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Precision Volume Measurement System

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PRECISION VOLUME MEASUREMENT SYSTEM

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Abstract

A new precision volume measurement system based on a Kansas City Plant (KCP) design was built to support the volume measurement needs of the Gas Transfer Systems (GTS) department at Sandia National Labs (SNL) in California. An engineering study was undertaken to verify or refute KCP's claims of 0.5% accuracy. The study assesses the accuracy and precision of the system. The system uses the ideal gas law and precise pressure measurements (of low-pressure helium) in a temperature and computer controlled environment to ratio a known volume to an unknown volume.

Acknowledgment

The author gratefully acknowledges the designer and builder of the PVMS in California, Andrew Shugard. Also, Lyle Cain from KCP the designer of the original system, which this PVMS was based on.

Contents

Page

Figures

Tables

Abbreviations

cc or cm^3	cubic centimeter
GTS	Gas Transfer Systems Department
KCP	Kansas City Plant
PVMS	Precision Volume Measurement System
REF	Reference Volume
UUT	Unit Under Test

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1 Project Background

1.1 Motivation

A new precision volume measurement system was completed in 2002 for the volume measurement needs of the Gas Transfer Systems (GTS) department. The GTS department tests and designs tritium reservoirs. During testing it is important to know the exact volume of a test reservoir after it has been welded and machined. The original Precision Volume Measurement System (PVMS) was built in 1983 and uses a pressure ratioing system to relate an unknown volume to a known volume, as documented in the Klevgard reports [1]. Since then, the original system became contaminated with trace amounts of silicone oil, making the system unusable for clean, volume measurement. The new PVMS system allows a clean environment for accurate volume measurement while reducing the testing time from a few hours to only 10 minutes. It has the capability to accurately measure volumes ranging from 25 to 2500 cm^3.

The design of the PVMS was based on an existing system in the Kansas City Plant (KCP) designed by Lyle J Cain. KCP claims their design has an accuracy of 0.5%. Before Sandia's system could be put to laboratory use, the accuracy of the new PVMS needed to be verified. The following engineering studies and testing chronicled herein were used to calibrate and determine the new PVM system's accuracy limits.

1.2 System Features

Figures 1.1 and 1.2 show the entire PVMS system. The computer runs a code allowing the user to run a volume test manually or automatically. The automatic run mode allows the temperature and volume data to be saved in a file, and the measurement system can be run up to 15 times on the same volume without user intervention.

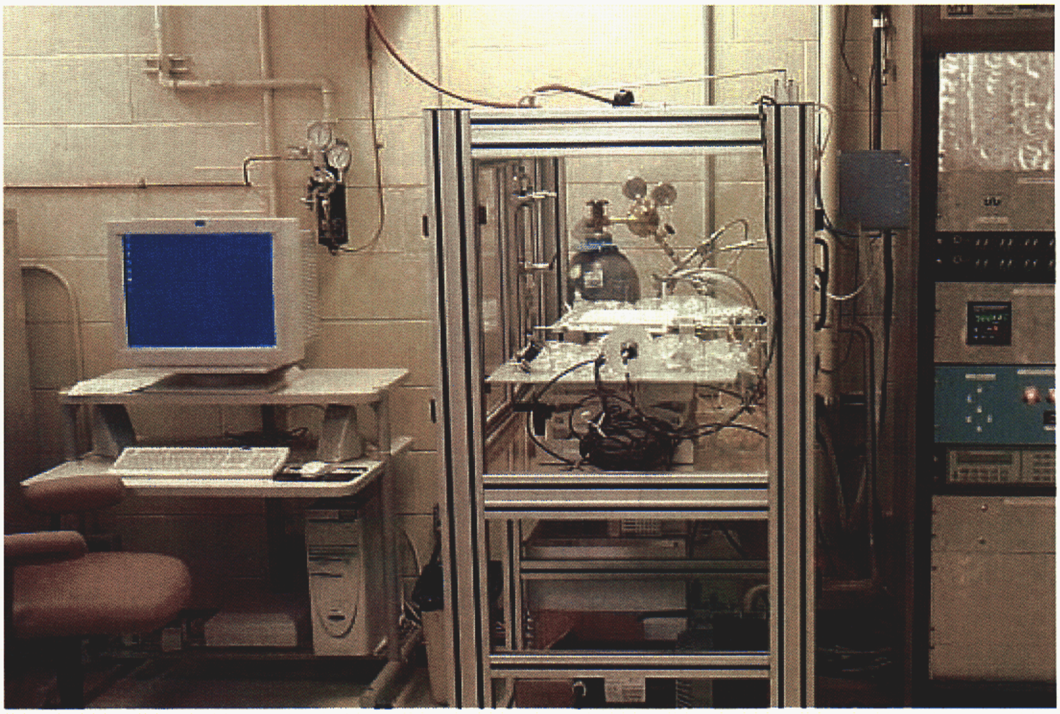

Figure 1.1: Front View of PVMS.

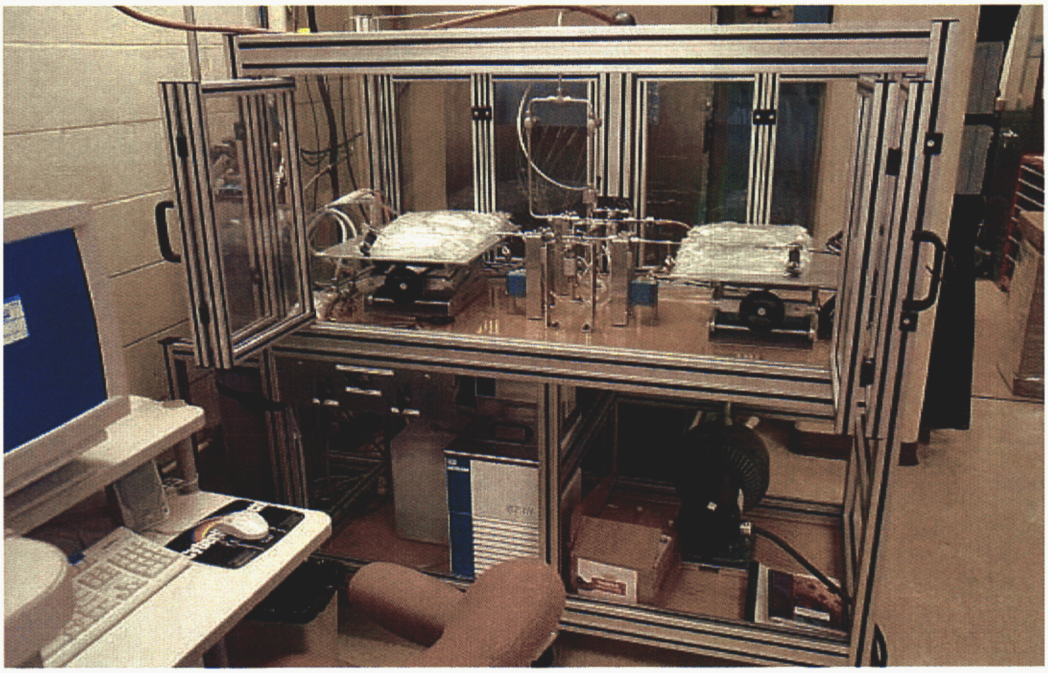

Figure 1.2: Side View of PVMS.

