the calculated values are extremely small but have a great effect on whether the clay body and glaze will survive the thermal shock of oven and stove top use. For a better understanding of CTE values the second edition of *Ceramic Science for the Potter* by W G Lawrence and R R West lists the CTE for what is described as ". . .some of the more shock resistant ceramic bodies. . ." along with their recommended values for ovenware and Flameware clay bodies. Figure 15-1 in the book shows a CTE value for stoneware as $4.5 \times 10^{-6}$ in./C or 4.5 PPM, ovenware as $3 \times 10^{-6}$ in./C or 3 PPM and Flameware as $2 \times 10^{-6}$ in./C or 2 PPM.

## CLAY BODY AND GLAZE DESIGN CONSIDERATIONS:

Based on the above discussion, the most important design formulation factors should be as follows:

- The reduction of Thermal Expansion of both the clay body and the glaze to as close to or lower than $2 \times 10^{-6}$ in./C should be the first priority.
- Emphasis on the fact that both the clay body and glaze must have a low enough thermal expansion in order to be successful.
- The elimination of cristobalite inversion in the clay body.
- If the addition of micro fine silica is eliminated from the clay body and a minimum of 10% feldspar is present then any additional silica being ejected from the clay matrix during the firing should melt as it is produced and eliminate this inversion phase.

The formulation of a low thermal expansion clay body and base glaze will require that both the clay body and glaze be low in silica and high in low thermal expansion material, such as Lithium, which is found in spodumene and petalite. The glaze should be matte and crystal-

*Figure 3: **The Orton 1600D Dilatometer with computer interface.***



line in nature which limits the use of computer software for their design since crystal formation is not quantitatively predictable. The use of a scientific instrument called a 'dilatometer' is the only instrument capable of measuring the percent of lineal change (PLC) and calculating the CTE in order to determine if both the clay body and glaze are correctly matched.

It should be noted here that PLC and CTE are of different calculated values. The dilatometer calculates and charts the PLC (Y-axis) as the temperature rises (x-axis).

The CTE is a calculated value through the use of the data developed by the dilatometers

**DILATOMETER CHART FOR TEST SAMPLES**
Flameware Clay Body 2F – ID 034 – File: EXP00034
Flameware Base Glaze #15 – ID 035 – File: EXP00035
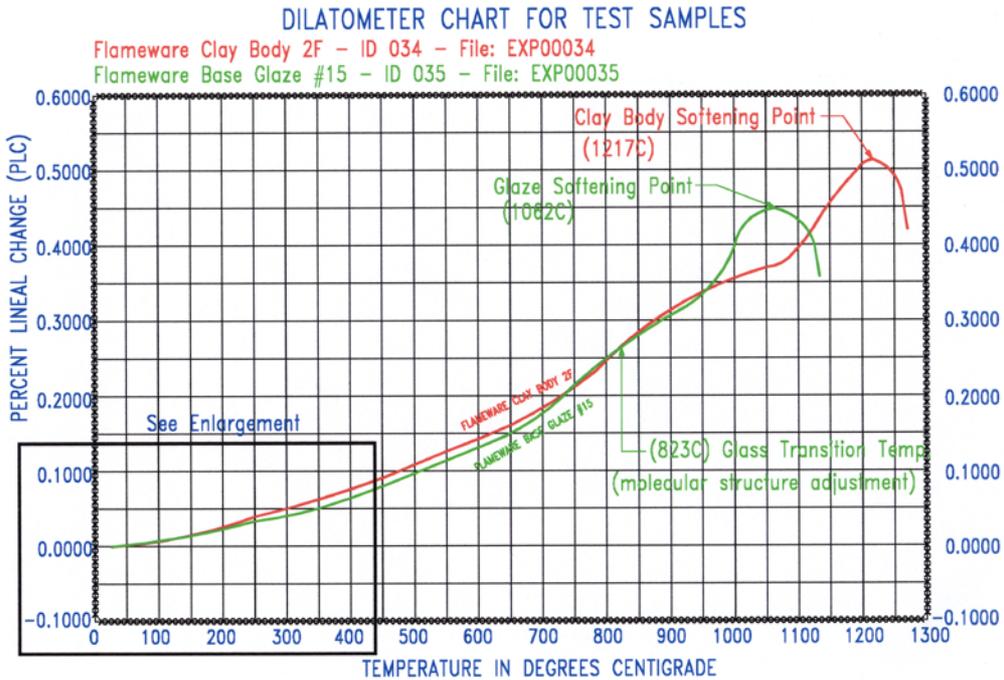
Fig 4: *Dilatometer Chart for Flameware Clay Body 2F and Glaze #15.*

