RECEIVED
AUG 12 1999
OSTI

*Determination of H_2 Diffusion Rates
through Various Closures on
TRU Waste Bag-Out Bags*

Los Alamos
NATIONAL LABORATORY

*Los Alamos National Laboratory is operated by the University of California
for the United States Department of Energy under contract W-7405-ENG-36.*

An Affirmative Action/Equal Opportunity Employer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither The Regents of the University of California, the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by The Regents of the University of California, the United States Government, or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of The Regents of the University of California, the United States Government, or any agency thereof. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

*Determination of H_2 Diffusion Rates
through Various Closures on
TRU Waste Bag-Out Bags*

*Phillip D. Noll, Jr.
E. Larry Callis
Kirsten M. Norman*

DETERMINATION OF H₂ DIFFUSION RATES THROUGH VARIOUS CLOSURES ON TRU WASTE BAG-OUT BAGS

by

Phillip D. Noll, Jr., E. Larry Callis, and Kirsten M. Norman

ABSTRACT

The amount of H₂ diffusion through twist and tape (horse-tail), wire tie, plastic tie, and heat sealed closures on transuranic (TRU) waste bag-out bags has been determined. H₂ diffusion through wire and plastic tie closures on TRU waste bag-out bags has not been previously characterized and, as such, TRU waste drums containing bags with these closures cannot be certified and/or shipped to the Waste Isolation Pilot Plant (WIPP). Since wire ties have been used at Los Alamos National Laboratory (LANL) from 1980 to 1991 and the plastic ties from 1991 to the present, there are currently thousands of waste drums that cannot be shipped to the WIPP site. Repackaging the waste would be prohibitively expensive. Diffusion experiments performed on the above mentioned closures show that the diffusion rates of plastic tie and horse-tail closures are greater than the accepted value presented in the TRU-PACT II Safety Analysis Report (SAR). Diffusion rates for wire tie closures are not statistically different from the SAR value. Thus, drums containing bags with these closures can now potentially be certified which would allow for their consequent shipment to WIPP.

Introduction

Hydrogen gas is generated in TRU waste by the interaction of alpha particles with hydrogenous waste materials. The build-up of hydrogen gas in waste containers is a significant concern for the Department of Energy (DOE) and LANL waste programs. An acceptable rate of diffusion of hydrogen gas through twist and tape closures (commonly called "horse-tails") is specified in the TRUPACT-II SAR (NuPac, 1992) as 5.58×10^{-7} moles/sec./mole fraction. Thus, the horse-tail method of closure is the only characterized and approved closure method for 14 mil polyvinyl chloride (PVC) TRU waste bag-out bags. However, during the 1980s and 1990s many bag-out bags were sealed using either a wire or plastic tie placed around a twisted and taped portion of the bag. Since the addition of a wire or plastic tie could potentially reduce the amount of hydrogen gas diffusion through the closure (compared to the horse-tail closure alone), there is concern regarding the possibility of the build up of hydrogen gas in these waste drums. Further, since these types of closures have not been previously characterized, drums containing bag-out bags with these closures cannot be shipped to WIPP.

In order to address this problem, bag-out bags with these closures were subjected to H₂ diffusion experiments. In these experiments the H₂ diffusion coefficient of various closures was determined via gas mass spectrometry. Heat sealed bags were also evaluated to determine the amount of H₂ gas diffusion through the walls of the bag per unit area. This value was used as a baseline and subtracted from the values obtained for wire tie, plastic tie, and horse-tail bags to provide the diffusion through the closure only. The results of these experiments reveal that, while there are significant differences in the rates of H₂ diffusion through the different closures (wire ties have the most restricted H₂ diffusion followed by plastic ties, and finally horse tails), the rate of H₂ diffusion is faster than, or similar to, that specified in the SAR (NuPac, 1992). Thus, it appears that the use of plastic or wire ties does not significantly restrict the flow of H₂ gas out of the bag-out bags.

Methodology

Experimental:

Hydrogen diffusion rates through various bag-out bag closures were determined by mass spectrometric measurements of the loss rate of hydrogen through the closure at ambient pressure and temperature. The open ends of the 14 mil PVC bags were mounted on 15" (38.8 cm) diameter flanges machined from aluminum stock (Fig. 1). Air-tight seals were achieved by clamping the bags between the aluminum flange and a 1" (2.5 cm) wide, 1/8" (3 mm) thick rubber gasket using worm-drive clamps. The aluminum flanges have both inlet and outlet valves (Fig. 1) to facilitate flushing of gases (Ar/H₂ mix, He) into, and out of, the mounted bags.

Figure 1. Front and back of the 15" (38.8 cm.) diameter aluminum flange.

Once a bag is mounted, a commercially available 6% H₂–94% Ar gas mixture was flushed into the bag so as to achieve a hydrogen concentration of 4–6% within the mounted bag. The absolute concentration of H₂ in the bag is not critical as only the rate of change in concentration is needed for these experiments. The outlet valve was left open for several minutes to ensure equilibration between the pressure outside the bag and the pressure inside the bag. The bag was then left undisturbed for about an hour prior to sampling to further ensure pressure equilibration.

The H₂ diffusion rate through the BAG + CLOSURE was then determined by taking a small sample from the bag three times a day for 3–7 days. Sampling was performed by attaching the outlet valve of the flange directly to the inlet system of the mass spectrometer with a short length of flexible steel tubing. The sample volume was kept low (about 7 cc) to avoid disturbing the system ambient pressure significantly. The sample was analyzed by gas mass spectrometry to determine the amount of H₂ gas (vol %) remaining within the bag at each sampling interval. The rate of change of the H₂ concentration provides the diffusion coefficient (see below). All measurement data, including ambient temperature, pressure, date, time, % H₂, etc., were recorded on "travelers" (see Appendices A and B).

Five bags of each closure type (horse-tail, heat sealed, wire tie, plastic tie) were prepared by technicians who normally perform this task. The bags were mounted on the stands (a total of five stands were used; see Fig. 2) and the diffusion coefficients for the BAG + CLOSURE were determined in random order. Care was taken to ensure that bags of the same closure type were mounted on different aluminum stands to account for any variances in the diffusion coefficient due to possible differences in the aluminum stands themselves. In addition, diffusion coefficients for several BAGS + CLOSURE were determined in replicate to obtain a sense of the reproducibility of the measurements (see section on "Repeat Analyses"). In these cases, the same bag was mounted to two or three different aluminum stands and the diffusion coefficient determined each time.

Figure 2. Five bag-out bags with various closure types mounted for analysis.

The mass spectrometer used was a Finnigan MAT-271 magnetic sector instrument (Fig. 3) designed for high precision measurements of gas composition. This instrument is equipped with both Faraday cup and electron multiplier detectors, a heated inlet system, and a computer controlled data acquisition and control system. The mass resolution is adjustable from 250 to 3000. The data for the present set of experiments were taken at a resolution of 250.

Calibration of the mass spectrometer was carried out using individual pure gases. A commercially prepared mixed gas standard (Scott Mix) was analyzed to verify the calibration (Table 1). Any gas component of this mixed standard that fell outside of 2% of the accepted value was recalibrated using the pure gas. Additionally, samples of atmosphere, the Ar/H₂ mix, and the He gas used for bag volume determinations were also analyzed (Table 1).

Figure 3. The Finnigan Mass Spectrometer.

The final diffusion coefficient through each CLOSURE was obtained by subtracting the average diffusion coefficient for the heat sealed bags (normalized to surface area) from the diffusion coefficient of the bag of interest (also normalized to surface area). This eliminates the diffusion component through the walls of the bag thus allowing the diffusion rate of the CLOSURE to be determined.

Table 1. Representative Mass Spectrometric Analysis of a Mixed Gas Standard (Scott Mix), Atmosphere, He Gas, and H₂/Ar Gas Mixture. All values in vol %.

<i>Scott Mix 6/10/97 Aliquot</i>								
8/1/97	Run 1 2:17 PM	Run 2 2:22 PM	Run 3 2:34 PM	Accept. Value	Mean	Std. Dev.	%RSD	% Dev. from Accept Value
H ₂	4.028	4.025	4.032	4.027	4.028	0.004	0.090	0.029
He	51.695	51.691	51.731	51.637	51.706	0.022	0.042	0.133
N ₂	10.045	10.058	10.138	10.161	10.080	0.050	0.498	-0.793
CH ₄	1.004	1.005	1.005	0.998	1.005	0.001	0.068	0.693
CO	10.157	10.160	10.074	10.107	10.130	0.049	0.486	0.231
O ₂	2.606	2.607	2.616	2.573	2.610	0.005	0.197	1.426
Ar	10.222	10.215	10.191	10.186	10.209	0.016	0.160	0.229
CO ₂	10.242	10.238	10.214	10.311	10.232	0.015	0.147	-0.770
Total	100.00	100.00	100.00	100.00	100.00			
Sample Size	23.59 mT	23.36 mT	22.46 mT		23.14 mT			

<i>Atmosphere (major constituents)</i>								
8/1/97	Run 1 2:11 PM	Run 2 2:29 PM	Run 3 2:40 PM	Accept. Value*	Mean	Std. Dev.	%RSD	% Dev. from Accept Value
N ₂	77.111	77.615	77.627	78.084	77.451	0.294	0.380	-0.810
O ₂	20.665	20.810	20.811	20.946	20.762	0.084	0.405	-0.879
Ar	0.937	0.941	0.943	0.934	0.940	0.003	0.336	0.683
CO ₂	0.048	0.044	0.052	0.033	0.048	0.004	8.113	45.693
Total	98.76	99.41	99.43	100.00	99.20			
Sample Size	27.86 mT	27.85 mT	27.79 mT		27.83 mT			

<i>He Gas</i>						
8/1/97	Run 1 2:51 PM	Run 2 2:55 PM	Run 3 4:11 PM	Mean	Std. Dev.	%RSD
H ₂	0.001	0.002	0.001	0.001	0.001	53.847
He	99.942	99.952	99.914	99.936	0.020	0.020
CO	0.031	0.025	0.000	0.019	0.016	86.755
O ₂	0.026	0.022	0.085	0.044	0.035	79.863
Total	100.00	100.00	100.00	100.00		
Sample Size	25.05 mT	41.40 mT	27.19 mT	31.21 mT		

<i>H₂/Ar Mixture</i>						
8/4/97	Run 1 10:11 AM	Run 2 10:17 AM	Run 3 10:23 AM	Mean	Std. Dev.	%RSD
H ₂	5.915	5.907	5.896	5.906	0.009	0.161
CO	0.094	0.131	0.162	0.129	0.034	26.430
O ₂	0.087	0.123	0.135	0.115	0.025	21.627
Ar	93.898	93.834	93.801	93.844	0.050	0.053
CO ₂	0.006	0.006	0.006	0.006	0.000	6.215
Total	100.00	100.00	100.00	100.00		
Sample Size	24.19 mT	24.17 mT	22.46 mT	23.14 mT		

*From the 56th ed. of the CRC Handbook of Chemistry and Physics. P. F-206.

Calculations:

For the conditions of these experiments, where a fixed volume of gas is equilibrating with the atmosphere in which the H_2 concentration is essentially zero, we have:

$$\frac{dF}{dt} = -\lambda F(t)$$

Where $F(t)$ = molar concentration of H_2 in the chamber (bag)
 λ = constant for a given barrier and chamber volume, at constant temperature and pressure

integrating:

$$F(t) = F_0 e^{-\lambda t}$$

Where F_0 = the initial H_2 concentration.

This can also be expressed as:

$$\ln F(t) = \ln F_0 - \lambda t$$

Hence, by linear regression analysis of $\ln F(t)$ vs. time; the constant, λ (slope), can be determined.

The diffusion coefficient for a particular item can be defined as:

$$D = \frac{H_2 \text{ flow across barrier}}{\text{Concentration differential across barrier}}$$

If the number of moles of gas in the test chamber (bag) is M , then:

$$D = \frac{\frac{dF}{dt} \cdot M}{F(t)} = \frac{-\lambda F(t) \cdot M}{F(t)} = -\lambda M$$

The value of M is calculated as:

$$M = (V_1 / k) \cdot (P_a / P_{stp}) \cdot (T_{stp} / T_a)$$

Where V_1 = Volume of bag (liters)
 P_a = Average ambient pressure during experiment
 P_{stp} = Standard pressure (760 Torr)
 T_a = Average ambient temperature during experiment
 T_{stp} = Standard temperature (273.15 K)
 k = molar volume constant (22.414 liters/mole) at STP

In order to determine M , the volume of each bag (as mounted) must be known (V_1 in the above equation). The bag volume was initially determined by injecting a small known amount of He gas into the mounted bag and, after equilibration, measuring the He concentration in the bag. The Torr-liters of gas (atmosphere—assume no He in atmosphere) in the bag before the injection of the He is:

$$P_a \cdot V_1$$

Where P_a = ambient pressure, and
 V_1 = bag volume (unknown).

After injection of the He, the total Torr-liters of gas in the bag is:

$$P_a \cdot V_1 + \Delta P \cdot V_m$$

Where V_m = calibrated volume of inlet system.

The % He after injection is:

$$\% \text{ He} = \frac{\Delta P \cdot V_m}{P_a \cdot V_1 + \Delta P \cdot V_m} \times 100$$

Solving for V_1 (bag volume):

$$V_1 = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right]$$

The % He is measured on the mass spectrometer. All of the other variables are known and V_1 is calculated. The calibrated volume of the inlet system (V_m) was determined using a known volume (a 51.757 cc steel sample bottle whose volume was determined gravimetrically) pressurized with He gas and the following relation:

$$V_m = \frac{V_c P_c}{P_2} - V_c$$

Where $V_c = 51.757$ cc

P_c = Pressure in V_c

P_2 = Pressure in $V_c + V_m$

V_m = volume of the inlet system

For experiments prior to 5/97, the volume of the inlet system was determined to be ($n = 6$): $239.63 \text{ cc} \pm 0.150 \text{ cc}$ (0.063% RSD). For experiments after 5/97, the volume of the inlet system was found to be: $239.34 \text{ cc} \pm 0.058 \text{ cc}$ (0.024% RSD). The appropriate V_m is listed on each individual traveler (see Appendices A and B). The bag volume is then used to calculate the number of moles of gas in the bag as described above. The resulting H_2 diffusion coefficient (D) has dimensions of moles/sec./mole fraction.

Results

H₂ Diffusion Coefficient Determinations:

Results for these experiments are presented in Tables 2–5. Raw data are presented in Appendix A. The diffusion coefficients are determined using the relation:

$$D = -\lambda M$$

as described above. Hydrogen diffusion coefficients for heat sealed bags are presented in Table 2. The mean H_2 diffusion rate of 1.260×10^{-10} moles/sec./mole fraction (normalized to surface area) is used as a baseline diffusion rate per unit area of H_2 through the walls of the bags. This value is multiplied by the surface area of each bag to obtain the amount of diffusion through the walls of each bag. This new value is then subtracted from the total H_2 diffusion rate (for horse tail, wire tie, and plastic tie) determined for each BAG + CLOSURE in order to determine the diffusion coefficient through the CLOSURE only.

Nine determinations of the H_2 diffusion coefficient through horse-tail closures are presented in Table 3. The mean diffusion coefficient through the closure is 1.68×10^{-6} moles/sec./mole fraction. This value is somewhat higher than that reported by Callis et al. (1995) as well as the SAR value (NuPac, 1992) for horse tail closures (5.58×10^{-7} moles/sec./mole fraction) and may reflect variability in the way the closure was performed (i.e., different technicians performing this task). Table 4 presents the results of nine determinations of the H_2 diffusion coefficient on bags with wire tie closures and Table 5 displays the results of 7 determinations of the H_2 diffusion coefficient on bags with plastic tie closures.

H_2 diffusion through the bag walls is fairly constant with a value of $3.0\text{-}3.4 \times 10^{-7}$ moles/sec./mole fraction ($\pm 12\%$). H_2 gas is lost dominantly through the closure with only a minor component diffusing through the walls of the bag. These results indicate that the H_2 diffusion rates for the various closures increase in the following order: heat sealed < wire tie < plastic tie < horse tail.

Table 2. Experimentally Determined Hydrogen Diffusion Rates through Heat-Sealed Bags (bag volume determined by He injection).

