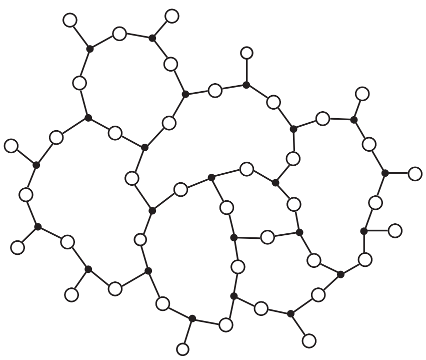
TECHNOTES 4

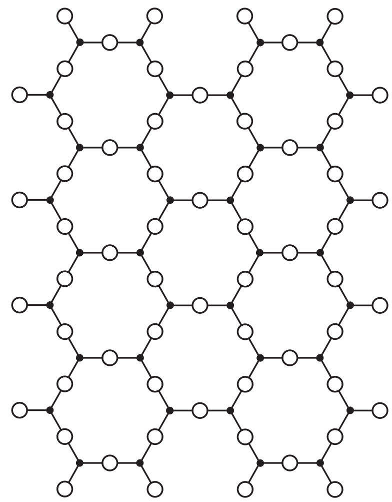
A Technical Supplement from Bullseye Glass Co.

Heat & Glass

Understanding the Effects of Temperature Variations on Bullseye Glass



Amorphous structure



Crystalline structure

THE UNIQUE NATURE OF GLASS, THE *SUPERCOOLED LIQUID*

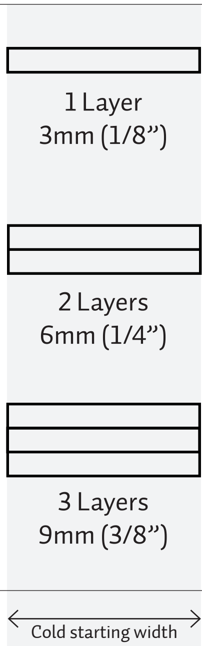
Glass is an *amorphous* material. Its molecules are not arranged in a regular, specific pattern, like those of a crystalline material, but are random in their configuration.

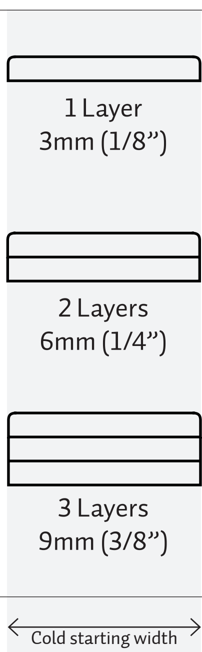
Because of its amorphous molecular configuration, glass reacts to heat differently than do other materials. Whereas metals change from a solid to a liquid at a specific temperature (a *melting point*), glass goes through a very gradual transformation—from a material that behaves like a solid to a material that behaves like a liquid. It is this unique characteristic of glass that allows it to be blown or to be worked in the myriad ways we call *kilnforming*.

Even in its solid form, glass exhibits the molecular structure of a stiff liquid. For this reason, glass at room temperature is sometimes referred to as a *supercooled liquid*. As it is heated, glass gradually begins to behave more and more like a liquid until, at temperatures above 2000°F (1093°C), it will flow easily, with a consistency similar to honey. The temperatures at which glass is worked in a kiln are usually between 1000–1700°F (538–927°C). Within this range, a wide variety of effects may be achieved by using a variety of processes.

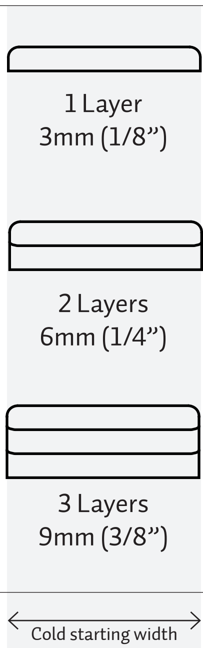
BEHAVIOR OF GLASS WHEN HEATED

The following chart gives a broad overview of how Bullseye glasses act in different temperature ranges. All Bullseye glasses do not behave identically. Some very slight variations can occur, depending on the viscosity of the individual glass. Furthermore, the specific kiln, set-up, and firing cycle used will have a direct impact on the results achieved at any given temperature.

