Understanding Firing Schedules

Learn about the components of a glass firing schedule so you can create your own schedule for any project you want to try.

BASICS – Ramp - Temperature - Hold
HEATWORK – Time/Temperature Tango.
COE – how it affects firing schedules.
VISCOSITY – how it affects firing schedules.
THICKNESS– how it affects firing schedules
PREDICTION - ending accidents.
ANNEALING – how and why
EVENIVITY– the magic word.
VOLUME CONTROL
SPECIAL SCHEDULES for special effects.

My Personal Promise

The temperatures and times I refer to here for firing schedules are not guesswork and are not copied from comments of others. There are the result of 40 years working as a glass artisan and over 20,000 kiln firings. I made it a point to do comparison tests to rigid standard. Some of those tests are included in chapters here.

Dennis Brady
Glass Campus Publishing

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Understanding Firing Schedules

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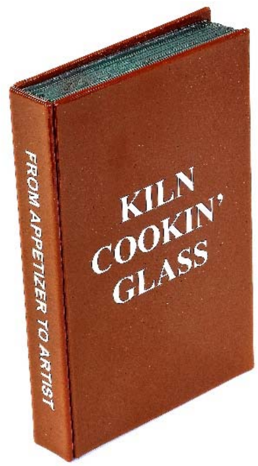
Introduction



What happens to glass when fired in a kiln depends directly on the firing schedule. When you first learn to fuse and cast glass, you start by using firing schedules created by others. Just like when you first learn to cook you start by using recipes developed by others and published in cook books. As you expand your skills and want to experiment with new ideas and techniques you might want to learn how to create your own custom firing schedules. You might want to create a recipe that isn't in any book.

You might at first think firing schedules are too complicated and too difficult for you to create your own. Not so. When you understand the components of firing schedules and how each part of a schedule affects what happens to the glass you will be able to create a specific schedule to produce any result you want.

Just take baby steps. Break it down into the elements. There can be many segments in a firing schedule but each segment consists of only three elements.

> **Ramp** – the speed at which temperatures rises or falls.
> **Temperature** – the temperature you take the glass to.
> **Hold** – how long you stay at that temperature.

Each of those elements has a purpose. It's often easy to compare firing schedules to cooking recipes. When someone asks, "How long does it take to cook a roast, the first answer is "It depends". It depends on how big the roast is and how well you want it cooked. It's the same with glass. How thick is it and how well do you want it cooked.

I hope this guide will convince more people to put more effort into understanding the elements of firings schedules so they can create a firing schedules for any project they want to try and not rely so much on asking other for a firing schedule.

Attitude

Different people have different motivations. Some individuals take a glass art class to learn a technique so they can use that technique to make projects later. Others want only to make a project to take home. It's the same with glass firing schedules. Not everyone has the same desire to understand them. Some want to learn all the steps and stages and what each is for so they can create their own personal custom firing schedules for anything they might want to try. They want to know how things happen and why they happen. Others have no interest in how and why. They just want someone to provide a schedule for whatever it is they want to make. It's like cooking. Some individuals want to understand how food responds to heat in different ways and experiment to new ways to cook. Others just want to be provide a list of recipes to work with.

I once had a student I was trying to teach the elements of firing schedules tell me,

I don't' care about the science stuff. I just want to make art.

This guide is being created specifically for those of you that want to understand all the hows and whys and what ifs - but for those that don't care about that and want only a "cook book" list of firing schedules, a collection of specific schedules is included at the end of the book.

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Understanding COE

What is COE?

COE means “Coefficient of Expansion”. It’s the measure of how much glass expands when it’s heated and how much it contracts when cooled. A higher number COE glass expands more than a lower number COE. Some of the most common COE glass used for glass art are:

COE 104	Moretti & Effretre
COE 96	Used for fusing and the most common choice for glass blowing
COE 90	Used for fusing. Also the most common COE of bottle glass.
COE 82	Float glass made for windows.
COE 33	Borosilicate glass

What determines COE?

The COE of any glass is not accidental. Every material has a COE. Glass is made by melting together a mix different materials. Each of those materials has a COE. The COE of the finished glass is determined by an average based on the percentage of each material in the mix. Glass makers can create different specific COE glass by altering the ingredient mix. If one of the ingredients has a higher COE than is wanted in the finished glass art, the glass maker can use less of that material and more of something with a lower COE to create glass of the desired COE.

Why is COE important?

COE doesn’t matter in stained glass but is extremely important in fusing, torchworking and furnace work.. If different glass is melted together and isn’t the same COE it will refuse to fuse. You must take special care to be sure all the glass you use is matching COE. Both COE 90 and COE 96 glass are made specially for fusing, they will not fuse to each other.

How does COE relate to firing temperature?

The higher the number COE the lower the temperature it softens at.

COE 96 glass tack fuse 1350°F (732°C)
COE 90 glass tack fuse 1370°F (743°C)
COE 82 glass tack fuse 1425°F (775°C)

Why identity glass only by COE?

Many people have asked, "Why refer to COE when viscosity and other factors also contribute to compatibility?" Because it's a convenient and effective way to begin the explanation of why some glass is fuse compatible to other glass and some glass is not compatible. When glass makers first started making glass that was made to a higher standard and factory tested to be trusted to fuse to other glass they needed to explain to glass artisans why there was a difference and why not all glass could be trusted to fuse together. Explaining COE was a good place to start. It provided a number as a guide. Borosilicate glass is COE 33. Float glass is COE 82. Bullseye glass is COE 90. Spectrum Glass is COE 96. Glass of a different number COE is not compatible. Viscosity is as important as COE but explaining that could come later. Start by explaining COE. It's enough to start the lesson of why not all glass can be fused together.

Some people want to understand more about the chemistry of glass and the science that explains how glass responds to heat and what makes glass compatible to other glass. Many others don't care. They just want to learn enough to use the glass to produce successful fuse firings in their kiln. To start, it's enough for them to know to use only glass that is marked "Tested Compatible" from the same glass maker and of the same COE. Some glass makers don't just make glass of one COE but make both 90 and 96. It's important to use only "Tested Compatible" glass but equally important to use only glass that is marked the same COE. Uroborus Glass made both COE 90 and COE 96 glass. So does Wissmach Assuming all glass from the same glass maker would be compatible is wrong. COE 90 glass is not compatible with COE 96 glass even if from the same glass maker.

Also, many artisans have tested and confirmed that glass of the same COE made by different glass makers is fuse compatible and they routinely mix glass from different manufacturers. As have thousands of other artisans, I have fused Bullseye 90 with Uroborus 90 and fused Spectrum 96 with Wissmach 96. COE is not the only factor that determines if glass is fuse compatible but it is a good place to start. A simple guideline that will help you understand COE.

- **Glass of different COE will not be compatible.**
- **Glass of matching COE might be compatible but might not be.**

It's important to teach artisans the importance of viscosity in glass compatibility but don't forget that COE is equally important and is still the best way to begin teaching why some glass is compatible and some is not.

Viscosity

Viscosity is how liquid a material is. How easily it flows and at what temperature it softens. Water has a lower viscosity than oil so flows more easily. Not all glass has the same viscosity. Just as different COE can make glass incompatible, so can different viscosity. Glass might be the same COE but have enough different viscosity to be incompatible. If pieces of glass in contact with each other have a different viscosity one will be less liquid than the other and will resist melting into the more liquid glass.

For example, Gaffer Glass is the same COE 96 as the “Systems 96” glass made for fusing but has a significantly lower viscosity so is not compatible to fuse to the “Systems 96” glass. That does not mean the viscosity must be a perfect match. Wissmach Glass makes a COE 96 glass that is a lower viscosity than “Systems 96” glass but the difference is so little it can be reliably fused to it by compensating for the difference with slightly slower ramp speeds.

Even with glass factory tested as compatible viscosity difference can be a problem. In projects using both black and white glass the black glass has a lower viscosity than the white glass. It melts at a lower temperature and becomes more liquid. This can be a special problem if you fire a project that has black glass pressing against white glass. You will need to adapt your firing schedule to allow for this difference. As your project heats up, the black glass will expand and soften while the white glass is still firm. As your project cools down, the black glass will contract and harden while the white glass is still soft. The viscosity difference causing the different colors of glass to expand and contract at different rates can cause your project to crack. Too allow for the viscosity difference you should reduce the ramp speeds up and down to slow the different rates of expansion and contraction.

Why does it matter?

High viscosity glass resists flowing so requires either higher temperature or long hold time than low viscosity glass. You must consider that when creating firing schedules.

Compatibility

Most glass fusing today evolved from stained glass artisans experimenting with ways to use the cut off scraps from making lamps and windows. Most of their kiln firings were tests to learn what glass will successfully fuse to other glass. Multiple failures taught them that not all glass is compatible. Recognizing an interest in fusing glass, glass makers responded by making glass specially for fusing. They produced it to a careful formula and factory tested it for compatibility. The key there is “factory tested”. Glass that was tested and passed the test was labeled “Tested Compatible”. That ended the need for artisans to do all their own tests. Just buy only glass labeled “Tested Compatible” from the glass maker and they were free to intermix different colors to fuse together. Probably the two most significant contributions to interest in fusing glass was the factory tested glass and the electronic controllers that ended the need to babysit your kiln. Although COE is still used as a guide to fuse compatibility it is wrong to assume it is the only factor that determines compatibility. COE matters but viscosity matters just as much. COE determines how much glass expands when it's heated. Viscosity determines how fast it expands and how liquid it becomes when heated. Glass of the same COE can have such different viscosity it is incompatible.

It's about balance

Compatibility of different glass is not determined by just COE or by just viscosity. It’s determined by the balance between the two. The only glass that is perfectly compatible is pieces of glass from the same original sheet. For fusing purposes, the glass you use need not be perfectly compatible but only compatible enough to contain the stress from any difference in COE or viscosity. Sometimes close is good enough.

