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and  
THE FIFTY-EIGHTH ANNUAL

**SYMPOSIUM  
ON THE  
ART OF SCIENTIFIC  
GLASSBLOWING**

**2013**



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THE  
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The American Scientific Glassblowers Society  
P.O. Box 453  
Machias, NY 14101  
Phone: 716-353-8062  
FAX: 716-353-4259  
natl-office@asgs-glass.org

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# Contents

## Papers

Design Mathematics for the Glass Shop By Richard Ponton .....	3
Glassblowing <i>in Situ</i> , Tools and Techniques By James R. Hodgson .....	19
The Physics of Blowing Glass By David G. Daenzer .....	25
Shop Talk: Design, Construction and Remodel of the Chemistry Department Glass Shop at University of Wisconsin-Madison By Tracy Owen Drier .....	35
Where Scientific Glass Is Trending and How Can We Adapt? By Michael J. Souza.....	45

## Other Information

2013 Technical Posters .....	53
2013 Technical Workshops.....	55
2013 Exhibitors .....	56
2013 Symposium Attendees.....	58

# Papers



# Design Mathematics for the Glass Shop

by  
Richard J Ponton\*

## ABSTRACT

*A discussion of basic geometric formulas such as volume and surface area and their use in the design of laboratory equipment.*

We as glassblowers are generally not called on to simply manufacture glass to predetermined designs. Often we are brought into the design phase of the equipment we eventually make. Part of these design consultations inevitably comes around to questions like: “What tubing will you use?” and “How long will that be?” as well as other similar questions.

Over the years, I have found myself more and more frequently calculating answers to these questions. Since I work for a consumer products development company, it is very important that manufactured items be of reliable and quantifiable size: a 1 liter vessel should hold 1 liter. The need for exact reliability and reproducibility is important should claims against patents ever arise.

Since nearly all glassware is a simple series of connected cylinders, spheres and conical shapes, and given that most of our glassware is used to contain liquid or gas or to insulate/transfer thermal energy, I rely frequently on calculations of volume and surface area.

In this paper, I will be covering some basic math equations that I use frequently in my design engineering prior to blowing any glass. This paper assumes a basic level of algebraic ability. I assume that everyone can move numbers and unknown variables easily from one side of an equation to another.

The first thing that should be stated is simply that one must carefully monitor the units while doing calculations. As glassblowers, we frequently deal with both metric and fractional dimensions, often on the same drawing; for example, a customer may request a 20 mm diameter test tube that is 9 inches long. From an engineering standpoint and from a mechanical standpoint, those numbers are rubbish and unworkable. Typically I do everything in my power to keep my inches and millimeters away from each other. Since our tubing is sold by metric numbers in most cases, I choose to convert all my drawings to metric values whenever possible. To convert a millimeter dimension to an American fractional dimension, the following conversion factor is used:

$$v_e = \frac{v_a}{25.4}$$

Where:  
 $v_e$  = value in inches  
 $v_a$  = value in millimeters

Another common confusion on units is in volume. As I said, in our industry we frequently use millimeters to denote most of our linear dimensions like length and diameter (such as a 150 mm tube, 520 mm long). We also use milliliters to denote volumes (a 10 ml vial

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\* The Procter & Gamble Co., R&D Support Services, 5289 Vine St., Cincinnati, OH 45217. Email: ponton.rj@pg.com.

or a 1000 ml flask). However, there is danger here.

1 milliliter = 1 cubic centimeter

1 cm x 1 cm x 1 cm = 1 cm<sup>3</sup> = 1 milliliter ( ml)

If you multiply in millimeters, however:

1 mm x 1 mm x 1 mm = 1 mm<sup>3</sup> = 1 microliter (μl)

When calculating volumes you must either convert your mm into cm *before* calculation, convert your μl into ml *after* calculation, or use a conversion factor built into your formula. I use conversion factors. In computer programming there is a common acronym: GIGO: Garbage in, garbage out. The theory is that you want to make sure that you create your code in a way that allows you to put values into your problem that are familiar to you, and then receive answers that are familiar to you. I want to be able to simply put millimeter values into a formula and get cubic centimeter values out. I will explain this more clearly when we get into the math.

Also, in geometry, all calculations done with a round object use the item's radius as opposed to the diameter. The radius of a circle is equal to one half the diameter of that circle and for the purpose of this paper, radii will be used for all the calculations. For reference:

$$r = \frac{d}{2} \quad \text{Where } r = \text{radius and } d = \text{diameter.}$$

## VOLUME OF A CYLINDER

By far the most commonly used formula in my shop is the formula to calculate the volume of a cylinder. Since our tubing is round, all of our glassblown equipment typically contains a series of cylinders, so this is quite handy.

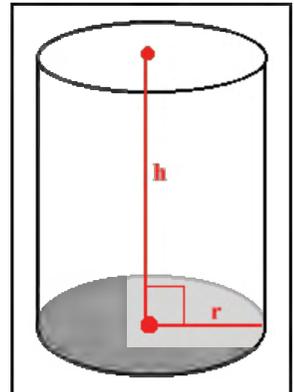
Where:

r = radius of the cylinder

v = volume

h = height of cylinder

$$v = \pi r^2 h$$



As an example: a customer requests a flat bottomed vessel that holds 3100 ml and is around 7.5" long. What tubing should the glass shop use? The first thing that must be done is the 7.5" dimension must be converted to a useful metric number:

$$\begin{aligned} v_e &= \frac{v_a}{25.4} \\ &= 7.5 = \frac{v_a}{25.4} \\ &= v_a = 190.5 \end{aligned}$$

The cylinder's height is now seen to be 190.5 mm. Once we have that value, we can then simply plug all known values into the formula, and after a little algebraic reconfiguration, isolate the variable and calculate. You will also notice the first use of the aforementioned

conversion factor which is the addition of the dividing of the problem by 1000. This effectively converts the cubic millimeters into cubic centimeters.

$$\begin{aligned}
 v &= \pi r^2 h \\
 &= 3100 = \frac{\pi r^2 190.5}{1000} \\
 &= \frac{3100(1000)}{\pi 190.5} = r^2 \\
 &= 5179.85 = r^2 \\
 71.97 &= r
 \end{aligned}$$

Rounding 71.97, we get a radius of 72 mm. Since the radius is half the diameter, we know the inner tubing diameter has to be 144 mm to hold the 3100 ml required. A quick check of the available tubing from our suppliers tells us that 150 mm tubing with a 3 mm wall will be the desired material.

### VOLUME OF A SPHERE

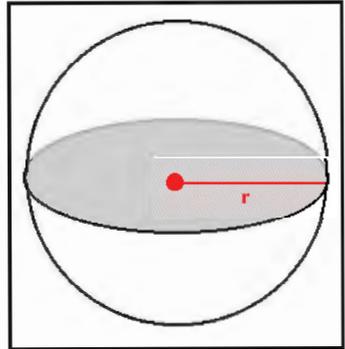
After cylinders, spheres are the next most common shape we use, both in the form of full spheres (flasks) and hemispheres (round bottoms).

A sphere's volume is equal to 2/3 the volume of the circumscribed cylinder (a cylinder the diameter of the sphere, with the top and bottom touching the top and bottom of the sphere as well).

$$v = \frac{4}{3}\pi r^3$$

An example of where this can be used would be: a customer requests a round receiving flask that can hold 1500 ml. How big around is the resultant flask?

$$\begin{aligned}
 v &= \frac{4}{3}\pi r^3 \\
 &= 1500 = \frac{\frac{4}{3}\pi r^3}{1000} \\
 &= \frac{1500(1000)}{\frac{4}{3}\pi} = r^3 \\
 &= 358098 = r^3 \\
 71 &= r
 \end{aligned}$$



The radius is 71 mm, so the flask would need an internal diameter of 142 mm. The outer diameter would depend on the customer's desired wall thickness.

## VOLUME OF A CONE

The next shape discussed is probably the least used, but it is important nonetheless: cones. The formula for a cone is yet another derivation of the cylinder formula. Mathematically, a cone's volume is equal to 1/3 of the volume of its circumscribed cylinder.

Where:

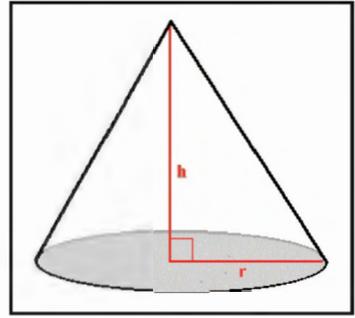
v = volume

r = radius at bottom of cone

h = height to tip

$$v = \frac{1}{3} \pi r^2 h$$

$$= v = \frac{\pi r^2 h}{3}$$



A sample use would be when a customer needs a conical end on a column 100 mm in diameter, 48 mm long. In this case, what would the volume of the conical end be?

$$v = \frac{\pi r^2 h}{3}$$

$$= v = \frac{\left( \frac{\pi 50^2 48}{3} \right)}{1000}$$

$$= v = 125.66$$

The volume of the cone rounds to 126 ml.

## VOLUME OF A CONICAL FRUSTUM

Knowing the volume of a conical frustum is far more applicable to glassblowers than that of a standard cone. A conical frustum is, simply described, a cone with the tip cut off. The math is a little more complex since you need to factor both radii.

Where:

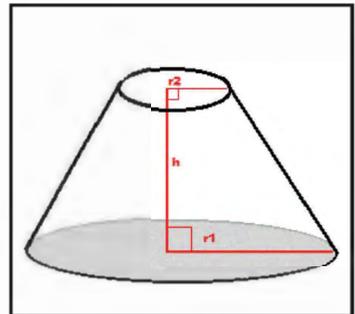
v = volume

R = radius at large end

r = radius at small end

h = height between circles

$$v = \frac{\pi (R^2 + Rr + r^2) h}{3}$$



So here I imagine a customer requesting a column with a conical end that tapers to a 4 mm stopcock. You are using 50 mm x 2.5 mm wall tubing. The taper will be 55 mm long. What

would the volume be of the bottom? Math below:

$$v = \frac{\pi(R^2 + Rr + r^2)h}{3}$$

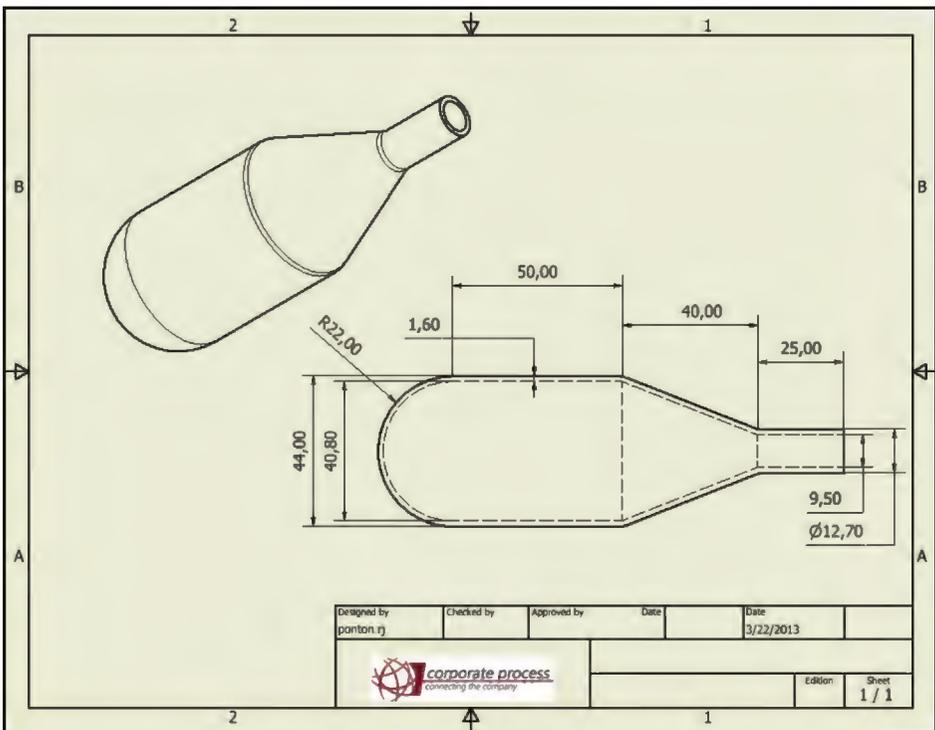
$$= v = \frac{\pi(22.5^2 + 22.5[2] + 2^2)55}{3}$$

$$= v = 31.98$$

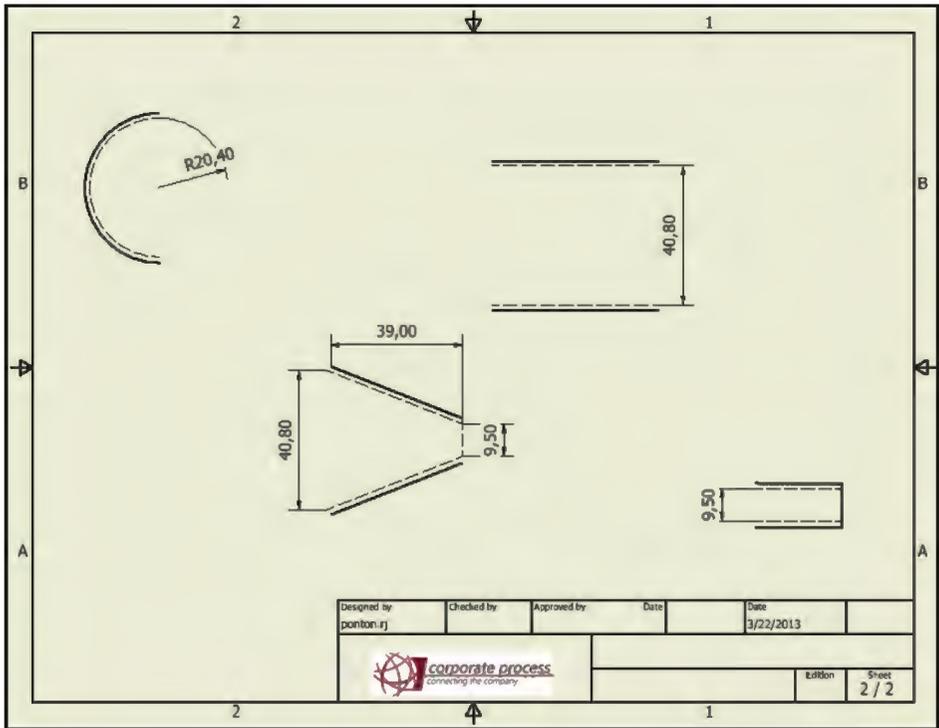
The volume here would be 32 ml.

