# PCTFE as a Solution to Stress-Induced Birefringence in Atom Trap Viewports

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**Abstract**

At TRIUMF Neutral Atom Trap (TRINAT), the current goal is a measurement of the angular asymmetry of beta particles with respect to the nuclear spin, $A_\beta$, from the beta decay of spin-polarized $^{37}$K nuclei. We characterize the degree of circular polarization of the optical pumping light with the Stokes parameter $S_3$; with an $S_3$ value of 0.999 required to spin polarize 99.95% of the atoms.

One major difficulty we encountered was stress-induced birefringence on the viewports of the atom trap. An alternative to the commonly used fully annealed copper gaskets was o-rings. An eventual solution was found with PCTFE o-rings which provided a compromise of stress-relief and sealing which made our viewports suitable for UHV. We can characterize the birefringence of viewports using $\Delta n$ [see Solmeyer, Rev. Sci. Instrum. 82 (2011) 066105], and we further understand the birefringence by demonstrating the relationship between $S_3$ and $\Delta n$ for circularly polarized light. We have found PCTFE (Polychlorotrifluoroethylene)to be a suitable sealing material , achieving vacuum of $3 \times 10^{-9}$ Torr of nitrogen before bakeout, and below $5 \times 10^{-10}$ Torr after baking. The helium permeation of PCTFE was also quantified, with a permeation constant value of $K = (3.0 \pm 0.7) \times 10^{-8} scc \cdot cm \cdot s^{-1} \cdot cm^{-2} \cdot atm^{-1}$ measured.

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# 1 Defining $S_3$ and $\Delta$n

$S_3$ is defined as

$$S_3 = \sqrt{1 - S_{lin}^2} \tag{1}$$

Where

$$S_{lin} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{2}$$

Solmeyer relates $\Delta n$ and the extinction ratio for linearly polarized light as

$$\frac{I_{min}}{I_{max} + I_{min}} = \frac{1}{2}(1 - cos(kL\Delta n + \phi)) \tag{3}$$

Where k is the wave number $\frac{1}{\lambda}$, L is the thickness of the glass, and $\Delta n$ is the birefringence of the glass.In the case of linearly polarized light, $\phi$ can be considered zero. However, for circularly polarized light $\phi$ is $\frac{\pi}{2}$. We can combine the previous equations in the following way: From Equation (3):

$$I_{max} + I_{min} = \frac{2I_{min}}{1 - cos(kL\Delta n + \frac{\pi}{2})} \tag{4}$$

$$I_{max} - I_{min} = \frac{2I_{min}}{1 - cos(kL\Delta n + \frac{\pi}{2})} - 2I_{min} \tag{5}$$

From Equations (1) and (2):

$$S_3^2 = 1 - \left(\frac{I_{max} - I_{min}}{I_{max} + I_{min}}\right)^2 \tag{6}$$

Therefore:

$$S_3^2 = 1 - \left(\frac{\frac{2I_{min}}{1-cos(kL\Delta n+\frac{\pi}{2})} - 2I_{min}}{\frac{2I_{min}}{1-cos(kL\Delta n+\frac{\pi}{2})}}\right)^2 \tag{7}$$

$$S_3^2 = 1 - cos^2(kL\Delta n + \frac{\pi}{2}) \tag{8}$$

Therefore for circularly polarized light we can define

$$S_3 = sin(kL\Delta n + \frac{\pi}{2}) \tag{9}$$

$S_3$ relates to atom cloud polarization (P) as

$$P = \frac{1 + S_3}{2} \tag{10}$$

# 2 Experimental Setup

## 2.1 Generating Circularly Polarized Light

Linearly polarized light enters a Liquid Crystal Variable Retarder (LCVR) at 45° to the axis of the LCVR, creating circularly polarized light. It is then passed through a rotating analyzing polarizer followed by a power meter, from which the maximum and minimum power of the circularly polarized light can be determined. The analyzing polarizer place before the viewports indicates the 'baseline' $S_3$ value, while if it is placed after the viewports, the impact of the viewports on $S_3$ can be evaluated.

