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Evaluation of Glovebox Gloves for Effective Permeation Control

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Summary

A research and development task was undertaken to determine the permeabilities of hydrogen and dry air through different polymeric glove materials that are used to maintain the integrity of glovebox secondary containment. Fifteen different glove samples were obtained from four different manufacturers and samples cut from these gloves were tested. The gloves included baseline butyl rubber, Viton®, Dupont ® Hypalon®, polyurethane, as well as composite gloves. The testing indicated that all of the vendor's butyl rubber gloves and the Jung Viton® gloves performed comparably in both gases.

Background

Recently, Tritium operations temporarily changed a Radiological Buffer Area (RBA) to a Contamination Area (CA) due to excessive tritium permeation out of a glovebox. The resultant tritium permeation into the air in the contamination area created tritiated water. This tritiated water is more readily absorbed by workers and could pose a significant health problem. This incident prompted the evaluation of alternate glove materials, to determine whether gloves having better resistance to abrasion and wear have sufficient resistance to gas permeation. Inside the glovebox tritiated oxides form which then have to be stripped from the system via magnesium beds (mag bed). Finding more permeation-resistant gloves would reduce costs, particularly by reducing the use of and perhaps the number of magnesium beds used in the facility. Since mag beds are expendable and must periodically be replaced reducing the number of mag beds used would significantly lower operating and maintenance costs. Also, there is little baseline permeation data for common glovebox glove materials. Interim modifications and operational changes, such as reducing the amount of vacuum grease, incorporation of abrasion resistant overgloves, and improved glovebox and glove inspections has enabled Tritium operations to roll back the area to an RBA. However, several of these measures result in operator inconvenience and have costs associated with them that may be avoided. By characterizing the gloves it will be possible to compare gloves from the current vendors and to determine if new vendors or materials are available to minimize mag bed usage and promote cost savings.

This task characterized the permeability of air and dry hydrogen through samples taken from a total of 15 polymeric glovebox gloves from 4 different manufacturers. The gloves by manufacturer, type and thickness are listed in Table 1. This testing establishes baseline data that can be utilized for glove specifications. Through this characterization, it will also be possible to assess the performance of the current gloves in use in the facility

Gloves for this task were provided by suppliers North, Piercan, Guardian, and Jungitec. North 15 and 30 mil butyl and Piercan 15 and 30 mil butyl are the gloves currently approved for use in Tritium operations. Due to the incident referred to above, a Piercan polyurethane Hypalon® (UY) overglove is used to protect from abrasion in some instances.

Permeability is a material property that indicates the rate at which a certain phase, typically gas, of matter passes through the material in question. The flux J is the amount of gas exiting a given permeation barrier per unit area per unit time. The flux of a gas permeating a membrane is related to the permeability by.

$$J = P (p_1 – p_2) / L$$

in which p_1 is the high partial pressure on the entrance side of a membrane, p_2 is the partial pressure on the opposite (exit) side, and L is the thickness of the membrane. Q is the quantity of permeating material. It is the flux times the surface area (A) of the sample times the time (t).

$$Q = J * A * t$$

Permeability (P) is equal to the Diffusivity (D) multiplied by the Solubility (S) of the material, P = SD. $Diffusivity = \frac{L^2}{6*\theta}$. The variable L is the thickness of the material and θ is the time at which break through is achieved. For this study

$$Permeability\ (P) = \frac{V(cm^3)*L\ (in)*MV\ @STP*slope\ \ of\ test\ (\frac{Torr}{\sec})}{SA\ (in^2)*R*T(K)*P(cmHg)}\ .$$

Where V = expansion volume (cm^3), L = sample thickness (cm), MV = slope of permeation curve at steady state (Torr/s), SA = surface area (in^2), R = universal gas constant (6236 $cmHg*cm^3/gmol*K$), T = temperature (K) and P = test pressure difference (P_{source} - $P_{expansion}$ ~ P_{source}).

$$(1\ Barrers = \frac{10^{-10}cm^3\,gas\ @\ STP*cm}{cm^3*s*cmHg})$$

The measured and calculated values can be used to determine the potential for contamination in the facility by gas permeating the various glove materials.

Gloves were received from North, Piercan, Guardian, and Jungitec, with the identity shown in **Error! Reference source not found.**.

Table 1. Glove Manufacturer, compound, and thickness used in this study

Manufac.	Compound	Nominal Thickness (mils)	ID
North	Butyl Rubber	15	NB15
North	Butyl Rubber	30	NB30
Piercan	Butyl Rubber	15	PB15
Piercan	Butyl Rubber	30	PB30
Piercan	Electrostatic Butyl Rubber	15	PESDB15
Piercan	Electrostatic Butyl Rubber	24	PESDB24
Piercan	Polyurethane	15	PU15
Piercan	Hypalon®	25	PY25
Piercan	Poyurethane-Hypalon® (UY)	20	PUY20
Guardian	Butyl Rubber	15	GB15
Guardian	Butyl Rubber	30	GB30
Jung	Viton®	24	JV24
Jung	Viton®	31	JV31
Jung	Butyl Viton® composite (BV)	20	JBV20
Jung	Butyl Hypalon® composite (BH)	27.5	JBH30

Experimental

Sample Preparation

Each glove sample was cut out using a 2 7/8" circular die. The top of the glove was labeled with a T to indicate the sample orientation in the apparatus. The sample was inserted into the sample holder in the middle of the permeation rig. A modified centering ring with a Viton®/silicon O-ring was used clamped between two flanges to create the seal.

Each sample was tested at 3 of 4 (70, 140, 350, 700 Torr) pressures depending on sample thickness. The entire system was then baked out for at least 12 hours and allowed to cool for 3 hours.

Testing Protocol

An existing gas permeation apparatus was used for this testing (Figure 3). The apparatus is designed so the sample separates the source side of gas stream from the permeant side. The disk sample thickness was measured and recorded then it was placed between the O-ring and the upper flange in the sample holder, Figure 2. The clamp was tightened, then the entire volume was evacuated to a pressure below 5×10^{-6} Torr. Often the system was baked (heated) between 90 and 120°C to ensure suitable pressures were achieved. A leak test was conducted before the first test was performed to establish a baseline rate of rise (ROR) for the specific test. This ROR ensured that a suitable seal was achieved in the apparatus and the ROR from permeation was sufficiently high to allow interpretation of the results. After the leak test was completed, the system was evacuated for about two hours to pressures comparable to the pressure achieved prior to the leak test, i.e., 5×10^{-6} Torr or lower. A permeation test at the first target pressure test was performed by isolating the source and permeant sides, and increasing the source side of the apparatus to either 70 or 140 Torr depending on material thickness. The time, permeant and source pressures, and sample temperature were monitored and digitally recorded. Air Liquide Research grade hydrogen and Air Liquide industrial grade dry air were used for the

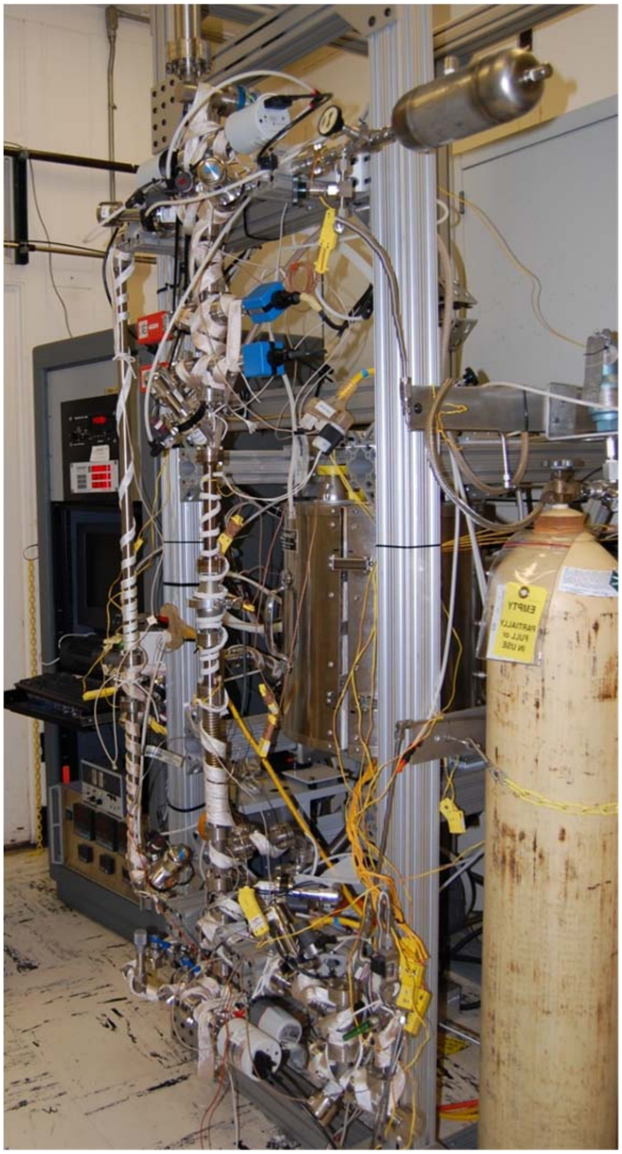

Figure 1. Permeation test apparatus.

Figure 2. Sample holder.

tests. The hydrogen tests were terminated after reaching a pressure of at least 5.0X10^{-2} Torr in the permeant side of the apparatus, and the air tests were terminated at a pressure of 3.0X10^{-2} Torr. These ending pressures were determined based on the curve fitting of the data. Several of the earlier tests were not run long enough to reach these pressures and resulted in correlation coefficient (R^2) of 0.99 rather than the 0.999 R^2 that is attained for the higher pressures listed above.

For the hydrogen testing, after the initial permeability test, a "saturation" test was performed. This test was completed by evacuating the permeant side half of the apparatus for ~ 10 minutes and then closing the appropriate valves and capturing the test data. Since this test starts with the sample already saturated with the test gas, it is used to provide a second permeability measurement value. The diffusivity could not be determined in the saturation tests.

Due to the relatively slow ROR testing under air, only permeation tests that provide both diffusivity and solubility data were conducted using air as the permeant. Also due to time constraints, only the "thin" gloves were tested and no 30 mil gloves were included.

Most tests were conducted at room temperature. The 30 mil North Butyl was tested at room, 50 and 75°C to observe the effect of temperature on the permeability.

Samples were removed from the sample holder and the post-test thickness was measured. In addition, the samples were visually examined for permanent set or deformation. Due to time constraints only single samples were tested. The diffusivity, permeability and solubility were calculated for each sample and pressure. These data were determined from the pressure readings initially from the active Pirani gauges and later from the pressure readings from a 10 Torr Barocel capacitance manometer. The pressure on the source side of the apparatus was maintained using a capacitance manometer to measure the pressure and an electronically controlled valve and an open manual valve while evacuating the gas with a scroll pump, which is a common feed-and- bleed pressure control system. A volume calibration for the apparatus was run first with the Pirani gauges and then once the Barocel capacitance manometer was added to know the sample volume for calculations. These calibrations were also performed at the elevated temperatures.

Results and Discussion

A typical raw data plot is shown in Figure 3 for hydrogen permeation through Guardian 15 mil Butyl rubber at 350 Torr. The data exhibit a region of increasing pressure rise with time followed by a steady state region. The steady state part of the data is used to determine the time lag, θ, by curve fitting the data and back extrapolating through zero, and the slope for the permeation calculations. Note that the leak data reveals an excellent seal of the apparatus.

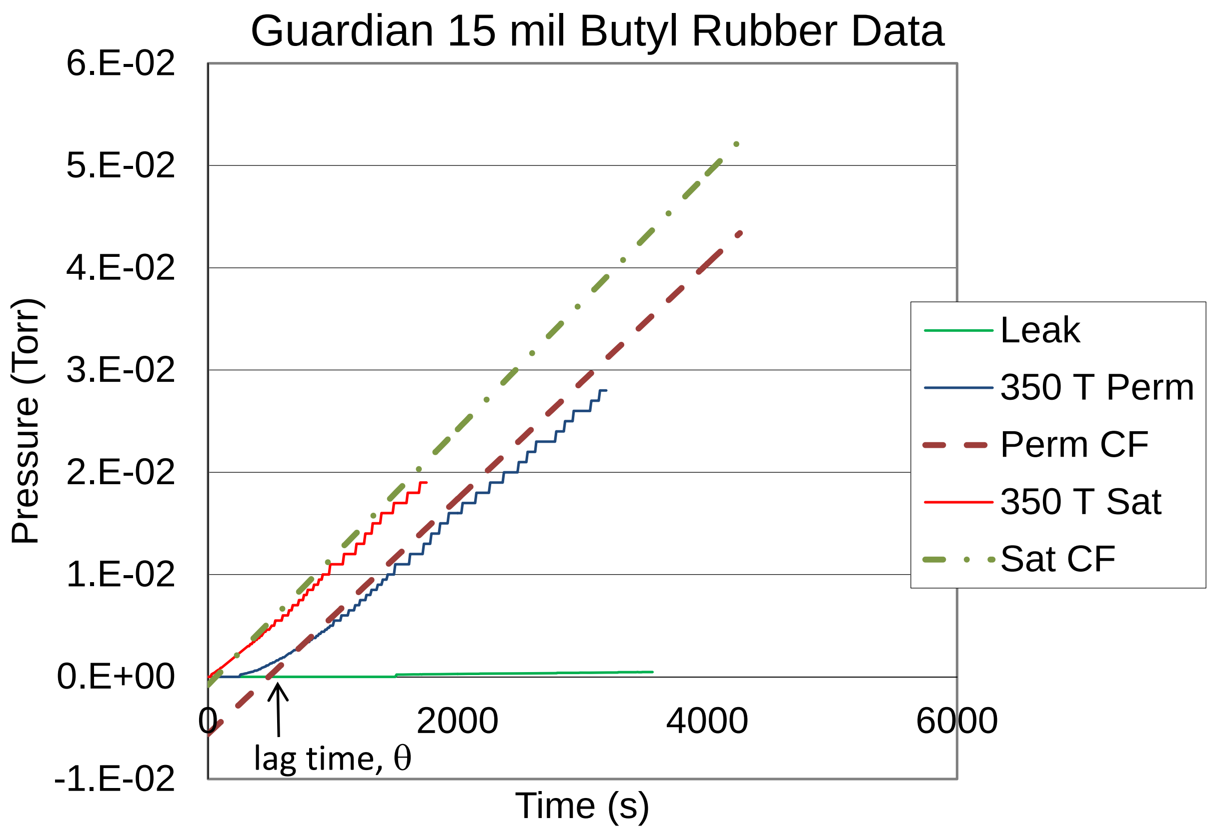

Figure 3. Raw data plot showing time lag and slope (CF) used for permeability calculations. Both initial transient and saturation tests plotted.

Table 2. Average time lag data for the different glove compounds and manufactures.

Average Lag Time (sec)				
ID	H_2	Stdev.	Dry Air	Stdev.
NB30	1642	416	NA	NA
NB15	806	150	10200	3229
GB30	1000	207	NA	NA
GB15	664	153	5257	1244
PB30	2234	309	NA	NA
PB15	477	150	3971	610
PESDB24	821	148	NA	NA
PESDB15	1129	779	7517	659
PU15	653	482	3528	1168
PY25	536	301	1337	4112
PUY20	568	265	1963	2364
JV24	952	311	13321	1024
BV20	451	217	2143	678
BH27.5	1027	425	6365	548

The time lag data for hydrogen and dry air permeation for all the gloves are shown in Table 2. These data indicate a significantly greater lag time for dry air compared with hydrogen. This is an expected result due to the difference in molecular size comparing air and hydrogen. The time lag data exhibit a significant variability based on the standard deviations. This amount of variation is typical for permeability testing which may have variations as large as a factor of 10.

Table 3. Average Hydrogen and Air Permeability

Average Permeability 10^{-10} cc H_2 * cm / (cm^2 *cm Hg) -- Barrers					Permeability *10^{-7} cc H_2 * cm / (cm^2 *atm)	
ID	H_2	Stdev.	Dry Air	Stdev.	H_2	Air
NB30	7.7	2.5	NA	NA	0.58	NA
NB15	7.5	0.67	0.58	0.03	0.57	0.044
GB30	8.9	1.1	NA	NA	0.68	NA
GB15	8.4	0.50	0.53	0.03	0.64	0.040
PB30	6.8	0.52	NA	NA	0.52	NA
PB15	9.8	0.64	0.65	0.01	0.74	0.049
PESDB24	9.0	1.6	NA	NA	0.68	NA
PESDB15	11	2.8	0.48	0.05	0.84	0.036
PU15	8.5	0.70	0.85	0.02	0.65	0.065
PY25	8.7	0.53	0.66	0.01	0.66	0.052
PUY20	12	1.2	0.59	0.03	0.91	0.044
JV24	5.2	1.5	0.49	0.01	0.39	0.037
JBV20	11	0.11	1.5	0.03	0.84	0.11
JBH27.5	12	1.3	1.0	0.03	0.91	0.076

Table 4. Average Hydrogen and Air Diffusivity

Average Diffusivity (1X10^{-8} cm^2/s)				
ID	H_2	Stdev.	Dry Air	Stdev.
NB30	61	14	NA	NA
NB15	52	10	26	19
GB30	75	15	NA	NA
GB15	60	16	30	21
PB30	44	6.6	NA	NA
PB15	66	21	34	23
PESDB24	46	7.5	NA	NA
PESDB15	25	12	2.5	0.23
PU15	65	39	8.8	2.5
PY25	97	41	2.8	7.2
PUY20	70	27	-3.7	26
JV24	51	20	3.3	0.24
JBV20	88	34	18	5.2
JBH27.5	71	30	12	1.0

The average Permeability for each glove material is presented in Table 3. Average Hydrogen and Air Permeability The Diffusivity and Solubility data were also calculated and are listed in Table 4 and Table 5. The individual calculated permeability, diffusivity, lag time, and solubility for each sample and test condition are presented in Appendix A.

Table 5. Average Hydrogen and Air Solubility

Average Solubility (cc@STP/cc-atm)				
ID	H2	Stdev.	Dry Air	Stdev.
NB30	0.10	0.04	NA	NA
NB15	0.11	0.02	0.15	0.05
GB30	0.09	0.03	NA	NA
GB15	0.11	0.02	0.06	0.02
PB30	0.12	0.02	NA	NA
PB15	0.12	0.04	0.07	0.01
PESDB24	0.16	0.05	NA	NA
PESDB15	0.44	0.37	0.15	0.03
PU15	0.19	0.13	0.08	0.03
PY25	0.08	0.04	0.02	0.06
PUY20	0.13	0.04	0.02	0.02
JV24	0.09	0.03	0.07	0.05
JBV20	0.10	0.03	0.07	0.02
JBH27.5	0.15	0.08	0.07	0.01

The room temperature permeability of the butyl rubber gloves varies between 7 and 11 barrers (10^{-10} cc H_2 * cm / (cm^2 *cm Hg), regardless of glove manufacturer. The permeability data, with one standard deviation error bar is presented in Figure 4 for hydrogen and Figure 5 for air. This data presentation indicates that the permeability of butyl gloves, regardless of curing treatment, has a similar value. A statistical analysis of the hydrogen permeability indicates that all these values are consistent with each other and these determined values for the butyl rubber are consistent with literature data (1).The polyurethane and Hypalon® gloves exhibit comparable permeabilities to the butyl gloves with values of 8.5 and 8.7, respectively. The Jung Viton® glove exhibits the lowest hydrogen permeability of the materials tested with a value of about 5 barrers. This permeability value was determined to be statistically significantly lower. The composite gloves, i.e., Piercan Polyurethane-Hypalon®, Jung Butyl-Hypalon®, and Butyl-Viton®, all exhibit higher permeabilities than the pure compound gloves. The hydrogen permeability varies between 11 and 12 for these compositions. .

The dry air permeation data showed similar trends. The air permeability through each butyl glove varied between 0.48-0.65 barrers. There is not a significantly lower or higher performing glove from the butyl materials tested. The Viton® glove had a dry air permeability of about 0.49 barrers, at the lower end of the butyl range. The polyurethane and Hypalon® gloves were at the high end or above the Butyl rubber range, as was the Piercan polyurethane-Hypalon®. The Jung Butyl-Viton® and Jung Butyl-Hypalon® exhibited air permeabilities about twice the Butyl rubber gloves.

Note that several of the results exhibit high standard deviations. Additional replicate testing is necessary to decrease the amount of scatter and ascertain whether there are significant differences between the butyl rubber gloves. The composite gloves are certainly from a different population, and additional characterization is needed prior to recommending incorporation of these materials into the facility.

The data tabulated above are plotted in Figure 4 and Figure 5. The plots show the average permeability and standard deviation. It is interesting to note the small amount of scatter in the Viton® data and the significantly higher scatter, i.e, larger error bars, for the Piercan ESDB.

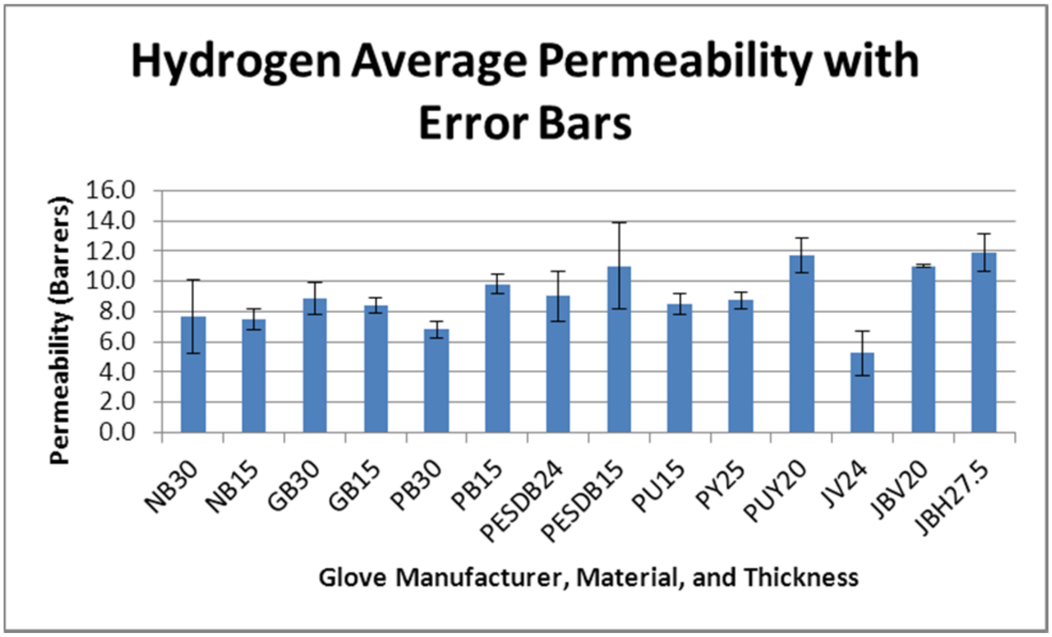

Figure 4. Hydrogen Average Permeability with Error Bars

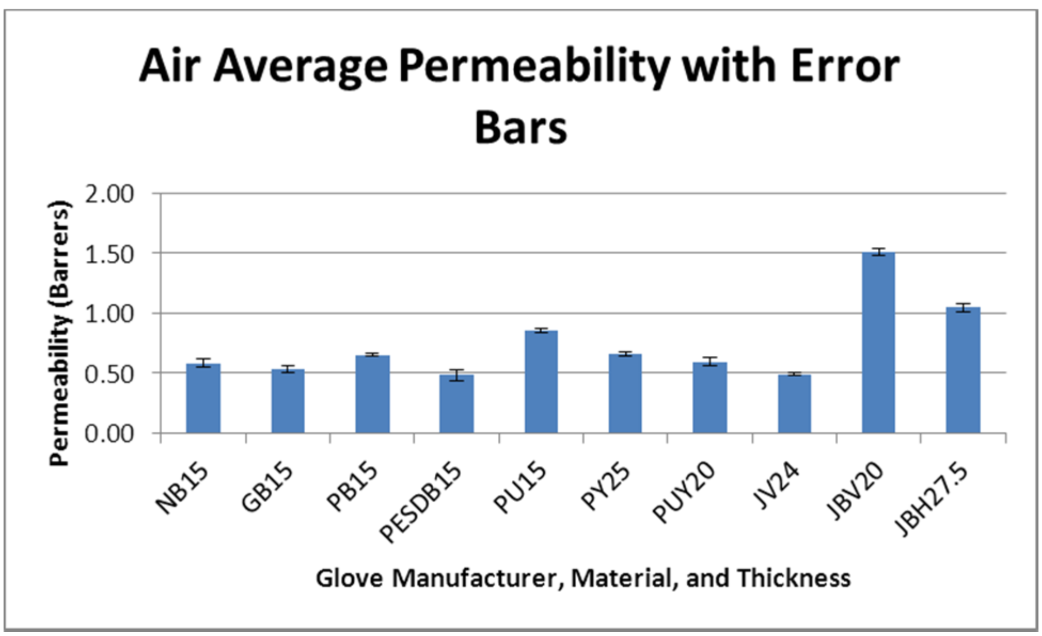

Figure 5. Air Average Permeability with Error Bars

Effect of Temperature

All baseline testing was conducted at room temperature, since glovebox gloves are almost always used at ambient room temperature. However, the ability to predict permeation effects at elevated temperature is of interest, so a North Butyl rubber glove was tested at elevated temperatures. Because of time constraints, only one series of experiments was conducted. This test was intended to confirm that the logarithm of the polymer permeability would decrease linearly with respect to the reciprocal of the absolute temperature increases in a manner consistent with an Arrhenius process. Tests were conducted using hydrogen at 50°C and 75°C at 140, 350, and 700 Torr. The results are shown in Table 6 and Figure 6. The individual temperature – pressure data plot is included in Appendix B.

Table 6. North Butyl Rubber test data at room and elevated temperature.

North 30 mil Butyl Temperature Test Comparison			
Pressure (Torr)	Temperature (°C)		
	22	50	75
140	10.	19.	42.
350	5.4	18	40.
700	5.32	17.47	41.06

*The Permeability units are in Barrers
(10^{-10} cc gas @ STP * cm/cm^2*s*cm Hg)

There is an increase in the permeability between the room temperature and 75°C, it is not linear as expected for a typical material with only one thermally activated process occurring. The details of the mechanism change cannot be readily identified using permeability tests; however, other analytical tests such as dynamic mechanical analysis (DMA) may be used to elucidate material changes with temperature and frequency. DMA testing was performed on the all of the glove samples to give an idea of the characteristic changes in the gloves throughout a temperature range. Succinctly, the DMA testing showed a change in the North 30 mil butyl glove structure over this temperature range, See Glove Dynamic Mechanical Analysis (Ref 5) for more details. The temperature range tested is within the Vendor recommended use range for these polymers and may be experienced occasionally in the Tritium facility. To better characterize all of the gloves, especially for areas in the plant not at room temperature, further temperature permeability tests would need to be performed.

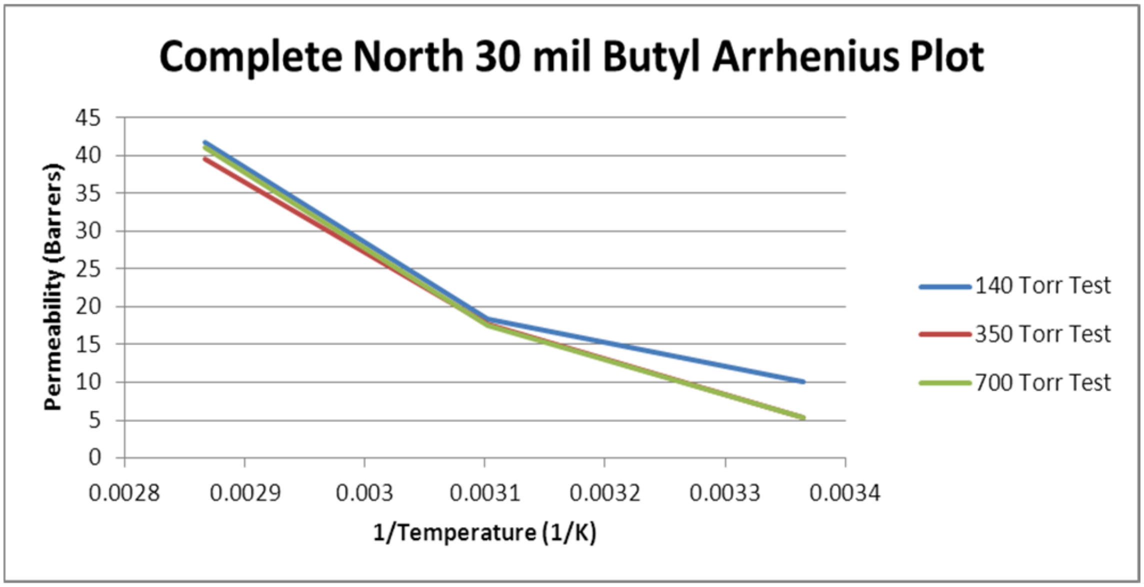

Figure 6. Arrhenius Plot of North 30 mil Butyl Temperature Tests

Appendix C and D contain the graphs of the Edited and Raw Permeability data for each test, respectively.

The values determined above can subsequently be used to estimate the flux through the gloves for oxygen ingress and tritium (T_2) egress. The average value of the hydrogen and air permeability in Barrers and other units for the various glove types are listed in Table 7 and Table 8, respectively. The tritium and oxygen permeation through a glove can be estimated using the following assumptions and constants. A glove has a surface area of 3375 cm^2, the tritium content is 0.5 µCi/cm^3 (2.1x10^{-7} cm^3 T_2/cm^3), the internal glovebox pressure is -0.5 in H_2O, the glove descriptions accurately reflect the nominal thickness, e.g., a North 15 mil is nominally 0.015" thick, the glovebox and room are at 25°C, and air is 21% O_2. The calculations for each glove type and thickness is listed in Table 10.