Below 1000°F (538°C)	**WHAT YOU SEE**	**WHAT IS HAPPENING PHYSICALLY**	**KILNFORMING PROCESS**
	1 Layer: Rigid, no visible changes, edges sharp. 2 & 3 Layers: Same as above.	Glass expanding or contracting at a rate determined by its *coefficient of expansion*. Subject to *thermal shock* below approximately 850°F (454°C).	Upper end of this range is where *annealing* occurs, at the *anneal* soak temperature of 900°F (482°C).

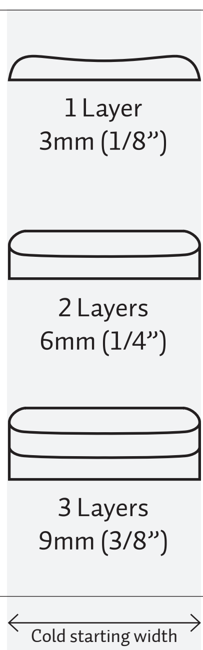
1000°–1250°F (538°–677°C)	**WHAT YOU SEE**	**WHAT IS HAPPENING PHYSICALLY**	**KILNFORMING PROCESS**
	At upper end of range: 1 Layer: Edges just begin to soften and round. 2 & 3 Layers: (Same as above.) Layers will not stick together unless held for a long time.	Glass is beginning to soften and act like a stiff liquid, but still maintains its original shape. Glass is transitioning from behaving like a solid to behaving like a liquid; also known as the *transformation range*.	Most *painting* or *enameling* is done at these temperatures. Bullseye glass will *bend* or *slump* if held at the upper end of range. A soak in the 1150°–1250°F (621°–677°C) range is often employed to remove air from between layers, which reduces the number and size of bubbles in the finished piece.

1250°–1350°F (677°–732°C)

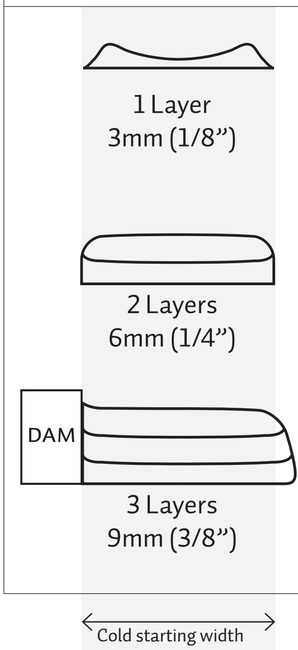


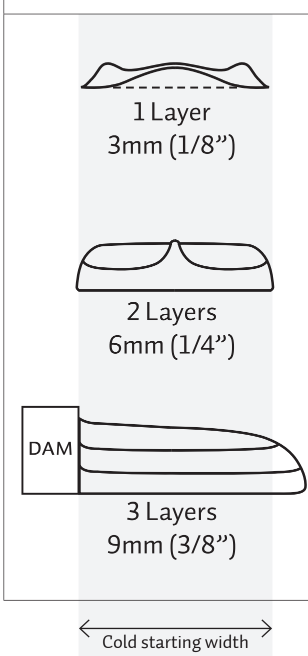
WHAT YOU SEE	WHAT IS HAPPENING PHYSICALLY	KILNFORMING PROCESS
1 Layer: Edges of glass slightly rounded, surface begins to look glossy. 2 & 3 Layers: (Same as above.) Layers appear to be sticking together.	If held at the top end of this range too long, crystals may grow: *devitrification*.	*Fire polishing*, the removal of fine abrasions on the glass surface, can be accomplished. Glass begins to sag fully at upper end of range. Glass surfaces will stick together, called *sintering* or *tack fusing*.