## 2.2 O-ring Viewport Design

The viewport with which o-rings were used was a CF flange with an inlaid o-ring groove. The o-ring in the groove supports the viewport (650-1050nm anti-reflection coated) which is compressed onto the o-ring by an aluminum plate and six titanium 6-32 screws. $\frac{1}{4}$-28 bolts at 96 in-lbs sealed the CF to the rest of the system, while the 6-32 screws were carefully tightened to between 6 and 10 in-lbs for PCTFE and 15 in-lbs for FKM and FFKM. The viewports used are Thorlabs "B" 650-1050nm antireflection coated viewports. The part number for the Accuglass viewport is 112667.

# 3 Copper Gaskets

Pre-manufactured viewports made from glass welded onto a CF compatible flange were attached to the system using $\frac{1}{4}$-28 bolts at varying torques. It was found that the birefringence of the viewports was strongly correlated to the torque applied to the viewports, as can be seen in Figure 1.

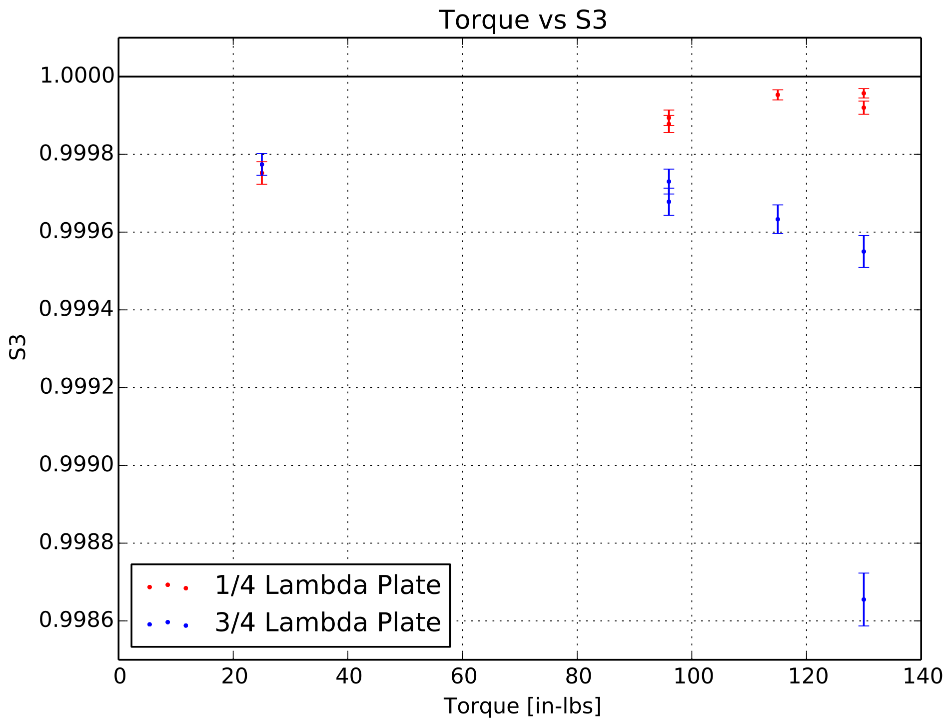


Figure 1: $S_3$ gets worse or better depending on the handedness.

# 4 FKM and FFKM O-rings

FKM and FFKM orings provided excellent stress relief for the viewports. The $S_3$ values from light passed through the viewports were consistently above 0.9998. However, the air permeation and outgassing properties of the materials led to a maximum achieved vacuum of $3 \times 10^{-8}$, which is insufficient for atom trapping experiments which require UHV.It should be noted that this pressure was achieved when the chamber had not been baked and there were possible leaks in the Swagelock and NPT fittings. Considerably better vacuum could have been achieved if these issues had been resolved.