Pretest for compatibility

Unless you have deep enough pockets to afford very expensive equipment, there is no way to test glass before fusing for compatibility. You have 3 options.

- Use only glass from a specific glass maker that is labeled "Tested Compatible"
- Fire samples onto a reliable standard glass (usually fusible clear) and test after firing to confirm it was a compatible fuse.
- Lucky lottery method. Hope to get lucky. Pray to the kiln gods (sacrificing a chicken on the BBQ helps) to make sure all your glass is compatible.

After fusing test for compatibility

- **Freezer test** – Wrap the project in tissue or paper towel and put it in the freezer for two or more hours. Remove it from the freezer, unwrap it and allow to thaw. Thawing will encourage incompatible fused glass to crack.
- **Polarized lens** – Hold the project sandwiched between two pieces of polarized film. Incompatibility will exhibit as a halo around the incompatible glass. Polarized film is inexpensive and easy to find. If you don’t have polarized film you can pop the lens out of a pair of polarized sunglasses to do your test.

Self compatible glass

All glass is compatible to itself. While you cannot trust a piece of glass from one sheet of glass to be compatible to a piece from a different sheet of glass you can trust it to be compatible to a piece from the same original sheet. That applies to all glass – especially if you want to work with art glass or float glass. It doesn't mean pieces from different sheets will not be compatible. It just means you cannot safety assume they will be. If you want to work with art glass or with float glass, it's only fully safe if you only fuse together pieces that came from the same sheet or from the same production batch. Some glass artisans that use a lot of float glass buy it in full cases to be sure they have a large supply of reliably compatible glass.

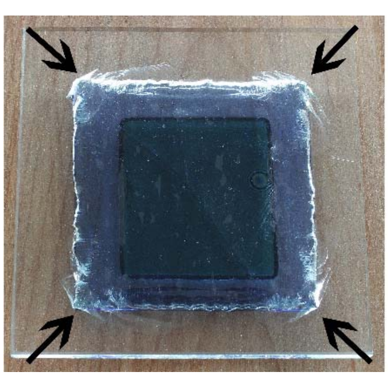
Compatibility failure

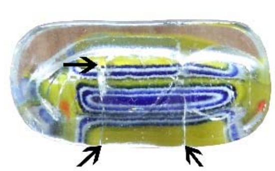
Glass projects cracking because bits of glass were fused together that are not fuse compatible is a huge concern for artisans fusing or casting glass. It's especially a concern because it doesn't always happen right away. Most of the time it happens in the kiln during the firing or as soon as the project is removed from the kiln but sometimes it happens later. Sometimes days later or even months later. You might have a treasured piece on display on a shelf and "some ting" happens. The "ting" is the sound glass makes when it cracks. Sometimes it doesn't just ting but explodes when the stress built up in the glass is released.

Identifying incompatibility cracks

Fusing incompatible glass can cause your project to crack but so can many other things. Some things to check to identify what most likely caused your project to crack.

- **Incompatible glass** – The glass cracked around or across a specific piece of glass.
- **Thermal Shock** – Heating glass too fast or cooling it too fast can cause it to crack. If the break has rounded edges, it broke while heating up. If the break has sharp edges, it likely broke after fusing and while cooling but that would apply only if it had been heated to at least tack fuse. A project fired only to slump or drape temperature could have cracked while heating up and still have sharp edges.
- **Inadequate anneal** – Annealing relieves stress creating during the kiln firing.
- **Uneven heat distribution** – Molds with uneven thickness (thicker in some parts than other parts) will experience uneven heat distribution and uneven annealing in the glass. That's why molds made from slip cast ceramic are so much more trustworthy than those made from sculpted clay.





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Kilnforming Definitions

Miscommunication is often a result of not understanding terms or definitions. It's a good practice to avoid technical jargon wherever possible but it's near impossible to explain glass firing schedules if you don't understand the terms commonly used to describe different fusing processes.

Casting – Melting glass into a mold to adopt the pattern in the mold.

Drape - Placing glass over a convex shaped mold or object and heating it until it is soft enough to bend over the mold.

Slump - Placing glass onto a concave shaped mold like a bowl and heating it until it is soft enough to bend into the mold.

Fire Polish - Heating glass until a thin surface of the glass melts enough to produce a shine like wet paint.

Sinter - Heating glass until it begins to soften and bonds together but not yet soft enough to form a reliable fuse.

Tack Fuse - Heating until surfaces in contact with each other have softened enough the pieces of glass touching each other fully bond together.

Contour Fuse - Heating glass past tack fuse temperature but not yet full fuse temperature so the glass fully bonds and begins to flow but not enough to flow to a common level. A contour fuse is usually considered to be halfway between a tack fuse and a full fuse.

Full Fuse - Heating glass to the temperature it fully melts and flows to a uniform level.

Anneal - Holding the glass at a fixed temperature long enough to relieve the stress created by heating and cooling.

Fusing Temperatures (for COE 96 glass)

Drape	1200°F (650°C)
Slump	1250°F (675°C)
Fire Polish	1300°F (705°C)
Sinter	1325°F (718°C)
Tack Fuse	1350°F (732°C)
Contour Fuse	1400°F (760°C)
Full Fuse	1450°F (788°C)

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Ramp

Ramp Speed

Ramp speed is the rate at which temperature is increased or decreased. It is usually shown as degrees per hour. Controlling ramp speed is important to avoid cracking the glass. When glass is heated it expands. When it cools it contracts. If you increase temperature too fast the outside of the glass is heated and expanding as it softens but the inside of the glass is still hard and cool. The pressure created between the warm outside and the cooler inside can cause the glass to crack. The opposite happens when you cool the glass too fast. The outside of the glass is contracting and hardening as it cools while the inside of the glass is still warm and soft. How fast you can safely increase or decrease temperature depends on the total thickness of the glass.

Thickness variance

To determine how fast it is safe to increase and decrease temperature you must consider how thick the glass is. Thicker glass takes longer to heat and to cool. But, how fast is safe for glass of uniform thickness is much different than for a glass project with variations in thickness. When you apply heat, the thinner parts of the projects will soften quicker than the thicker parts. The opposite happens when cooling. The thinner parts will cool and harden quickly while the thicker parts remain warm and soft. Too much difference will cause the glass to crack. To calculate the total thickness to determine ramp speed, you must add the difference in thickness to the actual glass thickness.

For example. If you place a 1/4 inch (6mm) thick piece on a 1/4 inch (6mm) thick base the actual thickness is1/2 inch (12mm) but to allow for the difference in thickness you should consider the thickness to be 3/4" (18mm).

6mm base + 6mm added + 6mm difference = 18mm

Suggested Ramp Speeds

3mm	500° F/hour	260°C
6mm	400° F/hour	205°C
9mm	300° F/hour	150°C
12mm	200° F/hour	95°C
18mm	100° F/hour	40°C

This is needed ONLY at temperatures below 1000°F (540°C). Glass will not thermal shock above that temperature if the temperature has been equalized through the glass to that level or higher. Equalizing temperature at that level will allow you to increase temperature much faster if you wish. When you calculate your firing schedule you have two options:

- Apply a consistent temperature increase up to performance temperature.
- Hold at 1000°F (540°C) to equalize the temperature than ramp as fast as you wish up to performance temperature.

It is generally assumed it is always safest to ramp slow. Slow is safe. But, slow temperature change (up or down) above that temperature encourages devitrification and gives the glass more time to move. There are times when you don't want it to move.

Ramp Speed Safety Levels

We each make our own choice for how fast we choose to ramp glass in a kiln just as we each choose how safe to drive our car on the road. Some choose to always go so slow it is universally assured to be safe. Some want to understand how slow is reasonably safe. Others choose to push the limits.

1. **Lickety split.** For a rush job when the need for speed justifies the risk of failure.
2. **Speed limit safe.** Under usual conditions it is accepted as safe.
3. **Super safe.** Slow enough to allow for variable conditions.
4. **Bulletproof.** A turtle trot so slow only the direct intervention of an infuriated glass god could cause failure.

Steel vs Ceramic

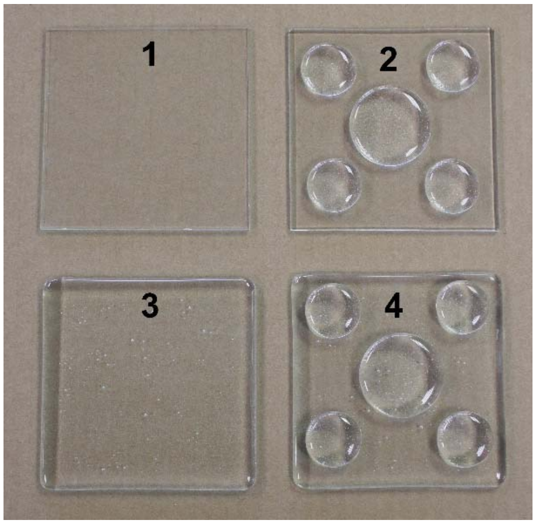
It is almost universally assumed you should slump into ceramic molds and drape over steel molds. That's because both ceramic and steel expand and contract at different rates than glass. If you slump into a steel mold, the steel expands as it heats up and the glass expands to fill the enlarged space. As the mold and glass cool, the steel contracts faster than the glass and presses so firmly against the glass it can easily crack the glass or lock on so tight it's not possible to remove the glass from the mold. The reverse happens when you drape over ceramic. As the mold and glass cool after the drape temperature, the glass contracts faster than the mold and can easily crack or lock on so tight it's not possible to remove the glass from the mold. That doesn't mean you can never drape over ceramic or slump into steel. It means if you do that you must significantly reduce the ramp speed in your firing schedule. A safe working guideline is to ramp at half the speed you usually would for that thickness of glass.

