MuID Leak Rate Calculations

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1 Introduction

In constructing the MUID panels we need to be sure that the system is leak tight before installation into the experiment. To accomplish this the Iarocci tubes are checked at the tube factory in Italy and checked again upon receipt at the panel factories at BNL and in Japan. Finally, the completed gas circuits are checked.

2 Measuring the Leak Rate in the Iarocci Tube Factory

The process of checking the tubes in Italy is performed by submersing the tubes in a foot of water and ensuring that endcaps leak at a rate less than one bubble per minute. If we estimate the bubble radius, $R_b = 2\,\mathrm{mm}$, we obtain a maximum leak rate per tube (two endcaps) of: $(dV/dt)_{max} = 6.7 \cdot 10^{-2}\,\mathrm{cc/min}$.

3 Obtaining the Leak Rate from a Pressure Drop Measurement

In the panel factories we need to be able to check the leak rates for a tube (or panel) without putting the tubes under water. To do this, we overpressure the tubes with a gas to $P_{tube} \approx P_{atm} + 30\,\mathrm{mbar}$ and measure the drop in the overpressure over a period of time.

Care must be exercised in calculating a leak rate from this pressure drop because the Iarocci tubes are thick-walled baloons and therefore expand and contract in response to pressure differences on the two sides of their walls. In one sense this makes our job more difficult; a given leak rate translates into a much lower pressure drop than it would for a stiff-walled tube. But in another sense our job is much easier; our sensitivity to changes in ambient conditions is also reduced.

One critical number to know through this entire report is the expandability of the tubes. This was measured at ORNL and at the panel factory in KEK to be $dV = 0.01\,V dP$ when dP is the overpressure measured in mbar.

Now we calculate the leak rate (assuming atmospheric pressure of 1 atm) from a measured rate of change of the overpressure:

$$\left(\frac{dV}{dt}\right)_{leak} = \frac{1}{P_{atm}} \frac{d(nRT)_{tube}}{dt}. \tag{1}$$

We obtain $d(nRT)_{tube}$ from:

$$\begin{aligned} P_1 V_1 &= n_1 RT && (2) \\ P_2 V_2 &= n_2 RT = (P_1 + dP)(V_1 + dV) && (3) \end{aligned}$$

$$d(nRT)_{tube} = (n_2 - n_1)RT = P_1 V_1 + V_1 dP + P_1 dV + dPdV - P_1 V_1 \tag{4}$$

Canceling terms, dropping the $dPdV$ term, and dropping subscripts we obtain:

$$d(nRT)_{tube} = V dP + P dV. \tag{5}$$

We measure the first term through the pressure drop, but the second term we need to infer from the pressure drop and the measured expandability of the tubes. If we always write the pressure in units of mbar and assume $P = P_{atm} = 1000\,\text{mbar}$, we obtain:

$$
\begin{aligned}
d(nRT)_{tube} &= VdP + P_{atm} \cdot (0.01 VdP) && (6)\\
&= VdP \cdot (1 + 10) && (7)\\
&= 11\, VdP && (8)
\end{aligned}
$$

So, the leak rate is primarily given by the volume-change term.

We finally obtain:

$$\frac{dV}{dt} = \frac{11V}{1000}\frac{dP}{dt}, \tag{9}$$

where V and dV are measured in the same units and dP is measured in mbar.

It is interesting to compare the sensitivity of the pressure drop measurement to the submersion measurement. In order to find the pressure drop corresponding to the maximum allowable leak rate for shipped tubes (as calculated above) we set: $(dV/dt)_{max} = 6.7 \cdot 10^{-2}\,\text{cc/min}$:

$$
\begin{aligned}
\left(\frac{dP}{dt}\right)_{max} \frac{[\text{mbar}]}{[\text{min}]} &= \frac{1000}{11V} \cdot \left(\frac{dV}{dt}\right)_{max} && (10)\\
&= \frac{1000}{11V\,[\text{cc}]} \cdot 6.7 \cdot 10^{-2} && (11)
\end{aligned}
$$

So the corresponding pressure drop per tube depends on the volume of the tube tested:

$$
\begin{aligned}
\text{Long tubes} \quad &: \quad \left(\frac{dP}{dt}\right)_{max} = 0.0015\,\text{mbar/min}\ (\ = 0.9\,\text{mm}\,\text{H}_2\text{O/hr}) && (12)\\
\text{Short tubes} \quad &: \quad \left(\frac{dP}{dt}\right)_{max} = 0.0024\,\text{mbar/min}\ (\ = 1.5\,\text{mm}\,\text{H}_2\text{O/hr}) && (13)
\end{aligned}
$$

Note that the required leak rates for an assembled gas circuit are identical because both V and dV in equation 10 are multiplied by the number of tubes in the circuit.