1350°–1400°F (732°–760°C)

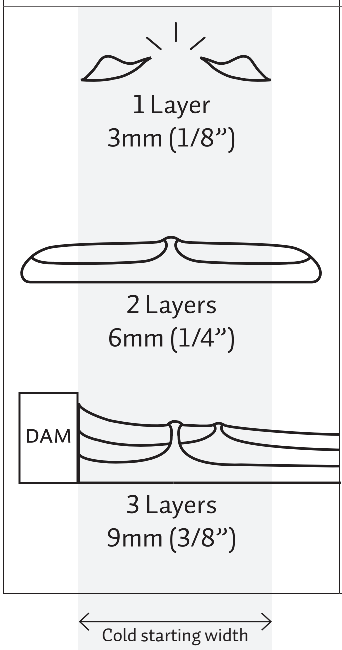


WHAT YOU SEE	WHAT IS HAPPENING PHYSICALLY	KILNFORMING PROCESS
1 Layer: Starts to contract and bead up at edges. 2 & 3 Layers: Layers are stuck together, upper edges rounded; footprint of glass remains constant.	Surface tension is overcoming gravity. *Devitrification* may occur.	Glasses stick together with edges rounded, called *tack fusing*.

1400°–1500°F (760°–816°C)	**WHAT YOU SEE**	**WHAT IS HAPPENING PHYSICALLY**	**KILNFORMING PROCESS**
	1 Layer: Center of piece may become extremely thin as perimeter thickens and *needlepoints*. 2 & 3 Layers: Layers fully fused at upper end of range. Glass begins to move beyond original footprint unless constrained by dams or molds.	At upper end of range, gravity begins to overtake surface tension. Any air trapped between glass and shelf or between layers will expand.	At the lower end of the range, *tack-fusing*. At the upper end of the range, *full fusing* or *kilncarving* with fiber paper.

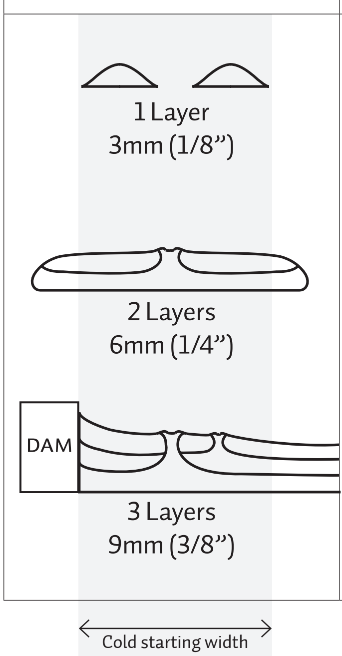
1500°–1600°F (816°–871°C)	**WHAT YOU SEE**	**WHAT IS PHYSICALLY HAPPENING**	**KILNFORMING PROCESS**
	1 Layer: Air trapped between the thin center of the glass and the top surface of the shelf may rise up and form a bubble. 2 & 3 Layers: Surface smooth and watery, bubbles within glass or trapped between layers may rise to surface. Unless contained, glass will flow freely until it reaches 6mm (1/4") thickness.	Viscosity continues to decrease, allowing glass to flow under the force of gravity. Glass also becomes more reactive with materials with which it is in contact. At the upper end of the range, glass sticks more readily to shelf separators and mold materials, and compatibility characteristics may begin to change.	*Full fusing* or *kilncasting*. At upper end of range, glass is flowing sufficiently to fill small cracks in molds.

1600°–1700°F (871°–927°C)



WHAT YOU SEE	WHAT IS HAPPENING PHYSICALLY	KILNFORMING PROCESS
1 Layer: Bubble will burst, leaving crater. 2 & 3 Layers: Glass is flowing like molasses. Glass may flow off edge of shelf. Must be constrained by molds or dams. Bubbles rising from lower layers will pull lower glass up to surface.	Viscosity continues to decrease, and flow is increased.	Glass is fluid enough to perform *combing* with wet metal rod, and *kilncasting*.

