The First Five Years
1992-1996

the **Bell Jar**

Vacuum Technique and Related Topics for the Amateur Investigator

Reference Number: FF0701

The First Five Years
1992-1996

The content of this booklet is derived from articles which have appeared in **the Bell Jar** (ISSN 1071-4219), the quarterly journal of vacuum technique and related topics in physics for the amateur experimenter. Further information on this journal will be supplied on request from:

the Bell Jar
35 Windsor Drive
Amherst, NH 03031
www.belljar.net
shansen@tiac.net

Contents

Forward

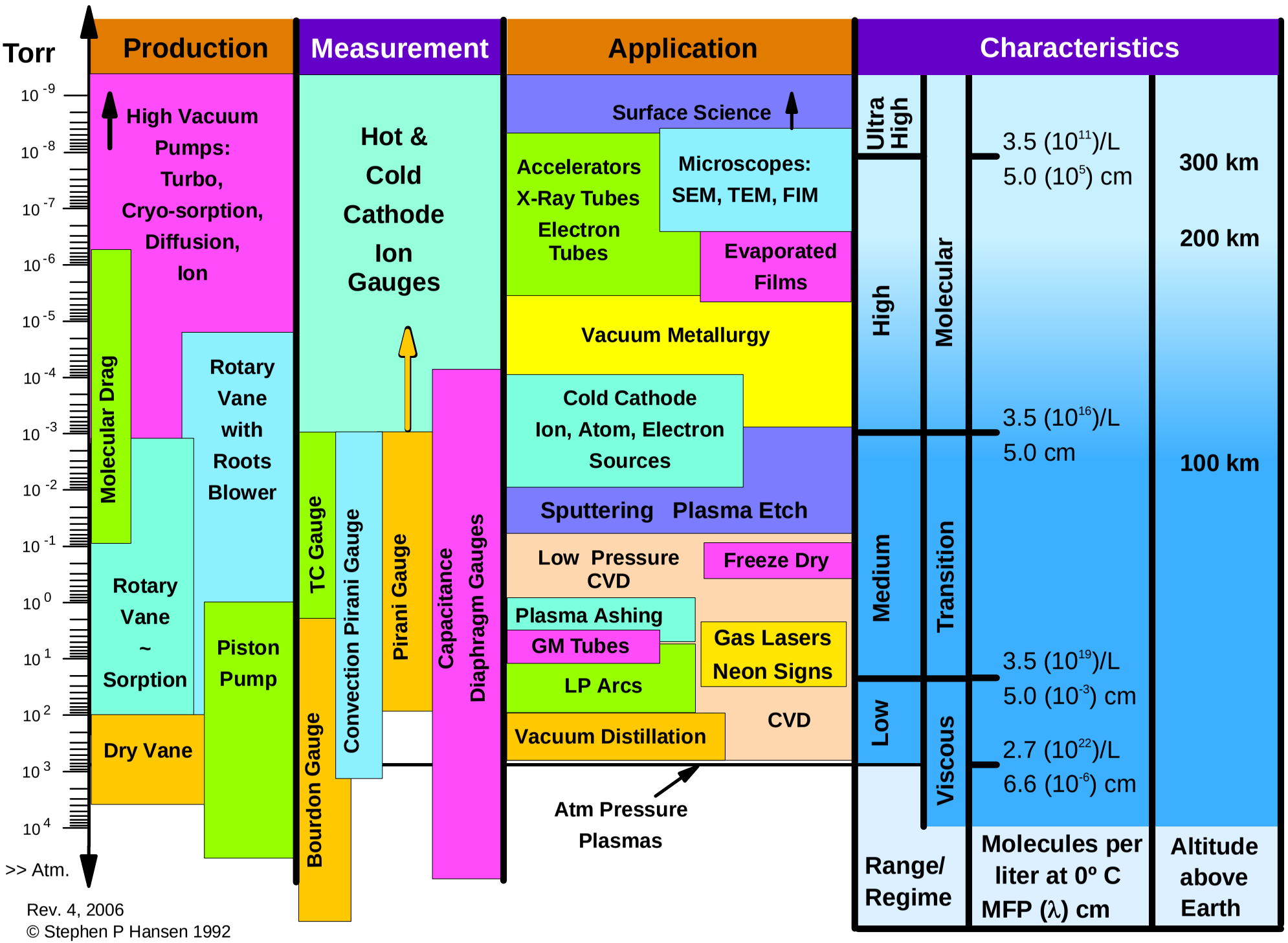
The incentive for producing this compilation came from several factors: I was getting tired of handling the boxes and folders containing the hardcopy issues; My wife, Chris, was getting tired of these same boxes, strewn all around the upstairs bedrooms; Volume 1, originally produced on an obsolete word-processing typewriter, existed only in print form and the originals were getting rather dog-eared; Some of the later issues were in peril because a number of the electronic files had gotten corrupted; A certain percentage of each issue (classifieds and the like) had gotten outdated; The sets of back issues were beginning to cost more than I thought they should.

As a result, I have finally produced the work now at hand. When I announced this project, over one year ago, I thought it would be pretty easy to pull up all of the files and stick them together in some coherent form. However, for some of the reasons noted above, and because I just had to tinker a bit, it turned into a larger project.

In this compilation are all of what I feel are the useful articles from the 20 issues that comprised Volumes 1-5. To keep the length manageable and the content relevant, I did cut out the time-sensitive items and the various bits of commentary. I will keep my eye out for items that should have been retained in this compilation but fell through the cracks. They will be collected and will appear at some future date, either in the next compilation or in a regular issue. I did try to correct a few errors, although I'm sure that there are still a few lurking in these pages. As I find these (or they are brought to my attention) I will publish corrections in later publications and/or on line. Some attempt was made to group articles by topic so referring to a related article shouldn't be difficult.

Steve Hansen
November 1999

The chart on the next page depicts how vacuum is produced (types of pumps), how it is measured (types of gauges) and how it is used. This compilation will touch on most of these items.


Torr
Production
Measurement
Application
Characteristics
10 -9
10 -8
10 -7
10 -6
10 -5
10 -4
10 -3
10 -2
10 -1
10 0
10 1
10 2
10 3
10 4
>> Atm.
High Vacuum Pumps: Turbo, Cryo-sorption, Diffusion, Ion
Molecular Drag
Rotary Vane with Roots Blower
Rotary Vane ~ Sorption
Piston Pump
Dry Vane
Hot & Cold Cathode Ion Gauges
TC Gauge
Convection Pirani Gauge
Pirani Gauge
Capacitance Diaphragm Gauges
Bourdon Gauge
Surface Science
Accelerators X-Ray Tubes Electron Tubes
Microscopes: SEM, TEM, FIM
Evaporated Films
Vacuum Metallurgy
Cold Cathode Ion, Atom, Electron Sources
Sputtering Plasma Etch
Low Pressure CVD
Freeze Dry
Plasma Ashing
GM Tubes
Gas Lasers Neon Signs
LP Arcs
CVD
Vacuum Distillation
Atm Pressure Plasmas
Ultra High
High
Medium
Low
Molecular
Transition
Viscous
3.5 (10^11)/L
5.0 (10^5) cm
3.5 (10^16)/L
5.0 cm
3.5 (10^19)/L
5.0 (10^-3) cm
2.7 (10^22)/L
6.6 (10^-6) cm
300 km
200 km
100 km
Range/ Regime
Molecules per liter at 0° C MFP (λ) cm
Altitude above Earth
Rev. 4, 2006
© Stephen P Hansen 1992

Basics of Vacuum

Background

"Modern atomic physics is the child of the vacuum pump."

Karl K. Darrow, a researcher at Bell Laboratories, made this statement in his 1932 book "Electrical Phenomena in Gases." Indeed, the development of vacuum pumps capable of reaching very low pressures has been intertwined with most of the advances in physics since the mid-nineteenth century. The simple low pressure electrical discharge tubes developed by Geissler and others quickly progressed from curiosities to devices with significant implications. The discovery of x-rays by Roentgen in 1895 represented a watershed. The identification of the electron and the invention of the cathode ray oscilloscope tube happened at about the same time. Other developments quickly followed: the vacuum tube made the radio industry possible and vacuum coating processes led to new types of optical elements as well as to integrated circuits. The scanning electron microscope, mass spectrometer, laser, computer, microwave oven, compact disk and even plasma treated tire cords would all be fiction without vacuum and vacuum processes.