### PUTTING IT ALL TOGETHER

Of course, volumes have additive properties, so when you are designing a complex piece of apparatus and there are straight sections mixed with round and tapered sections, the parts can be calculated separately and the resultant volumes can be added together. As an example, look at the sample vial shown below:



The part can be broken down into four separate sections: a hemisphere, a conical frustum, and two different cylinders:



Once the part can be visualized this way, it becomes a simple matter of calculating each component, then summing the four parts together. The formula then becomes:

$$v_t = v_s + v_{c1} + v_f + v_{c2}$$

Where:

$v_t$  = total volume

$v_s$  = volume of half sphere

$v_{c1}$  = volume of center cylinder

$v_f$  = volume of frustum

$v_{c2}$  = volume of top cylinder

The math:

$$v_s = \frac{4}{3}\pi 20.4^3 (.5) / 1000 = 17.78$$

$$v_{c1} = \frac{\pi 20.4^2 (50)}{1000} = 65.37$$

$$v_f = \frac{\pi 50}{3} (20.4^2 + 20.4[4.75] + 4.75^2) / 1000 = 6.79$$

$$v_{c2} = \frac{\pi 4.75^2 (25)}{1000} = 1.78$$

$$v_t = 17.78 + 65.37 + 6.79 + 1.78 = 91.72$$

The total volume of the sample vial shown is 91.72 ml.

## SURFACE AREA OF A CYLINDER

Moving on, we now look at surface area. In our industry, this is most common in the design engineering of heat exchangers and condensers. Here again, we need to talk about units. As earlier, all the unit warnings still hold true, but we also need to consider surface area values. Since all the calculations to follow use millimeters, our answers will come in the format of square millimeters. Conventionally in the US, we are used to seeing inches squared. In the documentation I provide customers with the quality assurance details of their equipment, I typically include both values. To find the square inch value of the unit, I convert my answer from  $\text{mm}^2$  to  $\text{in}^2$ . The conversion is:

$$a_e = a_o(0.00155)$$

Where:

$a_e$  = area in inches

$a_o$  = area in millimeters

We start with the surface area of a cylinder. The first and most important question to ask is exactly WHICH surface area you need. True surface area is the sides, top and bottom. Sometimes you only need parts of the surface area. The most commonly used part of the surface area in glassblowing is the lateral surface area, which is just the column part (visualize the center of a roll of tape). Sometimes you need to also consider the bottom (like a beaker) and sometimes you need the full surface area (like a soup can with the top still on).

The formula will suitably change depending on what part of the surface area you need:

$$a = 2\pi r h$$

$$a = 2\pi r h + \pi r^2$$

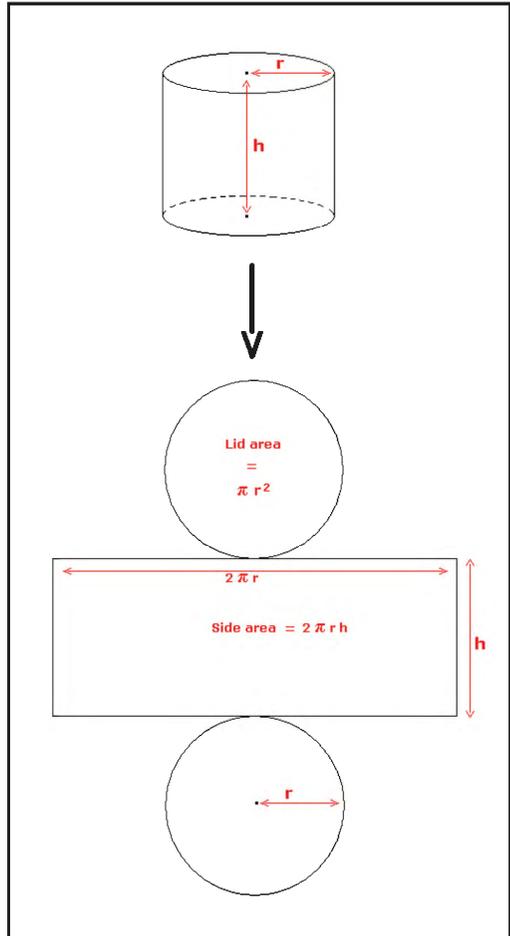
$$a = 2\pi r h + 2\pi r^2$$

Where:

$a$  = surface area (in  $\text{mm}^2$ )

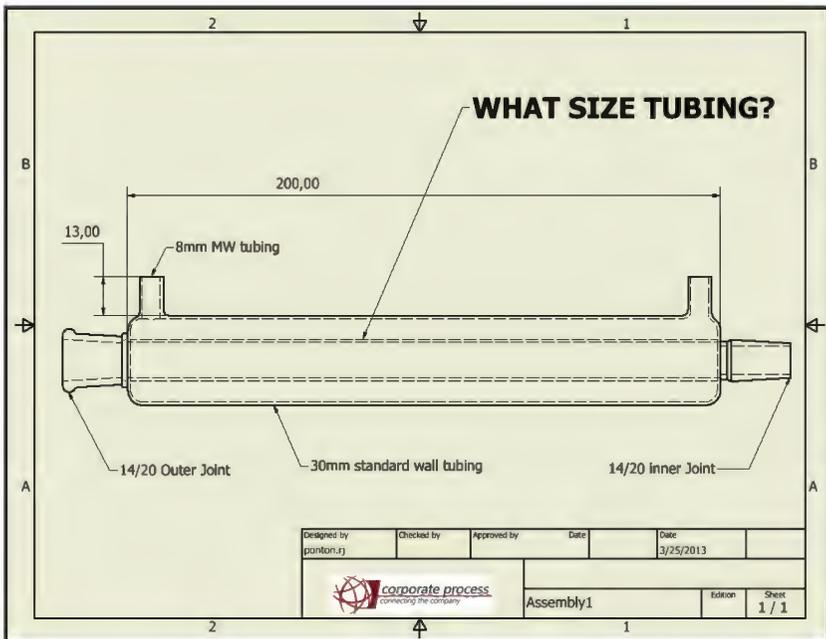
$r$  = radius

$h$  = height of cylinder



Looking at an example, let us say our customer wanted a condenser with a 200 mm path

length, and 7 in<sup>2</sup> of surface area.



The question here is: what size tubing do we use?

The first step will be to convert the fractional 7 inches<sup>2</sup> into millimeters<sup>2</sup>:

$$\begin{aligned}
 a_e &= a_o(0.00155) \\
 &= 7 = a_o(0.00155) \\
 &= a_o = 4516.13
 \end{aligned}$$

The requested surface area is 4516.13 mm<sup>2</sup>.

Since we are looking at an open ended tube, we are not looking at the top or bottom, so here we are calculating the lateral surface area only. Now that we know the metric surface

area, we can just plug our known values into the given formula, do the algebra, move our known's to one side, isolate the unknown (in this case radius) and we have our answer:

$$\begin{aligned} a &= 2\pi rh \\ &= 4516.13 = 2\pi r(200) \\ &= \frac{4516.13}{400\pi} = r \\ &= r = 3.59 \end{aligned}$$

Rounding down, we use a radius of 3.5 mm, which is a diameter of 7 mm. In this case, we were calculating the interior dimension of the tube. A quick check of our tubing stock shows that 9 mm standard wall has a 7 mm inner dimension.

## SURFACE AREA OF A SPHERE

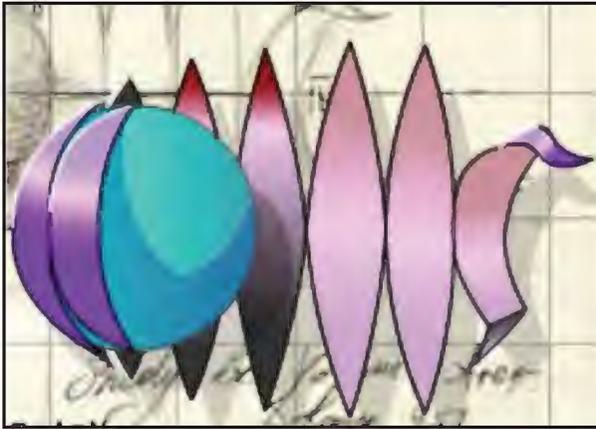


Image source: <http://www.nanofolio.org/win/size03.php>

A sphere's surface area is calculated with a pretty simple formula:

$$a = 4\pi r^2$$

Where:

a = surface area

r = radius

And of course, a round bottom is a hemisphere, and the value is divided in half.

As an example, let us calculate the surface area of a test tube 34 mm i.d. x 302 mm long with a round bottom end.

x 302 mm tube with round bottom has 285 mm of straight tubing, 17 mm of round bottom. So first we look at the round bottom alone:

$$a_x = \frac{4\pi r^2}{2}$$

Where:

$a_x$  = area of round bottom

$r$  = radius

Note: we divide by 2 because of the hemisphere

Then we calculate the surface area of the cylinder (lateral):

$$a_o = 2\pi rh$$

Where:

$a_o$  = area of tube (lateral)

$r$  = radius of tube

$h$  = height of tube

The math:

$$a_i = 2\pi rh$$

$$= a_i = 2\pi 17(285)$$

$$= a_i = 30442 \text{ mm}^2$$

$$a_x = \frac{4\pi r^2}{2}$$

$$= a_x = 2\pi 17^2$$

$$= a_x = 1815.84 \text{ mm}^2$$

$$a = a_i + a_x$$

$$= a = 30442 + 1815.84$$

$$= a = 32257.84 \text{ mm}^2$$

I then convert the  $\text{mm}^2$  value to  $\text{in}^2$  for the convenience of the client:

$$a_e = a_o(0.00155)$$

$$a_e = 32257.84(0.00155)$$

$$= a_e = 49.99 \text{ in}^2$$

The surface area is either  $32258 \text{ mm}^2$  or  $50 \text{ in}^2$ .

## SURFACE AREA OF A CONE

When calculating the surface area of a cone, we again need to think about the necessity (or lack thereof) of calculating the surface area of the base circle. Generally, in the glass shop, we do not need that part of the surface area; so once again, we are usually looking at the lateral surface area of a cone.

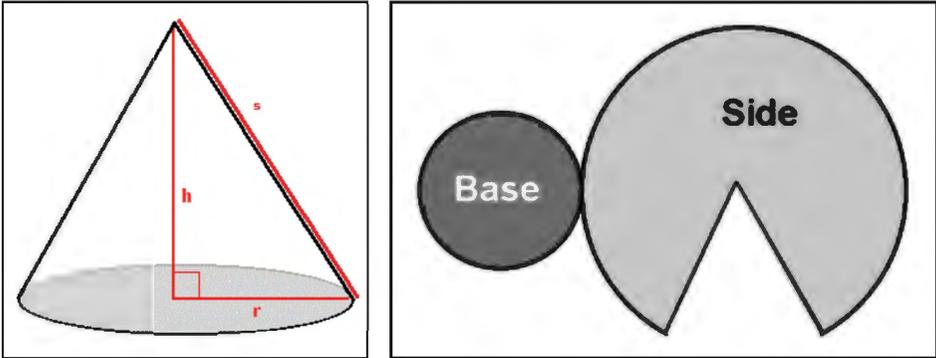


Image source: <http://www.nanofolio.org/win/size03.php>

Our formula is either:

$$a = \pi r s$$

$$a = \pi r s + \pi r^2$$

whether you need the lateral or full surface area, respectively.

Where:

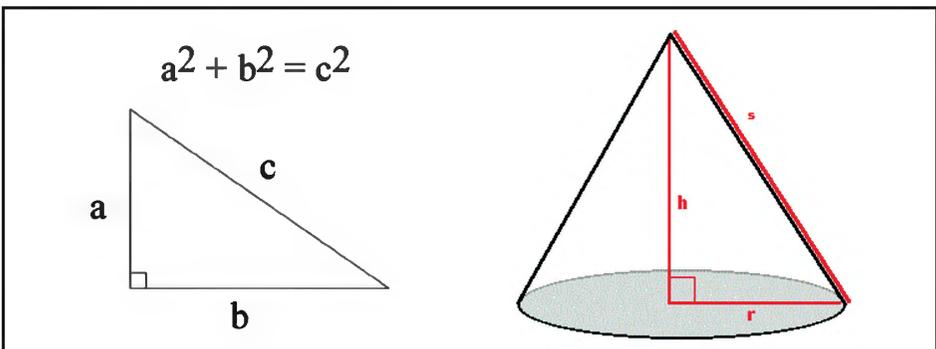
a = surface area

r = base radius

s = slant height

To calculate the surface area of the conical end of a dry ice condenser, we first look at the design specifications: our client here requests one with a 75 mm base and wishes it to be 60 mm long. Since it is open ended, we are looking at the lateral area. We need to find the slant height before we continue. With the radius and height we can find that out with a little trigonometry.