experimental run. According to Ron Roy, the glaze line on the Dilatometer PLC chart should be slightly below the clay body line in order for the glaze to be in compression and prevent crazing. If the glaze line is above the clay body line then the glaze will be in tension and craze, if not immediately, then some time later. If the glaze line is too far below the clay line then you stand the chance of having the glaze 'shiver' off of the pot, either immediately or at some point in the future, depending on the PLC differences between the clay body and glaze. This is true for all clay bodies and glazes and not just Flameware.

Although quartz inversion is not a problem at oven and stove top temperatures, its elimination should be a natural function of a lower thermal expansion clay body. The final proof of the product will be in extensive repetitive heating and cooling testing on a stove top burner above the maximum cooking temperature being recommended for the ware.

Fig. 5: *Dilatometer Chart Area Enlargement for Flameware Clay Body 2F and Glaze #15.*
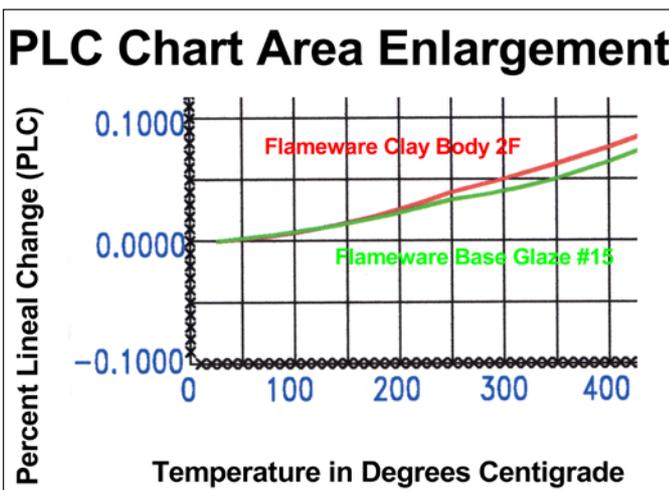


## OTHER CONSIDERATIONS

What will be the target firing temperature? Will the clay body retain its form at that temperature and will the glaze remain stable or will it run or pit? If clay body and glaze samples can be produced successfully and fired at the target firing temperature then dilatometer testing of these samples will show the 'softening point' of each material, which will aid the designer in determining if further formula adjustments are needed.

Is the clay body plastic enough for throwing on the potters wheel or will other forming methods be employed? Since bentonite has a

**Left table (Fig. 6)**

ID#: 034
Sample Name: Flameware Clay Body 2F
File: EXP00034

Run Date: 10/18/10
Run Time: 16:29
Operator: GJC

Sample Length: 1.000 in.
Atmosphere: Air
Temp. Range (deg C): 26 - 1270
Remarks: New Calibration Run Completed

