

Creating X-Ray Optics for the Baby International Axion Observatory

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Abstract

The International Axion Observatory (IAXO) aims to use direct detection to find axions by converting them into x-ray photons for detection. A prototype for IAXO (named Baby IAXO) will serve as a proof of concept for IAXO, while also providing novel sensitivity for axions. The Wolter I X-Ray Telescope design was used for the X-Ray optics, with semi circular glass substrates slumped to create the optic. A general formula for slumping X-Ray optics was defined, providing uniformly slumped glass.

1 Introduction

Axions are small, theorized particles that interact very weakly with light. This makes them great dark matter candidates. In addition, axions could explain the strong charge parity problem, which is the problem where CP symmetry under the strong force seems to be preserved in all observations in nature. Currently, there is nothing in the standard model that dictates that CP Symmetry has to be conserved. The existence of an axion (and thus an axion field) would cancel out any term that allowed for strong CP symmetry violation, thus solving the strong CP problem. Axions are hypothesized to convert into photons (and vice versa) via Primakoff radiation [Per23] under extreme electromagnetic conditions, such as inside the sun. X-Ray photons can convert into axions of the same energy level, and travel to Earth. The axions from the sun can then convert back to x-ray photons under extreme electromagnetic conditions. The International Axion Observatory (IAXO) is a helioscope that sets out to directly detect axions coming out of the sun by using a large superconducting magnet to create the electromagnetic conditions required to turn the axions into coming out of the sun back into x-ray photons (see figure 1).

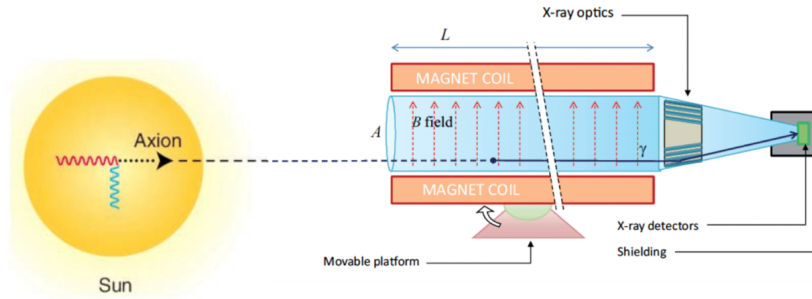


Figure 1: Basic design of axion helioscopes. Axions are converted back into x-ray photons under the intense B field of the helioscope, and then focused into the detector by the x-ray optics. [Per23]

1.1 X-Ray Telescope Design

X-Ray optics are required to focus the x-ray photons. X-Ray photons can only reflect off glass at very shallow angles, or else they will either be absorbed by the glass or pass through it unreflected. Because of this, a telescope will have to position its mirrors at a shallow angle, and allow for a long

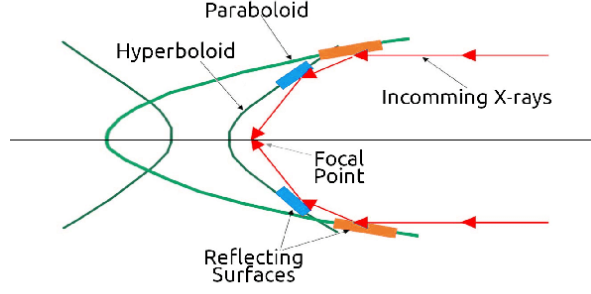


Figure 2: Side cross section of the Wolter I Telescope Design. (Image Credit: Mehdi Abbasian Motlagh and Gohar Rastegarzadeh)

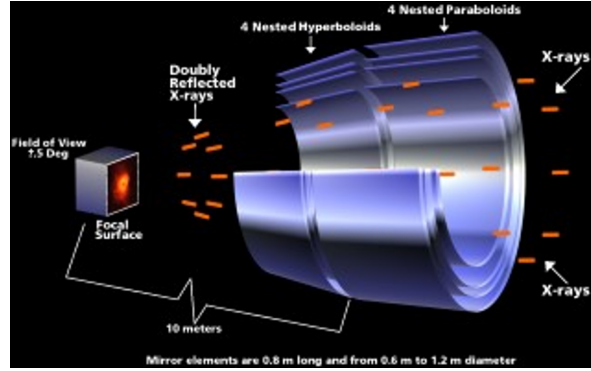


Figure 3: 3D Model of the Wolter I X-Ray Telescope Design (Image Credit: NASA/Chandra/ Smithsonian Astrophysical Observatory)

focal length. IAXO and BabyIAXO will utilize the Wolter 1 X-Ray telescope design, which is made of layers of cylindrical shells that have either a parabolic curve or a hyperbolic curve (see figure 3). The x-ray photons bounce off the parabolic curved shells, and then will bounce off the hyperbolic curved shells into focus. The parabolic mirrors will be angled θ degrees from the plane of incoming xray photons, and the hyperbolic mirrors will be angled 3θ degrees from the plane, where θ is a small angle. These mirrors will be in the form of circular shells, with the shells varying in radii between 91 mm to 215mm. Circular shells will be made by slumping flat sheets of D263 Schott glass using mandrels.