Date Run	Bag	Total Vol. (L)	Moles (From Traveler)	$-\lambda$	Surface Area (Cm. ²)	D _{total} (m/sec./m. fract.)	D _{if} (D/Surface Area)	D _{Bag} (m/sec./m. fract.)
28-May-98	HS-1	6.56	0.2057	0.0050	1943.0	2.840E-07	1.462E-10	2.449E-07
4-Dec-98	HS-1 X	15.65	0.4889	0.0020	2726.0	2.752E-07	1.009E-10	3.435E-07
27-Aug-97	HS-2 A	12.98	0.4085	0.0039	2337.4	4.471E-07	1.913E-10	2.946E-07
22-Jun-98	HS-2 B	5.63	0.1760	0.0036	1856.0	1.762E-07	9.493E-11	2.339E-07
15-Jul-98	HS-2 C	4.86	0.1520	0.0042	1856.0	1.788E-07	9.632E-11	2.339E-07
4-Aug-97	HS-3	13.27	0.4186	0.0033	3219.0	3.814E-07	1.185E-10	4.057E-07
4-Dec-98	HS-3 X	12.83	0.4009	0.0020	2784.0	2.242E-07	8.053E-11	3.508E-07
11-Aug-97	HS-4 A	8.27	0.2607	0.0031	2395.4	2.252E-07	9.402E-11	3.019E-07
15-Jul-98	HS-4 B	5.54	0.1732	0.0081	1896.6	3.877E-07	2.044E-10	2.390E-07
4-Dec-98	HS-4 X	10.81	0.3379	0.0026	2575.2	2.447E-07	9.502E-11	3.245E-07
4-Aug-97	HS-5 A	18.10	0.5709	0.0020	3172.6	3.203E-07	1.010E-10	3.998E-07
22-Jun-98	HS-5 B	5.12	0.1601	0.0060	1905.3	2.656E-07	1.394E-10	2.401E-07
24-Sep-98	HS-5 C	5.88	0.1830	0.0062	1792.2	3.150E-07	1.758E-10	2.259E-07
Mean						2.866E-07	1.260E-10	2.953E-07
STD						8.202E-08	4.152E-11	6.489E-08
% RSD						28.62	32.94	21.98

Table 3. Experimentally Determined Hydrogen Diffusion Rates through Horse-Tail Closures (bag volume determined by He injection).

Date Run	Bag	Total Vol. (L)	Moles (From Traveler)	$-\lambda$	Surface Area (Cm. ²)	D _{total} (m/sec./m. fract.)	D _{if} (D/Surface Area)	D _{Bag} (m/sec./m. fract.)	D _{Closure} (m/sec./m. fract.)
27-Aug-97	HT-1 A	5.98	0.1878	0.0406	2627.4	2.118E-06	8.061E-10	3.311E-07	1.787E-06
15-Jul-98	HT-1 B	3.16	0.0989	0.0620	2418.6	1.704E-06	7.046E-10	3.048E-07	1.399E-06
24-Sep-98	HT-1 C	4.78	0.1487	0.0523	2383.8	2.159E-06	9.056E-10	3.004E-07	1.858E-06
28-May-98	HT-2	5.44	0.1705	0.0368	2789.8	1.741E-06	6.239E-10	3.516E-07	1.389E-06
11-Aug-97	HT-3 A	12.66	0.3997	0.0271	3062.4	3.012E-06	9.836E-10	3.859E-07	2.626E-06
22-Jun-98	HT-3 B	4.26	0.1331	0.0416	2546.2	1.538E-06	6.042E-10	3.209E-07	1.218E-06
24-Sep-98	HT-3 C	6.57	0.2044	0.0475	2378.0	2.695E-06	1.133E-09	2.997E-07	2.395E-06
11-Aug-97	HT-4	7.13	0.2250	0.0264	2824.6	1.653E-06	5.850E-10	3.560E-07	1.297E-06
4-Aug-97	HT-5	5.90	0.1861	0.0311	3364.0	1.606E-06	4.775E-10	4.239E-07	1.182E-06
Mean						2.025E-06	7.582E-10	3.416E-07	1.683E-06
STD						5.226E-07	2.148E-10	4.242E-08	5.271E-07
% RSD						25.81	28.32	12.42	31.31

Table 4. Experimentally Determined Hydrogen Diffusion Rates through Wire Tie Closures (bag volume determined by He injection).

Date Run	Bag	Total Vol. (L)	Moles (From Traveler)	λ	Surface Area (Cm. ²)	D _{total} (m/sec./m. fract.)	D _{sr} (D/Surface Area)	D _{bag} (m/sec./m. fract.)	D _{Closure} (m/sec./m. fract.)
28-May-98	WT-1	5.13	0.1606	0.0233	2610.0	1.039E-06	3.979E-10	3.289E-07	7.096E-07
27-Aug-97	WT-2	6.10	0.1922	0.0213	2708.6	1.138E-06	4.200E-10	3.413E-07	7.964E-07
11-Aug-97	WT-3 A	6.85	0.2164	0.0093	3004.4	5.608E-07	1.867E-10	3.786E-07	1.822E-07
22-Jun-98	WT-3 B	5.20	0.1626	0.0162	2563.6	7.308E-07	2.851E-10	3.231E-07	4.077E-07
15-Jul-98	WT-3 C	4.12	0.1289	0.0331	2418.6	1.183E-06	4.893E-10	3.048E-07	8.786E-07
27-Aug-97	WT-4 A	10.56	0.3324	0.0089	2807.2	8.181E-07	2.914E-10	3.538E-07	4.643E-07
22-Jun-98	WT-4 B	4.49	0.1403	0.0162	2476.6	6.302E-07	2.545E-10	3.121E-07	3.181E-07
24-Sep-98	WT-4 C	5.13	0.1596	0.0170	2604.2	7.541E-07	2.896E-10	3.282E-07	4.259E-07
4-Aug-97	WT-5	7.60	0.2397	0.0108	3184.2	7.211E-07	2.265E-10	4.013E-07	3.198E-07
					Mean	8.416E-07	3.157E-10	3.413E-07	5.003E-07
					STD	2.241E-07	9.896E-11	3.160E-08	2.390E-07
					% RSD	26.63	31.35	9.26	47.77

Table 5. Experimentally Determined Hydrogen Diffusion Rates through Plastic Tie Closures (bag volume determined by He injection.).

Date Run	Bag	Total Vol. (L)	Moles (From Traveler)	λ	Surface Area (Cm. ²)	D _{total} (m/sec./m. fract.)	D _{sr} (D/Surface Area)	D _{bag} (m/sec./m. fract.)	D _{Closure} (m/sec./m. fract.)
5/28/98	PT-1	7.12	0.2229	0.0171	2610.0	1.058E-06	4.054E-10	3.289E-07	7.292E-07
8/4/97	PT-2	8.28	0.2612	0.0153	3358.2	1.110E-06	3.306E-10	4.232E-07	6.869E-07
8/11/97	PT-3 A	6.92	0.2184	0.0166	3245.1	1.008E-06	3.107E-10	4.089E-07	5.993E-07
7/15/98	PT-3 B	5.43	0.1699	0.0258	2702.8	1.217E-06	4.503E-10	3.406E-07	8.760E-07
9/24/98	PT-3 C	4.75	0.1478	0.0378	2395.4	1.552E-06	6.480E-10	3.019E-07	1.250E-06
8/27/97	PT-4	7.66	0.2412	0.0204	2656.4	1.364E-06	5.134E-10	3.348E-07	1.029E-06
5/28/98	PT-5	5.16	0.1617	0.0275	2673.8	1.237E-06	4.626E-10	3.370E-07	9.001E-07
					Mean	1.221E-06	4.459E-10	3.560E-07	8.674E-07
					STD	1.891E-07	1.147E-10	4.471E-08	2.227E-07
					% RSD	15.49	25.72	12.64	25.67

The percent relative standard deviation (RSD) for these measurements is rather large (22–48%) reflecting the large variability in the closures themselves, presumably a result of the process by which the closures are produced. The next section describes the various sources of error that may contribute to these large standard deviations.

Sources of Error:

As mentioned above, one of the most noticeable features of this data set is the rather large standard deviations associated with the mean H_2 diffusion coefficients (22–48% RSD) for the various closures. Several sources of error that may contribute include:

- 1) the measurement of the volume/surface area of the bag
- 2) leakage from the bag or in the sampling lines
- 3) lack of pressure equilibration
- 4) volume of gas
- 5) differences in the amount of diffusion through the bag walls
- 6) differences related to different personnel making the closures

In order to calculate the number of moles of gas (M) in a test bag, the volume of the bag must be known. Bag volumes determined by the He injection method described above (see Calculations section) can only be regarded as an estimate as many surfaces of the bag are touching near the closure (resulting from the twisted bag) thus reducing the effective bag volume. In addition, some bags sag under their own weight (especially those with large volumes; see Fig. 2) thus further reducing the effective volume while maintaining the same surface area. Some bags may have been fully inflated when the bag volume was determined which would result in an increase in bag volume relative to the same surface area. The uncertainty on the detection of a relatively small He peak (for large volume bags) will also add to the uncertainty of the bag volume measurement. Surface areas, however, were measured after the closure was removed from the bag and the bag laid flat. This variability in bag volume determination coupled with the inherent variability of the closures (performed by various technicians with varying degrees of vigor) represent the two largest sources of error for these measurements. An estimated margin of error for these measurements $\pm 10\%$.

Leakage of H_2 from the bag at the contact of the bag with the mounting flange or from the sampling lines may also contribute to the overall error of the measurements. The use of quality high-vacuum components minimized the possibility of leakage from the sampling lines and no leakage was detected. To evaluate whether or not the bags leaked at the flange seal, a set of heat sealed bags was mounted with a caulk-like material (commonly used for insulation around window panes) between the bag and the flange. These are denoted in Table 2 with the letter "X". The rubber gasket was then placed on the bag as usual and held tight with worm clamps. Results from these tests (Table 2) show little difference in the measured H_2 diffusion coefficients between bags mounted with caulk and those where caulk was not used suggesting that there was little, if any, leakage of H_2 at the mounting flange.

A third source of bias stems from the possibility that the inside bag pressure did not equilibrate with the ambient pressure. Nonequilibrium would be evidenced by a nonlinear relation of $\ln H_2$ concentration vs. time. Examination of these plots (see the Appendices) shows that there were no significant deviations from linearity, with the internal precision of the slope determinations being typically better than 5%.

There is some speculation (Liekhus, 1994) that the volume of gas in a test volume may influence the diffusion coefficient determination. This was evaluated by mounting bags such that there was a range of bag volumes tested. Bag volumes ranged from 3 to 18 liters. Examination of the data in Tables 2–5 shows that the larger the moles of gas in the bag, the smaller the constant λ which, at first glance, would seem to support Liekhus' speculation. However, the diffusion coefficient "D" is the product of $-\lambda$ and M which results in relatively constant "D" values for a given BAG + CLOSURE. Plots of "D" vs. bag volume and surface area (Figs. 4 and 5) show that the diffusion coefficient is relatively independent of bag volume or surface area within two standard deviations of the mean for each closure type.

Yet another source of error comes from the assumption that H_2 diffusion through the walls of the bag is the same for every bag. Variations in bag thickness would result in different amounts of H_2 diffusion through the bag walls. Since the diffusion through the closure is determined by difference, these variations will add an error term to the rate of diffusion through the closure.

Finally, considerable variability exists in the actual preparation of the closures. Different technicians use different techniques and different amounts of energy when preparing the various closures on the bags. The sheer number of personnel performing this task over the last 10 or so years has contributed greatly to the variability of the closures themselves. While the data presented here is for only one set of experiments, it is believed that the data are directly applicable to actual TRU waste bag-out bags contained in 55 gallon drums at LANL.

Most of the errors described above are much smaller than the standard deviation of the mean for each closure type. As such, to be conservative, the total error on the diffusion coefficient for each closure is taken as one standard deviation of the mean for that closure.

Figure 4. "D" vs. bag volume. All diffusion coefficients are within two standard deviations of the mean indicating that the diffusion coefficient is not a function of bag volume or the number of moles of gas in the bag.

Figure 5. "D" vs. surface area. All diffusion coefficients are within two standard deviations of the mean showing that the diffusion coefficient is independent of surface area.

Alternate Method of Bag Volume/Surface Area Determination:

In an effort to mitigate the problems associated with measuring the bag volume by the injection of He and recording the associated pressure drop (i.e., the bags are not a reproducible "rigid" shape, but instead could sag or be inflated), an alternate method of determining the bag volume/surface area was evaluated. The horse-tail, plastic tie, and wire tie bags, as mounted on the aluminum flanges, were assumed to represent right circular cones. This has the affect of "standardizing" the bag shape and thus averaging out discrepancies in the bag volume determinations.

Where h = height
 r = radius
 s = side length

In this case, the bag volume is:

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

and the lateral surface area can be calculated as:

$$Lateral\ Surface\ Area = \pi rs$$

A cross-section of a mounted bag is shown in Fig. 6:

Figure 6. Cross section of a mounted bag-out bag.

The total volume would then be the volume of a cone plus the volume contained within the aluminum flange (a right circular cylinder with a volume of 3.92 L).

The volume of the heat sealed bags was calculated assuming one half the volume of a right circular cylinder with the same radius and height:

The value of h is calculated using the measured value of s and the angle θ (r and s are known). The estimated volume of the heat sealed bag is calculated as:

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

If the volume of a heat sealed bag is one half the volume of a right circular cylinder with the same r and h , then the surface area must be equal to one half the lateral surface area plus the area of one end of the cylinder:

$$Surface Area = \pi r (r + h)$$

Again, the total volume includes the volume of the aluminum flange plus the bag volume. The recalculated data are presented in Tables 6–9.

Table 6. Experimentally Determined Hydrogen Diffusion Rates through Heat-Sealed Bags (bag volume determined by geometric calculation).

							Al. Flange	Calculated	Moles -λ- (From Travelers					
	Bag	X	Theta	h	Vol. Cyl.	Vol. Bag	Vol. of Cyl.	Total Vol.	But using calculated	Surface Area	D _{total}	D _{if}	D _{Bag}	
Date Run		(Cm.)	(Degrees)	(Cm.)	(Cm. ³)	(L)	(L)	(L)	Bag Volume)	(Cm. ²)	(m/sec./m. fract.)	(D/Surface Area)	(m/sec./m. fract.)	
5/28/98	HS-1	19.9	0.0	0.0	0.0	0.00	3.92	3.92	0.1229	0.0050	1246.6	1.697E-07	1.361E-10	1.900E-07
12/4/98	HS-1 X	23.5	32.0	12.5	15542.3	7.77	3.92	11.69	0.3652	0.0020	2026.8	2.055E-07	1.014E-10	3.090E-07
8/27/97	HS-2 A	20.8	16.3	5.8	7242.8	3.62	3.92	7.54	0.2374	0.0039	1610.2	2.598E-07	1.613E-10	2.455E-07
6/22/98	HS-2 B	20.1	7.7	2.7	3345.8	1.67	3.92	5.60	0.1750	0.0036	1414.6	1.751E-07	1.238E-10	2.156E-07
7/15/98	HS-2 C	20.1	7.7	2.7	3345.8	1.67	3.92	5.60	0.1752	0.0042	1414.6	2.060E-07	1.456E-10	2.156E-07
8/4/97	HS-3	27.8	44.1	19.3	24084.2	12.04	3.92	15.97	0.5037	0.0033	2455.6	4.589E-07	1.869E-10	3.743E-07
12/4/98	HS-3 X	24.3	34.8	13.8	17240.0	8.62	3.92	12.54	0.3919	0.0020	2112.1	2.191E-07	1.038E-10	3.220E-07
8/11/97	HS-4 A	20.6	14.8	5.2	6543.6	3.27	3.92	7.20	0.2274	0.0031	1575.1	1.964E-07	1.247E-10	2.401E-07
7/15/98	HS-4 B	20.1	7.7	2.7	3345.8	1.67	3.92	5.60	0.1752	0.0081	1414.6	3.922E-07	2.773E-10	2.156E-07
12/4/98	HS-4 X	23.1	30.4	11.7	14580.7	7.29	3.92	11.21	0.3503	0.0026	1978.6	2.537E-07	1.282E-10	3.016E-07
8/4/97	HS-5 A	27.3	43.1	18.7	23271.3	11.64	3.92	15.56	0.4908	0.0020	2414.8	2.754E-07	1.140E-10	3.681E-07
6/22/98	HS-5 B	20.2	8.7	3.0	3784.4	1.89	3.92	5.82	0.1819	0.0060	1436.6	3.018E-07	2.101E-10	2.190E-07
9/24/98	HS-5 C	19.9	0.0	0.0	0.0	0.00	3.92	3.92	0.1220	0.0062	1246.6	2.100E-07	1.684E-10	1.900E-07
											Mean	2.557E-07	1.524E-10	2.620E-07
											Stdev	8.578E-08	4.947E-11	6.498E-08
											% RSD	33.55	32.45	24.80

Table 7. Experimentally Determined Hydrogen Diffusion Rates through Horse-Tail Closures (bag volume determined by geometric calculation).