Unfortunately, even though it pervades our technology and our lives, vacuum is a field that has not been very accessible to the amateur and the non-specialist, mainly due to a severe lack of information specifically targeted toward that audience. Amateur vacuum experimentation did have a period of activity in the late 1950s and 1960s. For those who remember, two good examples were C.L. Stong's *Amateur Scientist* column in Scientific American and the amateur oriented pumps, kits and plans once offered by the firm of Morris & Lee of Buffalo, NY. Between the two, an impressive array of apparatus emerged from the efforts of ambitious basement experimenters. Reported were a variety of gas lasers, x-ray tubes, potential drop accelerators, mass spectrometers, simple & compound electron microscopes and high altitude chambers, to name a few. All of these were cobbled together with converted refrigeration compressors, single stage diffusion pumps, copper & glass tubing, sealing wax and a lot of ingenuity. The staying power of these endeavors is evidenced by the continued recycling of plans, often in the form of poor imitations, for a number of the vacuum related projects in Stong's columns.

In the intervening years there has been an almost complete lapse in the availability of up-to-date information on vacuum technique and apparatus specifically targeted toward the amateur, educator, or professional who likes to tinker. *the* Bell Jar was created at the start of 1992 to bring together those experimenters who have an established interest in vacuum as well as to promote vacuum technique as an interesting and challenging hobby.

Eight years later, the readership numbers in the hundreds and contributors range from true amateurs to professionals with established credentials in the field. This diversity has made for a lively publication and has resulted in favorable comments from the professional community. It is hoped that this compilation, containing material from the first five years of *the* Bell Jar, will help to inspire a new generation of amateurs to undertake experimentation in the fascinating field of vacuum technology.

Some Vacuum Fundamentals

"One man's vacuum is another man's sewer."

-N. Milleron, 1970

Vacuum technology covers a very wide range of pressures and conditions. Vacuum to a person doing fiberglass laminating is very different from the vacuum used by a neon sign worker. A thousand times better than this is the level of vacuum used in electron devices such as x-ray and TV picture tubes. And, a thousand to a million times better than this is the degree of vacuum used in research on the surfaces of materials.

A vacuum system typically consists of one or more pumps which are connected to a chamber. The former produces the vacuum, the latter contains whatever apparatus requires the use of the vacuum. In between the two may be various combinations of tubing, fittings and valves. These are required for the system to operate but each introduces other

about 1.3 megajoules of energy on hand for whatever use you might want to make of it. If desired, the *Pressure ▪ Volume per Area per Time* outgassing term could be referred to as the *Area-specific Energy Flow Rate*, which perhaps also some intuitive relevance to the outgassing process in general.

Mr. McKeown has quite a few expressions in his short article but only three equations, namely:

$$joule = watt \times second$$

$$joule\ per\ second = watt$$

$$(watts/sq.\ meter) / 1333.2 = torr\text{-}liter / (cm^2 - sec)$$

Now, the first two are certainly correct, absolutely and totally consistent with the *SI* system of units. However, the third is not a valid equality. I recognize the point that writer McKeown is trying to make through the use of the equation, namely that a numerical value taken from O'Hanlon's work and appearing there in units of W/m^2 can be divided by 1333.2 to produce a new number which will have the units of $torr\text{-}liter / (cm^2 - sec)$. I hope your other readers also recognize that this is indeed McKeown's apparent intention in presenting the equation. However, the conversion factor implied is nevertheless incorrect and should instead be written:

$$1\ torr \cdot liter / (cm^2 \cdot s) = 1333.2\ W/m^2$$

This can easily be confirmed by first recalling that, in the *SI* system of units, the equation:

$$1\ W = 1\ N \cdot m/s$$

can be thought of as a definition for the watt (actually 1 J/s), where N is the Newton and s is seconds. Now, the Torr unit of pressure can be expressed in *SI* units as:

$$1\ Torr = 133.322368421\ N/m^2$$

Combining the previous two equations will eventually give:

$$1\ W/m^2 = 7.5 \cdot 10^{-4}\ Torr \cdot liter / (cm^2 - s)$$

An interesting calculation involving W/m^2 can be made using an ordinary household lightbulb, which has a surface area of approximately 1/100 of a square meter. If a 25 watt bulb is used (which is about the lowest wattage to be found in this larger size bulb), then the power per unit area is approximately 2500 W/m^2. This number is about 10 orders of magnitude greater than values commonly encountered in outgassing calculations, and really has no relevance to outgassing problems whatsoever. It serves as an interesting calculational exercise only.

Mike McKeown replies: Bill Harrison points out that as an equation my expression is simply wrong. I should have written out my expression longhand: 'If you are given an outgassing value as qqq x 10^{-q} W/m^2 and you wish to convert it into a value in Torr-liter/cm^2/sec units, then divide the numerical value qqq x 10^{-q} by 1333.2'. I apologize for any confusion I may have caused. I know it is difficult enough remembering whether to divide or multiply by the conversion factor without me throwing an incorrect equation at you. But it is nice to know that at least one person out there reads an article on the conversion of measurement units. Bill, my thanks.

Pump Oils and Other Furry Animals

This article was originally presented in Volume 5, Number 2

.

PROLOGUE

Blame Steve for this article. I kept putting him off, hoping he'd forget. "Well, you see Steve, an article of that length ... with my work load. Sheese....." But, nooooo. Like every editor, he's pushy. And in case you don't know it, he's also big. I find that combination very convincing. So, here's the scoop on pump fluids. Unfortunately, until Steve springs for a decent DTP program, you're stuck looking at scruffy, word processing depictions of molecules.

First I'll survey the general properties of vacuum pump fluids needed for mechanical and diffusion pumps. Then I'll delve into fluid chemistry and try to rationalize differences in stability, lubrication etc. Finally, I'll summarize applications and price. I know, I know - for the home experimentalist (or 'HE' as I non-chauvinistically call you) with a vacuum system, the last should be first.

Putting Vacuum Systems Together

This following articles cover the construction of vacuum systems of varying complexity. The first article is compiled from a series of articles that appeared in Volumes 1 and 2 and relates to my system, at least as it existed in the 1992-1993 timeframe. (Actually, while I've upgraded a number of things, the basic system remains pretty much the same.) The rest of the material ranges from descriptions of simple systems to Alan Ward and John Moon's ambitious dual chamber evaporator project.

An Amateur's Vacuum System

Steve Hansen

The editor's system will be described. This particular system was designed to be flexible and includes a large chamber (mechanically pumped) plus a diffusion pumped port which may be connected to a variety of apparatus and chambers.

OVERVIEW

Before getting to the specifics of this particular implementation, two figures from John Strong's classic *Procedures in Experimental Physics* [1] delineate very nicely the two broad classes of vacuum system. The first, the static system (see Figure 1.17), is designed for obtaining the highest degree of vacuum possible. These systems incorporate cold traps (when diffusion pumps are used), have no organic materials in the high vacuum side, and are bakeable. While Strong's sketch shows an all glass system, stainless steel or aluminum would be today's norm and the diffusion pump would probably be replaced by a turbomolecular, sputter-ion or other dry high vacuum pump.

The second, the kinetic system (see Figure 1.18), is designed for flexibility and frequent venting. Organics may be used in the high vacuum side and a cold trap (in the case of diffusion pumped systems) is optional. Obtainable vacuum would be in the 0.01 to 0.001 mTorr range with pump speed and patience compensating for the relatively gassy materials which may be used in the system. In the case of today's commercial systems, the distinction may be somewhat blurred (due to the advances in fittings and materials as well as newer pump technologies) but the differentiation is still applicable in the context of amateur built systems. The system described in this article is of the kinetic variety. This allows for a broad range of uses, permits the use of a variety of "alternative" construction methodologies and materials, and most important - is entirely adequate for an amateur's usual requirements (although I'm sure there is someone out there who wants to get into atomic level surface analysis).

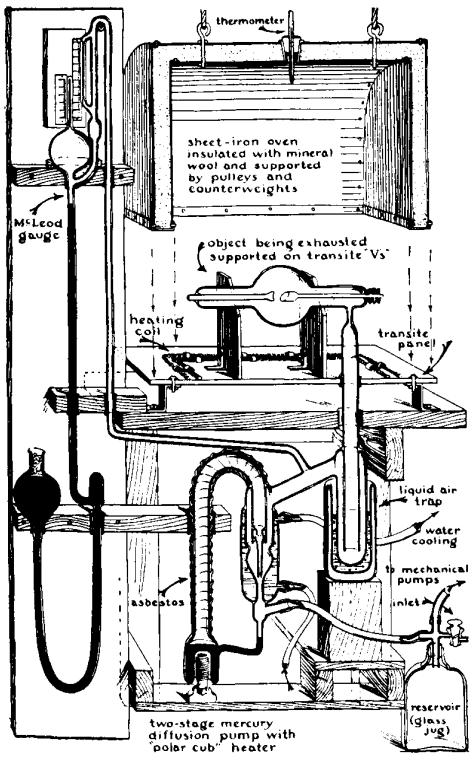


Figure 1.17 - Strong's Depiction of a Static System. From Ref. 1, used with permission.