Above 1700°F (927°C)



WHAT YOU SEE	WHAT IS PHYSICALLY HAPPENING	KILNFORMING PROCESS
1 Layer: Crater fully opened. 2 & 3 Layers: *Boiling* type of activity continues.	Viscosity continues to decrease.	*Kilncasting* with a plugged crucible/reservoir that is unplugged to allow the glass to flow, once it is fully molten.

GOALS OF A FIRING SCHEDULE

Understanding the behavior of glass within different temperature ranges allows you to create a *firing schedule* or series of steps that will properly heat and cool glass in a kiln. Using a firing schedule, you can accomplish the two basic objectives of kilnforming, which are:

- To bring the glass body to a temperature where it can be formed in the manner or process selected.
- To return the glass to room temperature in a stable condition (i.e., free of unwanted internal stress).

A firing schedule (sometimes called a *firing cycle* or *firing profile*) may be subdivided in various ways.
At Bullseye, we generally break the firing schedule down into the following eight stages:

1. INITIAL HEAT ROOM TEMP TO 1000°F (538°C)
Until glass reaches a temperature of about 850°F (454°C), it can shatter (undergo *thermal shock*), if heated too quickly or unevenly. Because the glass is always cooler than the thermocouple during initial heat, we extend the initial heating range to 1000°F (538°C) to make sure the glass is at least at 850°F (454°C) before moving to rapid heat. There are no negative consequences to heating too slowly in this range, other than lost production efficiencies. Therefore, at Bullseye, we are generally very conservative in our heating rate for first firings: ~400°F/hr (222°C/hr).

The smaller the individual pieces making up the project, the faster the initial heating can be.

2. PRE-RAPID HEAT SOAK 1000°–1250°F (538°–677°C)
This optional-but-useful stage in the cycle, in which the glass is held at a specific temperature, is designed to even out the temperature within the glass body before the rapid ascent to process temperature, to allow for a faster ascent, and, in some cases, to *squeeze* air from between layers or within any gaps in the interior lay-up. A pre-rapid heat soak at ~1225°F (663°C) is required for a gold-bearing striking glass to achieve its target color.

3. RAPID HEAT
1000°F (538°C) TO FORMING / PROCESS TEMP
The primary objective in this temperature range is to move as quickly as possible to the process temperature so as to avoid *devitrification* (growth of crystals on the glass surface), but not to fire so rapidly as to cause bubbles to be trapped between layers.

4. PROCESS SOAK 1000°–1700°F (538°–927°C)
This is the temperature range at which glass can be formed by using various processes, such as slumping, tack fusing, full fusing, or kilncasting. The same effects or processes can be accomplished whether firing to a lower temperature for a longer time or to a higher temperature for a shorter time. This interplay between firing temperature and firing duration is the basis of *heat work*. In general, one has greater control with a longer process soak at a lower temperature, as long as this temperature is not within the devitrification range. At Bullseye, we soak for an average of 10 minutes at process temperature for most basic firings.

5. RAPID COOL PROCESS TEMP TO 900°F (482°C)
Glass should be brought down to the anneal-soak temperature as quickly as possible, once it has been formed, to avoid devitrification and save unnecessary cooling time. However, Bullseye does not recommend opening the kiln widely to vent at these temperatures. Opening to vent can set up a temperature differential within the glass body that will necessitate increased time at a lower temperature to bring back temperature equilibrium.

Rather than opening the kiln to vent, we recommend allowing the kiln to cool at its own rate (which will vary based on the kiln-wall insulation and mass of material in the kiln), to about 900°F (482°C).

6. ANNEAL SOAK 900°F (482°C)
As glass heats, it expands; as it cools, it contracts. These processes set up stresses within glass, especially between the interior and the surface of a glass body. To relieve these stresses, which can lead to strain or breakage at room temperatures, it is necessary to cool glass in a very controlled manner, through a predetermined temperature gradient. This controlled process for cooling glass is called *annealing*.