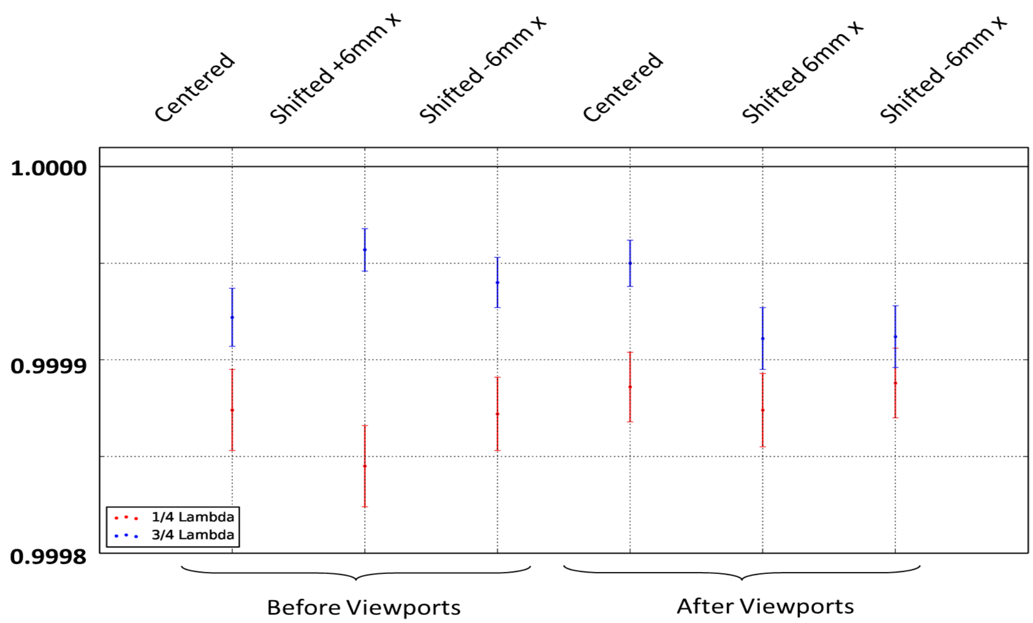


Figure 2: $S_3$ values are very high and do not change significantly with horizontal translation (almost within errors).

# 5 PCTFE O-rings

The viewports using standard o-ring size -124 PCTFE o-rings were assembled in a clean room. Before assembly, the o-rings were inspected under a microscope for imperfections, then ultrasounded for 30 minutes in deionized water to remove any residual oil or dust from the manufacturing and inspection processes. A ring (OD = 1.8", ID = 1.2") of 0.005" thick Kapton film was used to cushion the viewport against the aluminum plate holding it in place. When we started using PCTFE, we used the same torque on the screws as we had used with the FKM/FFKM (15 in-lbs). This resulted in high levels of birefringence (in some instances $S_3$ was reduced to 0.98) and breaking two viewports. To resolve this we started to use torques for the 6-32 screws between 4 and 10 in-lbs, with the best compromise between leaking and stress-relief occurring at 6-8 in-lbs

We also tried polishing several o-rings before ultrasounding with 0.3$\mu$m aluminum oxide powder in water on a polishing cloth, but this didn't end up improving the stress-relieving quality of the o-ring, so they were not used on the final system, and the $S_3$ values were not as good as when the o-rings that had not been polished were used. A possible reason for this is the potential for hardening of the surface of the o-ring during polishing which would put more stress on the viewport.

When the viewports with the PCTFE o-rings were installed on either the main system or the test setup, the CF bolts were tightened with the 6-32 screws loose, before tightening the screws. The final viewports used on the system were Thermech I on the top of the chamber at 8 in-lbs on the screws, and APT I on the top of the system, with 6 in-lbs on the screws. Both viewports used fully annealed copper gaskets to attach to the CF and the CF bolts were tightened to 96 in-lbs.

If either of the main system viewports were to fail or be damaged, I would recommend replacing it with the other Thermech o-ring at 6-8 in-lbs. Following that, I would use the unpolished APT o-rings before resorting to using the polished ones.

| O-ring | Kapton | Polish | Torque used in tests |
|---|---|---|---|
| APT I | Yes | No | 6-8 in-lbs |
| APT II | Yes | No | 8 in-lbs |
| APT III | Yes | Yes | 8 in-lbs |
| APT IV | Yes | Yes | 4 in-lbs with 316 SS screws |
| Thermech I | Yes | No | 8-10 in-lbs |
| Thermech II | Yes | No | Not tested |

# 6 Measuring $S_3$ on the Test Setup

The test setup consisted of a 1.1mW 770nm laser being reflected 90° off a mirror and following a straight path through a linear polarizer, a LCVR, the viewports, an analyzing polarizer, and finally a power meter. The baseline $S_3$ would be determined first by rotating the analyzing polarizer before the viewport, and then the $S_3$ could be measured after the viewport simply by moving the analyzing polarizer to after the viewports. The optical elements and path of the light could also be shifted so that the light did not hit the viewports in their centers. The angle of the primary polarizer with respect to the LCVR is crucial, especially since the optimum angle for each handedness of light is slightly different. The best angle to use is between the two optimum angles for a compromise between the handed-ness'. The following are the $\Delta n$ values achieved on the test setup with the final viewports.