1.3 Operation Summary

The new PVMS uses a pressure ratioing system to determine the volume of a vessel. This is the same method used in the old PVMS documented by Klevgard, and it is based on the ideal gas law.

$$PV = nRT \qquad \text{Ideal Gas Relation} \qquad (1\text{-}1)$$

In this relation P is pressure, V is volume, n is the number of moles, R is the ideal gas constant and T is the temperature. When using an ideal gas and holding temperature constant in a closed system, Boyle's Law can be used to relate a known volume, V_{kn}, to an unknown volume, V_{unk}.

$$P_{kn} \cdot V_{kn} = P_{unk} \cdot V_{unk} = Const \qquad \text{Boyle's Law} \qquad (1\text{-}2)$$

The relation to determine V_{unk} becomes:

$$V_{unk} = V_{kn} \cdot \frac{P_{kn}}{P_{unk}} \qquad \text{Basic Unknown Volume Equation} \qquad (1\text{-}3)$$

The PVMS uses a ratioing system similar to this to determine the volume of the unknown vessel. Although the system is based on first principles, it is slightly more complicated than the ideal scenario. Figure 1.3 shows the diagram of the PVM system and Figure 1.4 shows the corresponding view of the actual hardware.

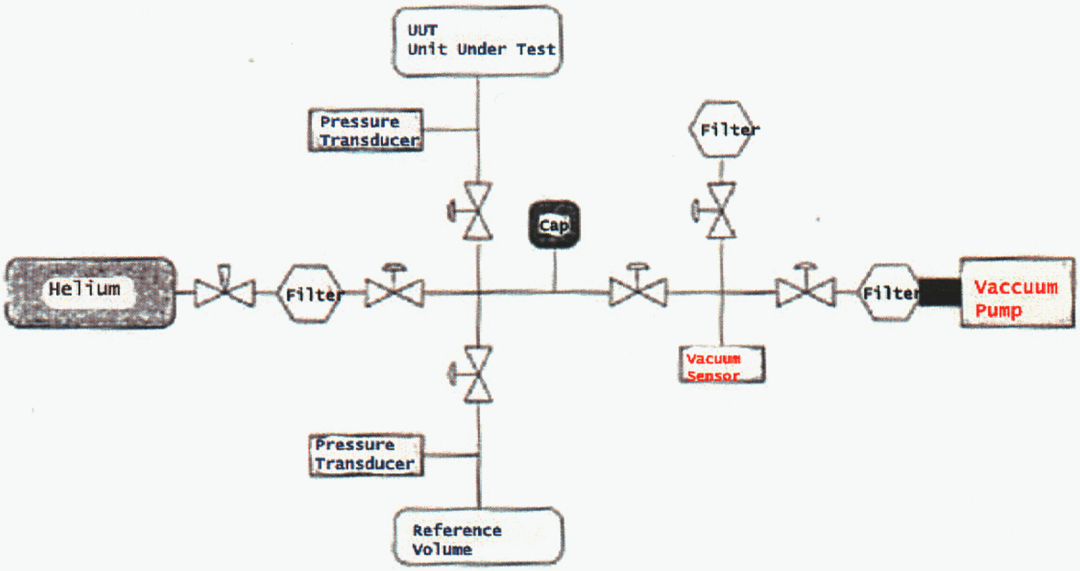

Figure 1.3: Diagram of PVMS from L. J. Cain [2].

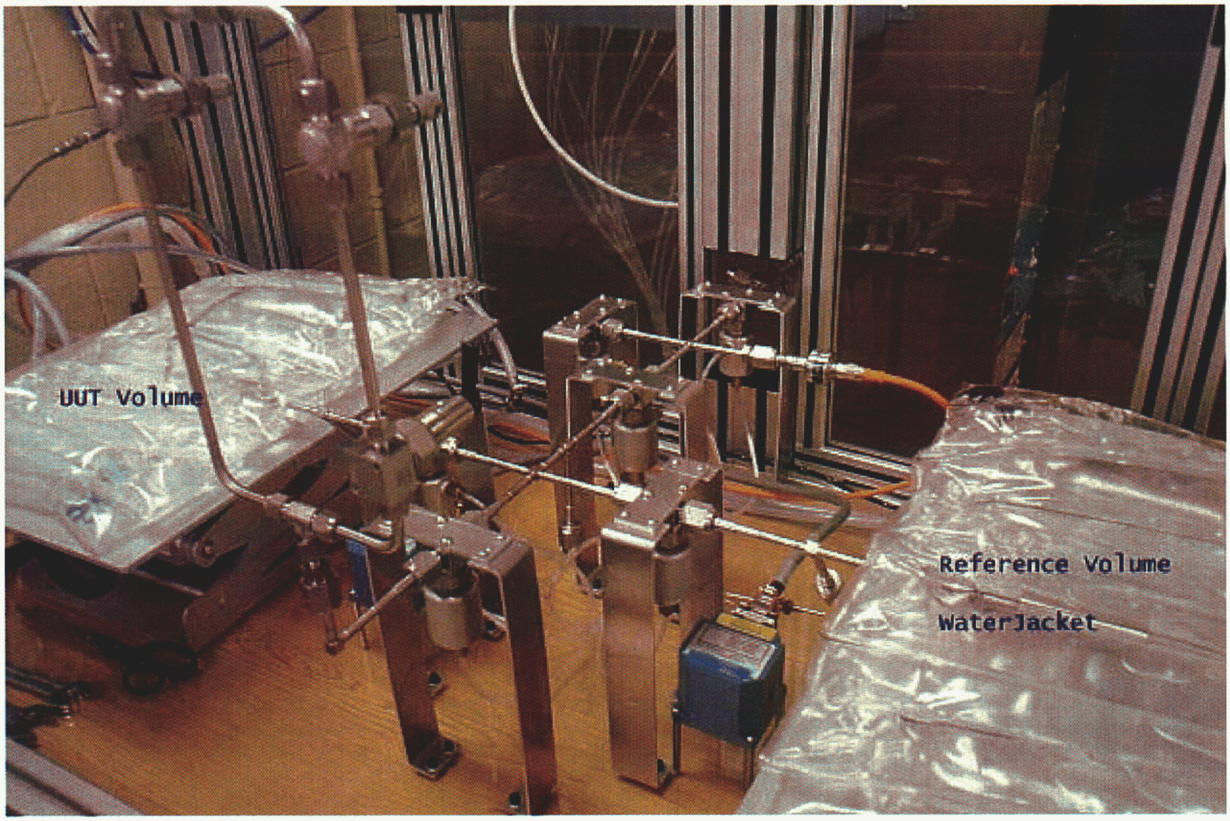

Figure 1.4: Close up View of Actual PVMS.