1.2 Slumping technique

A flat sheet of glass would be placed on top of the mandrel with both sides resting on the ledges of the mandrel. Slumping glass took place in three different stages. Each stage of slumping had the slumping oven heat up by a certain rate (measured in C/min) to a certain temperature, then held the oven at that temperature for a certain period of time. The glass would then slump into the mandrel, with the concave side (or the optical surface) facing upwards, therefore not in contact with the mandrel. These settings were experimentally optimized to produce the lowest Half Power Diameter (HPD) for IAXO. The glass would then be cooled off to around 50 degrees C before being taken out of the oven. The back of the glass would then be painted with a black tempera paint before being scanned for HPD.

1.3 Laser Scanner

The laser scanner utilizes a laser than scans up and down the substrate of glass before being redirected to a PSD detector for readout. Each substrate of glass would then be scanned across the length of the glass using a laser scanner to determine what the HPD of the optic would be had it just been made using identical substrates of glass. Due to technical difficulties with the laser scanner, the laser

scanner was not used to analyze any substrates of glass at time of writing. The laser scanner will be used in the future to identify the quality of glass.

2 Slumping Technique

The slumping technique for the 91mm mandrel included three stages of slumping. The first one was to heat up the glass at a rapid rate (15C/min) to a modest temperature of 310C, which is below the strain point of the glass. The glass continued to heat up at a slower rate (9C/min) to its strain point of 529C. The oven then sits at a 529C for a select number of minutes. Each oven has its own temperature gradient due to heat leaving the front of the oven (the front of the oven, even when closed, still loses some heat, a problem which the back of the oven does not have). This gradient can cause one part of the glass to slump more than the other, producing an uneven piece of glass that is not beneficial to producing a low HPD. Giving the oven time to thermalize at the strain temperature minimizes the temperature gradient before heating up further. The more temperature gradient an oven has, the higher the thermalization time. After thermalizing, the temperature rises at a slow rate (5C/min) to its soak temperature. The soak temperature is dependent on the diameter of the glass. The glass is held at a certain soak temperature, depending on the settings used for each diameter. The glass is then cooled off, with the oven remaining closed until it cools down to a temperature of 500C, at which point the oven is opened to cool the glass down further. The glass is taken out of the oven when the temperature is lower than 70C. Slumping, from first putting the glass into the oven to taking it out after cooling, takes around 2 - 2.5 hours per glass substrate. Settings for the soak temperature and the soak time had to be carefully considered to make sure the glass was neither underslumped or overslumped, both of which would produce skewed pieces of glass. Three ovens were used to test the settings for slumping, which were named oven 16, oven 3 and oven 18.

2.1 Ideal Thermalization time at Strain Point

Thermalization was chosen at strain point as the strain point is the temperature in which the glass becomes more "relaxed" and acts more like a liquid. Thermalizing at this point allows for the glass to thermalize at the highest temperature possible without slumping it (slumping ideally, takes place around and at the soak point). The ideal thermalization time for slumping was dependent on the oven used, more specifically what the temperature gradient of the oven was. The less thermal gradient that was present in the oven, the less time was needed to thermalize at the strain point. Thermalization times between three to ten minutes were tested for each of the three ovens. These thermalization temperatures were experimentally chosen.

2.2 Ideal Soak Temperature for lower radii mandrels

Different soak temperatures were tested at lower radii mandrels to see which one could produce the most optimal and consistent HPD. The first soak temperature tested was 620 C. This high soak temperature would reduce the amount of time it would take to slump each piece of glass. On average, a piece of glass would only remain at the soak time for 2-3 minutes before fully slumping. Thermalization was chosen at strain point to reduce the amount of slumping happening during the first thermalization stage. However, due to the lower soak time, the oven would not have enough time to properly thermalize. This meant that for the majority of the soak time that the glass had, most of it was spent slumping in a large temperature gradient, causing uneven slumping. Lowering the soak temperature would increase the soak time, allowing the piece of glass to slump for longer under a thermalized oven. Soak temperatures of 600 C and 605 C were tested to compare results that were produced with 620 C.