| Viewport | $\Delta n \times 10^{-6}$ for $\frac{3\lambda}{4}$ | $\Delta n \times 10^{-6}$ for $\frac{\lambda}{4}$ |
|---|---|---|
| Thermech I | $-5.23 \pm 0.34$ | $-0.66 \pm 0.34$ |
| APT I | $-1.17 \pm 0.34$ | $1.48 \pm 0.34$ |

### 6.1 Optimum Voltages for Test Setup

The optimum voltages for the LCVR ended up being 2.283V and 1.421V for the VAC on a voltmeter. A DAC was used to more accurately control the voltages, and when the wavefunction generator which drove the LCVR was set to 4V, the DAC voltages entered were 4.125V and 2.570V.

### 6.2 Horizontal Shifts

For both the PCTFE and the FKM/FFKM, we found that the light was not affected very much by shifting the beam off-center on the viewports (see p.148 of Claire's log for the PCTFE, and p.85 for Viton/Kalrez). When we moved the beam 6mm off center in the case of PCTFE, the magnitude of the difference in $\Delta n$ between a centered and un-centered beam was just $3.4 \times 10^{-7}$. For FKM/FFKM, see Figure 2 for a detailed set of horizontal shift measurements typical of the FKM/FFKM orings.

## 7 Measuring $S_3$ on the Main System

On the main system, measuring the $S_3$ value was slightly more complicated. The light could either be shone through a stack on the top viewport, or through a stack on the bottom. The analyzing polarizer would then be rotated on the other side of the chamber. Before the bakeout, we measured the $S_3$ in the middle of the viewport with the light traveling from the top of the chamber to the bottom. Drifting power levels made measuring the maximum and minimum powers needed to calculate $S_3$ somewhat difficult. Before baking, we measured the $S_3$ in the middle of the chamber (light traveling from top to bottom) and from that calculated the $\Delta n$ contributions from each viewport. Note that for the bottom viewport, the $\Delta n$ value is positive. As I am uncertain whether the sign reverses when the direction of the light is reversed, the estimated birefringence for the worse case I took to be $-2.45 \times 10^{-6}$.

| Viewport | $\Delta n \times 10^{-6}$ for $\frac{3\lambda}{4}$ | $\Delta n \times 10^{-6}$ for $\frac{\lambda}{4}$ |
|---|---|---|
| Top (Thermech I) | $-5.6 \pm 1.8$ | $-5.4 \pm 1.7$ |
| Bottom (APT I) | $1.9 \pm 1.6$ | $2.45 \pm 1.6$ |

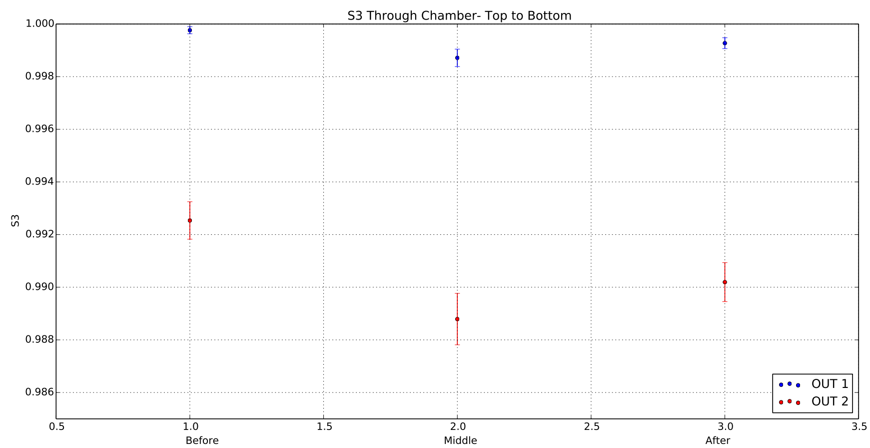


Figure 3: Measured $S_3$ values on main system (pre-bakeout) for each handedness with light going top to bottom.