Table 7. Average Permeability of Hydrogen in Barrers and more common engineering units.

Vendor	Compound	Thickness	Ave Barrers (10^{-10} cm^3 @stp*cm / (cm^2*s*cmHg))	StDev	ccH_2*cm / (cm^2*s*atm)
NORTH	Butyl	All	7.0	1.03	5.3E-08
Guardian	Butyl	All	8.6	0.90	6.6E-08
Piercan	Butyl	All	8.3	1.64	6.3E-08
Piercan	ESDB	All	9.4	1.919	7.1E-08
Piercan	U	15	8.7	0.71	6.6E-08
Piercan	Y	25	8.7	0.44	6.6E-08
Piercan	UY	20	8.4	0.64	6.4E-08
Jung	V	24	5.3	0.58	4.0E-08
Jung	BV	20	11.0	1.26	8.4E-08
Jung	BH	27.5	11.9	1.83	9.0E-08

Table 8. Average air permeability for compounds tested in Barrers and more common units.

Vendor	Compound	Ave (Barrers)	Std Dev (Barrers)	Ave (cc O_2 @STP *cm cm^2*s*atm)	Std Dev (cc O_2 @STP *cm cm^2*s*atm)
NORTH	Butyl	0.58	0.032	4.4E-09	2.43E-10
Guardian	Butyl	0.53	0.027	4.0E-09	2.05E-10
Piercan	Butyl	0.65	0.015	5.0E-09	1.13E-10
Piercan	ESDB	0.48	0.045	3.7E-09	3.46E-10
Piercan	U	0.85	0.017	6.5E-09	1.32E-10
Piercan	Y	0.66	0.015	5.0E-09	1.13E-10
Piercan	UY	0.59	0.035	4.5E-09	2.64E-10
Jung	V	0.49	0.007	3.7E-09	5.51E-11
Jung	BV	1.51	0.031	1.1E-08	2.36E-10
Jung	BH	1.05	0.034	8.0E-09	2.60E-10

The calculations for permeation through each glove indicates that lower permeabilities result in lower overall permeation events and that thicker gloves of the same compound will exhibit lower permeation. This can be more readily observed by examining the graphical data in Table 9. This chart shows that Viton at 24 mils is superior to butyl at 30 mils and that there may be subtle differences between the different vendor butyl. It also indicates that the Piercan ESDB is inferior to the other vendor Butyl.

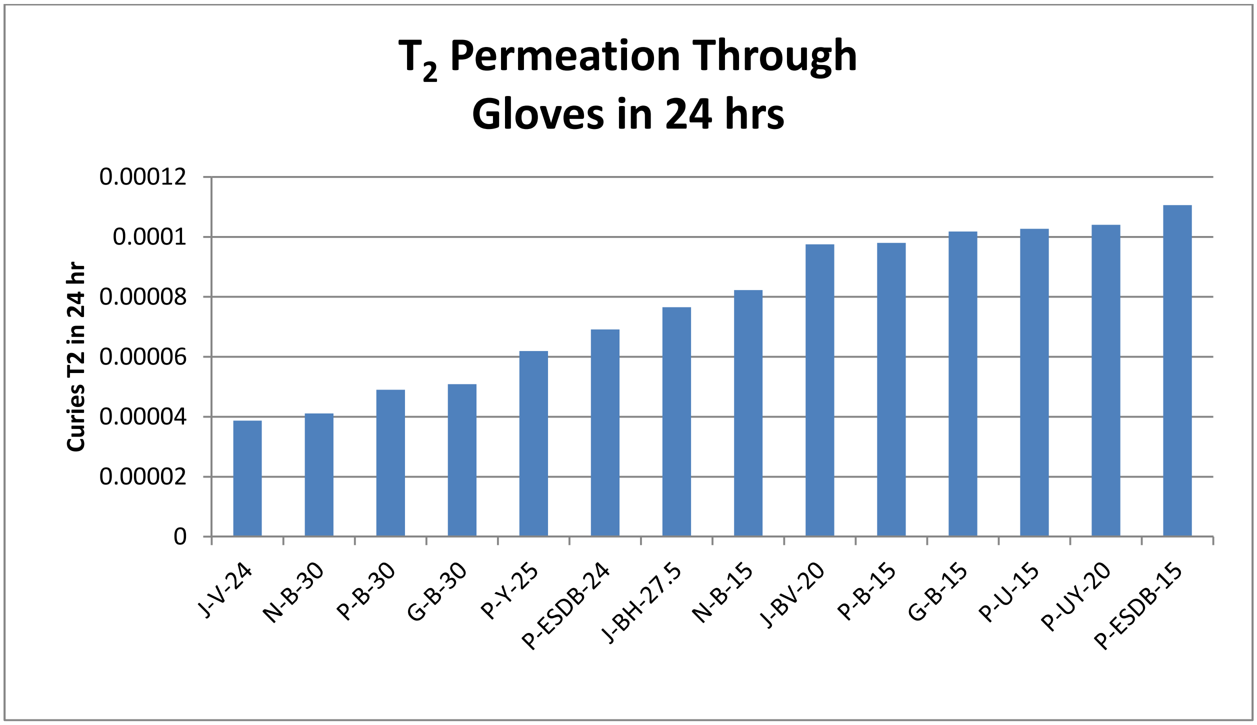

Table 9. Graphical representation of tritium permeation in 24 hours for each glove type and thickness tested.

Table 10. Permeation calculation and comparisons for various thickness and compound gloves.

Tritium	Day ccT2	Week cc T2	Year cc T2	uCi / day	uCi/week	uCi/year
N-B-30	4.11E-05	2.88E-04	1.50E-02	97.9	685.	35700
N-B-15	8.23E-05	5.76E-04	3.00E-02	196	1371	71500
G-B-39	5.09E-05	3.56E-04	1.86E-02	121	848	44200
G-B-15	1.02E-04	7.12E-04	3.72E-02	242	1696	88400
P-B-30	4.90E-05	3.43E-04	1.79E-02	117	816	42600
P-B-15	9.80E-05	6.86E-04	3.58E-02	233	1633	85100
P-ESDB-24	6.91E-05	4.84E-04	2.52E-02	164	1151	60000
P-ESDB-15	1.11E-04	7.74E-04	4.04E-02	263	1842	96100
P-U-15	1.03E-04	7.19E-04	3.75E-02	244	1711	89200
P-Y-25	6.19E-05	4.34E-04	2.26E-02	147	1032	538000
P-UY-20	1.04E-04	7.28E-04	3.80E-02	248	1733	90400
J-V-24	3.87E-05	2.71E-04	1.41E-02	92	645	33600
J-BV-20	9.75E-05	6.83E-04	3.56E-02	232	1624	84700
J-BH-27.5	7.66E-05	5.36E-04	2.79E-02	182	1275	665000
Oxygen	Day cc O_2	Week cc O_2	Year cc O_2	mg O_2/day	mg O_2/week	mg O_2/year
N-B-30	3.9	27.3	1422	5.1	35.7	1860
N-B-15	7.8	54.6	2845	10.2	71.4	3720
G-B-39	3.5	24.8	1294	4.6	32.5	1690
G-B-15	7.1	49.6	2589	9.3	65.0	3390
P-B-30	4.4	30.5	1592	5.7	40.0	2080
P-B-15	8.7	61.1	3185	11.4	79.9	4170
P-ESDB-24	4.0	28.2	1473	5.3	37.0	1930
P-ESDB-15	6.5	45.2	2357	8.4	59.1	3080
P-U-15	11.4	79.5	4147	14.9	104.1	5430
P-Y-25	5.3	37.2	1939	7.0	48.7	2540
P-UY-20	5.9	41.5	2165	7.8	54.3	2830
J-V-24	4.1	28.8	1500	5.4	37.6	1960
J-BV-20	15.1	105.9	5520	19.8	138.5	7220
J-BH-27.5	7.6	53.4	2782	10.0	69.8	3640

Conclusions

Butyl Rubber samples from gloves supplied have a permeability of between 5 and 11 Barrers at room temperature.

The Viton® rubber gloves exhibit the lowest permeability for both air and hydrogen.

The effect of temperature on the permeability between room temperature and 75°C is not as expected and additional testing indicated that a material property change may have occurred.

Additional testing to improve the amount of scatter in the data is needed to determine if the gloves are truly from different populations and to obtain additional temperature data.

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Appendix A

	Hydrogen Permeability (Barrers)												
Man.	Mat'l	Thick (mil)	ID	Perm70	Sat70	Perm140	Sat140	Perm350	Sat350	Perm700	Sat700	Ave.	Stdev.
NORTH	Butyl	30	NB30	NA	NA	12	14	6.2	7.9	6.5	7.3	8.9	2.8
NORTH	Butyl	30	NB30	NA	NA	8.0	8.1	5.4	5.9	5.4	5.8	6.4	1.2
NORTH	Butyl	15	NB15	7.6	8.3	6.6	7.2	7.0	8.4	NA	NA	7.5	0.67
Guardian	Butyl	30	GB30	NA	NA	9.71	11	7.8	8.7	7.5	8.7	8.9	1.1
Guardian	Butyl	15	GB15	8.0	8.0	8.2	8.6	8.3	9.4	NA	NA	8.4	0.50
Piercan	Butyl	30	PB30	NA	NA	6.9	7.8	6.7	6.8	6.1	6.6	6.8	0.52
Piercan	Butyl	15	PB15	9.5	10	10	11	9.0	9.3	NA	NA	9.8	0.64
Piercan	ESDB	24	PESDB24	NA	NA	10	12	8.9	9.4	7.0	7.1	9.0	1.6
Piercan	ESDB	15	PESDB15	14	17	11	12	7.9	8.4	NA	NA	12	2.0
Piercan	ESDB	15	PESDB15	13	NA	10	NA	8.0	NA	NA	NA	10	0.53
Piercan	U	15	PU15	8.0	NA	7.8	NA	7.6	NA	NA	NA	7.8	0.25
Piercan	U	15	PU15	8.9	9.3	8.9	9.6	9.1	9.1	NA	NA	9.2	5.3
Piercan	Y	25	PY25	NA	NA	8.1	8.3	9.0	8.9	9.1	9.1	8.7	0.5
Piercan	UY	20	PUY20	8.5	9.2	7.9	7.9	18	19	NA	NA	12	1.2
Jung	V	24	JV24	NA	NA	5.7	6.2	4.9	5.1	4.8	4.8	5.2	1.5
Jung	BV	20	JBV20	NA	NA	11	12	9.4	9.8	11	13	11	0.11
Jung	BH	27.5	JBH27.5	NA	NA	14	NA	11	NA	11	NA	12	1.3

				Hydrogen Solubility (cc@STP/cc-atm)									
Man.	Mat'l	Thick (mil)	ID	Perm70	Sat70	Perm140	Sat140	Perm350	Sat350	Perm700	Sat700	Ave.	Stdev.
NORTH	Butyl	30	NB30	NA	NA	0.14	0.16	0.07	0.09	0.06	0.07	0.10	0.04
NORTH	Butyl	30	NB30	NA	NA	0.16	0.16	0.08	0.09	0.07	0.08	0.11	0.04
NORTH	Butyl	15	NB15	0.14	0.15	0.10	0.11	0.09	0.10	NA	NA	0.11	0.02
Guardian	Butyl	30	GB30	NA	NA	0.12	0.14	0.08	0.09	0.06	0.07	0.09	0.03
Guardian	Butyl	15	GB15	0.12	0.12	0.12	0.12	0.08	0.09	NA	NA	0.11	0.02
Piercan	Butyl	30	PB30	NA	NA	0.13	0.15	0.13	0.13	0.09	0.10	0.12	0.02
Piercan	Butyl	15	PB15	0.15	0.16	0.12	0.12	0.08	0.08	NA	NA	0.12	0.04
Piercan	ESDB	24	PESDB24	NA	NA	0.21	0.24	0.13	0.14	0.11	0.11	0.16	0.05
Piercan	ESDB	15	PESDB15	0.44	0.54	0.27	0.30	0.13	0.14	NA	NA	0.30	0.16
Piercan	ESDB	15	PESDB15	1.39	NA	0.49	NA	0.22	NA	NA	NA	0.70	0.61
Piercan	U	15	PU15	0.38	0.40	0.24	0.26	0.12	0.12	NA	NA	0.25	0.12
Piercan	U	15	PU15	0.12	NA	0.06	NA	0.05	NA	NA	NA	0.07	0.04
Piercan	Y	25	PY25	NA	NA	0.12	0.13	0.06	0.06	0.06	0.06	0.08	0.04
Piercan	UY	20	PUY20	0.16	0.17	0.08	0.08	0.15	0.15	NA	NA	0.13	0.04
Jung	V	24	JV24	NA	NA	0.12	0.13	0.09	0.09	0.05	0.05	0.09	0.03
Jung	BV	20	JBV20	NA	NA	0.08	0.09	0.14	0.15	0.08	0.09	0.10	0.03
Jung	BH	27.5	JBH27.5	NA	NA	0.24	NA	0.13	NA	0.08	NA	0.15	0.08

	Hydrogen Lag Time (sec)									
Man.	Mat'l	Thick (mil)	ID	Perm70	Perm140	Perm350	Perm700	Ave.	Stdev.	% Error
NORTH	Butyl	30	NB30	NA	1433	1334	1123	1297	159	12
NORTH	Butyl	30	NB30	NA	2396	1891	1674	1987	370	19
NORTH	Butyl	15	NB15	962	792	662	NA	806	150	19
Guardian	Butyl	30	GB30	NA	1220	971	809	1000	207	21
Guardian	Butyl	15	GB15	779	724	490	NA	664	153	23
Piercan	Butyl	30	PB30	NA	2424	2402	1877	2234	309	14
Piercan	Butyl	15	PB15	635	459	338	NA	477	150	31
Piercan	ESDB	24	PESDB24	NA	992	724	747	821	148	18
Piercan	ESDB	15	PESDB15	879	679	468	NA	675	205	30
Piercan	ESDB	15	PESDB15	2784	1267	699	NA	1583	1078	68
Piercan	U	15	PU15	1571	974	460	NA	1002	556	55
Piercan	U	15	PU15	479	234	200	NA	304	152	50
Piercan	Y	25	PY25	NA	884	355	369	536	301	56
Piercan	UY	20	PUY20	871	453	381	NA	568	265	47
Jung	V	24	JV24	NA	1206	1044	606	952	311	33
Jung	BV	20	JBV20	NA	340	702	312	451	217	48
Jung	BH	27.5	JBH27.5	NA	1474	980	628	1027	425	41

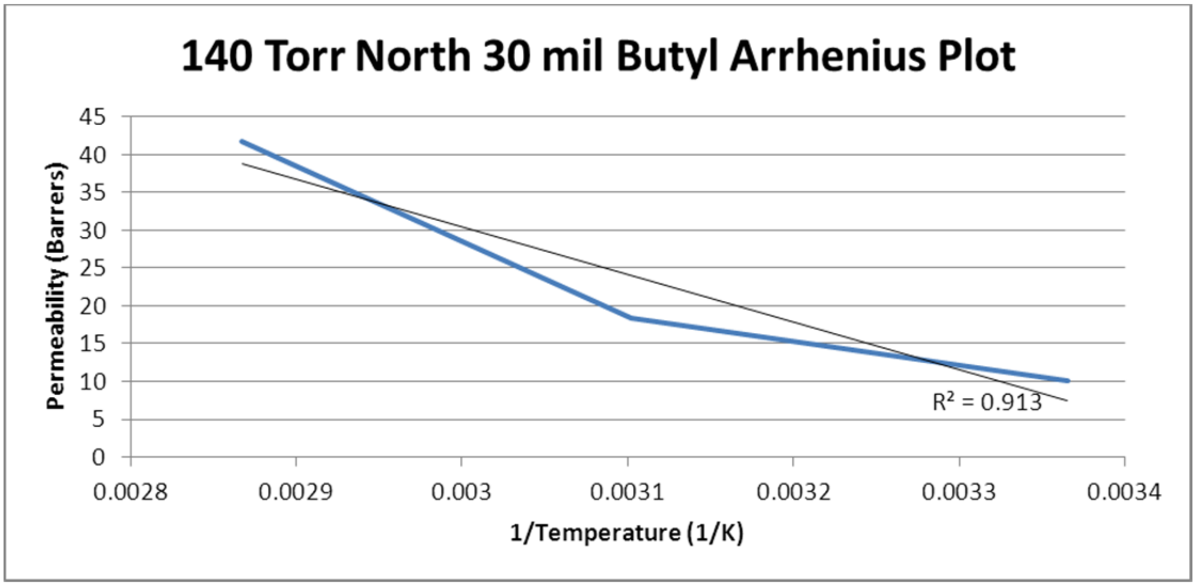
	Hydrogen Diffusivity (1E-8 cm^2/s)								
Man.	Mat'l	Thick (mil)	ID	Perm70	Perm140	Perm350	Perm700	Ave.	Stdev.
NORTH	Butyl	30	NB30	NA	65	70	83	73	9.3
NORTH	Butyl	30	NB30	NA	39	49	56	48	8.5
NORTH	Butyl	15	NB15	42	52	62	NA	52	9.6
Guardian	Butyl	30	GB30	NA	60	75	90	75	15
Guardian	Butyl	15	GB15	49	53	78	NA	60	16
Piercan	Butyl	30	PB30	NA	40	40	52	44	6.6
Piercan	Butyl	15	PB15	47	65	88	NA	66	21
Piercan	ESDB	24	PESDB24	NA	37	51	50	46	7.5
Piercan	ESDB	15	PESDB15	24	31	45	NA	34	11
Piercan	ESDB	15	PESDB15	7	15	28	NA	17	10
Piercan	U	15	PU15	18	28	60	NA	35	22
Piercan	U	15	PU15	52	107	125	NA	95	38
Piercan	Y	25	PY25	NA	49	123	118	97	41
Piercan	UY	20	PUY20	41	78	93	NA	70	27
Jung	V	24	JV24	NA	37	43	74	51	20
Jung	BV	20	JBV20	NA	103	50	112	88	34
Jung	BH	27.5	JBH27.5	NA	44	66	103	71	30

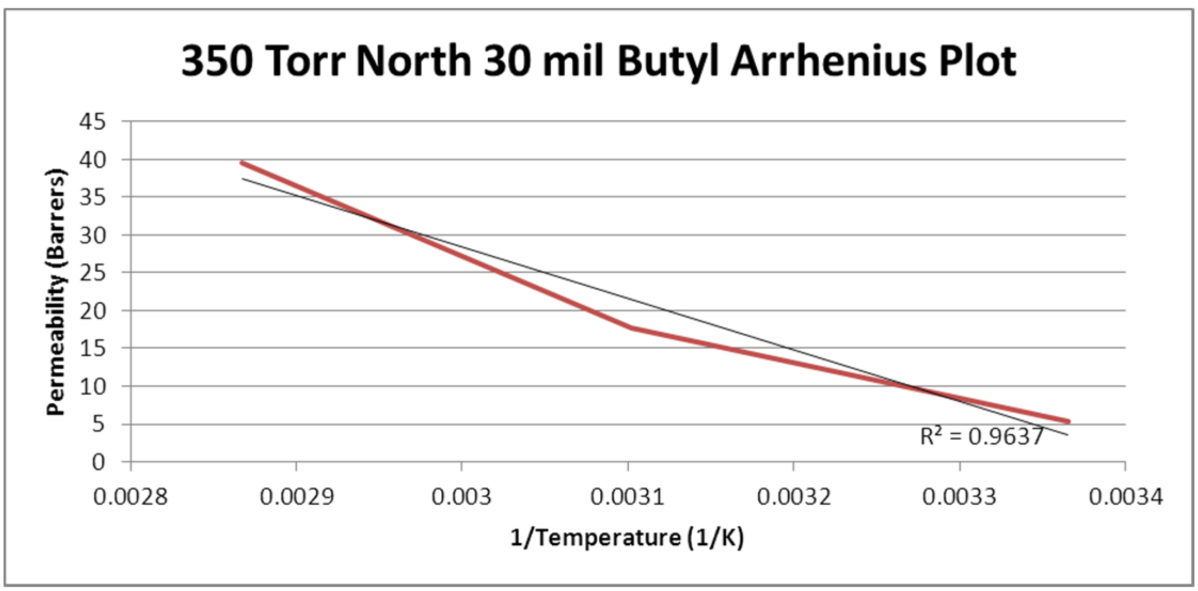
Dry Air Permeability (Barrers)								
Man.	Mat'l	Thick (mil)	Perm140	Perm350	Perm700	Sat700	Ave.	Stdev.
NORTH	Butyl	15	0.61	0.60	0.54	NA	0.58	0.03
Guardian	Butyl	15	0.55	0.49	0.55	NA	0.53	0.03
Piercan	Butyl	15	0.63	0.66	0.67	NA	0.65	0.01
Piercan	ESDB	15	0.53	0.50	0.42	NA	0.48	0.05
Piercan	U	15	0.85	0.88	0.83	0.86	0.85	0.02
Piercan	Y	25	NA	0.64	0.67	NA	0.66	0.02
Piercan	UY	20	NA	0.56	0.58	NA	0.57	0.01
Jung	V	24	0.50	0.50	0.48	NA	0.49	0.01
Jung	BV	20	1.5	1.5	1.5	NA	1.51	0.03
Jung	BH	27.5	1.1	1.1	1.0	NA	1.05	0.03

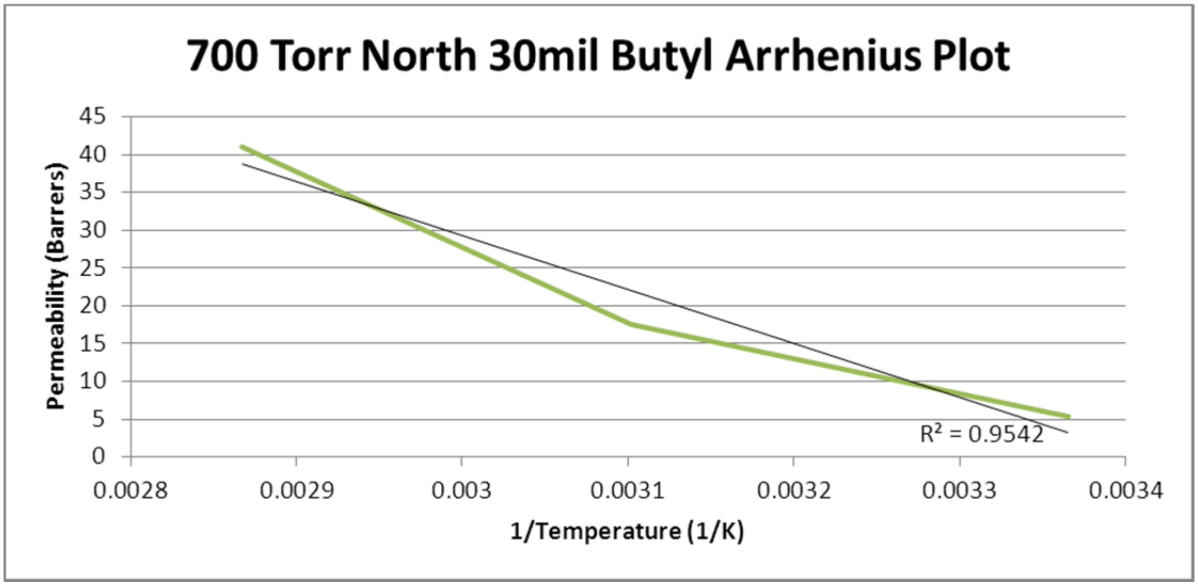
Dry Air Solubility (cc@STP/cc-atm)								
Man.	Mat'l	Thick (mil)	Perm140	Perm350	Perm700	Sat700	Ave.	Stdev.
NORTH	Butyl	15	0.21	0.15	0.08	NA	0.15	0.05
Guardian	Butyl	15	0.05	0.06	0.08	NA	0.06	0.02
Piercan	Butyl	15	0.05	0.08	0.08	NA	0.07	0.01
Piercan	ESDB	15	0.18	0.16	0.12	NA	0.15	0.03
Piercan	U	15	0.12	0.07	0.05	0.06	0.08	0.03
Piercan	Y	25	NA	0.06	0.07	NA	0.06	0.01
Piercan	UY	20	NA	0.02	0.04	NA	0.03	0.01
Jung	V	24	0.11	0.00	0.10	NA	0.07	0.05
Jung	BV	20	0.06	0.05	0.10	NA	0.07	0.02
Jung	BH	27.5	0.07	0.08	0.06	NA	0.07	0.01

Dry Air Lag Time (sec)							
Man.	Mat'l	Thick (mil)	Perm140	Perm350	Perm700	Ave.	Stdev.
NORTH	Butyl	15	14248	10005	6346	10200	3229
Guardian	Butyl	15	3783	5162	6826	5257	1244
Piercan	Butyl	15	3114	4476	4325	3971	610
Piercan	ESDB	15	8133	7815	6603	7517	659
Piercan	U	15	5148	2994	2442	3528	1168
Piercan	Y	25	NA	3975	4507	4241	266
Piercan	UY	20	NA	2500	4553	3526	1026
Jung	V	24	12827	14747	12389	13321	1024
Jung	BV	20	1923	1445	3061	2143	678
Jung	BH	27.5	6189	7107	5799	6365	548

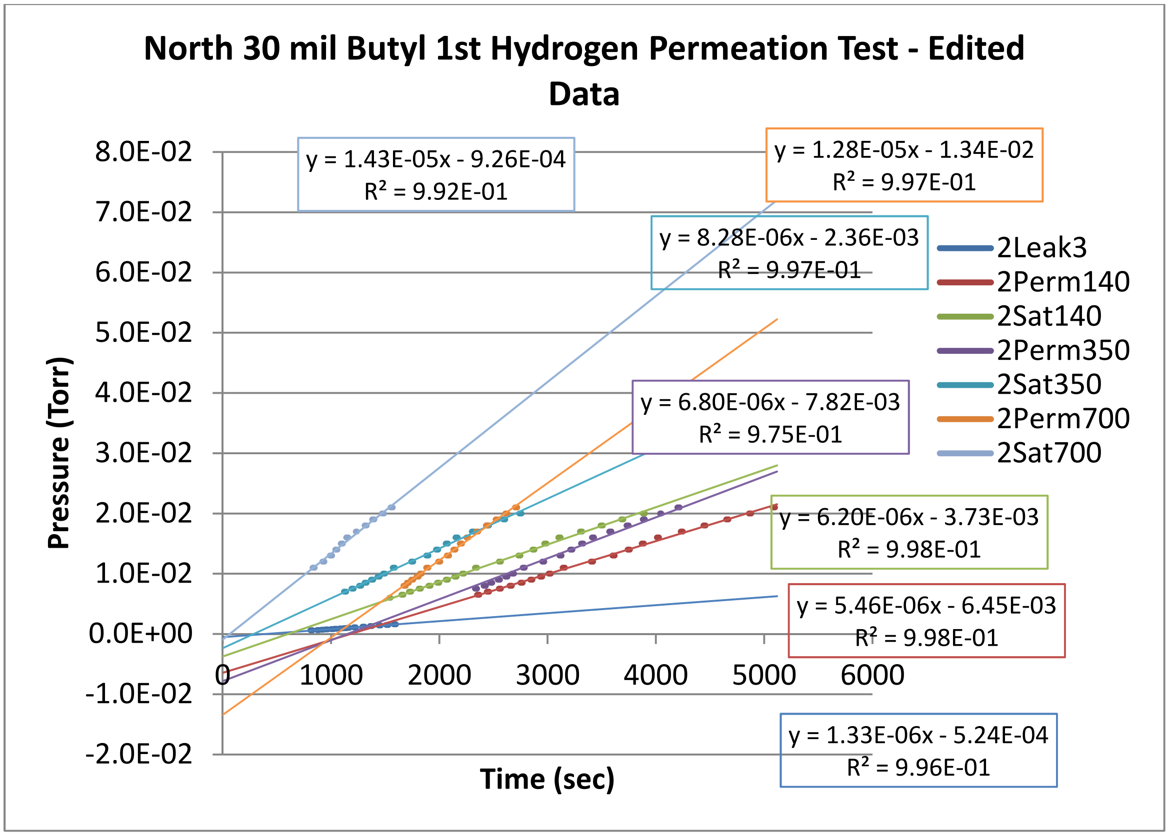
Dry Air Diffusivity (1E-8 cm^2/s)							
Man.	Mat'l	Thick (mil)	Perm140	Perm350	Perm700	Ave.	Stdev.
NORTH	Butyl	15	2.2	3.1	4.9	3.4	1.1
Guardian	Butyl	15	9.2	6.7	5.1	7.0	1.7
Piercan	Butyl	15	9.0	6.3	6.5	7.2	1.2
Piercan	ESDB	15	2.2	2.3	2.8	2.5	0.23
Piercan	U	15	5.4	9.4	11	8.8	2.5
Piercan	Y	25	NA	8.4	7.4	7.9	0.5
Piercan	UY	20	NA	18	10	14.3	4
Jung	V	24	3.4	3.0	3.6	3.3	0.24
Jung	BV	20	18	24	11	18	5.2
Jung	BH	27.5	12	11	13	12	1.0