2.3 Ideal Soak Temperature for higher radii mandrels

Soak temperatures at higher radii are lower than those of lower radii mandrels. This is due to the glass itself being heavier, which allows the glass to slump easier. The first temperature investigated on the higher radii mandrels was 570 C, which is the lowest temperature that glass of this size will slump at within a realistic time frame.

2.4 Ideal Glass Length and width

The length of all glass pieces are 200 mm long. The width of a glass piece is dependent on the size of the mandrel. Glass pieces were first cut to the entire outer diameter of the mandrel. This was 96mm for the 91A mandrel, 101mm for the 95C mandrel, and 221mm for the 215B mandrel. Although the 215B mandrel worked nicely at this width, the lengths for the 91A and the 95C mandrel worked inconsistently. The front corners of the glass (the corners that were closest to the oven's door) would fail to slump evenly with the rest of the glass. This would leave the glass skewed, which made for poor quality. The second idea for glass length was to cut the substrate in between the outer diameter and the inner diameter of the glass mandrel. The widths of the glass were 94mm for the 91A mandrel and 98mm for the 95C mandrel. The 215B mandrel did not need its width changed, as the glass for this mandrel never came out skewed. This is likely due to the fact that the larger pieces are easier to slump due to their increased weight. The result of decreasing the glass width decreased the probability of a piece of glass coming out skewed.

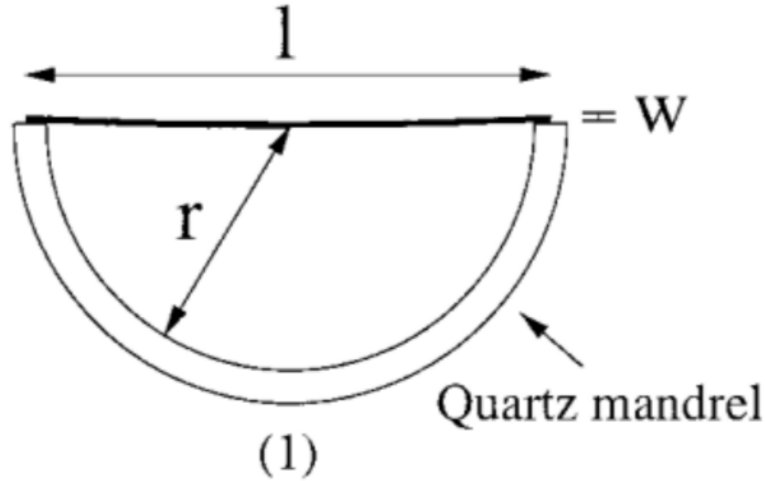


Figure 4: A quartz mandrel with a substrate of glass placed on top. l spans the outer diameter of the mandrel (which is 96mm for the 91A mandrel, 101mm for the 95C mandrel, and 221mm for the 215B mandrel.[ea03]

3 Laser Scanner

3.1 Laser Beam Path

The quality of the glass was intended to be checked using a Laser Scanner. The optical set up utilizes a laser that gets reflected off of two steering mirrors (see figure 5), then hits a pentaprism (which redirects the beam upward) located on a stage that can move linearly. The laser will then go through a beam splitter to hit a larger mirror angled at 45 degrees, where it will then be redirected towards a mirror that can move rotationally, which will redirect the beam towards the piece of glass being scanned. The laser beam will then redirect back towards the rotational mirror, to the 45 degree mirror, then off the beamsplitter and into the PSD detector. For each scan, the linear stage will move 250 mm, before moving back to its original position. This allows the laser to scan the length of the glass. The data will be recorded by a program called Labview and the data will then be analyzed using code made in IDL.

3.2 Scanning

The back of each piece of glass was painted with black tempera paint with the purpose of absorbing any light that was transmitted through the optical surface of the glass. This prevented any total internal reflection inside the glass, which would have created a second beam that would have thrown off the results of the scan. Substrates of glass were scanned twenty minutes after the black tempera paint at been applied but not after an hour. This is because the paint took twenty minutes to dry enough for our application, however not enough to fully grip the piece of glass, which would slightly change the shape of the glass, and would in turn throw off the results of the scan. Each piece of glass is scanned up and down 31 times, with each time measuring a different azimuthal position of the slumped glass. Each scan is overlayed in a plot as shown in figure 6. The Bow Height refers to the irregularities among the glass in the scan (as shown on the y axis of figure 6). These irregularities are scratches and divots on the surface of the glass. These scratches and divots scatter x ray photons in random directions, rather than bouncing them towards the detector, which in turn decreases the effective efficiency of the x-ray optics, where the efficiency of the x-ray optic is calculated as:

$$\epsilon = \gamma_{detector} / \gamma_{incoming}$$

, where $\gamma_{detector}$ is the amount of photons that hit the detector and $\gamma_{incoming}$ is the total number of x-ray photons that enter the x-ray optic.