The Pythagorean theorem tells us that in any right triangle:



If we look at the diagram of the cone, we see that the radius, height and slant make up a right triangle, with the slant being the hypotenuse (c component) of the triangle. We can therefore use the Pythagorean Theorem to find the slant height:

$$s^2 = r^2 + h^2$$

$$= s = \sqrt{r^2 + h^2}$$

In the case of our example, our math works out thus:

$$s^2 = r^2 + h^2$$

$$= s^2 = 37.5^2 + 60^2$$

$$= s^2 = 5006.25$$

$$= s = 70.75$$

Once we know that the slant angle is 70.75 mm, we can find the surface area:

$$a = \pi r s$$

$$= a = \pi(37.5)(70.75)$$

$$= a = 8335.61$$

Converted to fractional:

$$a_e = a_o(0.00155)$$

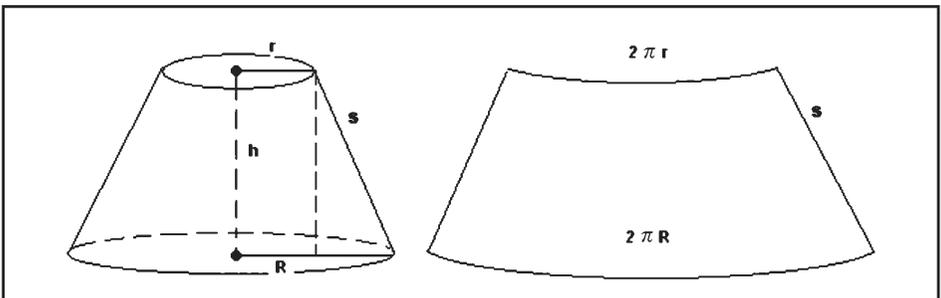
$$= a_e = 8335.61(0.00155)$$

$$= a_e = 12.92$$

I tell my customer that the surface area of the cone is either 8335.61 mm<sup>2</sup> or 12.92 in<sup>2</sup>.

### **SURFACE AREA OF A CONE FRUSTUM**

The surface area of a conical frustum like its volume is a bit more complicated since you need to account for the radii at both the top and the bottom.



To solve the lateral surface area of this shape, we modify the formula for the cone's area as follows:

$$a = \pi(r + R)s$$

Where:

a = area

R = large radius

r = small radius

s = slant height

h = height

And to find the slant height, we again use the Pythagorean Theorem, but likewise we need to make a modification:

$$\begin{aligned}(R - r)^2 + h^2 &= s^2 \\= s &= \sqrt{(R - r)^2 + h^2}\end{aligned}$$

To calculate the area, let us modify the example from our cone: 75 mm base diameter, 60 mm tall, but this time let us have it end not at a tip but rather with a 24 mm opening. The first thing we need to do is find our slant height:

$$\begin{aligned}s &= \sqrt{(R - r)^2 + h^2} \\= s &= \sqrt{(37.5 - 12)^2 + 60^2} \\= s &= \sqrt{4250.25} \\= s &= 65.19\end{aligned}$$

Now that we know the slant height is 65.19 mm, we can calculate the surface area:

$$\begin{aligned}a &= \pi(r + R)s \\= a &= \pi(12 + 37.5)65.19 \\= a &= 10137.6\end{aligned}$$

Converted to fractional:

$$\begin{aligned}a_e &= a_o(0.00155) \\= a_e &= 10137.6(0.00155) \\= a_e &= 15.71\end{aligned}$$

The frustum in question has a surface area of 10137.6 mm<sup>2</sup> or 15.71 in<sup>2</sup>.

It is also worth mentioning that in the example we only calculated the lateral surface area; if needed, you can add in the surface area of either the large base circle (R) or the

smaller circle at the top (r) or both:

$$a = \pi(r + R)s + \pi r^2$$

$$a = \pi(r + R)s + \pi R^2$$

$$a = \pi(r + R)s + \pi R^2 + \pi r^2$$

## DEALING WITH COILS

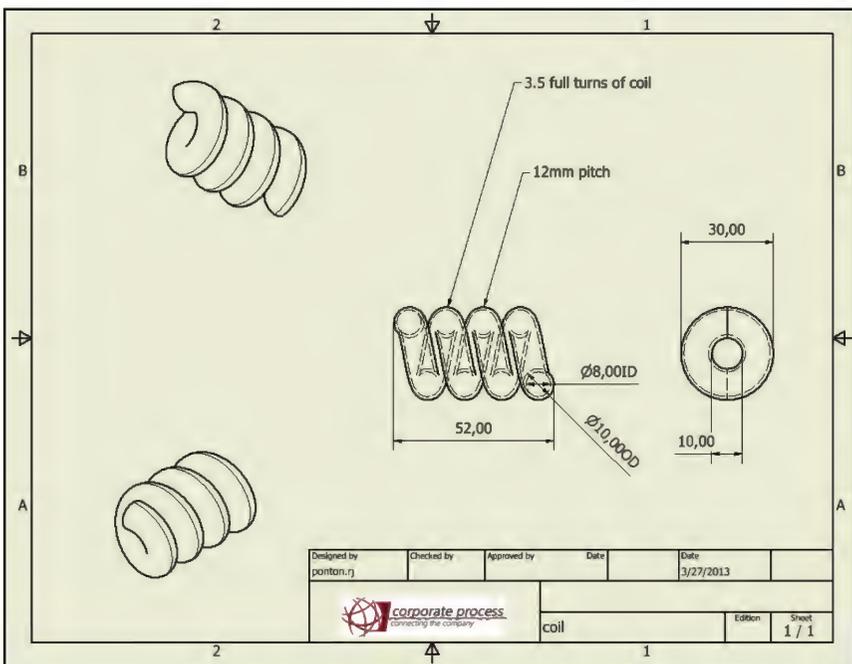
At the onset, trying to calculate the volume and area of a coil would seem daunting. There seems to be a lot of complexity: the tubing the coil is made of its i.d., its o.d., the coil's i.d. and o.d., the pitch, the number of turns, the pitch, length, center to center dimensions, as well as others.



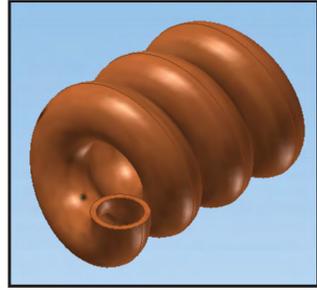
Realistically, a coil is not that complicated. It is at the end of the day nothing but a very bent up cylinder, and we can easily calculate those now, right?

All we need to do is mathematically straighten out the coil and we can calculate it as a long skinny cylinder. How do we do that? We need to once again fall back on the Pythagorean Theorem. This technique is a way to compare the number of coil wraps to the circumference of the circle that each coil ring makes up, while accounting for the number of individual rings made up.

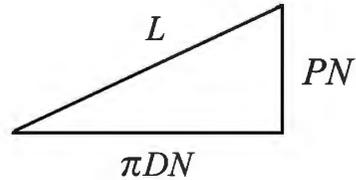
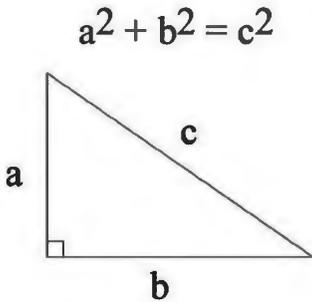
Let us use a small, short coil as an example:



This coil has a 30 mm o.d., 3.5 turns of coil, and a pitch of 12 mm. It is 52 mm long, and was made out of 10 o.d. standard wall tubing (8 mm i.d.).



As it turns out, calculating right triangles is a clever way to find many different types of numbers that have a proportional relationship to each other. Let us look at two triangles, our basic textbook example, as well as one with some information from our coil:



$$L^2 = (\pi DN)^2 + (PN)^2$$

In our second example, the “a” side of the triangle was replaced by “PN”, the “b” side with “ $\pi DN$ ”, and the “c” side with “L”:

Where:

D = coil outer diameter (tubing + mandrel)

N = number of turns

P = pitch

L = length of straightened out tube

If we “trig out” the triangle, we will get the exact length of the coil. A fun exercise to do with a coil you have is to plot the triangle on paper scaled 1 to 1, then cut it out. If you roll the triangle up along the long end (the  $\pi DN$  edge) and slide it over the coil, the L side will spiral down the coil exactly along the top edge of the coil.

Returning to the example we are working on, let us straighten out the coil with numbers:

$$\begin{aligned} L^2 &= (\pi DN)^2 + (PN)^2 \\ &= L^2 = (\pi 30[3.5])^2 + (12[3.5])^2 \\ &= L^2 = (329.87)^2 + (42)^2 \\ &= L^2 = 110576 \\ &= L = 332.5 \end{aligned}$$

Now that we know that there is a 332.5 mm cylinder smashed up in that coil, we can quickly calculate the volume and surface area:

$$\begin{aligned}
 v &= \pi r^2 h \\
 &= v = \frac{\pi 4^2 (332.5)}{1000} \\
 &= v = 16.71
 \end{aligned}$$

$$\begin{aligned}
 a_o &= 2\pi r h \\
 &= a_o = 2\pi 5(332.5) \\
 &= a_o = 10445.8 \text{ mm}^2 \\
 a_e &= a_o (0.00155) \\
 a_e &= 10445.8(0.00155) \\
 &= a_e = 16.19
 \end{aligned}$$

The coil has a volume of 16.7 ml, and a surface area of either 10448.8 mm<sup>2</sup> or 16.19 in<sup>2</sup>.

With all these formulas, glassblowers can quickly and easily provide their customers with specific data about their work, and also use this information to drive their design of equipment, matching their requirements to the glass materials available to the glass shop.

# Glassblowing *In Situ*, Tools and Techniques

by  
James R. Hodgson\*

## ABSTRACT

*General techniques, principles, planning and thought processes for glassblowing in place, outside the glass shop, will be addressed.*

## INTRODUCTION

*in situ* (in sīt' oo). *Latin*. In (its original) place

*in situ* (in sīt' oo). *Glassblowing*. Installing permanent glassware, usually a vacuum system, on a laboratory rack or framework. Rather than using demountable joints, the components are fused together using standard glassblowing techniques.

Although every installation job is different, it is helpful to have as much information as possible before commencing the work. Often it will be your own design, but sometimes it may be assembling prefabricated component sections of someone else's design.

These photos (Photos 1, 2, and 3) showing a completed installation and some of the



**Photo 1.** Typical photoreactor installation



**Photo 2.** Rough layout of parts



**Photo 3.** Clamps provided for assembly

\* Kansas State University, Department of Chemistry, 213 CBC Bldg, Manhattan, Kansas, 66506. Email: hodgson@ksu.edu.

component parts were emailed with the following request: "...My research group has a photoreactor that needs to be assembled. There are about 13 glass joints that need to be assembled. I attached a diagram of the photoreactor for you to look at. I am wondering if you would be able to do this and if so what do you think the best method is...."

There are some general principles for glassblowing *in situ* that will help the job go smoothly. They are as follows:

## GENERAL PRINCIPLES

- Prepare well and prepare for the worst
- Think about possible safety concerns
- Do hardest seals/parts/areas first
- Minimize blowing volume, isolate sections
- Clamp tightly before making seals
- Go over every seal twice
- Flame anneal – use a portable polariscope
- Relieve tension in inconspicuous areas
- Leak check, Tesla coil

Let us now review each of these separately.

## PREPARE WELL AND PREPARE FOR THE WORST

Make a supply list of everything you think you may need for the job. This is especially important if you are traveling several hours to get to the installation site. The following supply list is a good place to start:

### Measuring and Calculation

Protractor  
Vernier calipers  
Tape measure, meter stick, ruler  
Calculator  
Pencil and Sharpie®  
Paper

### Tools

Dremel tool and diamond bits  
Tip wrench (for hot tips)  
Nut drivers, metric/standard  
(for hose clamps)  
Crescent and tank wrenches  
Pliers and vise grips  
Hose clamps  
Allen wrench set  
Diamond files  
Scissors, bandage cutting style  
Tesla coil

### Glassblowing Tools

Didymium glasses  
Striker  
Tweezers, multiple sizes, self-closing  
Glass knife  
Tungsten picks with various shapes  
Graphite reamers, various sizes  
(very short can be useful)  
Rod rest (made from copper pipe hanger)  
Graphite plate  
Small graphite paddle  
Plurostopper with swivel  
Blowhose with swivel  
Extra long blowhose  
Various size silicone stoppers, especially small  
ones (inside bore of stopcock)  
Graphite/paper plugs for stopcocks (lightweight)  
Ring stand and assorted clamps  
Foil (also to cover components)  
Various wraps (working in tight quarters,  
need protection from fire checking )

## Torches and Associated

Small torch with disposable gas/oxygen cylinders and regulators

Bethlehem PME sharp flame torch  
(versatile torch without changing tips)

Stand to hold torch

Extra long hose for hand torch

Small oxygen cylinder and regulator

Natural gas cylinder and regulator

## Miscellaneous Supplies

Leather gloves (protection for short seals or flame splash)

White cotton gloves

Emery cloth

Stopcock grease

Teflon<sup>®</sup> tape

3M electrical tape (to provide temporary seals while glassblowing others)

Wire

Cullet bucket, dustpan, broom

Think about the sequence of operations. This can be as simple as running through things in your mind. It is sometimes helpful to write down the order in which you are going to do the work. This may help identify some corners you cannot get out of.

Prepare all your components and have extra parts ready if possible. If you are ready to seal on a stopcock and it slips out of your hand, you can only catch it on your foot so many times!

Have all the tools you think you will need readily at hand. Tungsten picks with bends or hooks grab the glass more easily and can reach more places than a straight tungsten. Pull down glass rod to a small diameter appropriate for filling a small hole. Short graphite reamers with flats ground on the taper allow you to reach places and enlarge holes that might be inaccessible with a longer reamer (Photo 4).



**Photo 4.** *Tools at the ready*

## SAFETY CONCERNS

Be aware of the area in which you are working. If you are working in an operating lab, there may be ongoing experiments. What are they and what problems might they pose? Are there compressed gas cylinders located nearby?

Look for the proximity of flammable items. Many reactions require solvents. Are there any flammable solvents in the vicinity?

Know where safety equipment is located. Where is the fire extinguisher? Where is the safety shower? Where are the exits?

Ask if there are things you should be made aware of before starting to work. Is the ventilation system working properly?

Make sure any used or contaminated systems are thoroughly cleaned of any potential hazardous or explosive residue. No one will look out for your safety like you do. Often non-glassblowers are not aware of the potential health problems contaminants can cause. Sometimes a solution can lead to a problem.....like cleaning with acetone!

## DO THE HARDEST PARTS FIRST

Figure out where the glassblowing will be most challenging. Do that part first while you are fresh and save the easier work for last.

Think about flame splash and protect vulnerable areas from fire checking. A fire check on



a stopcock body would be almost impossible to repair. Ceramic fiber wrap held on with wire can protect a stopcock or seal from flame splash (Photos 5 and 6).