A Homebuilt Thermocouple Gauge Controller

I. INTRODUCTION

The thermocouple (or T/C) gauge is one of the more common and cost effective gauges for vacuum pressure measurement in the 1 Torr to 1 milliTorr range. The T/C is usually found in the forelines of high vacuum systems (i.e. between the roughing and diffusion pumps) as well as in single pump systems of the sort used to evacuate sign tubes.

Like most vacuum gauges, the T/C gauge does not measure pressure directly as do, for example, manometers of the McLeod or Bourdon type. Instead, these vacuum gauges depend on changes of a physical characteristic of the residual gas within the gauge tube. In the case of the T/C gauge, and all other thermal conduction gauges, that characteristic is the thermal conductivity of the gas.

A thermal conduction gauge may be thought of as a defective vacuum insulated thermos bottle (Figure 1). Each has a hot element (coffee for one, a filament in the case of the other) within a vacuum wall. There are two ways of removing heat: conduction (molecule to molecule) and radiation. For both coffee and warm filaments the primary path at atmospheric pressure is conduction. As it turns out, the thermal conductivity of air is nearly constant down to a fairly low pressure - about 1 Torr. Then it begins to change rather linearly with pressure down to a value of about 1 mTorr, whereupon conduction through the gas ceases to be a major factor. At that point, the dominant loss factors are conduction through wall and leads, and radiation. What might be surprising to many people is that a fairly good vacuum is needed in a thermos. With a bit higher pressure, you might as well have no vacuum. In the case of the thermal conduction gauge, operation will only occur within the sloped portion of the curve. An interesting experiment would be to nick open a thermos bottle refill and measure the cool-off rates for hot water with the bottle evacuated to a number of pressures. The result would be a useful, but very slow, thermal conduction gauge.

The T/C gauge contains two elements: a heater (filament) and a thermocouple junction which contacts the filament. With the filament current held constant, as the pressure within the tube is decreased the filament will become hotter because of the improved thermal insulation provided by the increasingly rarefied gas. This temperature is sensed by the thermocouple junction. Measurement is accomplished by reading the thermocouple junction voltage on a sensitive meter which has previously been calibrated against a manometer. Simple T/C gauges may be obtained from a variety of sources such as Duniway Stockroom or Kurt J. Lesker Co. These consist of the gauge tube itself, a power supply for the filament, and moving coil (d'Arsonval) meter for displaying the pressure. Tubes usually have a 1/8" male pipe thread for coupling to the vacuum line and an octal (vacuum tube) base for mating with a socket. In newer gauges, the power supply is usually nothing more than a plug-in type ac adapter with a potentiometer for adjusting the current. Each type of T/C tube has its own calibration curve. Also, as there are some structural variations from tube to tube within a type, each has its own filament current rating. The current at which the gauge will conform to the calibration curve is imprinted on each tube. Also, T/C gauges are calibrated for air. As different gases have varying thermal conductivities, the gauge will not be accurate when working with, for example, argon or carbon dioxide.

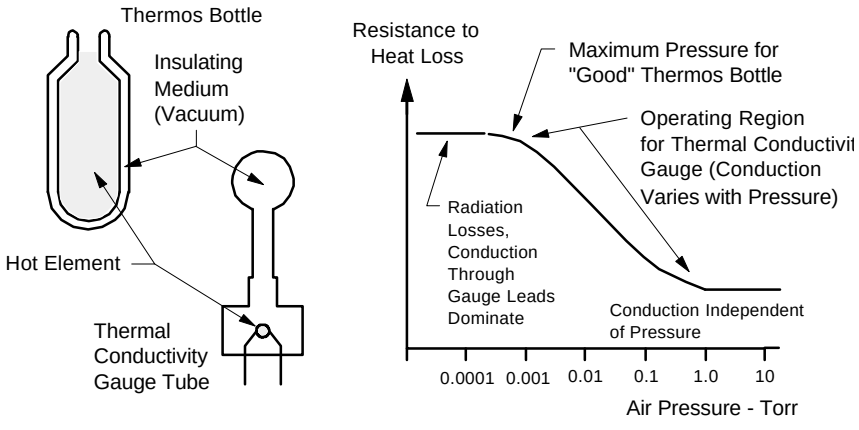


Figure 1 - Thermal Conduction in Gauges and Thermos Bottles

How to Make a Glass to Metal Seal

Kevin E. Bennet

Abstract: Using simple glassblowing techniques to fabricate a gas discharge tube with a tungsten-glass seal for the electrode.

I've tried glassblowing but have never been very successful. I think that much of the reason is that I've never paid much attention to getting a good torch. In this article, Kevin Bennet describes a good solution to getting a usable torch and flame and then shows how to do some useful glasswork. - *Editor*

Caution: Glassblowing requires working with sharp glass, high temperature flames, hot glass and hot metal. Be very careful keep flammable materials away from your work area and take care not to cut or burn yourself. Wear safety glasses at all times when working with glass, hot or cold. Also, keep a pan of cool water nearby into which to put your hand should you burn yourself. The sooner you cool the burn, the less damage to your skin!

I. INTRODUCTION

Many of the useful and most interesting things to be done with vacuum systems involve the introduction of electricity into the evacuated enclosure. This electrical feedthrough represents one of the most basic techniques in vacuum glasswork and also one of the most difficult to be done reliably on a routine basis. However, the selection of the correct materials combined with proper technique and practice will yield reliable seals. Industry has developed glass to metal seals on a production basis as may be seen in such everyday items as lightbulbs and electron tubes. As an example, each string of holiday lights requires 100 glass to metal seals and millions of these are made each year. In learning any new skill, expect failure at first. Practice is required to become successful and proficient.

The difficulty in glass to metal seals lies in the low strength of glass in tension combined with the differences in expansion between the glass and metal components of the seal. Without going into the theory of stress and expansion coefficients, the solution to the problem of glass to metal seals is to use a metal and glass combination where expansion is matched at all temperatures and where the metal forms an adherent oxide coating to allow the glass to stick to the metal and seal tightly. A variety of metals which approximate these needs are available for this service including platinum (for soda lime glasses), molybdenum (for silica glasses), tungsten (for borosilicate glasses), a copper/iron composite known as Dumet (for lead glasses), as well as copper and various iron alloys (such as Kovar) for a variety of glasses.

II. ABOUT GLASS

Of the commonly available glasses, the borosilicate variety (known by various trade names like Pyrex®, Kimax®, etc.) is the most forgiving of thermal shock during the glassblowing process. This is the material of choice for most laboratory glassware.

Soda lime glass is the glass from which most consumer products are made. Examples include bottles and light fixture globes. This type of glass cannot be worked by torch in any resonable manner. Soda lime laboratory tubing is made, but it is not recommended for scientific glassblowing.

Lead glass has a history of use in the fabrication of neon signs, incandescent lamps and electron tubes. Lead glass can be purchased from scientific or neon sign suppliers. This glass will crack very easily with the application of a torch and requires considerable patience to work. Dumet wire (copper coated iron) for making glass to metal seals may be recovered from any lightbulb. Lead glass requires a lower temperature flame such as from a propane or natural gas and air torch in order to be worked effectively.

Getting back to borosilicate glasses, thin walled glass (from about 0.75 to 1.0 mm) is the easiest to form and the easiest to flame anneal (remove residual stress). Since glass is a poor conductor of heat, the use of a torch on thicker glass results in the development of severe strain which then results in cracks. Thus, bell jars, which are made from heavy glass, are very difficult to modify or repair with a torch.

III. THE TORCH

Bunsen burners and the propane torches commonly used for plumbing will not work properly with borosilicate glasses. While these will melt the glass, the temperature of the flame simply is not high enough to

Reference Number: FF0701

How to Make Buckyballs

Greg Konesky

Abstract: How, with simple apparatus, an amateur has duplicated the technique developed by Huffman and Krätschmer to synthesize and isolate that soccer ball shaped molecule of carbon, C_{60} , otherwise known as Buckminsterfullerene or Buckyballs..