Ramp Cause to Crack Test

Objective To determine what ramp speeds induce thermal shock cracks on different thickness glass.

Materials 4 – 4” x 4” glass tiles all COE 96

1. 3mm
2. 3mm with 6mm pebbles
3. 6mm
4. 6mm with 6 mm pebbles



The test

Test rate to 1100°F (595°C) If glass is to suffer thermal shock it will happen below that. Drop to anneal 960°F (515°C) hold 60 minutes. Cool at test rate. Did a series of 11 tests starting at 200°F per hour with each consecutive test increased by 50°F up to final test at 700°F per hour. Each test was done with fresh glass to be sure it wasn’t influenced by having been fired before. Only clear glass was used to be sure different viscosity from different colours affected the results.

These tests were done to show how thicker glass, or glass of variable thickness, is more likely to experience thermal shock cracking. I did these tests with 4 inch x 4 inch glass because it was easy to fire all together in a small kiln I had complete confidence could be trusted to fire to perfectly accurate temperature. Kilns that fire a little hotter will produce different results, larger pieces of glass are more likely to experience thermal shock cracks and some colors of glass might be more susceptible to thermal shock.

In these tests the glass failed to crack even when ramped as fast as 700°F per hour.

Hold

Hold Times

It takes time for heat to travel into or out of glass. How long you should hold glass at a specific temperature to have that happen depends on the thickness of the project. Thicker projects require more time to allow the glass to heat or cool to equalized the temperature. To make it easy to remember performance temperatures for different functions I choose to work with rounded off easy to remember numbers and vary the hold time at those temperatures to allow for any difference in the projects. The benchmark hold times I use for 1/4 inch thick (6mm) projects on COE 96 glass are:

1000°F (540°C)	Temperature Equalization - 20 minutes.
1200°F (650°C)	Drape – 10 minutes
1250°F (675°C)	Slump – 20 minutes
1300°F (705°C)	Fire Polish – 3 minutes
1350°F (732°C)	Tack Fuse – 15 minutes
1400°F (760°C)	Contour Fuse – 20 minutes
1450°F (788°C)	Full Fuse – 20 minutes
960°F (515°C)	Anneal – depends on thickness.

There are some firings where it’s needed to allow extra time to complete the desired effect. For “puddles”, thick pebble firings and projects with thick elements on a base that you want fired to a full flat fuse you will need to increase time at top temperature to 25 or more minutes. For short span slumps as needed to make strips to weave glass, you need to increase time to 30 or more minutes. For drape firings with an extension more than a few inches you will need to either reduce time or temperature. Handkerchief vases are best done at only 1150°F (620°C).

Hold long enough to do the job but not so much longer you do too much. Holding too long at 1000°F or at anneal won’t do any harm but holding at performance temperature can cause your project to do a lot more than you wanted it to do. Increasing hold time will do the same as increasing temperature.

Temperature Equalization

Not all projects need to have temperature equalized at 1000°F. I do it on most firings because it allows me to significantly increase ramp speed after that hold and by doing it always it becomes a habit I don’t forget. Glass will not experience thermal shock cracking if the temperature has been equalized at or above that temperature.

To paraphrase an old an apt saying:

Better to do and not need than to need and not do.

Temperature

Different temperatures produce different effects. Some important temperatures to remember for COE 96 glass are:

800°F (425°C) Strain Point. A secondary anneal to relieve residual stress.

960°F (515°C) Anneal. The temperature at which the glass is held to relieve stress created by heating it to a higher temperature.

1000°F (540°C) Thermal Shock Safety. If you hold at that temperature long enough to equalize the temperature entirely through your glass project, you can safely ensure your project will not crack from thermal shock. You can then safely increase temperature as fast as your kiln is able to increase temperature.

1200°F (650°C) Drape. At this temperature, if your glass project has one end extended out unsupported, the glass is soften enough gravity will cause it to bend down. This is a guideline temperature. The greater the span the less temperature or time needed to cause the glass to sag.

1250°F (675°C) Slump. To slump glass into a mold where the glass is supported around the perimeter requires higher temperature than to drape it. The wider the span the less temperature required to cause the glass to sag.

1300°F (705°C) Fire Polish. At this temperature a thin surface of the glass has melted to produce a shiny polish like wet paint. This is hot enough to put a full shine on the glass but not yet hot enough to produce a reliable tack fuse.

1350°F (732°C) Tack Fuse. At this temperature two pieces of compatible glass in contact with each other will permanently fuse together. This is also the maximum temperature you can safely fire to before the glass adopts the 6mm rule and begins to change thickness (either to thin or to thicken) to become 1/4" (6mm) thick
.

1400°F (760°C) Contour Fuse. At this temperature the glass will melt down to a texture halfway between a tack fuse and a full fuse.

1450°F (788°C) Full Fuse. This is the temperature required to fully melt the glass down to a uniform 1/4" (6mm) thickness.

1600°F (870°C) Gentle flow. At this temperature glass will flow smoothly through the mesh for a screen melt or from a pot in a vitrigraph.

1700°F (925°C) Full flow. At this temperature glass will flow quickly from a pot in a vitrigraph and is liquid enough to be easily combed.

1800°F (982°C) Fully liquid. Taking glass to this temperature is usually done only to be poured.

1850°F (1010°C) This is the temperature ceramic clay is fired at to produce ceramic molds for use in draping or slumping glass.

Rounding off Temperatures

To make it easier to remember temperatures, glass artisans that work in Fahrenheit have rounded off the numbers.

Drape 1200
Slump 1250
Tack fuse 1350
Contour fuse 1400
Full fuse 1450

When converted to Celsius, the numbers are not so rounded off so are not so easy to remember. I alternate between working in both F & C but because my memory sucks I don't try to remember the direct converted Celsius figures and have instead rounded them off to figures I can more easily remember.

Drape 1200F = 649C use 650C
Slump 1250F = 675C use 675C
Fire Polish 1350F = 732C use 735C
Tack Fuse 1425F = 774C use 775C
Contour Fuse 1500F = 816C use 815C
Full Fuse 1575F = 857C use 860C
Full Flow 1600F = 871C use 870C
Comb 1700F = 927C use 925C

Using rounded off numbers will make it easier to remember the numbers which will make it less likely you make a mistake in programming a firing schedule.

Anneal

Heating and cooling glass in your kiln introduces stress in the glass. Holding the heated glass at a set temperature releases that stress. Inadequately annealed glass can crack. Just like incompatible glass fused together in a kiln that crack might not happen right away. It might be in a few days, in weeks or even months. One of my favourite ways to describe the purpose of annealing:

Imagine you've had a day when everything that could go wrong did to wrong. You're stressed to the limit of your ability to control and ready to explode. You go home, crank up the hot tub and pour a big glass of iced cold beverage. Sit in that hot soothing water sipping that cold drink and let all that stress ooze out into the hot water.

Anneal Temperature

Anneal temperature is different for each different COE glass. You should check with the glass maker what the recommended anneal temperature is for their glass. The most common ones used for fusing are:

COE 96 anneal at 960°F (515°C)
COE 90 anneal at 900°F (480°C)
COE 82 (float glass) anneal 1050°F (565°C)

If you aren't sure what the correct anneal temperature is for the glass you're using, you can program a slow ramp down from the estimated high to the estimated low point. For example, you could include a segment that drops at 50°F (10°C) from 1050°F (565°C) to 900°F (480°C).

Second Anneal

Although not important on small projects, on large projects you should include a secondary anneal to release stress at the "strain point" by programming a slow ramp from the first anneal temperature down to the glass strain point. That's at 800°F (425°C) for COE 96 glass.

Anneal Time

Just as your ramp speed is determined by the thickness of your project, so is anneal time. The thicker the glass the longer the anneal time. The anneal times I use for COE96 glass are:

1/4" (6mm) 60 minutes
3/8" (9mm) 90 minutes
1/2" (12mm) 120 minutes
5/8" (15mm) 150 minutes

Any easy to remember guideline is to start with 60 minute anneal hold for a 1/4 inch (6mm) thick project and add 30 minutes for each extra 1/8" (3mm) of thickness. Not annealing long enough can leave stress in the glass that can cause it to crack later. Sometimes a lot later. Annealing longer than needed can do no harm. If you're not confident how long is enough, go a little longer than you guess is right.

Shotgun Anneal

Shotgun anneal is the term used when you skip the hold at anneal temperature. The glass is just allowed to cool through the anneal temperature range. For small projects like pebbles or jewelry cabochons you can safely eliminate any hold time to anneal in your firing schedule. The glass will sufficiently anneal as it cools. I routinely do pebbles and cabochons in a single segment firing schedule.

600°F (315°C) dph to 1450°F (790°C) hold 30 minutes.

Multiple Firings

If your project requires multiple firings to complete there is a risk of stress accumulating in the glass. It’s a good practice to increase the anneal time in each consecutive firing by 50%. For example, for a project 6mm thick.

1st firing anneal 60 minutes
2nd firing anneal 90 minutes
3rd firing anneal 135 minutes
4th firing anneal 203 minutes.

Cry Factor

Not every artisan agrees with the need to increase anneal time for subsequent firings and not all agree with how long anneal time should be. You must make your own decision whether or not to allow a longer anneal.

- Are you in a hurry or don’t mind taking extra time?
- How important is the project. How much will you cry if it fails?

Remember…..

Annealing too long can do no harm but annealing too little creates disasters.

Drape

Drape Temperature

When you set glass onto a mold and heat it to soften and sag it has one end sitting on the mold and the other end suspended in space. Because there is nothing restricting the unsuspended end from dropping, it drops in less time or at lower temperatures than glass does when slumped into a mold where it is being held at both ends. I had always assumed a drape would happen about twice as fast as a slump Tests at different times and temperatures demonstrated a drape happens almost 4 times as fast as a slump.