**Photo 5.** *Protecting seals and stopcock*

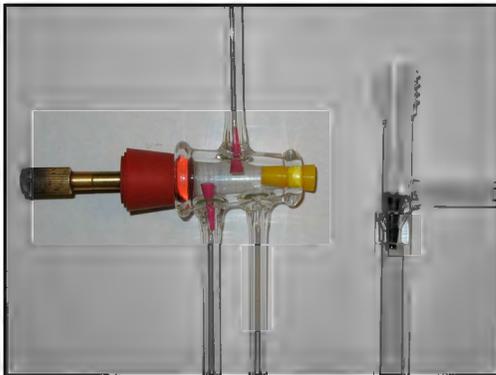
Do the back side or most inaccessible portion of a seal first. Avoid holes in the back side of a seal whenever possible by touching the back first and hinging forward. It is always easier to fix a hole on the side nearest you.



**Photo 6.** *Wrap protecting stopcock body*

## MINIMIZE BLOWING VOLUME

Large volumes result in a time delay when making a seal. When you blow, the pressure does not increase immediately and when you stop blowing the pressure does not decrease immediately. It can be quite frustrating or alarming when you are trying to blow and it appears you are not, or alternately, when you quit blowing but the hot glass in the area of the seal continues to enlarge. The solution is to decrease the volume by isolating areas as much as possible.



**Photo 7.** *Small stoppers isolate areas*

Isolate areas to be sealed with small stoppers, electrical tape or parafilm.

Block the bore of a stopcock or valve using a pair of tweezers and small silicone stoppers. These techniques may also provide an access point to blow. (Photo 7)

## **CLAMP TIGHTLY BEFORE SEALING**

A clamp which is loose may move after the job is completed. This may put physical stress on the glass which is not apparent but which leads to breakage down the road. Clamp holders and clamps should always be tightly secured.

Align the clamp jaws for the best grip on the glass and clamp the components firmly in place. Components should not move or wiggle.

Clamps should not be loosened or adjusted after seals are completed. Again, this may put physical stress on the glass which will lead to breakage just as surely as thermal stress.

## **GO OVER SEALS TWICE**

Spend extra time clearing the seal in hard to reach areas. Work small areas to offset the effect of gravity on the glass. This will help prevent sagging, and although the seal may not be quite as smooth, the wall thickness will be more even. Avoid abnormally thick or thin areas which may be hard to flame anneal.

Go over each seal twice. This technique, along with general cleanliness of the glass, will assure an absence of pinhole leaks when the job is finished.

## **RELIEVE TENSION AND FLAME ANNEAL**

If clamping must be done after sealing, then extra care must be taken to relieve any tension in the glass by allowing it to adjust itself. The smoothest appearance will result from heating a broad area gently and evenly.

Become comfortable and competent with flame annealing. Use the sodium flare and your previous experience as indicators of adequate annealing.

Spend extra time annealing hard to reach areas. The fact that they are hard to reach makes it more likely that you may not adequately flame anneal them.

Use a handheld polariscope when possible (Photo 8).

## **LEAK CHECKING**

A small vacuum pump with a variety of adapters and a Tesla coil are usually sufficient for leak checking. Use your eyes to spot possible problems and try checking the seals for leaks as you progress. Professional work is not complete unless you know the seals are good.



**Photo 8.** *Portable polariscope*

## ***FINIS***

Since the paper begins with Latin, I thought it should end with Latin as well. I do not believe you will need any help with the translation.

This is a picture of the finished photoreactor installation (Photo 9).



**Photo 9.** *Completed photoreactor installation*

## **ACKNOWLEDGEMENTS**

I would like to express my appreciation to Kansas State University and the Department of Chemistry for their support of the scientific glassblowing facility and their continuing encouragement in my professional endeavors. And to those glassblowers, who by example and teaching, encourage a desire to do good work.

# The Physics of Blowing Glass

## A Qualitative Discussion of the Forces Involved and Employed in the Glassblowing Process

by  
David G. Daenzer\*

### ABSTRACT

*Glassblowers use and react to many basic laws of physics. This presentation is a qualitative discussion of the forces involved in working glass: surface tension, thermal expansion, gravity, centripetal force, air pressure, and others. It is my hope that by thinking about the physical forces behind the process, the glassblower may gain some insight that will assist in the resolution of a problem or challenge.*

This paper will consider some of the forces involved in blowing glass. It will be qualitative in nature because it will not focus on numbers since glassblowers seldom use numbers when actually blowing glass. I will not be telling the glassblower anything that is not already known from experience. It is my hope that by thinking about the physical forces behind the process, the glassblower may gain some insight that will assist in the resolution of problems or challenges that arise.

I begin with the smallest forces, those at the atomic level. These are the forces, generally attractive, between atoms and molecules. Before looking at the atomic forces, I want to make a quick reference to molecular motion. Understanding this motion is useful since it helps to explain some of the behaviors of glass experienced during the glassblowing process.

Atoms are in constant motion at the temperatures we live with. This particular figure (see Figure 1) is more representative of a gas, but the atoms in solids are also in motion, more vibrating than actually moving around. As single molecules vibrate, the effect of the motion is the same. When the atoms or molecules are moving

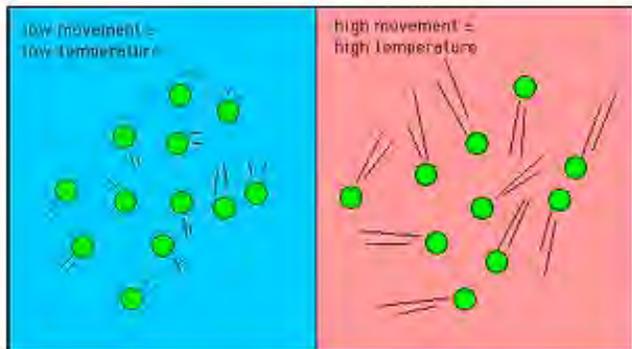


Figure 1

slowly, we measure a low temperature. Faster movement, or vibration, is measured as a higher temperature and indicates higher energy. At higher temperatures, the molecules bang into each other at higher speeds and take up more space. Think of a group of people standing quietly in a bunch, close together. If they start to move a bit, they bump into their neighbors and pretty soon the bunch has to use more floor area to accommodate the motion. In solids, like glass, more vibration of the molecules results in them taking up more space.

Atomic forces are responsible for atomic structure. The atomic structure of glass may be represented by Figure 2.

This is not a borosilicate glass, since there are no boron atoms. It does give the idea of the relative size of various atoms and more importantly, the concept that the structure is random. But there is still a structure. The molecular bonds are represented by the black lines and very light bands. Notice that there is a strong  $\text{SiO}_2$  structure, the black, white, and pink dots, with the  $\text{Na}^+$  and  $\text{Ca}^{2+}$  ions stuck into the  $\text{SiO}_2$  structure. This is typical of glasses. In a borosilicate glass, the boron ion would be found in the structure where the sodium and calcium ions are found in this diagram.

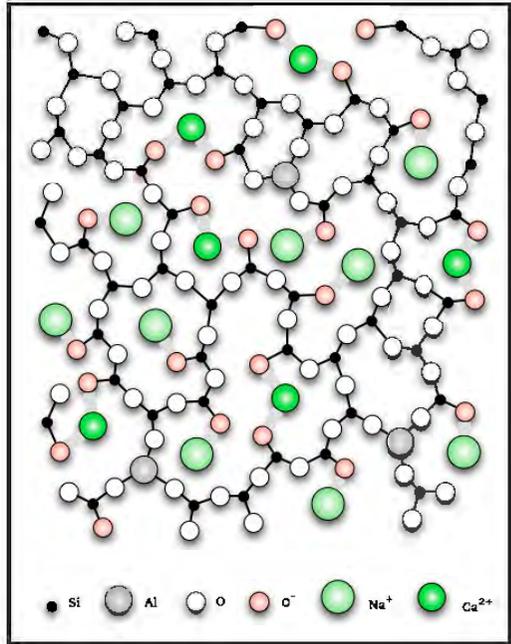


Figure 2

The atomic structure of glass gives glass its specific properties. They are not true forces, but they may be thought of as forces because they do affect the movement of glass when it is being worked.

Let us begin, briefly, with viscosity. Viscosity might be defined as a measure of a fluid's resistance to flow. The viscous state in glass is achieved by heating it. Glass is a nice material to work with because it has a relatively large range of changing viscosity with temperature. Once it begins to soften, more heat, more energy, results in less viscosity, a more fluid material. Remember, the molecular bonds are still there holding the glass together, but as temperature rises, some of the bonds are broken and are rearranging.

The atomic structure and forces are also responsible for surface tension. Surface tension is a subtle "force" that has a major impact when working the glass. It is one of the most useful properties of glass.

Figure 3 is a representation of a drop, let us say of water. It can also represent the end of a piece of fire polished glass rod or a cross section of the edge of a piece of tubing that has been fire polished. Atomic forces cause materials to move to the lowest energy situation possible.

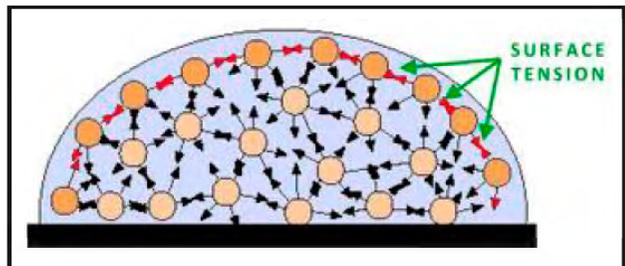


Figure 3

The atoms and molecules in the bulk of the mass, those with all black arrow bonds in the diagram, experience a neutral environment since they are surrounded by neighboring molecules. Those on the surface, lacking neighbors on one side, have more bonding with their

surface neighbors, the red arrows. This is referred to as cohesion. Adhesion refers to the bonding between the drop and the surface it is on. Adhesion is not generally a concern for the glassblower, except perhaps in the case of glass-to-metal and glass-to-ceramic seals. It turns out that the lowest energy situation results in a sphere. Of course, the drop is on a surface in the diagram so there is some adhesion between it and the surface. Gravity is also a factor. While this picture (see Figure 4) is not reality, it gives a good idea of a drop with no adhesion to the surface on which it sits. It displays the notion of surface tension and gravity in equilibrium.



Figure 4

The details of Figure 5 are not directly related to glass, but it illustrates the concepts of cold seal and glass flow. The upper Figure would be a cold seal. It depicts a tenuous connection with the surface. The sharp contact angle is important to note. You might consider the black line as a lever that can pop the drop off the surface. This is similar to the situation with a cold seal where a bit of sideways pressure on the seal will cause failure. It is essentially a levering situation. The lower Figure would represent a “good” seal. Notice that the contact angle is useless as a lever.

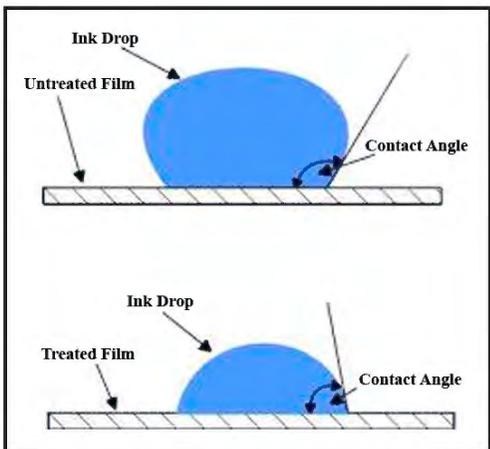


Figure 5

In a fused glass seal, there is no contact angle. Surface tension, the lowest energy situation, results in a nice smooth joint. Rather than a treated surface, a smooth joint in glass is achieved by applying sufficient heat to get the molecules on the surface of two pieces of glass moving fast enough to break their bonds and rebound to the other piece of glass. Then surface tension will move the glass to form a smooth joint.

In conclusion, surface tension is the “force” that causes the rounded ends on glass rods, smooth joints, and uniform cylinders. It is not by accident that so much glassware is symmetric: surface tension is part of the reason.

Thermal expansion, more correctly, thermal linear expansion, is another property resulting from the structure of glass. The term, coefficient of expansion, (COE) is used to refer to its measurement. It may also be referred to as (CTE), coefficient of thermal expansion. Thermal expansion is always a major concern when blowing glass and may rightly be thought of as a force. It has broken many a piece of glassware. A good deal of time is spent compensating for it and it affects how the glass is handled and worked. Remember, as the glass heats up, the heat imparts energy to the molecules and they start to

move, i.e., vibrate, more. The more they vibrate, the more space they take up. The glass expands. These asymmetric vibrations are dependent on the chemical composition and bonding in the glass. Soda-lime glass has a relatively large, open structure that leads to a large coefficient of expansion. Quartz is rather organized with a fairly tight structure leading to a low coefficient of expansion. Borosilicate glass is in between on the tightness of the structure and therefore falls between when it comes to thermal expansion.

Thermal expansion affects the design of the pieces we make. It is a consideration for both the construction phase and the use of a particular item. One example of a compensation for thermal expansion is the spiral (see Figure 6).



Figure 6

Think of it as a spring, and it does indeed have a bit of springiness. A typical use is in a spiral condenser (see Figure 7).

Granted, the spiral in a spiral condenser is primarily there to increase surface area for better heat transfer, but it also ensures that the condenser will not fail due to thermal expansion of the inner component. Another compensation for thermal expansion is the glass bellows (see Figure 8).



Figure 7

Glass bellows are sometimes necessary in longer condensers with straight tube inner components or where there is an extreme temperature difference between the interior component and the exterior tube. It is not just in the final use but also during construction that thermal expansion is a consideration. A number of years ago, someone was making very long condensers. While the final use would



Figure 8

not have been a problem, the condensers were breaking during the annealing process. It was essentially a case of the oven ramping up too quickly. The outer tube was heating and expanding faster than the inner tube. The laws of physics explained the problem and presented the solution. Slow down the ramping to allow the inner tube to heat at the same rate as the outer so that both tubes would expand at the same rate.

Thermal expansion is also responsible for stress and strain in glass. Thermally induced stress is the result of fast cooling through the transition range of the glass. At temperatures above the transition temperature, the structure becomes more open, expanded. Fast

cooling through the transition temperature locks in this slightly expanded structure that has a different coefficient of expansion. In the cooled piece, the competing coefficients of expansion of the various sections of glass result in residual stress.