I. INTRODUCTION

Buckyballs, also known by the more proper term Buckminsterfullerine, are hollow, cage-like carbon molecules. The buckyball family may have as few as 32 carbon atoms but the upper limit continues to be extended with such forms as nanotubes and bucky-onions (concentric spheres of buckyballs). The family of these peculiar molecules are known as fullerenes.

Buckyballs have been made to enclose virtually every atom on the periodic table and the characteristics of these modified fullerenes range from insulator to semiconductor to superconductor. They can also act as "soft" organic ferromagnets, act as frequency doublers and optical limiters, be compressed to form diamond, or act as a foundation for diamond thin films on a variety of substrates. Buckyballs are also being proposed as massive projectiles for molecular accelerators: the molecules have been accelerated to tens of MeV with their structure remaining intact. Best of all, they are relatively easy to make.

II. THE REACTOR

The simplest synthesis route uses a carbon arc within an inert atmosphere. The arc throws off a fine black soot which contains several different types of fullerenes. C_{60} predominates with a lesser amount of C_{70}. I've used both helium and argon atmospheres with equal success. The pressure that the arc operates in should be within a range of 100 to 300 Torr, although this does not appear to be too critical.

The electrical power supply for the arc does, on the other hand, have to be quite substantial. This must be able to provide 100 or more amps at 15 to 20 volts. AC or DC appears to work about the same. The former is

Various forms of carbon such as graphite and diamond have been known for millenia. Very recently a new form has been discovered. In 1985, a group at Rice University realized that a new molecule consisting of 60 atoms of carbon could be produced by the laser ablation of graphite in an atmosphere of helium. This group proposed that the shape of the molecule had a very special structure. Mathematically, the shape is a truncated icosahedron. In more common terms, this is the shape and layout of a soccer ball. The molecule was termed buckminsterfullerene in honor of the architect Buckminster Fuller , who became famous for his work with geodesic dome structures.

Until 1990 when Donald R. Huffman and Wolfgang Krätschmer developed a methods for both producing fullerenes from a carbon arc operated in an inert atmosphere and then being able to separate the fullerenes from the other forms of carbon in the residue (mostly graphite), only miniscule amounts of fullerines had ever been isolated. As a result of this breakthrough, research into the properties and potential uses of the fullerenes has proceeded at a very fast rate.

As this article shows, the methods are simple and amenable to use by amateur researchers. - *Ed.*

Reference Number: FF0701

The Production of Phosphors: An Introduction

Ely Silk
616 N.W. 68th Terrace, Ft. Lauderdale, FL 33321

I. INTRODUCTION

The production of phosphors suitable for use on x-ray screens or for visualizing electron beams is easily within the realm of the amateur scientist. In industry and in laboratory phosphor research, great pains are taken to insure that the highest purity, cleanest environment, and most pristine manufacturing equipment are employed in the production of phosphors. Often, special atmospheres and very high temperatures are required for creating the phosphors . Sometimes electrical and magnetic fields are needed. Also, state-of-the-art analytical instruments are used to monitor chemical composition and crystalline state of the phosphors at various stages during production.

Fortunately for our purposes in this article, we are not concerned with most of the restrictions listed, nor do we need to monitor the process. However, for repeatability, as well as to obtain a phosphor with satisfactory properties, we will need to use AR (analytical reagent grade) purity chemicals wherever possible. The area used for phosphor production should be well-ventilated and clean. ***Also, familiarity with the proper handling and storage of potentially toxic chemicals should be a basic requirement before launching your career with phosphors.***

In addition to the chemicals, a high-temperature furnace, some quartz crucibles and covers, distilled water, access to a laboratory balance, various pieces of lab glassware and a mortar & pestle are required.

The high-temperature oven I use is an L&L kiln. This can maintain a maximum temperature of 1250° C. A Honeywell UDC 2000 controller is used to maintain the chosen temperature to within 3° C.

Ideally, an oven which can reach 1600° C and which can operate under various atmospheres is desirable. However, those ovens are very pricey! I limit myself to phosphors which can be produced below 1250° C. I do use a tube furnace along with quartz tubes when I must have a controlled atmosphere (e.g., flowing hydrogen, argon, nitrogen, etc.), but here again I have a limiting temperature maximum: below 1100° C in this case.

II. PHOSPHOR SELECTION AND NOMENCLATURE

There are as many different phosphors as there are applications which require them. The phosphor to use is dependent on the following requirements:

1. The source of excitation: alpha particles, electrons, x-rays, heat, ultraviolet light, high-frequency electrical power, etc.
2. The preferred wavelength of light emission: what "color" should the phosphor emit when excited?
3. Stability under the conditions of the application: Can it withstand the imposed environmental conditions such as humidity, atmospheric oxygen, light exposure and so forth during handling? And, can it withstand the source of excitation? An electron beam at 50 kV has quite a bit of energy and it can "burn" the phosphor if it bombards the same area for a prolonged period of time. This gets worse at higher beam currents/ (Hence, a booming market for computer screen savers!)

One of the easiest phosphors to prepare is Cub. ZnS:[Zn]. The nomenclature for this phosphor is translated as follows: Cubic zinc sulfide with zinc atoms as the presumed activator. In "phosphorese," an activator is an atom or ion which is added to a compound (usually in trace quantities) to promote the emission of light. The activator ions find their way to surface sites on the host phosphor crystals, inside the host crystals in interstitial sites, as well as inside the host crystal in substitutional sites whereby the activator atom replaces the atom of the host crystal. Thus, solid solutions of the activator within the host crystalline compound can be formed. The colon is followed by the chemical abbreviation of the activator and indicates that the activator is present in variable (nonstoichiometric) proportions.

In our first phosphor example, brackets ([Zn]) surround the free atom indicating that the presence of the atom or ion is conjectured and not actually proven. Generally, we add a small quantity of a compound (e.g., manganous oxide) to our host in which case there is no question about the presence of the activator. In zinc sulfide which is exposed to a high temperature, some of

The Evolution of the X-Ray Tube

Dan Smith
8904 Cypress, Cotati, CA 94931

The First

Roentgen's first experiments were with an ordinary Crookes tube with a bit harder vacuum than was customary - on the order of one-millionth of an atmosphere or about 1 micron Hg. The vacuum was produced by a mercury displacement pump, most likely a Sprengel pump. It was necessary to have the right amount of residual gas: too much would result in a normal glow discharge and the tube would be too conductive. Too little and an excessively large induction coil would be required for the tube to conduct [1].

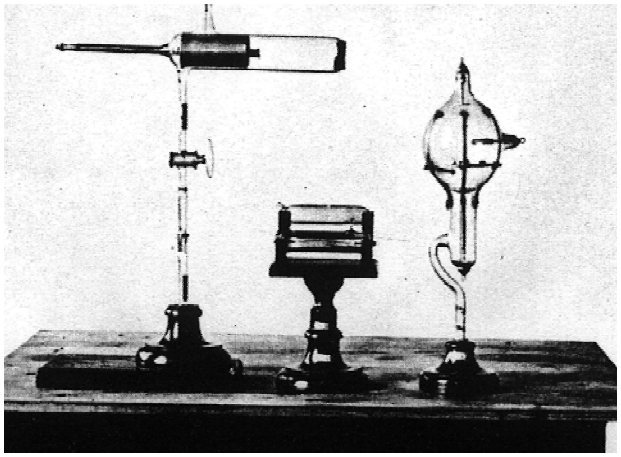


Figure 1 - Roentgen's Apparatus. Lenard tube to the left, Crookes tube at right.

A flat aluminum disk cathode produced the cathode ray stream that would be accelerated by a wide anode. The stream merely impinged on the glass walls of the tube with the x-rays originating from the interaction of the cathode ray stream with the glass wall. The radiographs that resulted were murky but none-the-less magical. The lack of clarity was due to the lack of focus of this crude x-ray source [2]. Heat dissipation was soon found to be a problem and the glass itself was a poor generator of x-rays due to the low atomic number of the elements in the glass (e.g. silicon) [3].

In order produce substantial quantities of x-rays the speed of the electrons needs to be very high. To achieve this, a tube needs to sustain a voltage drop of at least 40 kV. This translates to an induction coil with a spark of about 2 inches. A tube with a 75 kV potential accelerates the electrons to about half of the velocity of light. Roentgen was using a coil that would produce a 5 inch spark. Some of Roentgen's apparatus is shown in Figure 1.