In order to meet the assumptions made in Boyle's law, low pressure Helium, 30 psia, is used as the "ideal" working gas. It is also important to keep the temperatures of the unknown volume and the known volume constant, respectively UUT (Unit Under Test) and REFERENCE VOLUME in the diagram. The solution developed by KCP and implemented in this system is to envelope the two volumes with "water jackets." Water circulates through the water jackets from a temperature controlled circulator. Thermistors are placed on the outside surface of the reservoirs and their outputs are connected to the computer controls through a serial port. The measurement system will not run unless the temperature difference between the two volumes is less than 0.5 degrees C.

Also, pressure transducers are connected at the inlets of both volumes to verify that the system has stabilized. When the difference in pressure between subsequent readings of each individual volume is less than 0.0002 psi, the system is considered stabilized. This is based on the ideal gas assumption that, with a constant volume, pressure and temperature are directly proportional, so an increase in pressure would also mean an increase in temperature. When pressure stabilizes, in turn, so does the temperature.

Now, the volume measurements can be made for the constant temperature system. The PVMS takes two sets of pressure measurements to solve for the unknown volume. The solution is derived in Lyle Cain's report [2] using the forward and reverse ratio equations. In the forward ratio, the reference volume is pressurized to approximately 30 psi, P_1, and the UUT is at about 15 psi, P_2. Then the valve between the two volumes is opened and the equalized pressure is measured, P_3. The reverse process is then performed where the UUT is pressurized to about 30 psi, P_4, and the reference volume is at 15 psi, P_5. The reverse process is also allowed to equalize pressure, yielding P_6. The ratio of the unknown volume to the known volume is a function of the 6 measured pressures in the PVMS process, as shown in equation 1-4.

$$R = \frac{V_{Unk} + Tu_1}{V_{Kn} + Tu_2} = \left[\frac{(P_1 - P_2)}{\left\{ \frac{(P_4 - P_6) \cdot (P_2 - P_3)}{P_5 - P_6} \right\} - P_2 + P_3} \right] \qquad \text{Volume Ratio} \qquad (1\text{-}4)$$

Where, Tu_1 and Tu_2 are the tubing volumes outside of the pressure transducer used to attach the volumes to the system. V_{unk} is the volume of the UUT and V_{kn} is the reference volume.

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2 Characterizing the Accuracy and Precision

In order to determine the accuracy and precision of the system, 10 reference volumes were gravimetricly measured in KCP and used to compare the PVMS measurements. The reference volumes consist of sets of 2 independent: 25, 50, 75, 150, and 2500 cc volumes. Table 2.1 has the list of the reference volumes. All volumes have an accuracy of ±0.1 %.

Table 2.1: Reference Volumes

Serial Number	Volume (cm^3)
SHUGARD25-1	25.756
SHUGARD25-2	25.740
SHUGARD50-1	51.062
SHUGARD50-2	50.895
SHUGARD75-1	76.737
SHUGARD75-2	76.910
SHUGARD150-1	149.112
SHUGARD150-2	148.974
SHUGARD2500-1	2695.2
SHUGARD2500-2	2693.4

2.1 Non-canceled tubing calculation

Before determining the performance of the PVMS, the tubing that connects the volumes to the PVMS had to be calculated. The tubing is located on each side of the PVMS, just outside of the pressure transducers and its volume is not factored out in the volume ratio calculation, 1-4. This tubing is used as a transition to attach the reference and unknown volumes to the system. In order to determine the tubing value, two volumes of different size were placed on each end of the PVMS. The 25-1 and the 50-1 reference volumes were used for the tubing calculation. Volumes of different sizes were chosen avoid dividing by a number close to zero in the tubing equation, equation 2-3. It was also important to use the smallest volumes, because the absolute volumetric uncertainty of the reference volumes is a percentage of the size of the volume, so a variance in a reading for a small volume will be a smaller absolute volume error than the percentage of a larger volume.

To solve for the tubing values, the basic definition of the volume ratio was used. The PVMS solves for the volume ratio of the unknown volume to the reference volume plus their respective tubing attachments as shown in equation 2-1. The known reference volumes are represented as V_1 and V_2 in equation 2-1.

$$R_1 = \frac{V_1 + T_1}{V_2 + T_2} \quad \text{and} \quad R_2 = \frac{V_2 + T_1}{V_1 + T_2} \qquad \text{Volume Ratio Equations} \qquad (2\text{-}1)$$

In this case, V_1 is SHUGARD25-1 and V_2 is SHUGARD 50-1, and T_1 and T_2 are the unknown tubing values. The ratios R_1 and R_2 are obtained by running the PVMS, once with 25-1 as the reference volume and 50-1 as the UUT, and then reversing the reference and UUT volumes. The end result is two equations and two unknowns. Tu_1, the reference side tubing and Tu_2 the UUT side tubing are found by equations 2-2 and 2-3.

$$Tu_1 = R_1 \cdot (V_2 + Tu_2) - V_1 \qquad \text{UUT Tubing} \qquad (2\text{-}2)$$

$$Tu_2 = \frac{((R_2 + 1) \cdot V_1) - ((1 + R_1) \cdot V_2)}{R_1 - R_2} \qquad \text{Reference Tubing} \qquad (2\text{-}3)$$

Both ratio tests were run 15 times, the ratios were used to calculate the tubing values, and the results were averaged. The tubing values were found to be 6.09195 cc and 6.09820 cc for Tu_1 and Tu_2 respectively. The complete set of tubing data can be found in the Appendix.

2.2 Theoretical Prediction Based on Error Propagation

Now that the tubing values have been found, a theoretical prediction of the accuracy and precision of the PVMS can be derived. The accuracy of the test equipment and the temperature range over which the test is performed both play a large role in the accuracy and precision of the PVMS measurements. Two basic measurement tools are used in the PVMS. They are pressure transducers and thermistors. The pressure transducers have a ±0.01 % accuracy on each reading, so that is factored into equation 1-4. There is also 0.5° C temperature range for which the system can operate with a thermistor accuracy of ±0.1° C. This was incorporated into the ratio equation using Boyle's law for constant volume, by multiplying by T_1 of the forward ratioing equation and dividing by T_2 in the reverse ratio equation. Equation 2-4 shows an example of all of the accuracy variables incorporated into equation 1-4.

$$R = \left[\frac{(a \cdot P_1) - (b \cdot P_2)}{\left\{ \frac{(d \cdot P_4 - (P_6 \cdot f)) \cdot (b \cdot P_2 - (c \cdot P_3))}{e \cdot P_5 - (P_6 \cdot f)} \right\} - (P_2 \cdot b) + P_3 \cdot c} \right] \frac{T_2 + g + i}{T_1 + h + j} \qquad (2\text{-}4)$$

Where ***a*** through ***f*** represent the pressure transducer accuracy 1 ±0.01 %, ***g*** and ***h*** are the thermistor accuracy ±0.1 ° C, and ***i*** and ***j*** take into account the temperature range of ±0.25 degrees Celsius. Methodically iterating through each possible combination of these variables generated a plot of accuracy and precision in the measurement system shown in Figure 2.1. From Figure 2.1, the precision of the volume measurement system is predicted to be between ±0.01 % and 0.08% for volume ratios of 0.3 to 6. In all cases the precision is predicted to be well below the 0.5% expectations of the system. Accuracy also is predicted to exceed the VMS expectations, with the worst accuracy percentage being ±0.065 %.