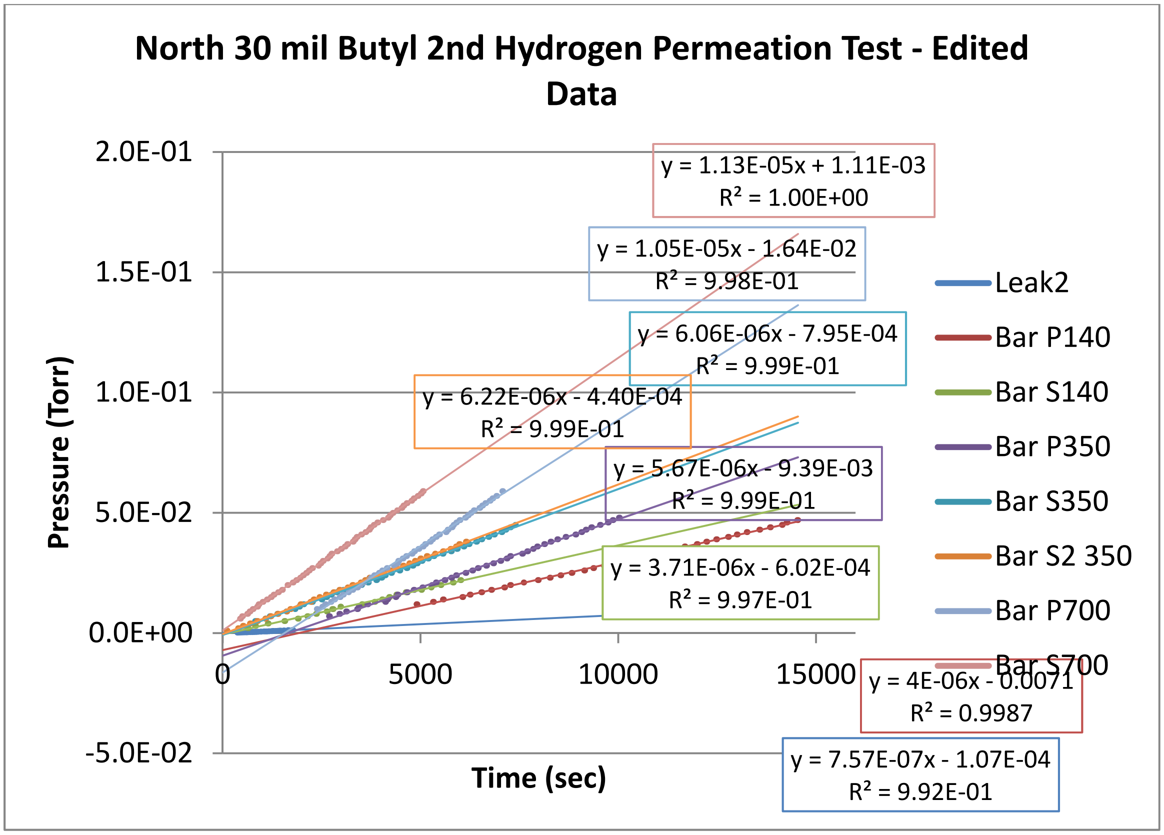

140 Torr North 30 mil Butyl Arrhenius Plot
Permeability (Barrers)
45
40
35
30
25
20
15
10
5
0
0.0028
0.0029
0.003
0.0031
0.0032
0.0033
0.0034
1/Temperature (1/K)
R² = 0.913

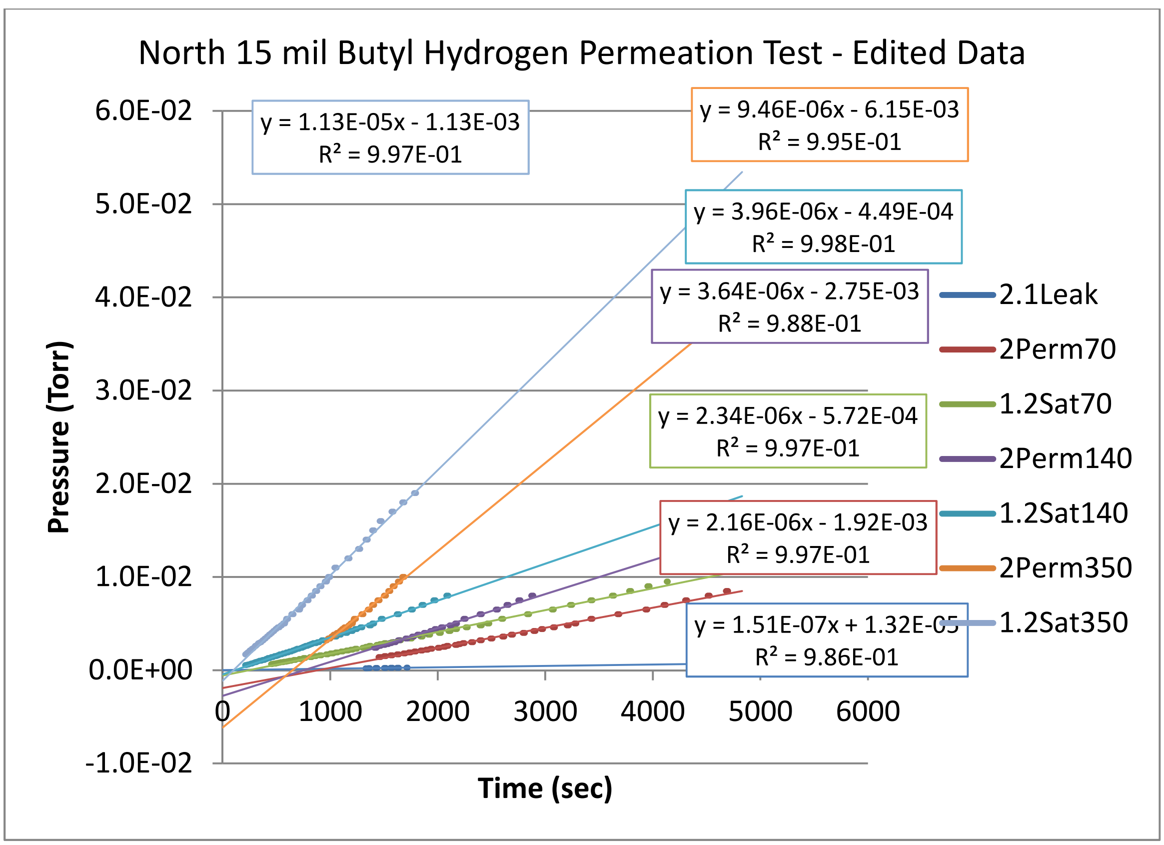

350 Torr North 30 mil Butyl Arrhenius Plot
Permeability (Barrers)
45
40
35
30
25
20
15
10
5
0
0.0028
0.0029
0.003
0.0031
0.0032
0.0033
0.0034
1/Temperature (1/K)
R² = 0.9637

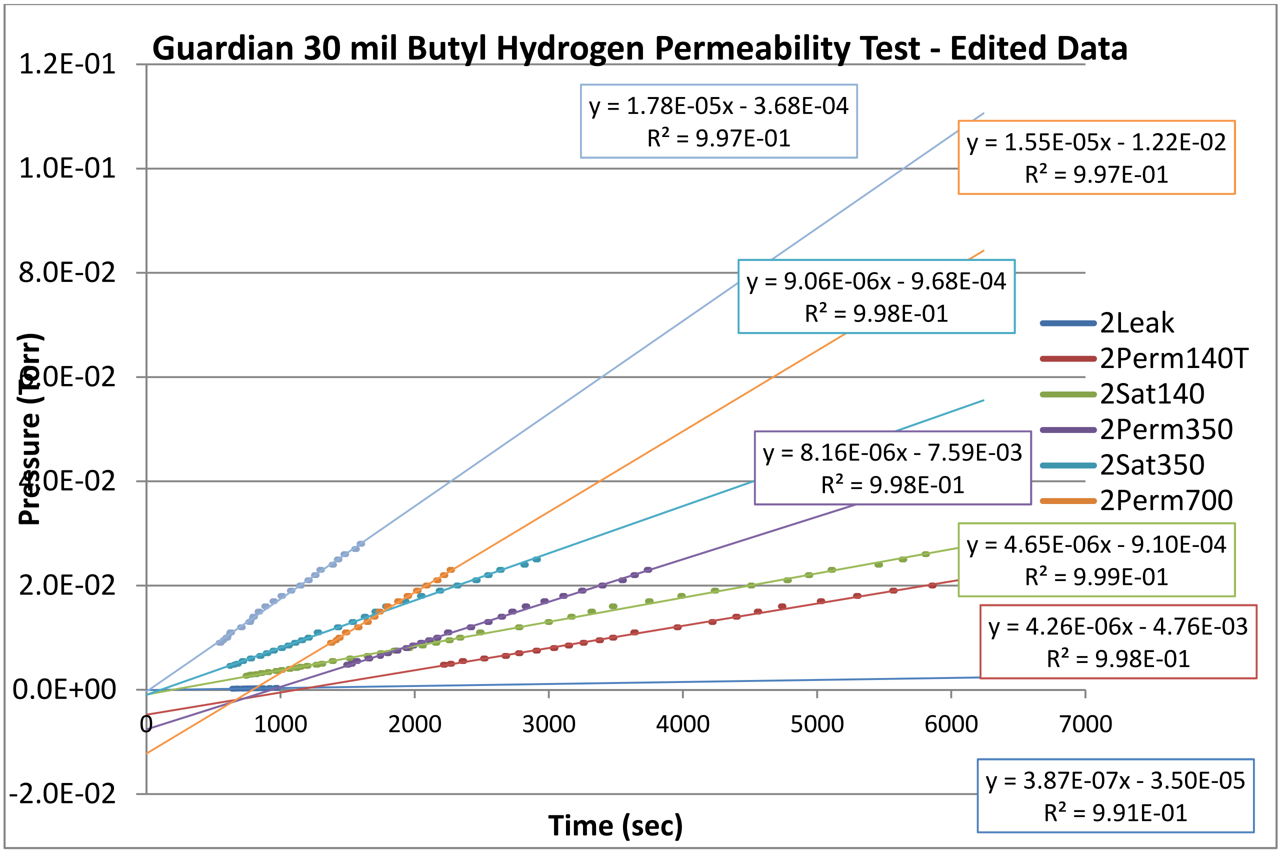

700 Torr North 30mil Butyl Arrhenius Plot
Permeability (Barrers)
45
40
35
30
25
20
15
10
5
0
R² = 0.9542
0.0028
0.0029
0.003
0.0031
0.0032
0.0033
0.0034
1/Temperature (1/K)

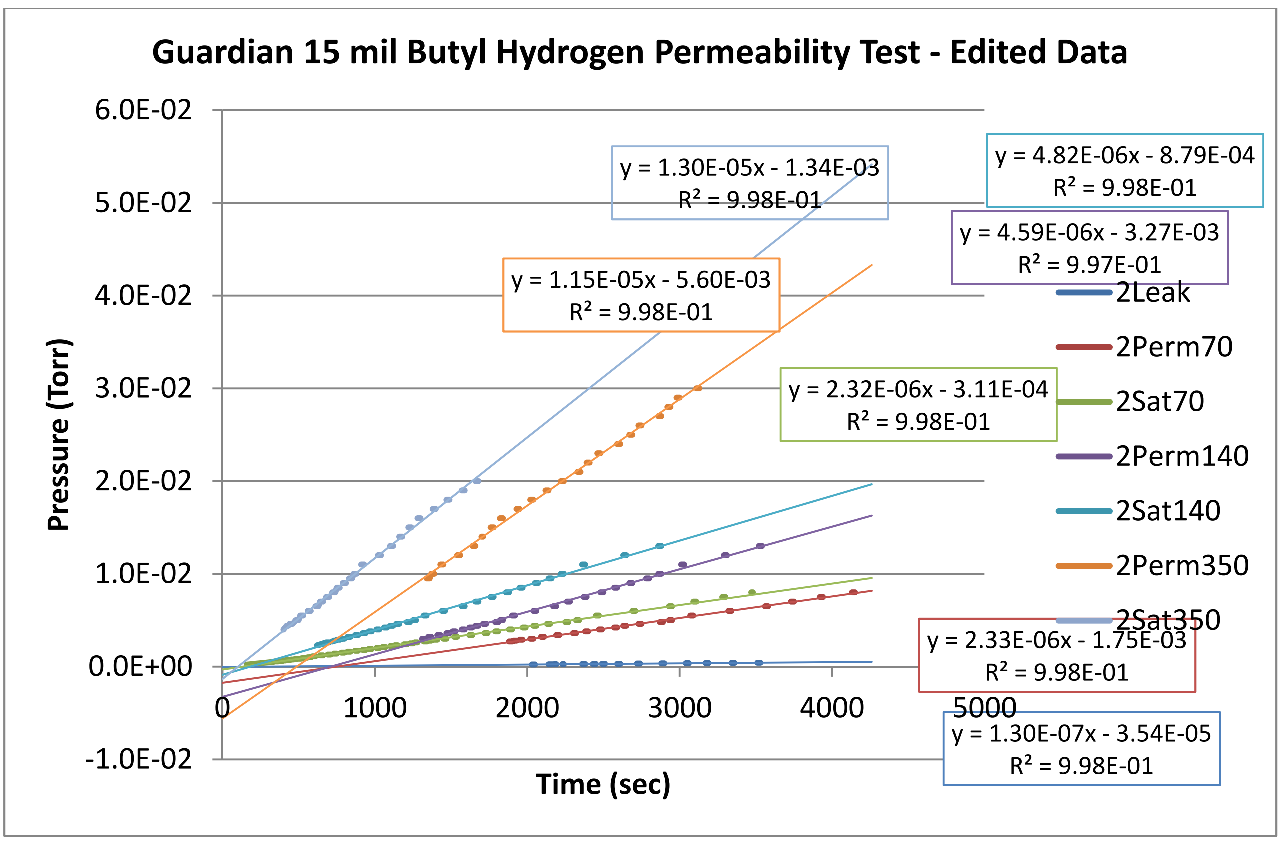
Appendix C: Edited Data Graphs

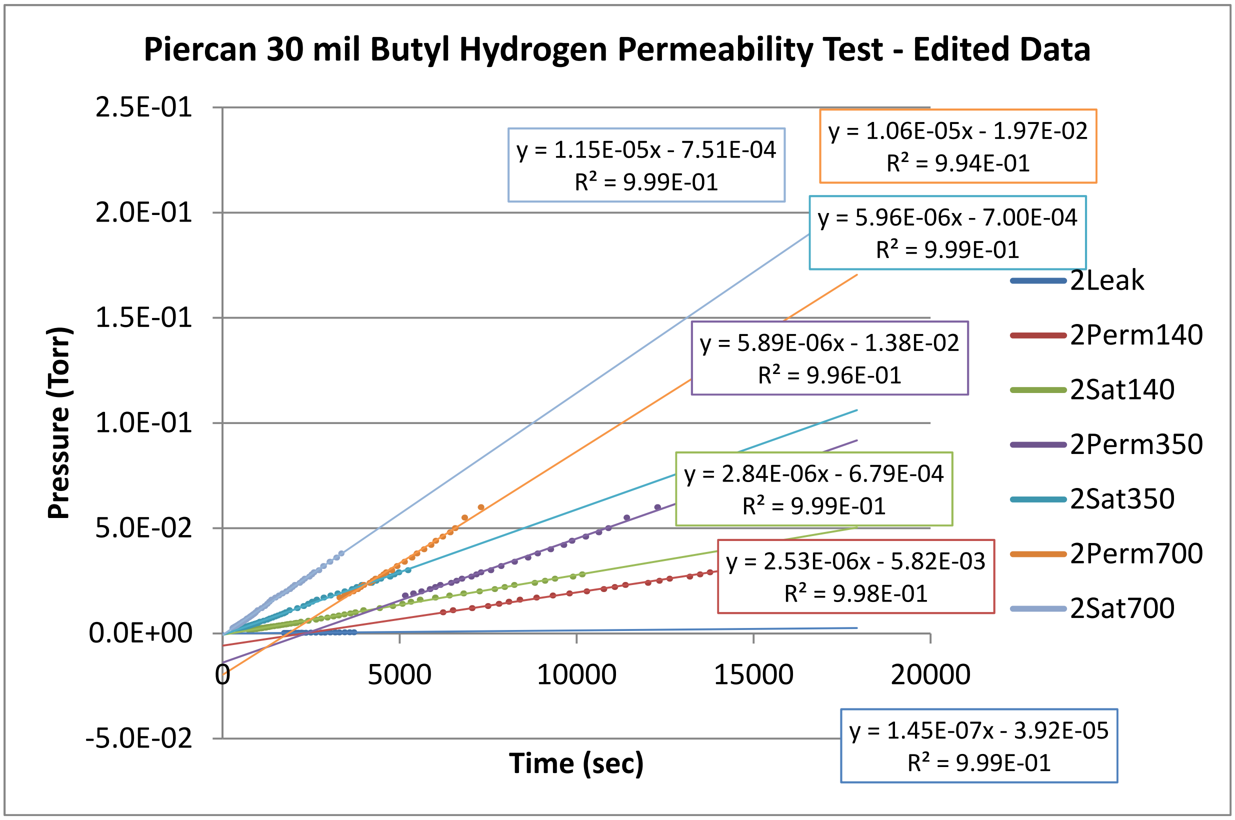


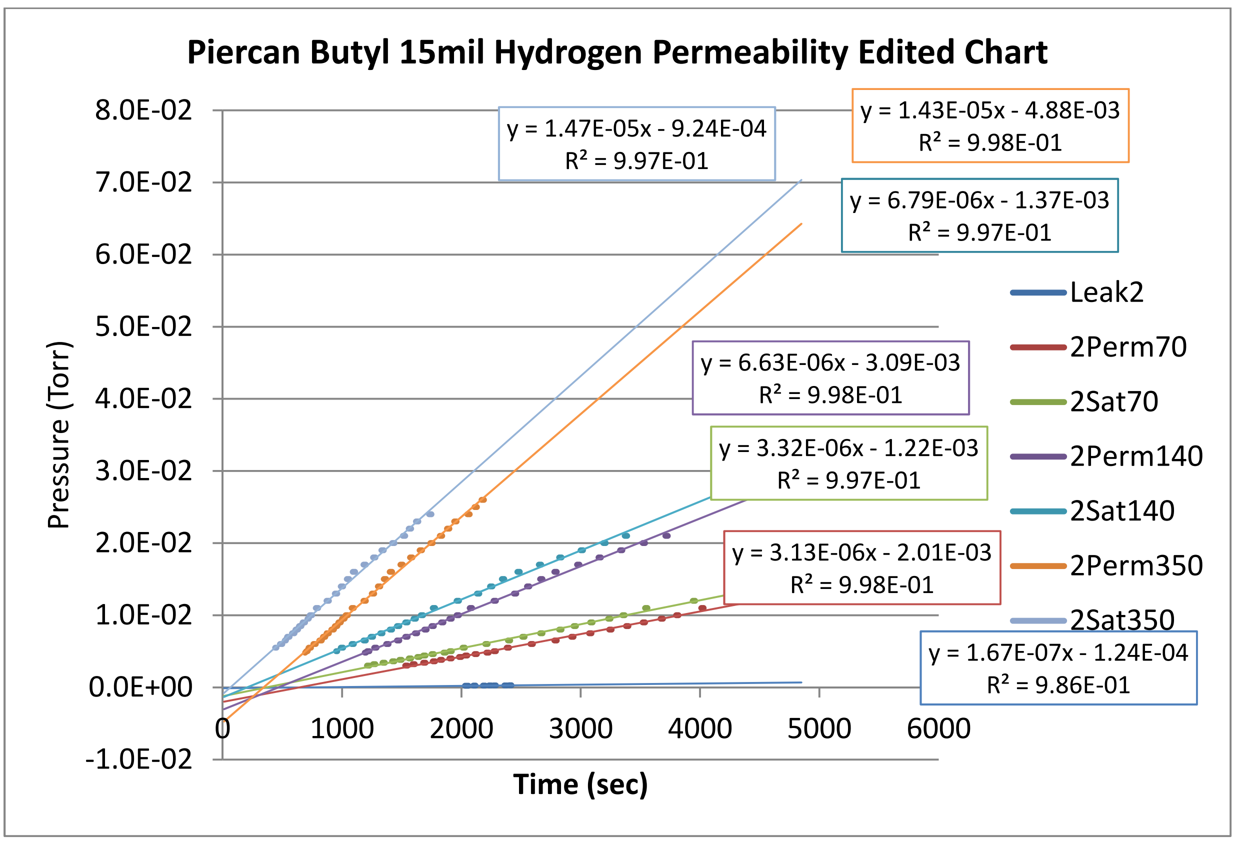

North 30 mil Butyl 2nd Hydrogen Permeation Test - Edited Data
Pressure (Torr)
Time (sec)
2.0E-01
1.5E-01
1.0E-01
5.0E-02
0.0E+00
-5.0E-02
0
5000
10000
15000
y = 1.13E-05x + 1.11E-03
R² = 1.00E+00
y = 1.05E-05x - 1.64E-02
R² = 9.98E-01
y = 6.06E-06x - 7.95E-04
R² = 9.99E-01
y = 6.22E-06x - 4.40E-04
R² = 9.99E-01
y = 5.67E-06x - 9.39E-03
R² = 9.99E-01
y = 3.71E-06x - 6.02E-04
R² = 9.97E-01
y = 4E-06x - 0.0071
R² = 0.9987
y = 7.57E-07x - 1.07E-04
R² = 9.92E-01
Leak2
Bar P140
Bar S140
Bar P350
Bar S350
Bar S2 350
Bar P700
Bar S700

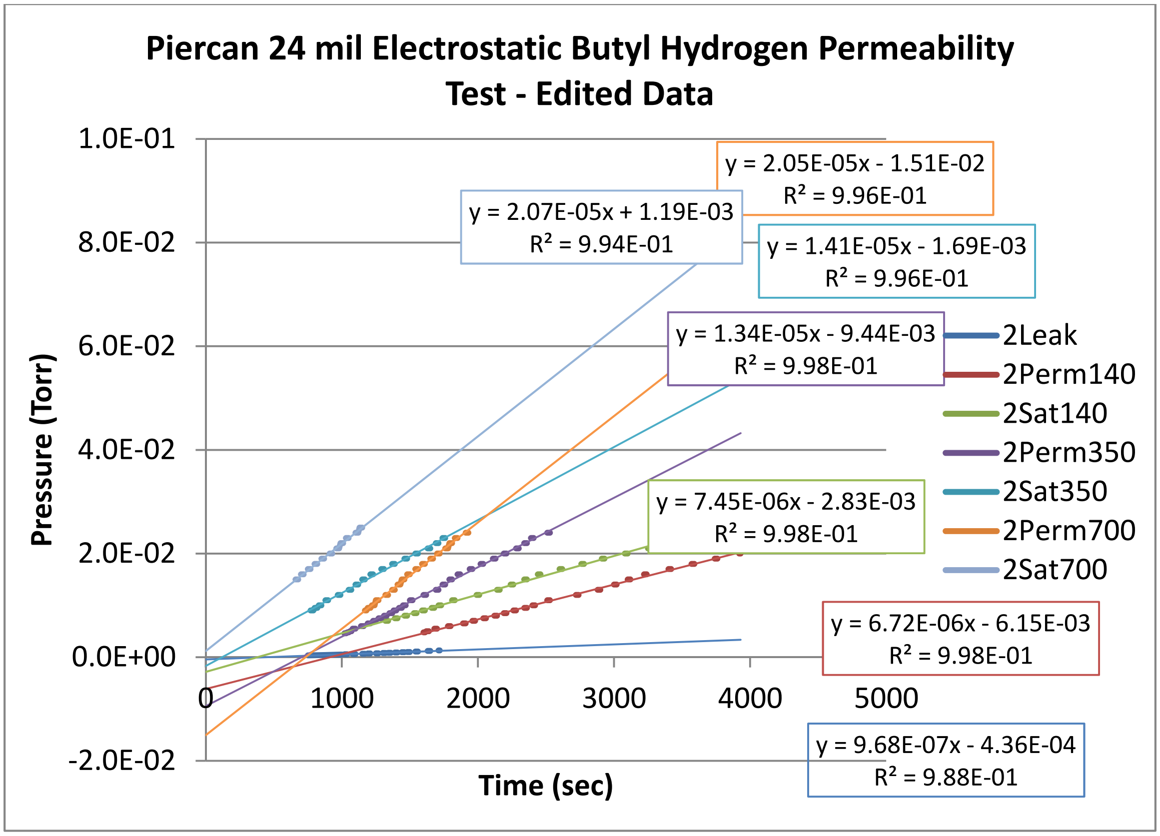

North 15 mil Butyl Hydrogen Permeation Test - Edited Data
Pressure (Torr)
Time (sec)
6.0E-02
5.0E-02
4.0E-02
3.0E-02
2.0E-02
1.0E-02
0.0E+00
-1.0E-02
0
1000
2000
3000
4000
5000
6000
y = 1.13E-05x - 1.13E-03
R² = 9.97E-01
y = 9.46E-06x - 6.15E-03
R² = 9.95E-01
y = 3.96E-06x - 4.49E-04
R² = 9.98E-01
y = 3.64E-06x - 2.75E-03
R² = 9.88E-01
y = 2.34E-06x - 5.72E-04
R² = 9.97E-01
y = 2.16E-06x - 1.92E-03
R² = 9.97E-01
y = 1.51E-07x + 1.32E-05
R² = 9.86E-01
2.1Leak
2Perm70
1.2Sat70
2Perm140
1.2Sat140
2Perm350
1.2Sat350

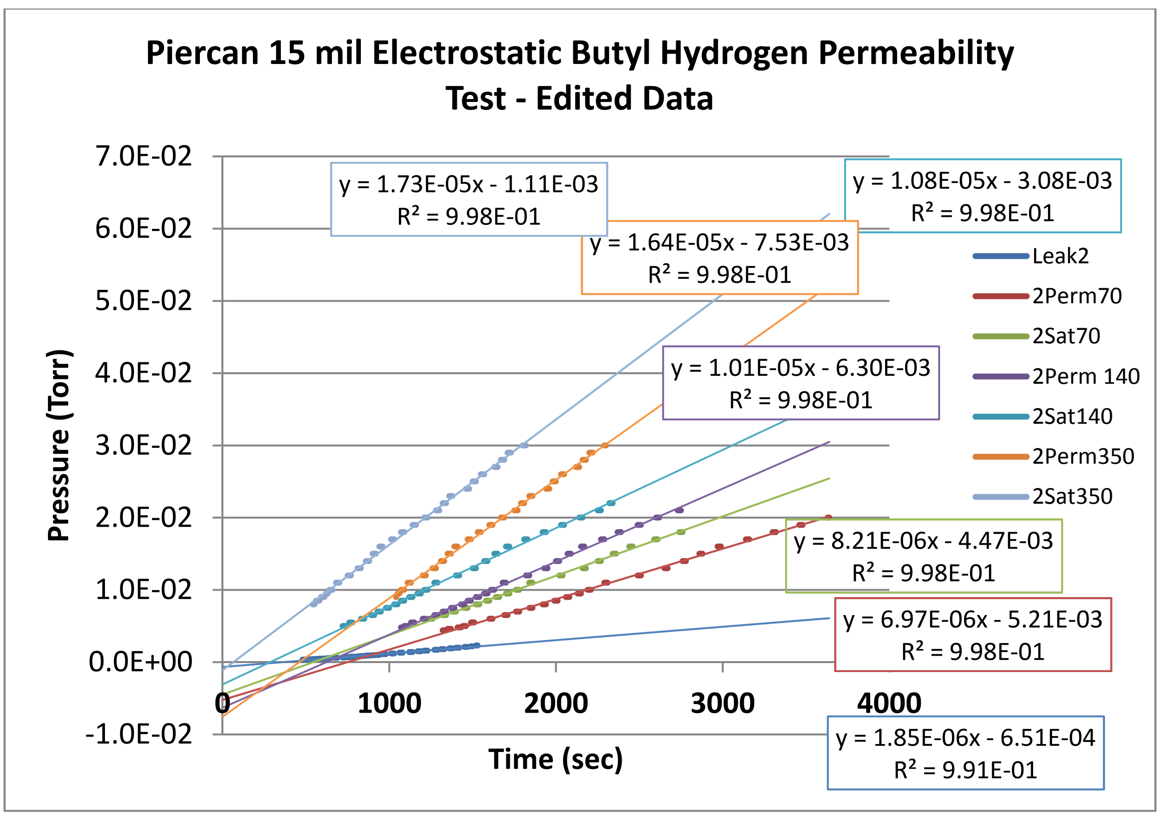

Guardian 30 mil Butyl Hydrogen Permeability Test - Edited Data
Pressure (Torr)
Time (sec)
y = 1.78E-05x - 3.68E-04
R² = 9.97E-01
y = 1.55E-05x - 1.22E-02
R² = 9.97E-01
y = 9.06E-06x - 9.68E-04
R² = 9.98E-01
y = 8.16E-06x - 7.59E-03
R² = 9.98E-01
y = 4.65E-06x - 9.10E-04
R² = 9.99E-01
y = 4.26E-06x - 4.76E-03
R² = 9.98E-01
y = 3.87E-07x - 3.50E-05
R² = 9.91E-01
2Leak
2Perm140T
2Sat140
2Perm350
2Sat350
2Perm700
1.2E-01
1.0E-01
8.0E-02
6.0E-02
4.0E-02
2.0E-02
0.0E+00
-2.0E-02
0
1000
2000
3000
4000
5000
6000
7000