It Depends

The time and temperature needed to cause glass to soften enough to drape depends on the span and on the weight of the glass. My benchmark temperature for slumping glass is 1250°F (675°C) but for draping it's 1200°F (650°C). That's a guide to work from. I add or subtract time or temperature depending how far out the glass extends. A short extension will require higher temperature or more time than a longer extension. Heavier glass will sag faster so will require less time or temperature.

Air Side & Mold Side

When you fire glass over or into a mold the heat softened glass will adopt some texture from where if pressed against the mold. The side of the glass not touching the mold will polish perfectly smooth. When you plan your glass project you should carefully consider which side you want to end up facing out.

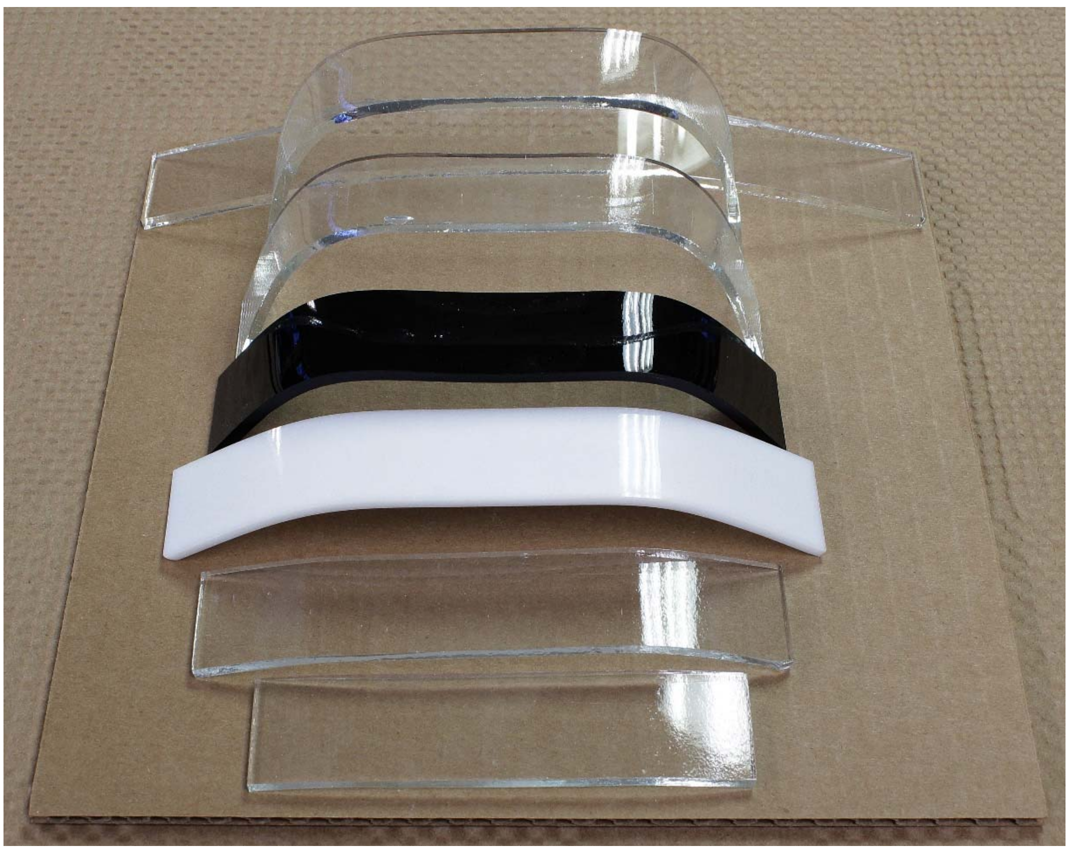
- **Texture out.** If your project has some texture and you want the texture side facing out and the non-textured side facing in, you will drape it over a mold. The inside of that project will adopt any texture from the mold but there are ways to minimize texture on your mold. A slow ramp will reduce the amount of texture the glass adopts from the mold. If you slump a textured product into a mold with the texture facing down into the mold you will lose some of the texture. The weight of the glass pressing down will cause some of the texture to flatten out

- **Smooth out.** If it's important you have a perfectly smooth polished outside you should drape it.

Drape Test

1” wide strips over different glass different lengths set on a 2” wide mold fired to 1250°F (650°C) with a 20 minute hold.   From rear to front:

8 inch 3mm Float
8 inch Wissmach 96 Clear
8 inch Oceanside 96 Clear
6 inch Oceanside 96 black
6 inch Oceanside 96 white
5 inch Oceanside Clear
4 inch Oceanside Clear



This test provides 3 conclusions:

1. The more the glass overhangs unsupported the more it drops.
2. Float glass drops much less than art glass.
3. White glass drops more than clear or black glass.

Understanding Firing Schedules

Slump

How fast glass sags and at what temperature it sags depends on the same variables for slumping as for draping. Your firing schedule must allow for these variables.

Weight

Weight encourages glass to sag. Heavy thick glass will sag faster than thinner light weight. glass.

Uneven Weight

A special concern slumping glass is being sure it drops evenly into the mold without one side dropping faster than another resulting in a lopsided project.   If your glass project has a symmetrical pattern it is likely to drop uniformly. If the pattern is asymmetrical with one part heavier than another part the heavier part is likely to drop first.   If the mold you use is intended to produce a flat bottom, the bottom will then not be centered. To avoid this problem some glass artisans prefer to used “ball” molds that have a uniform curvature that have no flat point for a bottom.   With those molds it doesn’t matter if one part of the glass comes down quicker than another part.

Perimeter Weight

Slumping a project with greater weight around the outer rim than in the middle of the project can encourage the project to trap air under the middle parts.   For such a project you should use a slower ramp speed at the temperature the glass begins to soften and sag.

Span

A wide span will sag faster and at lower temperature than a narrow span.   When you slump glass into a mold where the glass will stop dropping when it comes to the bottom of the mold it’s not a concern if your firing schedule is a little too long or too hot. But it can be a problem in projects where you slump through a drop ring where you want the glass to either stop dropping before it touches the bottom or you want to control how much it presses against the bottom.

Depth

The deeper the mold the more likely the glass will fail to drop evenly.   For projects like deep bowls, many artisans will either choose to instead drape the project over a mold or to slump in a series of consecutively deeper molds. Slump first in a shallow mold, then in a moderately deep mold then finally in a deep mold.

Air Side & Mold Side

Just as with a drape firing, the softened glass will adopt some texture from the mold. You should plan ahead which side you want to be the perfectly smooth polished air side.

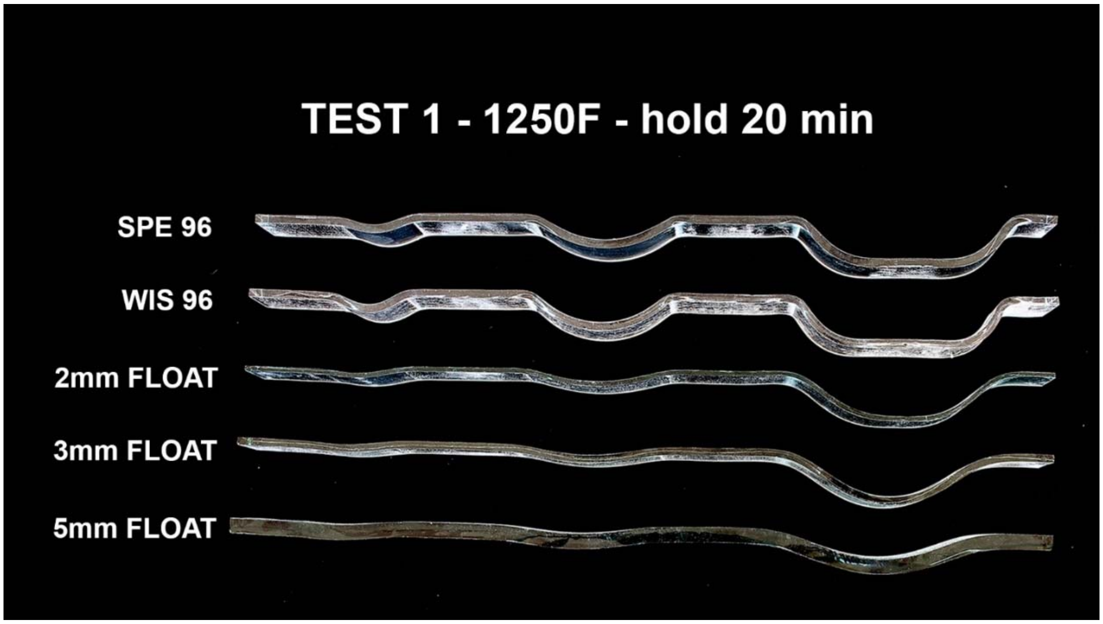
Mold Resistance

How easily and how fast glass drops into a mold depends also on how much resistance the mold provides.   How smooth is the mold? How easily does the glass slide into it?