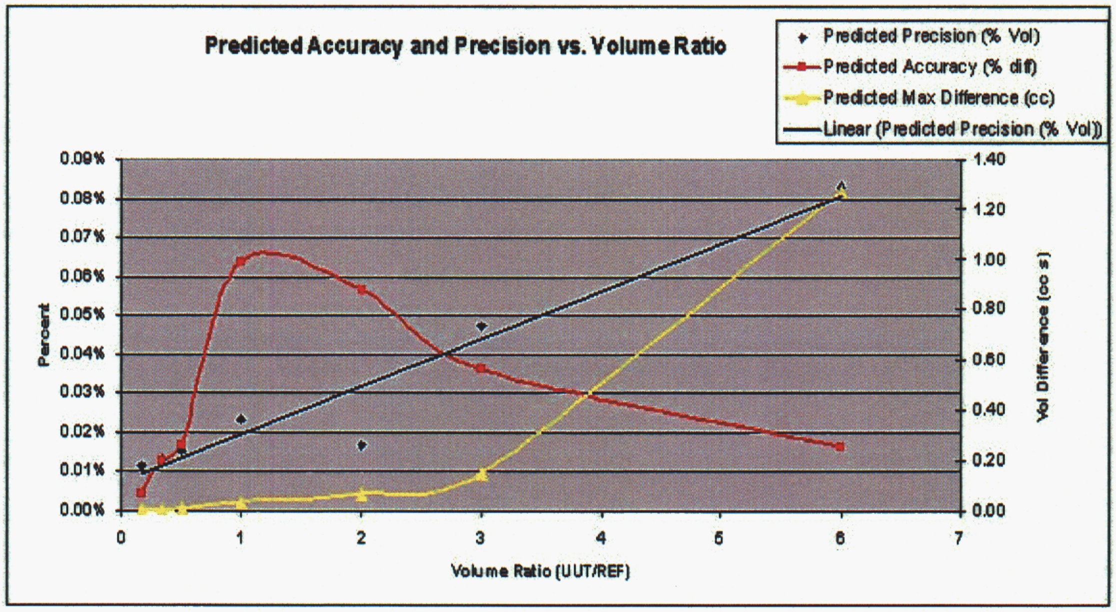

Figure 2.1: Chart of Predicted Accuracy% as a Function of Volume Ratio.

Figure 2.1shows that the precision is expected to get worse as the volume ratio increases from one. The accuracy percentage curve in figure 2.1 can be misleading. The trend shows the accuracy improving as the volume ratio deviates from one. It must be remembered that this accuracy is determined as a percentage of volume of the UUT, so as the UUT gets larger, the same absolute volumetric uncertainty would be a smaller percentage. The actual trend for accuracy is best understood when looking at the difference in volume curve. It shows that for all ratios less than 3, the difference in volume from the actual volume is less than 0.2 cm^3. Section.2.3 will show how well the PVMS performance matches up to the predicted precision and accuracy.

2.3 Test Plan & System Performance

Two groups of tests were performed to determine the actual accuracy and performance of the PVMS. The first group of tests measured each volume 15 times against another reference volume that gave a ratio as close to 1 as possible. The precision and accuracy of the system were determined for the case when both the reference and UUT volumes were close to the same value, as the system was intended. The second group of tests used the 25-1 volume as the small volume and varied the volumetric ratio from 0.33 to 6. All tests were run 15 times, the volume data represented is the average value from these tests. The accuracy was determined as the percent volume difference of the average from the known UUT volume value. The precision was determined as the standard deviation of the data divided by the average data value.

In the first set of testing, the PVMS performed remarkably well. The precision of the measurements were within an error less than ±0.017 % as shown in Figure 2.2.

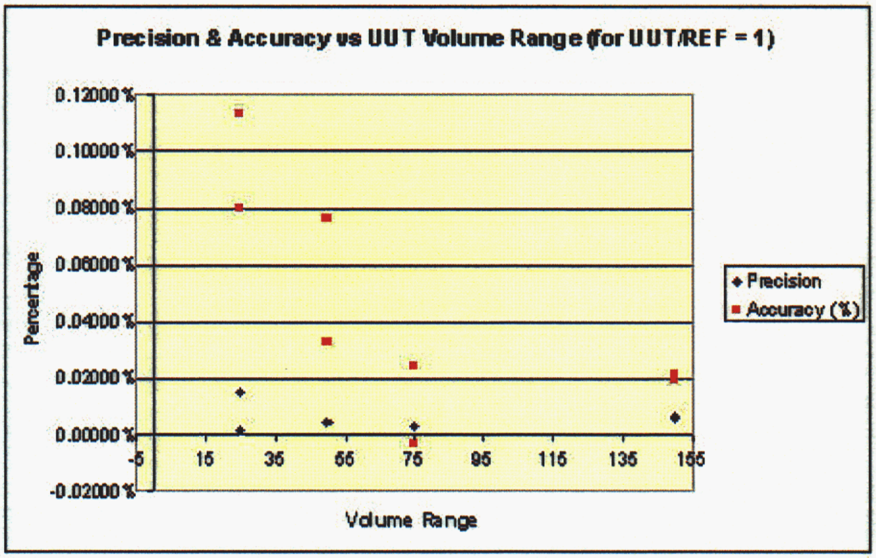

Figure 2.2: Measured Precision & Accuracy vs. UUT Volume Range.

The accuracy error For volumes 50cc s and greater was under 0.08% of the volume being measured. For small volumes, such as the 25cc volumes, the accuracy fell just below 0.12% of the volume being measured. This exceeds the expected performance of 0.5% accuracy. Note that the reference volumes that were measured gravimetricly all have an error of ±0.1 %, so the PVMS measurements all lie within the certainty of our known volume values as well. Figure 2.2 shows graphically that, even though the precision and accuracy are good for all volume sizes down to 25 cc, there is a trend. As the volume size decreases, the accuracy as a percentage of volume has a tendency to deteriorate. As the volumes decrease, a small deviation in the volume from the actual volume is a more significant difference. For example, the volume measurements tend to only differ from the actual volume by 0.05cc on average. This small difference is 0.0022% of 2500 cm^3, but it is as large as 0.22% for 25 cm^3. As a result, for volumes that are less than 50 cm^3 the accuracy is best stated as a volume ±0.05 cm^3.