3.3 Future use of the laser scanner

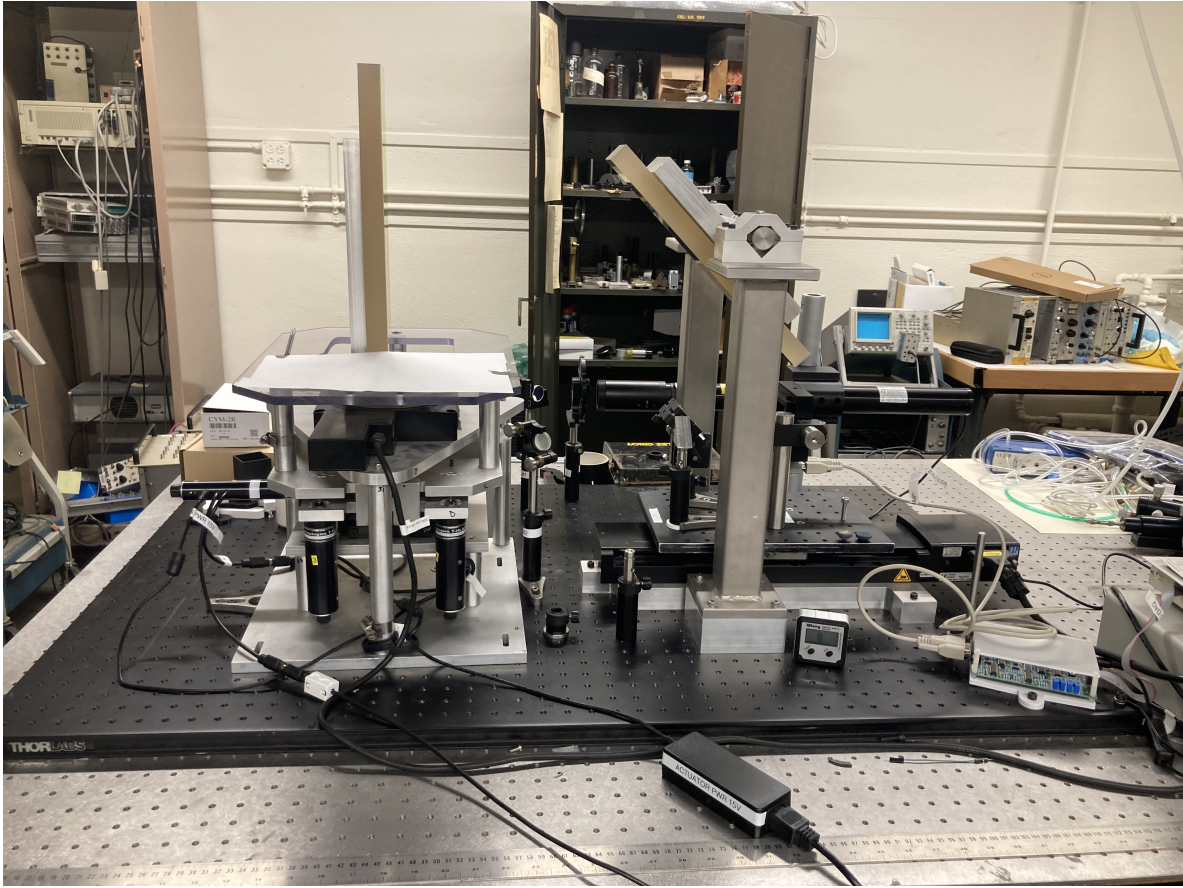


Figure 5: Laser Scanner.

4 Results

Figure (4) and (5) shows the analysis of each of the slumped glass substrates. Glass quality was determined by visibly checking the overall shape. Out of shape substrates were considered "skewed". A skewed substrate typically does not have all four of its corners touch the surface it lays on, which causes the substrate to wobble when pressed back and forth. By pressing 3 corners of the glass to a table, the magnitude of the skew could be identified by how far off the table the substrate was. Substrates with corners more than 10 mm up in the air were considered "Skewed" (S), where corners with less than 10 mm of height were considered either "moderately skewed" (MS) or if the skew was very minuscule and barely noticeable, "slightly skewed" (SS). Unevenly slumped substrates (US) were also recorded as their own category. The skew of larger radii mandrels could not be identified using this method (L), and thus another method of determining overall glass shape (such as using the laser scanner) must be used for these substrates. To measure how uniformly each substrate was slumped, the length of the front side and back side of each piece of glass was measured. The lower the length of the substrate, the more the substrate has slumped. A uniformly slumped substrate would have equal front and back lengths. The difference between the two is shown as a measure of the uniformity, where a lower difference means more uniformity. All parameters for stage 1 stayed consistent throughout all substrates of glass (Temperature rises at 15 C/min the stage instantly ends at 310C). The second stage had a rising temperature of 9C and the third stage had a rising temperature of 5C unless otherwise noted below. Although multiple soak temperatures for lower radii substrates worked (for example, D16-620-0 worked well with a soak temperature of 620 C, while D16-626-0 had a great shape with a soak temperature of 600C), the vast majority of non-skewed glass was slumped at 620 C.