Although the error involved in reading the manometer would allow this sensitivity in principal, systematic errors (as described below) reduce the sensitivity of the pressure drop measurement.

4 Affect of Temperature Changes on the Pressure Drop Measurement

As pointed out by Y. Mao and Z. Li at the KEK panel factory, temperature changes will affect the pressure drop measurements. To see this, recall equation 5:

$$d(nRT) = VdP + PdV. \tag{14}$$

From this we get:

$$dP = \frac{d(nRT) - PdV}{V} \tag{15}$$

Plugging in the expandability of the tubes:

$$
\begin{aligned}
dP\,[\text{mbar}] &= \frac{d(nRT) - 0.01VdP\,[\text{mbar}]\,P_{atm}\,[\text{mbar}]}{V} && (16)\\
&= \frac{d(nRT)}{V} - 10dP\,[\text{mbar}] && (17)
\end{aligned}
$$

Rearranging,

$$
\begin{aligned}
dP\,[\text{mbar}] &= \frac{d(nRT)}{11V} && (18)\\
&= \frac{P[\text{mbar}]}{11}\frac{dT}{T} && (19)\\
&\approx 3\,\text{mm}\,\text{H}_2\text{O}/^\circ\text{C} && (20)
\end{aligned}
$$

Note that this is the temperature of the gas *inside the LST*, which we do not measure.

5 Affect of Atmospheric Pressure Changes on the Pressure Drop Measurement

Y. Mao and Z. Li also noted that changes in atmospheric pressure will also modify the observed pressure difference.

Assume an increase in atmospheric pressure. The pressure inside the tube will also increase, but not enough to completely counter the increase in atmospheric pressure, thus the pressure difference between the overpressurized tube and the atmosphere is reduced. The reduction in the pressure difference results in a volume reduction given by the expandanbility of the tubes:

$$dV = 0.01V dM\,[\text{mbar}] \tag{21}$$

Note, that I have used dM to denote the change in the pressure difference across the walls of the Iarocci tube. dP in the following equation will refer to the absolute pressure change inside the tube. The absolute pressure increase inside the tubes gives a volume reduction according to the ideal gas law:

$$dV = V dP/P \tag{22}$$

Equating these volume reductions we observe that the observed pressure difference is given by:

$$dM\,[\text{mbar}] = 100 dP/P \tag{23}$$

Assuming $P = 1000$ mbar, we get:

$$
\begin{aligned}
dM\,[\text{mbar}] &= dP\,[\text{mbar}]/10 && (24)\\
&= 1\,\text{mm}\,\text{H}_2\text{O}/\text{mbar} && (25)
\end{aligned}
$$

6 Measurements in the BNL Factory

W. Tian measured the pressure drop for gas circuits with different numbers of LSTs over a period of roughly four hours. These measurements were made in order to try to disentangle a pressure drop due to a settling of the system from a pressure drop due to an actual leak.

Figure 1 below shows the actual pressure drop as a function of time for the different gas circuits. The lines are linear fits to the pressure drop for times greater than 2.5 hours. The assumption is that settling will be complete by that time.

Figure 2 below shows the extracted leak rates for the different circuits (simply a linear relationship with a slope given by the fit described above).

Figure 3 below shows the difference of these two distributions - the contribution of settling to the pressure drop measurement.

The fact that the system does settle, and the fact that the measurements are affected (at the level of interest) by temperature and pressure variations suggests a measurement strategy in which the system is pressureized, allowed to sit for a few hours and measurements taken for a relatively short period of time (half an hour) at that point. Of course, a large leak will show up well before the settling time is over, so searching for such leaks should begin as soon as it is obvious that they exist.