The solution is annealing. The process of annealing is to raise the temperature above the transition temperature and then slowly cool through the transition range. Slow cooling allows the structure to settle into its lowest energy state before it becomes locked into position. The result is a homogeneous mass with the same structure and therefore the same coefficient of expansion throughout.

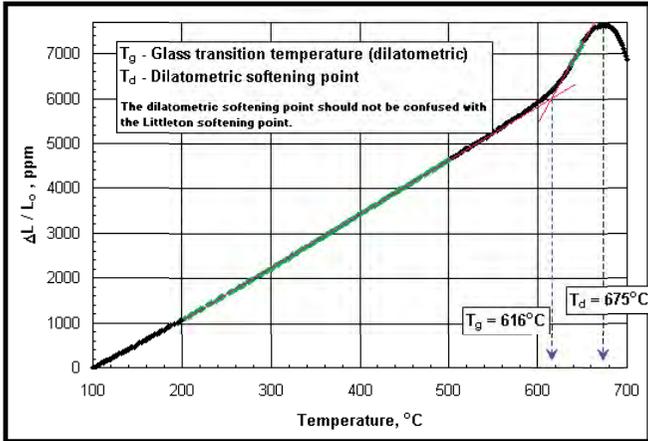


Figure 9

Figure 9 is an expansion curve for a glass.

This is a qualitative discussion, so the numbers on the graph are not the focus. However, in looking at them, this could be a borosilicate glass. The shape of the curve is of interest for our discussion. Temperature is on the x-axis, the bottom. Change of length is on the y-axis, vertical. Beginning from the left,

the first part of the graph is relatively straight and represents solid glass. The section where the curve turns up is the transition range, and it is really a range. The transition temperature is determined as the intersection of the two red lines that are extensions of the slopes of the regions on either side of the transition range. Though slightly arbitrary, it is a reasonable and consistent method to determine a specific temperature for transition. Just remember that transition is a range, the whole curved section, not just a specific temperature. Notice that the slope to the right of the transition range is steeper than on the left. It is typical for glass expansion rates to increase at higher temperatures. The structure is beginning to change. It is more open and bonds are breaking down. It has a different coefficient of expansion. Recall that it is fast cooling that locks in this more open structure leading to residual stress. The top of the curve is the softening point. The change of length starts to fall off as the glass becomes viscous, and workable. Coefficient of expansion no longer has any meaning. It should be noted that repeated working or extended working at higher temperatures and even repeated annealing will eventually change the coefficient of expansion of the glass. This is because some of the alkali ions will move around changing the structure of the glass.

A secondary effect of repeated working and annealing is phase separation (see Figure 10, next page).

A homogeneous structure is ideal. Phase separation results in silica-rich and borate-rich sections in the glass that lead to changes in the coefficient of expansion in the relative areas. Repeated high temperatures only exacerbate the situation. In quartz glass, devitrification, a separation between the amorphous phase and the crystalline phase of the glass, occurs.

One final comment on coefficient of expansion related to glass-to-metal seals is warranted. While glasses generally have nice straight line expansion up to the transition range, many metals do not. While a metal's coefficient of expansion might match a glass and while it might work at the sealing temperature and at room temperature, if the expansion curves are too mismatched, failure will occur during the cooling process. Consider the Invar

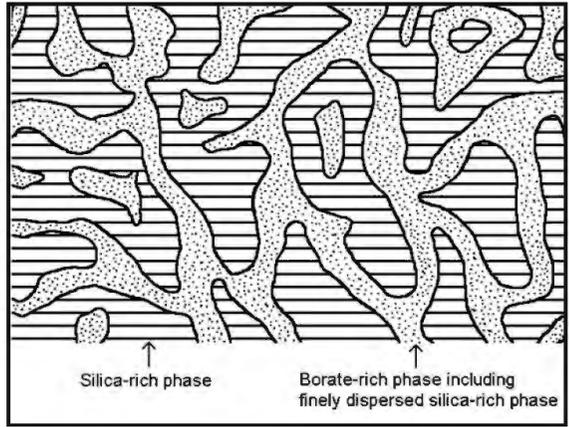


Figure 10

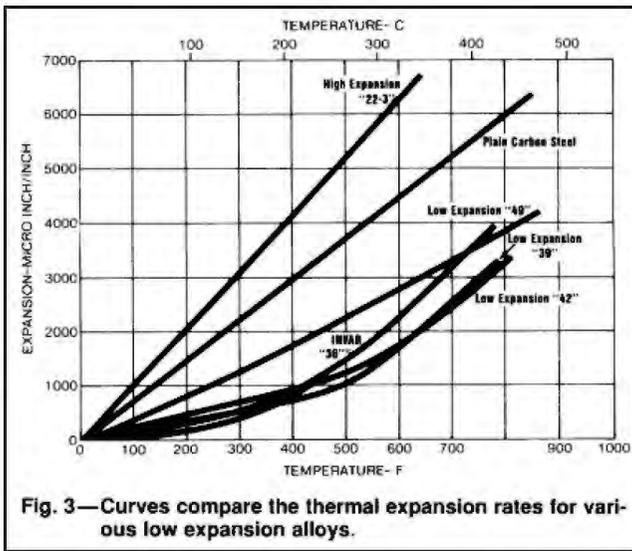


Figure 11

curve and a straight curve as seen in Figure 11.

Failure at 400° is likely.

I mention brittleness more in relation to handling the glass rather than actually working it, although it does have an impact on cutting and grinding. Again, it is explained by the structure. Recall this representation of a typical glass (see Figure 2).

A representation of quartz glass (see Figure 12) shows that while still a bit vari-

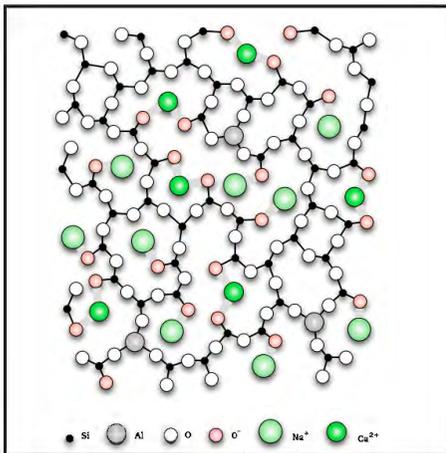


Figure 2

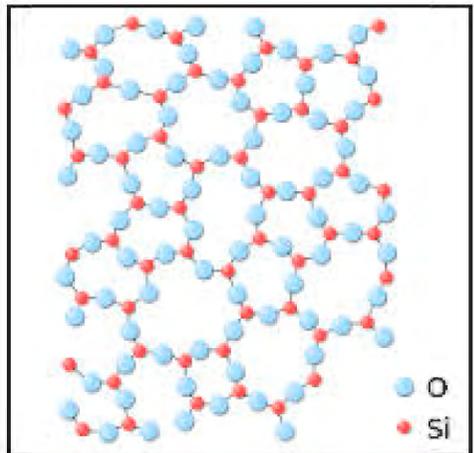


Figure 12

able, because it is amorphous, the structure is much more closely organized. It is approaching the rigid structure that we would see in a quartz crystal. Crystals are brittle because they have very clean lines of bonds and are prone to cleavage along those lines. If the cut edge of a piece of quartz tubing is tapped on a table, it will invariably crack. Borosilicate is less likely to do so. And based on structure, a soda-lime glass should be even less likely to crack. The “softer” the glass, appropriately called softer, the less brittle it is because the structure is more random and does not contain cleavage lines.

The first force to consider at the macro level is gravity. Gravity is the attractive force between two objects that have mass. In glassworking, earth’s gravity is the only one of importance. Consider the figure of the man in Figure 13 as a section of soft glass.

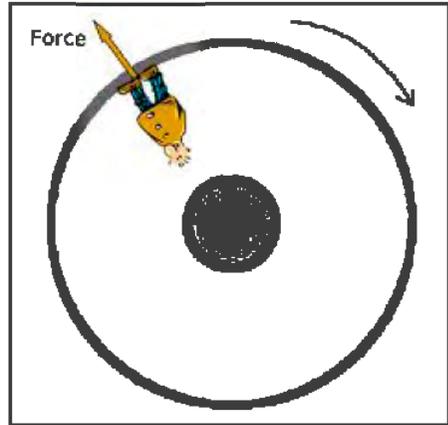


Figure 13

Gravity pulls him down. Rotation pulls him back up. By changing the speed of rotation, gravity is used to move the glass to the required area. By controlling the speed of rotation or angle of a piece of work, gravity can be used to pull or sag the glass in the desired direction. Consider what working in a weightless environment might be like. While it would be quite interesting, one would soon realize how useful gravity is in the glassblowing process.

I have one aside on vacuum rack *in situ* work. Here, gravity is generally a problem since one cannot rotate the glass. Something to remember is that surface tension is a relatively strong force. If there is sufficient mass of glass above a seal, surface tension will smooth out the joint, even pulling a thinner amount up before gravity moves the glass if the entire area has not been heated too much.

Differential air pressure is a primary means of moving glass around. This is typically balancing or unbalancing the air pressure on the inside and outside of a vessel.

Atmospheric pressure, although it varies somewhat, is a relative constant in glass working. In an open vessel, by that I mean a vessel that has at least one opening to the atmosphere, the air pressure inside and outside are the same atmospheric pressure. We can change the relative air pressures by one of two methods. We can blow, which effectively increases the internal pressure of the vessel and causes it to expand, or we can suck, which reduces the internal pressure so that atmospheric pressure causes the vessel to collapse. The situation is the same for a closed vessel but it is a bit more difficult to control the relative internal and external pressures in this case. Keeping molecular motion in mind, faster moving molecules, air or any other gas that is enclosed in the vessel will take up more space. Slower moving molecules take up less space. Heating the closed vessel will cause the molecules to move faster, take up more space, and cause the vessel to expand if the glass is molten.

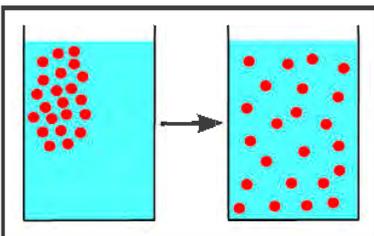


Figure 14

Heating the closed vessel will cause the molecules to move faster, take up more space, and cause the vessel to expand if the glass is molten.

In Figure 14, if the closely grouped dots on the left were encased by molten glass and they were heated,

they would move faster, take up more space, and expand as represented on the right. The encasing glass would expand. Too much heat with softened glass and a closed vessel glass gives the result seen in Figure 15.



Figure 15

If the closed vessel is allowed to cool while the glass is soft, collapse is the result. As the air molecules inside the vessel slow down, take up less space, and reduce the internal pressure, atmospheric pressure pushes in the walls of the vessel (see Figure 16).

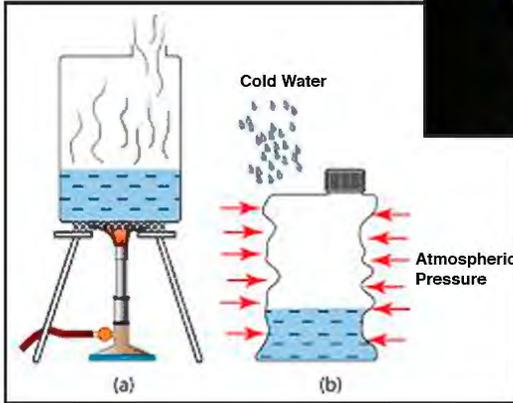


Figure 16

In the closed vessel, it is a matter of balancing the internal and external pressures by applying heat to the vessel.

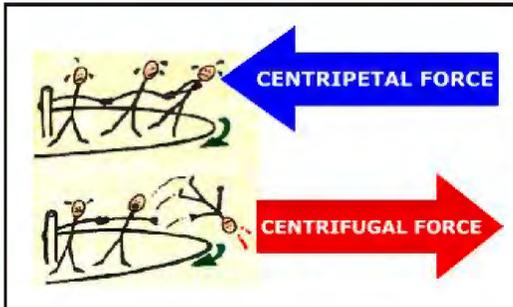


Figure 17

Centripetal/centrifugal force is relevant to spinning glass by hand or in a lathe. Centripetal force keeps objects moving in a circular path rather than “flying off” (see Figure 17).

Centrifugal force causes things to fly off. Centrifugal force is really a misnomer since there is not an outward force in any of the situations we are seeing. It is actually a case of inertia that causes the object to continue on a straight line path (see Figure 18).

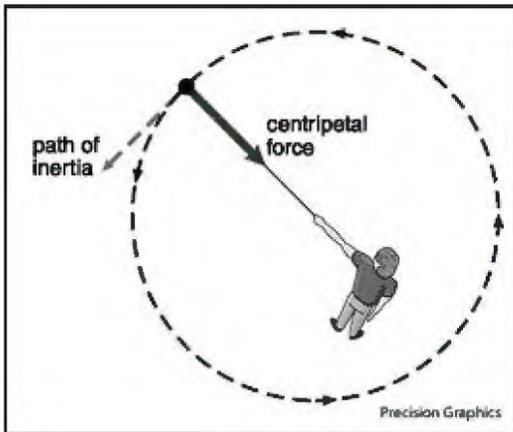


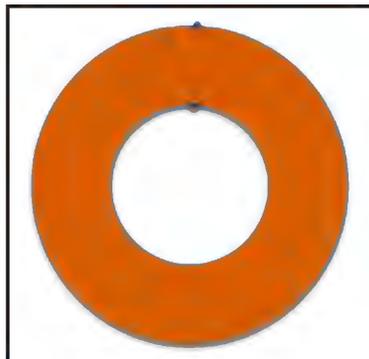
Figure 18

A view from above of the man in Figure 17 who is falling off the merry-go-round would show him following a straight line path of inertia as shown in Figure 18.