It is not probable that the volume needed to be measured will always have a ratio of one with respect to the reference volume. In turn, the second set of testing varied the ratio of UUT to reference volume from 0.01 to 100. Figure 2.3 shows the results for ratios varying from 0.33 to 6.

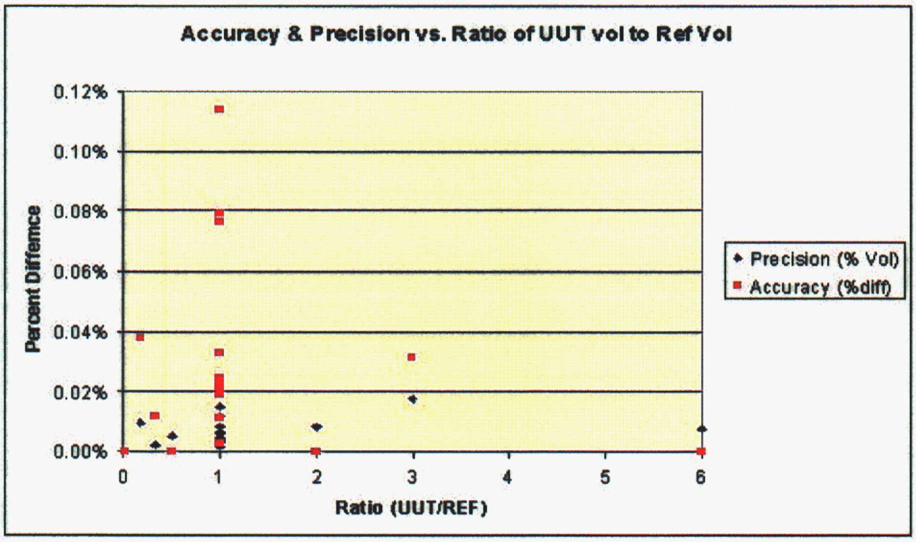

Figure 2.3: Measured Accuracy & Precision vs. Volume Ratio.

All of the accuracies were under ±0.04 % with an average precision of ±0.018 %, with the exception of the ratio of one. The three data points that lie above this accuracy limit are for volume of less than 50 cm^3, and as stated before, their accuracy is better represented as an absolute volume of ±0.05 cm^3. Ratios of 0.01 and 100 were run to verify that ratios above 6 would still yield valid results. In these cases the accuracy was ±0.5 % with a precision of ±0.1 %. Thus, for all reasonable ratios less than 100, the accuracy and precision would fall within this limit. Typical examples of the individual test data can be found in the Appendix.

The accuracy of the PVMS depends largely on the temperature range that the system is operating in. All volume data was recorded along with the average temperature of the system, as shown in the Appendix. Consistently, the volume data points that matched the reference volumes with the least amount of absolute volume difference were found at temperatures within 23.285 ±0.1° C. If the system were to be improved at all the temperature controls could be tightened, but this is not necessary since the accuracy and precision are already within the certainty of the volume values measured gravimetricly.

The other large factor that plays into the accuracy and precision is the flow rate of the helium gas. The first set of tests had to be re-run because the flow rate was initially too high for volumes of 50 cc and below. All results presented are test run with the optimized helium flow rate. For a volume of 25 cm^3, the flow rate was measured as a 0.5 psi per second. It was set at this rate for easy validation by the operator. The PVMS program updates its data on the output screen every three seconds, so if the flow rate is ever changed it can be verified in the manual mode of the PVMS program by letting the helium into one 25 cc volume in the system and validating the change in pressure. For large volumes of 2500 cm^3 per side or more, the second flow valve can be opened on the PVMS to let gas flow freely into the system. The second valve speeds up the measurement system for large volume without sacrificing the accuracy, because the heat created by the flow of gas is quickly dissipated into the large volume.

The actual performance turned out to exceed the predicted results although they did follow the same trends as shown in Figures 2.4 and 2.5. The only outlying point in the measured accuracy is for a ratio of 1 for the 25 cc volumes, where percent accuracy is not a good indicator, as stated before.

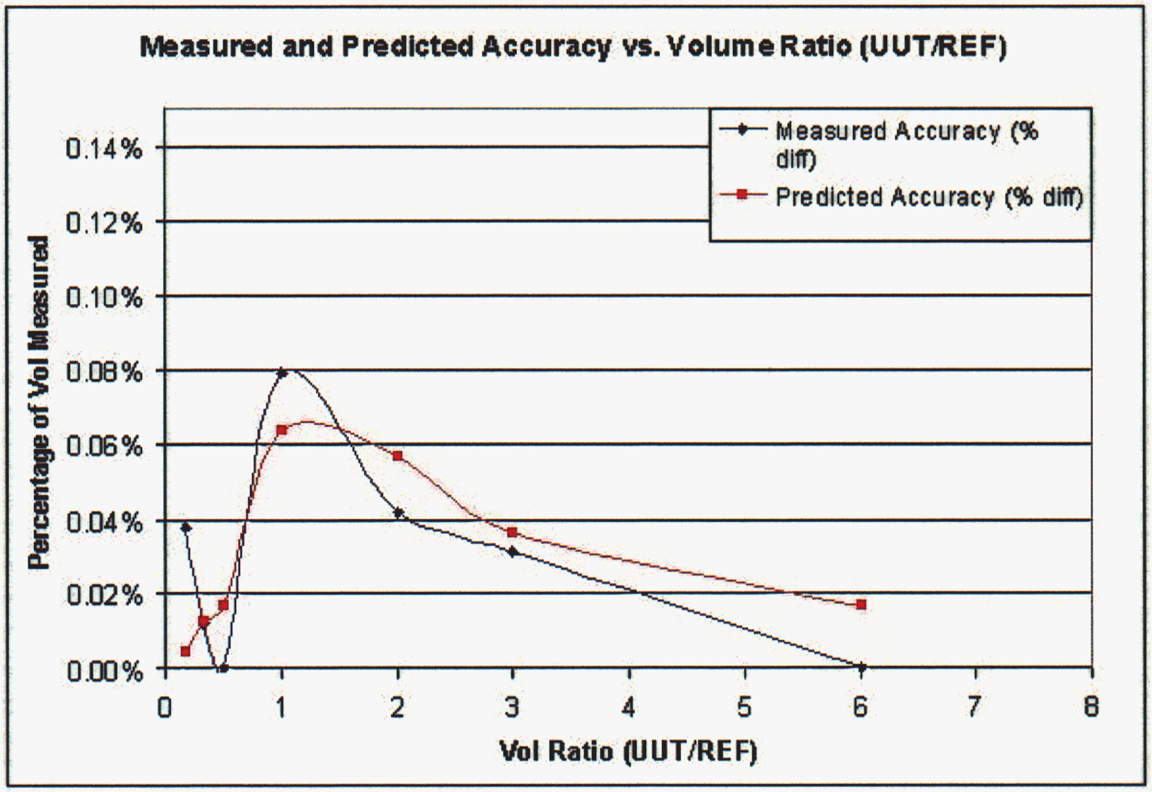

Figure 2.4: Measured and Predicted Accuracy vs. Volume Ratio.