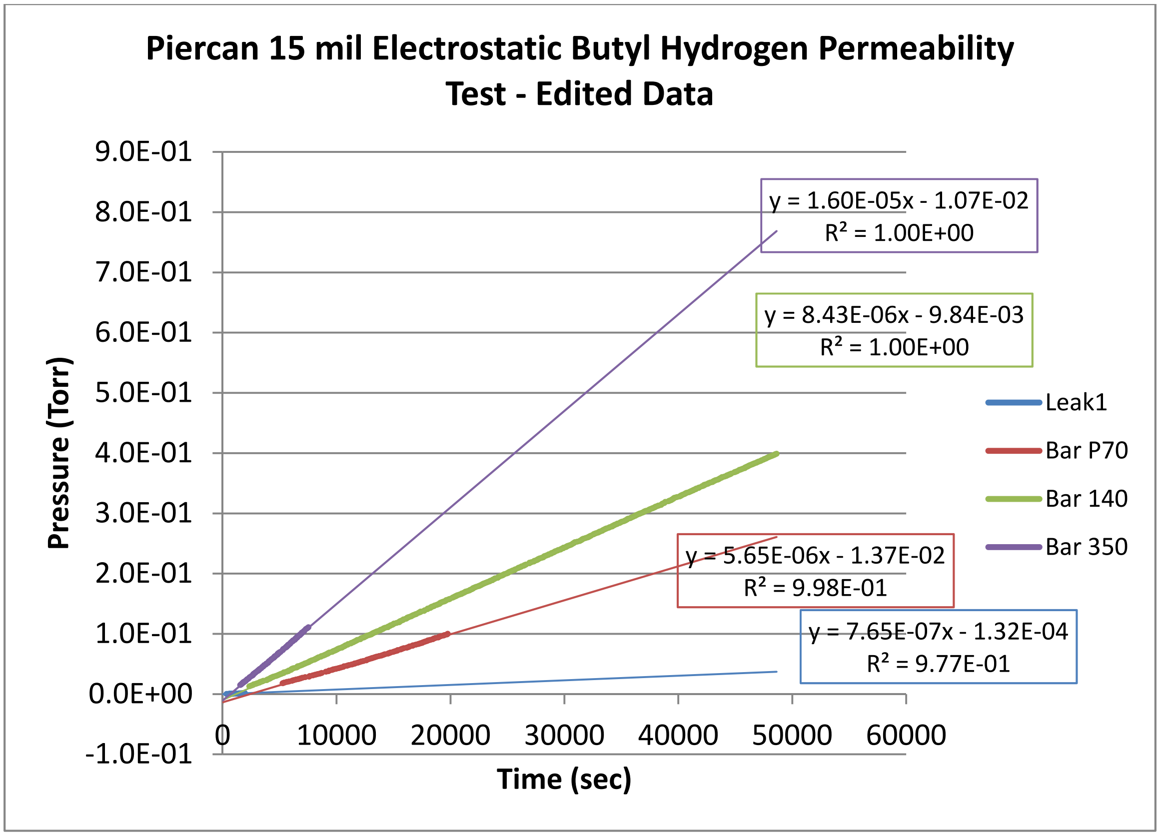

Guardian 15 mil Butyl Hydrogen Permeability Test - Edited Data
Pressure (Torr)
Time (sec)
y = 1.30E-05x - 1.34E-03
R² = 9.98E-01
y = 4.82E-06x - 8.79E-04
R² = 9.98E-01
y = 4.59E-06x - 3.27E-03
R² = 9.97E-01
y = 1.15E-05x - 5.60E-03
R² = 9.98E-01
y = 2.32E-06x - 3.11E-04
R² = 9.98E-01
y = 2.33E-06x - 1.75E-03
R² = 9.98E-01
y = 1.30E-07x - 3.54E-05
R² = 9.98E-01
2Leak
2Perm70
2Sat70
2Perm140
2Sat140
2Perm350
2Sat350
6.0E-02
5.0E-02
4.0E-02
3.0E-02
2.0E-02
1.0E-02
0.0E+00
-1.0E-02
0
1000
2000
3000
4000
5000

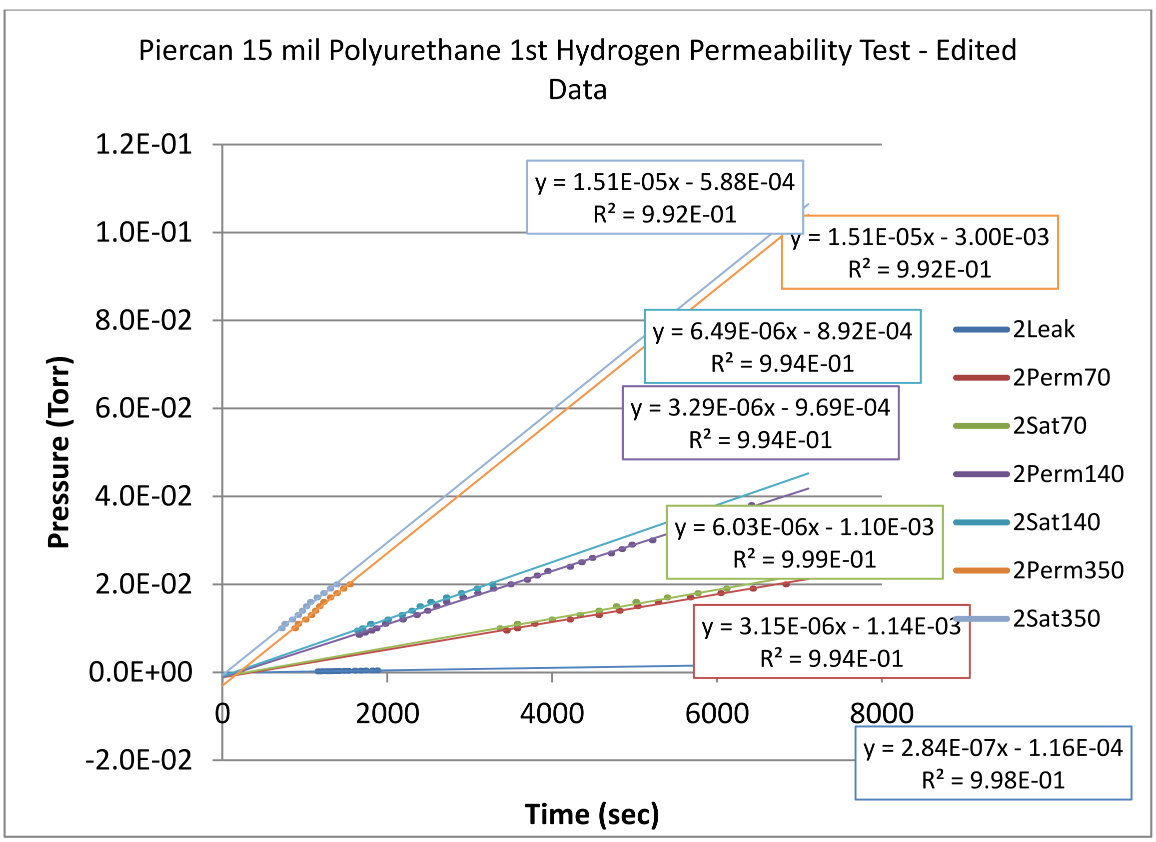

Piercan 30 mil Butyl Hydrogen Permeability Test - Edited Data
Pressure (Torr)
Time (sec)
y = 1.15E-05x - 7.51E-04
R² = 9.99E-01
y = 1.06E-05x - 1.97E-02
R² = 9.94E-01
y = 5.96E-06x - 7.00E-04
R² = 9.99E-01
y = 5.89E-06x - 1.38E-02
R² = 9.96E-01
y = 2.84E-06x - 6.79E-04
R² = 9.99E-01
y = 2.53E-06x - 5.82E-03
R² = 9.98E-01
y = 1.45E-07x - 3.92E-05
R² = 9.99E-01
2Leak
2Perm140
2Sat140
2Perm350
2Sat350
2Perm700
2Sat700

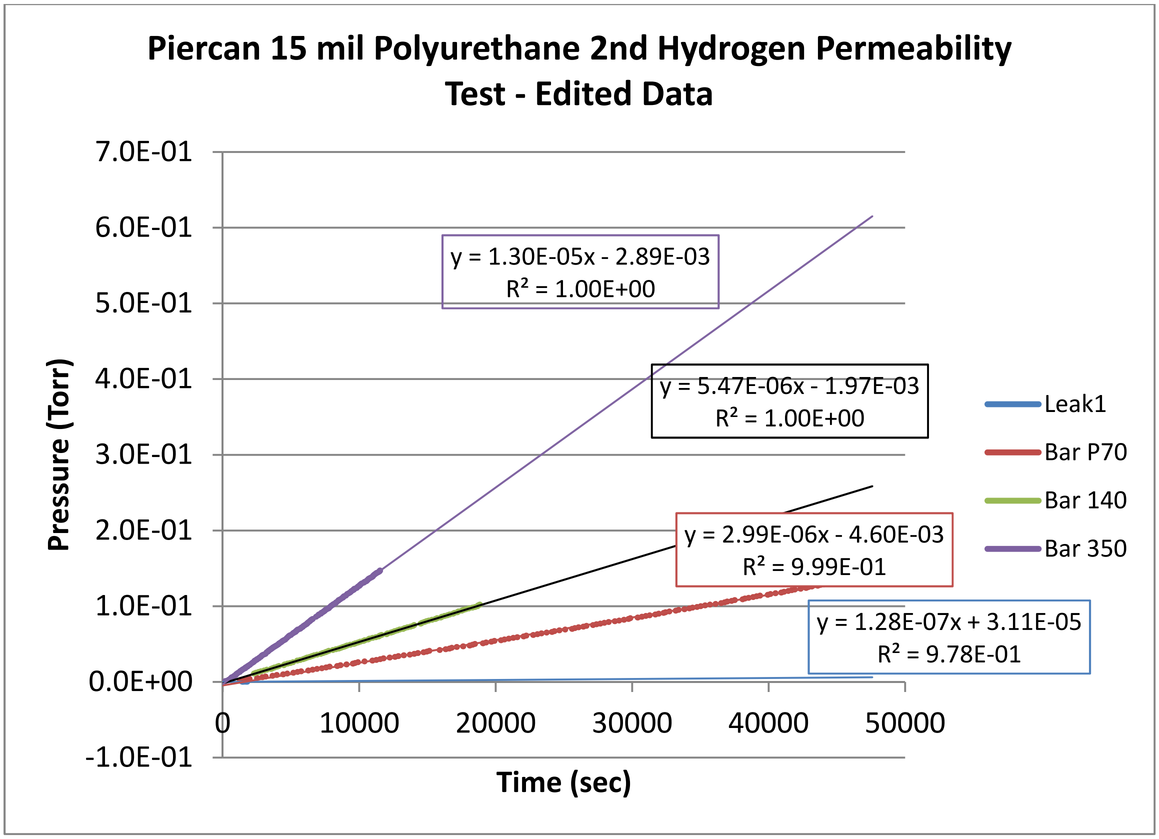

Piercan Butyl 15mil Hydrogen Permeability Edited Chart
Pressure (Torr)
Time (sec)
y = 1.47E-05x - 9.24E-04
R² = 9.97E-01
y = 1.43E-05x - 4.88E-03
R² = 9.98E-01
y = 6.79E-06x - 1.37E-03
R² = 9.97E-01
y = 6.63E-06x - 3.09E-03
R² = 9.98E-01
y = 3.32E-06x - 1.22E-03
R² = 9.97E-01
y = 3.13E-06x - 2.01E-03
R² = 9.98E-01
y = 1.67E-07x - 1.24E-04
R² = 9.86E-01
Leak2
2Perm70
2Sat70
2Perm140
2Sat140
2Perm350
2Sat350

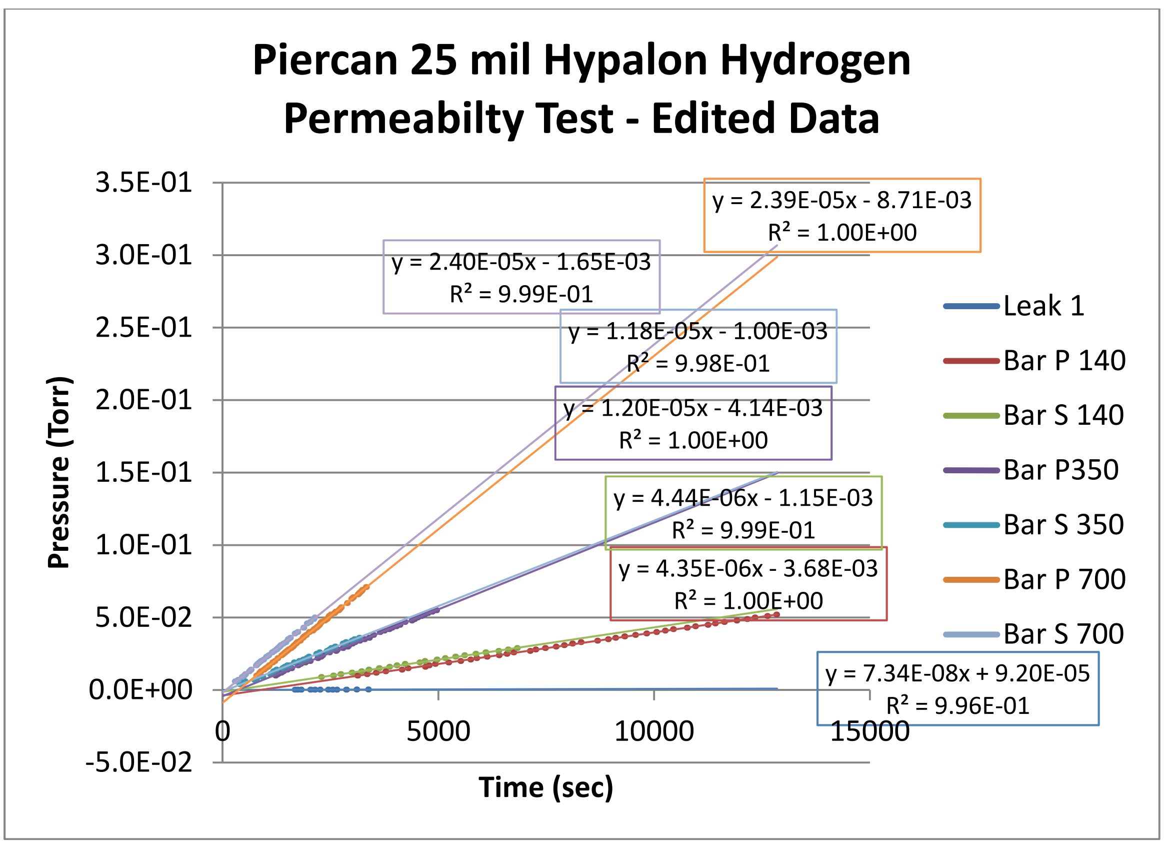

Piercan 24 mil Electrostatic Butyl Hydrogen Permeability Test - Edited Data
Pressure (Torr)
Time (sec)
1.0E-01
8.0E-02
6.0E-02
4.0E-02
2.0E-02
0.0E+00
-2.0E-02
0
1000
2000
3000
4000
5000
y = 2.05E-05x - 1.51E-02
R² = 9.96E-01
y = 2.07E-05x + 1.19E-03
R² = 9.94E-01
y = 1.41E-05x - 1.69E-03
R² = 9.96E-01
y = 1.34E-05x - 9.44E-03
R² = 9.98E-01
y = 7.45E-06x - 2.83E-03
R² = 9.98E-01
y = 6.72E-06x - 6.15E-03
R² = 9.98E-01
y = 9.68E-07x - 4.36E-04
R² = 9.88E-01
2Leak
2Perm140
2Sat140
2Perm350
2Sat350
2Perm700
2Sat700

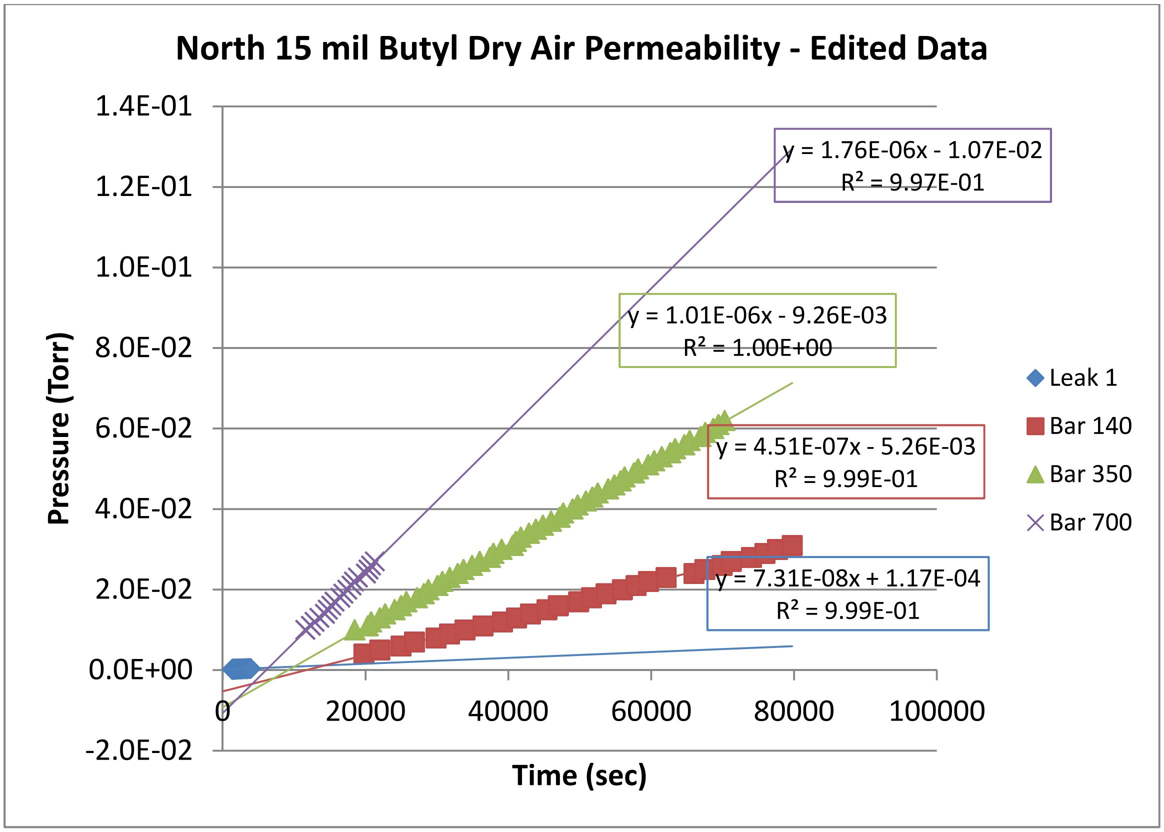

Piercan 15 mil Electrostatic Butyl Hydrogen Permeability Test - Edited Data
Pressure (Torr)
Time (sec)
7.0E-02
6.0E-02
5.0E-02
4.0E-02
3.0E-02
2.0E-02
1.0E-02
0.0E+00
-1.0E-02
0
1000
2000
3000
4000
y = 1.73E-05x - 1.11E-03
R² = 9.98E-01
y = 1.08E-05x - 3.08E-03
R² = 9.98E-01
y = 1.64E-05x - 7.53E-03
R² = 9.98E-01
y = 1.01E-05x - 6.30E-03
R² = 9.98E-01
y = 8.21E-06x - 4.47E-03
R² = 9.98E-01
y = 6.97E-06x - 5.21E-03
R² = 9.98E-01
y = 1.85E-06x - 6.51E-04
R² = 9.91E-01
Leak2
2Perm70
2Sat70
2Perm 140
2Sat140
2Perm350
2Sat350

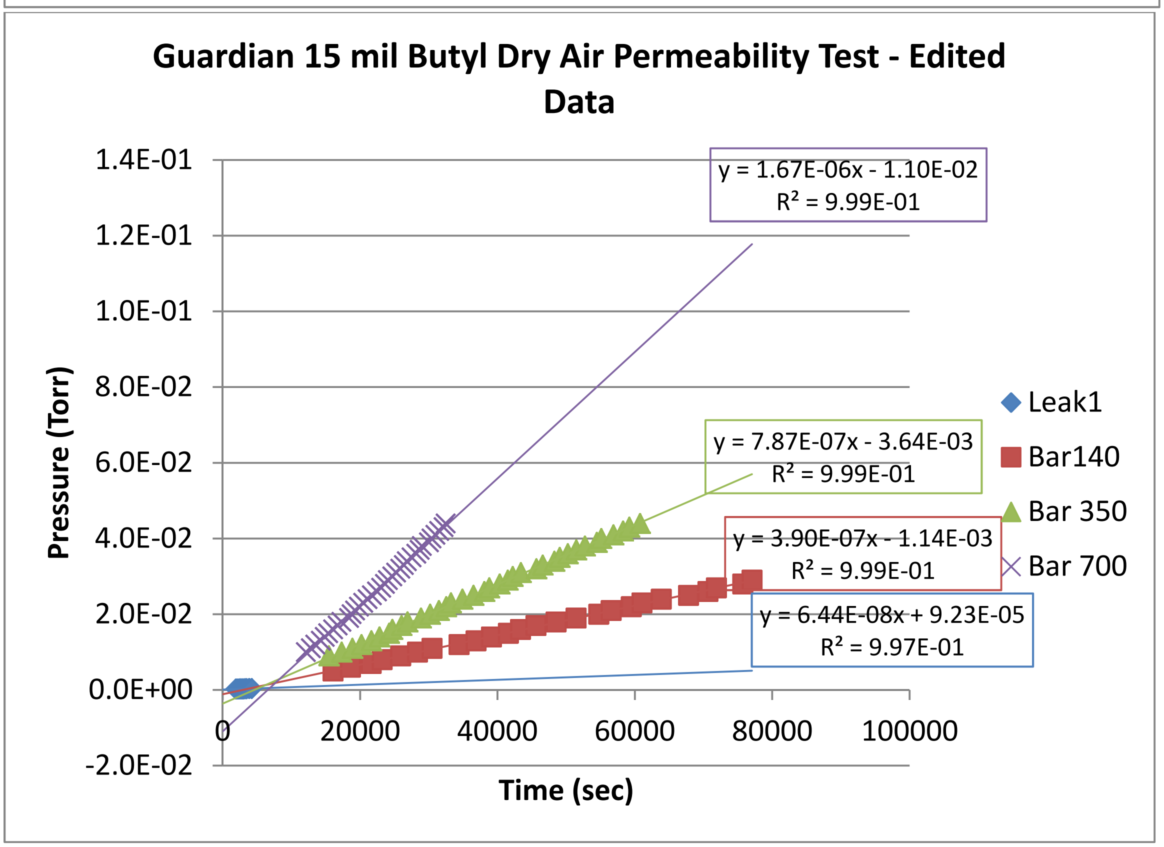

Piercan 15 mil Electrostatic Butyl Hydrogen Permeability Test - Edited Data
Pressure (Torr)
Time (sec)
9.0E-01
8.0E-01
7.0E-01
6.0E-01
5.0E-01
4.0E-01
3.0E-01
2.0E-01
1.0E-01
0.0E+00
-1.0E-01
0
10000
20000
30000
40000
50000
60000
y = 1.60E-05x - 1.07E-02
R² = 1.00E+00
y = 8.43E-06x - 9.84E-03
R² = 1.00E+00
y = 5.65E-06x - 1.37E-02
R² = 9.98E-01
y = 7.65E-07x - 1.32E-04
R² = 9.77E-01
Leak1
Bar P70
Bar 140
Bar 350

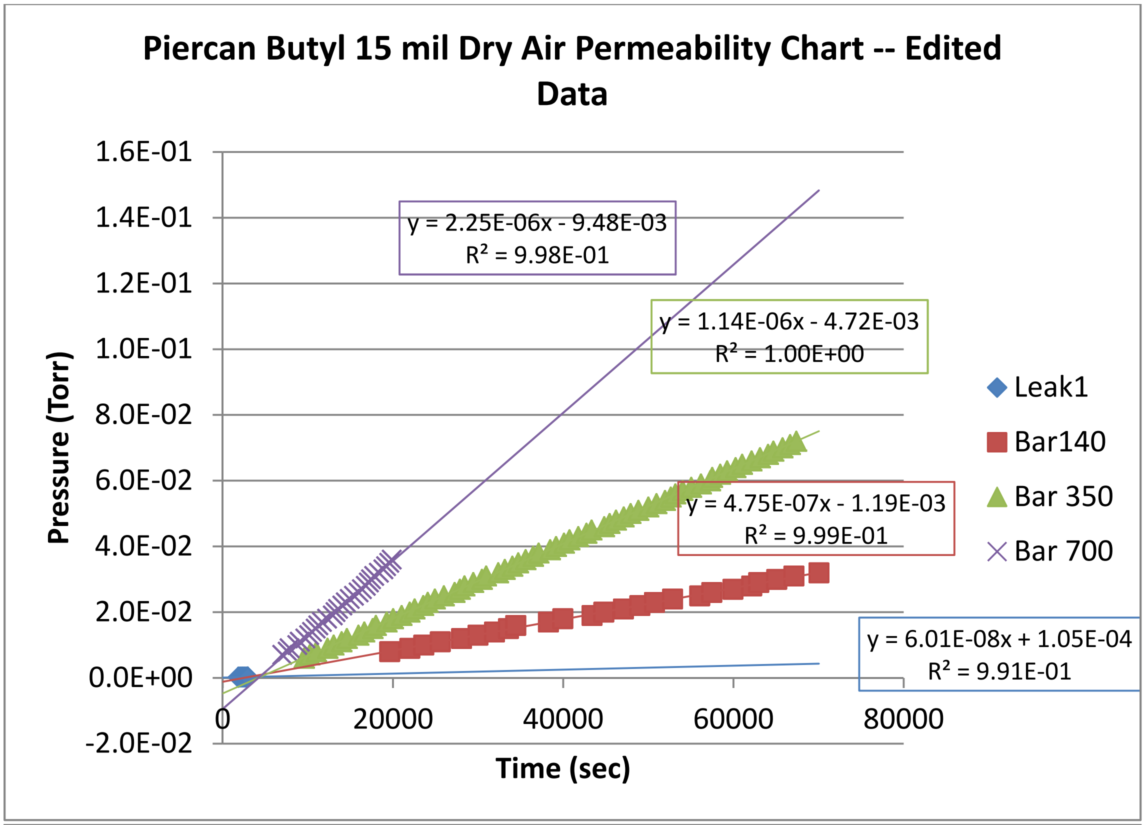

Piercan 15 mil Polyurethane 1st Hydrogen Permeability Test - Edited Data
Pressure (Torr)
Time (sec)
1.2E-01
1.0E-01
8.0E-02
6.0E-02
4.0E-02
2.0E-02
0.0E+00
-2.0E-02
0
2000
4000
6000
8000
y = 1.51E-05x - 5.88E-04
R² = 9.92E-01
y = 1.51E-05x - 3.00E-03
R² = 9.92E-01
y = 6.49E-06x - 8.92E-04
R² = 9.94E-01
y = 3.29E-06x - 9.69E-04
R² = 9.94E-01
y = 6.03E-06x - 1.10E-03
R² = 9.99E-01
y = 3.15E-06x - 1.14E-03
R² = 9.94E-01
y = 2.84E-07x - 1.16E-04
R² = 9.98E-01
2Leak
2Perm70
2Sat70
2Perm140
2Sat140
2Perm350
2Sat350

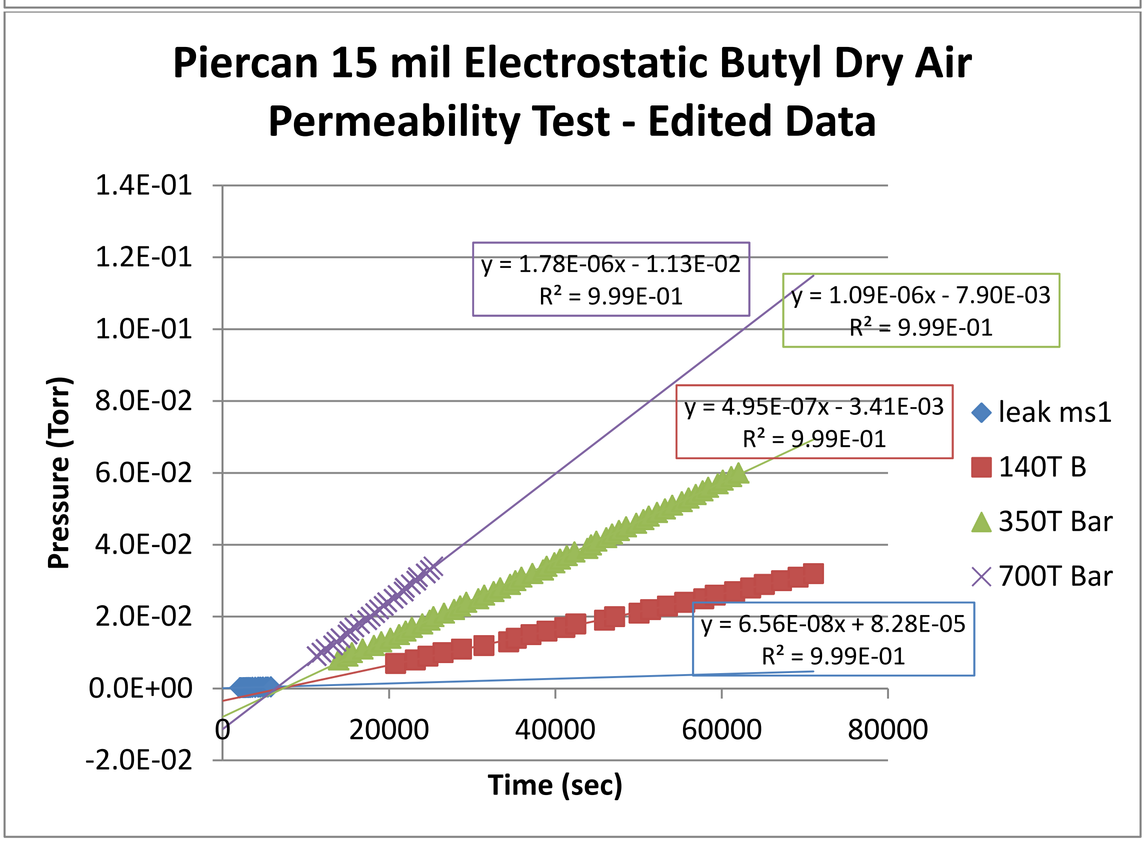

Piercan 15 mil Polyurethane 2nd Hydrogen Permeability Test - Edited Data
7.0E-01
6.0E-01
5.0E-01
4.0E-01
3.0E-01
2.0E-01
1.0E-01
0.0E+00
-1.0E-01
Pressure (Torr)
0
10000
20000
30000
40000
50000
Time (sec)
y = 1.30E-05x - 2.89E-03
R² = 1.00E+00
y = 5.47E-06x - 1.97E-03
R² = 1.00E+00
y = 2.99E-06x - 4.60E-03
R² = 9.99E-01
y = 1.28E-07x + 3.11E-05
R² = 9.78E-01
Leak1
Bar P70
Bar 140
Bar 350