Date Run	Bag	X (Cm.)	Theta (degrees)	h (Cm.)	Cone Vol. (L)	Cyl. Vol. (L)	Calculated Total Vol. (L)	Moles -λ- (From Travelers But using calculated Bag Volume)		Surface Area of a Cone (Cm. ²)	D _{total} (m/sec./m. fract.)	D _{if} (D/Surface Area)	D _{Bag} (m/sec./m. fract.)	D _{Closure} (m/sec./m. fract.)
8/27/97	HT-1 A	22.7	28.4	10.8	4.48	3.92	8.40	0.2641	0.0406	1417.4	2.978E-06	2.101E-09	2.161E-07	2.762E-06
7/15/98	HT-1 B	20.9	17.2	6.2	2.56	3.92	6.48	0.2027	0.0620	1304.8	3.493E-06	2.677E-09	1.989E-07	3.294E-06
9/24/98	HT-1 C	20.6	14.2	5.0	2.10	3.92	6.02	0.1873	0.0523	1286.0	2.718E-06	2.114E-09	1.960E-07	2.522E-06
5/28/98	HT-2	24.1	34.1	13.5	5.60	3.92	9.52	0.2984	0.0368	1505.1	3.046E-06	2.024E-09	2.294E-07	2.817E-06
8/11/97	HT-3 A	26.4	41.0	17.3	7.20	3.92	11.12	0.3512	0.0271	1652.1	2.647E-06	1.602E-09	2.519E-07	2.395E-06
6/22/98	HT-3 B	22.0	24.8	9.2	3.83	3.92	7.75	0.2421	0.0416	1373.6	2.798E-06	2.037E-09	2.094E-07	2.589E-06
9/24/98	HT-3 C	20.5	13.7	4.8	2.01	3.92	5.94	0.1848	0.0475	1282.9	2.436E-06	1.899E-09	1.956E-07	2.241E-06
8/11/97	HT-4	24.4	35.1	14.0	5.82	3.92	9.74	0.3076	0.0264	1523.8	2.259E-06	1.483E-09	2.323E-07	2.027E-06
8/4/97	HT-5	27.3	43.1	18.7	7.76	3.92	11.68	0.3684	0.0311	1708.4	3.179E-06	1.861E-09	2.604E-07	2.919E-06
										Mean	2.840E-06	1.978E-09	2.211E-07	2.618E-06
										Stdev	3.803E-07	3.418E-10	2.404E-08	3.807E-07
										% RSD	13.39	17.28	10.87	14.54

Table 8. Experimentally Determined Hydrogen Diffusion Rates through Wire Tie Closures (bag volume determined by geometric calculation).

Date Run	Bag	X (Cm.)	Theta (degrees)	h (Cm.)	Cone Vol. (L)	Cyl. Vol. (L)	Calculated Total Vol. (L)	Moles (From Travelers But using calculated Bag Volume)	Surface Area of a Cone (Cm. ²)	D _{total} (m/sec./m. fract.)	D _{fr} (D/Surface Area)	D _{Bag} (m/sec./m. fract.)	D _{Closure} (m/sec./m. fract.)	
5/28/98	WT-1	22.5	27.7	10.5	4.35	3.92	8.27	0.2589	0.0233	1408.1	1.674E-06	1.189E-09	2.146E-07	1.460E-06
8/27/97	WT-2	23.4	31.4	12.2	5.06	3.92	8.99	0.2830	0.0213	1461.3	1.675E-06	1.146E-09	2.228E-07	1.452E-06
8/11/97	WT-3 A	25.9	39.7	16.6	6.88	3.92	10.80	0.3410	0.0093	1620.8	8.838E-07	5.452E-10	2.471E-07	6.367E-07
6/22/98	WT-3 B	22.1	25.7	9.6	3.98	3.92	7.90	0.2469	0.0162	1383.0	1.110E-06	8.024E-10	2.108E-07	8.988E-07
7/15/98	WT-3 C	20.9	17.2	6.2	2.56	3.92	6.48	0.2027	0.0331	1304.8	1.861E-06	1.426E-09	1.989E-07	1.662E-06
8/27/97	WT-4 A	24.2	34.6	13.7	5.71	3.92	9.63	0.3032	0.0089	1514.4	7.462E-07	4.927E-10	2.309E-07	5.153E-07
6/22/98	WT-4 B	21.4	21.1	7.7	3.19	3.92	7.12	0.2224	0.0162	1336.1	9.989E-07	7.477E-10	2.037E-07	7.953E-07
9/24/98	WT-4 C	22.5	27.5	10.4	4.30	3.92	8.23	0.2561	0.0170	1404.9	1.210E-06	8.613E-10	2.142E-07	9.959E-07
8/4/97	WT-5	27.5	43.5	18.9	7.85	3.92	11.77	0.3713	0.0108	1717.8	1.117E-06	6.502E-10	2.619E-07	8.551E-07
Mean											1.253E-06	8.735E-10	2.228E-07	1.030E-06
Stdev											3.911E-07	3.168E-10	2.062E-08	4.009E-07
% RSD											31.22	36.27	9.26	38.92

Table 9. Experimentally Determined Hydrogen Diffusion Rates through Plastic Tie Closures (bag volume determined by geometric calculation).

Date Run	Bag	X (Cm.)	Theta (degrees)	h (Cm.)	Cone Vol. (L)	Cyl. Vol. (L)	Calculated Total Vol. (L)	Moles (From Travelers But using calculated Bag Volume)	Surface Area of a Cone (Cm. ²)	D _{total}	D _f	D _{Bag}	D _{Closure}	
								(m/sec./m. fract.)		(D/Surface Area)	(m/sec./m. fract.)	(m/sec./m. fract.)		
5/28/98	PT-1	22.5	27.7	10.5	4.35	3.92	8.27	0.2589	0.0171	1408.1	1.229E-06	8.729E-10	2.146E-07	1.014E-06
8/4/97	PT-2	29.0	46.5	21.0	8.73	3.92	12.65	0.3990	0.0153	1811.7	1.696E-06	9.360E-10	2.762E-07	1.420E-06
8/11/97	PT-3 A	28.0	44.6	19.6	8.16	3.92	12.09	0.3818	0.0166	1750.7	1.763E-06	1.007E-09	2.669E-07	1.496E-06
7/15/98	PT-3 B	23.3	31.2	12.1	5.02	3.92	8.95	0.2800	0.0258	1458.1	2.006E-06	1.376E-09	2.223E-07	1.784E-06
9/24/98	PT-3 C	20.7	15.3	5.4	2.26	3.92	6.18	0.1923	0.0378	1292.3	2.020E-06	1.563E-09	1.970E-07	1.823E-06
8/27/97	PT-4	22.9	29.6	11.3	4.69	3.92	8.62	0.2714	0.0204	1433.1	1.535E-06	1.071E-09	2.185E-07	1.316E-06
5/28/98	PT-5	23.1	30.2	11.6	4.82	3.92	8.74	0.2738	0.0275	1442.5	2.095E-06	1.452E-09	2.199E-07	1.875E-06
										Mean	1.763E-06	1.182E-09	2.308E-07	1.532E-06
										Stdev	3.100E-07	2.753E-10	2.918E-08	3.145E-07
										% RSD	17.58	23.28	12.64	20.52

Figure 7 shows a plot of surface area vs. bag volume. Solid symbols represent bag volumes determined by He gas injection and surface areas measured on the bags laid flat. The two curves are models of the total volume and surface area assuming a right circular cone for horse tail, wire tie, and plastic tie bags and one half of a right circular cylinder for the heat sealed bags as described above. Bags whose volume and surface area were determined geometrically plot on the model curves. The problems associated with the volume determination by He injection (namely inflated bags or drooping bags with surfaces touching) cause variability with respect to the measured surface area.

The geometric calculation serves to average out irregularities in the bags due to mounting and twisting near the closures. The calculated amount of diffusion through the wall of the bag for horse tail, wire ties, and plastic ties is again very similar. Overall the mean diffusion coefficients have slightly lower % RSD when using the geometric volumes and surface areas.

Repeat Analyses:

Tables 10–11 show the results of numerous repeat analyses of selected bags (bag volume determined by He injection and geometry, respectively). Repeat analyses were undertaken in order to obtain an evaluation of the reproducibility of the H₂ diffusion measurements. Repeat analyses consisted of mounting a particular bag on a different mounting flange for each repeat H₂ diffusion coefficient determination.

Sources of error for the repeat analyses consist of those described above with the exception of errors due to the variability of the closures due to different technicians as well as variable rates of diffusion through the walls of the bag. These two sources of error do not apply since it is the same bag that is being measured repeatedly. The heat sealed bags display the least variability, as would be expected since the bag volume measurement does not suffer from the problems inherent to twist and tape type closures (namely, portions of the bag touching due to twisting). The bags were also mounted in such a way as to minimize sagging.

The standard deviation of the heat sealed bags ranges from 10 to 33% RSD (by either He injection or geometric calculation). Horse tails range from 15–36% (He injection) and 7–15% (geometry), wire ties range from 19–73% (He injection) and 29–47% (geometry), and plastic ties are around 35% RSD (He injection) and 9% (geometry). On average, the reproducibility of measurements for a particular closure ranges from 10–35% (He injection) and 7–30% (geometry). This range is similar to the overall standard deviations of the mean for each closure type. This probably represents the intrinsic variability for each closure.

Figure 7. The relationship of surface area to bag volume. Bags whose volumes and surface areas were determined geometrically plot on the model curves. Bags whose volumes were determined by He gas injection plot off curves due to variable bag volume for a given surface area. Bag volumes can vary while surface area remains constant because of inflated or sagging bags as described in the text.

Table 10. Repeat Analyses of Various Bag-out Bags (bag volume determined by He injection).

Date Run	Bag	Bag Vol. (L)	Surface Area (sq. Cm.)	D m/sec/m. fract.	Dsf (D/Surface Area)	Diff. thru bag	Diff. thru closure
Horse Tail							
8/27/97	HT-1 A	5.98	2627	2.118E-06	8.0612E-10	3.31E-07	1.787E-06
7/15/98	HT-1 B	3.16	2419	1.704E-06	7.0454E-10	3.05E-07	1.399E-06
9/24/98	HT-1 C	4.78	2384	2.159E-06	9.05697E-10	3.00E-07	1.859E-06
	Mean			1.99E-06	8.05E-10	3.12E-07	1.68E-06
	STD			2.52E-07	1.01E-10	1.66E-08	2.47E-07
	RSD			12.62	12.49	5.32	14.70
Horse Tail							
8/11/97	HT-3 A	12.66	3062	3.013E-06	9.83869E-10	3.86E-07	2.627E-06
6/22/98	HT-3 B	4.26	2546	1.538E-06	6.04037E-10	3.21E-07	1.217E-06
9/24/98	HT-3 C	6.57	2378	2.695E-06	1.13331E-09	3.00E-07	2.395E-06
	Mean			2.42E-06	9.07E-10	3.36E-07	2.08E-06
	STD			7.76E-07	2.73E-10	4.49E-08	7.56E-07
	RSD			32.14	30.08	13.40	36.35
Wire Tie							
8/11/97	WT-3 A	6.85	3004	5.608E-07	1.8666E-10	3.79E-07	1.821E-07
6/22/98	WT-3 B	5.20	2564	7.308E-07	2.85068E-10	3.23E-07	4.077E-07
7/15/98	WT-3 C	4.12	2419	1.183E-06	4.89126E-10	3.05E-07	8.782E-07
	Mean			8.25E-07	3.20E-10	3.36E-07	4.89E-07
	STD			3.22E-07	1.54E-10	3.85E-08	3.55E-07
	RSD			38.99	48.17	11.46	72.57
Wire Tie							
8/27/97	WT-4 A	10.56	2807	8.181E-07	2.91429E-10	3.54E-07	4.643E-07
6/22/98	WT-4 B	4.49	2477	6.302E-07	2.54462E-10	3.12E-07	3.181E-07
9/24/98	WT-4 C	5.13	2604	7.541E-07	2.89571E-10	3.28E-07	4.259E-07
	Mean			7.34E-07	2.78E-10	3.31E-07	4.03E-07
	STD			9.55E-08	2.08E-11	2.10E-08	7.58E-08
	RSD			13.01	7.48	6.34	18.82
Plastic Tie							
8/11/97	PT-3 A	6.92	3245	1.008E-06	3.10622E-10	4.09E-07	5.990E-07
7/15/98	PT-3 B	5.43	2703	1.217E-06	4.50274E-10	3.41E-07	8.764E-07
9/24/98	PT-3 C	4.75	2395	1.552E-06	6.47908E-10	3.02E-07	1.250E-06
	Mean			1.26E-06	4.70E-10	3.51E-07	9.08E-07
	STD			2.74E-07	1.69E-10	5.42E-08	3.27E-07
	RSD			21.80	36.09	15.47	35.96

Table 10 (Cont'd.). Repeat Analyses of Various Bag-out Bags (bag volume determined by He injection).

Date Run	Bag	Bag Vol. (L)	Surface Area (sq. Cnt.)	D m/sec./m. fract.	Dsf (D/Surface Area)	Diff. thru bag
Heat Sealed						
5/28/98	HS-1	6.56	1934	2.840E-07	1.46846E-10	2.44E-07
12/4/98	HS-1 X	15.65	2726	2.752E-07	1.00954E-10	3.44E-07
	Mean			2.80E-07	1.24E-10	2.94E-07
	STD			6.22E-09	3.25E-11	7.06E-08
	RSD			2.23	26.19	24.04
Heat Sealed						
8/27/97	HS-2 A	12.98	2337	4.471E-07	1.91281E-10	2.95E-07
6/22/98	HS-2 B	5.63	1856	1.762E-07	9.49353E-11	2.34E-07
7/15/98	HS-2 C	4.86	1856	1.788E-07	9.63362E-11	2.34E-07
	Mean			2.67E-07	1.28E-10	2.54E-07
	STD			1.56E-07	5.52E-11	3.50E-08
	RSD			58.22	43.31	13.78
Heat Sealed						
8/4/97	HS-3	13.27	3219	3.814E-07	1.18484E-10	4.06E-07
12/4/98	HS-3 X	12.83	2784	2.242E-07	8.05316E-11	3.51E-07
	Mean			3.03E-07	9.95E-11	3.78E-07
	STD			1.11E-07	2.68E-11	3.88E-08
	RSD			36.71	26.97	10.25
Heat Sealed						
8/11/97	HS-4 A	8.27	2395	2.252E-07	9.40135E-11	3.02E-07
7/15/98	HS-4 B	5.54	1897	3.877E-07	2.04418E-10	2.39E-07
12/4/98	HS-4 X	10.81	2575	2.447E-07	9.50217E-11	3.25E-07
	Mean			2.86E-07	1.31E-10	2.88E-07
	STD			8.87E-08	6.35E-11	4.43E-08
	RSD			31.04	48.38	15.36
Heat Sealed						
8/4/97	HS-5 A	18.10	3173	3.203E-07	1.00958E-10	4.00E-07
6/22/98	HS-5 B	5.12	1905	2.656E-07	1.39401E-10	2.40E-07
9/24/98	HS-5 C	5.88	1792	3.150E-07	1.75762E-10	2.26E-07
	Mean			3.00E-07	1.39E-10	2.89E-07
	STD			3.02E-08	3.74E-11	9.66E-08
	RSD			10.05	26.97	33.47

Table 11. Repeat Analyses of Various Bag-out Bags (bag volume determined geometrically).