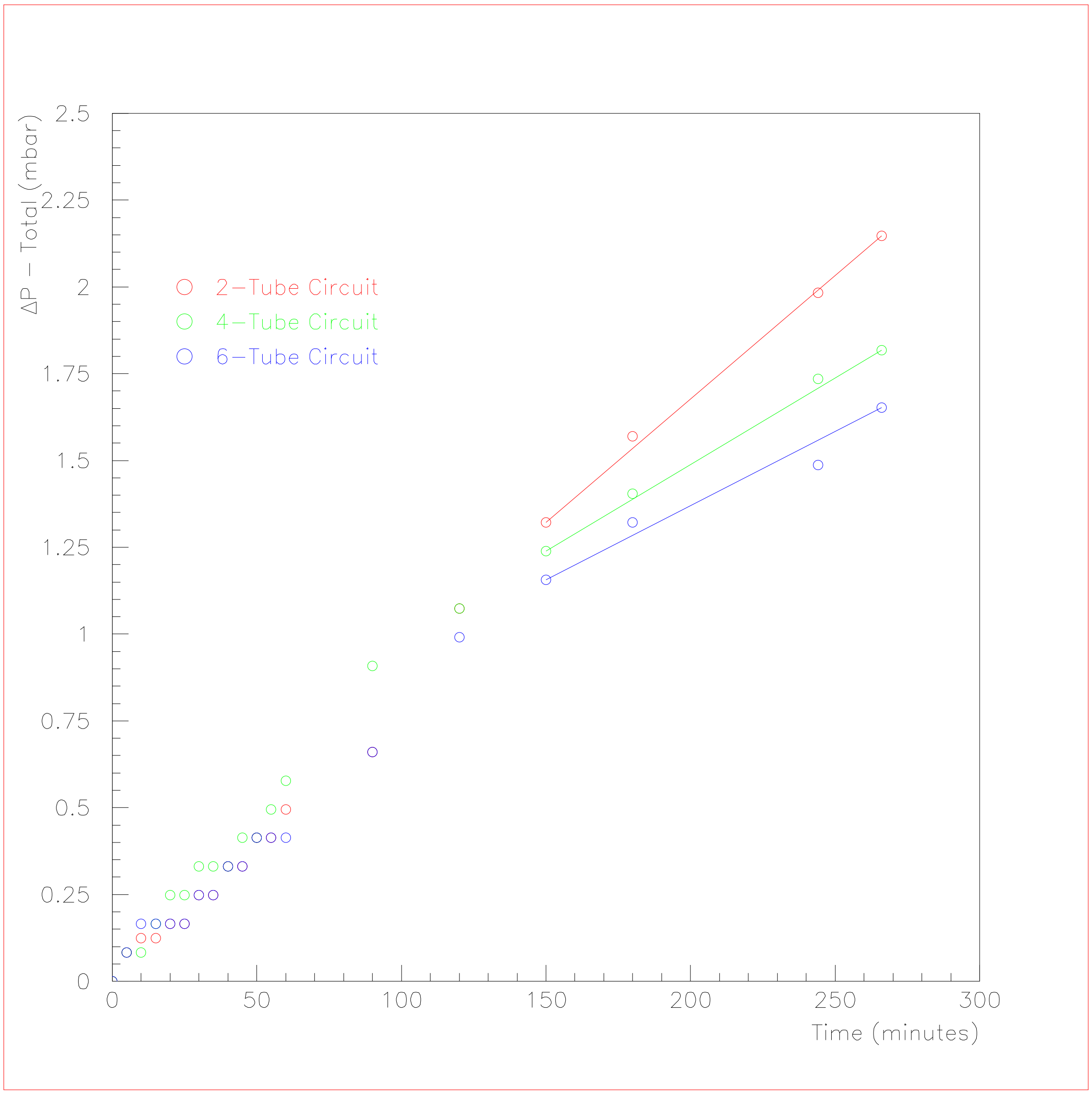

Figure 1: Measured pressure drop for gas circuits with different numbers of tubes. Courtesy, W. Tian.