Looking at Figure 19, it is clear that the dot on the inside of the orange donut will cover a shorter distance than the one on the outside if the donut

were to make one revolution. If the donut were spinning, the outer dot would be moving faster, covering more distance in the same time than the inner dot and would therefore

have more inertia. It would take more centripetal force to keep the outer dot moving in a circle. It is relatively easy to spin out large tubing because it is large. The inertia of a section of glass on the tubing is high because it is moving fast. In one revolution, it covers the distance of the circumference of the tubing,  $\sim 3.14 \times$  the diameter. A spot on 100 mm tubing would travel about a foot in one revolution. It is quite easy to spin it fast enough to overcome surface tension and flare out or expand the tubing. A spot on capillary tubing covers almost no distance in a revolution. Surface tension will always win out. It would be next to impossible to spin it fast enough to expand the tubing. The control of inertia and centripetal force can be a useful method to manipulate glass when differential pressure is not an option.



**Figure 19**

The flame itself is a force. Two aspects of the flame impart forces to the glass: flame velocity and flame direction.

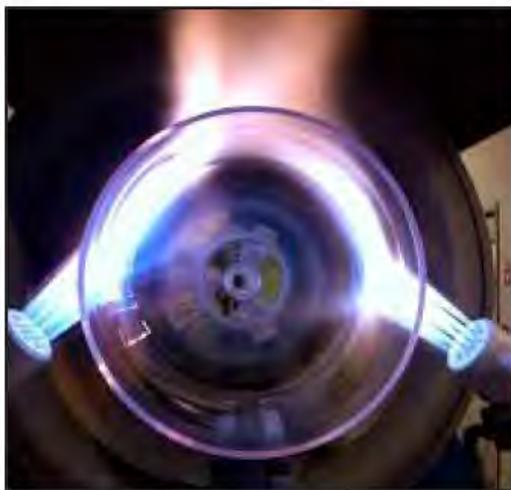


**Figure 20**

The speed of the combustion gases in a sharp flame can physically push molten glass around. A bushy flame with lower speed combustion gas molecules will provide heat with less direct movement of the molten glass.

A sharp flame pointed at the axis of a tube will tend to push it in since the combustion gases are impinging directly on the tubing (see Figure 20).

A tangential flame, impinging at a glancing angle will move the molten glass less (see Figure 21).



**Figure 21**

Mechanical force is where human energy is put into the process. This involves pushing, pulling, bending, and sticking glass together. The glass can be tooled, usually with graphite rods or paddles. It can also be molded (see Figure 22, next page).

Glass is a material in the physical world, subject to the forces of its environment. It must be worked in that environment. One will be better able to control and use these forces with an understanding of how they act and interact. Most glassblowers know from experience what I have shared here. It



Figure 22

is my hope that this presentation has provided the opportunity to think about aspects of the process from a different perspective and that it may better equip the glassblower to address the inevitable issues that arise when blowing glass.

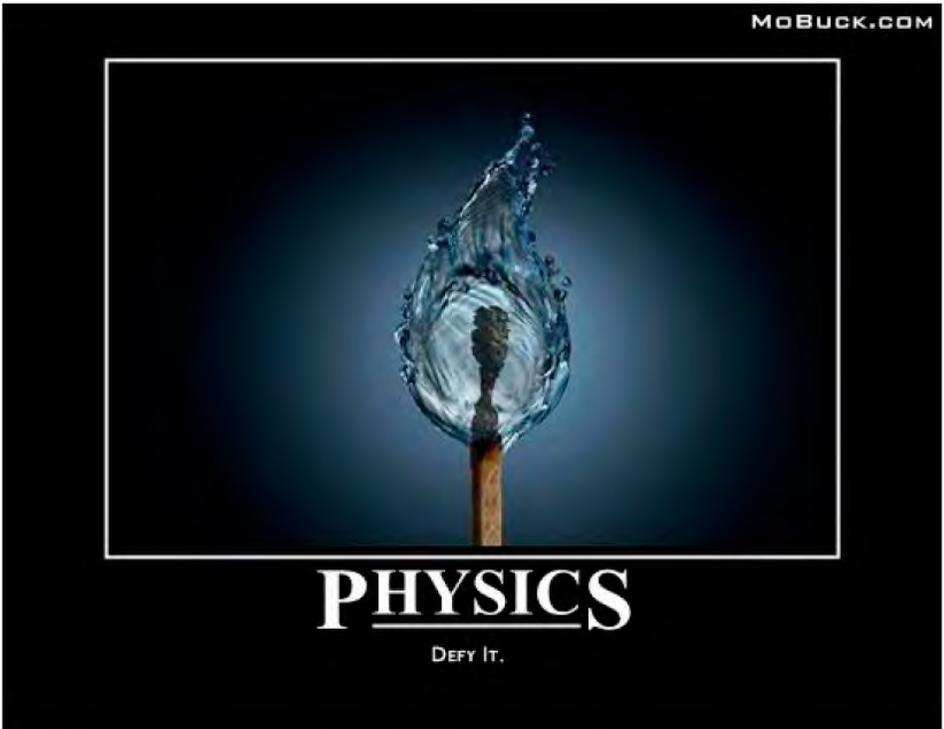


Figure 23

# Shop Talk: Design, Construction and Remodel of the Chemistry Department Glass Shop at the University of Wisconsin-Madison, Summer-Fall 2012

by  
Tracy Owen Drier\*

## ABSTRACT

*The opportunity to relocate and design a glass shop is an exciting challenge. In the late summer of 2012, I was given that opportunity. Changes were made to improve the shop layout, work flow, customer interactions, and safety. This paper will outline these changes as they relate to the remodel of the Chemistry Department's glass shop.*

## INTRODUCTION

This will be the third glass shop that I have occupied at UW-Madison and the second move since I began working in the Chemistry Department in 2000. The first move was presented at the 54th ASGS Symposium in 2009 in Vancouver, Washington and can be found in that year's *Proceedings*.

The current Chemistry Department building is shown in Photo 1. Photos 2-6 (next page) are the two earlier shop configurations.



**Photo 1.** *UW-Madison Chemistry Building*

\* University of Wisconsin – Madison, Chemistry Department, 1101 University Ave., Madison, WI 53706.  
Email: [drier@chem.wisc.edu](mailto:drier@chem.wisc.edu).



**Photo 2.** Glass shop, circa 2000



**Photo 3.** Glass shop, circa 2000



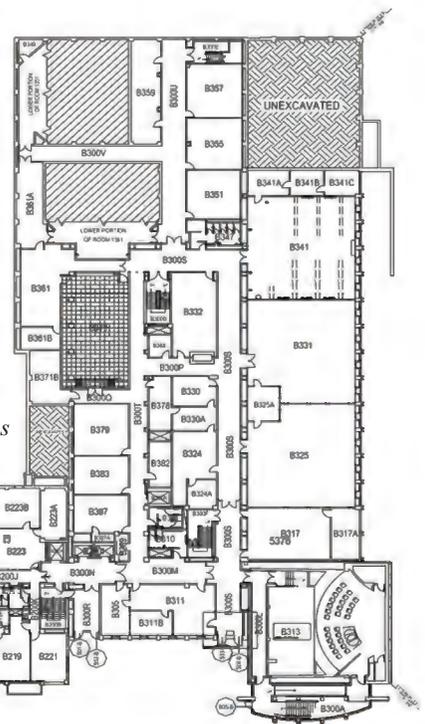
**Photo 4.** Glass shop, 2000 - 2012



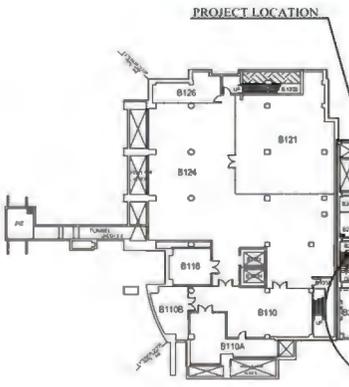
**Photo 5.** Glass shop, 2000 - 2012



**Photo 6.** Glass shop, 2000 - 2012



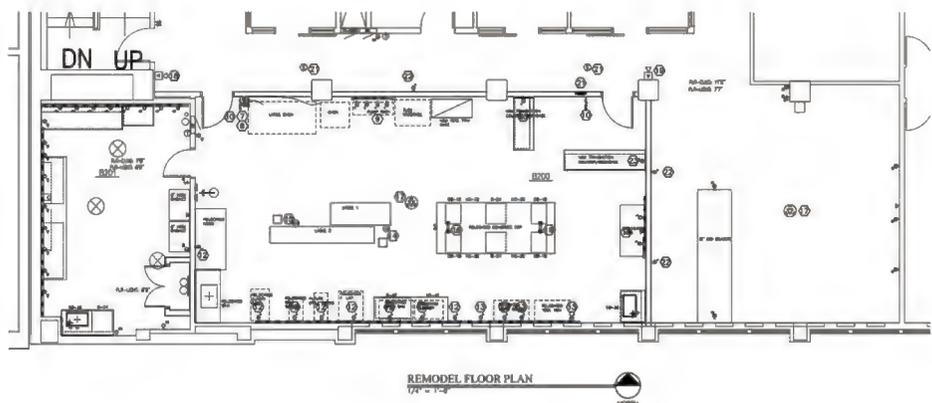
**Photo 7.** New Glass Shop Location



The new glass shop location is highlighted in Photo 7. It is at street level.

As soon as I learned of the move, I knew that I needed to be proactive in the shop design so that it would not be designed for me. I took a look at what had worked in the last space and what could be improved in terms of work flow, shop layout, safety (ventilation) and piping.

To begin, I took measurements of all the equipment that was to be moved as well as the dimensions of the new space. Using graph paper, I created a scale model of the new shop with all of the equipment that needed to fit. At this point it was easy to manipulate the equipment into the fixed space layout to analyze work flow. Once I had the equipment layout established, I obtained the vendor catalog for casework and cabinetry and began deciding on casework. Working off the catalog dimensions, I also created scale models of these pieces to make sure that everything fit. The next Monday I was able to give this layout to the design engineer to show what I needed my shop to look like. This scale modeling process was the most significant thing I did during the entire project: it set the tone that I was going to be involved, and let the design engineer know that there are certain things that a glass shop requires that are unusual compared with a “typical” lab. Photo 8 shows the new shop layout.



**Photo 8.** *New glass shop layout*

## BEFORE

The new glass shop would be located in what was one half of the Physical Chemistry Laboratory. Photos 9 and 10 show photographs of the space before remodeling.



**Photo 9.** *New glass shop, before*



**Photo 10.** *New glass shop, before*

## **SAFETY**

Ventilation was an issue that was critical to me. This was necessary for both respiratory health and physical comfort. It is necessary to exhaust gasses such as nitrogen oxides and carbon monoxide, extremely small particles (silicon oxide and boron oxide) as well as heat. Canopy hoods would be needed at the burner sources as well as over the annealing/burn-out ovens.

Proper chemical handling safety also dictated a fume hood.

National safety regulations for chemistry labs require a certain number of air changes per hour. For the sake of safety, I asked for the maximum ventilation possible from the given practical limitations of the building's air handling system. The new glass lab is on the ground floor and the air handling equipment is on the roof so there was a practical limitation as to how much ventilation was possible; it was, however, more than double the required air changes for a typical chemistry lab, so I was happy.

Ventilation hoods over specific equipment are shown in Photos 11 – 14.



**Photo 11.** *Ventilation, fume hood*



**Photo 12.** *Ventilation, oven hood*



**Photo 13.** *Ventilation, lathe hoods*



**Photo 14.** *Ventilation, bench hood*

The large work bench island is where I also teach an introductory scientific glassblowing course during the spring semester. A sliding glass screen was added to deflect torch vapors up and into the hood rather than direct them to the student across the island. The glass is typical window glass, and when National hand torches are used, there have been no issues. Photos 15 and 16 show the sliding windows in position and in use. Sliding them into their home position out of the way keeps the bench open for laying out larger projects (Photo 14).



**Photo 15.** *Ventilation, sliding shields*



**Photo 16.** *Ventilation, sliding shields*

## PIPING

Gas piping is 1-1/2" black pipe at 5 PSI. Individual lines are run to the manifolds at each lathe and the bench. The oxygen delivery is through 3/4" brazed copper.

The existing oxygen manifold was relocated (Photo 17) to the new shop. Normally OFF solenoid valves for the gas and oxygen lines with panic buttons at each entrance are shown in Photos 18 and 19.

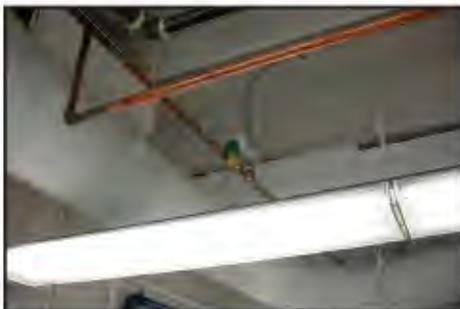
The large manifold blocks from the last shop were reused (Photo 20). The gas valves on these manifolds were replaced with ball valves to provide maximum flow.



**Photo 17.** *Piping and safety, oxygen manifold*



**Photo 18.** *Piping and safety, gas shut-off valve and solenoid*



**Photo 19.** *Piping and safety, oxygen shut-off solenoid*



**Photo 20.** *Piping and safety, reused piping manifolds with quick connects*

## DEMOLITION AND RECONSTRUCTION

Photos 21–40 (next page) show the general sequence of deconstruction and rebuilding the new shop. The Department glass shop was down for 2 1/2 months while construction was going on. A temporary location at the UW art glass lab (Photo 38) allowed glass work for the Chemistry Department to continue throughout construction.



**Photo 21.** Demolition of old physical chemistry lab for new glass lab



**Photo 22.** Demolition of storage area



**Photo 23.** Demolition



**Photo 24.** Reconstruction, laying up shop walls



**Photo 25.** Reconstruction, painting



**Photo 26.** Reconstruction, tile



**Photo 27.** Reconstruction, setting casework, long sink



**Photo 28.** Reconstruction, setting casework



**Photo 29.** *Reconstruction, casework for customer service area*



**Photo 30.** *Reconstruction, casework for central island bench*



**Photo 31.** *Reconstruction, setting in glassworking equipment*



**Photo 32.** *Reconstruction, ventilation piping*



**Photo 33.** *Reconstruction, glass tubing storage (white) and glass components storage*



**Photo 34.** *Reconstruction, casework in storage area*



**Photo 35.** *Reconstruction, view into storage area*



**Photo 36.** *Reconstruction, hanging hoods over lathes*



**Photo 37.** *Reconstruction, hanging hood over island work area*



**Photo 38.** *Temporary work area at the UW Art Glass Lab.*



**Photo 39.** *Reconstruction, wet working area*



**Photo 40.** *Reconstruction*



**Photo 41.** *Moving in*



**Photo 42.** *Moving in*

The finished lab is shown in Photos 43 – 53.