Measured precision also out performed our predictions as shown in figure 2.5. It was predicted that precision would degrade as the volume ratio increased from one. However, the actual measured performance stayed fairly constant regardless of volume ratio at less than ±0.018 %. This proves that the PVMS is not operating under worst case conditions, as the predicted performance assumes.

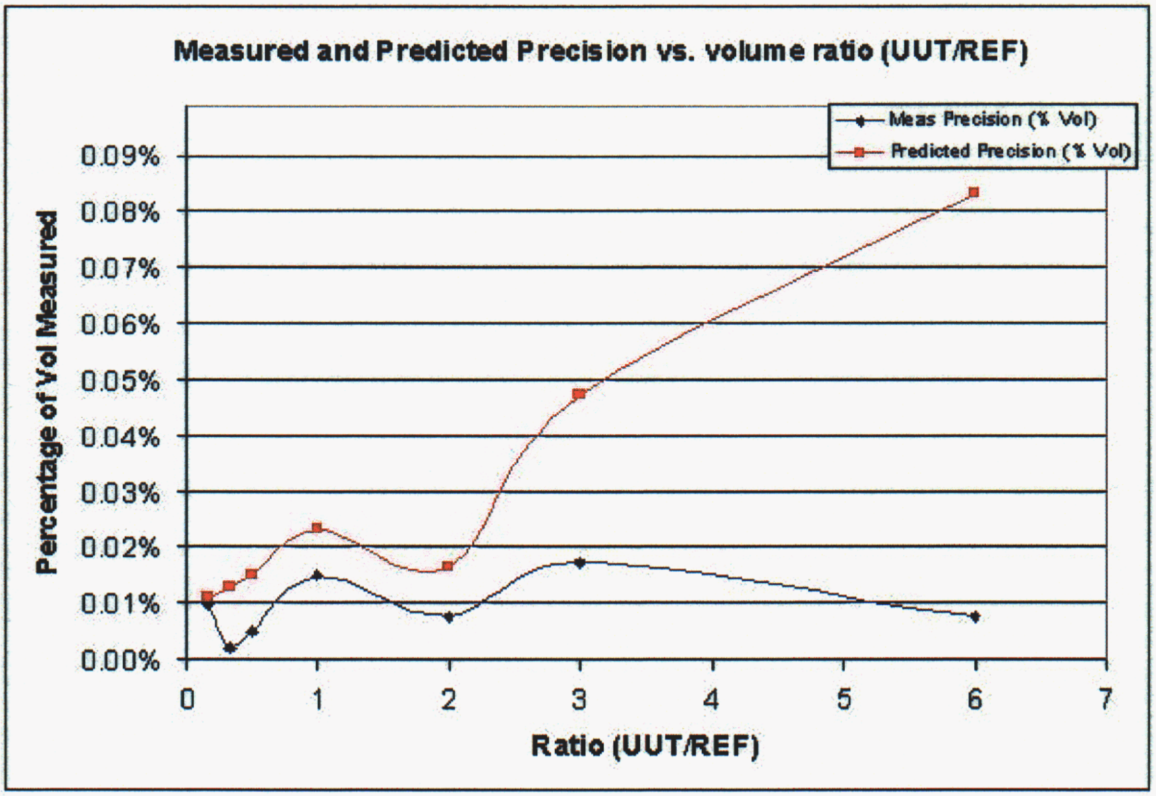

Figure 2.5: Measured and Predicted Precision vs. Volume Ratio.

It should be remembered that the predicted values were based on the worst case scenarios of precision and accuracy of the measurement instruments. The predicted results also assumed the pressure measurements put into the formula were the average with no initial deviation due to the accuracies of the instrument, which explains why the actual performance exceeds our predictions.

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3 Summary

In conclusion, this accuracy and precision study validated KCP's claims that the new PVMS operates with 0.5% accuracy or better. The final performance was considered to be the worst accuracy and precision for all of the ratios and for volumes greater than 50 cm^3. The actual performance of the PVMS has an accuracy of 0.04% by volume with a precision of 0.018% for volumes of 50 cm^3 or greater. For volumes less than 50 cm^3, the accuracy is ±0.05 cm^3 with the same precision performance. The final accuracy of the machine is summarized as:

Table 3.1: Final Accuracy and Precision of PVMS

Accuracy:	Ref. Vol	0.1%	**Precision:**	Ref. Vol	0.0%
	PVMS	0.04%		PVMS	0.018%
Total System		0.14%			0.018%

For volumes 50 cc and greater the total system uncertainty is ±0.158 %

For volumes less than 50 cc the total uncertainty is ±0.05 cc plus 0.018% of the measured volume.

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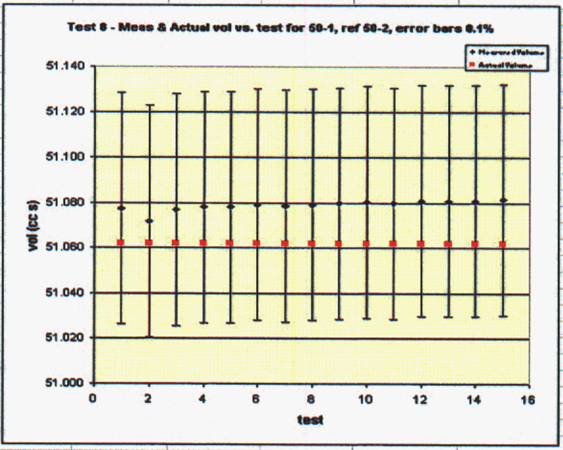
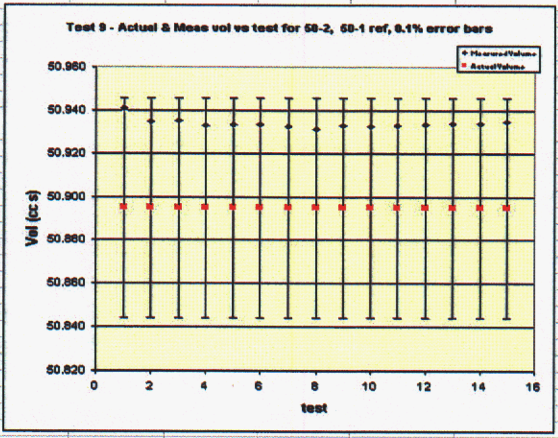
AppendixTypical Accuracy and Precision Data