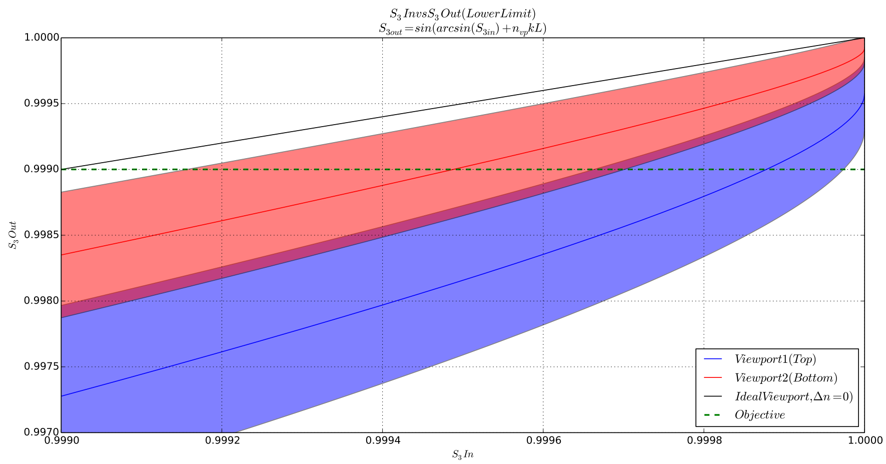


Figure 4: Projected worst case $S_3$ values for each main system viewport compared to incoming $S_3$.

## 7.1 Optimum Voltages for Main System

### 7.1.1 Bottom Stack

For the bottom stack on Leonid's multimeter (TRINAT 23 p. 69-70): Voltage 2 = 2.03565V, Voltage 1 = 5.63220V. This value should be considered approximate as the voltage, as well as the power, was drifting throughout measurement.

### 7.1.2 Top Stack

For the top stack on Leonid's multimeter: OUT1: 2.00961V, OUT2:5.81312V. This value should be considered approximate as the voltage, as well as the power, was drifting throughout measurement. Furthermore, the stack requires significantly more tuning in the future to optimize the $\frac{\lambda}{4}$ light at the higher voltage, as only about 0.99 was achieved for $S_3$ for this handedness.

| Stack | Voltage 1 | Voltage 2 |
|---|---|---|
| Top | 2.00961V | 5.81312V |
| Bottom | 5.63220V | 2.03565V |

# 8 Rate of Rise Test

To make sure that the viewports did not leak at a rate that would affect the vacuum, a rate of rise test was performed. The system with two viewports was pumped to approximately 5 Torr and sealed, while the pressure was monitored. The leak rate achieved with the two viewports that would be used on the final system was approximately 0.2mTorr per hour after outgassing, which extrapolates to a theoretical pressure of $1.5 \times 10^{-10}$ Torr on the final system.

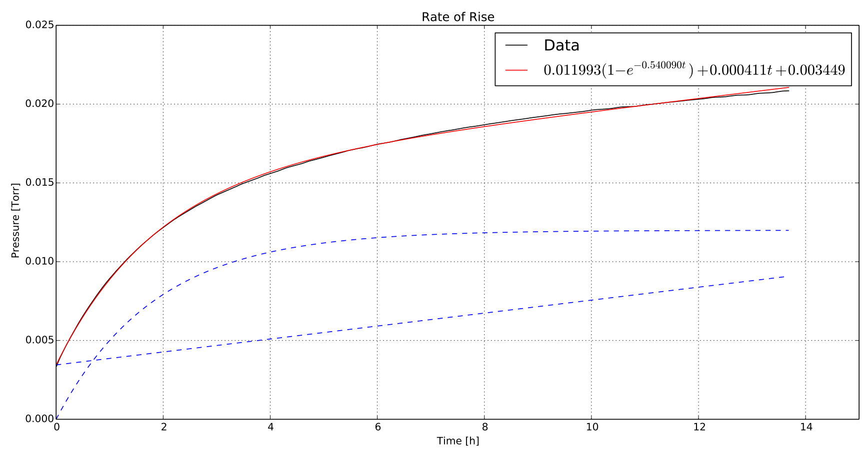


Figure 5: Rate of rise with both viewports used on the final chamber. About half of the linear leak can be attributed to leaky Swagelock and NPT fittings.