Safety Shut-off: 0.10%
Shut-off Range (deg C): 1000 - 1300

Firing Schedule

| Rate (C/min) | Temp. (deg C) | Time (min) |
|---|---|---|
| 6.00 | 1300 | 0 |

| Temp. (deg C) | Time (min) | PLC | Alpha CTE (1E-6in/inC) | DCE (1E-6in/inC) |
|---|---|---|---|---|
| 26 | 33.07 | 0.0000 | | |
| 50 | 48.98 | -0.0008 | -0.32 | 2.07 |
| 100 | 68.98 | 0.0043 | 0.58 | 1.16 |
| 150 | 81.83 | 0.0148 | 1.19 | 2.05 |
| 200 | 91.29 | 0.0260 | 1.49 | 2.59 |
| 250 | 99.62 | 0.0394 | 1.76 | 3.32 |
| 300 | 107.95 | 0.0509 | 1.86 | 3.44 |
| 350 | 116.28 | 0.0628 | 1.94 | 2.37 |
| 400 | 124.63 | 0.0787 | 2.10 | 2.62 |
| 450 | 132.97 | 0.0934 | 2.20 | 3.07 |
| 500 | 141.33 | 0.1115 | 2.35 | 1.82 |
| 550 | 149.66 | 0.1274 | 2.43 | 2.60 |
| 600 | 157.99 | 0.1360 | 2.37 | 3.37 |
| 650 | 166.34 | 0.1621 | 2.60 | 4.03 |
| 700 | 174.69 | 0.1817 | 2.70 | 5.34 |
| 750 | 183.05 | 0.2202 | 3.04 | 7.42 |
| 800 | 191.38 | 0.2525 | 3.26 | 7.07 |
| 850 | 199.76 | 0.2836 | 3.44 | 3.73 |
| 900 | 208.14 | 0.3117 | 3.57 | 6.82 |
| 950 | 216.46 | 0.3319 | 3.59 | 3.14 |
| 1000 | 224.82 | 0.3533 | 3.63 | 4.45 |
| 1050 | 233.20 | 0.3690 | 3.60 | 0.95 |
| 1100 | 241.58 | 0.3958 | 3.69 | 11.57 |
| 1150 | 249.95 | 0.4655 | 4.14 | 10.70 |
| 1200 | 258.32 | 0.5089 | 4.33 | 5.72 |
| 1250 | 266.66 | 0.4896 | 4.00 | -18.66 |
| 1270 | 270.02 | 0.4193 | 3.37 | |

**Right table (Fig. 7)**

ORTON DILATOMETER MODEL 1600D

ID#: 035
Sample Name: Flameware Base Glaze 15
File: EXP00035

Run Date: 10/19/10
Run Time: 16:58
Operator: GJC

Sample Length: 1.000 in.
Atmosphere: Air
Temp. Range (deg C): 26 - 1133
Remarks: New Calibration Run being used

Safety Shut-off: 0.10%
Shut-off Range (deg C): 1000 - 1300

Firing Schedule

| Rate (C/min) | Temp. (deg C) | Time (min) |
|---|---|---|
| 6.00 | 1300 | 0 |

| Temp. (deg C) | Time (min) | PLC | Alpha CTE (1E-6in/inC) | DCE (1E-6in/inC) |
|---|---|---|---|---|
| 26 | 14.40 | 0.0000 | | |
| 50 | 30.00 | 0.0025 | 1.02 | 1.59 |
| 100 | 50.03 | 0.0056 | 0.76 | 0.83 |
| 150 | 62.87 | 0.0129 | 1.04 | 2.26 |
| 200 | 72.34 | 0.0233 | 1.34 | 2.26 |
| 250 | 80.67 | 0.0336 | 1.50 | 1.40 |
| 300 | 88.97 | 0.0405 | 1.48 | 3.49 |
| 350 | 97.33 | 0.0515 | 1.59 | 2.28 |
| 400 | 105.67 | 0.0642 | 1.72 | 2.19 |
| 450 | 114.01 | 0.0802 | 1.89 | 2.25 |
| 500 | 122.35 | 0.0980 | 2.07 | 2.20 |
| 550 | 130.69 | 0.1137 | 2.17 | 2.26 |
| 600 | 139.04 | 0.1238 | 2.16 | 3.28 |
| 650 | 147.38 | 0.1501 | 2.41 | 4.94 |
| 700 | 155.73 | 0.1767 | 2.62 | 7.41 |
| 750 | 164.10 | 0.2154 | 2.98 | 6.81 |
| 800 | 172.44 | 0.2483 | 3.21 | 7.70 |
| 850 | 180.79 | 0.2816 | 3.42 | 3.00 |
| 900 | 189.14 | 0.3049 | 3.49 | 5.86 |
| 950 | 197.52 | 0.3364 | 3.64 | 8.08 |
| 1000 | 205.87 | 0.3990 | 4.10 | 14.27 |
| 1050 | 214.24 | 0.4460 | 4.36 | 3.50 |
| 1100 | 222.59 | 0.4321 | 4.02 | -8.09 |
| 1133 | 228.12 | 0.3577 | 3.23 | |

*Left: Fig. 6: **Test Data from Dilatometer Run 034 for Flameware Clay Body 2F.***
*Right: Fig. 7: **Test Data from Dilatometer Run 035 for Flameware Base Glaze #35.***

high swell and shrinkage rate in a clay body when combined with water, in order to improve plasticity I prefer to use macaloid.