Date Run	Bag	Bag Vol. (L)	Surface Area (sq. Cm.)	D m/sec./m. fract.	Dsf (D/Surface Area)	Diff. thru bag	Diff. thru closure
Horse Tail							
8/27/97	HT-1 A	8.40	1417	2.978E-06	2.10128E-09	2.161E-07	2.762E-06
7/15/98	HT-1 B	6.48	1305	3.493E-06	2.67681E-09	1.989E-07	3.294E-06
9/24/98	HT-1 C	6.02	1286	2.718E-06	2.11383E-09	1.960E-07	2.522E-06
	Mean			3.06E-06	2.30E-09	2.037E-07	2.860E-06
	STD			3.94E-07	3.29E-10	1.084E-08	3.948E-07
	RSD			12.86	14.31	5.32	13.81
Horse Tail							
8/11/97	HT-3 A	11.12	1652	2.647E-06	1.60199E-09	2.519E-07	2.395E-06
6/22/98	HT-3 B	7.75	1374	2.798E-06	2.03712E-09	2.094E-07	2.589E-06
9/24/98	HT-3 C	5.94	1283	2.436E-06	1.89904E-09	1.956E-07	2.241E-06
	Mean			2.63E-06	1.85E-09	2.189E-07	2.408E-06
	STD			1.82E-07	2.22E-10	2.933E-08	1.745E-07
	RSD			6.92	12.04	13.40	7.24
Wire Tie							
8/11/97	WT-3 A	10.80	1621	8.838E-07	5.45249E-10	2.471E-07	6.367E-07
6/22/98	WT-3 B	7.90	1383	1.110E-06	8.02353E-10	2.108E-07	8.988E-07
7/15/98	WT-3 C	6.48	1305	1.861E-06	1.42619E-09	1.989E-07	1.662E-06
	Mean			1.28E-06	9.25E-10	2.189E-07	1.066E-06
	STD			5.12E-07	4.53E-10	2.509E-08	5.327E-07
	RSD			39.82	49.00	11.46	49.98
Wire Tie							
8/27/97	WT-4 A	9.63	1514	7.462E-07	4.92726E-10	2.309E-07	5.153E-07
6/22/98	WT-4 B	7.12	1336	9.989E-07	7.47662E-10	2.037E-07	7.953E-07
9/24/98	WT-4 C	8.23	1405	1.210E-06	8.61303E-10	2.142E-07	9.959E-07
	Mean			9.85E-07	7.01E-10	2.162E-07	7.688E-07
	STD			2.32E-07	1.89E-10	1.371E-08	2.414E-07
	RSD			23.58	26.94	6.34	31.39
Plastic Tie							
8/11/97	PT-3 A	12.09	1751	1.763E-06	1.00683E-09	2.669E-07	1.496E-06
7/15/98	PT-3 B	8.95	1458	2.006E-06	1.37566E-09	2.223E-07	1.784E-06
9/24/98	PT-3 C	6.18	1292	2.020E-06	1.56287E-09	1.970E-07	1.823E-06
	Mean			1.93E-06	1.32E-09	2.287E-07	1.701E-06
	STD			1.45E-07	2.83E-10	3.538E-08	1.785E-07
	RSD			7.49	21.51	15.47	10.50

Table 11 (Cont'd.). Repeat Analyses of Various Bag-out Bags (bag volume determined geometrically).

Date Run	Bag	Bag Vol. (L)	Surface Area (sq. Cm.)	D m/sec./m. fract.	Dsf (D/Surface Area)	Diff. thru bag
Heat Sealed						
5/28/98	HS-1	3.92	1943	1.697E-07	8.73239E-11	2.962E-07
12/4/98	HS-1 X	11.69	2726	2.055E-07	7.53949E-11	4.156E-07
	Mean			1.88E-07	8.14E-11	3.559E-07
	STD			2.54E-08	8.44E-12	8.440E-08
	RSD			13.52	10.37	23.72
Heat Sealed						
8/27/97	HS-2 A	7.54	2337	2.598E-07	1.11144E-10	3.563E-07
6/22/98	HS-2 B	5.60	1856	1.751E-07	9.43677E-11	2.829E-07
7/15/98	HS-2 C	5.60	1856	2.060E-07	1.10991E-10	2.829E-07
	Mean			2.14E-07	1.06E-10	3.074E-07
	STD			4.28E-08	9.64E-12	4.237E-08
	RSD			20.05	9.14	13.78
Heat Sealed						
8/4/97	HS-3	15.97	3219	4.589E-07	1.42568E-10	4.907E-07
12/4/98	HS-3 X	12.54	2784	2.191E-07	7.87132E-11	4.244E-07
	Mean			3.39E-07	1.11E-10	4.575E-07
	STD			1.70E-07	4.52E-11	4.689E-08
	RSD			50.01	40.81	10.25
Heat Sealed						
8/11/97	HS-4 A	7.20	2395	1.964E-07	8.20107E-11	3.652E-07
7/15/98	HS-4 B	5.60	1897	3.922E-07	2.06812E-10	2.891E-07
12/4/98	HS-4 X	11.21	2575	2.537E-07	9.85071E-11	3.926E-07
	Mean			2.81E-07	1.29E-10	3.489E-07
	STD			1.01E-07	6.78E-11	5.359E-08
	RSD			35.85	52.51	15.36
Heat Sealed						
8/4/97	HS-5 A	15.56	3173	2.754E-07	8.68037E-11	4.836E-07
6/22/98	HS-5 B	5.82	1905	3.018E-07	1.5842E-10	2.904E-07
9/24/98	HS-5 C	3.92	1792	2.100E-07	1.17151E-10	2.732E-07
	Mean			2.62E-07	1.21E-10	3.491E-07
	STD			4.73E-08	3.59E-11	1.168E-07
	RSD			18.03	29.76	33.47

Measurement of Diffusion Rate through Closures Only:

To verify that the large standard deviations of the data presented above are due to the intrinsic variability of the closures themselves, the H_2 diffusion coefficients of several additional bags (wire and plastic ties) were measured using a method of bag mounting that allows for the direct determination of the H_2 diffusion through the closure only (Fig. 8).

Figure 8. Bag mounted on 2 liter steel cylinder with bag closure penetrating sealing flange. Inlet and outlet valves visible at rear of 2 liter cylinder.

In this case a bag was mounted on the end of a 2 liter steel cylinder with the closure of the bag passing through a hole in the sealing flange. In this configuration, there is a negligible amount of diffusion through the remaining bag material; most diffusion occurs through the closure only. Also, the chamber volume in this case is nearly constant at 2 liters thus reducing errors due to volume measurements (surface area is irrelevant). A total of four bags was evaluated in this way, two of which were also evaluated as described above by mounting the bags on the 15" diameter flange. It should be noted that these bags were prepared by a different technician which will likely introduce more variability in the determination of "D". The results of these tests are presented in Table 12.

The values of " D_{closure} " determined for bags P-2 and P-7 mounted on the 15" aluminum flange (e.g., see Fig. 2) compare favorably with the values of " D_{total} " as determined for the closure only (bags mounted on the 2 liter chamber as in Fig. 8). The mean "D" for the plastic tie closure (mounted on the 2 liter chamber) is somewhat less than the mean value determined earlier (Tables 5 and 9) which probably reflects the fact that these closures were performed by a different technician using different techniques, once again displaying the inherent variability of these closures.

Table 12. Experimentally Determined Hydrogen Diffusion Rates through Various Closures (bag volume determined by He injection).

Date Run	Closure	Bag	Total Vol. (L)	Moles (From Traveler)	$-\lambda$	Surface Area (Cm. ²)	D_{total} m/sec./m. fract.	D_{if} (D/Surface Area)	D_{Bag} m/sec./m. fract.	$D_{Closure}$ m/sec./m. fract.
Full Bag										
19-Nov-96	Plastic Tie	P-2	7.35	0.2270	0.0206	2958.0	1.297E-06	4.385E-10	3.728E-07	9.242E-07
19-Nov-96	Plastic Tie	P-7	5.06	0.1573	0.0170	2859.4	7.428E-07	2.598E-10	3.603E-07	3.825E-07
									Mean	6.533E-07
									STD	3.830E-07
									% RSD	58.63
Closure Only (bags mounted on 2 liter chamber)										
31-Mar-99	Plastic Tie	P-7	2.00	0.0617	0.0303		5.200E-07			
29-Mar-99	Plastic Tie	P-2	1.98	0.0615	0.0435		7.420E-07			
17-Mar-99	Plastic Tie	P-1	1.95	0.0607	0.0261		4.395E-07			
						Mean	5.672E-07			
						STD	1.567E-07			
						% RSD	27.62			
Closure Only (bag mounted on 2 liter chamber)										
23-Mar-99	Wire Tie	W-9	2.00	0.0623	0.0450	0.0	7.788E-07			

Interpretation of Data:

Even with the large variability of the diffusion rates for the four closures, several conclusions relating to the H₂ diffusion out of the bag-out bags can be presented. Figure 9 is a summary figure displaying all of the results of this study, the results of an earlier study (Callis et al., 1995), as well as the accepted diffusion rate taken from the SAR (NuPac, 1992). From these data it is apparent that there are real differences in the diffusion rates for each of the four bag closure methods tested. Heat sealed bags obviously have the lowest H₂ diffusion rates followed by bags with wire tie closures, bags with plastic tie closures, and finally the horse-tail bags.

To evaluate whether the H₂ diffusion coefficients determined for the four closure types are statistically different from the value reported in the SAR, a significance test of the means was performed (Miller and Miller, 1988). This test compares the mean diffusion coefficient for a particular closure to the SAR (true) value:

$$t_{calc} = (mean - true) \cdot \frac{\sqrt{n}}{s}$$

If $|t_{calc}|$ exceeds the critical t value ($t_{critical}$ from t -distribution table) then the null hypothesis is rejected and it can be said that there is a statistical difference between the mean value for a particular closure and that of the SAR value (NuPac, 1992). As can be seen from Table 13, most of the closures have mean H₂ diffusion coefficients that are statistically different from the value reported in the TRU-PACT II SAR (NuPac, 1992) at either the 95% or the 99% confidence level. However, the diffusion rates are HIGHER than that specified in the SAR except for the wire tie closure and the plastic tie closure measured on the 2 liter chamber which are not statistically different from the accepted value. The H₂ diffusion coefficients for horse-tails determined by Callis et al. (1995) are likewise not statistically different from the SAR (NuPac, 1992) value.

These experiments show that most closures on PVC bag-out bags allow for the diffusion of H₂ gas at a rate higher than that currently specified in the SAR (NuPac, 1992). The two determinations that approach the SAR value are not statistically different from that value.

Figure 9. Summary of results from the H₂ diffusion experiments. Horse-tail and plastic tie closures have diffusion rates higher than the SAR (NuPac, 1992) value. Wire tie diffusion rates are either higher than, or not statistically significant from, the SAR value. Error bars are % RSD.

Table 13. Determination of Statistical Difference between Mean Value for a Particular Closure Type and the Accepted Value in the TRU-PACT II SAR.

Closure	Mean Diff. Coef.	n	s	t (calc)	t (critical)		Statistical Diff?	
					95% Conf.	99% Conf.	95% Conf.	99% Conf.
HT (He Injection)	1.68E-06	9	5.31E-07	6.35	2.31	3.36	yes	yes
PT (He Injection)	8.74E-07	7	2.23E-07	3.75	2.45	3.71	yes	yes
WT (He Injection)	4.91E-07	9	2.40E-07	0.84	2.31	3.36	no	no
HS (He Injection)	2.96E-07	13	6.61E-08	14.33	2.18	3.05	yes	yes
HT-Callis	5.53E-07	7	1.84E-07	0.07	2.45	3.71	no	no
HS-Callis	2.85E-07	2	1.77E-09	218.12	12.71	63.66	yes	yes
HT (Geom. Calc.)	2.68E-06	9	3.80E-07	16.75	2.31	3.36	yes	yes
PT (Geom. Calc.)	1.60E-06	7	3.13E-07	8.81	2.45	3.71	yes	yes
WT (Geom. Calc.)	1.09E-06	9	3.98E-07	4.01	2.31	3.36	yes	yes
HS (Geom. Calc.)	2.62E-07	13	5.85E-08	18.27	2.18	3.05	yes	yes
PT (Closure Only)	5.67E-07	3	1.57E-07	0.10	4.3	9.92	no	no
SAR	5.58E-07							

Conclusions

While there can be considerable variation in the amount of H₂ diffusion through different closures (due to the fact that many different technicians prepare the bags using different techniques and with different degrees of vigor), the results of these experiments suggest that the use of wire or plastic ties probably does not significantly restrict the flow of H₂ gas out of TRU-waste bag-out bags. The mean diffusion coefficients for horse-tail and plastic tie closures are significantly higher than the accepted value in the SAR (NuPac, 1992). The mean diffusion coefficient for wire tie closures is not statistically different from the SAR (NuPac, 1992) value. Heat sealed bags, however, do have significantly lower H₂ diffusion rates, and drums containing heat sealed bag-out bags will likely need to be evaluated on a case-by-case basis.

References

- Callis, E.L., Capps, J.H., Smith, M.C., and Marshall, R.S., 1995, Hydrogen Venting Characteristics of Commercial Carbon-Composite Filters and Applications to TRU Waste, Los Alamos report LA-UR-95-1447, 31p.
- CRC Handbook of Chemistry and Physics, 56th edition, p. F-206.
- Liekhus, K.J., 1994, Transport Characteristics Across Drum Filter Vents and Polymer Bags, Idaho Nat. Engineering Laboratory report EGG-WM-11454.
- Miller, J.C. and Miller, J.N., 1988, Statistics for Analytical Chemists, John Wiley and Sons, New York, 227 p.
- NuPac, 1992, Safety Analysis Report for the TRUPACT-II Shipping Package, Rev. 10, Federal Way, Washington, Nuclear Packaging, Inc.

APPENDIX A

**Project Travelers and Determination of Lambda for Horse-Tail,
Wire Tie, Plastic Tie, and Heat Sealed Bags**

Stand #4.

H₂ Diffusion Project Traveler

Analyst: PDN/KML

Date and Time: 5/28/98 8:58

Bag Number: HS-1

Closure type: Heat Sealed

Knowns: $P_{sup} = 760$ Torr $T_{sup} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.34$ cc

Bag Volume (V_i) Determination

$P_a = 580.41$ $P_1 = 981.60$ $P_2 = 879.64$ $\Delta P = 101.96$

%He in bag = 0.637 (Measured on Mass Spec.)

$$V_i = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \underline{6.56 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
5/28/98 2:32	24.9/582.12	4.82
5/29/98 7:54am	23.8/583.05	4.480
5/29/98 2:00pm	24.6/582.18	4.390
5/29/98 4:13pm	24.9/581.36	4.325
6/1/98 10:41am	24.5/582.29	3.074
6/1/98 2:11pm	24.9/581.810	3.037
6/2/98 8:14	24.0/581.33	2.773

mean 24.5/581.92

$\lambda = -0.00497$ (Least Squares)
24.5°C

$T_a = 297.6^\circ \text{K}$

(Average)

$P_a = 581.92$ Torr

$M = (V_i/k) \cdot (P_i/P_a) \cdot (T_{sup}/T_a) = 0.2057$ mole

H₂ Diffusion Coefficient

$D = -\lambda M = 1.022$ moles/hr./mole fract.

2.840×10^{-7} moles/sec./mole fraction

Comments:

HS-1

Stand # 1

H₂ Diffusion Project Traveler

Analyst: PDN

Date and Time: 12/4/98 3:00pm

Bag Number: HS-1 X

Closure type: Heat Sealed

Knowns: $P_{sup} = 760$ Torr $T_{sup} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.34$ cc

Bag Volume (V_1) Determination

$P_a = 582.52$ $P_1 = 959.16$ $P_2 = 716.50$ $\Delta P = 242.66$

%He in bag = 0.633 (Measured on Mass Spec.)

$$V_1 = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{15650.96 \text{ mL}}{15.65 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
12/4/98 3:38pm	25.7/576.08	5.251
12/7/98 11:24am	24.5/578.00	4.604
12/8/98 10:47am	24.7/581.51	4.393
12/9/98 1:36pm	24.9/577.36	4.169
12/10/98 2:15pm	25.1/584.00	3.960
12/11/98 9:18am	24.6/583.44	3.797
12/14/98 9:09am	24.8/584.55	3.274

$\lambda = -0.002026$ (Least Squares)

$T_a = 298.05$ K (Average)

$P_a = 580.71$ Torr

$$M = (V_1/k) \cdot (P_1/P_{sup}) \cdot (T_{sup}/T_2) = 0.48936845$$

H₂ Diffusion Coefficient

$$D = -\lambda M = 9.906 \times 10^{-4} \text{ moles/hr./mole fract}$$

$$2.752 \times 10^{-7} \text{ moles/sec/mole fract}$$

Comments: Bag sealed to flange w/caulk, Rubber gasket, hose clamp.