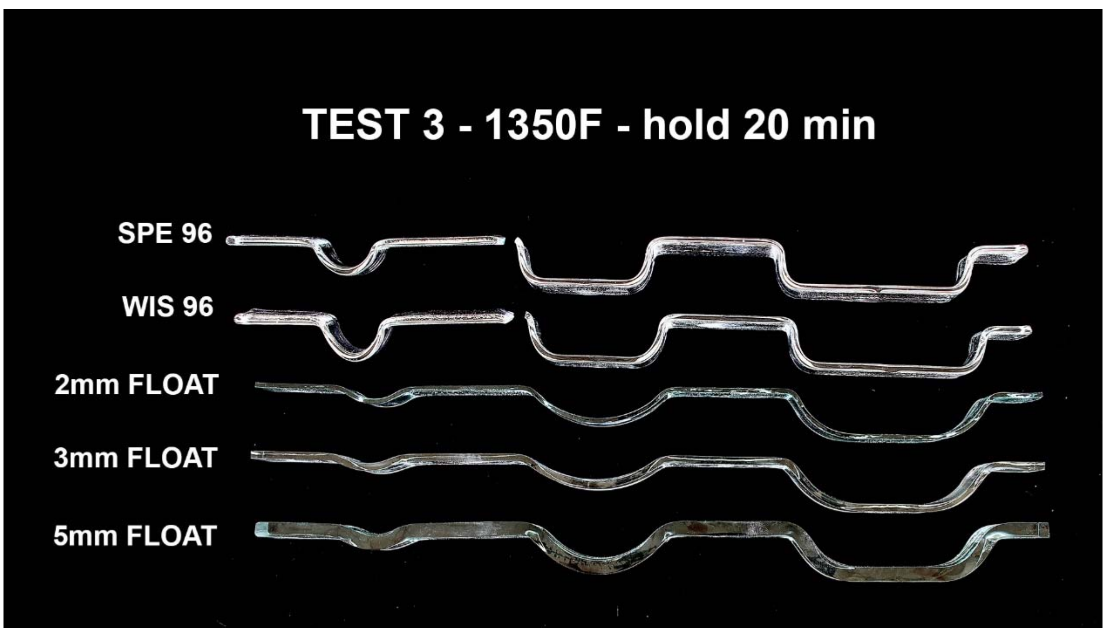
Understanding Firing Schedules

Glass Campus

Tests slumping different glass demonstrates how different glass slumps different amounts.



Slumping to a higher temperature significantly increases the amount of slump.



Drops

A drop is when you place a flat fused panel of glass over a flat mold with a hole cut in it. It can be a mold like a donut with a round hole, it can be a square panel with a square hole, or it can be any shape you want to have glass to drop through.

No mold side

Because the glass drops through a hole the glass is not pressing against a mold other than the portion left on the mold and that part is usually removed. The result is a fully smooth polish on both the inside and outside of the glass.

Can be any elevation

The flat mold can be set in your kiln at any elevation you want to produce any depth of slump you want. Depth is restricted only by the depth of your kiln.

Unpredictable

With a drape or slump mold you can predict what time and temperature is needed to produce different effects. Not so much with drops. There are so many variables (COE, viscosity, thickness, span, depth, etc) that affect how fast glass will drop through the opening in your drop mold it's extraordinarily difficulty to accurately calculate a specific firing schedule. The usual practice is to program a low slump temperature with a very long hold and peek in the kiln to tell when you want the drop to stop. My usual practice for drops is to program to slump at 1200°F (650°C) with a 3 hour hold. About 20 or 30 minutes after the kiln temperature has reached that temperature, start looking to see how far the glass has dropped. When it has dropped as far I as want it to, I stop the hold and drop temperature as fast as possible down to anneal temperature. Most electronic controllers allow you to program in a "Skip Step" that will tell the controller to end that segment and jump to the next segment.

Accelerates

The soft glass oozes down slowly but not at a steady speed. As it falls it picks up speed and starts to fall faster.

Brake factor

When you're driving your car and step on the brakes you don't stop immediately. The car slows and travels for while before coming to a full stop. The same with glass. You can turn the kiln elements off but there is still residual heat in the glass and in the kiln that will cause the glass to continue moving. You must allow for that when you stop the drop.

How to peek.

You can open the kiln lid to peek or you can position the project so you can remove the peep hole plug and look to see if your project has dropped as far as you want it to.

Fuse

Glass is an interesting material. When you apply heat it softens. The more heat you apply the softer it gets. You can apply just a little heat to make it as soft as cooked pasta so it can be formed into or over molds, you can apply a little more heat so it will fuse to other glass or you can apply a lot of heat so you can pour it like syrup. You can control how soft glass gets by controlling how much heat you apply to it. A little heat for slumping, still more heat for fusing and a lot of heat for casting. To fuse glass to other glass you can vary how much the glass fuses by varying the temperature you heat it to.

Tack Fuse

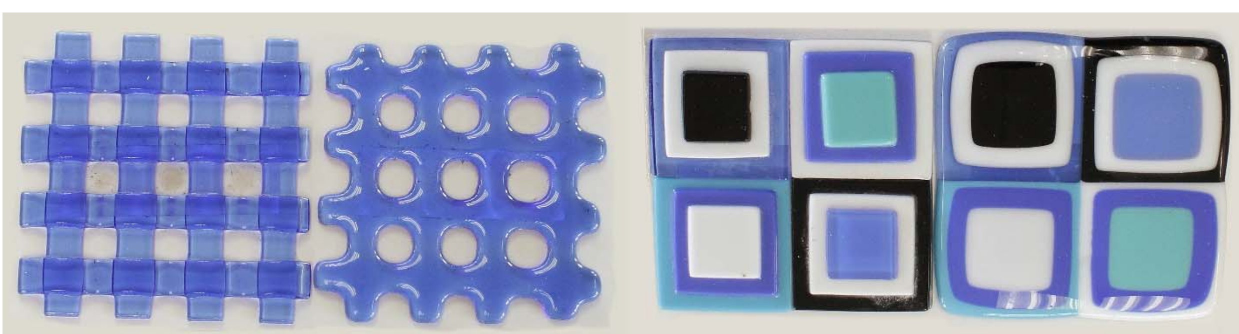
Heating until glass surfaces touching each other have softened enough the pieces of glass will permanently bond together. It looks as if they have glued together the way you might glue pieces of wood together with carpenter's glue. For COE 96 glass this happens at 1350°F (732°C).

Contour Fuse

Heating glass past tack fuse temperature but not yet full fuse temperature so the glass begins to flow but not enough to flow to a common level. A contour fuse is usually considered to be halfway between a tack fuse and a full fuse. For COE 96 glass his is usually done at 1400°F (760°C).

Full Fuse

Heating glass to a temperature high enough it fully melts and flows to a uniform level. A full fuse for COE 96 glass happens at 1450°F (788°C). Heating to a higher temperature will make the glass more liquid and encourage it to flow faster. Holding it at that temperature longer will allow the glass more time to spread to a smooth uniform level.



Tack fuse ***Full fuse*** ***Tack fuse*** ***Full fuse***

Casting

Casting glass can be done either in a mold in the kiln or with glass melted in a crucible in the kiln with the glass removed and poured into a mold outside the kiln. Glass casting is almost always done with cullet, frit or scraps you don't care if they crack. The temperature increase you can use is restricted only by concern with cracking the container it's in. There is no reason to care if the glass being used will crack while temperature in increasing so it's common to crank it up full throttle as fast as possible and care only about anneal time and cooling speed.

In a Kiln

- **open mold** - Scraps of glass placed in an open faced mold and melted to fill the mold. The most common practice is to use the same firing schedule used for full fuse firings. Many artisans will fire open faced molds in the same load as a full fuse project.

- **sandcasting** - An impression is made in sand and filled with glass scraps to be melted to fill the mold. Unless the sand is in a container that might crack if heated too fast, there is no reason to restrict how fast the temperature is increased. Ramp up to full melt, hold long enough to complete a full melt, drop to anneal and ramp down as is safe for the thickness of the project.

- **drip pour** - A crucible stood over the mold to allow molten glass to pour from the bottom of the crucible into the mold to fill the mold. The schedule for this would be the same as for a sandcasting in the kiln.

Outside a kiln

Glass is heated in the kiln in a crucible. When heated to a full melt it is scooped out and poured into a mold outside the kiln. To allow for the glass cooling too fast as soon as it's taken from the kiln, glass is usually heated to at least 1800°F (982°C) and more often to 2000°F (1095°C). As soon as the pour is complete the project is transferred to a kiln to be annealed and allowed to cool at the speed needed to avoid cracking.

Vitrigraph

You can cast glass into a mold from a vitrigraph by allowing the molten glass to pour into a mold. There's a risk the glass will cool too fast and crack so doing this requires either keeping the mold heated or contained in some insulating material. Once the mold is filled, quickly transfer the glass filled mold to a kiln to annealed and cooled.

Torch

You can melt glass with a torch to flow into a mold. Just as with a vitrigraph, you need to either heat the mold or insulate it to prevent the glass from cooling too fast.

Heatwork

Heartwork is the term used to describe how glass responds to heat in a kiln. It is the result of the combination of time and temperature. Holding the glass at a set temperature for more time will increase the effect. Taking the glass to a higher temperature will also increase the effect. It's like cooking a roast in your oven. If you take it to a higher temperature it will cook more. If you hold it at a set temperature for a longer time it will cook more. Whether you're cooking glass in a kiln or cooking a roast in your oven, increasing either time or temperature will cook it more. Heatwork is a time/temperature tango. What happens to one directly affects what happen to the other.

Time/temperature relationship

Which produces the greatest change? I did a series of slump tests on different makes of glass and different colors comparing how much more or less the glass dropped when the temperature was increased or decreased 10°F with how much it changed when the time was increased or decreased 10 minutes. Not all makes of glass and all colors responded exactly the same amounts but the ratio of change did prove relatively constant. Increasing temperature caused slightly more than increasing time but the difference was close enough you can use a guideline to expect every 10° temperature change will produce the same as 10 minutes of time change.

A series of 8 test firings to compare how increasing and decreasing the temperature compares with increasing or decreasing the time held at the performance temperature. All temperatures show are Fahrenheit.

Time/temperature comparison test

A test was done firing identical size pieces of different glass in the same kiln at the same span at different times and temperatures. The objective was to determine how increasing or decreasing time compared with increasing or decreasing temperature in a firing schedule.