Well water and public utility water supplies contain minerals that will adversely affect the performance of Flameware clay bodies and glazes. Use only distilled water for mixing both the clay body and glazes. When 'throwing' on the potters wheel make sure that it has been thoroughly cleaned beforehand and that only distilled water is used in the slop bucket.

The finished ware should have an even wall thickness for an even thermal conductivity over the ware. Also, the thinner the wall thickness the smaller the temperature difference over the ware. Pots with a finished thickness after firing of approximately 3/16 inch or 5 mm appear to perform satisfactorily.

The design of your pots will be critical in order to reduce thermal stresses. Avoid sharp angles and footed bottoms on pots since those are places where high concentrations of stress will occur during heating.

Some low thermal expansion materials like spodumene undergo an irreversible expansion phase in the firing which will leave the ware more porous than desirable. In order to counteract this porosity problem at the desired firing temperature a combination of low expansion materials should be employed.

A low thermal expansion clay body will fuse itself to the kiln shelf during the firing unless some sort of separation material, such as a non-silica based kiln wash, is used. Also, the clay body will fuse to itself during the firing at the rims of lids so a bond-breaking material will need to be used around the rims of pots with lids. This material might be refractory fibre paper with a firing temperature rating higher than the firing temperature.

Along with testing for thermal expansion, testing should also be conducted for acid resistance, resistance to alkalis and testing for vitrification, at a minimum. See Chapter 3 of *Mastering Cone 6 Glazes* by John Hesselberth and Ron Roy for recommended testing procedures.

### FLAMEWARE CLAY BODY AND BASE GLAZE FORMULATION GUIDELINES

At present, the clay body and base glaze experiments that I have conducted have been for cone 9 to 10. Therefore, the guidelines to follow only apply to the experimentation that I have conducted thus far.

- Use at least 10% feldspar in the clay body and glaze.
- Do not add additional micro silica to the clay body or glaze.
- The silica to alumina ratio for both the clay body and glaze should be about 4.0 for a matte glaze.
- The percent (%) of Lithium (Li2O) for the clay body should be at 2.0% or greater with the glaze containing a slightly greater percentage.
- Do not add any additional iron to the formulas and use clays low in iron content.
- Use Macaloid as a plasticizer in the clay body. A plasticizer will certainly be needed.
- Use a 60 mesh screen for sieving the glaze to ensure that all of the ingredients pass through the mesh since Spodumene in particular will not all pass through a 100 mesh screen.

A Discussion of Experimental Data and Charts for Flameware Clay Body 2F and Base Glaze #15 Developed at Marrowstone Pottery

Clay Body 2F was the result of extensive experimentation through a progression of clay body formulations that culminated with the current design formula. Previous formulas using ingredients that contained high iron content influenced the colour response of the glazes in a negative way and were eventually abandoned. Also, the iron would sometimes burst through the glaze surface and pit the ware enough to make it defective. Another problem with all of the earlier clay body formulas was the porous nature of the clay after firing which tested out on the average to about 7.5 percent water absorption due to the use of spodumene as the only source of lithium in the clay body and glaze.

Clay Body 2F contains only low iron ingredients and a combination of low thermal expansion ingredients in order to achieve a tightly vitrified clay body with an average water absorption of .7 percent when fired to cone 9 and looks similar to a white stoneware clay body in the plastic form. Low expansion plasticizers have also been added in order to achieve a throwing clay quality.