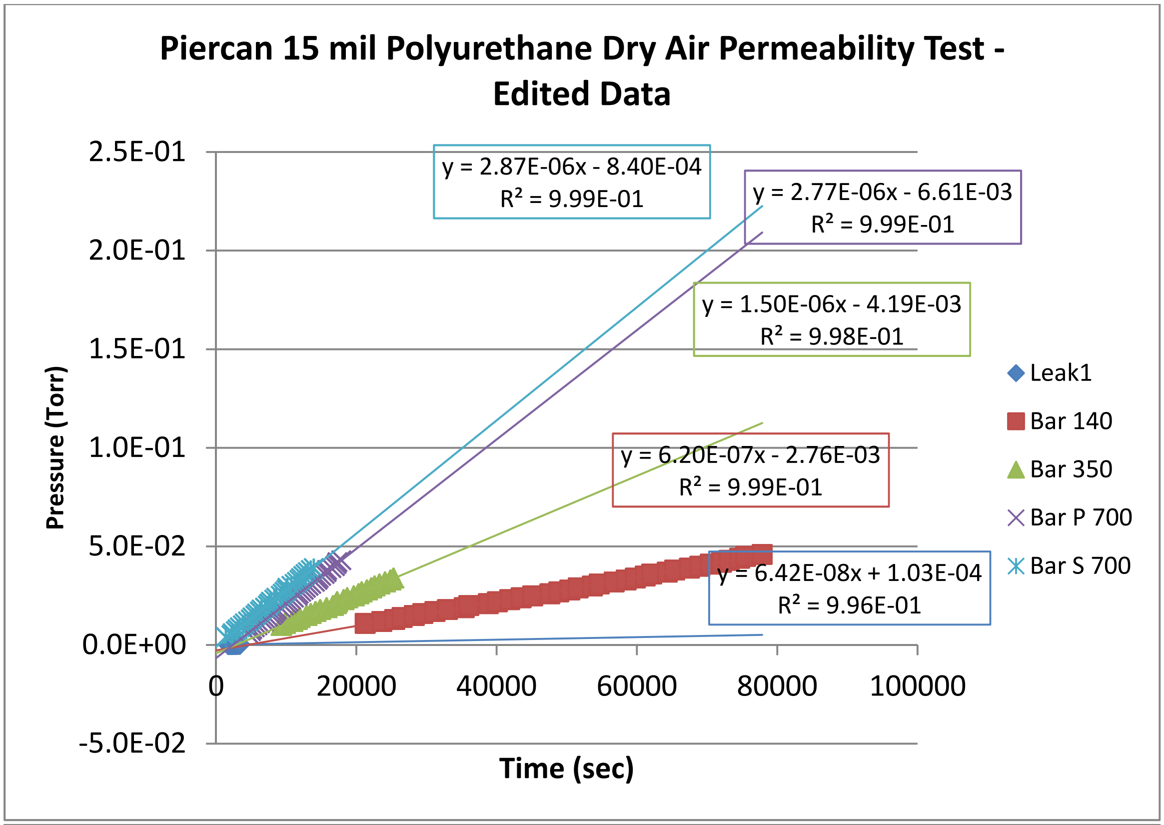

Piercan 25 mil Hypalon Hydrogen Permeabilty Test - Edited Data
3.5E-01
3.0E-01
2.5E-01
2.0E-01
1.5E-01
1.0E-01
5.0E-02
0.0E+00
-5.0E-02
Pressure (Torr)
0
5000
10000
15000
Time (sec)
y = 2.39E-05x - 8.71E-03
R² = 1.00E+00
y = 2.40E-05x - 1.65E-03
R² = 9.99E-01
y = 1.18E-05x - 1.00E-03
R² = 9.98E-01
y = 1.20E-05x - 4.14E-03
R² = 1.00E+00
y = 4.44E-06x - 1.15E-03
R² = 9.99E-01
y = 4.35E-06x - 3.68E-03
R² = 1.00E+00
y = 7.34E-08x + 9.20E-05
R² = 9.96E-01
Leak 1
Bar P 140
Bar S 140
Bar P350
Bar S 350
Bar P 700
Bar S 700

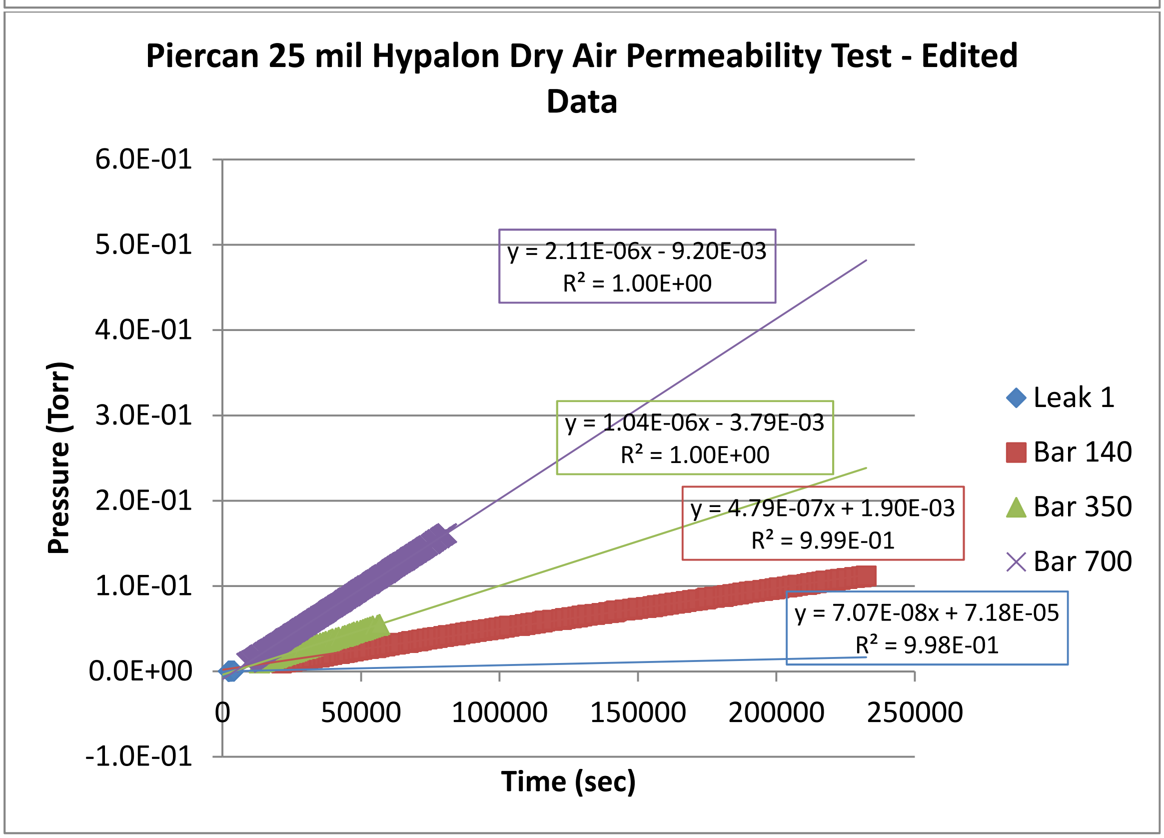

North 15 mil Butyl Dry Air Permeability - Edited Data
y = 1.76E-06x - 1.07E-02
R² = 9.97E-01
y = 1.01E-06x - 9.26E-03
R² = 1.00E+00
y = 4.51E-07x - 5.26E-03
R² = 9.99E-01
y = 7.31E-08x + 1.17E-04
R² = 9.99E-01
Leak 1
Bar 140
Bar 350
Bar 700
Pressure (Torr)
1.4E-01
1.2E-01
1.0E-01
8.0E-02
6.0E-02
4.0E-02
2.0E-02
0.0E+00
-2.0E-02
0
20000
40000
60000
80000
100000
Time (sec)

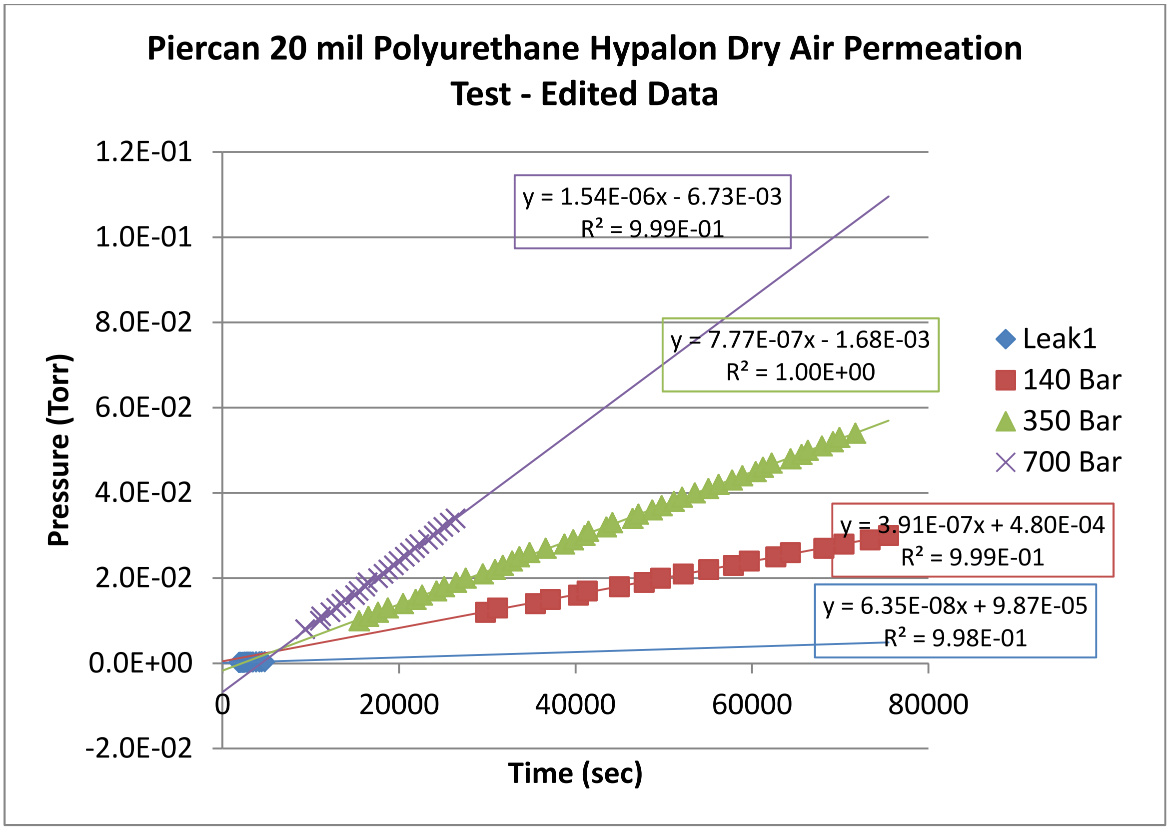

Guardian 15 mil Butyl Dry Air Permeability Test - Edited Data
y = 1.67E-06x - 1.10E-02
R² = 9.99E-01
y = 7.87E-07x - 3.64E-03
R² = 9.99E-01
y = 3.90E-07x - 1.14E-03
R² = 9.99E-01
y = 6.44E-08x + 9.23E-05
R² = 9.97E-01
Leak1
Bar140
Bar 350
Bar 700
Pressure (Torr)
1.4E-01
1.2E-01
1.0E-01
8.0E-02
6.0E-02
4.0E-02
2.0E-02
0.0E+00
-2.0E-02
0
20000
40000
60000
80000
100000
Time (sec)

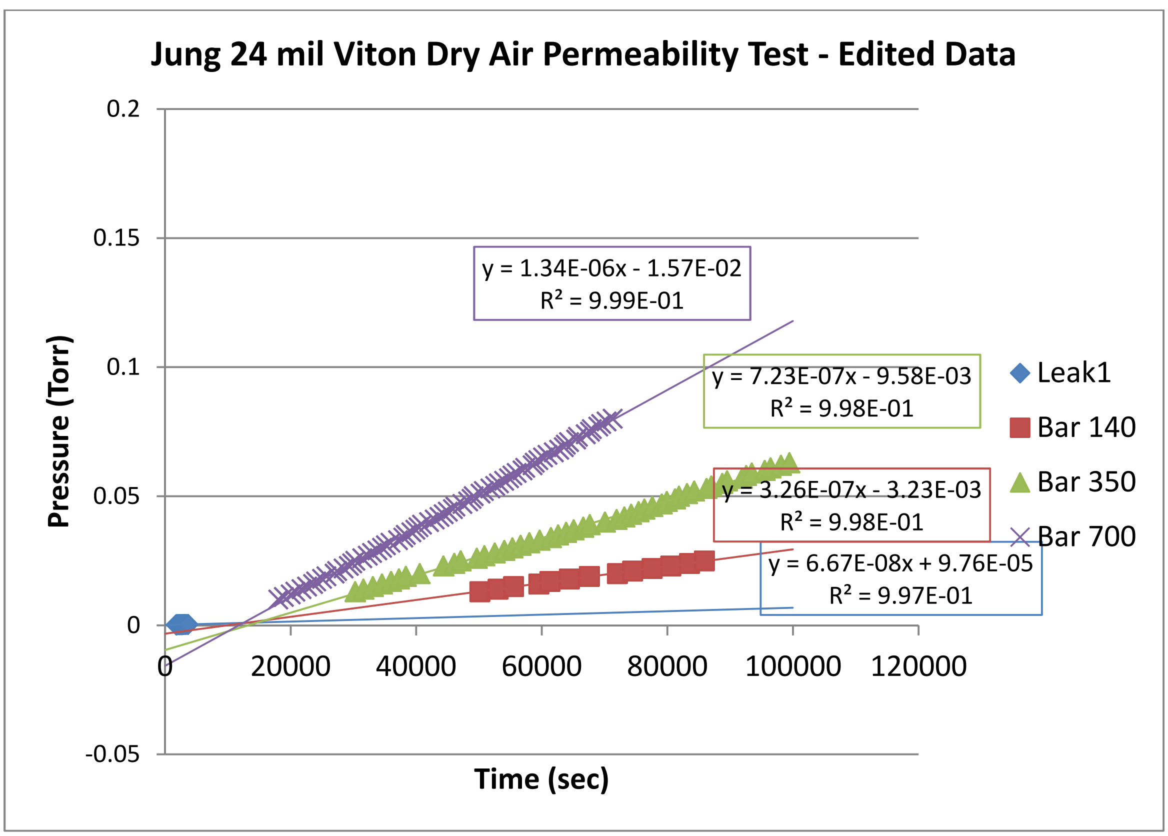

Piercan Butyl 15 mil Dry Air Permeability Chart -- Edited Data
y = 2.25E-06x - 9.48E-03
R² = 9.98E-01
y = 1.14E-06x - 4.72E-03
R² = 1.00E+00
y = 4.75E-07x - 1.19E-03
R² = 9.99E-01
y = 6.01E-08x + 1.05E-04
R² = 9.91E-01
Leak1
Bar140
Bar 350
Bar 700
Pressure (Torr)
1.6E-01
1.4E-01
1.2E-01
1.0E-01
8.0E-02
6.0E-02
4.0E-02
2.0E-02
0.0E+00
-2.0E-02
0
20000
40000
60000
80000
Time (sec)

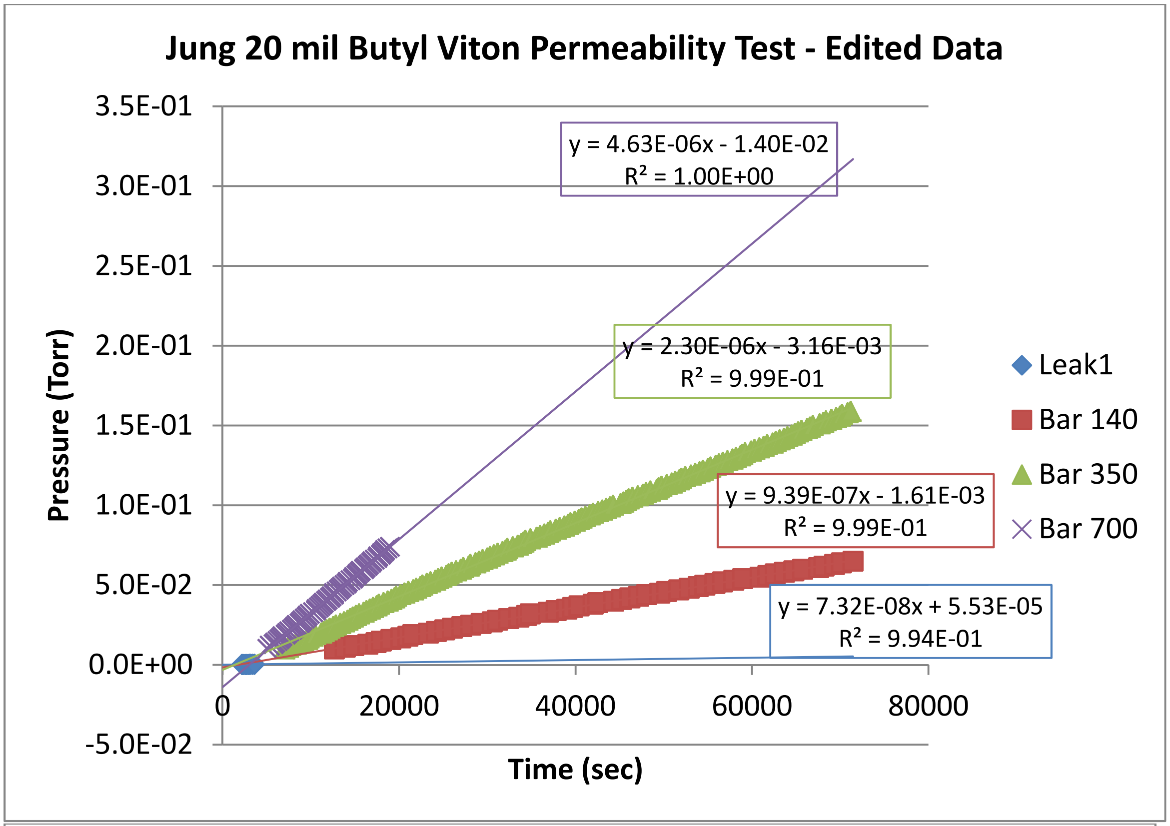

Piercan 15 mil Electrostatic Butyl Dry Air Permeability Test - Edited Data
y = 1.78E-06x - 1.13E-02
R² = 9.99E-01
y = 1.09E-06x - 7.90E-03
R² = 9.99E-01
y = 4.95E-07x - 3.41E-03
R² = 9.99E-01
y = 6.56E-08x + 8.28E-05
R² = 9.99E-01
leak ms1
140T B
350T Bar
700T Bar
Pressure (Torr)
1.4E-01
1.2E-01
1.0E-01
8.0E-02
6.0E-02
4.0E-02
2.0E-02
0.0E+00
-2.0E-02
0
20000
40000
60000
80000
Time (sec)

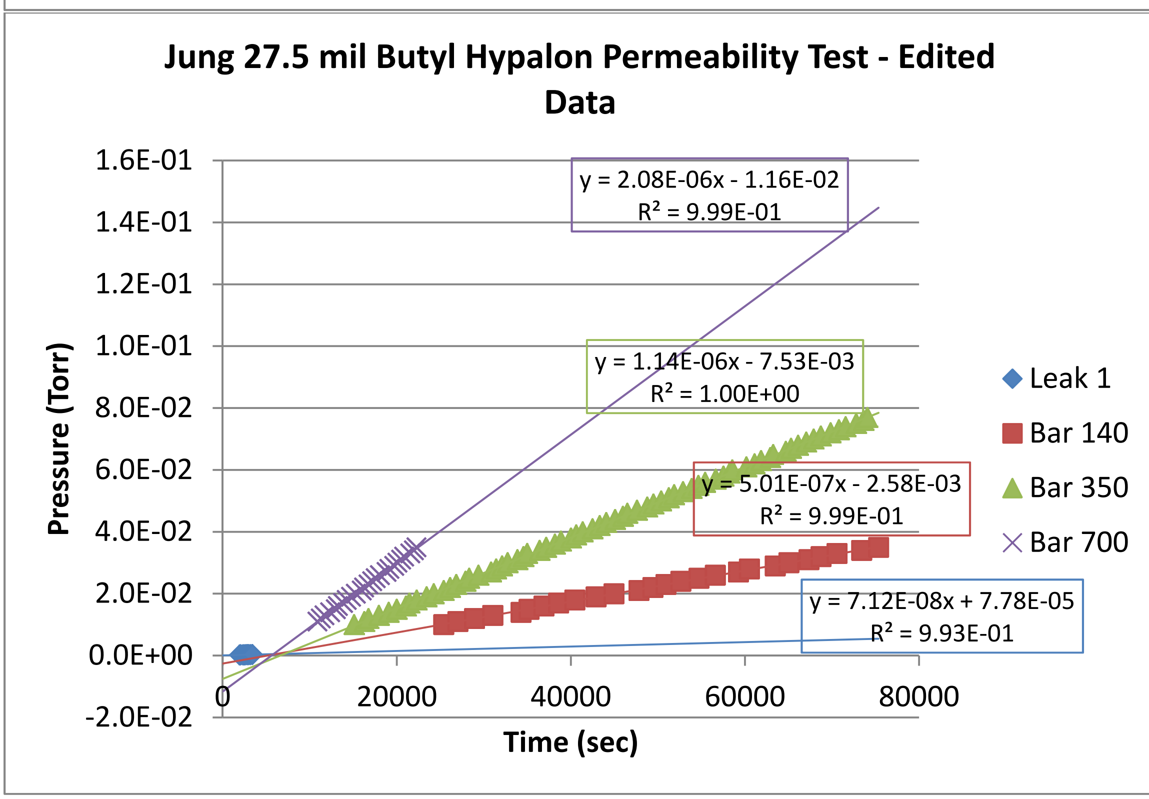

Piercan 15 mil Polyurethane Dry Air Permeability Test - Edited Data
y = 2.87E-06x - 8.40E-04
R² = 9.99E-01
y = 2.77E-06x - 6.61E-03
R² = 9.99E-01
y = 1.50E-06x - 4.19E-03
R² = 9.98E-01
y = 6.20E-07x - 2.76E-03
R² = 9.99E-01
y = 6.42E-08x + 1.03E-04
R² = 9.96E-01
Leak1
Bar 140
Bar 350
Bar P 700
Bar S 700
Pressure (Torr)
Time (sec)
2.5E-01
2.0E-01
1.5E-01
1.0E-01
5.0E-02
0.0E+00
-5.0E-02
0
20000
40000
60000
80000
100000

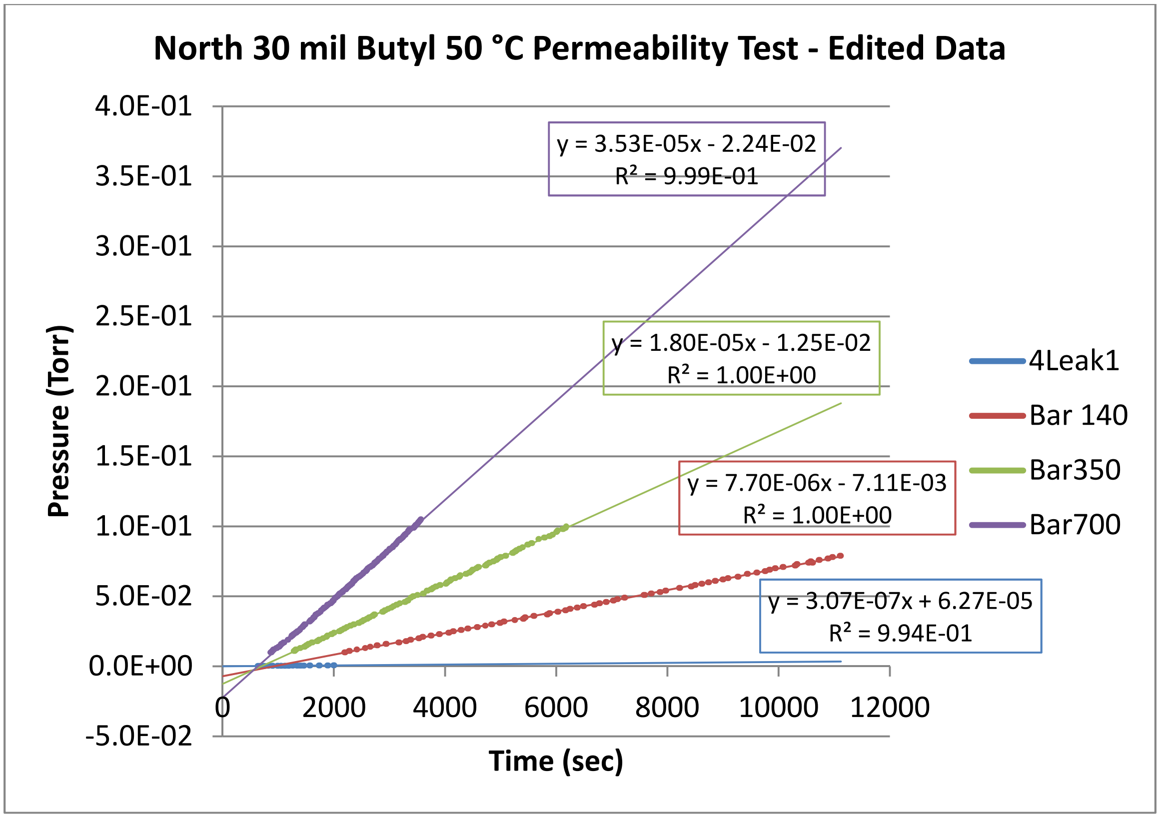

Piercan 25 mil Hypalon Dry Air Permeability Test - Edited Data
y = 2.11E-06x - 9.20E-03
R² = 1.00E+00
y = 1.04E-06x - 3.79E-03
R² = 1.00E+00
y = 4.79E-07x + 1.90E-03
R² = 9.99E-01
y = 7.07E-08x + 7.18E-05
R² = 9.98E-01
Leak 1
Bar 140
Bar 350
Bar 700
Pressure (Torr)
Time (sec)
6.0E-01
5.0E-01
4.0E-01
3.0E-01
2.0E-01
1.0E-01
0.0E+00
-1.0E-01
0
50000
100000
150000
200000
250000