The Focus Tube

Some improvements were necessary and, as early as 1896 the first focus-type tubes (see Figure 2) were introduced. These had a concave aluminum cathode. With the radius of the curve in the cathode approximately twice that of the cathode-anode spacing, the cathode rays would converge to a sharp spot on the anode. The anode was angled at 45 degrees and was of a high melting point, high atomic weight metal such as platinum [1]. The focused beam of cathode rays combined with the high atomic weight of the anode material provided a point-source of "harder" x-rays that would produce a more well-defined image with a shorter exposure. The glass envelope was blown into a round bulb-shape around the anode in order to reduce electrostatic stress across the surface of the tube [3]. This allowed the use of higher potentials.

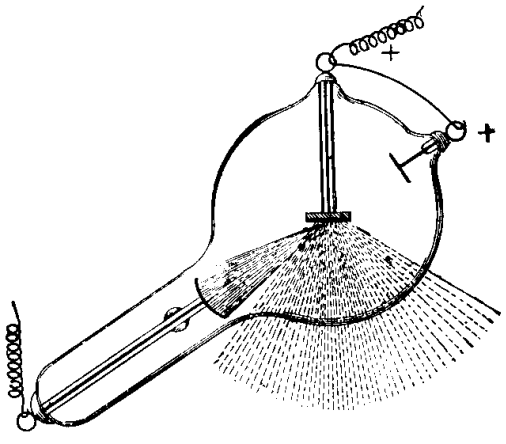


Figure 2 - Focus Tube.

Reference Number: FF0701

Geiger Counters and Power Supplies

David M. Raley, PE
P.O. Box 7, Laurel Hill, NC 28351

I. INTRODUCTION

By the time you finish this paragraph thousands of gamma rays, or particles, will have passed through your body, a number of beta particles will penetrate your skin to varying depths and your skin will repel some alpha particles. This is so even if you are not playing around with high voltage and vacuum. If you are so engaged, there is a good chance that your dose is higher.

The only alpha particles you have to worry about are the ones that are emitted by radon or other gases that you have breathed into your lungs. You can also forget about the gamma radiation that makes it straight through your body. That leaves the beta particles that penetrate and the gamma rays that interact. "Them's be the buggers to sweat." If you are a member of the majority of readers who already know these things, please be patient while the 10 percent who didn't get the word are brought up to speed.

Generally speaking a sub-atomic particle travels until it collides with the nucleus of an atom. It may then be absorbed by or bounce off the nucleus. If it is absorbed it will affect the nucleus in some way. From time to time that nucleus is in an atom in the DNA chain of one of your cells. A possible result is that the cell will mutate the next time it replicates. The vast majority of mutations are degenerate; most of them simply die, some of them become cancerous. If your immune system is working right the mutated cells are eliminated. Females face an extra hazard in that it sometimes happens that a ripe egg is hit and the immune system mistakes it for having been fertilized and allows it to attach as would a zygote. The result is almost always a tumor but parthenogenesis is a fact of life despite all the jokes about the doctor searching the horizon for the camels.

There has always been background radiation, more in the distant past than now. Some say that were it not for background radiation, life would not exist. I don't know about that; my belief is that we are stressed to tolerate a certain amount of the stuff and no more. What's the limit for long term exposure? Two percent above background? Five? Ten? Fifty? Two Hundred? I don't know that either. What's the goal? To keep our surroundings as close to the natural background as possible.

Before you can take precautions you have to be able to measure what you are trying to avoid. Low level radiation gives us a special problem. It is completely random in nature. While you would have no difficulty at all in detecting an increase of two percent if you were measuring fruit, flour or frequency. You could watch the meter of a Geiger counter from now on and never be able to say for sure if the background radiation was up or down by that amount.

The solution here is an accumulation Geiger counter. The classical device counts each interaction that takes place in the detector tube over a selected period. The longer the selected period the more the random nature of the interactions is smoothed out. By interfacing with a computer you can learn many fine things with a minimum of effort. One of the things that you can learn is whether or not there is an alpha emitting gas, say radon 220, in the air you breathe.

I have made a lot of closed tube readings using counts per hour, finding that the measurements vary for different locations within my house and that the safest place on my property is in my dog's house where the average is 3,033 counts per hour. The hound's house is wood, mine is masonry. Most likely the reduced risk of stray bullets from hunters or from woods fires makes the masonry safer overall. There is no doubt at all that masonry would give more protection from regional short term nuclear events.

How about your house? Would you be safer outdoors? Would you be better off without that super-insulation? Should you leave the room, or the county, when your grade-A, US Choice science project is running? If there were some sort of nuclear accident nearby would you be able to prove that your property had a safe background level before the accident? Would you even KNOW if there were such an accident if it happened one dark night and nobody talked? Is that rock your kid brought home a stray radioactive meteorite?

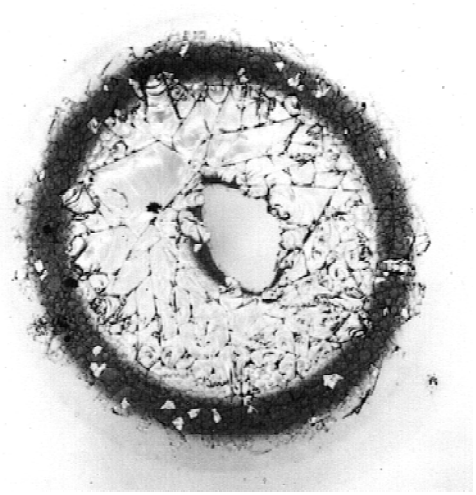
Stay tuned and learn how to build your own accumulation Geiger counter.

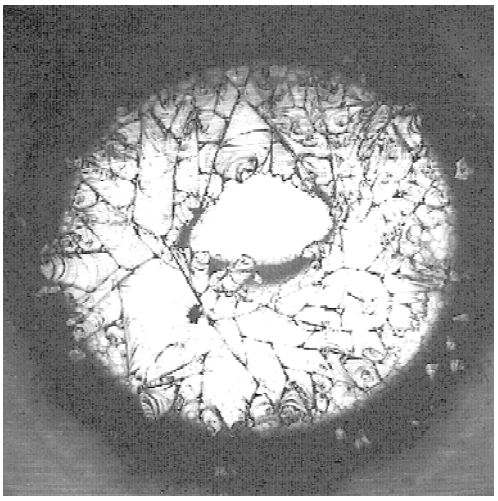
II. BACKGROUND

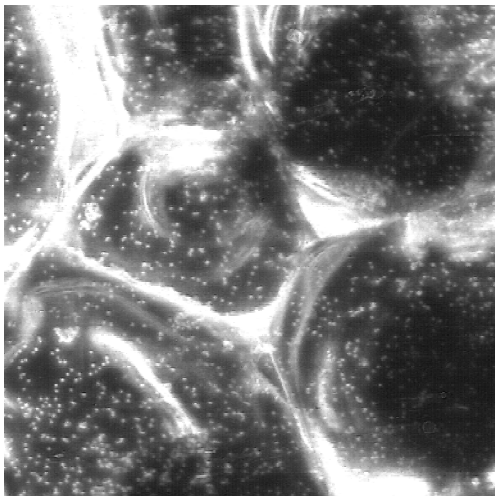
The Geiger counter is named for the Geiger tube. The Geiger tube was invented by Hans Geiger and improved by Wilhelm Müller. The proper name is Geiger-Müller tube or counter but it is almost always shortened to Geiger or G-M.

The tube consists of a gas filled outer cylinder with a fine wire running the length of the center. Brass is often used for the cylinder, tungsten for the wire and argon for the gas. I have used copper tubing for the cylinder and stainless steel guitar strings for the wire with good results. The cylinder can be structural or enclosed in glass. Almost any gas, even air will work with some degree of satisfaction. If you are looking for direct alpha from household radon you'll use air and like it, but the best gas for most purposes is argon with a little bit of impurity for quenching. Many tubes on the market use a mixture of neon and helium.