*** Changed volume flow setting for the VMS, because it was filling too quickly. Will have to repeat all 25 cc tests**



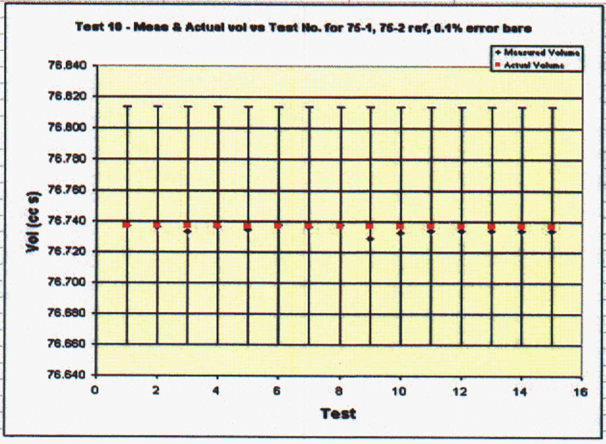
Test 8 - 50 cc-2 Reference, 50 cc-1 Unknown

Refrence Volume	50.895	cc	Shugard-50-#2		
UUT Volume	51.062	cc	Shugard-50-#1		
Ref Side Tubing	6.09820	cc			
UUT Side Tubing	6.09195	cc			
Ratio UUT/Ref					
Test_No.	Vol. ratio	Measured Volume	Actual Volume	Difference	Temp(Deg_C)
1	1.00309	51.077	51.062	0.01535671	23.2395
2	1.00299	51.072	51.062	0.00965739	23.2715
3	1.00308	51.077	51.062	0.014786778	23.288
4	1.0031	51.078	51.062	0.015926642	23.3065
5	1.0031	51.078	51.062	0.015926642	23.3195
6	1.00312	51.079	51.062	0.017066506	23.34
7	1.00311	51.078	51.062	0.016496574	23.3385
8	1.00312	51.079	51.062	0.017066506	23.341
9	1.00313	51.080	51.062	0.017636438	23.338
10	1.00314	51.080	51.062	0.01820637	23.34
11	1.00313	51.080	51.062	0.017636438	23.34
12	1.00315	51.081	51.062	0.018776302	23.344
13	1.00315	51.081	51.062	0.018776302	23.344
14	1.00315	51.081	51.062	0.018776302	23.3465
15	1.00316	51.081	51.062	0.019346234	23.3475
average	1.00311	51.07876		0.01676	23.32297
std dev	0.00004	0.00240		0.00240	0.03254
fractional deviation	0.000042	0.000047		0.143025	0.001395



Test 9 - 50 cc-1 Reference, 50 cc-2 Unknown

Refrence Volume	51.062	cc	Shugard-50-#1		
UUT Volume	50.895	cc	Shugard-50-#2		
Ref Side Tubing	6.09820	cc			
UUT Side Tubing	6.09195	cc			
Ratio UUT/Ref					
Test_No.	Vol. ratio	Measured Volume	Actual Volume	Difference	Temp(Deg_C)
1	0.99777	50.941	50.895	0.045780474	23.033
2	0.997664	50.936	50.895	0.039721492	23.1065
3	0.997667	50.936	50.895	0.039892973	23.114
4	0.997632	50.933	50.895	0.037892366	23.1155
5	0.997639	50.933	50.895	0.038292487	23.123
6	0.997638	50.933	50.895	0.038235327	23.1345
7	0.997623	50.932	50.895	0.037377924	23.132
8	0.997601	50.931	50.895	0.0361204	23.1365
9	0.997629	50.933	50.895	0.037720886	23.149
10	0.997623	50.932	50.895	0.037377924	23.16
11	0.997627	50.933	50.895	0.037606566	23.169
12	0.997638	50.933	50.895	0.038235327	23.1835
13	0.997649	50.934	50.895	0.038864089	23.1955
14	0.997644	50.934	50.895	0.038578288	23.203
15	0.997663	50.936	50.895	0.039664332	23.2065
average	0.99765	50.93376		0.03876	23.14410
std dev	0.00004	0.00219		0.00219	0.04526
fractional deviation	0.000038	0.000043		0.056476	0.001956



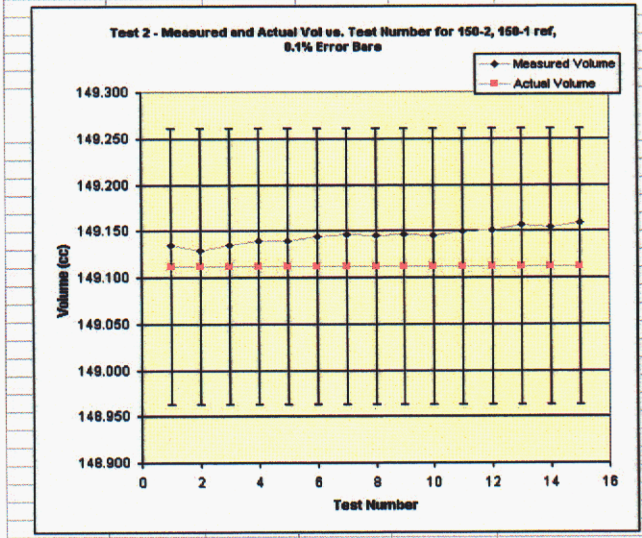
Test 10 - 75 cc-2 Reference, 75 cc-1 Unknown

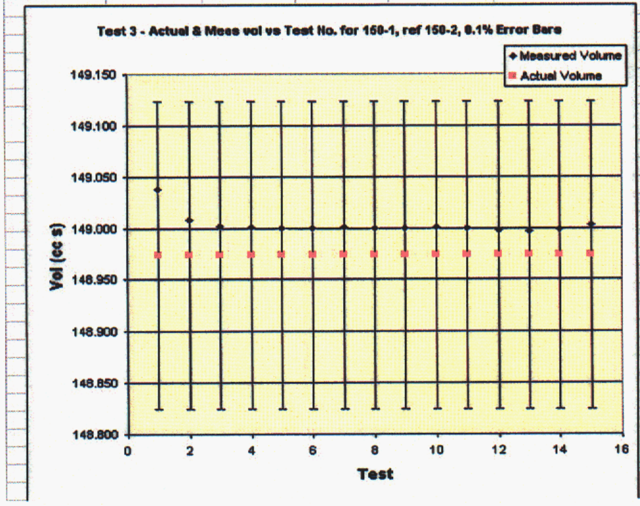
Refrence Volume	76.91	cc	Shugard-75-#2		
UUT Volume	76.737	cc	Shugard-75-#1		
Ref Side Tubing	6.09820	cc			
UUT Side Tubing	6.09195	cc			
Ratio UUT/Ref					
Test_No.	Vol. ratio	Measured Volume	Actual Volume	Difference	Temp(Deg_C)
1	0.997838	76.737	76.737	-0.000216009	23.2505
2	0.997829	76.736	76.737	-0.000963083	23.2615
3	0.997792	76.733	76.737	-0.004034386	23.2625
4	0.997835	76.737	76.737	-0.000465033	23.271
5	0.997807	76.734	76.737	-0.002789263	23.278
6	0.997845	76.737	76.737	0.000365049	23.2845
7	0.99783	76.736	76.737	-0.000880074	23.2955
8	0.997849	76.738	76.737	0.000697081	23.2955
9	0.997744	76.729	76.737	-0.00801878	23.3105
10	0.99779	76.733	76.737	-0.004200402	23.3205
11	0.997798	76.733	76.737	-0.003536337	23.3235
12	0.997799	76.734	76.737	-0.003453329	23.335
13	0.997799	76.734	76.737	-0.003453329	23.1955
14	0.997799	76.734	76.737	-0.003453329	23.203
15	0.997799	76.734	76.737	-0.003453329	23.2065
average	0.99781	76.73448		-0.00252	23.27290