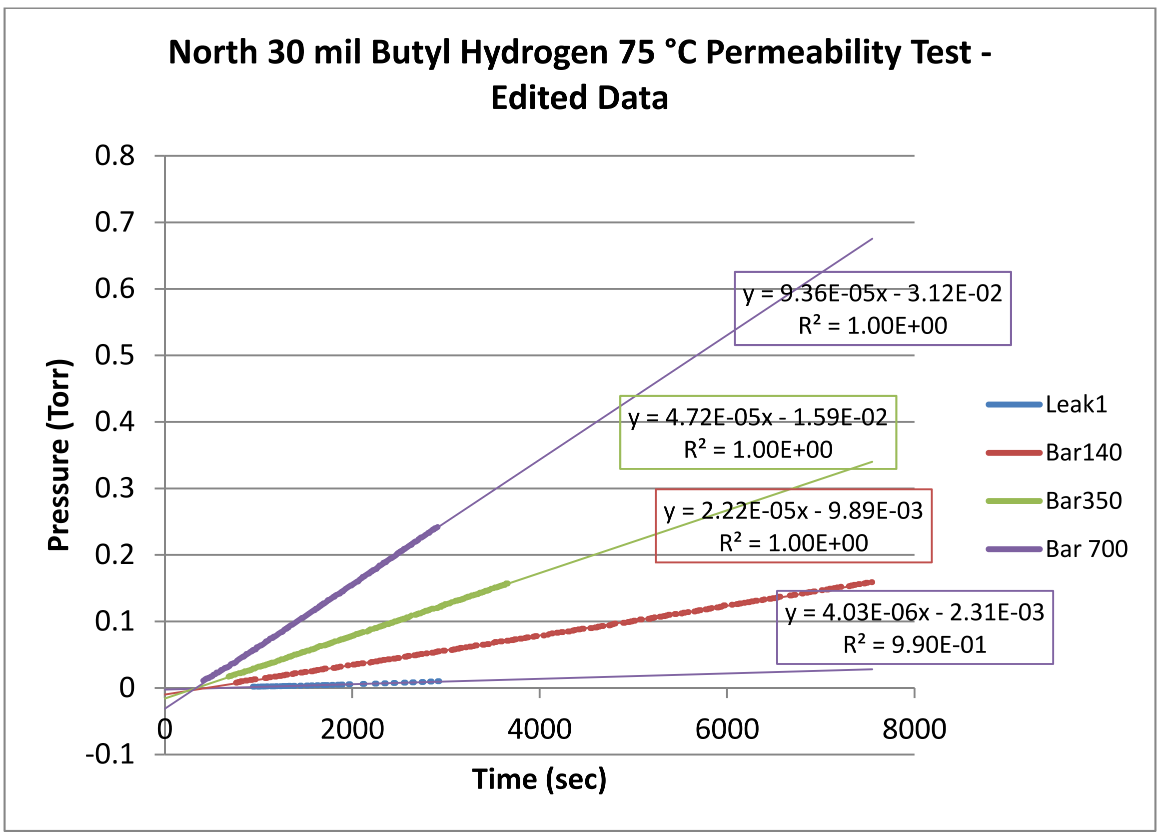

Piercan 20 mil Polyurethane Hypalon Dry Air Permeation Test - Edited Data
y = 1.54E-06x - 6.73E-03
R² = 9.99E-01
y = 7.77E-07x - 1.68E-03
R² = 1.00E+00
y = 3.91E-07x + 4.80E-04
R² = 9.99E-01
y = 6.35E-08x + 9.87E-05
R² = 9.98E-01
Leak1
140 Bar
350 Bar
700 Bar
Pressure (Torr)
Time (sec)
1.2E-01
1.0E-01
8.0E-02
6.0E-02
4.0E-02
2.0E-02
0.0E+00
-2.0E-02
0
20000
40000
60000
80000


Jung 24 mil Viton Dry Air Permeability Test - Edited Data
y = 1.34E-06x - 1.57E-02
R² = 9.99E-01
y = 7.23E-07x - 9.58E-03
R² = 9.98E-01
y = 3.26E-07x - 3.23E-03
R² = 9.98E-01
y = 6.67E-08x + 9.76E-05
R² = 9.97E-01
Leak1
Bar 140
Bar 350
Bar 700
Pressure (Torr)
Time (sec)
0.2
0.15
0.1
0.05
0
-0.05
0
20000
40000
60000
80000
100000
120000

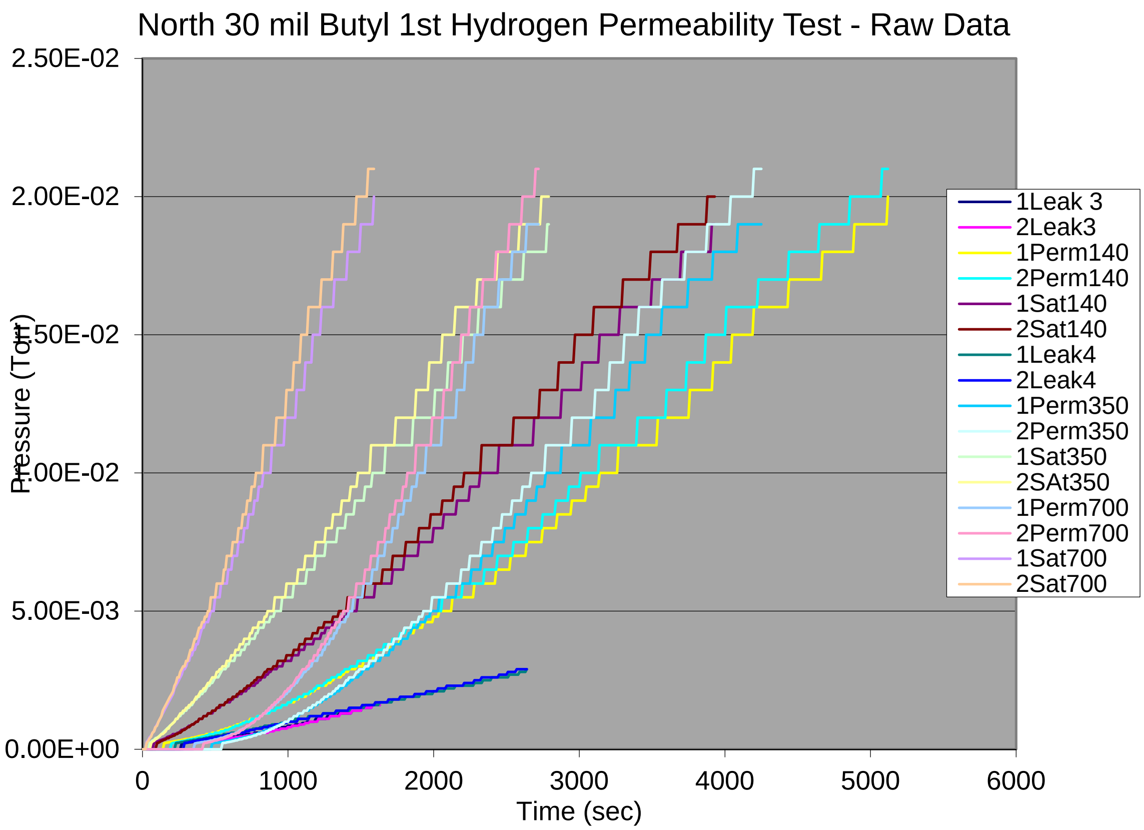

Jung 20 mil Butyl Viton Permeability Test - Edited Data
Pressure (Torr)
Time (sec)
3.5E-01
3.0E-01
2.5E-01
2.0E-01
1.5E-01
1.0E-01
5.0E-02
0.0E+00
-5.0E-02
0
20000
40000
60000
80000
y = 4.63E-06x - 1.40E-02
R² = 1.00E+00
y = 2.30E-06x - 3.16E-03
R² = 9.99E-01
y = 9.39E-07x - 1.61E-03
R² = 9.99E-01
y = 7.32E-08x + 5.53E-05
R² = 9.94E-01
Leak1
Bar 140
Bar 350
Bar 700

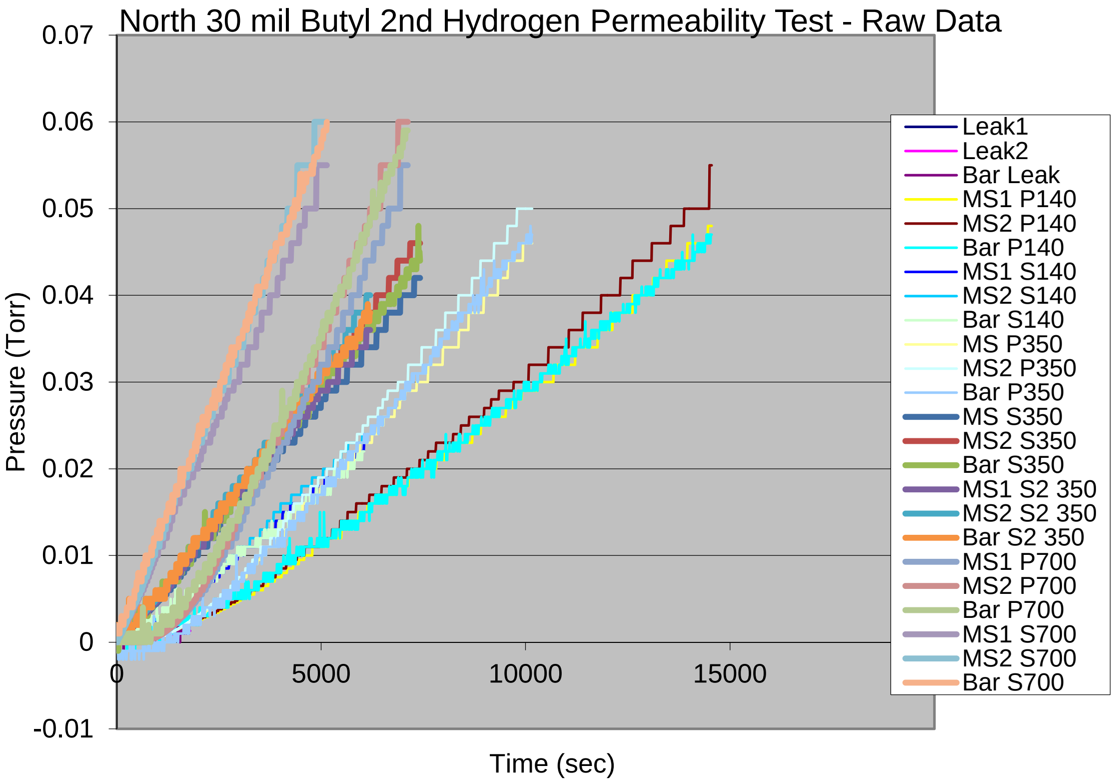

Jung 27.5 mil Butyl Hypalon Permeability Test - Edited Data
Pressure (Torr)
Time (sec)
1.6E-01
1.4E-01
1.2E-01
1.0E-01
8.0E-02
6.0E-02
4.0E-02
2.0E-02
0.0E+00
-2.0E-02
0
20000
40000
60000
80000
y = 2.08E-06x - 1.16E-02
R² = 9.99E-01
y = 1.14E-06x - 7.53E-03
R² = 1.00E+00
y = 5.01E-07x - 2.58E-03
R² = 9.99E-01
y = 7.12E-08x + 7.78E-05
R² = 9.93E-01
Leak 1
Bar 140
Bar 350
Bar 700

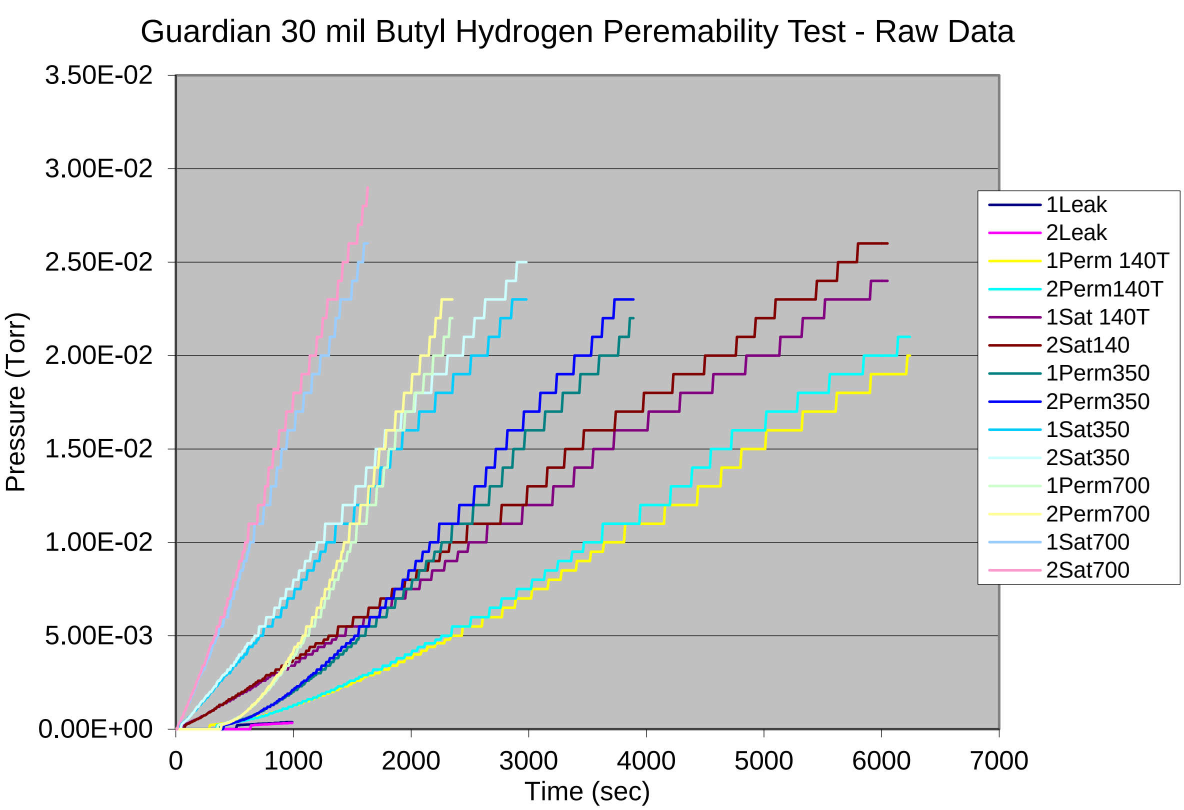

North 30 mil Butyl 50 °C Permeability Test - Edited Data
y = 3.53E-05x - 2.24E-02
R² = 9.99E-01
y = 1.80E-05x - 1.25E-02
R² = 1.00E+00
y = 7.70E-06x - 7.11E-03
R² = 1.00E+00
y = 3.07E-07x + 6.27E-05
R² = 9.94E-01
4Leak1
Bar 140
Bar350
Bar700
Pressure (Torr)
4.0E-01
3.5E-01
3.0E-01
2.5E-01
2.0E-01
1.5E-01
1.0E-01
5.0E-02
0.0E+00
-5.0E-02
0
2000
4000
6000
8000
10000
12000
Time (sec)

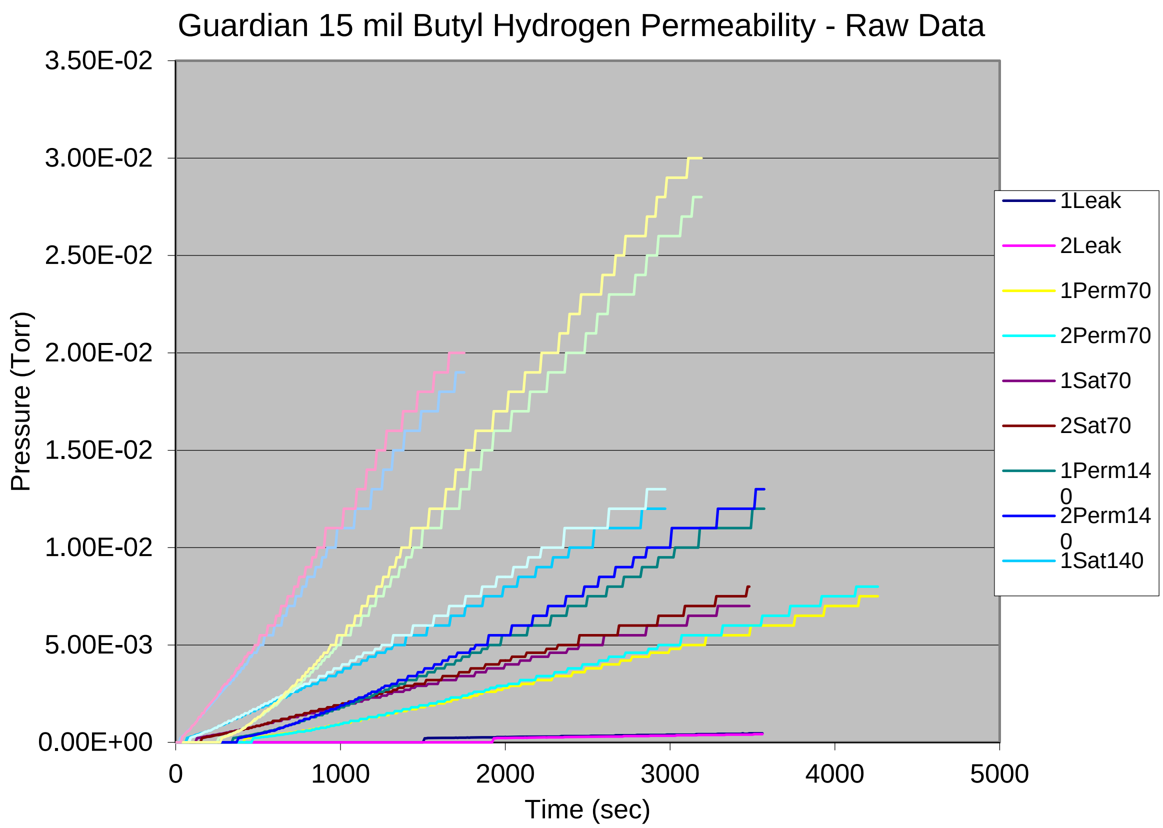

North 30 mil Butyl Hydrogen 75 °C Permeability Test - Edited Data
y = 9.36E-05x - 3.12E-02
R² = 1.00E+00
y = 4.72E-05x - 1.59E-02
R² = 1.00E+00
y = 2.22E-05x - 9.89E-03
R² = 1.00E+00
y = 4.03E-06x - 2.31E-03
R² = 9.90E-01
Leak1
Bar140
Bar350
Bar 700
Pressure (Torr)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
2000
4000
6000
8000
Time (sec)

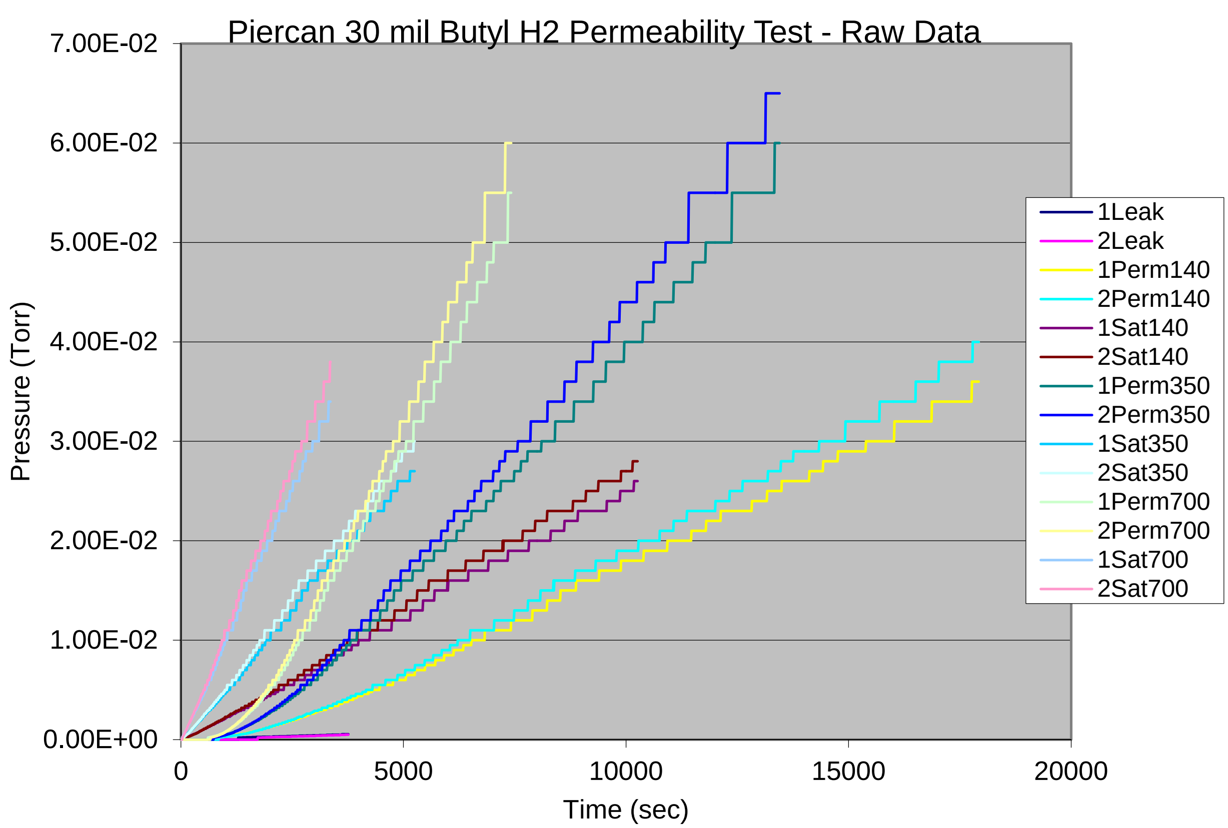
Appendix D: Raw Data Graphs

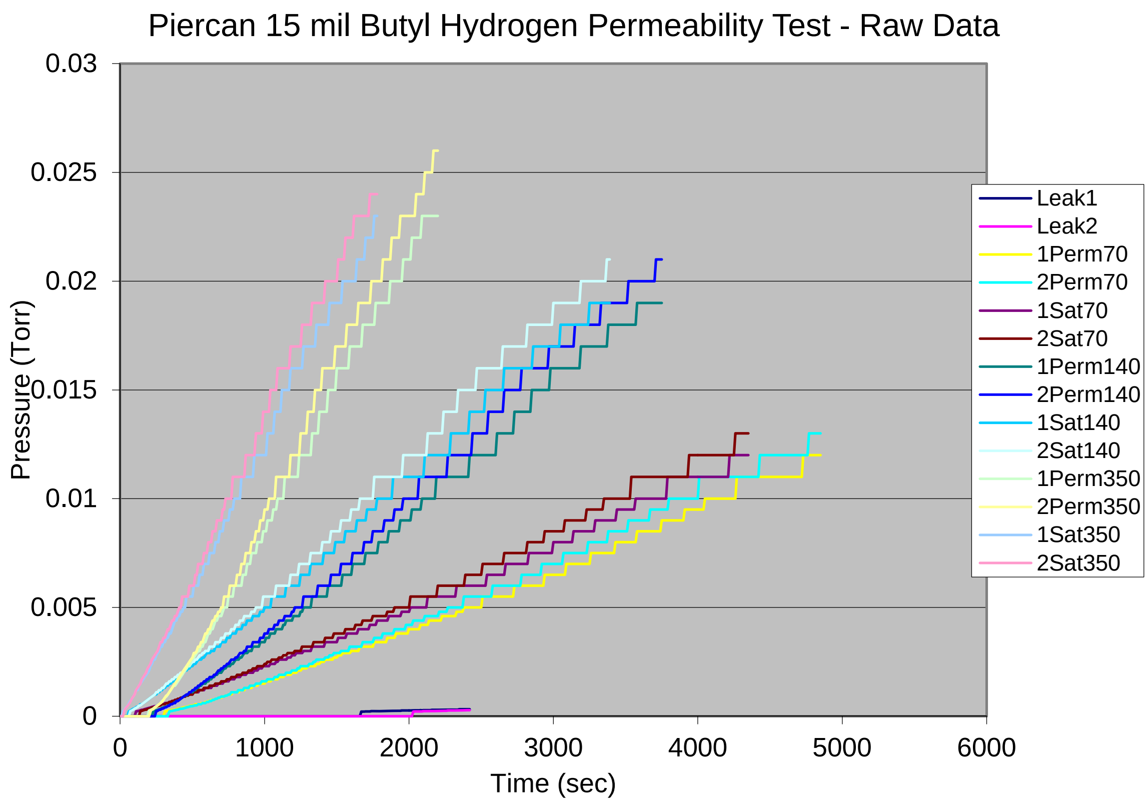


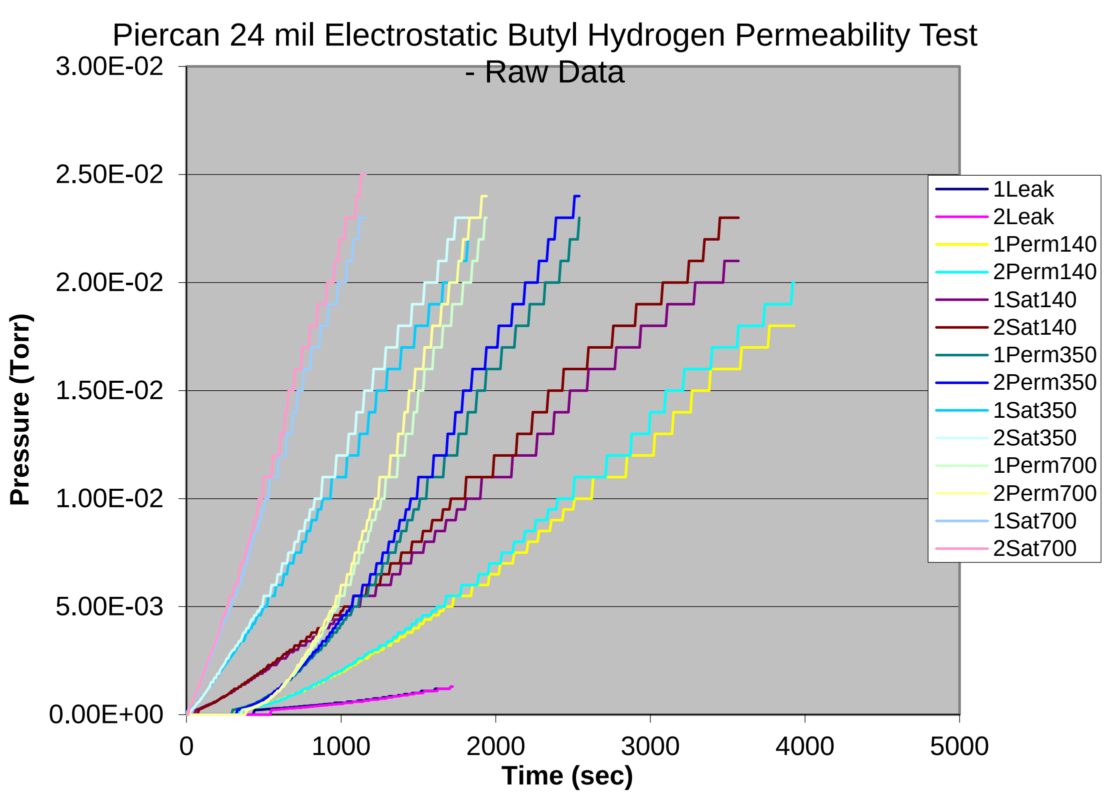

North 30 mil Butyl 2nd Hydrogen Permeability Test - Raw Data
Pressure (Torr)
Time (sec)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
5000
10000
15000
Leak1
Leak2
Bar Leak
MS1 P140
MS2 P140
Bar P140
MS1 S140
MS2 S140
Bar S140
MS P350
MS2 P350
Bar P350
MS S350
MS2 S350
Bar S350
MS1 S2 350
MS2 S2 350
Bar S2 350
MS1 P700
MS2 P700
Bar P700
MS1 S700
MS2 S700
Bar S700

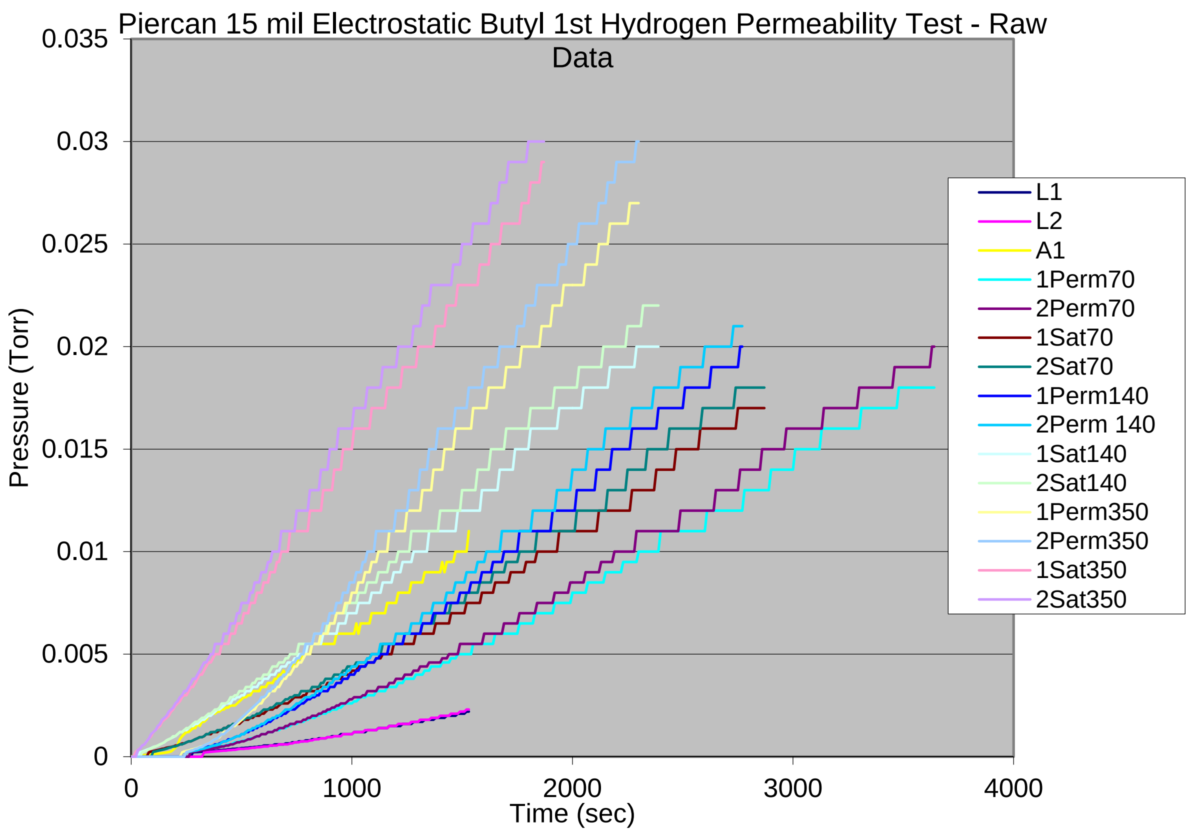

Guardian 30 mil Butyl Hydrogen Peremability Test - Raw Data
Pressure (Torr)
Time (sec)
3.50E-02
3.00E-02
2.50E-02
2.00E-02
1.50E-02
1.00E-02
5.00E-03
0.00E+00
0
1000
2000
3000
4000
5000
6000
7000
1Leak
2Leak
1Perm 140T
2Perm140T
1Sat 140T
2Sat140
1Perm350
2Perm350
1Sat350
2Sat350
1Perm700
2Perm700
1Sat700
2Sat700