When the proper voltage is applied across the tube through a dropping resistor about one percent of the particles passing through the gas will cause it to ionize and conduct. (Figures 1 and 2) When the tube conducts, a voltage pulse can be detected across either the resistor or the tube. An especially energetic particle can cause more than one pulse. Multiple pulses (bounces?) are also produced when the tube is right near the glow discharge voltage. The conduction continues until the ionization is quenched. Some tubes are self quenching and some are externally quenched. Until the tube







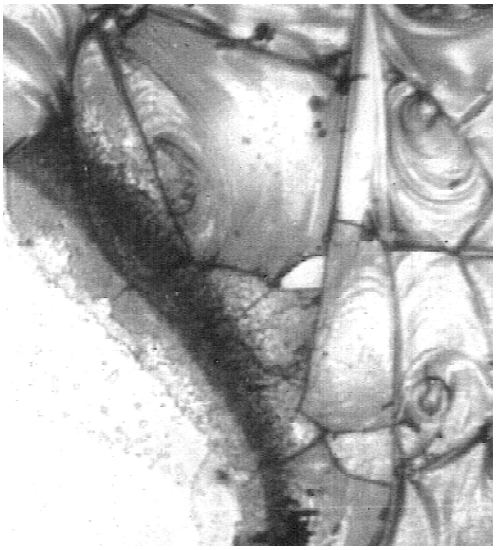


Figure 2 - Micrographs of Plasma Gun Target

Plate glass target was placed approximately 1 mm from the end of the plasma gun. All photographs are of the same target. One shot was fired using a 240 μF capacitor charged to 2 kV at a system pressure of 200 mTorr. All photographs are by the author.

Upper Left: Clear central area is the shadow of the 1/8" diameter center electrode. As the electrode was cut with a wirecutter, this area has an elliptical shape. Adjacent to the electrode shadow is a region of fractured glass. This fracturing is due to the shock wave and/or the intense heat caused by the pulse. The dark circular area is a copper rich region denoting the focusing effect of the plasma gun.

Upper Right: Same as the upper left photograph except with dark field illumination. The fracture region stands out in better detail.

Middle Left: Dark field closeup of the fracture region. Note the small dots. These are copper macroparticles that have been imbedded in the target.

Lower Left: Fracture region directly adjacent to the central electrode. Note the sharply defined copper-rich region at the perimeter of the electrode and the fracture and strain patterns in the fracture zone.

Some Resources and Ideas for Plasma Experiments

Plasma Experiments with Commercial Gas Tubes and More Ideas for Microwave Oven Conversions

I. INTRODUCTION

Over the past few months I have received a considerable amount of material from Prof. Robert Jones of the Department of Physics at Emporia State University in Emporia, KS. Prof. Jones' interests lie primarily with experimental plasma physics and he has constructed an interesting array of simple benchtop apparatus for plasma studies.

II. PLASMA EXPERIMENTS WITH GAS TUBES

Prof. Jones brought to my attention a number of articles that have appeared in the *American Journal of Physics*, a publication of the American Association of Physics Teachers. Each of these articles deals with experiments that may be performed with commercial gas tubes such as the OA4-G (argon-filled cold cathode triode), 884/885 (argon-filled thermionic triode), and 886 (mercury-vapor rectifier). All of these tubes (or equivalents) may be obtained for prices in the $5 to $12 range from suppliers such as Fair Radio Sales.

The use of commercial tubes permits a considerable amount of experimentation without the need for vacuum apparatus. However, the techniques, once understood, are completely applicable to "real" applications.

In this note I won't go into the details of the experiments but will only outline the experiments that are described. Detailed explanations of the concepts may be found in almost any text on plasma physics. Since most of these books are almost totally incomprehensible to the average mortal, a suggestion will be made at the end of the article.

The first article is ***New Elementary Experiments in Plasma Physics*** (I. Alexeff, J.T. Pytlinski and N.L. Oleson, September 1977). Four experiments are described:

- Plasma Familiarization - Measurement of *e/m* (charge to mass ratio of the electron) and the ionization potential of argon using the 884.
- Plasma Diagnostic Experiment - Measurement of plasma electron temperature and electron density by a single Langmuir probe using the OA4-G.
- Observation of the plasma electron frequency using the 866-A.
- Investigation of the decaying plasma using the 866-A.

The second experiment, as adapted by Jones, is diagrammed in Figure 1. I note this experiment because of the importance of the Langmuir probe in plasma diagnostics.

A Langmuir probe is nothing more than a wire that is inserted into a plasma to measure its potential. Early experimenters let the probe float and measured the voltage with a high impedance meter. That gave totally erroneous measurements because the floating probe would permit charges to accumulate. Langmuir's technique involved connecting the probe to a source of variable potential. The probe voltage is swept and the resulting current *vs.* voltage characteristic, will yield the electron and ion currents to the probe.

The figure shows how the OA4-G is connected for this experiment. A discharge is triggered between the cylindrical cathode at pin 2 and a ring shaped anode at pin 7. The electrode at pin 5 serves as the probe. This electrode is surrounded by a glass sleeve to a point at the plane of the ring anode. The unsheathed portion extends about 6 mm beyond the sleeve.

In the experiment, a discharge is struck between the anode and cathode. This may require about 200 volts. Once the discharge is started the voltage must be reduced to about 60 volts to avoid damaging the tube. After a period of warm-up, the probe is swept by incrementally varying the variable supply. A curve of the type shown in the figure will be developed.

As many plasma devices utilize magnetic confinement fields, a couple of articles describe experiments in which the OA4-G is immersed in a field. Now, all OA4-A tubes are not created equally. The above described tube with its long iron-alloy cathode is not appropriate for experiments with magnetic fields as the cathode quite effectively shields the discharge. However, there is a variation with a very short cathode in which the anode and probe structures are above the cathode, exposed. As the tube number is the same, you will have to do a bit of digging to find the right tube.

Experiments in a solenoidal field are described in ***Behavior of a Single Langmuir Probe in a Magnetic***

Reference Number: FF0701

A Brief Tutorial on the Glow Discharge - Part 1

Steve Hansen

I. INTRODUCTION

"Of all the new phenomena wherewith the world has been enriched by modern physics, there is none more beautiful than the glow in a suitably rarefied gas. In the tube between the electrodes, the "viewless air" takes form and color; it seems to condense into luminous mists, to gather itself into islands of variously tinted cloud, which zones of darkness divide.

"The charm of these phenomena is nothing lessened by remembering that in history they make their first appearance as precursors of the conquest of our present wisdom. Modern atomic physics is the child of the vacuum pump. When pressures of the order of a millimetre were attained, the glow revealed itself in its greatest splendor. Attracted by the sight, physicists forged onward to lower and ever lower pressures as fast as better pumps were made. The splendor waned; but the change was simplification. Ultimately the glory of luminous clouds was gone; but by that time there were sharp and clearcut beams of radiation in the tube: one proceeding from the cathode into the zone of the discharge, others in the opposite sense....and a radiation arising from the places where the beam of the first mentioned hit the wall or any other obstacle. It then transpired that the rays of the first type were free electrons, those of the second were free ionized atoms, the last were photons of a frequency higher than any yet known. So came about the discovery of electricity released from matter, of ionized atoms freely wandering in space, and of the X-rays."

This is how Karl K. Darrow begins the chapter on the self-sustaining glow discharge in his 1932 book "Electrical Phenomena in Gases" [1]. These two paragraphs poetically summarize the study of electrical discharges in vacuum beginning with Jean Picard's observation in 1676 of luminous flashes in the "empty" space of a barometer tube to Wilhelm Roentgen's discovery of the x-ray in 1895.

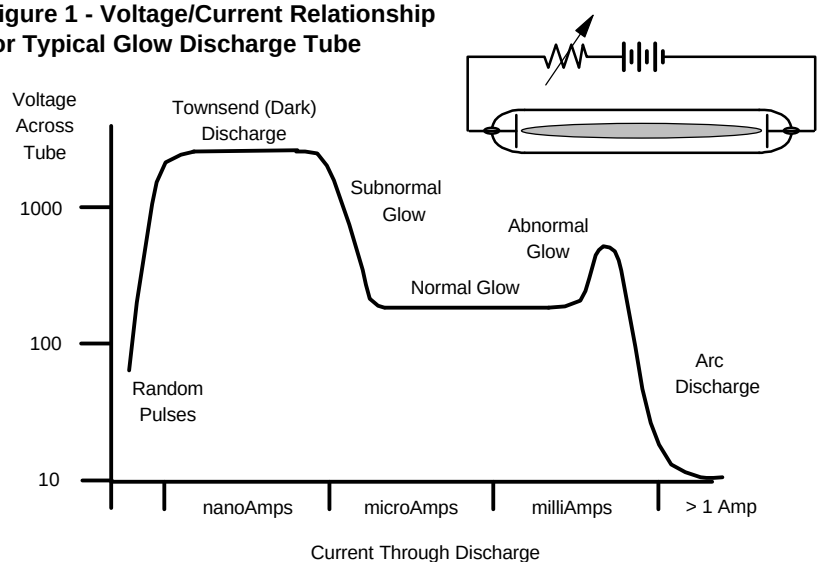
An earlier article in discussed some of the visual phenomena in a glow discharge tube. What follows is a thumbnail sketch, in far less eloquent terms than Darrow's description, of some other important characteristics of the glow discharge. A future article will cover additional aspects.