4.1 Differing Procedures

Several substrates of glass had different slumping formulas that were different from normal. Glass substrates D3-720-1 and D3-720-3, it is unsure if this substrate of glass has a thermalization time of 3 minutes or 10 minutes due to a lab notebook recording error, but is most likely 10 minutes. Substrates D16-717-1 and D16-717-2 had a length of 213mm and 220mm, respectively. Substrate D16-706-1 was made using the 95C mandrel. D16-622-0 had its temperature rising rate at 2 C/min. D3-710-2 heated up at a rate of 9 C/min during its first stage and ended its first stage at 529C, with the oven thermalizing at that temperature for 3 minutes. The lengths of the following substrates differed from 200mm: D16-717-1 had a length of 213mm long and D16-717-2 was 220mm long. Substrate D16-622-0 rose at a rate of 2 C/min during the third stage. Substrates D16-614-0 and a D16-614-1 only had two stages (thermalization time and temperature refer to the first stage, and soak time and temperature refer to the second stage in this case).

5 Analysis and General Formula

The recipe for substrates of glass is shown below. For shorter radii mandrels (radius $< 100\text{mm}$), a higher soak temperature produced a more consistent glass substrate. This is likely because lower soak times decreased the chance for the front corners of the glass substrate to get "caught" on the ledges of the mandrel, which would result in skewing of the glass. Furthermore, a lower soak time reduces the total number of time it takes to make a single glass substrate, thus improving the efficiency of this process. A lower soak time, however, creates the need to count the soak time using a stop watch, as the ovens only count time in one minute intervals, which is not enough to produce an ideal substrate (for example, slumping a piece of glass using the 91A mandrel will be underslumped if the soak time is set at 2 minutes, but it will be overslumped at 3 minutes). The opposite seemed to be true for higher radii mandrels. Due to the increased weight of higher radii substrates, the glass tended to slump at lower temperatures. Consequently, the best soak temperature for higher radii substrates (radius $> 200\text{mm}$) was lower. Due to the lower best soak temperature, the soak time had to be increased to fully slump the glass substrate. Higher radii substrates were also less prone to be caught on the ledges of the mandrel. Thermalization temperatures (or the "time at peak temperature" for stage 2) varied from oven to oven, however they were usually between 3 to 10 minutes. Ideal thermalization times may rise if thicker substrates of glass are used, due to the increased chance of a temperature gradient within the glass itself. The ideal thermalization temperature of three minutes for oven 18 was successful in