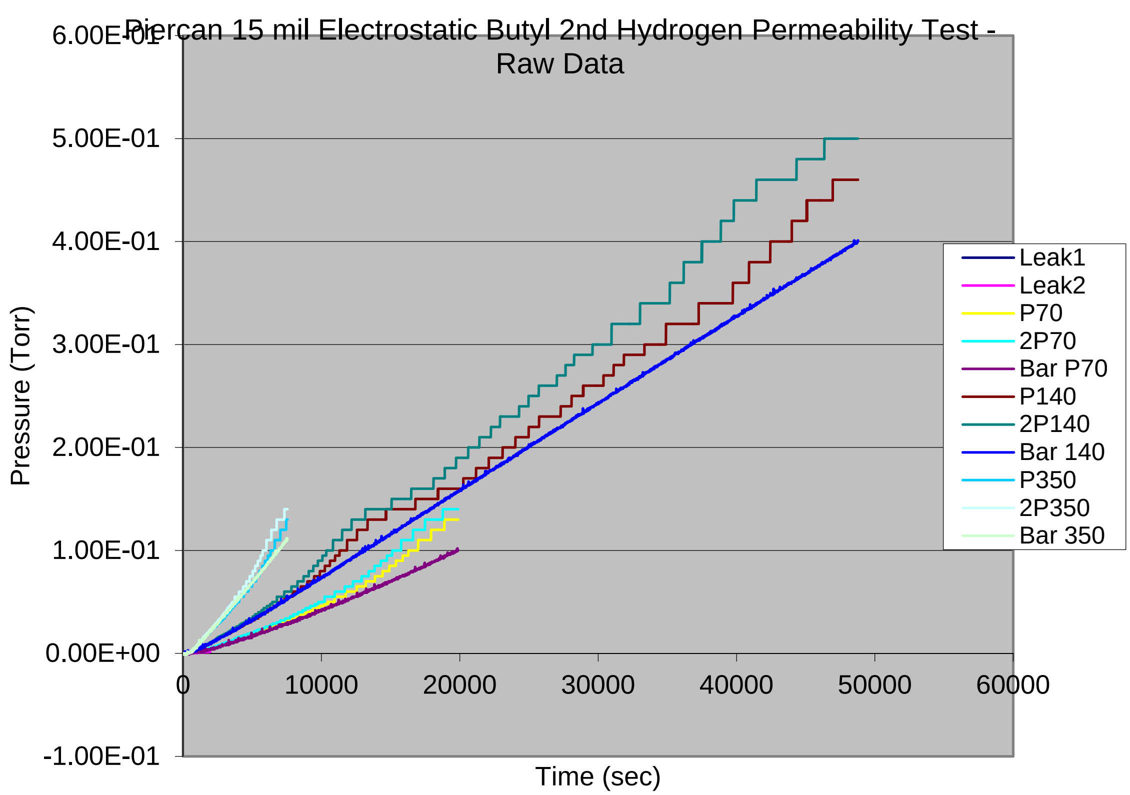

Guardian 15 mil Butyl Hydrogen Permeability - Raw Data
3.50E-02
3.00E-02
2.50E-02
2.00E-02
1.50E-02
1.00E-02
5.00E-03
0.00E+00
Pressure (Torr)
0
1000
2000
3000
4000
5000
Time (sec)
1Leak
2Leak
1Perm70
2Perm70
1Sat70
2Sat70
1Perm140
2Perm140
1Sat140

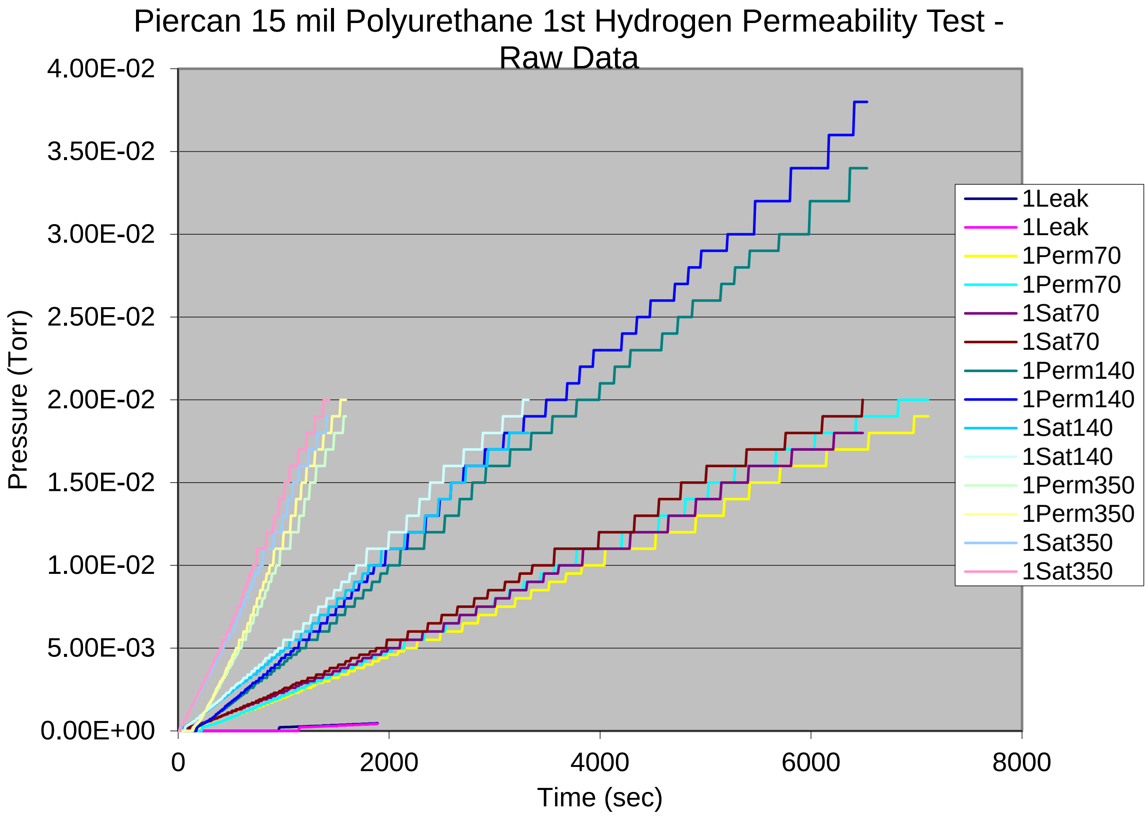

Piercan 30 mil Butyl H2 Permeability Test - Raw Data
7.00E-02
6.00E-02
5.00E-02
4.00E-02
3.00E-02
2.00E-02
1.00E-02
0.00E+00
Pressure (Torr)
0
5000
10000
15000
20000
Time (sec)
1Leak
2Leak
1Perm140
2Perm140
1Sat140
2Sat140
1Perm350
2Perm350
1Sat350
2Sat350
1Perm700
2Perm700
1Sat700
2Sat700

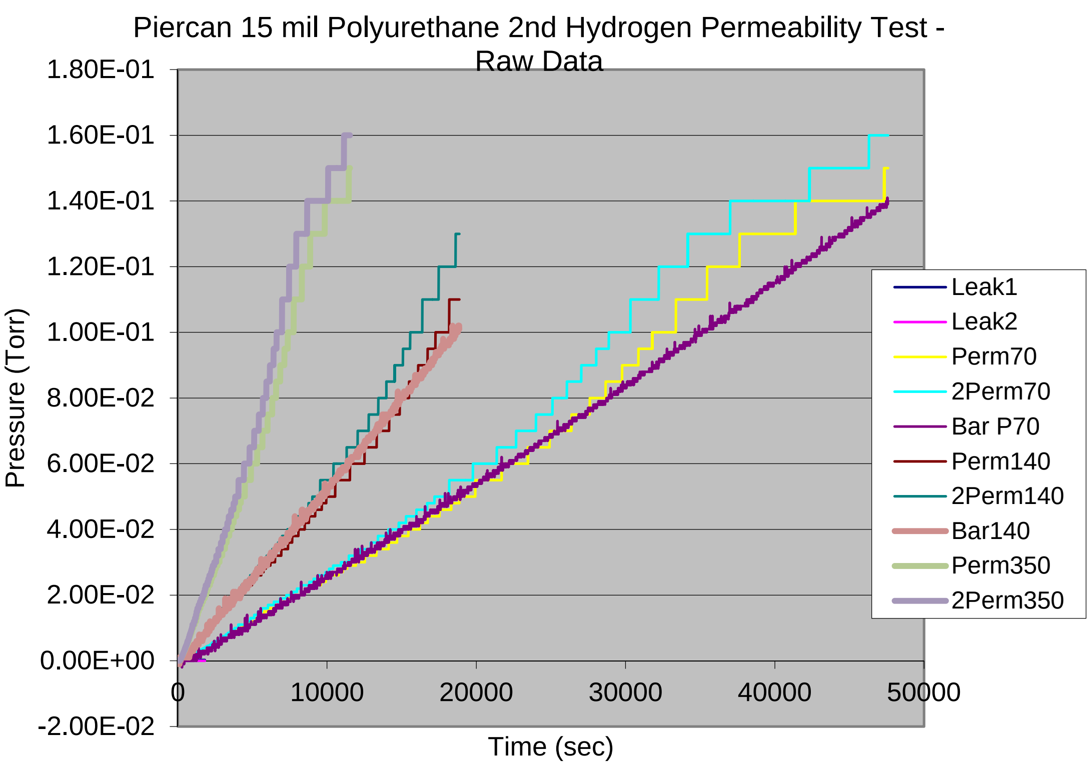

Piercan 15 mil Butyl Hydrogen Permeability Test - Raw Data
Pressure (Torr)
0.03
0.025
0.02
0.015
0.01
0.005
0
0
1000
2000
3000
4000
5000
6000
Time (sec)
Leak1
Leak2
1Perm70
2Perm70
1Sat70
2Sat70
1Perm140
2Perm140
1Sat140
2Sat140
1Perm350
2Perm350
1Sat350
2Sat350

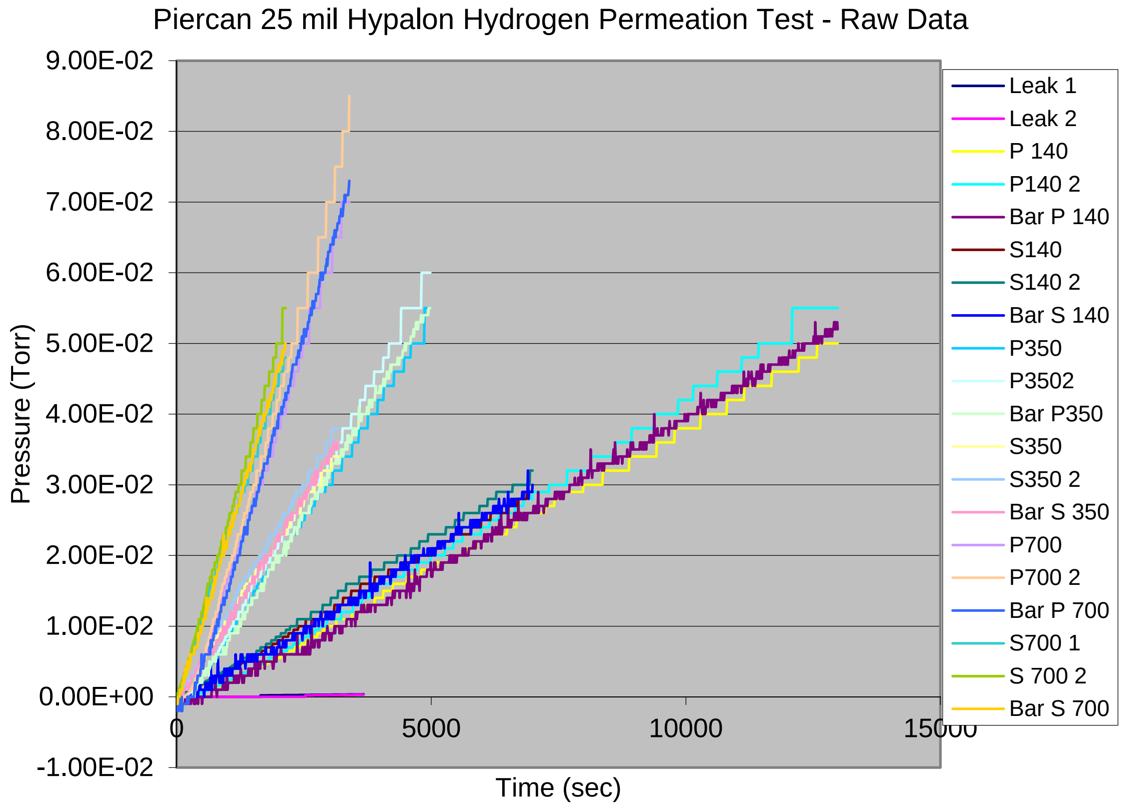

Piercan 24 mil Electrostatic Butyl Hydrogen Permeability Test - Raw Data
Pressure (Torr)
3.00E-02
2.50E-02
2.00E-02
1.50E-02
1.00E-02
5.00E-03
0.00E+00
0
1000
2000
3000
4000
5000
Time (sec)
1Leak
2Leak
1Perm140
2Perm140
1Sat140
2Sat140
1Perm350
2Perm350
1Sat350
2Sat350
1Perm700
2Perm700
1Sat700
2Sat700

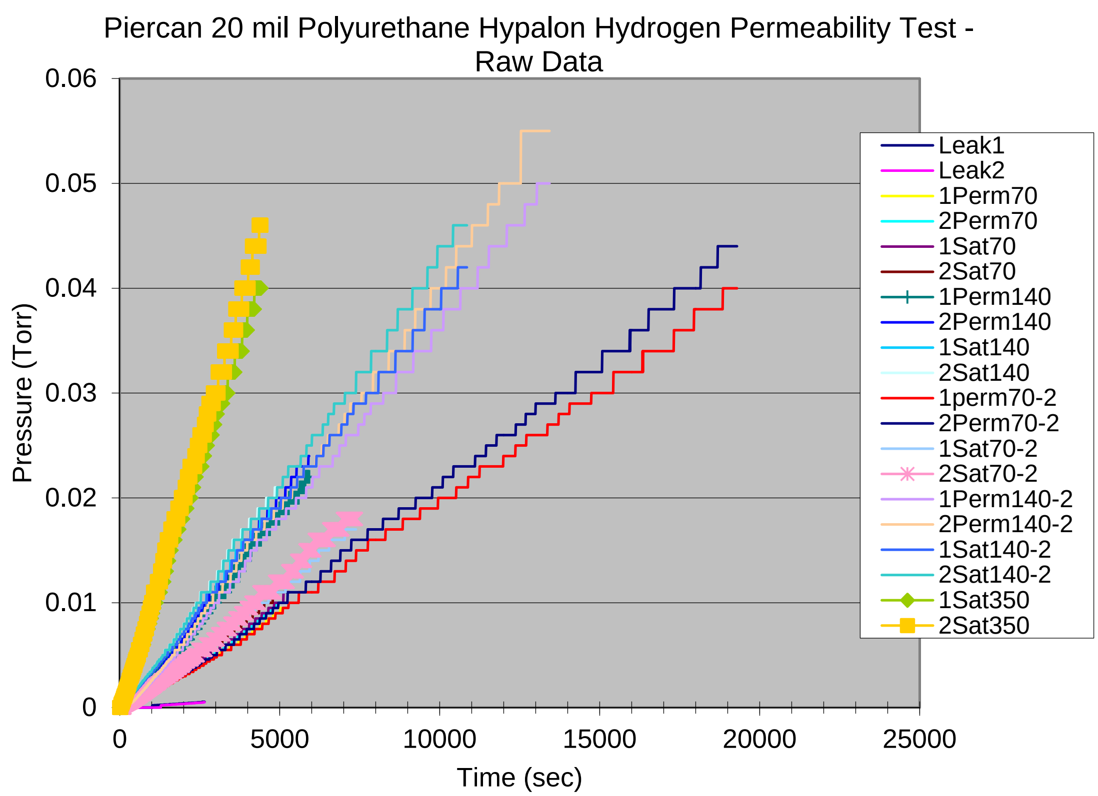

Piercan 15 mil Electrostatic Butyl 1st Hydrogen Permeability Test - Raw Data
Pressure (Torr)
Time (sec)
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
1000
2000
3000
4000
L1
L2
A1
1Perm70
2Perm70
1Sat70
2Sat70
1Perm140
2Perm 140
1Sat140
2Sat140
1Perm350
2Perm350
1Sat350
2Sat350

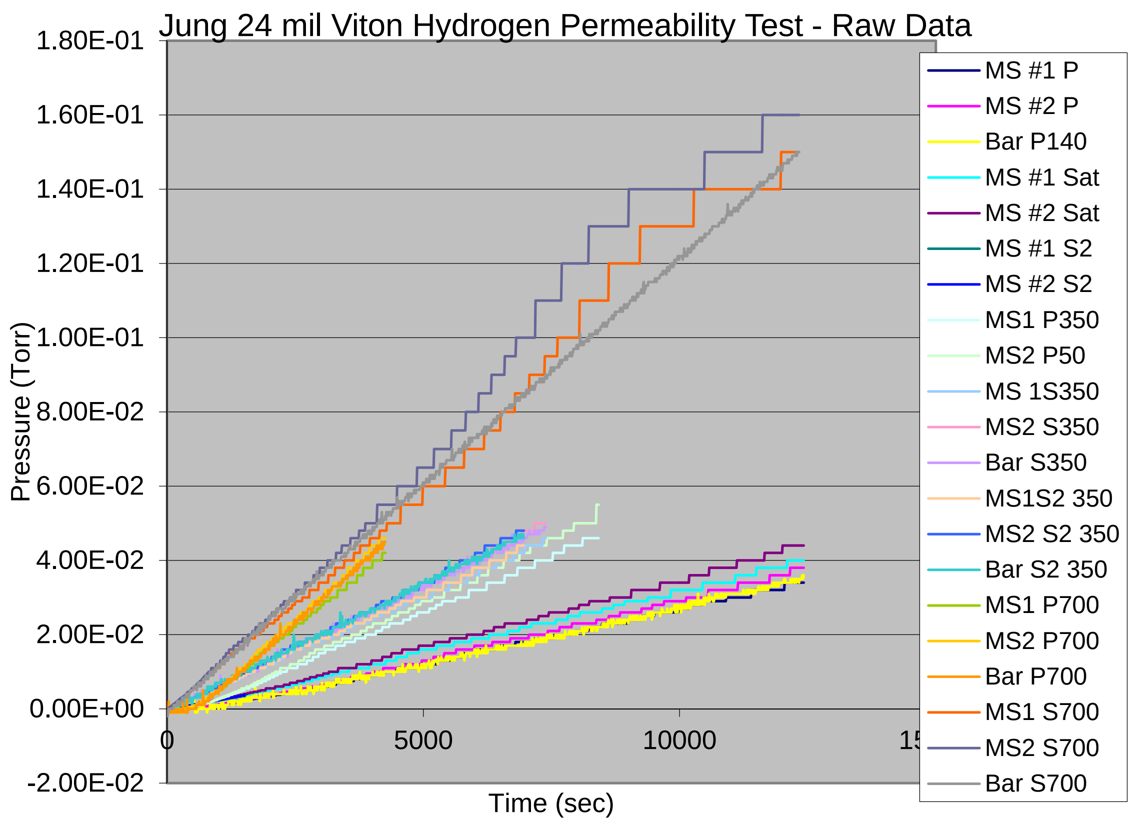

Piercan 15 mil Electrostatic Butyl 2nd Hydrogen Permeability Test - Raw Data
Pressure (Torr)
Time (sec)
6.00E-01
5.00E-01
4.00E-01
3.00E-01
2.00E-01
1.00E-01
0.00E+00
-1.00E-01
0
10000
20000
30000
40000
50000
60000
Leak1
Leak2
P70
2P70
Bar P70
P140
2P140
Bar 140
P350
2P350
Bar 350

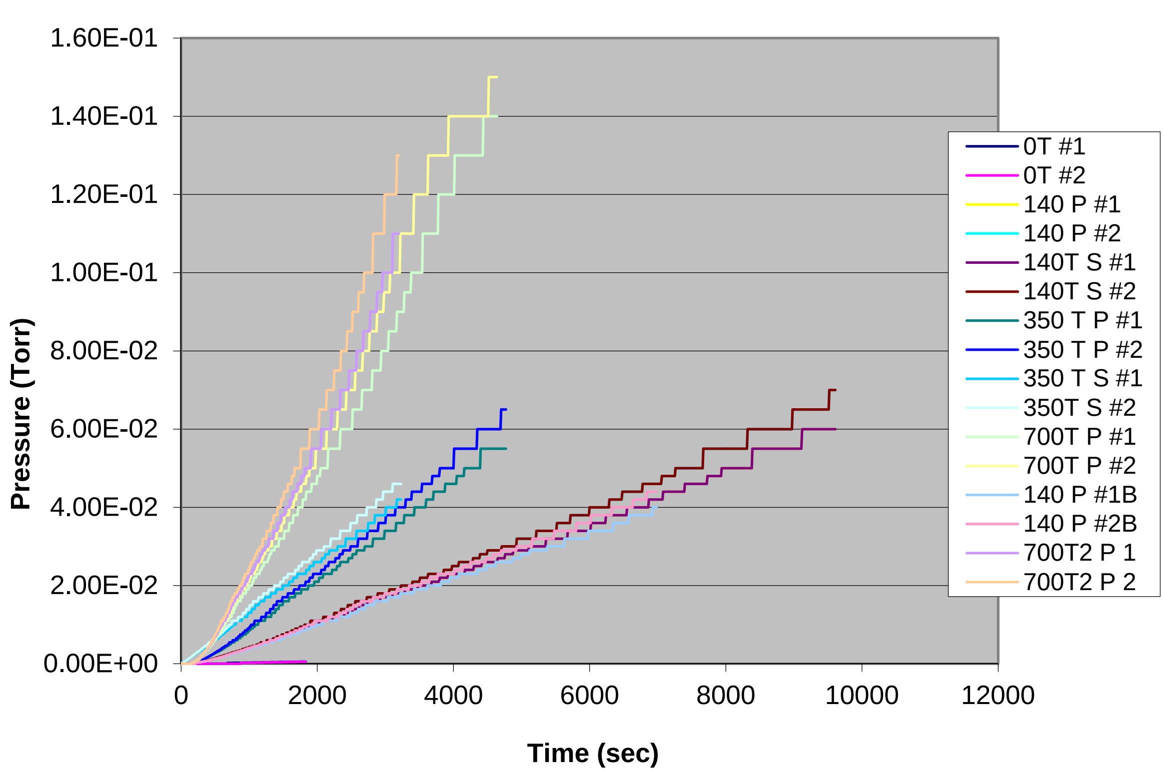

Piercan 15 mil Polyurethane 1st Hydrogen Permeability Test - Raw Data
Pressure (Torr)
Time (sec)
4.00E-02
3.50E-02
3.00E-02
2.50E-02
2.00E-02
1.50E-02
1.00E-02
5.00E-03
0.00E+00
0
2000
4000
6000
8000
1Leak
1Leak
1Perm70
1Perm70
1Sat70
1Sat70
1Perm140
1Perm140
1Sat140
1Sat140
1Perm350
1Perm350
1Sat350
1Sat350

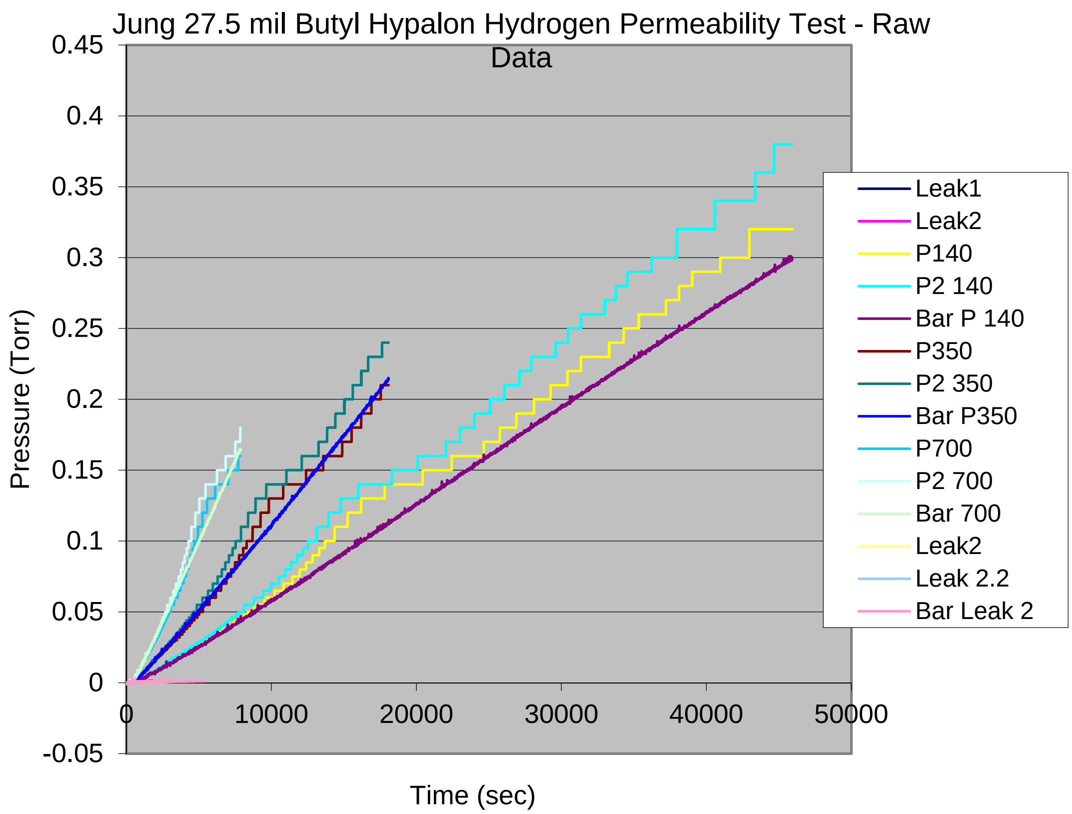

Piercan 15 mil Polyurethane 2nd Hydrogen Permeability Test - Raw Data
Pressure (Torr)
Time (sec)
1.80E-01
1.60E-01
1.40E-01
1.20E-01
1.00E-01
8.00E-02
6.00E-02
4.00E-02
2.00E-02
0.00E+00
-2.00E-02
0
10000
20000
30000
40000
50000
Leak1
Leak2
Perm70
2Perm70
Bar P70
Perm140
2Perm140
Bar140
Perm350
2Perm350

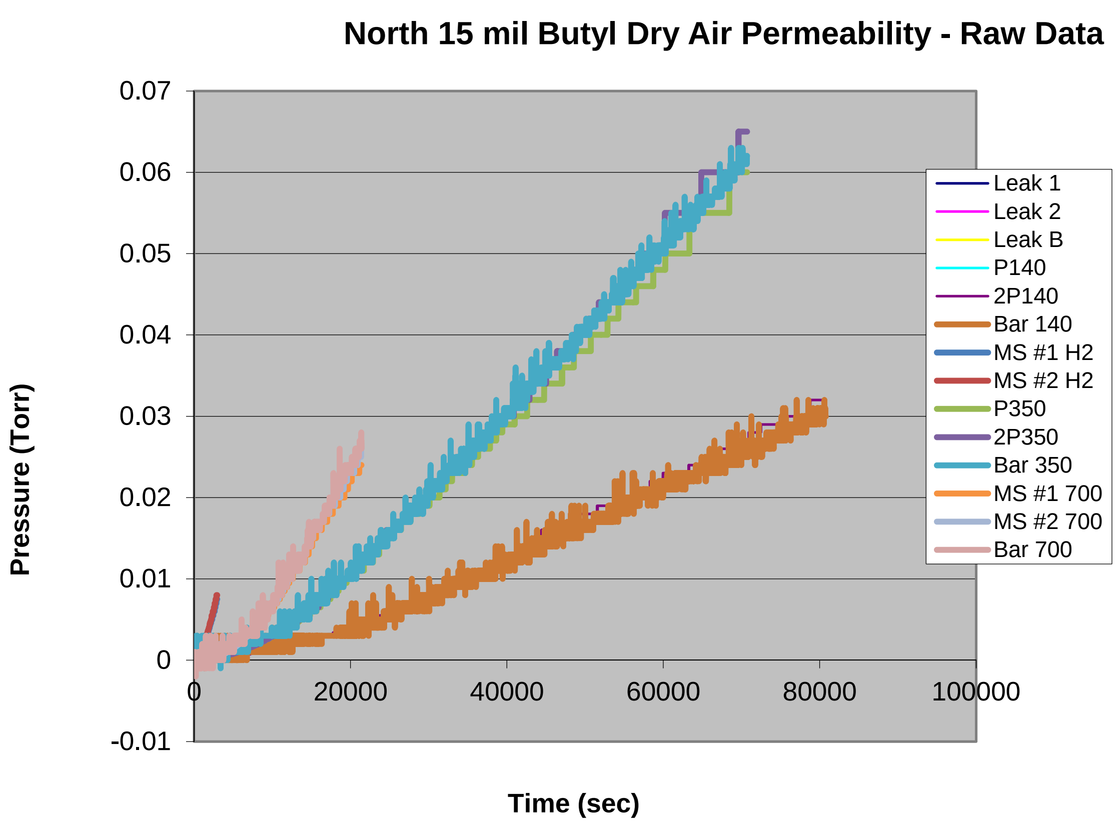

Piercan 25 mil Hypalon Hydrogen Permeation Test - Raw Data
Pressure (Torr)
Time (sec)
9.00E-02
8.00E-02
7.00E-02
6.00E-02
5.00E-02
4.00E-02
3.00E-02
2.00E-02
1.00E-02
0.00E+00
-1.00E-02
0
5000
10000
15000
Leak 1
Leak 2
P 140
P140 2
Bar P 140
S140
S140 2
Bar S 140
P350
P3502
Bar P350
S350
S350 2
Bar S 350
P700
P700 2
Bar P 700
S700 1
S 700 2
Bar S 700