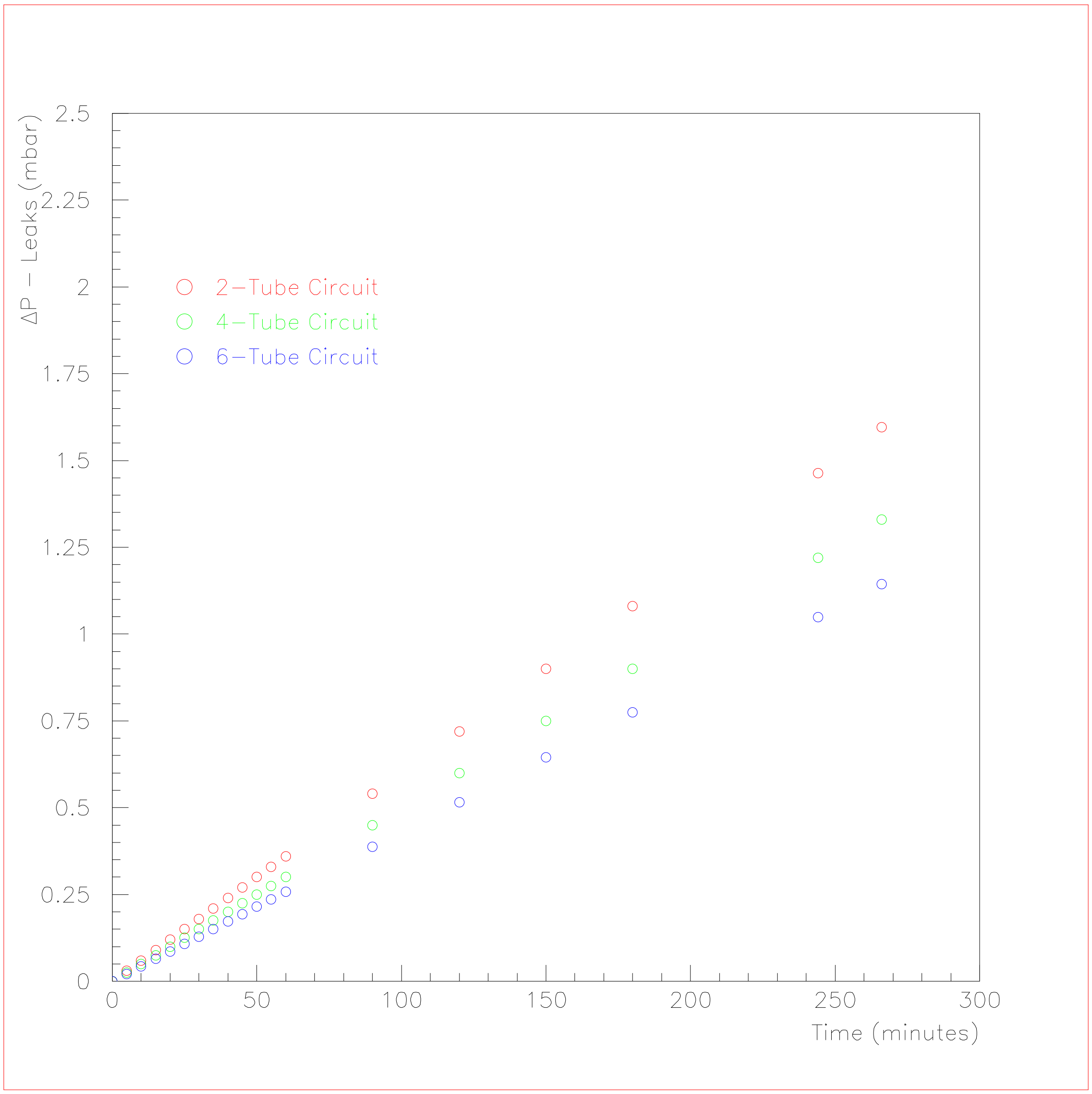

Figure 2: Contribution to the measured pressure drop due to leaks.