Glass used:	OGT Clear	Oceanside COE 96 clear
	OGT White	Oceanside COE 96 opal white
	OGT Black	Oceanside COE 96 opal black
	WIS Clear	Wissmach COE 96 clear
	WIS Blue	Wissmach COE 96 Reactive Blue Opal
	BUL Chart	Bullseye COE 90 Chartreuse
	FLOAT	3mm thick clear float glass

Comparing the figures shows changing the temperature has slightly more affect than changing the time but the difference is so slight it is reasonable to assume a 1 minute change in time is the same as a 1°F change in temperature.

Understanding Firing Schedules

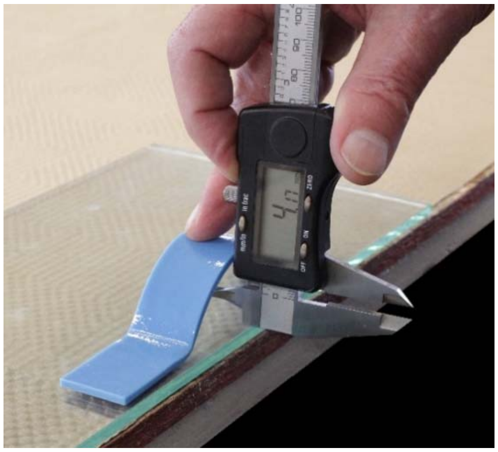
Glass Campus

Comparision chart with different glass at different time or temperature

		1	2	3	4	5	6	7	8
OGT Clear	mm	18.96	23	25.87	25.42	25.42	20.63	15.89	16.95
	fraction	95/128	29/32	1+1/64	1	1	13/16	5/8	85/128
OGT White	mm	15.94	18.21	25.87	22.46	24.48	22.12	17.43	22.03
	fraction	5/8	23/32	1+1/64	113/128	123/128	111/128	11/16	111/128
OGT Black	mm	22	25.09	25.87	25.25	25.14	22.55	23.96	25.61
	fraction	111/128	63/64	1+1/64	127/128	127/128	113/128	121/128	1+1/128
WIS Clear	mm	23.12	25.14	25.87	25.42	25.87	25.23	25.03	16.17
	fraction	29/32	63/64	1+1/64	1	1+1/64	127/128	63/64	81/128
WIS Blue	mm	25.87	25.87	25.87	25.87	25.87	24.69	23.13	24.8
	fraction	1+1/64	1+1/64	1+1/64	1+1/64	1+1/64	31/32	29/32	125/128
BUL Chart	mm	17.81	19.57	23.25	24.99	19.88	16.61	16.98	13.9
	fraction	45/64	49/64	117/128	63/64	25/32	21/32	85/128	35/64
Float	mm	7.91	12.24	16.69	20.35	10.63	8.73	9	3.95
	fraction	5/16	31/64	21/32	51/64	53/128	11/32	45/128	5/32
Temp/Time		1250° 20m	1260° 20m	1250° 30m	1270° 20m	1240° 20m	1250° 10m	1230° 20m	1250° 0m
Change		BASE	+ 10 deg	+ 10 min	+ 20 deg	- 10 deg	- 10 min	- 20 deg	- 20 min

Photos of the test results

Understanding Firing Schedules



Using electronic calipers to accurately measure the amount of slump for each of the 5 different pieces of glass in each of the 8 different firings.

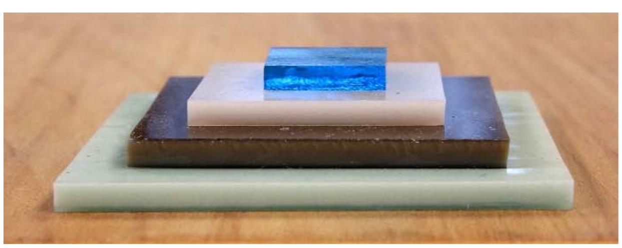
The chart shows differences in both mm and fraction of an inch.

Heat retention

When you create a firing schedule to produce a specific effect you must also consider heat retention. How long does heat remain in your kiln after the turn it off? You can turn the kiln elements off but there will still be some heat left in the kiln that will continue cooking your glass.

- **Lid elements**. Kilns with lid elements retain heat longer then those with only side elements. The heat retained in your kiln lid will continue to heat the class.
- **Brick vs ceramic fiber board**. Brick kilns retain heat longer than ceramic fiber and will retain heat longer. A firing schedule that produced the result you want in a brick kiln might not produce as much of a fuse as you want when done in a ceramic fiber kiln.
- **Kiln depth.** The extra space in a deeper kiln will retain heat longer than in a shallow kiln.

Both of these projects were identical size fired in the same kiln to identical firing schedule. The photo on the left was fire with side elements only and the one on the right with lid elements only.



Fired with side elements only

Fired with lid elements only

Evenivity

That's not a real word. I invented it as way to describe the importance of even heat distribution in a kiln and how it affects your firing schedule. The more evenly the heat is distributed, the faster the glass can be heated or cooled without cracking.

Some things that can cause uneven heat distribution

- Firing glass on the kiln floor. The kiln floor will retain heat. The glass cools quicker than the kiln floor.
- Placing the kiln shelf on the kiln floor. The same as firing on the kiln floor.
- Placing a mold on the kiln shelf. Any air trapped inside the mold will act as insulation preventing the glass from heating or cooling as fast as the mold.
- Uneven thickness mold. Heat will travel quickest through the thinnest parts which will cause some parts of the glass to heat or cool faster than other parts. Ceramic molds for fusing and casting glass are commonly made from slip cast clay because they are a uniform thickness.
- Cool spots in the kiln. If one part of your kiln is cooler than another part, glass in that part will fail to heat as fast as other parts.
- Kiln openings. A lid left part open or a vent hole left open can cause cool drafts that can cause the glass to crack.
- Failed element. If one of the elements in your kiln fails to generate heat you can have an area in your kiln cooler than other places.

Glass Thickness

A glass project that is a uniform thickness will heat and cool more evenly than one with a variation in thickness. It can be heated and cooled faster. A guideline I've found consistently reliable is to assume any variation in thickness is the same as extra thickness.

Glass Viscosity

The viscosity of glass will affect how fast it heats and cools. A project with glass with mixed viscosity will fail to heat and cool evenly.

Different kilns

- A kiln with lid elements will heat the glass more evenly in a fuse than one with only side elements.
- A kiln with both side and wall elements will heat the glass evenly for all projects.
- A kiln with the elements behind quartz panels will distribute heat more evenly than one with exposed elements.
- A kiln with floor elements as well as wall and lid elements would be superior.
- Probably the best possible would be a kiln with air flow like the convection ovens we used to cook food.

Testing for even heat distribution

An effective way to test if your kiln is producing identical results in different parts of the kiln is to fire identical projects in different places in the kiln.

Testing for uneven heat

Test produced identical results on each project

Adapting Schedules

Changing Time or Temperature

If you want to adapt a firing schedule to produce more of an effect, or less of an effect, you must change either the temperature or the time. Firing to a higher temperature will make the glass softer. Holding longer at the top temperature will allow the glass more time to respond to heat. Either adding more temperature or more time will increase the effect but will not necessarily produce the effect you want.

- **Higher temperature** to make the glass softer will also make it soften faster. Sometimes this is a good thing and sometimes a bad thing. Sometimes, like for a fire polish, you want the glass to soften so fast it doesn't have time to move. For some projects higher temperature is important to produce the effect you want. To create the strips for weaving glass you want to slump glass into spans as small as ½ inch (6 mm). The usual slump temperature is 1250°F (675°C) but even a 4 hour hold at that temperature will not induce the glass to slump into a span that small. It must be slumped at 1350°F (732°C).

- **Longer hold** allows the glass more time to respond to the heat so is usually a better solution for a drape or slump firing. Higher temperature makes the glass softer. That will increase the amount of texture the glass adopts from anything it touches. Holding longer at a lower temperature will give the glass time to move without needlessly softening the glass.

- **Firing faster** reduces the likelihood of creating devitrification in the glass. That's why firing schedules apply a temperature drop as fast as possible after the performance temperature down to anneal temperature.

Different Glass

The firing schedule times and temperatures referred to here are for COE 96 glass and do not necessarily apply for glass of any other COE.

- **COE 90.** COE 90 glass and COE 96 have a relatively similar chemistry so can use relatively similar firing schedules. My practice for using COE 90 glass is to use the same schedules I use for COE 96 but raise the top performance temperature 20°F and reduce anneal temperature to 900°F.

- **Moretti/Effetre.** This glass is COE 104 and used almost exclusively for torchwork.

- **Borosilicate** is COE 33 and requires considerably higher temperatures**.** It is used almost exclusively for torchwork. Although it can be used for fusing it is nearly impossible to avoid significant devitrification when fused.

- **Float Glass** is usually COE 82 but can vary as high as COE 86. It has too many differences to consider a direct comparison with firing schedules used for the glass made for fusing. If you want to work with float glass you will need to learn what firing schedules apply.

- **Bottle Glass.** The COE of bottle glass is inconsistent. It can be as low as 82 or as high as 96 but is most often close to COE 90.

Allowing for kiln error

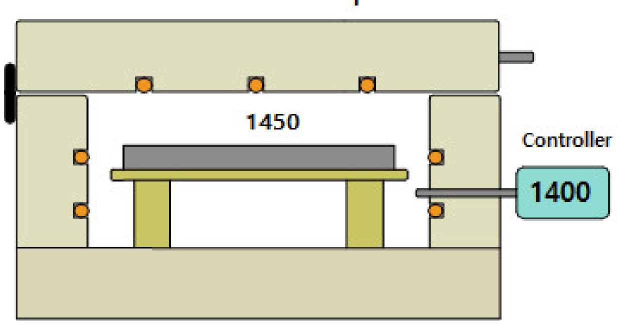
If your kiln fails to produce the results you expected you have two options.