HS-1 X

HS-2 A

H₂ Diffusion Project Traveler

564082

Analyst: KMN/PDN

Date and Time: 6/22/98 2:15pm

Bag Number: HS-2B

Closure type: Heat Sealed

Knowns: $P_{sup} = 760 \text{ Torr}$ $T_{sup} = 273.15 \text{ K}$ $k = 22.414 \text{ liters/mole}$ $V_m = 239.34 \text{ cc}$

Bag Volume (V_i) Determination

$P_a = \underline{580.56}$ $P_1 = \underline{970.63}$ $P_2 = \underline{871.00}$ $\Delta P = \underline{99.63}$

%He in bag = 0.724 % (Measured on Mass Spec.)

$$V_i = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{5632.018 \text{ mL}}{5.632 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
6/22/98 4:02pm	25.3/581.78	5.208
6/23/98 10:43am	25.2/581.98	4.901
6/23/98 4:02pm	25.6/579.78	4.816
6/24/98 8:06am	24.3/581.24	4.542
6/24/98 2:09pm	25.8/580.28	4.467
6/25/98 10:27am	24.7/582.00	4.122
6/25/98 4:04pm	25.8/580.31	4.044
6/26/98 8:40am	24.5/581.35	3.788
average	25.1/581.09	

$\lambda = \underline{-0.003604}$ (Least Squares)

$T_a = \underline{25.1^\circ \text{C}} (298.25^\circ \text{K})$
(Average)

$P_a = \underline{581.09 \text{ Torr}}$

$M = (V_i/k) \cdot (P/P_{sup}) \cdot (T_{sup}/T_a) = 0.1760 \text{ moles}$

H₂ Diffusion Coefficient

$$D = -\lambda M = \underline{6.341 \times 10^{-3} \text{ moles/hr./mole fraction}}$$

$$\underline{1.761 \times 10^{-7} \text{ moles/sec./mole fraction}}$$

Comments:

HS-2 B

Stand #4

Date and Time: 7/15/98 2:41pm

Closure type: heat sealed

Bag Volume (V_b) Determination

%He in bag = 0.833 (Measured on Mass Spec.)

$$V_1 = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% He} - 1 \right] = \frac{4861.899 \text{ mL}}{4.861}$$

Date and Time Temp./Press. % H₂ in Bag

$$\lambda = \frac{-0.004234}{26.8^{\circ}\text{C}} \text{ (Least Squares)}$$
$$T_a = \underline{300.0 \text{ K}} \quad (\text{Average})$$
$$P_g = \underline{585.172 \text{ Torr}}$$
$$M \cdot (V_1/k) \cdot (P/P_{\text{atm}}) \cdot (T_{\text{atm}}/T_1) = 0.1520 \text{ moles}$$

AUG 26.8/585.172

$$D = -\lambda M = 6.434 \times 10^{-4} \text{ moles/} \cancel{\text{cm}} / \text{mole frac}$$
$$1.788 \times 10^{-7} \text{ moles/sec./mole fraction}$$

Comments: Blue

HS-2C

H₂ Diffusion Project Traveler

Analyst: PDN

Date and Time: 8/4/97 11:02 am

Bag Number: HS-3

Closure type: Heat Sealed

Knowns: $P_{sp} = 760$ Torr $T_{sp} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.63$ cc

Bag Volume (V₁) Determination

$P_o = 584.43$ $P_1 = 977.81$ $P_2 = 771.30$ $\Delta P = 206.51$

%He in bag = 0.634 (Measured on Mass Spec.)

$$V_1 = \frac{\Delta P \cdot V_m}{P_o} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{13270.84}{13.27} \text{ L}$$

H₂ Diffusion Coefficient (D) Determination

	Date and Time	Temp./Press.	% H ₂ in Bag
1	8/4/97 1:47 pm	25.5/588.55	5.443
2	8/4/97 4:26 pm	25.6/588.39	5.402
3	8/5/97 9:18 am	24.0/588.81	5.162
4	8/5/97 1:41 pm	25.3/587.08	5.088
5	8/5/97 4:30 pm	25.7/585.99	5.026
6	8/6/97 16:23	25.7/584.72	4.640 88
7	8/7/97 3:54 pm	23.7/585.29	4.326
8	8/8/97 4:12 pm	25.3/581.70	4.003
9	8/11/97 8:21 am	22.3/584.40	3.188

mean: 24.8/586.10

$\lambda = -0.00328$ (Least Squares)

$T_a = 24.8^\circ \text{C}$ or 297.95 K

$P_a = 586.10$ torr (Average)

$$M = (V_1/k) \cdot (P_o/P_a) \cdot (T_{sp}/T_a) = 0.4186 \text{ mole}$$

H₂ Diffusion Coefficient

$$D = -\lambda M = 1.373 \times 10^{-3} \text{ m}^2/\text{s/mole fraction}$$

$$3.814 \times 10^{-7} \text{ m}^2/\text{sec/mole fraction}$$

Comments:

HS-3

Stand #3

H₂ Diffusion Project TravelerAnalyst: PDNDate and Time: 12/4/98 3:00pmBag Number: HS-3XClosure type: Heat SealedKnowns: $P_{sup} = 760$ Torr $T_{sup} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.34$ cc**Bag Volume (V₁) Determination**
 $P_a = \frac{587.94}{\text{pdn } 12/4/98}$
 $P_1 = 1022.42$
 $P_2 = 915.56$
 $\Delta P = 106.86$
%He in bag = 0.34 (Measured on Mass Spec.)

$$V_1 = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{12833.37 \text{ mL}}{12.83 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
12/4/98 3:32pm	25.6/576.04	5.159
12/7/98 11:18am	24.5/577.16	4.522
12/8/98 10:52am	24.4/581.64	
12/8/98 11:06am	24.5/581.20	4.323
12/9/98 1:31pm	24.9/577.36	4.096
12/10/98 2:10pm	25.1/583.97	3.877
12/11/98 9:23am	24.4/583.50	3.744
12/14/98 9:02am	24.7/584.52	3.225

 $\lambda = -0.002013$ (Least Squares)
 $T_a = 297.25 \text{ K}$
 $P_a = 580.65 \text{ Torr}$ (Average)

$$M = (V_1/k) \cdot (P_1/P_a) \cdot (T_m/T_a) = 0.400927589$$

H₂ Diffusion Coefficient

$$D = -\lambda M = 8.07 \times 10^{-4} \text{ moles/hr./mole fract}$$

$$2.242 \times 10^{-7} \text{ moles/sec/mole fract}$$

Comments: Bag sealed to flange
w/caulk, rubber gasket,
hose clamp.

HS-3 X

H₂ Diffusion Project Traveler

Analyst: PDN

Date and Time: 8/11/97 11:46 am

Bag Number: HS-4A

Closure type: Heat Sealed

Knowns: $P_{up} = 760$ Torr $T_{up} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.63$ cc

Bag Volume (V_1) Determination

$P_a = 585.37$ $P_1 = 969.54$ $P_2 = 594.36$ $\Delta P = 375.18$

%He in bag = 1.826 (Measured on Mass Spec.)

$$V_1 = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{8255.86 \text{ mL}}{8.256 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

	Date and Time	Temp./Press.	% H ₂ in Bag	
1	8/11/97 4:36 pm	24.9/583.61	4.839	$\lambda = -0.00311$ (Least Squares)
2	8/12/97 9:02 am	22.0/585.89	4.665	$T_u = 297.00$
3	8/12/97 9:03 pm	24.8/585.63	4.567	$P_a = 584.90$ (Average)
4	8/13/97 8:41 am	23.4/586.89	4.355	
5	8/13/97 2:41 pm	24.7/586.17	4.280	
6	8/15/97 10:58	23.2/581.28	3.6687	$M = (V_1/k) \cdot (P_a/P_{up}) \cdot (T_{up}/T_a) = 0.2607$

H₂ Diffusion Coefficient

$$D = -\lambda M = \frac{2.252 \times 10^{-7}}{\text{mols/sec/mole fraction}}$$

Comments:

~~200~~ Bag holder #1

HS-4 A

Stand #3

H₂ Diffusion Project TravelerAnalyst: PDNYKMNDate and Time: 7/15/98 2:18pmBag Number: HS-4 BClosure type: heat sealedKnowns: $P_{up} = 760$ Torr $T_{up} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.34$ cc**Bag Volume (V₁) Determination** $P_o = 586.06$ $P_1 = 995.87$ $P_2 = 893.71$ $\Delta P = 102.16$ %He in bag = 0.748 (Measured on Mass Spec.)

$$V_1 = \frac{\Delta P \cdot V_m}{P_o} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{5535.945 \text{ mL}}{5.54 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
7/15/98 3:57pm	27.8/589.58	4.785
7/16/98 8:18am	26.4/588.90	4.286
7/17/98 2:38pm	26.6/585.85	3.908
7/20/98 8:23am	25.7/583.91	1.973
7/21/98 1:38pm	27.2/582.82	1.540
Avg.	26.78/585.122	

 $\lambda = -0.00806$ (Least Squares)

26.78°C

 $T_o = 299.9$ K

(Average)

 $P_o = 585.112$ Torr

$$M = (V_1/k) \cdot (P/P_o) \cdot (T_o/T_2) = 0.173^{172573} \text{ moles}$$

H₂ Diffusion Coefficient

$$D = -\lambda M = 1.397 \times 10^{-3} \text{ moles/L} \cdot (\text{mole fraction})$$

$$3.880 \times 10^{-7} \text{ moles/sec} \cdot (\text{mole fraction})$$

Comments: B/C

HS-4 B

Stand #2

H₂ Diffusion Project Traveler

Analyst: P.D.N.

Date and Time: 12/4/98 3:00pm

Bag Number: HS-4X

Closure type: Heat Sealed

Knowns: $P_{sip} = 760 \text{ Torr}$ $T_{sip} = 273.15 \text{ K}$ $k = 22.414 \text{ liters/mole}$ $V_m = 239.34 \text{ cc}$

Bag Volume (V_i) Determination

$P_a = 584.20$ $P_1 = 961.66$ $P_2 = 840.50$ $\Delta P = 121.16$

%He in bag = 0.457 (Measured on Mass Spec.)

$$V_i = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{10812.037 \text{ mL}}{10.812 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time Temp./Press. % H₂ in Bag

12/4/98 3:43pm 25.6/576.08 5.337

12/7/98 11:10am 24.4/577.95 4.517

12/8/98 10:57am 24.4/581.44 4.254

12/9/98 1:44pm 24.9/577.35 3.965

12/10/98 2:04pm 25.2/582.98 3.715

12/10/98 2:20pm 25.1/584.00 3.715

12/11/98 8:56am 24.5/583.46 3.539

12/11/98 9:05am 24.4/583.50 3.539

12/14/98 9:15am 24.8/584.53 2.902

24.8/580.69

$\lambda = -0.002607$ (Least Squares)

$T_a = 297.95 \text{ K}$

(Average)

$P_a = 580.69$

$$M = (V/k) \cdot (P/P_{sip}) \cdot (T_{sip}/T_a) = 0.337887923$$

H₂ Diffusion Coefficient

$$D = -\lambda M = 8.909 \times 10^{-4} \text{ moles/hr./mole fact}$$

$$2.447 \times 10^{-7} \text{ moles/sec/mole fact}$$

Comments: Bag sealed to flange w/caulk, rubber gasket, hose clamp.

HS-4 X

H₂ Diffusion Project Traveler

Analyst: PDA

Date and Time: 8/4/97 11:01 am

Bag Number: HS-5A

Closure type: Heat Sealed

Knowns: $P_{sp} = 760 \text{ Torr}$ $T_{sp} = 273.15 \text{ K}$ $k = 22.414 \text{ liters/mole}$ $V_m = 239.63 \text{ cc}$

Bag Volume (V_i) Determination

$P_a = \underline{584.43}$ $P_i = \underline{998.87}$ $P_f = \underline{675.98}$ $\Delta P = \underline{322.89}$

%He in bag = 0.726 (Measured on Mass Spec.)

$$V_i = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{18103.48 \text{ mL}}{18.10 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

	Date and Time	Temp./Press.	% H ₂ in Bag
1	8/4/97 1:37 pm	25.5/588.55	5.182
2	8/4/97 4:15 pm	25.6/588.39	5.168
3	8/5/97 9:11 am	24.0/588.81	5.010
4	8/5/97 1:36 pm	25.3/587.08	5.001
5	8/5/97 4:25 pm	25.7/585.74	4.955
6	8/6/97 16:32	25.7/589.72	4.709
7	8/7/97 3:50	23.7/585.29	4.461
8	8/8/97 4:22 pm	25.3/588.70	4.268
9	8/11/97 8:13 am	22.3/584.40	3.752

mean: 24.8/586.10

$\lambda = \underline{-0.00202}$ (Least Squares)

$T_a = \underline{24.8^\circ \text{C or } 297.95 \text{ K}}$

(Average)

$P_a = \underline{586.10 \text{ Torr}}$

$M = (V/k) \cdot (P_i/P_{sp}) \cdot (T_{sp}/T_a) = \underline{0.5709 \text{ mole}}$

H₂ Diffusion Coefficient

$D = -\lambda M = \underline{1.153 \times 10^{-3} \text{ moles/hr./mole fract.}}$

$\underline{3.203 \times 10^{-7} \text{ moles/sec./mole fract.}}$

Comments:

HS-5A

H₂ Diffusion Project Traveler

Stand # 5

Analyst: KMN/PDN

Date and Time: 6/22/98 2:30 pm

Bag Number: HS-5 B

Closure type: Heat sealed

Knowns: $P_{sp} = 760 \text{ Torr}$ $T_{sp} = 273.15 \text{ K}$ $k = 22.414 \text{ liters/mole}$ $V_m = 239.34 \text{ cc}$

Bag Volume (V_i) Determination

$P_a = 581.26$ $P_i = 964.48$ $P_f = 865.17$ $\Delta P = 99.31$

%He in bag = 0.792% (Measured on Mass Spec.)

$$V_i = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{5122.23 \text{ mL}}{5.122 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
6/22/98 7:20 pm	25.0/582.22	5.019
6/23/98 11:00 am	24.9/581.77	4.520
6/23/98 3:49 pm	25.4/579.86	4.420
6/24/98 8:20 pm	24.3/581.23	4.004
6/24/98 1:50 pm	25.7/580.68	3.889
6/25/98 10:45 am	24.6/582.01	3.401
6/25/98 3:50 pm	25.9/580.47	3.295
6/26/98 9:54 am	24.4/581.39	2.948
average	25.0/581.2	

$\lambda = -0.005973$ (Least Squares)

$T_a = 25.0^\circ \text{C} (298.15^\circ \text{K})$
(Average)

$P_a = 581.2 \text{ Torr}$

$M = (V_i/k) \cdot (P_i/P_a) \cdot (T_{sp}/T_a) = 0.1601 \text{ moles}$

H₂ Diffusion Coefficient

$$D = -\lambda M = 9.563 \times 10^{-4} \text{ moles/sec. / mole fraction}$$

$$2.656 \times 10^{-7} \text{ moles/sec. / mole fraction}$$

Comments:

HS-5 B

Stand 4

H₂ Diffusion Project Traveler

Analyst: PDN

Date and Time: 9/24/98 2:03pm

Bag Number: HS-5C

Closure type: Heat Sealed

Knowns: $P_{up} = 760$ Torr $T_{up} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.34$ cc

Bag Volume (V_i) Determination

$P_o = 583.5$ $P_i = 905.1$ $P_z = 785.2$ $\Delta P = 119.9$

%He in bag = 0.83 (Measured on Mass Spec.)

$$V_i \cdot \frac{\Delta P \cdot V_m}{P_o} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{5876.19 \text{ mL}}{5.88 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	%H ₂ in Bag
9/24/98 2:26pm	26.6/581.2	5.30
9/25/98 8:18am	26.0/580.4	4.75
9/25/98 11:28am	26.4/579.9	4.66
9/25/98 3:56pm	26.7/577.8	4.54
9/28/98 7:44am	24.5/583.5	3.05

$\lambda = -0.006197$ (Least Squares)

$T_o = 26.04^\circ\text{C}$ or 299.19K

$P_o = 580.56$ (Average)

$M \cdot (V_i/k) \cdot (P_i/P_o) \cdot (T_o/T_z) = 0.1830$ mole

H₂ Diffusion Coefficient

$$D = -\lambda M = \frac{1.13 \times 10^{-3} \text{ m/hr.} \cdot \text{m.}^2}{3.149 \times 10^{-7} \text{ m/sec.} \cdot \text{m.}^2}$$

Comments:

HS-5 C

H₂ Diffusion Project Traveler

Analyst: PDN

Date and Time: 8/27/97 8:13 am

Bag Number: HT-1A

Closure type: Horse Tail

Knowns: $P_{up} = 760$ Torr $T_{up} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.63$ cc