Combining Both Tests 1 and 2 to Solve for Tubing Volumes

U1	148.974	cc
U2	76.737	cc
Ref_1	76.737	cc
Ref_2	148.974	cc

Test No	Ratio_1	Ratio_2	Ref Side Tubing (cc)	UUT Side Tubing (cc)
1	1.87104	0.534549	6.20498188	6.213769586
2	1.87105	0.534471	6.1951173	6.196393294
3	1.87107	0.534458	6.19279955	6.193137353
4	1.87109	0.534431	6.18804823	6.186408595
5	1.87114	0.534448	6.1867878	6.188372719
6	1.87118	0.534448	6.18436259	6.187076568
7	1.87124	0.534447	6.18101312	6.185131299
8	1.87122	0.534451	6.18228572	6.186432058
9	1.87130	0.534442	6.17639146	6.181885511
10	1.87127	0.534438	6.17754371	6.181880717
11	1.87126	0.534444	6.17904834	6.183615766
12	1.87135	0.534437	6.17257842	6.179071934
13	1.87140	0.534439	6.169578	6.177778685
14	1.87140	0.534443	6.17004217	6.178647331
15	1.87144	0.534446	6.16796604	6.178003183
average	1.87123	0.53445	6.18190	6.18651
std dev	0.000134	0.000028	0.010440	0.009286
fractional devia	0.000072	0.000053	0.001689	0.001501





Combining Tests 16 and 17 to Solve for Tubing Volumes

U1	25.756	cc
U2	51.062	cc
Ref_1	51.062	cc
Ref_2	25.756	cc

Test No	Ratio_1	Ratio_2	Ref Side Tubing (cc)	UUT Side Tubing (cc)
1	0.557156	1.79395	6.10491599	6.094890248
2	0.557178	1.79406	6.10309931	6.095135701
3	0.557187	1.79414	6.10145475	6.09473386
4	0.557176	1.79413	6.10120395	6.093965325
5	0.557175	1.79416	6.10038512	6.09345193
6	0.557171	1.79421	6.09891268	6.092402878
7	0.557161	1.79423	6.09793561	6.091286882
8	0.557165	1.79425	6.09760544	6.091331567
9	0.557164	1.79422	6.09833172	6.091679064
10	0.55716	1.7943	6.09608704	6.090199775
11	0.557153	1.79431	6.09550617	6.089476035
12	0.557157	1.79436	6.09440373	6.089090431
13	0.557156	1.79434	6.09487241	6.089294406
14	0.55724	1.79443	6.09643612	6.094966942
15	0.557152	1.79445	6.09185598	6.087385169
average	0.55717	1.79424	6.09820	6.09195
std dev	0.000022	0.000136	0.003536	0.002512
fractional deviation	0.000039	0.000076	0.000580	0.000412

Test 2 - 150 cc Reference, 150 cc Unknown, Using 6-4-2003 Algebreic Solution

Refrence Volume	148.974	cc
UUT Volume	149.112	cc
Ref Side Tubing	6.09820	cc
UUT Side Tubing	6.09195	cc

Test_No.	Vol.Ratio	Measured Volume	Actual Volume	Difference	Test Temperature
1	1.00099	149.134	149.112	0.021769199	23.317
2	1.00096	149.129	149.112	0.017117033	23.3205
3	1.00099	149.134	149.112	0.021769199	23.324
4	1.00102	149.138	149.112	0.026421365	23.3285
5	1.00102	149.138	149.112	0.026421365	23.3315
6	1.00105	149.143	149.112	0.031073531	23.3345
7	1.00107	149.146	149.112	0.034174975	23.3355
8	1.00106	149.145	149.112	0.032624253	23.3415
9	1.00107	149.146	149.112	0.034174975	23.3535
10	1.00106	149.145	149.112	0.032624253	23.371
11	1.00109	149.149	149.112	0.037276419	23.3835
12	1.0011	149.151	149.112	0.038827141	23.394
13	1.00113	149.155	149.112	0.043479307	23.4
14	1.00112	149.154	149.112	0.041928585	23.4015
15	1.00115	149.159	149.112	0.046580751	23.403
average	1.00106	149.14442		0.03242	23.35597
std dev	0.000055	0.008531		0.008531	0.032625
fractional deviation	0.000055	0.000057		0.263170	0.001397
percent diff		0.0057%		0.0217%	

Test 3 - 150 cc Reference, 150 cc Unknown

Refrence Volume	149.112	cc
UUT Volume	148.974	cc
Ref Side Tubing	6.09820	cc
UUT Side Tubing	6.09195	cc
Ratio UUT/Ref		

Test_No.	Vol Ratio	Measured Volume	Actual Volume	Difference	Temp(Deg_C)
1	0.99948	149.038	148.974	0.063538416	23.4405
2	0.999288	149.008	148.974	0.033738058	23.417
3	0.999246	149.001	148.974	0.027219229	23.4175
4	0.999242	149.001	148.974	0.026598389	23.4245
5	0.999238	149.000	148.974	0.025977548	23.4195
6	0.999236	149.000	148.974	0.025667127	23.412
7	0.999241	149.000	148.974	0.026443178	23.412
8	0.999234	148.999	148.974	0.025356707	23.4275
9	0.999234	148.999	148.974	0.025356707	23.425
10	0.99924	149.000	148.974	0.026287968	23.424
11	0.999233	148.999	148.974	0.025201497	23.4235
12	0.999221	148.997	148.974	0.023338974	23.424
13	0.999218	148.997	148.974	0.022873344	23.425
14	0.999231	148.999	148.974	0.024891076	23.4245
15	0.999254	149.002	148.974	0.028460911	23.4115
average	0.99926	149.00273		0.02873	23.42187
std dev	0.000064	0.009947		0.009947	0.007439
fractional deviation	0.000064	0.000067		0.346207	0.000318

1 References

1. P. A. Klevgard, *Precision Volume Measuring System.* Sandia: SAND84-8014 UC-700, November 1984
2. L. J. Cain, *Improved Volume Measurement Design and the Volume Criterion.* Federal Manufacturing and Technologies: DE-AC04-76-DP00613, May 2000

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