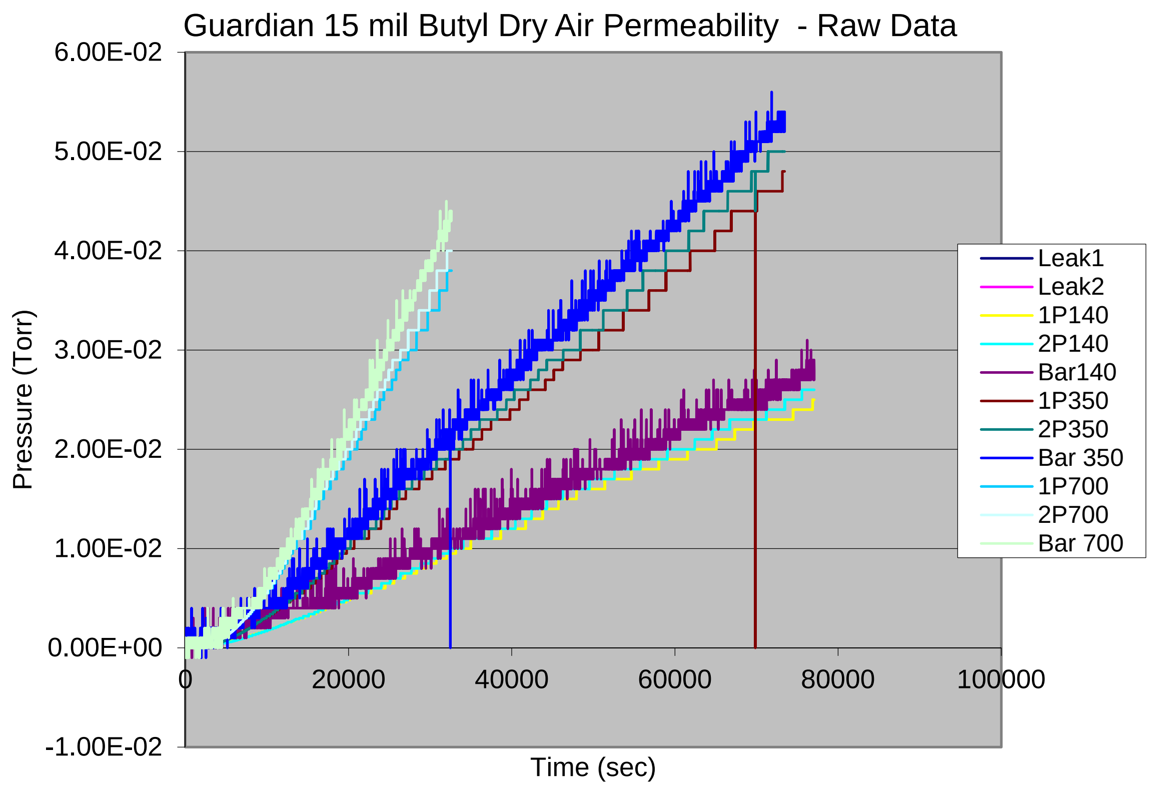

Piercan 20 mil Polyurethane Hypalon Hydrogen Permeability Test - Raw Data
Pressure (Torr)
Time (sec)
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5000
10000
15000
20000
25000
Leak1
Leak2
1Perm70
2Perm70
1Sat70
2Sat70
1Perm140
2Perm140
1Sat140
2Sat140
1perm70-2
2Perm70-2
1Sat70-2
2Sat70-2
1Perm140-2
2Perm140-2
1Sat140-2
2Sat140-2
1Sat350
2Sat350

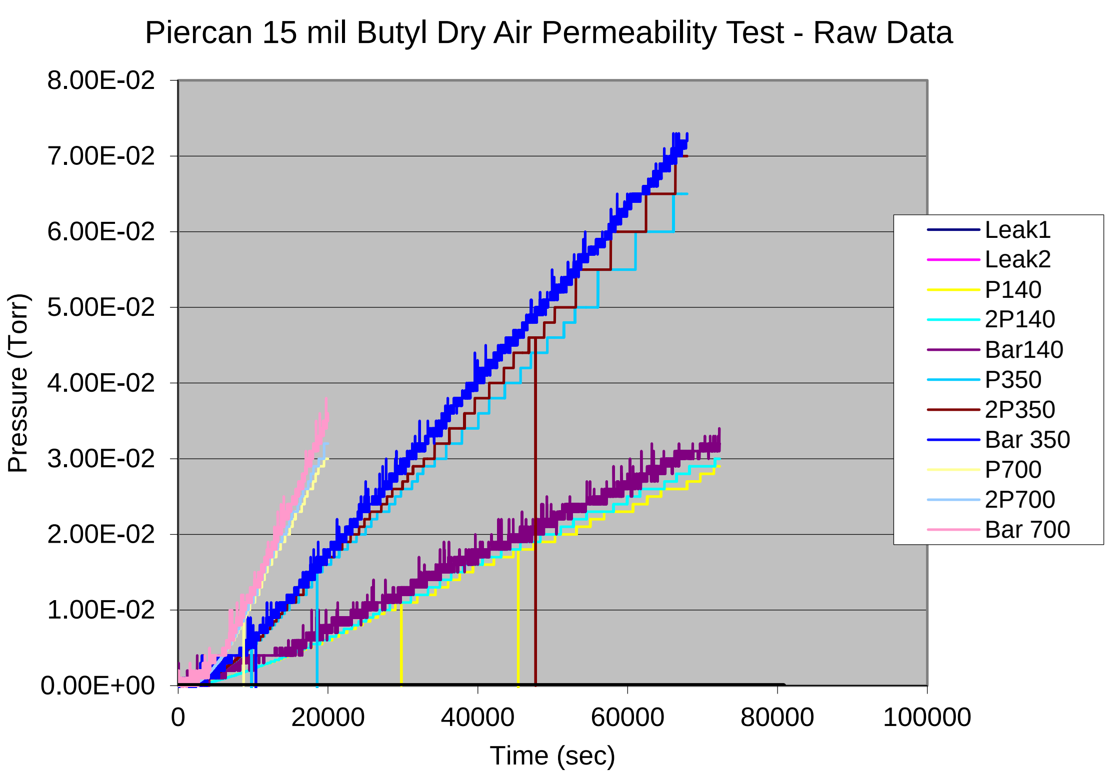

Jung 24 mil Viton Hydrogen Permeability Test - Raw Data
Pressure (Torr)
Time (sec)
1.80E-01
1.60E-01
1.40E-01
1.20E-01
1.00E-01
8.00E-02
6.00E-02
4.00E-02
2.00E-02
0.00E+00
-2.00E-02
0
5000
10000
MS #1 P
MS #2 P
Bar P140
MS #1 Sat
MS #2 Sat
MS #1 S2
MS #2 S2
MS1 P350
MS2 P50
MS 1S350
MS2 S350
Bar S350
MS1S2 350
MS2 S2 350
Bar S2 350
MS1 P700
MS2 P700
Bar P700
MS1 S700
MS2 S700
Bar S700

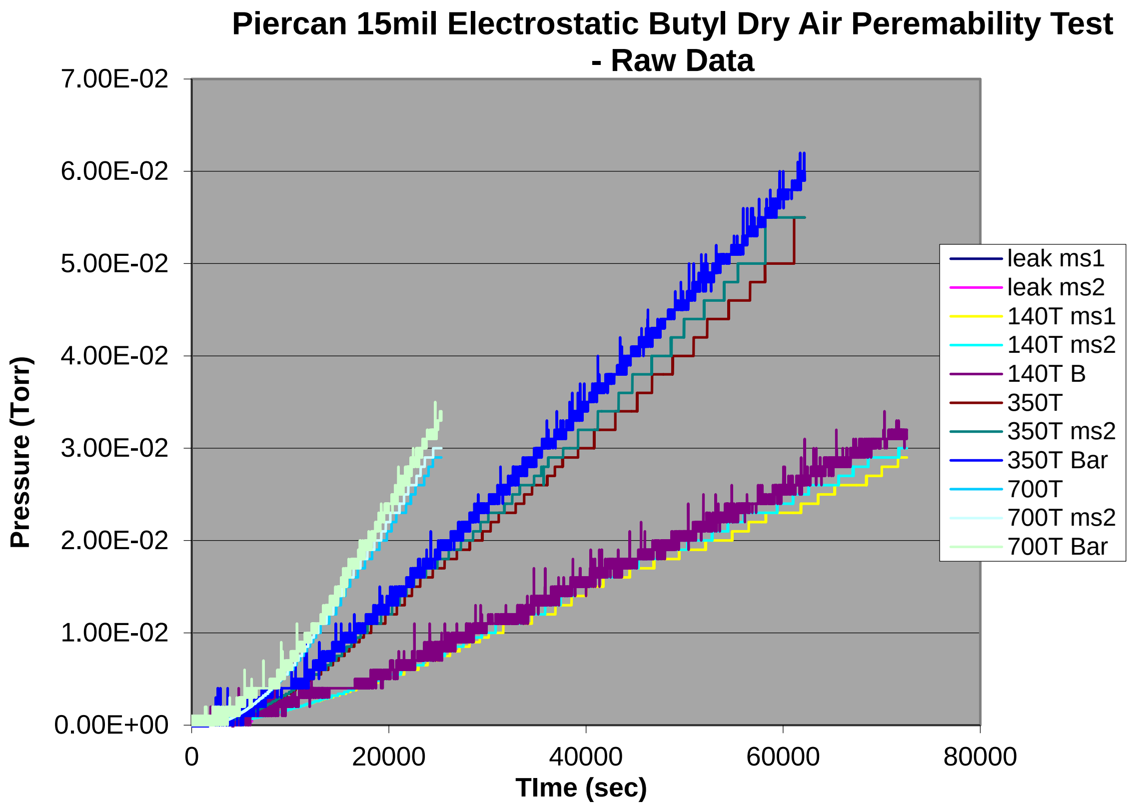

Jung 20 mil Butyl Viton Hydrogen Permeability Test - Raw Data
Pressure (Torr)
Time (sec)
1.60E-01
1.40E-01
1.20E-01
1.00E-01
8.00E-02
6.00E-02
4.00E-02
2.00E-02
0.00E+00
0
2000
4000
6000
8000
10000
12000
0T #1
0T #2
140 P #1
140 P #2
140T S #1
140T S #2
350 T P #1
350 T P #2
350 T S #1
350T S #2
700T P #1
700T P #2
140 P #1B
140 P #2B
700T2 P 1
700T2 P 2

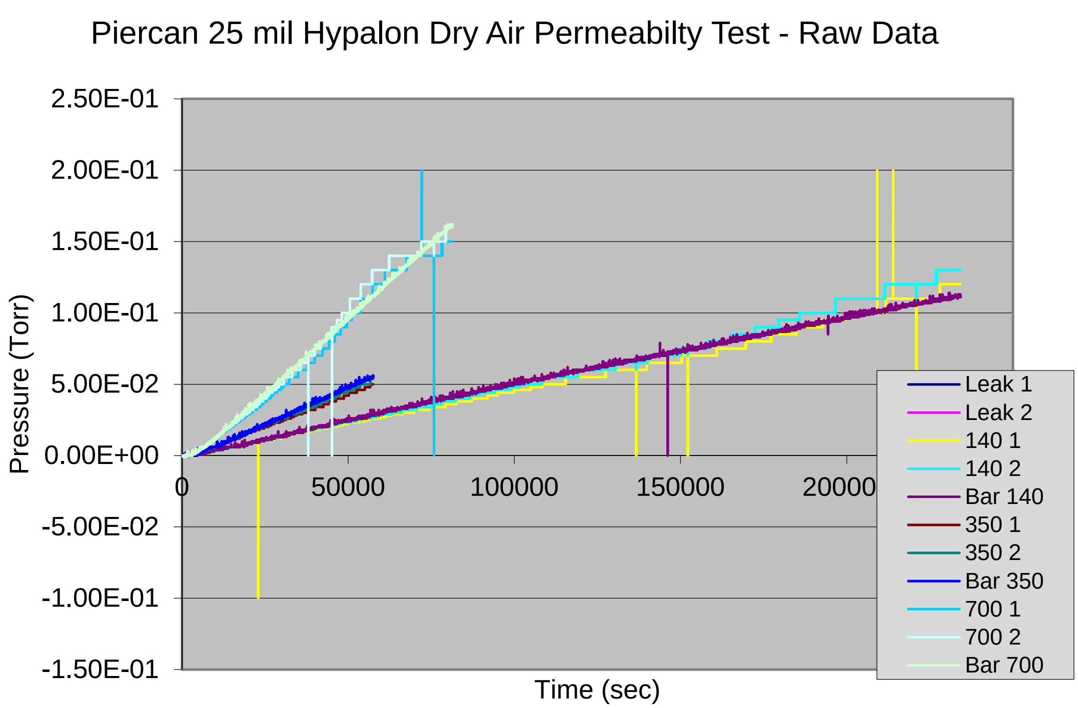

Jung 27.5 mil Butyl Hypalon Hydrogen Permeability Test - Raw Data
Pressure (Torr)
Time (sec)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
10000
20000
30000
40000
50000
Leak1
Leak2
P140
P2 140
Bar P 140
P350
P2 350
Bar P350
P700
P2 700
Bar 700
Leak2
Leak 2.2
Bar Leak 2

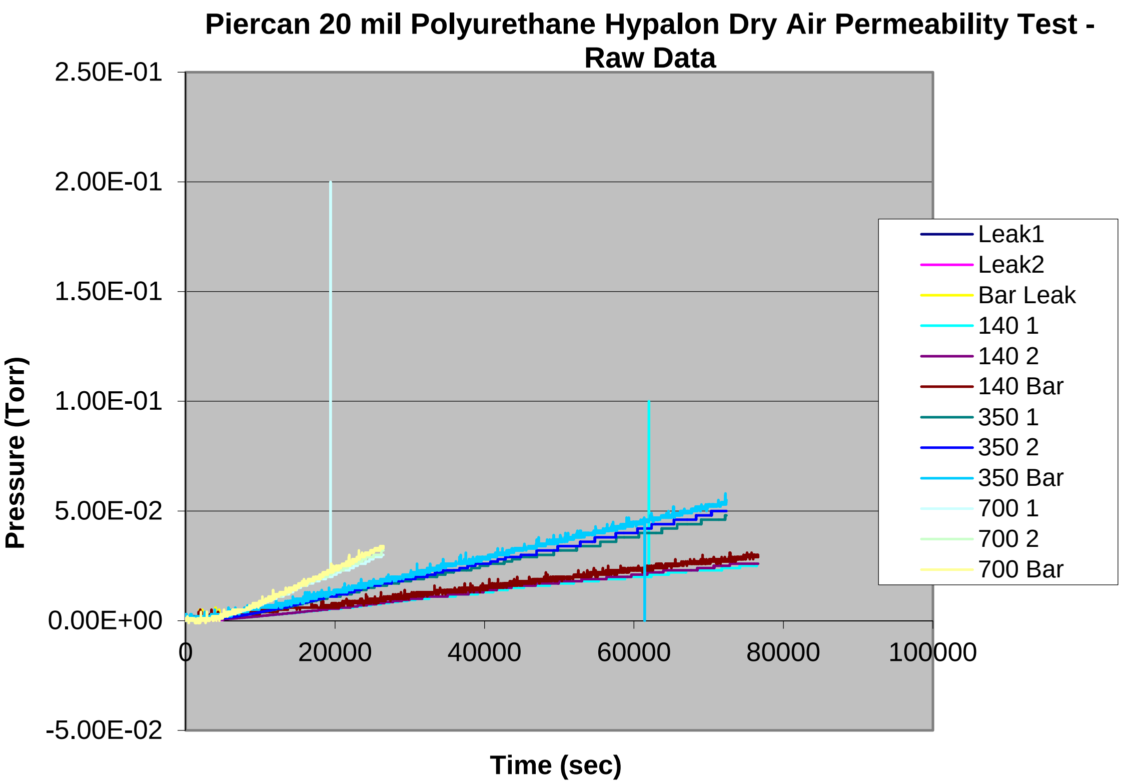

North 15 mil Butyl Dry Air Permeability - Raw Data
Pressure (Torr)
Time (sec)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
20000
40000
60000
80000
100000
Leak 1
Leak 2
Leak B
P140
2P140
Bar 140
MS #1 H2
MS #2 H2
P350
2P350
Bar 350
MS #1 700
MS #2 700
Bar 700

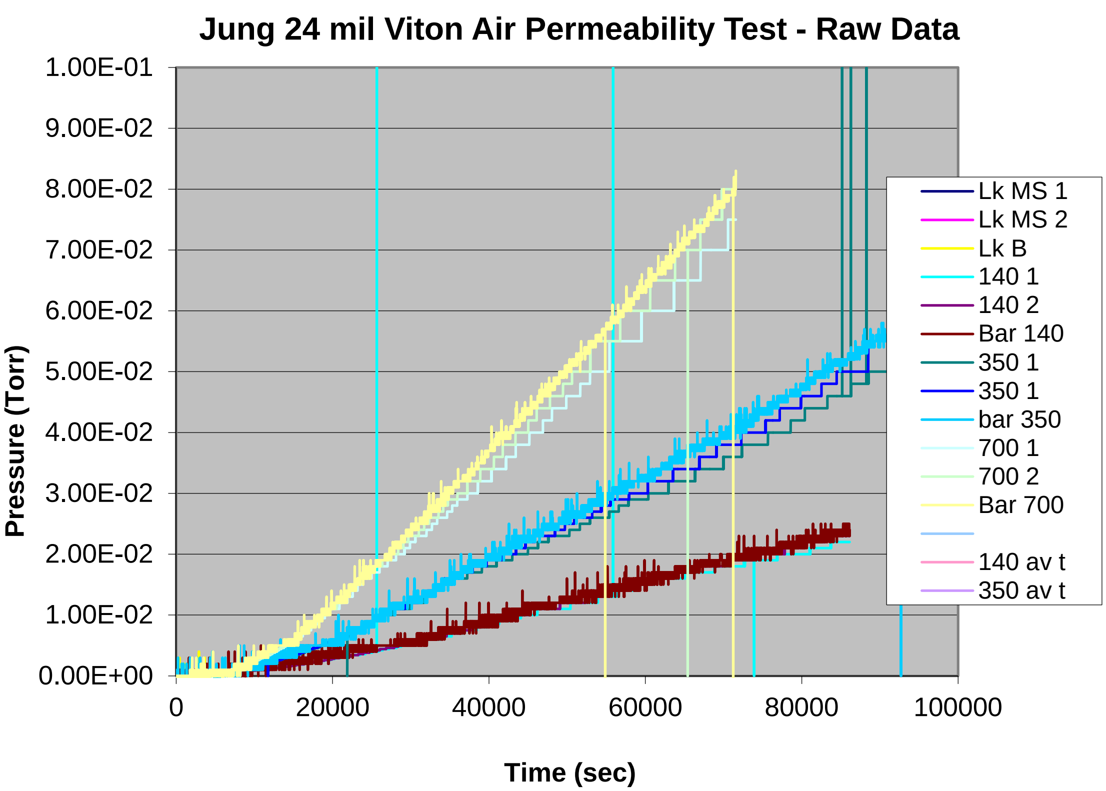

Guardian 15 mil Butyl Dry Air Permeability - Raw Data
Pressure (Torr)
6.00E-02
5.00E-02
4.00E-02
3.00E-02
2.00E-02
1.00E-02
0.00E+00
-1.00E-02
0
20000
40000
60000
80000
100000
Time (sec)
Leak1
Leak2
1P140
2P140
Bar140
1P350
2P350
Bar 350
1P700
2P700
Bar 700

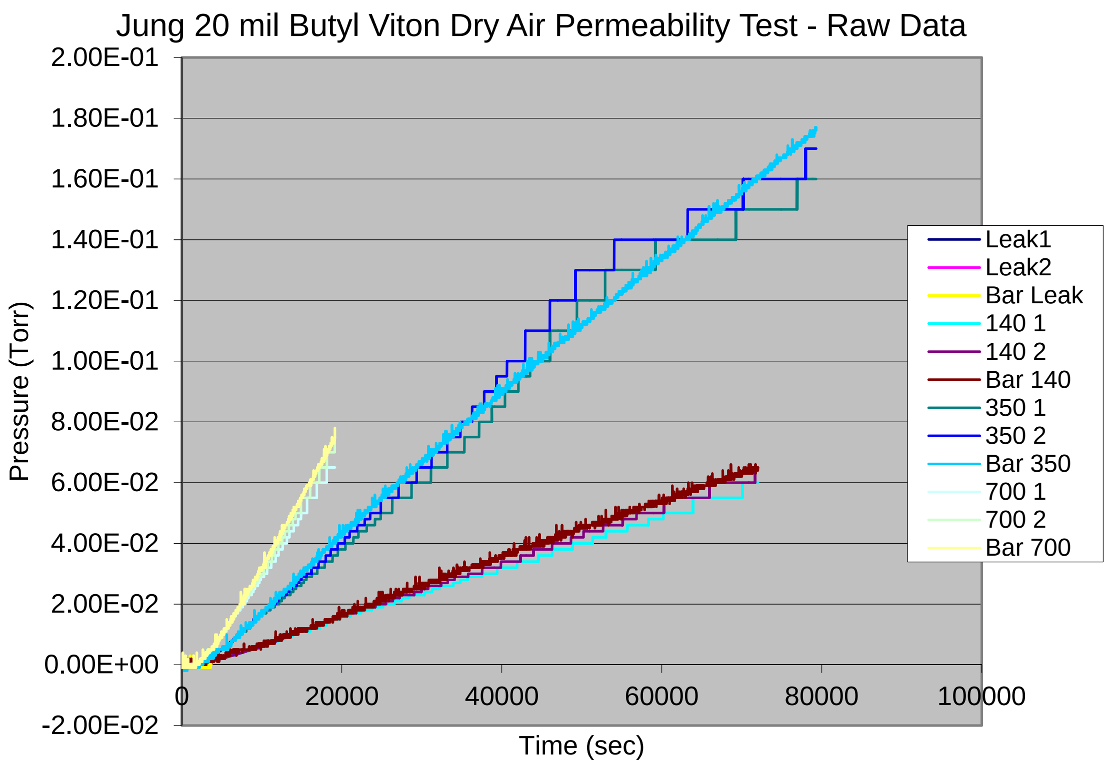

Piercan 15 mil Butyl Dry Air Permeability Test - Raw Data
Pressure (Torr)
8.00E-02
7.00E-02
6.00E-02
5.00E-02
4.00E-02
3.00E-02
2.00E-02
1.00E-02
0.00E+00
0
20000
40000
60000
80000
100000
Time (sec)
Leak1
Leak2
P140
2P140
Bar140
P350
2P350
Bar 350
P700
2P700
Bar 700

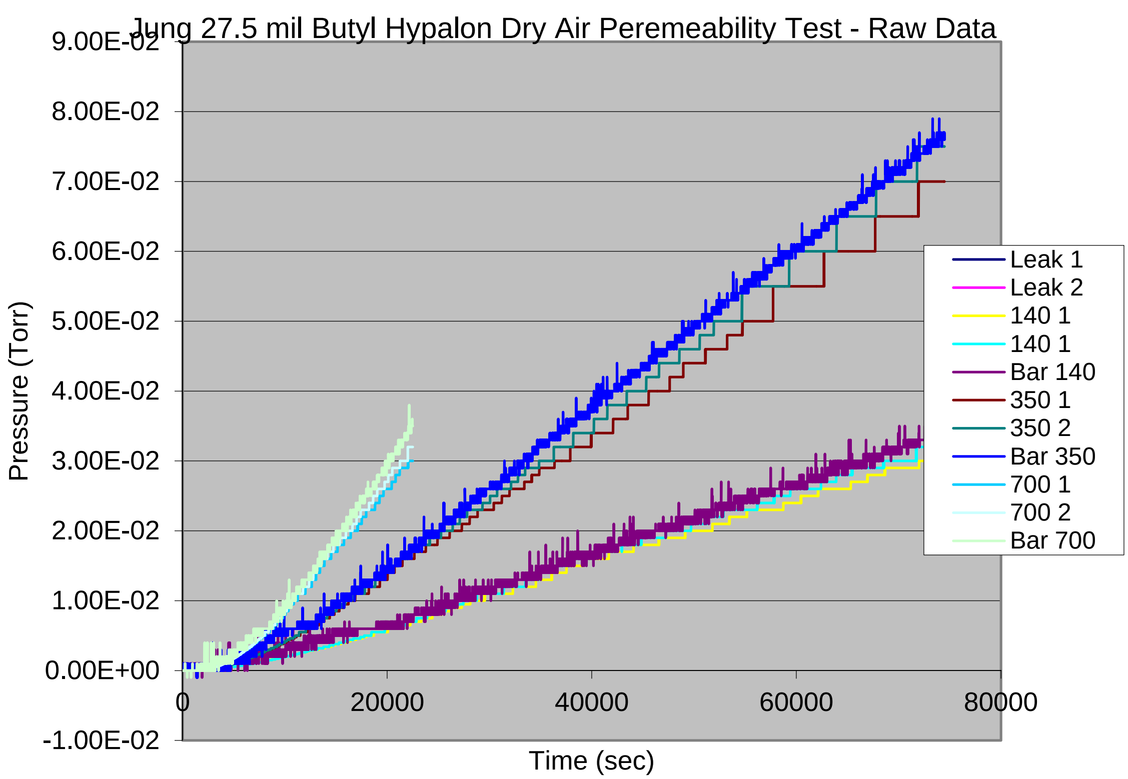

Piercan 15mil Electrostatic Butyl Dry Air Peremability Test - Raw Data
Pressure (Torr)
7.00E-02
6.00E-02
5.00E-02
4.00E-02
3.00E-02
2.00E-02
1.00E-02
0.00E+00
0
20000
40000
60000
80000
TIme (sec)
leak ms1
leak ms2
140T ms1
140T ms2
140T B
350T
350T ms2
350T Bar
700T
700T ms2
700T Bar


Piercan 25 mil Hypalon Dry Air Permeabilty Test - Raw Data
Pressure (Torr)
2.50E-01
2.00E-01
1.50E-01
1.00E-01
5.00E-02
0.00E+00
-5.00E-02
-1.00E-01
-1.50E-01
0
50000
100000
150000
20000
Time (sec)
Leak 1
Leak 2
140 1
140 2
Bar 140
350 1
350 2
Bar 350
700 1
700 2
Bar 700


Piercan 20 mil Polyurethane Hypalon Dry Air Permeability Test - Raw Data
Pressure (Torr)
Time (sec)
2.50E-01
2.00E-01
1.50E-01
1.00E-01
5.00E-02
0.00E+00
-5.00E-02
0
20000
40000
60000
80000
100000
Leak1
Leak2
Bar Leak
140 1
140 2
140 Bar
350 1
350 2
350 Bar
700 1
700 2
700 Bar


Jung 24 mil Viton Air Permeability Test - Raw Data
Pressure (Torr)
Time (sec)
1.00E-01
9.00E-02
8.00E-02
7.00E-02
6.00E-02
5.00E-02
4.00E-02
3.00E-02
2.00E-02
1.00E-02
0.00E+00
0
20000
40000
60000
80000
100000
Lk MS 1
Lk MS 2
Lk B
140 1
140 2
Bar 140
350 1
350 1
bar 350
700 1
700 2
Bar 700
140 av t
350 av t


Jung 20 mil Butyl Viton Dry Air Permeability Test - Raw Data
2.00E-01
1.80E-01
1.60E-01
1.40E-01
1.20E-01
1.00E-01
8.00E-02
6.00E-02
4.00E-02
2.00E-02
0.00E+00
-2.00E-02
Pressure (Torr)
0
20000
40000
60000
80000
100000
Time (sec)
Leak1
Leak2
Bar Leak
140 1
140 2
Bar 140
350 1
350 2
Bar 350
700 1
700 2
Bar 700


Jung 27.5 mil Butyl Hypalon Dry Air Peremeability Test - Raw Data
9.00E-02
8.00E-02
7.00E-02
6.00E-02
5.00E-02
4.00E-02
3.00E-02
2.00E-02
1.00E-02
0.00E+00
-1.00E-02
Pressure (Torr)
0
20000
40000
60000
80000
Time (sec)
Leak 1
Leak 2
140 1
140 1
Bar 140
350 1
350 2
Bar 350
700 1
700 2
Bar 700