The Dilatometer Chart with the PLC Chart Area Enlargement (figs. 4 and 5) is a compilation of clay and glaze test sample data from two dilatometer experimental runs. The chart clearly shows how closely matched the clay body is with the glaze from 26ºC to 400ºC which exceeds normal oven and stove top cooking temperatures. The clay body curve is in red and the glaze curve is in green. The chart shows the PLC value (Y-axis) as the temperature rises in degrees centigrade (X-axis). The data that follows (figs. 6 and 7) from these dilatometer runs shows that the average Alpha CTE for the clay body is $1.56 \times 10^{-6}$ in./C for temperatures between 100ºC to 400ºC. The average Alpha CTE for the glaze is $1.35 \times 10^{-6}$ in./C over the same temperature

Fig. 8: *Firing Schedule for Flameware Clay Body 2F and Glaze #15 on 7 August 2010.*
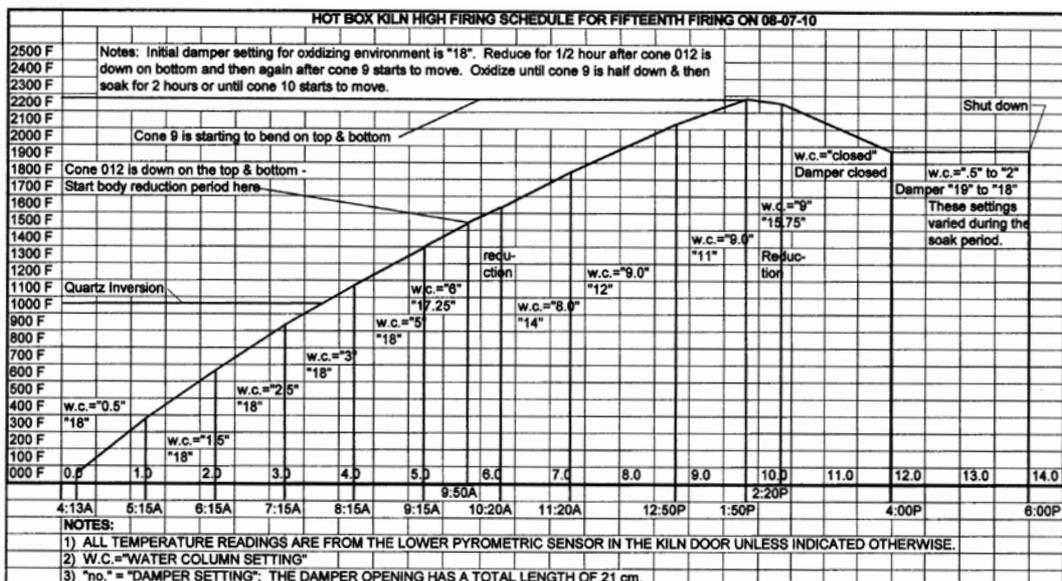
range. The Dilatometer CTE Data for both runs produced a typical anomaly at 50°C which has been ignored for purposes of the above analysis. The data also shows that for the temperature range of interest that the glaze curve falls slightly below the clay body curve which means that the glaze is in a slight compression. If the glaze curve were above the clay body curve then the glaze would be in tension and would most definitely craze.

Thermal Shock Testing of the test bowl shown in fig. 2 demonstrated that after 20 repetitions of heating it dry to 600°F (316°C) on a 15,000 btu burner on high heat and then plunging it into cold water with ice that there were no obvious defects seen on the glaze or clay body. Only long term testing and use, however, will show if problems develop.

The Water Absorption Tests for clay body 2F that follow the charts and data show that the clay body is fully vitrified and has a water absorption rate after two hours of boiling of only .7 percent, which is well below the 2 to 3 percent figure mentioned by Ron Roy in his coauthored book mentioned above.

The last chart shows the Firing Schedule (fig. 8) for the clay and glaze samples produced. The firing lasted approximately 14 hours, which included a two-hour soak period at the end of the firing. The downdraft kiln was initially kept in an oxidation atmosphere to slight reduction until cone 012 was touching down on top and bottom. The kiln was then put into a mild reduction for half an hour with the flame lapping out of the bottom spy hole by about one inch for body reduction. After that, the kiln was put back into an oxidation to neutral atmosphere until cone 9 started to bend on top and bottom. A glaze reduction period for another half hour followed. Cone 9 was touching down on top and bottom by the end of that reduction period and cone 10 was starting to bend. The burner pressure was reduced and the kiln was cooled to 1980°F (1082°C) and a two-hour soak period followed before the kiln was shut down for a three-day cooling period.