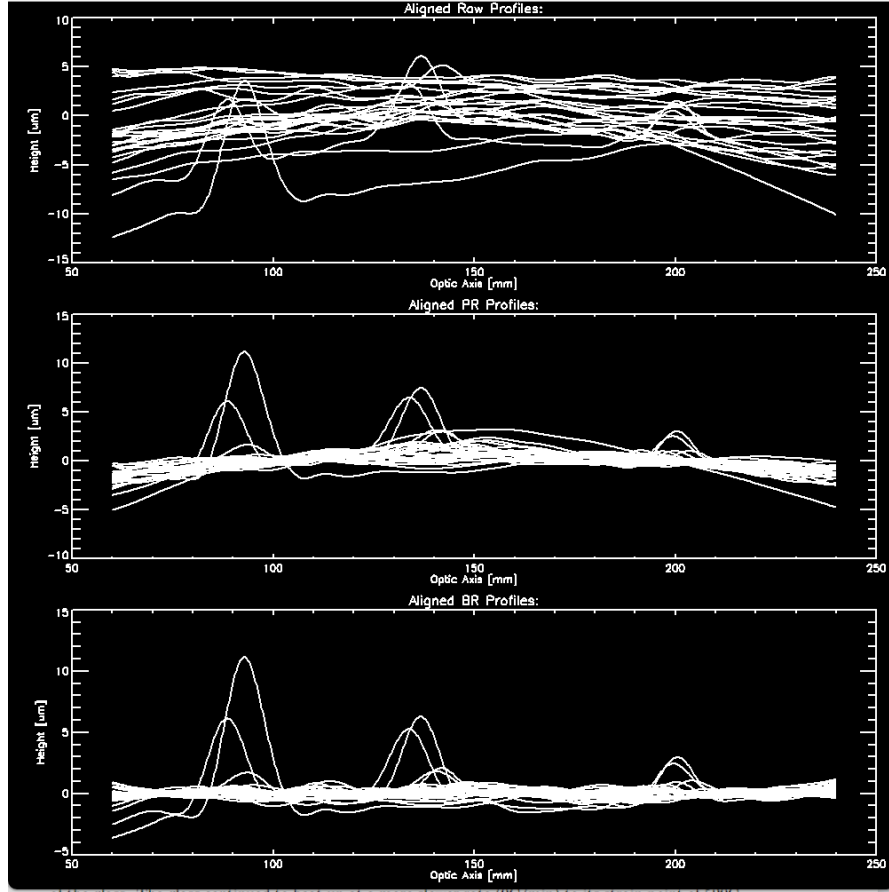


Figure 6: Results of scans on a single glass substrate overlaid on top of each other.

preventing uneven slumping and skewing, however it is unknown if this is due to the seal between the oven and its door, or if it is due to the forgiving nature of the higher radii mandrels. For shorter radii mandrels, cutting the glass to shorter widths prevented the glass substrate from catching the edges of the mandrel. For mandrel 91A, glass substrates with a width of 94 mm skewed significantly less than substrates with a width of 96 mm. Substrates with a lower width also skewed significantly less for mandrel 95B. Due to the lack of skewing involved with higher radii substrates, the glass length of 221 mm (spanning the whole outer diameter of the mandrel) worked.

5.1 Future Work

The temperature rise of stage 3, as well as the soak time of lower radii mandrels require further testing to optimize the general slumping formula, particularly for lower soak times. The use of a laser scanner would greatly help identifying the quality of glass. In future testing, the temperature rise of stages 1 and 2, as well as the peak temperature of stage 1 could be optimized further to decrease the amount of time that it takes to slump a glass substrate. Furthermore, the amount of scanning by the laser scanner was limited during this project, meaning that most of the results were by visual inspection. The larger radii substrates that were scanned were skewed, a property that couldn't be easily determined by the naked eye. Future testing could determine whether the glass length of the larger radii mandrels need to be trimmed down to a smaller size. More testing could also be done to determine which part of the glass was causing the skewing (front vs back, left vs right, etc). More scanning would also help fine tune the current general recipe into a more specific one with a lower HPD.

Table 1: Ideal Recipe for slumping 94mm substrates in 91A mandrel (in Oven 16)

	Stage 1	Stage 2	Stage 3
Temperature Rise (C/min)	15	9	5
Peak Temperature (C)	310	529	620
Time at Peak Temperature (min:sec)	0:00	3:00	3:00

Table 2: Ideal Recipe for slumping 98mm substrates in 95C mandrel (in Oven 3)

	Stage 1	Stage 2	Stage 3
Temperature Rise (C/min)	15	9	5
Peak Temperature (C)	310	529	620
Time at Peak Temperature (min:sec)	0:00	10:00	4:00

Table 3: Ideal Recipe for slumping 221mm substrates in 215B mandrel (in Oven 3)

	Stage 1	Stage 2	Stage 3
Temperature Rise (C/min)	15	9	5
Peak Temperature (C)	310	529	620
Time at Peak Temperature (min:sec)	0:00	3:00	11:00

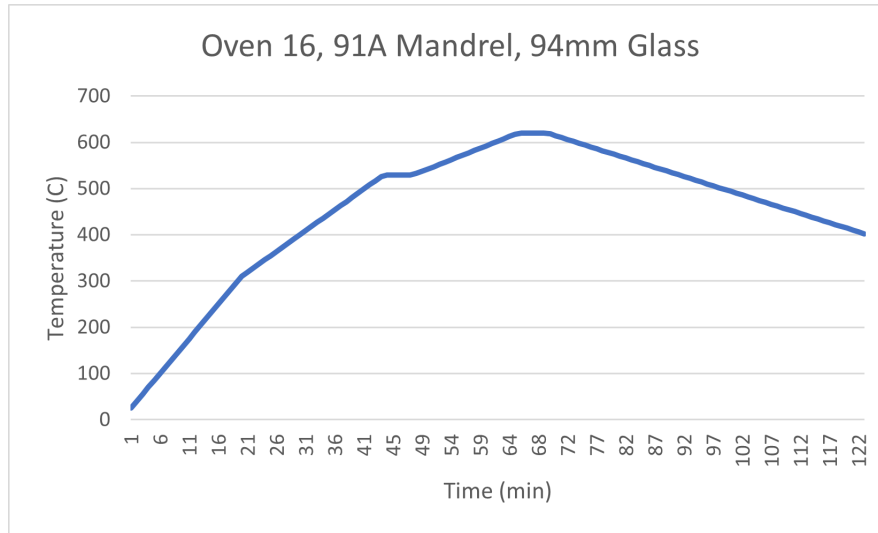


Figure 7: General Recipe for heating up the oven for 91A Mandrel substrates of glass