In the image, the rate of rise with two viewports and then none is plotted. The difference between two represents the contribution of the viewports to the leak. The remainder of the leak can be attributed to leaky Swagelock fittings which were bumped while removing or bolting on viewports (we had found leaks in the Swagelock fittings while performing the helium leak checks so they are the likely culprit.. In between these two measurements, we replaced one viewport (Thermech I) with a blank. The leak rate after doing this remained virtually unchanged, leading us to believe that the Thermech viewport was leak-free and the majority of the viewport leakage could be attributed to APT I.

# 9 Helium Permeation

To investigate the helium permeation of PCTFE, the viewports were surrounded with helium at atmospheric pressure and the leak rate of the helium in $atm \cdot cc \cdot s^{-1}$ was measured. The leak rate very reproducibly rose to a steady equilibrium, at which point the helium source was removed. Then, the leak rate decreased as the helium saturated within the o-ring dissipated into the vacuum. The same process was repeated with argon and no leak registered on an RGA after an hour.

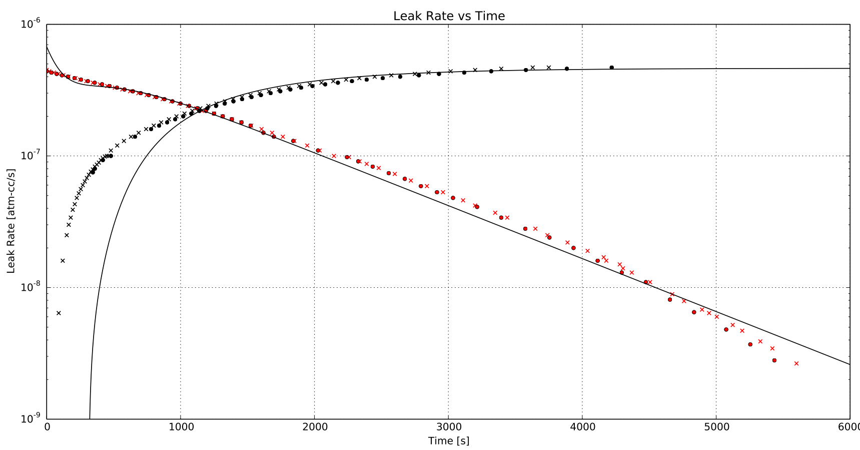


Figure 6: Rise and fall: leak rate- two different trials (very reproducible)

## 9.1 Fitting to the Diffusion Equation

The fits are using the diffusion equation found in W.G. Perkins: Permeation and Outgassing of Vacuum Materials and Sturm et. al: Permeation of atmospheric gases through polymer O–rings used in flasks for air sampling. The are the first three terms of the series solution, and are known to fail at low times. In this case, $P_o$ was assumed to be 1atm. d was defined as the average thickness of the o-ring, 0.205cm. A was the exposed area of the o-ring, 2.7cm$^2$. K, the permeation constant, is equal to $D \cdot S$.

The solution to the diffusion equation through a membrane while the membrane is saturating from a source is

$$F(x=d,t)=\frac{ADSP_o}{d}\Big(1+2\sum_{n=1}^{\infty}(-1)^n exp\Big[-\frac{Dn^2\pi^2t}{d^2}\Big]\Big) \tag{11}$$

The solution to the diffusion equation through a membrane when the source has been removed is

$$F(x=d,t)=\frac{-2ADSP_o}{d}\sum_{n=1}^{\infty}(-1)^n exp\Big[-\frac{Dn^2\pi^2t}{d^2}\Big] \tag{12}$$

Fit for the rise:

$$D=(3.94\pm0.04)\times10^{-6}cm^2\cdot s^{-1}$$
$$S=0.00651\pm0.00014scc\cdot cm^{-3}\cdot atm^{-1}$$

Fit for the fall:

$$D=(4.89\pm0.13)\times10^{-6}cm^2\cdot s^{-1}$$
$$S=0.00719\pm0.00027scc\cdot cm^{-3}\cdot atm^{-1}$$

When fitting our data to the diffusion equation, we found that the permeation constant, K, through PCTFE was $(3.0\pm0.6)\times10^{-15}m^2\cdot s^{-1}\cdot hPa^{-1}$, or $(3.0\pm0.7)\times10^{-8}scc\cdot cm\cdot s^{-1}\cdot cm^{-2}\cdot atm^{-1}$, when the fits from the rise and fall fits were averaged. This compares with a permeation constant of between 9 and 16 $\times10^{-8}scc\cdot cm\cdot s^{-1}\cdot cm^{-2}\cdot atm^{-1}$ for helium permeation of Viton [Peacock, JVST ].