II. EVOLUTION OF THE GLOW DISCHARGE

A glow discharge takes place in an evacuated tube with two electrodes. When a suitably high voltage is impressed across the tube, there will be a breakdown and the gas will form into a plasma, a neutral mix of positive ions and electrons.

Figure 1 depicts the voltage vs current relationship for a glow discharge tube of the dimensions that an amateur experimenter might work with, i.e. 1 inch diameter electrodes placed about 18 inches apart. This tube would be operated at a pressure where the characteristic forms of the discharge will be revealed, i.e. about 1 Torr.

Figure 1 - Voltage/Current Relationship for Typical Glow Discharge Tube



If the current is slowly ramped by decreasing the value of the resistor, the gas in the tube will go from a non-conducting state to one in which there are very low current random pulses (induced by, in the absence of anything else, the passage of naturally occurring ionizing rays) which create a very dim, sporadic illumination. Through this region the current rise is small compared with the increase in voltage drop. This eventually changes to a region where the voltage rise slows as current increases more drastically. In this region, the discharge is called *self-sustaining*

Some Experiments with Glow Discharge Produced Electron Beams

Steve Hansen

I. INTRODUCTION

In the article on page 2-28 I described a set of modular metal and glass components which can be used for a variety of electron, ion and molecular beam experiments as well as for plasma studies. In this article I will concentrate on some experiments with electron beam production using a cold cathode glow discharge source. These experiments are conducted in rough vacuum, 30 to 100 mTorr being the recommended range. The reader should also refer back to the two articles which covers some of the characteristics of the glow discharge. Additionally, several references are noted with this article.

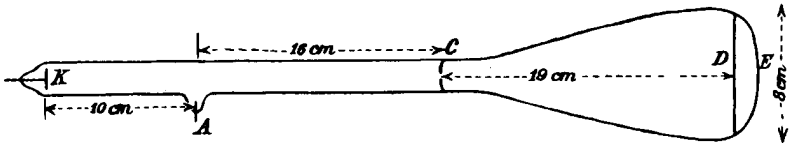


Figure 1 - Braun Tube (from *Annalen der Physik*, 1897)

Early cathode ray tubes made extensive use of glow discharges to produce electron beams. The Braun tube, dating from 1897 (see Figure 1), represented a practical application of the stream of development which progressed from Geissler to Crookes. This tube was the prototype of the modern phosphor-screened cathode ray tube. The Braun tube consisted of a narrow neck containing a pair of electrodes and a plate with a small aperture. With a discharge between the end mounted cathode (K) and the anode (A), electrons are liberated and accelerated through the anode region. A beam is formed when the electrons pass though the aperture (C). The beam then progresses to the screen (D) which provides the visual indication. External magnets could be used to deflect the beam as could internal electrostatic deflection plates.

When the electron beam passes through the coarse vacuum of the tube, there is a further focusing of the beam through an effect called *gas focusing*. This is caused by the electron beam's ionizing of the residual gas in the tube which then creates a positive space charge along the path of the beam. This positive 'channel' helps to prevent divergence of the beam.

The cold cathode CRT continued to be used even after the introduction of the more modern hard vacuum thermionic (filament) tubes. Particularly suited to the gas tube was the Dufour oscillograph where the phosphor was replaced by a piece of photographic film. The ruggedness of the Braun configuration along with

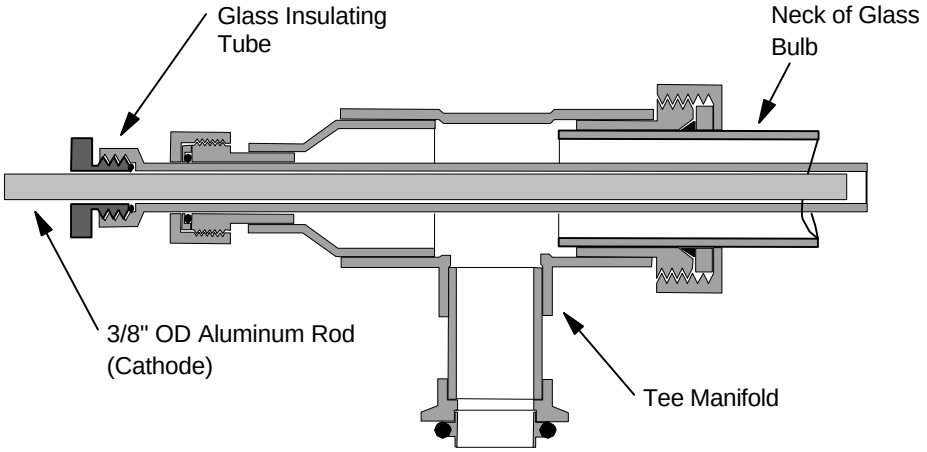


Figure 2 - Manifold and Cathode Assembly

Compression Plates for Stacked Electrode Assemblies

I. INTRODUCTION

A variety of interesting pieces of apparatus may be assembled from coaxial planar stacks of metal apertures and/or grids separated by suitable dielectrics. Examples would include dc accelerator columns, energy and mass analyzers, electron guns, gaseous and metal vapor ion sources, and so forth.

The MIT and Penn State electron optics kits described on page 3-87 are examples of a flexible approach to particle optics studies. As noted, the Kimball Physics *eV Parts* components provide a relatively easy way to fabricate complex research quality UHV compatible electron optics with a standard set of parts. All of these approaches create structures that are flange mounted for insertion into a vacuum chamber.

At the other end of the spectrum are the stacked and brazed or glued structures that have been used to make potential drop particle accelerators. Amateur built accelerators have used brass disk electrodes with intervening glass tubes which serve as segmented insulating columns as well as the walls of the vacuum chamber. Research accelerators have used ceramic tubes and, more recently, polyethylene disks as the insulating structures. In most cases, the seals between the electrodes and insulators have been made with epoxy cement. While this makes for a simple structure, the use of adhesive seals makes changes, even minor ones, very difficult (or impossible) to accomplish.

The O-ring based approach to stacked structures as shown in the article on the multiplate electron and ion source can be generalized to encompass other structures. This article will give details on a simple set of plates between which such structures may be placed.

II. COMPRESSION PLATES

The compression plates are fabricated as shown in Figure 1. I cut the plates from ½" Lexan sheet using a 3-¾" hole saw. This produced a disk about 3-5/8" in diameter. As the edge was a bit ragged, I turned the disk down to 3-½" with a lathe.

The central pedestal represents a totally perverse use of a 1.33" fixed Conflat flange. My only excuse is that it works quite nicely and the flanges are fairly cheap. The central bore is 5/8" diameter and is compatible with ½" copper water tube. The stub provides extra support to the tube and has a slight step in the end which perfectly matches the id of a standard 5/8" brass washer. To assemble the metal parts, clamp the water tube gently in a vise such that, when the flange is placed over the tube, the end of the tube is flush with the washer's upper face. With all mating surfaces cleaned and fluxed, solder with 2 to 4% silver-tin alloy.