The first phase of the annealing process is the anneal soak, which should help to equalize the temperature throughout the glass and relieve any stress that is present.

We soak Bullseye glasses at 900°F (482°C). The duration of the soak at this temperature depends upon both the thickness of the glass and how it is set up in the kiln. The goal is to achieve uniform temperature throughout the body of the glass.

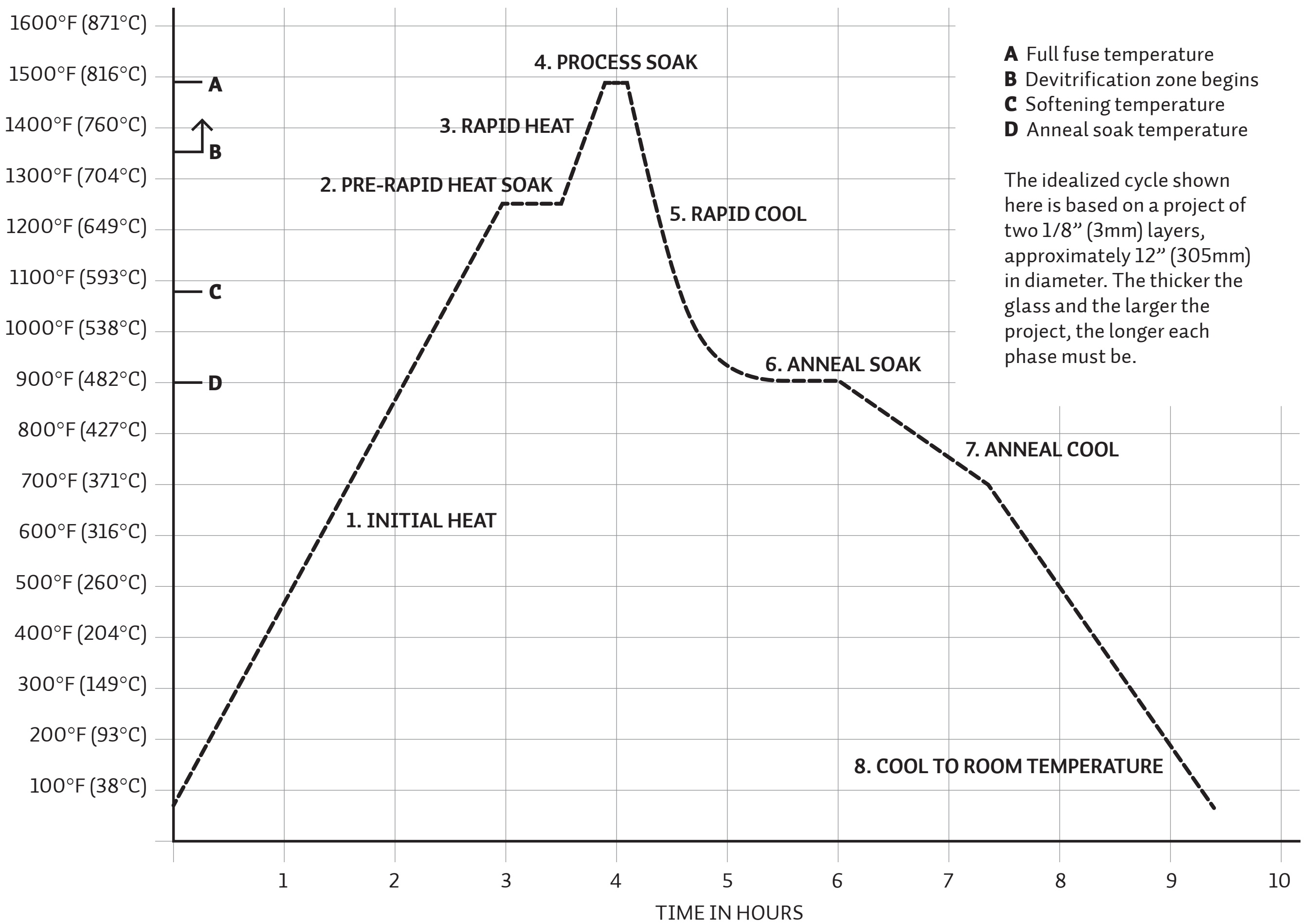
7. ANNEAL COOL 900°–700°F (482°–371°C)
Once the temperature within the glass body has become uniform during the anneal soak, it is gradually cooled through the rest of the annealing range. The rate of cooling required depends upon both the thickness (and variations in the thickness) of the glass and how it is set up in the kiln. The goal is to keep the temperature difference throughout the body of glass to within 10°F (5°C) from 900°–800°F (482°–427°C), and within 20°F (11°C) from 800°–700°F (427°–371°C).