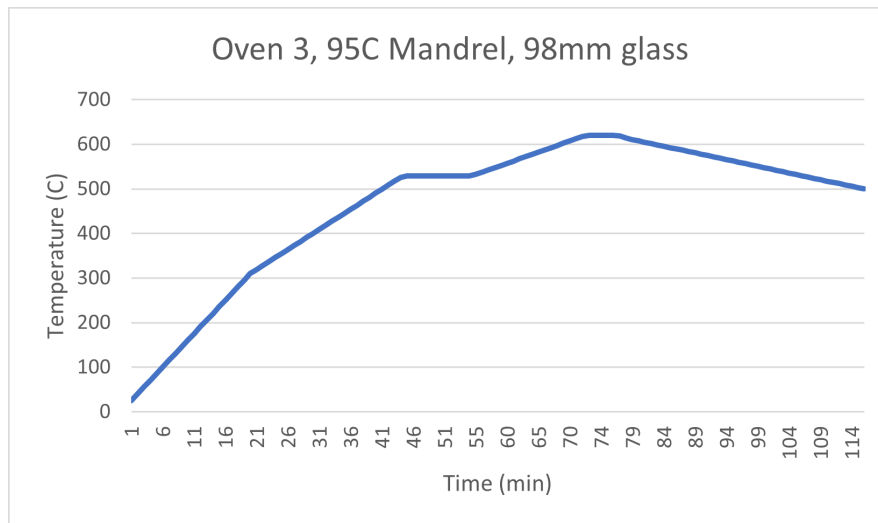


Figure 8: General Recipe for heating up the oven for 95C Mandrel substrates of glass

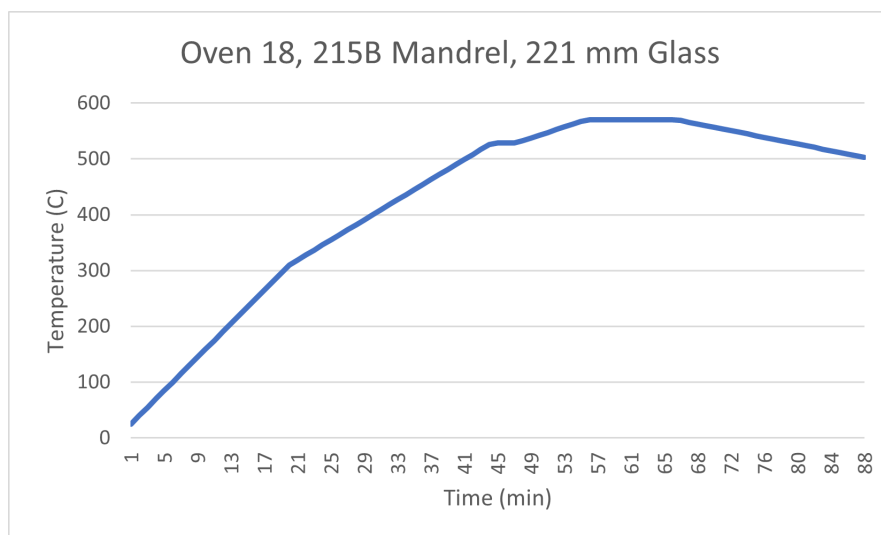


Figure 9: General Recipe for heating up the oven for 215B Mandrel substrates of glass