As the flange is designed to be flush with the 5/8" compression fitting on the manifold, it is important that the heads of the 8-32 screws be recessed. Three equally spaced holes on a 2-½" circle hold the tie-rods. I would recommend that one of the plates be drilled and tapped

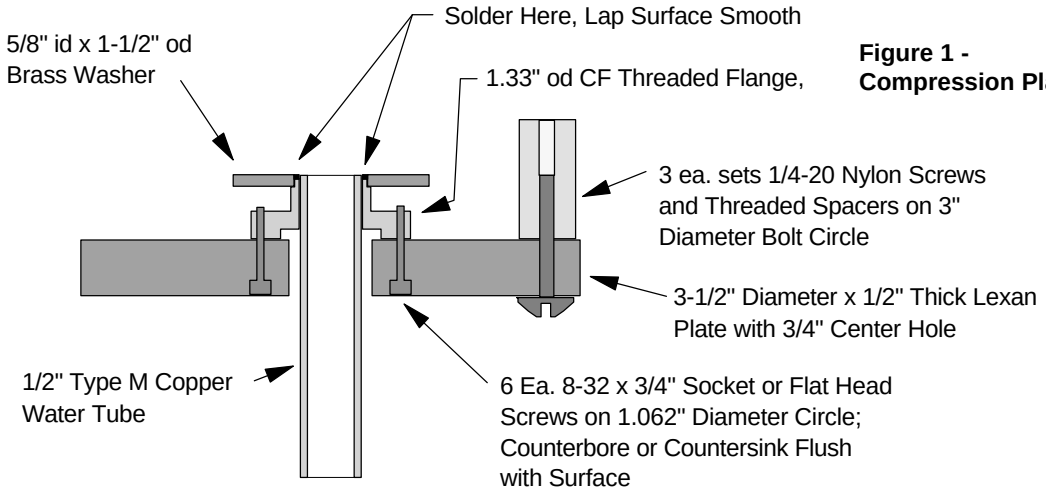


Figure 1 - Compression Plate

Reference Number: FF0701

A Home-Grown, Sealed Carbon Dioxide Laser

David Knapp

Dept. of Geological Sciences, University of Colorado, Boulder, CO 80309-0250

Abstract: The construction of a sealed, CO_2 gas discharge laser was undertaken as an independent study project. Glass laser tube design, as well as clear acrylic housing, make it an excellent demonstration tool. Sealed operation was characterized in mode, power, warm-up and stability over the period of weeks. Novel design approaches were used for expediency and cost saving. An anomalous turn-on behavior is also discussed.

In reviewing the vacuum related articles in Scientific American's The Amateur Scientist*, a high percentage of them dealt with the construction of lasers of various types. When I undertook t*BJ *I figured that lasers would also play a prominent role. That has not proven to be the case, perhaps due to the ready availability of low-cost HeNe and diode lasers.*

Certainly, if one needs a laser to perform a specific task, then the easiest route is to buy or borrow one. Here the laser is a means to an end, an appliance. But, if one wants to understand lasers, then there is no better way than to go through the experience of building and optimizing one.

I discovered this article, in unfinished form, on the Internet a few months ago. With minimal prodding, David agreed to complete the article for publication in this journal. While this article is fairly technical, it does approach the construction of the laser in the manner that an ambitious amateur would. Anyone undertaking such a project would also be advised to acquire a copy of the CO_2 laser article which appeared in The Amateur Scientist *of September, 1971*. - Ed.

I. INTRODUCTION

The construction of a sealed CO_2 laser was undertaken for several reasons. First, the CO_2 laser provides an impressive and graphic demonstration of quantum mechanical processes. Since the laser is constructed out of glass all of its components can be clearly seen if it is contained in an acrylic case. Finally, the laser produces more than 20 watts of coherent, monochromatic laser radiation, enough to burn paper and wood.

Another reason why this was undertaken was because all of the supplies, equipment and lab space were readily available; it only took time and inclination to exploit these resources to arrive at a useful device. It was also an achievable project as evidenced by the author's demonstration of a smaller, less complicated flowing gas CO_2 laser the previous semester in a junior physics lab course.

Most importantly, the author simply wanted to have a relatively compact, portable laser, which did not require bulky vacuum equipment or gas cylinders. In this manner, a CO_2 laser would be available for future work.

II. THE CO_2 LASER

The Resonator

The resonator used is confocal-confocal. Since the optics used in the this project were donated from a company, the author did not have a choice of mirror curvature. Since it was higher power and not best quality mode that was desirable, particular attention was not paid to resonator optimization. With the high reflectance mirror radius of curvature of 2.685 m, and output coupler radius of 5.072 m, the resonator is in the stable resonator regime at 0.66, as determined by the stability relation:

$$0 \le \left(1 - \frac{L}{R_1}\right) - \left(1 - \frac{L}{R_2}\right) \le 1$$

where L is the cavity length, here 65 cm, and R is the radius of curvature of the mirror.

Energy Transfer in the Discharge

The most commonly observed laser transitions in the CO_2 molecule, barring the use of any frequency tuning mechanisms, are from the CO_2 asymmetric stretch transitions, from the (00°1) to the (10°0) 10.6 micron and (02°0) 9.6 micron states, using the notation $V_1V_2°V_3$, where V_1 refers to the symmetric stretch quantum number, V_2 refers to the asymmetric stretch quantum number and V_3 refers to the asymmetric stretch quantum number.

There are literally dozens of other lasing transitions [6] which can be easily chosen by employing an intracavity grating. In a CO_2 laser, lasing of one

Some Recollections

Franklin Lee

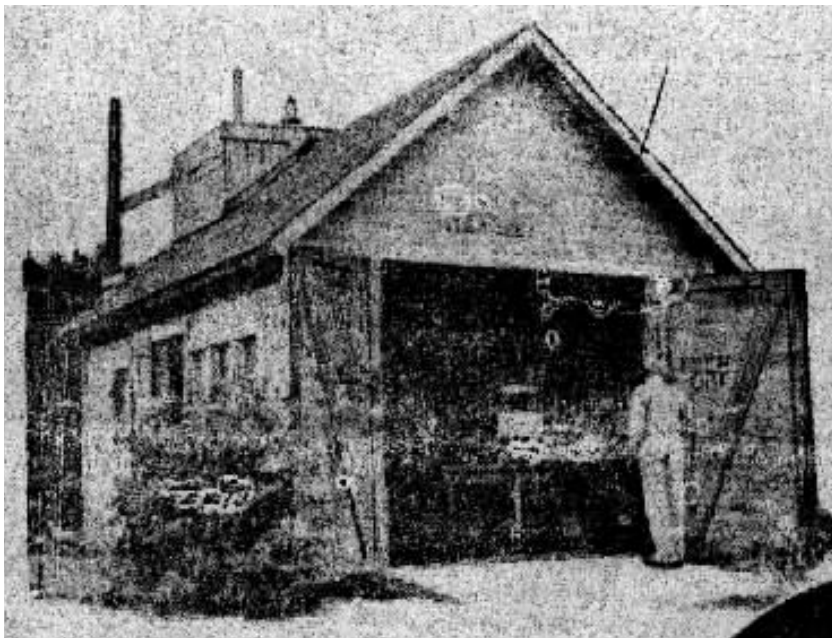
Certainly, in my case, this teacher and advocate of hands-on science was a major factor in my life's interests. Frank recently commented that he felt that he never lived up to his potential, that he could have been another Edison. Well, perhaps the world didn't need another Edison. The inspiration that Frank provided to others to do science, in my opinion, is of similar value, albeit harder to recognize and measure. The following material has been pieced together from several correspondences with Frank. - Ed.

I was born in a small town, Granite Falls, Minnesota, population 1500. For some reason that town was the home of a number of talented or famous people. There was Doctor Wellcome, one of the founders of Burroughs Wellcome Drug Company in England. There was Olai Lende, the inventor of many automobile components such as the differential, screw drive steering wheel, etc. Presidential candidate Hubert Humphrey's father had a drug store in Granite Falls before moving to No. Dakota. Senator Volsted lived across the street from Grandma Lee and Archibald Bush, a founder of 3M Company, came from Granite Falls. His charitable gifts exceeded $1 billion with $5 million a year going to Granite Falls for the schools, etc. Then there was Mildred Lee, my mother, first woman admitted to the Minnesota Bar, recognized poet and historian, and an early feminist.

My first attempt to use vacuum occurred in 1934 or 35. I was trying to make an electronic tube as my allowance was not enough to purchase a ready-made tube. I was 13 at the time and didn't realize what high vacuum was. I tried a water aspirator which got me to 30 mm Hg, the vapor pressure of water. What I got was a Geissler tube with blue light. This ended my childhood involvement with vacuum.

My last year in high school was rather turbulent. I was 15 at the time and running in all directions. I was making fireworks contrary to my parent's views. For a dollar, one could get 5 lbs. of sodium chloride at the hardware store. It was used as a weed killer. When mixed with charcoal or other combustible material it was a nice explosive. With a friend or two, I went outside town and blew up tin cans, split logs, etc. It could also be used to make colored flares. I also made a small cannon out of two pieces of steel pipe - 3/4" for the barrel which was placed within a piece of 1" that served as reinforcement. I would pack the barrel with 2" of "mix", put in a wad of cloth and insert a 3/4" glass marble as the projectile. The marble would go through 2-1/4" of pine. Once it missed the boards and went through one wall of a shed and out the other.

I did have the sense to stand behind the cannon while loading it. Once while loading it, the cannon



A photograph of Franklin Lee's Garage-Laboratory ca. 1934. In a magazine article about him this is described as the place where he "carries on his chemical and electrical research experiments. A network of charged wires keeps out the loiterers."