8. FINAL COOL TO ROOM TEMPERATURE
700°–80°F (371°–27°C)
Cooling to room temperature can be accomplished as quickly as possible, as long as the rate is not so rapid as to cause thermal shock.

In the Bullseye studio, for most firings of moderately-sized pieces of even 1/4" (6 mm) thickness, we allow the kiln to cool at its own rate, with the door closed, until the interior

IDEALIZED FIRING GRAPH

Shown on a time/temperature firing graph, the eight firing stages might look like this:



reaches about 200°F (93°C) or lower. Then the door is opened, allowing the glass piece to cool down until it can be handled with bare hands. For thicker work and works with variation in thickness, we keep the kiln door closed until the interior has reached room temperature.

THE ANTI-SUCKER PROCESS

Sometimes, fully three-dimensional pieces, such as those made in the lost-wax casting process, will come out of the mold with depressions or wrinkles that were not present in the original model. Such areas, called *suckers*, will appear to have taken on detail from the mold and shrunken away from it or *sucked-in*. Suckers can form during the cooling process, while the glass is shrinking or contracting in general. Hot glass has a lower viscosity than cold glass and, therefore, may become the focal point of shrinkage for the entire piece. If the entire piece of glass cools and contracts uniformly while it is in its plastic state, no suckers will form. However, suckers may form if there are thicker areas in the piece or areas that are likely to stay hot longer than other areas during the cooling process.

At Bullseye, we have found that suckers can usually be prevented through a series of processes. 1) Soaking/holding the glass at around 1250°F (677°C) during the rapid cooling stage to unify the temperature throughout the glass. 2) Cooling the glass as uniformly as possible from this point to the anneal soak temperature. 3) Incorporating a large reservoir into the casting that will remain full enough to be the thickest part of the casting and, therefore, the last area of the piece to cool off. It may be necessary to cover this reservoir with refractory fiber blanket to keep it from cooling too quickly. After firing, such a reservoir will have a concave meniscus that otherwise would have appeared as a sucker elsewhere on the body of the casting.

KILNFORMING PROCESS TEMPERATURES

PROCESS	TEMPERATURE RANGE	
Combing/Boiling	1600–1700°F	871–927°C
Kilncasting	1500–1600°F	816–871°C
Full fuse	1480–1550°F	804–843°C
Kilncarving (bas relief)	1500–1550°F	816–843°C
Strip technique	1470–1550°F	799–843°C
Tack fuse (edges soften slightly)	1290–1435°F	699–779°C
Sagging (cross section changes)	1255–1350°F	679–732°C
Fuse-to-stick (sintering)	1255–1330°F	679–721°C
Slumping (no thickness change)	1100–1300°F	593–704°C
Painting	1000–1250°F	538–677°C

PRACTICAL APPLICATION

It is important to keep in mind that firing schedules are only one part of the total firing story. While it is fine to solicit or share firing schedules, they should be treated only as points of departure because they constitute just one of many conditions and variables that can affect the outcome of a glass project. For instance, every kiln fires a little differently, and this is true even for two kilns of the same model. Other factors include, but are not limited to: the type of glass, the type and placement of the shelf in the kiln, the type and location of the thermocouple, and whether the piece is being fired for the first, second, or third time.