Glass Piece	Quality of Glass	Front end	Back end	Difference	Divots?
D16-614-0*	MS	78	78	0	no
D16-614-1*	MS	78	77.5	0.5	no
D16-615-0	NS	78	78	0	yes
D16-620-0	NS	78	78	0	no
D16-621-0	MS	78	78	0	no
D16-622-0	SS	78	78	0	no
D16-622-1	MS	78	78	0	no
D16-626-0	NS	77	77.5	0.5	no
D16-626-1	MS	79	79	0	no
D16-627-0	SS	79	79.5	0.5	no
D16-628-0	MS	79	78	1	no
D16-628-1	L	185	186	1	yes
D16-629-0	L	190	189	1	no
D16-705-0	L	185	185	0	no
D16-706-1	SS	84.5	82.5	2	no
D16-706-2	US	83.5	78.5	5	no
D16-710-1	MS	80.5	76	4.5	no
D16-710-3	US	85	78	7	no
D16-711-0	SS	79	84	5	??
D16-712-0	NS	78	78	0	no
D3-712-2	MS	79	78.5	0.5	no
D16-713-0	MS	79	79	0	no
D16-717-1	MS	79	78	1	no
D16-717-2	MS	78	78	0	no
D16-718-0	MS	82	78	4	no
D16-720-0	MS	79	77.5	1.5	no
D16-720-2	MS	78	78	0	no
D16-724-0	MS	79	77.5	1.5	no
D16-725-0	S	79	77	2	no
D16-725-3	MS	77	77.5	0.5	no
D16-731-1	NS	78	78	0	no
D18-731-2	L	185	186	1	maybe
D18-724-2	L	186	188	2	no
D18-725-2	L	185.5	185	0.5	no
D18-725-5	L	188	185	3	no
D3-706-3	MS	88.5	85	3.5	no
D3-706-0	S	80.5	78.5	2	no
D3-710-0	NS	83	82.5	0.5	no
D3-710-2	US	94	84	10	no
D3-711-1	SS	85	83	2	no
D3-712-1	SS	84	83	1	no
D16-712-3	MS	83.5	83	0.5	no
D3-713-1	S	85	82.5	2.5	no
D3-713-3	S	82.5	82	0.5	no
D3-717-0	S	87	82	5	no
D3-717-3	MS	82	82.5	0.5	no
D3-718-1	US	87.5	82.5	5	no
D3-720-1	SS	83	83	0	no
D3-720-3	S	83	83	0	no
D3-724-1	MS	82	82	0	no
D3-725-1	SS	81.5	81.5	0	no
D3-731-0	MS	82	82	0	no
D3-731-3	MS	82	82	0	unknown
D16-731-4	MS	78	78.5	0.5	unknown
D18-731-5	L	187	186	1	unknown

Table 4: The quality of each piece of glass.

Glass Piece	Soak ture	Tempera-	Soak Time	Thermalization Time	Thermalization Temperature
D16-614-0*	620		10:00	0:00	300
D16-614-1*	620		10:00	0:00	300
D16-615-0	620		3:00	3:00	529
D16-620-0	620		1:00	3:00	529
D16-621-0	620		2:00	3:00	550
D16-622-0	609		0:00	3:00	550
D16-622-1	620		2:00	3:00	509
D16-626-0	600		9:00	3:00	509
D16-626-1	600		14:00+/-1:00	3:00	529
D16-627-0	600		17:00	3:00	529
D16-628-0	610		7:00	3:00	529
D16-628-1	620		3:00	3:00	529
D16-629-0	570		11:00	3:00	529
D16-705-0	580		4:00	3:00	529
D16-706-1	600		14:00	3:00	529
D16-706-2	620		1:00	3:00	529
D16-710-1	620		2:00	3:00	529
D16-710-3	620		3:00	6:00	529
D16-711-0	620		2:30	3:00	529
D16-712-0	620		2:22	3:00	529
D3-712-2	620		3:33	10:00	529
D16-713-0	620		2:00	3:00	529
D16-717-1	620		2:22	3:00	529
D16-717-2	605		10:20	3:00	529
D16-718-0	605		8:40	3:00	529
D16-720-0	?		?	?	?
D16-720-2	620		10:00	3:27	529
D16-724-0	620		3:00	3:00	529
D16-725-0	620		4:00	3:00	529
D16-725-3	620		3:20	3:00	529
D16-731-1	620		4:00	3:00	529
D18-731-2	620		3:00	3:00	529
D18-724-2	570		10:30	3:00	529
D18-725-2	570		10:30	3:00	529
D18-725-5	570		10:30	3:00	529
D3-706-3	620		1	3:00	529
D3-706-0	620		2:30 - 3:00	3:00	529
D3-710-0	620		4:00	10:00	529
D3-710-2	620		1:00	3:00	580
D3-711-1	620		2:30	10:00	529
D3-712-1	620		3:32 +- 0:10	10:00	529
D16-712-3	620		2:30 +- 0:05	3:00	529
D3-713-1	620		10:00	10:00	529
D3-713-3	600		16:50 +- 0:03	10:00	529
D3-717-0	600		13:00	10:00	529
D3-717-3	600		18:32	10:00	529
D3-718-1	605		13:40	10:00	529
D3-720-1	620		3:27	10:00*	529
D3-720-3	620		3:00	10:00*	529
D3-724-1	620		4:00 +/- 0:20	3:00	529
D3-725-1	620		4:00	3:00	529
D3-731-0	620		4:00	3:00	529
D3-731-3	620		3:30	3:00	529
D16-731-4	620		4:00	3:00	529
D18-731-5	570		10:00	3:00	529

Table 5: Parameters for each piece of glass.

6 Acknowledgements

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