## 9.2 Permeation of Nitrogen and Oxygen

On the main system our partial pressures for $N_2$ and $O_2$ were less than $4.0\times10^{-13}$ atm and $1.1\times10^{-13}$atm, respectively. When we take into account the fact that the helium leak check was carried out with an atmosphere of helium (we must remember that air is 78% $N_2$ and 21% $O_2$), multiply by a pumping speed of 100L/s, and divide by 2 to account for there being two viewports on the main system, we get equilibrium leak rates of 2.57 and $2.62\times10^{-8}atm\cdot cc\cdot s^{-1}$. The limit of the leak rate can be expressed as

$$R_\infty=\frac{ADSP_o}{d} \tag{13}$$

Since the viewport dimensions have remained the same since the helium leak check, the values of A, $P_o$, and D can be considered constant. We know that the final leak rate of helium was $4 \times 10^{-7} atm \cdot cc \cdot s^{-1}$. Therefore we can say that

$$R_\infty \propto DS \equiv K \tag{14}$$

We can then calculate $K_N$ and $K_O$ to have upper limits of 0.195 and $0.199 \times 10^{-8} scc \cdot cm \cdot s^{-1} \cdot cm^{-2} \cdot atm^{-1}$. These are comparable to the values cited for $N_2$ and $O_2$ in Peacock's paper, which had K values for PCTFE as $(0.0004 - 0.3) \times 10^{-8} scc \cdot cm \cdot s^{-1} \cdot cm^{-2} \cdot atm^{-1}$ for nitrogen and $(0.02 - 0.7) \times 10^{-8} scc \cdot cm \cdot s^{-1} \cdot cm^{-2} \cdot atm^{-1}$ for oxygen. Peacock also cites K ranges of FKM/FFKM of $(0.05 - 0.3) \times 10^{-8} scc \cdot cm \cdot s^{-1} \cdot cm^{-2} \cdot atm^{-1}$ for nitrogen and $(1.0 - 1.1) \times 10^{-8} scc \cdot cm \cdot s^{-1} \cdot cm^{-2} \cdot atm^{-1}$ for oxygen. This validates PCTFE as a sealing choice over fluoroelastomers in terms of permeation.

# 10 Uncertainties and Sources of Error

## 10.1 VAC Voltage Drifting

I observed that the optimum LCVR voltage wasn't always the same over the course of several weeks. It is also important to note that the voltage will continue to drop as the LCVR "warms up" for several minutes before it stabilized. Measurements should only be made when the voltage has stabilized.

## 10.2 Power Drifting

The power of the light on the main system can drift significantly, making it difficult to achieve an accurate $S_3$ measurement. The higher the power drifts, the better $S_3$ gets, since the degree of polarization is inversely proportional to the sum of the minimum and maximum powers. This is a combination of the power of the laser light drifting and the linearly polarized light rotating with respect to the axis of the optical fiber.

## 10.3 $\Delta$n Direction Reversal

I am not sure if the $\Delta n$ value of a viewport switches sign when the light direction reverses, if it stays the same, or if the two values for different directions are unrelated. I tested this by measuring the total combined $\Delta n$

values of both viewports when measured top to bottom and bottom to top in the main chamber. However, the results were inconclusive because although the different $\Delta n$ values had opposite signs, they were not equal in magnitude. Exact values for this measurement can be found in the TRINAT 23 log book (April $25^{th}$ 2014). When I took measurements of $S_3$ in the center of the main chamber, I only used light traveling from the top to the bottom of the chamber. This means that the light traveling through the bottom viewport in the case of the experiment would be going the opposite way. I therefore estimated the worst case for the birefringence of the bottom viewport as the negative of the larger magnitude of $\Delta n$ I measured, $-2.45 \times 10^{-6}$. I am not too concerned about the end result, because the bottom viewport has consistently had less birefringence than the top viewport.