In the Bullseye Research and Education studio we take a fairly conservative approach to most firings. The following schedules are typical for the cycles we use for many projects. In each case, it should be fairly clear how the firing theory from previous pages applies to these real schedules.

SCHEDULE 1

First full-fuse firing of a 12" (305 mm) diameter piece, composed of two layers of 3 mm (1/8") "-0030" glass in a Paragon GL24 with top, side, and door elements:

STEP	RATE (DPH)		TEMPERATURE		HOLD
1. Initial heat Pre-rapid heat soak	400°F	222°C	1250°F	677°C	:30
2. Rapid heat Process soak	600°F	333°C	1490°F	810°C	:10
3. Rapid cool Anneal soak	AFAP*		900°F	482°C	:30
4. Anneal cool	150°F	83°C	700°F	371°C	:00
5. Final cool	AFAP*		70°F	21°C	:00

SCHEDULE 2

Slumping schedule for the same piece. See notes.

STEP	RATE (DPH)		TEMPERATURE		HOLD
1. Initial heat Process soak	300°F	166°C	1180°F	638°C	:10
2. Rapid cool Anneal soak	AFAP*		900°F	482°C	1:00
3. Anneal cool	100°F	55°C	700°F	371°C	:00
4. Final cool	AFAP*		70°F	21°C	:00

SCHEDULE 3

First tack-fuse firing of a piece composed of one layer of 4mm base glass and an application of frits and powders. See notes.

STEP	RATE (DPH)		TEMPERATURE		HOLD
1. Initial heat Process soak	600°F	333°C	1275–1450°F	691–788°C	:10
2. Rapid cool Anneal soak	AFAP*		900°F	482°C	1:00
3. Anneal cool	100°F	55°C	700°F	371°C	:00
4. Final cool	AFAP*		70°F	21°C	:00

* *As Fast As Possible* will be whatever cooling rate results from the kiln power being cut off by the controller. We do not advocate crash cooling. Rather, we advocate leaving the kiln closed, allowing it to cool naturally to the next temperature.

FIRING NOTES FOR SCHEDULE 2

- Notice that the initial heat for this schedule is more conservative than that recommended for schedule 1. This is because the piece being heated is now one solid, thicker piece of glass, which should be fired more slowly to ensure that it will heat evenly throughout.
- Notice that there is no pre-rapid heat soak in this schedule. This is because the piece in question has already been fused together, and there is no opportunity to remove air from between layers of glass, as there was in the initial firing.
- Slumping temperatures and hold times vary widely, depending upon the type and design of the mold, the glasses being slumped, and the desired effect. Slumping should always be confirmed visually.
- Because the slumped piece will be in contact with a mold that will have some thermal mass and may not be of a completely uniform thickness, and because a slumped piece will tend to cool unevenly, both the anneal soak and the anneal cool should be more conservative than they would be for pieces of comparable thickness that were merely flat fused.

FIRING NOTES FOR SCHEDULE 3

- The initial rate of heat for a single layer of glass with an application of frits and powders in a first firing is often faster than that used for two or more layers of glass. In practical application, such faster firing rarely presents a problem. In theory, however, such a piece could be more difficult to heat evenly if it is a less uniform arrangement of material than a piece made of even layers of sheet glass.
- Notice that there is no pre-rapid heat soak in this schedule. This is because the piece in question is composed of one layer of sheet glass with frits added on top. There are no top layers in this piece under which air could be trapped, as there were for the project described in Schedule 1.
- Process temperatures for tack-fused pieces depend upon the desired effect as well as the forms and colors of the glasses in question. Black powder (000100-0008), for example, will begin to fuse at a much lower temperature than White coarse frit (000113-0003).
- Notice that the anneal-cool stage for the tack-fused piece is more conservative than that proposed for the thicker, fully fused piece from Schedule 1. This is because tack-fused pieces tend to cool unevenly and should, therefore, be cooled more slowly to compensate.