- Adjust the thermocouple to compensate for the error factor.
- Compensate for the error by adapting the firing schedule. If you kiln produces too much or too little heat, reduce either the time or temperature. The Heatwork chapter explains how you can adjust either time or temperature to produce the change you want.

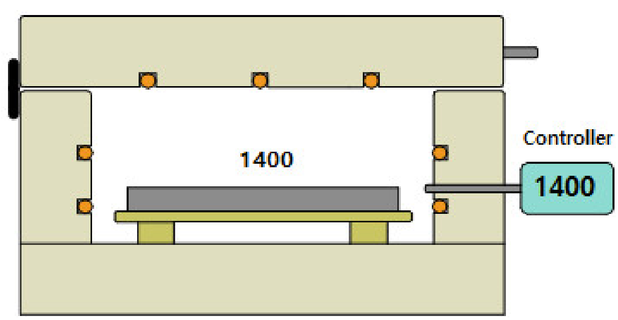
Shelf position

A kiln error in a project can be caused by placing the kiln shelf above the thermocouple. The higher the glass is positioned in the kiln the higher the temperature. The only level at which the glass is the temperature the thermocouple reads is level with the thermocouple.

Glass above thermocouple



Glass level with thermocouple



Special Schedules

There are exceptions to everything. Most of the work we do uses relatively similar firing schedules with a few variations in time and temperature but there are some projects that require significant changes from the schedules commonly used for fusing and slumping.

Bubble Squeeze

When glass softens and sags it often drops first along the outer perimeter. The faster it drops the more likely that happens. When this happens air can be trapped under the glass – either between the glass and the kiln shelf or between layers of glass. This trapped air can create bubbles. A bubble squeeze is a segment introduced into your firing schedule to provide a slow temperature increase after 1000°F (540°C) up to about 1200°F (650°C) to encourage the glass to drop evenly and not first along the outer edge.

Firing onto ceramic fiber paper or kiln paper is less likely to trap air between the glass and the kiln shelf than firing onto the kiln shelf. Inserting small pieces of glass under the glass or between the layers of glass is a more reliable way to prevent bubble entrapment than a programmed bubble squeeze.

Combing

For combing projects the glass is heated to 1700°F (925°C) so the glass is soft and fluid enough to be easily manipulated. It's your choice whether you want to ramp up slowly or rocket up as fast as possible. Either works. The usual practice is to open the kiln and do a quick rake through the glass and close the kiln. Opening the kiln causes a rapid temperature drop. How much it drops depends on how wide you open the kiln and how long you hold it open. You then wait for the kiln to heat back up enough to ready for the next comb. You need to program in a firing schedule that will allow your kiln to continue returning to top temperature until you have completely the number of combing passes needed.

Drop Rings

There are so many variations that can affect how long it takes to complete the drop, the usual firing schedule is to program a very long hold at about 1150°F (620°C) and peek to see when the glass has dropped as much as you want it to.

Fire Polish

The objective for a fire polish firing is to heat the glass enough to produce a surface polish and do it fast enough to not change the shape of the glass. That is done by heating the glass at whatever rate is safe to avoid cracking, holding it at 1000°F (540°C) long enough to be sure the glass has heated uniformly to that temperature then increasing temperature as fast as possible up to 1300°F (705°C). A polish takes only 3 to 4 minutes.

Glass Campus

Understanding Firing Schedules

Freeze & Fuse
A firing schedule for freeze and fuse castings requires a 30 minute hold at 400°F (205°C) to steam out all the water in the casting. The fuse is completed with a 35 minute hold at 1320°F (715°C).

Frit Castings
When you cast frit in a mold there is no reason to care about the glass cracking on the ramp up. You can safely ramp up as fast as possible to melt temperature.

Kiln Sculpture (aka embossing or kiln carving)
A 3mm thick project would be fired at usual tack fuse temperate. A 6mm or thicker project fired with a full fuse schedule.

Screen Melt
The metal mesh used for screen melts has a tendency to spall and leave little metallic specks in the glass. The usual practice for fuse projects is to drop as fast as possible from top temperature down to anneal. To ensure the glass melts and flow through the mesh, melts are usually done at 1600°F (870°C). As the glass cools the metal mesh sheds metallic particles that drop and embed in the molten glass. Other than using outrageously expensive surgical grade steel, I found no way to entirely prevent spalling but through extensive experiments learned that spalling could be encouraged to happen at a lower temperature where the glass has hardened enough the metal particles sat on the glass and not in it. They could be swept off after. The key to making that happen it to drop from top temperature down to fusing temperature and hold for 20 or 30 minutes than drop down to anneal temperature.

Tempered Glass Chips
The chips from a broken sheet of tempered glass are already broken up as small as they will break. Heating them up fast in a kiln won't break them up any smaller. The first step in your firing schedule can be as fast as possible. It's much different on the ramp down after anneal if you have fired your project to tack fuse. You must ramp extra slow. The glass chips will have fused together where they touch each other but there are many air pockets between the chips. Those air pockets act as insulation to prevent heat from spreading evenly through the glass. Some parts will cool faster than other parts and cause your project to crack as it cools. If you have tack fused tempered chip projects and return it to your kiln to be slumped or draped, you have the same concern with the ramp up. A recommended ramp speed is less than half that you would assume safe for glass that thick.

Rocket
For small projects like making pebbles from squares and pieces of rod, you can skip all the usual steps for ramp speed and anneal. Just a single segment – as fast as possible up to fuse temperature, hold long enough to complete the fuse and turn the kiln off to cool.

Understanding Firing Schedules

Vitrigraph

You have a pot full of glass you want to melt so if flows out the bottom of your vitrigraph kiln. Unless you're concerned about cracking the crucible holding the glass to be melted, there's no need to bring the temperature up slowly. You can just ramp up as fast as possible to the top temperature you want and hold at that temperature long enough to empty the crucible. The temperature you go to depends on how fast you want the glass to flow. How long to hold at that temperature depends on the size of the crucible and how long it will take to empty.

Weaving Strips

The usual temperature to slump is 1250°F (675°C) but that won't work on the small spans used to make the serpentine strips for weaving glass. I experimented with a 1/2 inch (12mm) span slump and even at a 4 hour hold the glass barely moved. Much higher temperature is needed to soften the glass enough to sage. The firing schedule for weave strips is to go to 1350°F (732°C) and hold for 30 minutes. Longer time would produce more slump but not significantly more. Higher temperature is essential. Be extra careful when experimenting with higher temperatures. 1350°F should be treated as a boundary not to be passed for 3mm thick glass. Above that temperature the 6mm Rule applies and glass begins to thicken.

Ceramic Molds

Yes you can fire ceramic clay to bisque state in your glass kiln to make molds for casting or slumping. Most kilns have a preset governor that prevents you from programming to fire higher than 1700°F (925°C). That governor can be reset to either 2000°F (2095°C) or 2350°F (1288°C). Changing the setting is done in a place the kiln makers call the "secret menu". Usually the same place you go to change temperature readings from F to C. If you're not sure how to access it in your controller ask the company that made your kiln or that made the controller on your kiln.

Steel vs Ceramic

It is almost universally assumed you should slump into ceramic molds and drape over steel molds. That's because both ceramic and steel expand and contract at different rates than glass. If you slump into a steel mold, the steel expands as it heats up and the glass expands to fill the enlarged space. As the mold and glass cool, the steel contracts faster than the glass and presses so firmly against the glass it can easily crack the glass or lock on so tight it's not possible to remove the glass from the mold. The reverse happens when you drape over ceramic. As the mold and glass cool after the drape temperature, the glass contracts faster than the mold and can easily crack or lock on so tight it's not possible to remove the glass from the mold. That doesn't mean you can never drape over ceramic or slump into steel. It means if you do that you must significantly reduce the ramp speed in your firing schedule. A safe working guideline is to ramp at half the speed you usually would for that thickness of glass.

Understanding Firing Schedules

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Creating Schedules

Firing schedules are recipes for cooking glass. If you can learn how to cook a roast in your kitchen oven you can learn how to cook glass in your kiln. Learn how ramp speed, temperature and hold times affect glass in a kiln. If you understand how the glass you use responds to heat at different temperatures and how it reacts to different increase and decrease in temperature it's easy to create a customized firing schedule for anything you want to do.

Plan the Steps

Ramp Up

- How fast should the temperature be increased?
- How would faster or slower ramp affect the result?
- Is an equalization hold needed?

Temperature

- What temperature is needed to produce the effect you want?
- How would lower or higher temperature affect the result?

Hold Time

- How long should the glass stay at that temperature to produce the effect you want?
- How long would more or less time affect the results?

Ramp Down

- How fast should the temperature be reduced?
- How would faster or slower ramp affect the result?

Special Considerations

- Are there any special issues that must be considered in your firing schedule?
- Is a bubble squeeze needed?
- Is the design likely to trap bubbles?
- Are there volume control concerns?
- Are there viscosity different issues?
- Are the thickness difference issues?

It's great if you can get your firing schedule perfect on your first try but if you have doubts it's better to undercook than to overcook. Just like cooking a roast in your kitchen oven, when you cook glass in your kiln you can always put it back in to cook some more but unless you have a time machine there is no way to go back to cook it less.