Bag Volume (V₁) Determination

$P_a = 588.80$ $P_1 = 996.11$ $P_2 = 665.82$ $\Delta P = 330.29$

%He in bag = 2.200 (Measured on Mass Spec.)

$$V_1 = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{5975.648 \text{ mL}}{5.9756 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time Temp./Press. % H₂ in Bag

8/27/97	28.5/585.05	
8/27/97 3:47 pm	27.9/583.69	4.567
8/28/97 9:08 am	24.1/584.42	2.240
8/28/97 3:54 pm	26.3/583.20	1.694
8/29/97 1:51 pm	25.9/582.67	0.698
9/2/97 7:57 am	21.4/588.42	0.018
9/3/97 1:03 pm	23.9/588.80	0.0148

$\lambda = \frac{-0.0364}{-0.0406}$ (Least Squares)

$T_a = \frac{278.05 \text{ K}}{278.25 \text{ K}}$
 $P_a = \frac{585.20 \text{ torr}}{584.48 \text{ torr}}$ (Average)

$$M = (V_1/k) \cdot (P_1/P_2) \cdot (T_1/T_2) = \frac{0.1881}{0.1878}$$

all as.

st 5

reason

→ mean (n=6) 24.9/585.20

→ mean (n=5) 25.1/584.48

below detection limit PDN 20448

H₂ Diffusion Coefficient

$$D = -\lambda M =$$

$1.90 \times 10^{-6} \quad n=6$
 $2.118 \times 10^{-6} \quad n=5 \checkmark$

Comments: bag mount #5

HT-1 A.G.)
HT-1 a

HT-1A (b)
HT-1b

Stand #1

H₂ Diffusion Project TravelerAnalyst: PDN/KMNDate and Time: 7/15/98 2:23 pmBag Number: HT-1 B (2)Closure type: horse tailKnowns: $P_{up} = 760$ Torr $T_{up} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.34$ cc**Bag Volume (V₁) Determination** $P_o = 585.76$ $P_1 = 993.27$ $P_2 = 884.89$ $\Delta P = 108.38$ %He in bag = 1.382 (Measured on Mass Spec.)

$$V_1 = \frac{\Delta P \cdot V_m}{P_o} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{3160.042 \text{ mL}}{3.16 \text{ L}}$$

H₂ Diffusion Coefficient (D) DeterminationDate and Time Temp./Press. % H₂ in Bag7/15/98 4:10 pm 27.7/584.65 5.2307/16/98 8:08 am 26.4/588.47 1.9337/17/98 2:30 pm 26.6/585.85 0.1697/20/98 8:34 am 25.9/583.97 0.0057/21/98 1:45 pm 27.1/582.73 0.004Avg 26.74/585.128

$$\lambda = \frac{-0.06203151 \text{ PDN } 9/21/98}{26.74^\circ \text{C}} \text{ (Least Squares)}$$

$$T_o = 299.9 \text{ K} \text{ (Average)}$$

$$P_o = 585.128 \text{ Torr}$$

$$M = (V_1/k) \cdot (P_1/P_o) \cdot (T_o/T_1) = 0.0989 \text{ moles}$$

H₂ Diffusion Coefficient

$$6.13 \times 10^{-3} \text{ PDN } 9/24/98$$

$$D = -\lambda M = 5.239 \times 10^{-6} \text{ moles/hr. / mole fraction}$$

$$1.704 \times 10^{-6} \text{ PDN } 4/24/98$$

$$1.455 \times 10^{-6} \text{ moles/sec. / mole fraction}$$

Comments: Blue

HT-1 B

HT-1 B 2

Stand 3

H₂ Diffusion Project Traveler

Analyst: PDN

Date and Time: 9/24/98 2:03pm

Bag Number: HT-1C

Closure type: Horse Tail

Knowns: $P_{up} = 760$ Torr $T_{up} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.34$ cc

Bag Volume (V_1) Determination

$P_o = 583.8$ $P_1 = 1028.7$ $P_2 = 905.1$ $\Delta P = 123.6$

%He in bag = 1.05 (Measured on Mass Spec.)

$$V_1 = \frac{\Delta P \cdot V_m}{P_o} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{4775.25 \text{ mL}}{4.78 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time Temp./Press. %H₂ in Bag

9/24/98 2:41pm 26.6/581.2 5.50

9/25/98 8:03am 26.0/580.4 2.19

9/25/98 11:43am 26.4/579.9 1.79

9/25/98 3:16pm 26.7/577.8 1.50

9/28/98 8:03am 24.5/583.5 0.05

8:11am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

9/28/98 8:22am 24.5/583.5 0.05

$\lambda = -0.05225$ (Least Squares)

$T_o = 26.04^\circ\text{C}$ or 299.19 K
(Average)

$P_o = 580.56$

$M = (V_1/k) \cdot (P/P_o) \cdot (T_o/T_2) = 0.14873$

H₂ Diffusion Coefficient

$$D = -\lambda M = 7.77 \times 10^{-3} \text{ m}^2/\text{hr}/\text{m. fract.}$$

$$2.16 \times 10^{-6} \text{ m}^2/\text{sec}/\text{m. fract.}$$

Comments:

N
-put
-shad!

HT-1 C

H₂ Diffusion Project Traveler

Stand #5

Analyst: PDN/KMN

Date and Time: 5/28/98 8:50

Bag Number: HT-2

Closure type: Horse Tail

Knowns: $P_{sup} = 760$ Torr $T_{sup} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.34$ cc

Bag Volume (V_1) Determination

$P_a = 580.18$ $P_1 = 980.99$ $P_2 = 880.45$ $\Delta P = 100.54$

%He in bag = 0.756 (Measured on Mass Spec.)

$$V_1 = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \underline{5.44 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp. ^{°C} / Press. ^{Torr}	% H ₂ in Bag
5/28/98 2:30	25.0°C / 582.23	4.96
5/29/98 7:42 am	23.8 / 583.05	2.826
5/29/98 1:52 pm	24.6 / 582.13	2.041
5/29/98 3:51 pm	25.1 / 581.42	1.497
6/1/98 10:35 am	24.6 / 582.26	0.150
6/1/98 2:01 pm	24.9 / 581.09	0.124
6/2/98 8:03 am	23.8 / 581.39	0.134 *
6/2/98 8:26 am	24.0 / 581.34	0.084
mean	24.6 / 581.93	

$$\lambda = \frac{-0.03675}{24.6^\circ\text{C}} \text{ (Least Squares)}$$

$$T_a = 297.7^\circ\text{K}$$

(Average)

$$P_a = 581.93 \text{ Torr}$$

$$M = (V/k) \cdot (P/P_a) \cdot (T_a/T_0) = 0.1705 \text{ moles}$$

H₂ Diffusion Coefficient

$$D = -\lambda M = 6.266 \times 10^{-3} \text{ moles/hr./mole fraction}$$

$$1.741 \times 10^{-6} \text{ moles/sec./mole fraction}$$

Comments: ^{Some} Gas in bag inadvertently pumped away. ^{Why} have to re-do this bag.

HT-2

H₂ Diffusion Project Traveler

Analyst: PDN

Date and Time: 8/11/97 11:46 am

Bag Number: HT-3A

Closure type: Horse Tail

Knowns: $P_{up} = 760$ Torr $T_{up} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.63$ cc

Bag Volume (V_i) Determination

$P_u = 584.81$ $P_i = 996.70$ $P_s = 679.92$ $\Delta P = 316.78$

%He in bag = 1.015 (Measured on Mass Spec.)

$$V_i = \frac{\Delta P \cdot V_m}{P_u} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{12,658.65 \text{ mL}}{12.66 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
8/11/97 4:30 pm	24.9/583.61	5.122
8/12/97 8:56 am	22.0/585.89	3.488
8/12/97 3:57 pm	24.8/585.63	2.944
8/13/97 8:36 am	23.9/586.89	1.890
8/13/97 2:35 pm	24.7/586.17	1.600
8/15/97 11:05 am	23.3/581.23	0.447

$\lambda = -0.02713$ (Least Squares)

$T_u = 297.00$
(Average)

$P_u = 584.90$

$$M = (V_i/k) \cdot (P_u/P_{up}) \cdot (T_{up}/T_u) = 0.3997$$

H₂ Diffusion Coefficient

$$D = -\lambda M = \frac{3.013 \times 10^{-6}}{\text{moles/sec/mole fraction}}$$

Comments:

Bag holder #2

HT-3 / A

H₂ Diffusion Project Traveler

Stand # 1

Analyst: KMN/PDN

Date and Time: 6/22/98 2:20pm

Bag Number: HT-3 B

Closure type: Horse Tail

Knowns: $P_{sp} = 760$ Torr $T_{sp} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.34$ cc

Bag Volume (V₁) Determination

$P_a = 580.60$ $P_1 = 968.55$ $P_2 = 866.57$ $\Delta P = 101.98$

%He in bag = 0.977% (Measured on Mass Spec.)

$$V_1 = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{4260.836 \text{ mL}}{4.261 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
6/22/98 4:11pm	25.2/581.71	5.449
6/23/98 10:35pm	25.3/581.87	2.549
6/23/98 3:55pm	25.7/579.83	2.035
6/24/98 7:58am	24.5/581.15	1.033
6/24/98 2:15pm	25.5/580.13	0.799
6/25/98 10:20am	24.7/581.87	0.339
6/25/98 4:10pm	25.8/580.24	0.266
6/26/98 8:36am	24.4/581.38	0.143
average	25.1/581.03	

$\lambda = -0.04161$ (Least Squares)

$T_a = 25.1^\circ\text{C} (298.25^\circ\text{K})$
(Average)

$P_a = 581.03$ Torr

$M = (V_1/k) \cdot (P_1/P_{sp}) \cdot (T_{sp}/T_a) = 0.1331$ moles

H₂ Diffusion Coefficient

$D = -\lambda M = 5.539 \times 10^{-3}$ moles/hr./mole fraction

1.538×10^{-6} moles/sec./mole fraction

Comments: Red line

HT-3 B

Stand. 1

H₂ Diffusion Project TravelerAnalyst: PDNDate and Time: 9/24/98 2:03pmBag Number: HT-3CClosure type: Horse TailKnowns: $P_{sp} = 760$ Torr $T_{sp} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.34$ ccBag Volume (V₁) Determination $P_a = 583.7$ $P_1 = 949.3$ $P_2 = 834.7$ $\Delta P = 114.6$ %He in bag = 0.71 (Measured on Mass Spec.)

$$V_1 = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{6571.39 \text{ mL}}{6.57 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
9/24/98 2:32pm	26.6/581.2	5.49
9/25/98 8:13am	26.0/580.4	2.43
9/25/98 11:33am	26.4/579.9	2.08
9/25/98 3:55pm	26.7/577.8	
9/25/98 3:46pm	26.7/577.8	1.71
9/25/98 7:54am	24.5/583.5	0.08

 $\lambda = -0.04746$ (Least Squares) $T_a = 26.04^\circ \text{C}$ or 299.19 K

(Average)

 $P_a = 580.56$

$$M = (V_1/k) \cdot (P_1/P_a) \cdot (T_a/T_0) = 0.204 \times 10^{-4} \text{ g}$$

H₂ Diffusion Coefficient

$$D = -\lambda M = 9.70 \times 10^{-3} \text{ m/hr/m.fact}$$

$$2.695 \times 10^{-6} \text{ m/sec/m.fact.}$$

Comments:

HT-3 C

H₂ Diffusion Project Traveler

Analyst: PDN Date and Time: 8/11/97 11:46am
 Bag Number: HT-4 Closure type: Horse Tail
 Knowns: $P_{\text{atm}} = 760 \text{ Torr}$ $T_{\text{atm}} = 273.15 \text{ K}$ $k = 22.414 \text{ liters/mole}$ $V_m = 239.63 \text{ cc}$

Bag Volume (V_1) Determination

$P_a = 584.63$ $P_1 = 964.57$ $P_2 = 602.69$ $\Delta P = 361.88$

%He in bag = 2.039 (Measured on Mass Spec.)

$$V_1 = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{7126.24 \text{ mL}}{7.126 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
8/11/97 4:14pm	24.7/583.61	5.357
8/12/97 8:35am	22.0/585.89	3.608
8/12/97 3:41pm	24.8/585.63	3.030
8/13/97 8:21am	23.8/586.87	1.940
8/13/97 2:30pm	24.7/586.17	1.657
8/15/97 11:35	23.3/581.2	0.485

$\lambda = -0.02644$ (Least Squares)
 $T_a = 297.00$ (Average)
 $P_a = 584.90$
 $M = (V_1/k) \cdot (P_a/P_{\text{atm}}) \cdot (T_{\text{atm}}/T_a) = 0.2250$

mean: 23.85/584.90

H₂ Diffusion Coefficient

$$D = -\lambda M = 1.653 \times 10^{-6} \text{ m}^2/\text{sec/mole fraction}$$

Comments:

Bag holder #5

HT-4

H₂ Diffusion Project Traveler

Analyst: PDN

Date and Time: 8/4/97 11:02 am

Bag Number: HT-5

Closure type: Horse Tail

Knowns: $P_{up} = 760$ Torr $T_{up} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.63$ cc

Bag Volume (V_i) Determination

$P_a = 584.43$ $P_i = 1003.12$ $P_f = 801.55$ $\Delta P = 201.57$

Left calib bulb
open so
 $V_m = 239.63$
+ 51.757
291.387 cc

%He in bag = 1.676 (Measured on Mass Spec.)

$$V_i = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{5895.89 \text{ mL}}{4.85 \text{ L}} = 5.90 \text{ L}$$

H₂ Diffusion Coefficient (D) Determination

	Date and Time	Temp./Press.	% H ₂ in Bag
1	8/4/97 2:00 pm	25.5/588.55	5.244
2	8/4/97 4:36 pm	25.6/588.39	4.925
3	8/5/97 9:32 am	24.0/588.81	2.964
4	8/5/97 1:55 pm	25.3/587.08	2.643
5	8/5/97 4:43 pm	25.7/585.94	2.420
6	8/6/97 16:00	25.6/584.72	1.099 exp
7	8/7/97 4:04 pm	23.7/585.29	0.510
8	8/8/97 4:37 pm	25.3/581.70	0.230
9	8/11/97 8:34 am	22.3/584.40	0.036

mean: 24.8/586.10

$\lambda = -0.03107$ (Least Squares)

$T_a = 24.8^\circ \text{C}$ or 297.95 K (Average)

$P_a = 586.10$ torr

$$M = (V_i/k) \cdot (P_a/P_{up}) \cdot (T_{up}/T_a) = 0.1861 \text{ mole}$$

H₂ Diffusion Coefficient

$$D = -\lambda M = 5.782 \times 10^{-6} \text{ m}^2/\text{hr}/\text{m}^2 \text{ fuel}$$

$$1.601 \times 10^{-6} \text{ moles/sec/mole fuel}$$

Comments:

HT-5

Stand #2

H₂ Diffusion Project Traveler

Analyst: PDN/KMN

Date and Time: 5/28/98 9:10

Bag Number: WT-1

Closure type: Wire Tie

Knowns: $P_{sp} = 760$ Torr $T_{sp} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.34$ cc

Bag Volume (V_1) Determination

$P_a = 581.28$ $P_1 = 981.35$ $P_2 = 881.45$ $\Delta P = 99.9$

%He in bag = 0.795 (Measured on Mass Spec.)

$$V_1 = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \underline{5.13 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
5/28/98 2:47	25.3/581.18	5.21
5/29/98 8:03	23.8/583.05	3.631
5/29/98 2:27	24.6/582.15	3.171
5/29/98 4:30	25.5/581.07	3.023
6/1/98 11:03	25.0/582.18	0.624
6/1/98 2:39	25.3/580.96	0.574
6/2/98 2:50	24.3/581.28	0.381

mean 24.8/581.81

$$\lambda = \frac{-0.02328}{24.8^\circ\text{C}} \text{ (Least Squares)}$$

$$T_a = \underline{298.0^\circ\text{K}} \text{ (Average)}$$

$$P_a = \underline{581.81 \text{ Torr}}$$

$$M = (V_1/k) \cdot (P/P_a) \cdot (T_{sp}/T_a) = 0.1606 \text{ moles}$$

H₂ Diffusion Coefficient

$$D = -\lambda M = \underline{3.739 \times 10^{-3} \text{ moles/hr./mole fraction}}$$

$$\underline{1.039 \times 10^{-6} \text{ moles/sec./mole fraction}}$$

Comments:

$$\frac{D}{V_1} = \underline{2.025 \times 10^{-7}}$$

WT-1

WT-2

H₂ Diffusion Project Traveler

Analyst: PDN

Date and Time: 8/11/77 11:46 am

Bag Number: WT-3A

Closure type: Wire Tie

Knowns: $P_{up} = 760$ Torr $T_{up} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.63$ cc