This firing schedule is not only used for Flameware pottery but is also a good schedule for stoneware. I have found that my glazes turn out brighter and without defects when there is a long soak period at the end of the firing and that the clay bodies deform less, especially the Flameware, when there is less than one quarter movement of cone 10.

As you can see from the Dilatometer Chart in fig. 4, the glaze is reaching the softening point much earlier than the clay body, which would have probably caused the glaze to run if not for its high alumina content and the fact that the glaze was applied thinly. Even though this glaze appears to be performing satisfactorily, I believe that further improvements are necessary to lower the thermal expansion a little further and to reduce the fluxes in order to extend the glaze softening point further to be able to apply the glaze thicker if desired. This will also change the soak temperature during the firing which should be greater than the glaze softening point in order to allow the glaze to smooth out and heal any pin holing which appears to be a problem with matte crystalline glazes of this type.

The chart also shows that both cristobalite inversion and quartz inversion are absent from the clay body curve. Along with the glaze adjustments mentioned above, it would also be interesting to perform testing of this glaze with a higher silica to alumina ratio using the guidelines established by Peter Sohngen in his article mentioned above under Cristobalite Inversion.

The Flameware clay samples were fired on 7 August, 2010, to a temperature of 2274°F (1246°C) as read on the pyrometer. Cone 9 was touching down on top and bottom and cone 10 had moved down about ¼ or to approximately two o'clock prior to the reduction and then soak period.

Two samples were tested. Both measured 4.7 cm x 9.3 cm x 1.2 cm in size. Sample #1 was not glazed on any side. Sample #2 was glazed on one side only. Both were heated on the burner to drive off any atmospheric moisture and quickly weighed for recording of their 'dry weight'. They were then left to cool down to room temperature before being placed in high boiling water on the stove top in a covered stainless steel container. Only distilled water was used for this experiment. The water continued to boil after placing the samples in it. The burner was then reduced to a medium boil for the next two hours. The distilled water placed in the stainless steel container was sufficient for the two hour time period so that additional water was not needed during that period of time, otherwise, the water would have been cooled down below the boiling point and the experiment would not have been accurate.

After the two hour period was completed, the container with the samples in it were taken to the sink and cooled down to room temperature by running cold water into the container. The samples were fully submerged in water during the cooling down procedure to prevent any water evaporation from the samples prior to weighing. The container with samples in water was then taken to the three-bar gram scale and each was taken out of the water separately, patted dry with a towel and immediately weighed for recording of their 'wet weight' reading. The formula for calculating the 'Percent of Water Absorption' is as follows:

[(wet wt. – dry wt.) / dry wt.] * 100 = percent of water absorption

Sample #1 = .69 percent and Sample #2 = .66 percent.

Any reading at or below 2 percent is assumed to indicate that the clay body is fully vitrified.

## Conclusion

Flameware clay body and glaze formulation will require that the reader either has or obtains (through study and experimentation preferably) a good understanding of the materials that make up a typical stoneware and porcelain clay body and glaze and has had experience in the preparation of clay bodies and glazes. The material preparation, ware formation, firing and finally the testing are all processes that are more demanding on the potter than for your typical stoneware or porcelain clay bodies and glazes. Dilatometer testing, along with the physical test procedures outlined in this article, is essential and the only path to the long-term success of your created product.

The pursuit of a successful Flameware clay body and base glaze is a passionate obsession for me. I feel that I am now close to the beginning of the journey. My hope is that this article stimulates a renewed interest, discussion and research in the subject by potters who are willing to follow a more rigorous scientific approach in order to achieve the end result.

"Success is a journey, not a destination. The doing is often more important than the outcome." Arthur Robert Ashe, Jr. 1943–1993.

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