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Understanding Firing Schedules

Volume Control

If you want to control the size of your project you must use a firing schedules that allows for how the glass can change size in response to time and temperature. You might want to be sure it remains the original size or you might intentionally want it to change size. Any discussion about firing schedules must include volume control issues. The viscosity of glass is such that when heated in a kiln to full melt temperature it will become1/4 inch (6mm) thick. Glass artisans refer to that effect as the “6mm Rule”. Sheet glass is originally made thinner (usually 2mm or 3mm) by drawing it through rollers. Glass can be made thicker than 6mm by pouring or casting it into a mold to prevent it from spreading out and becoming thinner.

6mm RULE

When art glass is fired to full fuse or higher, it moves to become a uniform 6 mm thick. If you start with thicker glass, it will press down and spread out the same way pancake batter spreads out when you pour it onto a griddle. If you start with thinner glass, it will draw in to contract as it moves to become thicker. The **6 mm Rule** is as persistent as gravity. If you toss something into the air, gravity will make it fall down. If you fire glass to above tack fuse temperature, it will move to become 6 mm thick. If you don’t want something to fall down, don’t throw it into the air. If you don’t want your glass to thin or thicken, don’t fire it above tack fuse temperature. Float glass responds exactly the same way. You must allow for this in your firing schedule.

Enemy or Ally?

If you understand how the 6mm rule affects glass you know how to avoid unwanted effects. You also know how to use it to create desired effects.

- **Dog bone** is when you fuse a piece of glass that is thinner than 6 mm thick and it pulls in to thicken to become 6 mm thick. The corners remain close to the original size but the sides curve inward like the shape of a dog bone. The only way to prevent your glass project from dog boning is to either not fire above tack fuse temperature or take care to be sure the combined mass of glass is at least 6 mm thick. If your fused project has dogboned you can straighten the edges out by coldworking either with a grinder or wet belt sander.

- **Bulging** is when the total mass of glass is more than a uniform 6 mm thick and the projects bulges out to become thinner. The edges push out more than the corners so the sides curve outward. The only way to prevent your glass project from bulging out is to either not fire above tack fuse, to fire into a containment mold or ensure the combined mass of glass is equivalent to 6 mm thick. If your project bulges, you can remove the bulge by either sawing it off or grinding it off.

- **Glass lace.** The 6 mm Rule need not be a problem. Sometimes you can use it to create interesting effects in glass like glass lace. If you spread out a layer of frit about 6 mm thick on your kiln shelf and fire it to full fuse the glass particles melt down and push out any air between them. The melted down glass is now less than 6 mm thick. Instead of fusing flat and drawing in like a dog bone, it opens holes in the glass so some parts are thicker while other parts are open holes like in Swiss cheese. The size of the holes created depends on the thickness of the glass you started with. A thicker layer of powder or frit will produce less holes. A thinner layer will produce more holes.

- **Puddles** are a way to use the 6 mm Rule to create striated patterns in glass. They are made by fusing stacks of glass and firing to full fuse. Often 10 or more layers of glass. This thick stack spreads out and melts down to 6 mm thick. It is then cut up or broken up into pieces. The pieces are stood on edge in the kiln and fired to full fuse to melt into rounded pebble shapes. The result is pebbles with a striated pattern created from the edges of the layers of glass. Regardless of how high the stack of pieces, if you fire the project to full fuse temperature and hold at that temperature long enough to allow the glass to flow, the end result will always be 6 mm thick. The more layers of glass you use in the project, the thinner the lines of different glass will be in your puddles.

- **Pebbles.** Perfectly round pebbles of varying sizes can be created by firing stacks of glass squares to full fuse temperature. When the glass melts, it draws in to form round pebbles. If you use stacks of consistent size squares you will produce consistent size pebbles. As well as perfectly round shapes, stacks of squares can be used to make oval, teardrop and even heart shapes.

3 mm ***6 mm*** ***9 mm*** ***12 mm***

Understanding Firing Schedules

Question Everything

In every question about what firing schedule to use the first answer is "It depends". It depends on many things. It depends on what you're trying to do but also depends on your opinions on what is the way to do it. Not everyone agrees. That's okay. Dissent is good. It encourages people to think. Question everything. We live in a society saturated with misinformation. Not everyone agrees on what firing schedules should be used for glass art. You must examine all the different suggestions and different opinions and decide which approach works best for you. Sometimes the differing opinions are misinformation but more often just differing opinions as to what is needed and why something should or should not be done.

Some of choices made in creating firing schedules are based on the premise, "It might help but can't harm". Examples would be the habit of holding the temperature at 1000°F (540°C) to equalize temperature before heating to a higher temperature. That is founded on the assurance thermal shock crack will never happen above that temperature so high speed temperature increase is safe above that temperature. Another example is my habit of increasing anneal time for subsequent firings. Both these are founded on the premise:

Better to do and not need than to need and not do.

You may believe those practices are unnecessary. That's your choice. We get to make our own choices.

Always go slow

That fits also with the premise "It might help but can't harm". It's fine if you have the luxury of time and don't care how long a firing takes to complete. What about the new hobbyist that has only one kiln and wants to do lots of projects and is anxious to know how fast they can safely fire their projects? What about the artist pushed to meet a deadline? What about the instructor that has so many student projects to fire it will take several kiln loads? They know going slow is always a good practice but they want to know how slow is needed? There are projects where time is your enemy and temperature your friend. Low and slow is a good general guideline but

Is NOT universally valid.

"Cause to Crack" tests

I questioned the "always go slow "axiom so choose to do my own tests. I fired sets of 4 inch x 4 inch tiles starting at 200°F per hour ((95°C) and continued testing at temperature rise increments of 50°F ((10°C) up to 700°F (371°C). None cracked. These tests confirmed I could safety increase temperature as fast as 700°F (371°C) per hour without cracking the glass. That's about twice as fast as is traditionally recommended and is about as fast as most kilns are able to increase temperature.

3 – 2 – 1 Expedited Cooling

The traditional claim had always been to let the glass cool to room temperature. I thought that unreasonable so did a series of “cause to crack” tests opening the kiln at different temperatures to see what temperature caused the glass to crack. I learned I could safely crack open the kiln at just below 400°F and fully open at just below 300°F. To make it assuredly safe and easy to remember I settled on 3-2-1.

- at 300°F crack the lid.
- at 200°F fully open the lid.
- at 100°F remove the glass and reload for the next firing.

For those working in celsius, that’s 150C – 100C – 50C.

Fire polish

I was making for commercial sale hundreds of projects cast in open face molds. They came out of the mold with slightly unpolished surface where the glass pressed against the mold. If I coldworked them, any design texture would be removed. I wanted to retain the design texture so experimented with the possibility of polishing the mold side by flipping over and firing in the kiln to switch the mold contact side to become the air polished side. A series of experiments confirmed it was possible with a relatively unconventional schedule.

1. 400F (205C) to 1000F (540C) hold 20
2. 9999 to 1300F (705C) hold 3
3. 9999 to 960F (515C) hold 60
4. 400F (205C) to 600F (315C) hold 0

I call this the **“Commando Raid”** schedule. Run in fast - do the job fast – get out fast. It works by understanding some important factors in how glass responds to heat.

- Thermal shock cracks will never happen above 1000°F (540°C). Equalizing the glass at that temperature is essential to making this work.

- Glass castings will sag when the glass is heated but glass doesn’t move fast. By increasing temperature as fast as possible it doesn’t have enough time to sag.

- Glass will fully polish to look like wet paint at 1300°F (705C).

- 3 minutes is all the time needed to produce a full polish.

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Understanding Firing Schedules

You choose

You get to choose. Do you choose to go slow because you were told you should go slow or because you understand how glass responds to heat and believe slow is the way to go? Do you expect others to provide firing schedules for you or do you choose to create your own firing schedules for your own projects?

I offer 3 suggestions:

- Too often something is done in a particular way for no reason other than it has always been done in that particular way.
- Sometimes the best way to do something is the way you haven't tried yet.
- Question Everything.

Speed Limits

Choosing a safe ramp speed for firing schedules is much like choosing a safe speed limit for a driving a section or road. There are two different ways to set a speed limit.

- Set the speed for when the road is clear and dry but drive slower when it is wet or icy.
- Set the limit slow enough to allow for the worst conditions.

You choose which method you prefer to use.

Keep Records

It's okay to make mistakes. We all do it, but it's not okay to repeat the same mistakes. The best way to avoid repeating mistakes is to keep records. Some of us have good memory and some of us have a not so good memory but the book has a perfect memory. There are many things you can do to improve your memory but the best of all memory training techniques is to remember to write it down. Keep notes and keep records. If you keep a record of the results what happened with you tried something you can refer back to that record the next time you try it. Did it produce the results you want? Was there some change you think should have been made.

I practice and promote a 3 step process when I open the kiln after a firing.

1. What is my first impression?
2. What might I have been done differently?
3. What ideas does it give me for other projects?

Save your failed projects

It's also important to keep some of your failed projects. Bring them out sometimes to remind yourself how far you've progressed. If you teach, those failures can be especially helpful to encourage students to accept failure as part of the learning experience.

Keep a kiln log

If you keep a record of the results of your projects you can refer back to it to help remember what happened and what you thought should be change or corrected. It doesn't matter how you keep it. Write notes in a note pad, record it in your computer or paper your shop with stick notes. Just do it. It can be just a few notes and comments or it can be as detailed as an encyclopedia. Just do something to keep records. The minimum it should include would be:

- **Project description.** What was it? Fuse, slump, drape, cast?
- **Molds.** What molds did you use – ceramic, steel, plaster?
- **What glass used.** What make and what colors.
- **Firing schedule.** What firing schedule did you use?
- **Results.** Wonderful, pretty good, barely acceptable or seriously sucked?
- **Suggestions.** What do you think might have improved the results?
- **Ideas.** What ideas did the project generate for new projects?

If you make work for sale, it should also include:

- **Time.** How long did it take to make?
- **Materials.** What was materials cost?
- **Suggestions.** How could you reduce time and/or materials cost?