**Photo 43.** *Central work island*



**Photo 44.** *Entrance to storage room*



**Photo 45.** *Storage room area with oxygen tank room (white)*



**Photo 46.** *Storage room area*



**Photo 47.** *Storage room with specialty tubing storage (blue) and cabinets*



**Photo 48.** *Wet working area*



**Photo 49.** *Lathe working area*



**Photo 50.** *Administrative area*



**Photo 51.** *Tubing storage cabinet and glass components storage*



**Photo 52.** *Flat glass working area*



**Photo 53.** *Workshop area with tools and mechanical parts storage*

## **ACKNOWLEDGEMENTS**

I would like to thank the University of Wisconsin – Madison Chemistry Department for their continued support and encouragement.

# Where Scientific Glassblowing is Trending and How Can We Adapt?

by  
Michael J Souza\*

## ABSTRACT

*This paper proposes the thesis that in the near future, if we want to enhance our earning potential, scientific glassblowing has to transform from a highly skilled manufacturing base and into a specialized service industry for new research and technology. During this transformation, being a member of the ASGS will play a substantial role in one's success.*

## PREFACE

The opinions expressed here by me are based on 40 years' experience as a scientific glassblower. Nearly half of my time was spent working in private industry and the rest as the glassblower at Princeton University. So while it is said that, "To a hammer, everything looks like a nail..." I will try and support this thesis by looking at the past and describing trends that indicate there may be some basis for my hypothesis.

### The Golden Age of Scientific Glassblowing 1940's to 1970's

Beginning in the 1940's the world was at war, and in the aftermath, the United States was the lone economy that had not been ravaged as a result of World War II. What followed was a longer more abstract conflict known as the Cold War. The battlefield was not as much between soldiers as it was for scientific and technological advantages.

By the 1940's, **electronic glassware** was an enormous source of jobs in scientific and industrial glass manufacturing. This field had ushered in new technologies such as radar, microwave, television and computers. All of these components required glass vacuum tubes. The job was tedious as most of the tubes were fabricated in assembly line fashion. However, the fallibility of the tubes (due primarily to burnt out filaments) and their demand assured the industry plenty of work.

A case in point is the ENIAC (Electronic Numerical Integrator And Computer). ENIAC was designed to calculate artillery-firing tables for the United States Army's Ballistic Research Laboratory and was first used to calculate statistics for modeling the hydrogen bomb.<sup>1</sup> It contained 17,468 vacuum tubes, 7,200 crystal diodes, 1,500 relays, 70,000 resistors, 10,000 capacitors and around 5 million hand soldered joints. It weighed more than 30 tons and took up more than 1,800 square feet.<sup>2</sup>

Several tubes burned out almost every day, leaving it nonfunctional about half the time. Special high-reliability tubes were not available until 1948. Most of these failures, however, occurred during the warm-up and cool-down periods when the tube heaters and cathodes were under the most thermal stress. Engineers reduced ENIAC's tube failures to

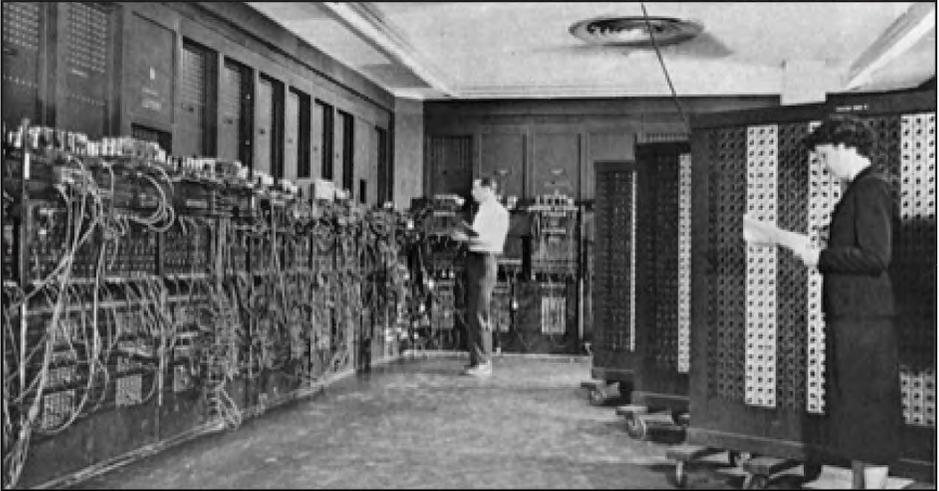
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\* Department of Chemistry, Princeton University, Princeton, NJ 08544. Email: mjsouza@princeton.edu.

<sup>1</sup> ENIAC's first use was in calculations for the hydrogen bomb. Moye, William T. (January 1996). "ENIAC: The Army-Sponsored Revolution." US Army Research Laboratory. Retrieved 2009-07-09.

<sup>2</sup> <http://encyclopedia2.thefreedictionary.com/ENIAC>. Accessed: May 19, 2013.

the more acceptable rate of one tube every two days. According to a 1989 interview with Eckert, “We had a tube fail about every two days and we could locate the problem within 15 minutes.”<sup>3</sup> In 1954, the longest continuous period of operation without a failure was 116 hours—close to five days.



**Photo shows the ENIAC** (Photo courtesy of U.S. Army)



**Detail of the back of a panel of ENIAC, showing vacuum tubes. This was taken from the computer lab, which has a glass window to the back of the piece of ENIAC on display at the Moore School of Engineering and Applied Science, at the University of Pennsylvania.**

<sup>3</sup> Alexander Randall 5th “A Lost Interview With ENIAC Co-inventor J. Presper Eckert.” *Computer World* (14 February 2006): 3. [http://www.computerworld.com/s/article/108568/Q\\_A\\_A\\_lost\\_interview\\_with\\_ENIAC\\_co\\_inventor\\_J\\_Presper\\_Eckert?taxonomyId=12&pageNumber=3](http://www.computerworld.com/s/article/108568/Q_A_A_lost_interview_with_ENIAC_co_inventor_J_Presper_Eckert?taxonomyId=12&pageNumber=3). Accessed: May 19, 2013.

<sup>4</sup> Original photo courtesy of the curator, released under GNU license. Copyright 2005 Paul W. Shaffer, curator of the University of Pennsylvania ENIAC Museum.

## FIFTY YEARS LATER

By the 1960's the vacuum tube was quickly being replaced by small transistors about the size of miniature jellybeans. They issued in new products like the transistor radio and at the same time ushered out a whole segment of glass industry jobs in electronic glassware. By the 1970's electronics were reinvented once more as the age of semiconductors quickly replaced the diode transistor. And on the 50th birthday of the invention of ENIAC, the University of Pennsylvania recreated the mammoth sized computer with all of its functions on a silicon chip. This chip would be smaller than a postage stamp measuring just 7.44 by 5.29 sq. mm, a chip which uses a 0.5 micrometer CMOS technology.

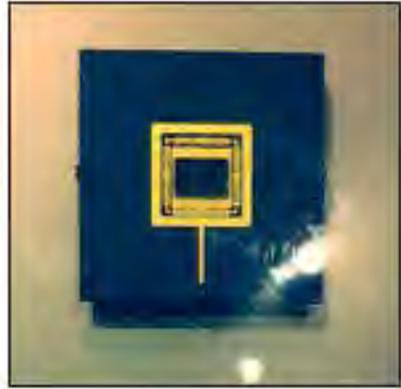
The salient point is that research and displacement technology had evolved in just 20 years from the vacuum tube to the transistor and next to the semiconductor. In our small niche of this universe, glassblowers were first essential in the development of the vacuum tube. However, with the advent of the transistors, our skills were quickly irrelevant. Yet, in the decade that followed, semiconductors proved to be a more disruptive technology. As a result, it created an entirely new demand for scientific glassblowers. Unlike the previous transistors, the ones grown on semiconductor chips are not products that can be stamped out and welded on assembly lines. Instead, chips are grown and hatched in pure quartz glassware.

Indeed this new industry now required a more proficient type of glassblower. One who could fabricate quartz glass to exacting tolerances and build the furnace tubes, boats, carriers and all of the associated infrastructure required to process semiconductors. Those low paying assembly line jobs on stem presses were replaced by highly skilled and well paid glassblowers who could fabricate quartzware. More importantly, the age of the digital revolution was born.

## ADVANCEMENTS IN CHEMISTRY

Since the days of Alchemy, glass and chemistry seem to have a natural affinity with each other, like a hand and glove. Fifty years ago, it seemed every major university with a chemistry department employed at least one or more scientific glassblowers in their department just to sustain all of the glassware required for the laboratories and the research groups. In addition, most chemistry doctoral programs required in-house glassblowers to teach scientific glassblowing to graduate students. Large pharmaceutical companies and chemical companies not only employed but also often groomed their own staff of scientific glassblowers.

That is no longer the case. The world has gotten smaller in many ways: the transportation of goods and services has centralized production. Trade barriers are no longer an issue and products can be shipped to most any location overnight. The digital age with



**ENIAC on a Chip, University of Pennsylvania, US, 1995.** *In celebration of ENIAC's 50th Anniversary, the machine was reimplemented using modern integrated circuit technology. The room-sized computer could now fit in the palm of your hand. Gift of Jan Van Der Spiegel and the University of Pennsylvania, 102719916*



**NMR Machine**



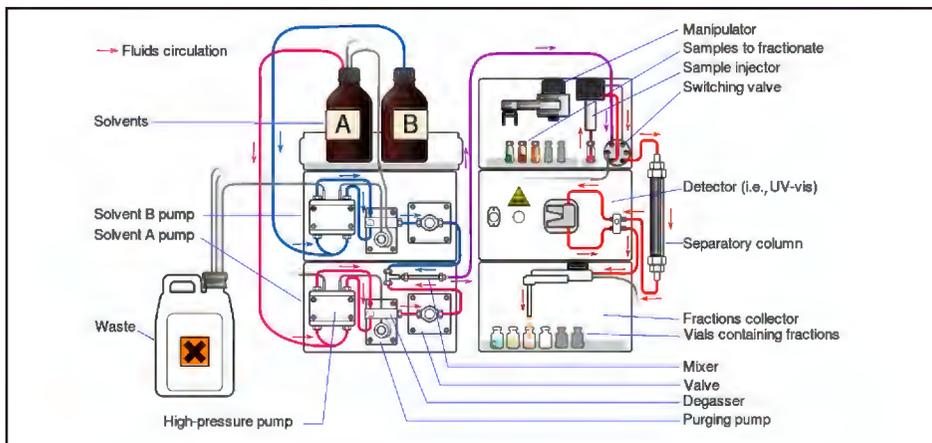
**NMR Tube.** *While the machine itself is often massive, the glassware required is miniscule.<sup>5</sup>*

Google, email, faxes, smart-phones, and videos connects the user to the provider instantly. So if it can be out on a shelf, it can be purchased when it is required. That means less inventory requirements for the customer. Instead, it puts the cost onto the supplier. And when technology switches quicker than ever that is an important efficiency. None of this of course is unique to our industry.

However technological advancements in analytical chemistry and in chemistry research as a whole have radically reduced both the size and scope of glassware required in industrial, pharmaceutical and academic chemistry labs around the world.

The foremost change has come from a technique known as **NMR (Nuclear Magnetic Resonance) Spectroscopy**, a technique that exploits the magnetic properties of certain atomic nuclei. It determines the physical and chemical properties of atoms or the molecules in which they are contained.

This single advancement now reduced the product requirement to test and characterize new compounds to just a few teardrops (about 1 inch of sample inside a 5 mm test tube). Traditional “wet chemistry” downsized into “minimumware” or “microware” kits. As a result, chemists can begin in volumes as small as 50 cc to 100 cc flasks. No longer would labs require liters of materials to distill, fractionate or purify in a tedious and expensive research process. Now that glassware could become smaller, it became cheaper and more easily replaced as new.



**Chromatography Schematic<sup>6</sup>**

<sup>5</sup> Photos and graphics courtesy of Wikipedia.

<sup>6</sup> Photos and graphics courtesy of Wikipedia.



**Chromatography** is not a new technique. It is both preparative and analytical. It separates the components of a mixture and can be used for analysis, or purification for use in a new compound. The premise is to create a mobile phase by one method and transfer it to a structure material to maintain the component in a stationary phase. It is a productive and elegant technique commonly used in organic chemistry to synthesize new drugs and chemicals. In most case, the glassware required for this process is primarily a lengthy test tube also known as a separatory column.

However, in the past twenty years due to the use of software and new technology, we have seen many new variations added to this technique that require little glassware. Indeed presently the following forms of chromatography are available to researchers:

- Liquid
- Gas
- Paper
- Planar Thin Layer,
- Chiral
- Fast Protein
- Counter Current
- Two Dimensional
- Reversed Phase
- Expanded Bed
- Size Exclusion
- Ion Exchange
- Super Critical
- Affinity, etc.



**Combinatorial Chemistry**<sup>7</sup>

#### **Separatory Column**<sup>7</sup>

Another advancement was **combinatorial chemistry** which is a sophisticated set of techniques used to synthesize, purify, analyze, and screen large numbers of chemical compounds, far faster and cheaper than was previously possible. Whereas classical synthetic chemistry involves the stepwise synthesis and purification of a single compound at a time, combinatorial chemistry makes it possible to synthesize thousands of different molecules in a relatively short amount of time. The glassware is reduced to slides and miniature vials arrayed in trays.

## **THE SPIN-OFFS AND THE PATENTS**

While it often seems the primary goal of research is to make one's task in life to be obsolete (after all find a cure for cancer and you are out of work), the outcome is more likely to produce a spin-off. In the field of traditional chemistry, these rapid advancements have narrowed the requirement for scientific glassblowers in the chemistry departments at universities and at pharmaceutical companies. They no longer need their own in-house manufacturing to run their labs. Instead, the field of inquiry has broadened. Indeed, the broadening of chemistry research has ventured into and created whole new areas of research.