Bag Volume (V_i) Determination

$P_a = 584.63$ $P_1 = 944.01$ $P_2 = 618.78$ $\Delta P = 329.23$

%He in bag = 1.969 (Measured on Mass Spec.)

$$V_i = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{6853.52 \text{ mL}}{6.85 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
8/11/77 4:20 pm	24.7/583.61	5.593
8/12/77 8:41 am	22.0/585.87	5.001
8/12/77 3:46 pm	24.8/585.63	4.751
8/13/77 8:25 am	23.4/586.89	4.062
9/13/77 2:25 pm	24.7/586.17	3.852
8/15/77 11:24	23.3/581.21	2.423

$\lambda = -0.00933$ (Least Squares)

$T_a = 297.00$

$P_a = 584.90$ (Average)

$M = (V_i/k) \cdot (P_a/P_{up}) \cdot (T_{up}/T_a) = 0.2162$

H₂ Diffusion Coefficient

$$D = -\lambda M = \frac{5.586 \times 10^{-7} \text{ moles/sec/mole fraction}}{5.6089}$$

pdn 8/27/77

Comments:

WT-3A

Stand #4

H₂ Diffusion Project TravelerAnalyst: KMN/PDNDate and Time: 6/22/98 2:25 pmBag Number: WT-3 BClosure type: Wire TieKnowns: $P_{sp} = 760$ Torr $T_{sp} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.34$ cc**Bag Volume (V_i) Determination** $P_o = 581.34$ $P_i = 967.67$ $P_2 = 865.78$ $\Delta P = 101.89$ %He in bag = 0.800 % (Measured on Mass Spec.)

$$V_i = \frac{\Delta P \cdot V_m}{P_o} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{5201.616 \text{ L}}{5.2016 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
6/22/98 2:31 pm	25.1/582.00	5.222
6/23/98 11:10 am	24.8/581.68	3.928
6/23/98 3:42 pm	25.4/579.91	3.670
6/24/98 8:27 am	24.4/581.32	2.775
6/24/98 1:39 pm	25.3/580.73	2.564
	25.1/581.19	
6/25/98 10:41 am	24.6/582.08	1.797
6/25/98 3:42 pm	25.6/580.58	1.663
6/26/98 9:00 am	24.5/581.49	1.246
average	25.0/581.19	

 $\lambda = -0.01618$ (Least Squares) $T_o = 25.0^\circ \text{C} (298.15^\circ \text{K})$
(Average) $P_o = 581.19$ Torr $M = (V/k) \cdot (P/P_o) \cdot (T_{sp}/T_o) = 0.1626$ moles**H₂ Diffusion Coefficient**

$$D = -\lambda M = 2.631 \times 10^{-3} \text{ moles/hr. / mole frac.}$$

$$7.307 \times 10^{-7} \text{ moles/sec. / mole fraction}$$

Comments:

WT-3 B

H₂ Diffusion Project Traveler

Analyst: PDN/KMN

Date and Time: 7/15/98 2:20 pm

Bag Number: WT-3 C

Closure type: wire tie

Knowns: $P_{sip} = 760 \text{ Torr}$ $T_{sip} = 273.15 \text{ K}$ $k = 22.414 \text{ liters/mole}$ $V_m = 239.34 \text{ cc}$

Bag Volume (V_b) Determination

$$P_0 = 585.91 \quad P_1 = 995.65 \quad P_2 = 895.39 \quad \Delta P = 100.26$$

%He in bag = 0.985 (Measured on Mass Spec.)

$$V_1 \cdot \frac{\Delta P \cdot V_m}{P_s} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{4116.922 \text{ mL}}{4.12 \text{ L}}$$

H. Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
7/15/98 4:05	27.7/584.58	5.274
7/16/98 8:12a	26.4/588.46	3.284
7/17/98 5:35p	26.6/585.85	1.102
7/20/98 8:30a	25.9/583.97	0.131
7/21/98 1:40pm	27.2/582.77	0.050

AUG 26.76/585.136

$$\lambda = \frac{-0.03305 \pm \sqrt{0.01982 \text{ mm}}}{26.76^\circ \text{C}} \quad (\text{Least Squares})$$
$$T_a = \underline{299.9 \text{ K}} \quad \text{--- (Average)}$$
$$P_a = 585.126 \text{ Torr}$$

$$M = (V_1/k) \cdot (P/P_{\text{atm}}) \cdot (T_{\text{atm}}/T) = \frac{0.1289}{81498 \text{ kPa}} \text{ moles}$$

H₂ Diffusion Coefficient

$$D = -\lambda M = \frac{4.260 \times 10^{-3} \text{ moles/lr. (mole fract.)}}{81098 \text{ mm}}$$

1.183×10^{-6}
 ~~1.076×10^{-6}~~ moles/sec./mole fraction

0198 KmH
Comments: Blue

WT-3 C

H, Diffusion Project Traveler

Analyst: PDN

Date and Time: 8/27/97 8:14am

Bag Number: WT-4A

Closure type: Wire Tie

Knowns: $P_{\text{sig}} = 760 \text{ Torr}$ $T_{\text{sig}} = 273.15 \text{ K}$ $k = 22.414 \text{ liters/mole}$ $V_m = 239.63 \text{ cc}$

Bag Volume (V_b) Determination

$$P_a = 588.80 \quad P_1 = 1013.29 \quad P_2 = 740.91 \quad \Delta P = 272.38$$

%He in bag = 1.039 (Measured on Mass Spec.)

$$V_1 \cdot \frac{\Delta P \cdot V_m}{P_s} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{10558.376}{10.558} \text{ L}$$

H, Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
8/27/97 4:04 ^{pm}	27.9/583.69	5.160
8/28/97 7:23 ^{am}	24.1/584.42	4.438
8/28/97 4:08 ^{pm}	26.3/583.20	4.215
8/29/97 2:05 ^{pm}	25.9/582.69	3.414
9/2/97 7:44 ^{am}	21.4/588.42	1.551
9/3/97 1:15 ^{pm}	23.9/588.80	1.179

$$\lambda = \underline{-0.00886} \quad (\text{Least Squares})$$
$$T_u = \underline{298.07} \quad (\text{Average})$$
$$P_u = 585.20$$

$$M = (V_1/k) \cdot (P_g/P_{\text{atm}}) \cdot (T_{\text{atm}}/T_g) = 0.3324$$

H, Diffusion Coefficient

$$D = -\lambda M = 8.180 \times 10^{-7} \text{ m/sec/m fr}$$

Comments: bag mount #2

$$\frac{D}{v_1} = 7.748 \times 10^{-8}$$

WT-4A

Stand # 3

Date and Time: 6/22/98 2:05 pm

Closure type: Wire Tie

Bag Volume (V_b) Determination

%He in bag = 0.913 % (Measured on Mass Spec.)

$$V_1 = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{4493.33 \text{ mL}}{4.493 \text{ L}}$$

mmHg (°C) (Torr)

$$\lambda = \underline{-0.01617} \quad (\text{Least Squares})$$
$$T_a = \underline{25.2^\circ\text{C}} (\underline{298.35^\circ\text{K}})$$

(Average)

$$P_o = \underline{581.13 \text{ Torr}}$$

$$M = (V/k) \cdot (P/P_{\text{sat}}) \cdot (T_{\text{sat}}/T) = 0.1403 \text{ moles}$$

[illegible]

$$D = -\lambda M = 2.269 \times 10^{-3} \text{ moles/hr./mole Frac.}$$

$$6.303 \times 10^{-7} \text{ moles/sec./mole fraction}$$

Comments:

WT-4 B

Stand 2

H₂ Diffusion Project Traveler

Analyst: PDN

Date and Time: 9/24/98 2:03pm

Bag Number: WT-4C

Closure type: Wire Tie

Knowns: $P_{\text{atm}} = 760 \text{ Torr}$ $T_{\text{atm}} = 273.15 \text{ K}$ $k = 22.414 \text{ liters/mole}$ $V_m = 239.34 \text{ cc}$

Bag Volume (V_1) Determination

$P_a = 583.9$ $P_1 = 960.4$ $P_2 = 851.8$ $\Delta P = 108.6$

%He in bag = 0.86 (Measured on Mass Spec.)

$$V_1 = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{513.65 \text{ mL}}{5.13 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
9/24/98 2:36pm	26.6/581.2	5.47
9/25/98 8:08am	26.0/580.4	4.15
9/25/98 11:37am	26.4/579.9	3.93
9/25/98 3:19pm	26.7/577.8	3.68
9/28/98 7:59am	24.5/583.5	1.21

$\lambda = -0.01701$ (Least Squares)

$T_a = 26.04^\circ \text{C}$ or 299.19 K
(Average)

$P_a = 580.56$

$$M = (V_1/k) \cdot (P_1/P_{\text{atm}}) \cdot (T_{\text{atm}}/T_a) = 0.1596$$

H₂ Diffusion Coefficient

$$D = -\lambda M = 2.715 \times 10^{-3} \text{ m}^2/\text{hr}/\text{m. fract}$$

$$7.54 \times 10^{-7} \text{ m}^2/\text{sec}/\text{m. fract}$$

Comments:

WT-4 C

H₂ Diffusion Project Traveler

Analyst: PDN

Date and Time: 8/4/97 11:01 am

Bag Number: WT-5

Closure type: Wire Tie

Knowns: $P_{sup} = 760$ Torr $T_{sup} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.63$ cc

Bag Volume (V_i) Determination

$P_o = 584.43$ $P_i = 1079.16$ $P_s = 597.09$ $\Delta P = 482.07$

%He in bag = 2.534 (Measured on Mass Spec.)

$$V_i = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{7602.66}{7.60} \text{ mL}$$

H₂ Diffusion Coefficient (D) Determination

	Date and Time	Temp./Press.	% H ₂ in Bag
1.	8/4/97 1:16 pm	25.5/588.55	5.203
2.	8/4/97 4:07 pm	25.6/588.39	5.136
3.	8/5/97 7:00 am	24.0/588.81	4.450
4.	8/5/97 1:28 pm	25.3/587.08	4.309
5.	8/5/97 4:21 pm	25.7/585.94	4.172
6.	8/6/97 16:41	26.7/589.72	3.218
7.	8/7/97 3:44 pm	23.7/585.29	2.546
8.	8/8/97 4:18 pm	25.3/581.70	1.929
9.	8/11/97 8:04 am	21.3/584.40	0.896

mean: 24.8/586.10

$\lambda = -0.01083$ (Least Squares)

$T_a = 24.8^\circ \text{C}$ or 297.95 K

$P_a = 586.10$ Torr (Average)

17.00 B = 583.68, T = 26.0

$M = (V_i/k) \cdot (P_i/P_{sup}) \cdot (T_{sup}/T_a) = 0.2397 \text{ mole}$

H₂ Diffusion Coefficient

$$D = -\lambda M = \frac{2.596 \times 10^{-3}}{7.212} \text{ m/hr./m. fract.}$$

$$= 7.192 \times 10^{-7} \text{ m/sec./m. fract.}$$

Comments:

$$\frac{D}{V_i} = 9.489 \times 10^{-8}$$

WT-5

Stand #1

Date and Time: 5/28/78 9.21

Closure type: Plastic Tie

Bag Volume (V_b) Determination

%He in bag = 0.77 (Measured on Mass Spec.)

$$V_1 \cdot \frac{\Delta P \cdot V_m}{P_2} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \underline{7.12 \text{ L}}$$

Date and Time Temp./Press. % H₂ in Bag

$$\lambda = \underline{-0.01709} \quad (\text{Least Squares})$$

24.87°C

$$T_u = \underline{298.0^\circ\text{K}} \quad (\text{Average})$$
$$P_o = \underline{581.82 \text{ Torr}}$$
$$M = (V/k) \cdot (P/P_{\infty}) \cdot (T_{\infty}/T) = 0.2229 \text{ moles}$$

H₂ Diffusion Coefficient

$$D = -\lambda M = 3.809 \times 10^{-3} \text{ moles/hr./mole fract.}$$
$$1.058 \times 10^{-6} \text{ moles/sec. / mole fraction}$$

Comments:

A-66

PT-1

H₂ Diffusion Project Traveler

Analyst: PDN

Date and Time: 8/4/97 11:02 am

Bag Number: PT-2

Closure type: Plastic Tie

Knowns: $P_{sp} = 760$ Torr $T_{sp} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.63$ cc

Bag Volume (V_1) Determination

$P_a = 587.43$ $P_1 = 989.76$ $P_2 = 751.37$ $\Delta P = 238.39$

%He in bag = 1.167 (Measured on Mass Spec.)

$$V_1 \cdot \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} \cdot 1 \right] = \frac{8278.05 \text{ mL}}{8.28 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

	Date and Time	Temp./Press.	% H ₂ in Bag
1	8/4/97 1:53 pm	25.5/588.55	5.436
2	8/4/97 4:32 pm	25.6/588.39	5.385
3	8/5/97 9:25 am	24.0/588.81	4.460
4	8/5/97 1:48 pm	25.3/587.08	4.207
5	8/5/97 4:37 pm	25.7/585.94	4.089
6	8/6/97 16:13	25.7/584.72	2.886 <i>exp</i>
7	8/7/97 3:59 pm	23.7/585.29	2.007
8	8/8/97 4:32 pm	25.3/581.70	1.353
9	8/11/97 8:30 am	20.3/584.40	0.459

mean: 24.8/586.10
11
277.95 K

$\lambda = -0.01530$ (Least Squares)

$T_a = 24.8^\circ \text{C}$ or 277.95 K
 (Average)

$P_a = 586.10$ torr

$M \cdot (V_1/k) \cdot (P_a/P_{sp}) \cdot (T_{sp}/T_a) = 0.2612 \text{ mole}$

H₂ Diffusion Coefficient

$$D = -\lambda M = \frac{3.996 \times 10^{-3} \text{ m}^2/\text{hr}/\text{mole}}{1.110 \times 10^{-6} \text{ m}^2/\text{sec}/\text{m. fact.}}$$

Comments:

PT-2

H₂ Diffusion Project Traveler

Analyst: PDN

Date and Time: 8/11/97 11:46 am

Bag Number: PT-3A

Closure type: Plastic Tie

Knowns: $P_{sp} = 760 \text{ Torr}$ $T_{sp} = 273.15 \text{ K}$ $k = 22.414 \text{ liters/mole}$ $V_m = 239.63 \text{ cc}$

Bag Volume (V₁) Determination

$P_a = 584.81$ $P_i = 1020.69$ $P_2 = 706.97$ $\Delta P = 313.72$

%He in bag = 1.825 (Measured on Mass Spec.)

$$V_1 = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{6915.23 \text{ mL}}{6.915 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag	$\lambda = -0.01662$ (Least Squares)
8/11/97 4:24 pm	24.9/583.61	5.262	$T_a = 297.00$ (Average)
8/12/97 8:51 am	22.0/585.89	4.237	
8/12/97 3:52 pm	24.8/585.63	3.824	
8/13/97 8:30 am	23.4/586.89	2.903	
8/13/97 2:30 pm	24.7/586.17	2.641	
8/15/97 11:12	23.3/581.20	1.184 eye	$P_a = 584.90$

$$M = (V_1/k) \cdot (P_a/P_{sp}) \cdot (T_{sp}/T_a) = 0.2184$$

H₂ Diffusion Coefficient

$$D = -\lambda M = 1.008 \times 10^{-6} \text{ m}^2/\text{sec}/\text{m}^2 \text{ foot}$$

Comments:

Bag holder #3

PT-3A

Stand #5

H₂ Diffusion Project TravelerAnalyst: DDN/KMNDate and Time: 7/15/98 2:36 pmBag Number: PT-3 BClosure type: plastic tieKnowns: $P_{sp} = 760$ Torr $T_{sp} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.34$ cc**Bag Volume (V_i) Determination** $P_a = \underline{585.84}$ $P_1 = \underline{994.68}$ $P_2 = \underline{894.92}$ $\Delta P = \underline{99.76}$ %He in bag = 0.745 (Measured on Mass Spec.)

$$V_i \cdot \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{5429.862 \text{ mL}}{5.43 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
7/15/98 3:52 pm	27.8/584.57	5.515
7/16/98 8:23 am	26.4/588.40	3.460
7/17/98 2:25 pm	26.6/585.85	1.562
7/20/98 8:38 am	26.1/584.04	0.262
7/21/98 1:30 pm	27.0/582.90	0.120
Avg	26.78/585.152	