For instance, organic chemistry has found ways to make carbon-based polymers and small molecules with incredible electronic properties. They can emit light, store photovoltaic energy and can even be used in lasers and transistors. Is it chemistry, or is it a materials

<sup>7</sup> Photo courtesy of Wikipedia.

science, electrical engineering, or photonics? The answer is yes to all of those disciplines. Actually all of these fields now fit into a category known as “Applied Research” and its roots can be traced to a very important piece of legislation known as “The **Bayh–Dole Act** or **Patent and Trademark Law Amendments** December 12, 1980.”

This uniquely bi-partisan piece of legislation provided key changes in the ownership of inventions created from the use of federal funding. Before the Bayh–Dole Act, federal research funding contracts and grants obligated inventors (wherever they worked) to assign inventions they made using federal funding to the federal government.<sup>8</sup> Instead Bayh-Dole permits a university, a small business, or a non-profit institution to elect to pursue ownership of an invention in preference to the government. Prior to the enactment of Bayh-Dole, the U.S. government had accumulated 28,000 patents but fewer than 5% of those patents were commercially licensed.<sup>9</sup>

As a result,

Universities and their inventors earned more than \$1.8-billion from commercializing their academic research in the 2011 fiscal year, collecting royalties from new breeds of wheat, from a new drug for the treatment of HIV, and from longstanding arrangements over enduring products like Gatorade.

Northwestern University earned the most of any institution reporting, with more than \$191 million in licensing income.... The 617 start-up companies formed in 2011 were a slight increase from the 613 reported in the previous year. Start-up companies appeared to be a growing focus for some of the institutions in the survey. In 2010, 12 institutions reported forming 10 or more companies; in 2011, 14 institutions did so....

The 157 universities that responded to the annual survey of the Association of University Technology Managers, released on Monday, completed 5,398 licenses and filed for 12,090 new patents. They also created 617 start-up companies.<sup>10</sup>

## **FRUITS OF THE GOLDEN AGE OF SCIENTIFIC GLASS-BLOWING: NEW SCIENCES, INNOVATIONS & INCENTIVES**

As I have tried to illustrate, the pace of technology, the lowering of tariffs and globalization has transformed many of our jobs from a narrow manufacturing base of vacuum electronics and industrial chemical glassware suppliers to a more service based industry of “Life Sciences” and specialty shops that can flourish if they are adaptable and can utilize special talents to address customers’ needs. This trend will continue to change the landscape of our work. In the past few decades one can easily list the following new technologies in which scientific glassblowing can mine new fields of work:

- **Photonics:** the manipulation of light i.e., lasers, emission, transmission, modulation, signal processing, amplification and detection or sensing of light.

<sup>8</sup> Ashley Stevens, “The Enactment of Bayh-Dole,” *Journal of Technology Transfer* 29 (2004): 93-99.

<sup>9</sup> “Technology Transfer, Administration of the Bayh-Dole Act by Research Universities,” U.S. Government Accounting Office (GAO) Report to Congressional Committees. May 7, 1978.

<sup>10</sup> Goldie Blumenstyk, “Universities Report \$1.8 ~Billion in Earnings on Inventions in 2011,” *The Chronicle of Higher Education* (Aug. 28, 2012). <http://chronicle.com/article/University-Inventions-Earned/133972>.

- **Organic Electronics:** OLEDs, plastic electronic materials, carbon based
- **Environmental Sciences:** physical and biological, atmospheric, soil science
- **Alternative Energy:** fuel cells, battery research, CO<sub>2</sub> reduction, bio-fuels, solar energy
- **Nanotechnology:** MicroElectronicalMechanicalSystems (MEMs), carbon nanotubes, graphene, sensors
- **Molecular Biology:** biological processes, DNA, RNA, cloning, stem cell research
- **Bio-Medical:** vascular models (Farlow Scientific), diagnostics, transplants, new funding to map brain function, artificial limbs and sensors
- **Government Expansion:** NASA, Dept. of Energy, NIST, EPA, DARPA
- **The Horizon:** spintronics, quantum computing, zero gravity materials, dark matter and dark energy, neutron filters and **SERF Magnetometry**

There are also new techniques available:

- **Bonding techniques:** diffusion, anodic, transfer tapes, frittable glasses, brazing and epoxies
- **Machining:** water-jet cutting, laser, ultra-sonic, CNC, centerless-grinding, lapping, polishing, etc.
- **New glasses and ceramics:** sealing glasses, optical glasses, envelope glasses, sapphire, sol-gel coatings, etc.

## THE ASGS, MORE IMPORTANT THAN EVER

*“We randomly picked 20 famous experiments that changed our world—Thomson’s discovery of electrons, Faraday’s work on electricity, and Newton’s splitting of white light into its component colors with a prism, for example—and found that 15 of them could not have been performed without glass tools.”*<sup>11</sup> Alan MacFarlane, Department of Social Anthropology, University of Cambridge

Science and technology continuously transform our Society and the workplace. Indeed, the jobs for making buggy whips a century ago were not so much lost as they were transformed into jobs in the new auto industry. While glass continues to be an indispensable tool in shaping our future, we must continue to adapt. The best way to do this is by becoming an active member of the ASGS:

- If you look through the archives of our publications (*Fusion* and *Proceedings*), you can easily see the chronicles of advancements taking place, both historically and in real time.
- If you participate in our electronic ASGS bulletin board, attend Section meetings, you are plugged into a network where problems can be solved, key suppliers can be identified and helping hands are always extended.
- If you go to symposia, attend professional seminars, workshops and technical papers, you will get a deeper understanding of the “science” behind scientific glassblowing.

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<sup>11</sup> Alan MacFarlane & Gerry Martin, “Beyond the Ivory Tower: A World of Glass,” *Science* 305:5689 (3 September 2004): 407-1408. DOI: 10.1126/science.109397.

- **If you participate as an officer, a committee chair**, contribute to publications, technical posters and workshop demonstrations, you can build a resume filled with accomplishments. More importantly you will have the satisfaction of being part of a legacy and a mission that truly elevates our profession.

In the near and distant future it is easy to suggest that technologies will grow at a faster pace. However, our recent history indicates that there are two ways to compete for those jobs as scientific glassblowers. One way is by manufacturing glass at lower margins, tighter efficiency and less pay. Even so, this downward spiral still does not address automation.

The alternative way is to become more intimate with those technologies and find ways to service their needs by being more informed and more adaptable in the marketplace. In this future, ideas and timely service will be a premium commodity. To succeed in this venue, you will need a deeper understanding of a customer's process and partner with them in the creative process. The pertinent question you should ask is, "What do you want your glassware to do?" and not simply, "What do you want me to build?" And the answers to those questions can best be found by being an active member of the ASGS.

The image shows a screenshot of a web browser window. The address bar contains the URL "193962\_1015016520631844\_1884927\_o.jpg". The main content of the page features the headline "If you want to get technical about it..." in a bold, black, serif font. Below the headline are three covers of the journal "FUSION". The first cover is for August 2007, featuring a glass jar with a rainbow-colored rim. The second cover is for May 2003, featuring a clear glass jar. The third cover is for November 2007, featuring a glassblower working with molten glass. At the bottom left of the page is the ASGS logo, which is a circular emblem with a glassblower's tools and the text "THE AMERICAN SCIENTIFIC GLASSBLOWERS SOCIETY" and "founded 1948". To the right of the logo is the text "Join us at: [www.asgs-glass.org](http://www.asgs-glass.org)".

## 2013 Technical Posters

Steven M. Anderson and Bruce Amat

### **“Pre-humidification of Compressed Gas Mixtures for Use in Large Scale Hepatocyte Steroid Culture”**

Mayo Clinic  
Medical Sciences SL-24  
Rochester, MN 55905  
anderson.steven@mayo.edu

Jeanne Bertonazzi

### **“Construction of an Ultra High Vacuum Plasma Cleaning Apparatus”**

Texas Tech University  
Department of Chemistry & Biochemistry  
Box 41061  
Lubbock TX 79409  
j.bertonazzi@ttu.edu

Jason Craig

### **“Cut Resistant Gloves: How to Choose”**

Oak Ridge National Laboratory  
Building 4500N MS6177  
1 Bethel Valley Road  
Oak Ridge, TN 37831  
craigjw@ornl.gov

Gary Coyne

### **“Construction of a Double-cooled Short Path Distillation Head”**

California State University - Los Angeles  
Chemistry Department Glass Shop  
5151 State University Drive  
Los Angeles, CA 90032  
gcoyne@calstatela.edu

Brian Ditchburn

### **“What is a Guelph Line?”**

Department of Chemistry  
University of British Columbia  
2036 Main Mall  
Vancouver, BC V6T 1Z1  
Canada  
scienceglass@gmail.com

Tracy Drier, Laura A. Halvorsen Monahan, Ilia Guzei, Ph.D.

**“Handle With Care: 19th Century Invertebrate Models in the 21st Century”**

Chemistry Department  
University of Wisconsin-Madison  
1101 University Avenue  
Madison, WI 53706  
drier@chem.wisc.edu

Richard Ponton

**“Drilling a 3.25” Hole In A Dessicator Lid”**

The Procter & Gamble Co.  
5289 Vine Street  
Cincinnati, OH 45217  
ponton.rj@pg.com

## 2013 Technical Workshops

Joseph Gregar – *Argonne National Laboratory*

**“Quartz Teflon® High Vacuum Valve Fabrication”**

Philip Legge – *Scientific Glass Designs*

**“Making A Straus Flask”**

Kyle Meyer – *Aldrich Chemical*

**“Fabricating Coloured Tubing From Rod”**

Robert Russell – *Chemglass Life Sciences*

**“Repairing Jacketed Flasks When Your Lair Is Full Of Ornaments For Your Mother-in-law’s Bridge Party”**

Robert Singer – *Technical Glass Products*

**“Quartz Thermowell”**

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Joe.plumbo@fdglass.com

### **GM Associates, Inc.**

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info@gmassoc.com

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2452 State Route 8

Lake Pleasant, NY 12108

800-232-9458

www.wiltindustries.com

Dan Wilt

dan@wiltindustries.com

## 2013 Symposium Attendees

Jim Abbott  
Steve Anderson  
Erin Austerberry  
Chandra Babbitt  
Jeff Babbitt  
Joel Babbitt  
Ruth Babbitt  
Barry Bankroff  
Scott Bankroff  
Sabrina Bélanger  
Patrick Bennett  
Jeanne Bertonazzi  
Ron Bihler  
Deanne Bihler  
Emily Bihler  
McKenna Bihler  
Richard Bock  
Marylin Brown  
Pat Brown  
Dan Brucker  
Deborah Camp  
Carl Carelli  
Evelyn Carelli  
Jacob Chambers  
Bonnie Clark  
Kyle Clark  
Brenda Cloninger  
Jerry Cloninger  
Cynthia Corio-Poli  
Jim Cornell  
Laura Cornell  
Dan Coyle  
Gary Coyne  
Jason Craig  
David Daenzer  
Katrina Daenzer  
Patrick DeFlorio  
Brian Ditchburn  
Dan Dotterweich  
Daniel Dotterweich  
Lucille Dotterweich  
Mary Dougherty  
Tracy Drier  
Kiva Ford  
Christopher Freeburn  
Alberta Gerhart  
Rick Gerhart  
Ben Gomez  
Joshua Greenfield  
Joseph Gregar  
Katie Gregar  
Adolf Gunther  
Inge Gunther  
Mike Hannis  
David Hatz  
Doni Hatz  
Newton Hill, Jr.  
Stephanie Hitchcock  
Carolyn Hodgson  
Jim Hodgson  
Adam Kennedy  
Paul Kirby  
Sue Kogut  
Georges Kopp  
Jack Korfhage  
Neal Korfhage  
Marie Lachapelle  
Elizabeth Landau Lawrence  
Andrew Ledden  
Philip Legge  
Ron Legge  
Sherri Legge  
Nicholas Lionberger  
Alejandra Martinez  
Andrea Martinez  
Atilano Martinez  
Blanca Martinez  
Saul Martinez  
Victor Mathews  
Pat Mathews

Jane McCollum  
Larry McCollum  
Matthew McDonald  
Frank Meints  
Kyle Meyer  
Nancy Mock  
Steve Moder  
Arleen Molodow  
Marv Molodow  
Sellby Moschell  
Eric Mueller  
Lee Mulholland  
Devon Murphy  
Thomas Murphy  
Craig Nagami  
Doug Navalinsky  
Lori Neu  
Douglas Nixon  
Mike Palme  
Sally Palme  
B.J. Polise  
Jenna Polise  
Bob Ponton  
Damien Ponton  
Henry Ponton  
Lynn Ponton  
Melissa Ponton  
Rick Ponton  
Riley Ponton  
Brian Power  
Arturo Ramirez  
Liz Reagan  
Arwen Revis  
Benjamin Revis  
Bob Russell  
Diana Russell  
Steve Russo  
Chris Sajdak  
Moshe Schandelson  
Michael Schiaffino  
Saki Selbovitz  
Dan Seme

J. Mark Sinclair  
Bob Singer  
Nancy Singer  
Laurie Sliwoski  
Phillip Sliwoski  
Jordan Smith  
Lorraine Smith  
Rick Smith  
Samantha Snider  
Mary Souza  
Mike Souza  
Michael Spina  
Christopher Surdam  
David Surdam  
Emily Surdam  
Regina Surdam  
Kevin Teaford  
Rhonda Teaford  
Brent Thorn  
Mary VanAntwerp  
Jordan Vandenhoff  
Kathryn Volk  
Daniel Walker  
Hollie Walker  
Isaac Walker  
Ruby Walker  
Rob Wallace  
Andy Wargo  
Dan Watson  
Jack Watson  
John Watson  
Lori Watson  
Nina Wheeler  
Klaus Widmann  
Siggi Widmann  
Daniel Wilt  
Kendal Wilt  
Colby Wise  
Don Woodyard  
Mohamed Younus  
Julan Zhao