 $\lambda = \underline{-0.02579}$ (Least Squares)

26.78 °C

 $T_a = \underline{299.9 \text{ K}}$

(Average)

 $P_a = \underline{585.152 \text{ Torr}}$ $M \cdot (V_i/k) \cdot (P/P_a) \cdot (T_{sp}/T_a) = 0.1699 \text{ moles}$ **H₂ Diffusion Coefficient**

$$D = -\lambda M = \underline{4.382 \times 10^{-3} \text{ moles/hr./mole fraction}}$$

$$\underline{1.217 \times 10^{-6} \text{ moles/sec./mole fraction}}$$

Comments: Blue

PT-3 B

Stand 5

H₂ Diffusion Project Traveler

Analyst: PDN

Date and Time: 9/24/98 2:03pm

Bag Number: PT-3C

Closure type: Plastic Tie

Knowns: $P_{sup} = 760$ Torr $T_{sup} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.34$ cc

Bag Volume (V_1) Determination

$P_a = 583.6$ $P_1 = 977.0$ $P_2 = 875.4$ $\Delta P = 101.6$

%He in bag = 0.87 (Measured on Mass Spec.)

$$V_1 = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{4747.66 \text{ mL}}{4.75 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
9/24/98 2:22 pm	26.6 / 581.2	5.58
9/25/98 8:23 am	26.0 / 580.4	2.83
9/25/98 11:24 am	26.4 / 579.9	2.53
9/25/98 3:51 pm	26.7 / 577.8	2.13
9/28/98 7:48 am	24.5 / 583.5	0.19

$\lambda = -0.03781$ (Least Squares)

$T_a = 26.04^\circ \text{C}$ or 299.19 K

$P_a = 580.56$ (Average)

$$M \cdot (V_1/k) \cdot (P_1/P_a) \cdot (T_a/T_0) = 0.14780$$

H₂ Diffusion Coefficient

$$D = -\lambda M = 5.59 \times 10^{-3} \text{ m}^2/\text{s} \cdot \text{m}^2 \text{ React}$$

$$1.55 \times 10^{-6} \text{ m}^2/\text{s} \cdot \text{m}^2 \text{ React}$$

Comments:

PT-3 C

H₂ Diffusion Project Traveler

Analyst: FDN

Date and Time: 8/27/97 8:14am

Bag Number: PT-4

Closure type: Plastic Tie

Knowns: $P_{sup} = 760 \text{ Torr}$ $T_{sup} = 273.15 \text{ K}$ $k = 22.414 \text{ liters/mole}$ $V_m = 239.63 \text{ cc}$

Bag Volume (V₁) Determination

$P_a = \underline{588.80}$ $P_1 = \underline{970.19}$ $P_2 = \underline{750.98}$ $\Delta P = \underline{219.21}$

%He in bag = 1.151 (Measured on Mass Spec.)

$$V_1 = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{766.798 \text{ mL}}{7.66 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
8/27/97 4:08pm	27.9/583.69	5.282
8/28/97 9:27am	24.1/588.42	3.710
8/28/97 4:13pm	26.3/583.20	3.262
8/29/97 2:10pm	25.9/582.67	2.110
9/2/97 7:36am	21.4/588.42	0.333
9/3/97 1:20pm	23.7/588.80	0.185
mean	24.92/585.20	

$\lambda = \underline{-0.02036}$ (Least Squares)

$T_a = \underline{298.07}$ (Average)

$P_a = \underline{585.20 \text{ torr}}$

$$M = (V_1/k) \cdot (P_1/P_a) \cdot (T_{sup}/T_a) = 0.24115$$

H₂ Diffusion Coefficient

$$D = -\lambda M = \underline{1.364 \times 10^{-6} \text{ m}^2/\text{sec}}$$

Comments: bag mount #1

PT-4

Stand #3

H₂ Diffusion Project Traveler

Analyst: PDN/KMN

Date and Time: 5/28/98 9:02

Bag Number: PT-5

Closure type: Plastic Tie

Knowns: $P_{sp} = 760$ Torr $T_{sp} = 273.15$ K $k = 22.414$ liters/mole $V_m = 239.34$ cc

Bag Volume (V_b) Determination

$P_a = 580.80$ $P_i = 981.94$ $P_2 = 881.02$ $\Delta P = 100.92$

%He in bag = 0.800 (Measured on Mass Spec.)

$$V_1 = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \underline{5.16 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
5/28/98 2:41	25/582.1	4.93
5/29/98 8:00am	23.8/583.05	3.096
5/29/98 2:16pm	24.7/582.12	2.626
5/29/98 4:18pm	25.4/581.18	2.486
6/1/98 10:59am	24.7/582.18	0.381
6/1/98 2:21pm	25.0/581.08	0.347
6/2/98 8:40am	24.2/581.34	0.225

mean 24.7/581.86

$$\lambda = \frac{-0.02754}{24.7^\circ \text{C}} \quad (\text{Least Squares})$$

$$T_a = \underline{297.8^\circ \text{K}} \quad (\text{Average})$$

$$P_a = \underline{581.86 \text{ Torr}}$$

$$M = (V_1/k) \cdot (P_i/P_{sp}) \cdot (T_{sp}/T_a) = 0.1617 \text{ moles}$$

H₂ Diffusion Coefficient

$$D = -\lambda M = \underline{4.452 \times 10^{-3} \text{ moles/hr./mole fract.}}$$

$$\underline{1.237 \times 10^{-6} \text{ moles/sec./mole fraction}}$$

Comments:

PT-5

APPENDIX B

Project Travelers and Determination of Lambda for Additional Experiments

(Bags Mounted on 2-liter Steel Chamber)

H₂ Diffusion Project Traveler

Analyst: PDN Date and Time: 3/17/99 11:11 a.m.
 Bag Number: P-1 blue tape Closure type: Plastic Tic
 Knowns: $P_{up} = 760 \text{ Torr}$ $T_{up} = 273.15 \text{ K}$ $k = 22.414 \text{ liters/mole}$ $V_m = 239.34 \text{ cc}$

Bag Volume (V₁) Determination

$P_a = \frac{711.40}{576.78}$ $P_1 = \frac{963.28}{936.28}$ $P_2 = \frac{823.77}{936.28}$ $\Delta P = 112.51$
 $\% \text{He in bag} = 2.34$ (Measured on Mass Spec.)

after purging w H₂/Ar
 Valve left open
 2 minutes for
 press equil b.

$$V_1 = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{He}} - 1 \right] = \frac{1948.485 \text{ mL}}{1.75 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag	Chamber
3/17/99 11:45	24.5 / 576.77	5.904	
3/18/99 11:23	25.1 / 579.47	3.186	
3/18/99 1:28 pm	25.5 / 578.65	3.016	
3/17/99 9:06 am	24.0 / 581.33	1.813	
3/17/99 3:45 pm	25.1 / 581.30	1.536	
3/22/99 8:27 am	24.4 / 577.74	0.536	

Computer Crashed!
 Reboot. → no H₂ detected.

$$\lambda = -0.02606 \text{ (Least Squares)}$$

$$T_a = 298.05 \text{ (Average)}$$

$$P_a = 578.78$$

$$M = (V_1/k) \cdot (P_1/P_a) \cdot (T_a/T_p) = 0.06072$$

H₂ Diffusion Coefficient

$$D = -\lambda M = 4.395 \times 10^{-7} \text{ m}^2/\text{sec/mole fract.}$$

3/22/99 8:44 am	24.4 / 577.78	0.281
3/22/99 3:44 pm	25.6 / 576.31	0.234
3/23/99 10:07 am	25.0 / 578.59	0.144
mean = 24.9 / 578.28		

Comments: 16 bolts
 diff. thru closure only
 mounted in steel apparatus
 w/closure sticking through flange

Plastic Tie (Closure Only) P-1

H₂ Diffusion Project Traveler

Analyst: PDN

Date and Time: 3/27/99 10:16am

Bag Number: P-2

Closure type: Plastic Tie

Knowns: $P_{\text{atm}} = 760 \text{ Torr}$ $T_{\text{atm}} = 273.15 \text{ K}$ $k = 22.414 \text{ liters/mole}$ $V_m = 239.34 \text{ cc}$

Bag Volume (V₁) Determination

$P_a = 583.46$ $P_1 = 885.84$ $P_2 = 775.90$ $\Delta P = 109.94$

%He in bag = 2.230 (Measured on Mass Spec.)

$$V_1 = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \underline{1.977 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
3/27/99 10:44	24.6/583.47	5.861
3/29/99 15:45	25.7/580.80	4.725
3/30/99 8:20	24.8/579.54	2.314
3/30/99 15:40	26.0/575.26	1.678
3/31/99 10:32	25.4/573.75	0.733

$\lambda = -0.04347$ (Least Squares)

$T_a = 298.49$
(Average)

$P_a = 578.57$

$$M = (V_1/k) \cdot (P_1/P_a) \cdot (T_m/T_a) = 0.06145$$

25.34/578.57

H₂ Diffusion Coefficient

$$D = -\lambda M = \underline{7.419 \times 10^{-7} \text{ m}^2/\text{sec/mole fract}}$$

Comments: Closure Only - 16 bolts
Seal - 2L chamber (steel)
Flushed w/H₂ + Ar, Valves left open for
10 minutes to equilibrate Press.

P-2 Closure Only

H₂ Diffusion Project Traveler

Analyst: PDN

Date and Time: 3/31/99 11:20 am

Bag Number: P-7

Closure type: Plastic Tie

Knowns: $P_{stp} = 760 \text{ Torr}$ $T_{stp} = 273.15 \text{ K}$ $k = 22.414 \text{ liters/mole}$ $V_m = 239.34 \text{ cc}$

Bag Volume (V₁) Determination

$P_a = 573.42$ $P_i = 961.26$ $P_2 = \frac{856.34}{\cancel{854.34}}$ $\Delta P = 104.92$

%He in bag = 2.145 (Measured on Mass Spec.)

$$V_1 = \frac{\Delta P \cdot V_m}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{104.92 \cdot 239.34}{573.42} \times \left[\frac{100}{2.145} - 1 \right] = \frac{98}{1.944} \text{ L}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time Temp./Press. % H₂ in Bag $\lambda = -0.03034$ (Least Squares)

3/31/99 11:42 25.7/573.19 5.865 $T_a = 297.75$

3/31/99 15:40 26.1/570.17 Computer Crashed! (Average)

3/31/99 15:47 26.1/570.16 5.132 $P_a = 573.37$

4/1/99 8:02 24.7/570.19 1.477

4/2/99 14:24 25.4/569.61 1.217

4/5/99 8:35 23.3/574.40 0.171

4/5/99 15:54 23.7/576.63 0.183

4/6/99 8:34 23.6/579.44 0.080

$$M = (V_1/k) \cdot (P_a/P_{stp}) \cdot (T_{stp}/T_a) = \frac{0.061695}{0.7538}$$

H₂ Diffusion Coefficient

$$D = -\lambda M = \frac{6.365 \times 10^{-6}}{\text{moles/sec/mole fraction}}$$

Comments: After flushing w/ H₂/Ar - valve left open for 10 minutes
test of closure only - 16 bolts!

P-7 Closure Only

H₂ Diffusion Project Traveler

Analyst: PDN

Date and Time: 11/19/96 11:14

Bag Number: P-2

Closure type: Plastic Tie

Knowns: $P_{stp} = 760 \text{ Torr}$ $T_{stp} = 273.15 \text{ K}$ $k = 22.414 \text{ liters/mole}$ $V_2 = 196.27 \text{ cc}$

Bag Volume (V₁) Determination

$P_o = 581.64 \text{ Torr}$ $P_1 = 983.1 \text{ Torr}$ $P_2 = 717.8 \text{ Torr}$ $\Delta P = 265.3 \text{ Torr}$

%He in bag = 1.204 (Measured on Mass Spec.)

$$V_1 \cdot \frac{\Delta P \cdot V_2}{P_o} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{7345.98 \text{ cc}}{7.3 \text{ Liters}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
11/19/96 15:57	26.7°/580.8T	5.168 %
11/20/96 7:30	26.0°/579.2T	3.827 %
11/20/96 10:25	26.4°/579.7T	3.631 %
11/20/96 13:41	26.0°/578.7T	3.416 %
11/20/96 15:55	26.6°/579.0T	3.277 %
11/21/96 7:17	24.9°/582.5T	2.338 %
11/21/96 11:44	25.6°/581.3T	2.131 %
11/21/96 14:19	25.6°/580.2T	
11/21/96 15:48	26.2°/580.2T	1.947 %

Mean: 26.05/580.18

$\lambda = -0.02057$ (Least Squares)

$T_o = 299.20$
 $P_o = 580.18$ } (Average)

$$M = (V_1/k) \cdot (P_o/P_{stp}) \cdot (T_{stp}/T_o) = 0.22618$$

H₂ Diffusion Coefficient

$$D = -\lambda M = 1.297 \times 10^{-6} \text{ moles/sec/mole fract}$$

Comments: Full Bag

P-2 Full Bag

H₂ Diffusion Project Traveler

Analyst: PDN

Date and Time: 11/19/96 14:12

Bag Number: P-7

Closure type: Plastic Tie

Knowns: $P_{sup} = 760$ Torr $T_{sup} = 273.15$ K $k = 22.414$ liters/mole $V_2 = 196.27$ cc

Bag Volume (V₁) Determination

$P_o = 580.75$ Torr $P_1 = 1040.5$ Torr $P_2 = 743.2$ Torr $\Delta P = 297.3$ Torr

%He in bag = 1.946 (Measured on Mass Spec.)

$$V_1 \cdot \frac{\Delta P \cdot V_2}{P_o} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{5062.70 \text{ cc}}{5.06 \text{ Liters}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
11/19/96 16:09	26.6°/580.8T	5.458%
11/20/96 7:38	26.2°/579.2T	4.339%
11/20/96 10:34	26.6°/579.6T	4.127%
11/20/96 13:50	26.1°/578.6T	3.931%
11/20/96 16:03	26.2°/579.0T	3.780%
11/21/96 7:25	24.7°/582.6T	2.862%
11/21/96 11:52	25.6°/581.3T	2.656%
11/21/96 15:55	26.8°/580.2T	2.464%

$\lambda = -0.017$ (Least Squares)

$T_o = 299.18$
 $P_o = 580.16$ } (Average)

$$M \cdot (V_1/k) \cdot (P_1/P_o) \cdot (T_o/T_2) = 0.1573$$

H₂ Diffusion Coefficient

$$D = -\lambda M = \frac{7.430 \times 10^{-7}}{\text{moles/sec/mole fraction}}$$

Comments: Full Bag

P-7 Full Bag

H₂ Diffusion Project Traveler

99
3/23/99 10:50 am

Analyst: PDN

Date and Time: 12/3/96 9:47

Bag Number: ~~W-9~~ W-9 yellow tape Closure type: wire Plastic Tie

Knowns: $P_{sp} = 760$ Torr $T_{sp} = 273.15$ K $k = 22.414$ liters/mole $V_g = 196.27$ cc
239.34

Bag Volume (V_g) Determination

$P_a = 578.23$ $P_i = 999.78$ $P_2 = 893.92$ $\Delta P = 105.86$

%He in bag = 2.14 (Measured on Mass Spec.)

$$V_g = \frac{\Delta P \cdot V_2}{P_a} \times \left[\frac{100}{\% \text{ He}} - 1 \right] = \frac{2003.72 \text{ mL}}{2.004 \text{ L}}$$

H₂ Diffusion Coefficient (D) Determination

Date and Time	Temp./Press.	% H ₂ in Bag
3/23/99 11:14 am	25.2/578.00	5.916
3/23/99 15:50	25.7/575.67	4.769
3/24/99 9:16	25.1/578.75	2.170
3/24/99 16:06	25.0/578.94	1.586
3/25/99 8:18	25.1/581.81	0.775
3/25/99 15:02	25.7/579.25	0.574
3/26/99 10:51	24.5/578.00	0.238

mean	25.34/578.66	

$\lambda = -0.045$ (Least Squares)

$T_a = 298.49$ (Average)

$P_a = 578.66$

$M = (V_g/k) \cdot (P_i/P_a) \cdot (T_a/T_2) = 0.06230$

H₂ Diffusion Coefficient

$$D = -\lambda M = 7.79 \times 10^{-7} \text{ m}^2/\text{s}$$

Comments: after purging w/ H₂/Ar -
valve left open for 7 minutes
for press. equil.
closure only

W-9