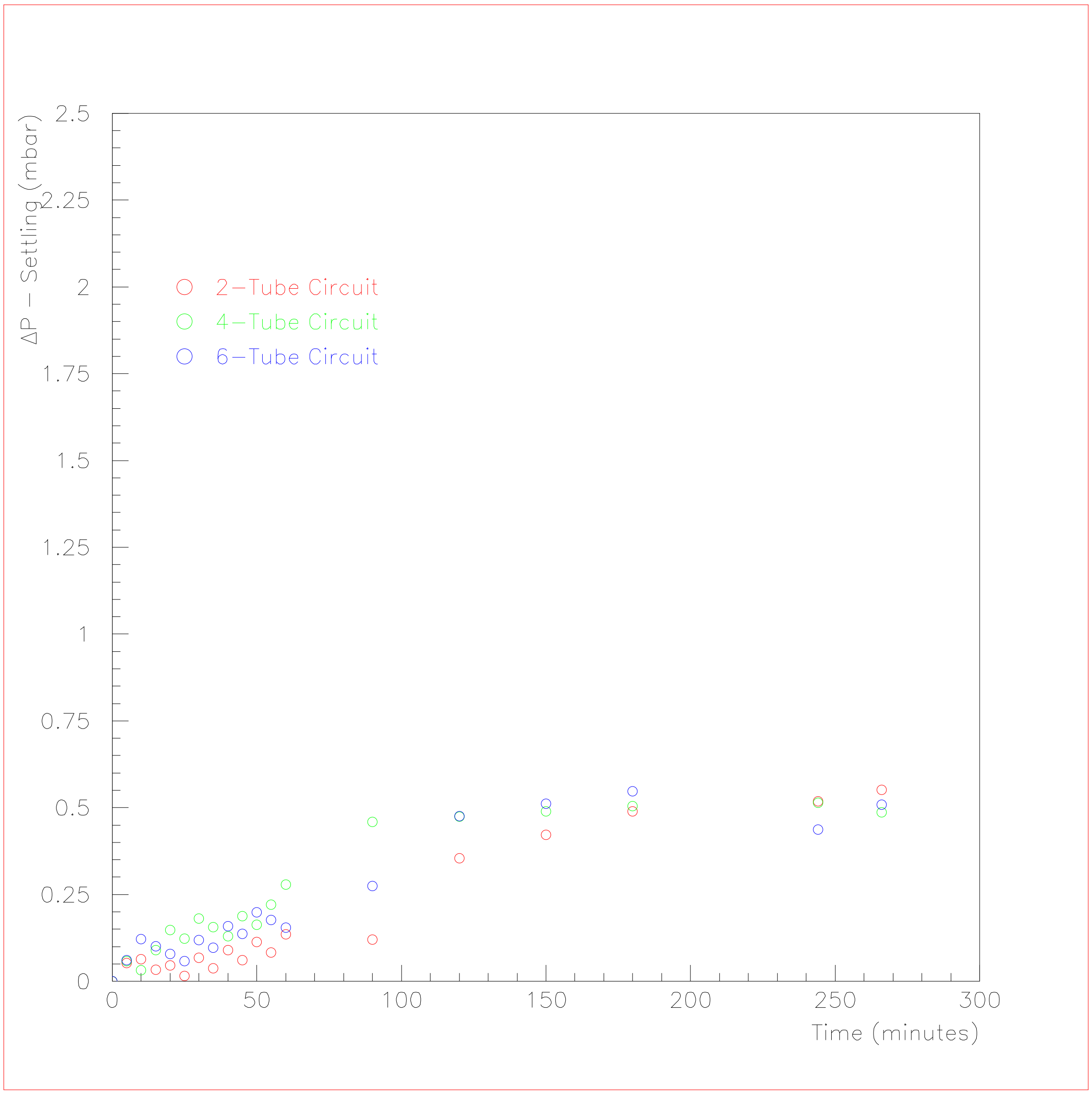

Figure 3: Contribution to the measured pressure drop due to settling.

7 Calculation of Mass-Flow Leak Rate

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We have established the following panel QA criteria: The change in the manometer heights summed over a panel side must be less than or equal to 20 mm gauge oil in half an hour where the measurement is made 3 hours after pressurization of the system. At this point the settling should be complete and the measured pressure drop should correspond to a real leak rate. To find the average dP/dt in mbar/min, multiply the difference in manometer heights by 2, divide by 30 minutes, multiply by the specific gravity of the gauge oil (0.82), divide by 10 to get from mm H_2O to mbar, and divide by 6 circuits: $< dP/dt >= 0.018$ mbar/min.

Note that we are not taking any credit for contributions to the pressure drop that may be inherent in the gas system itself (and not in the in-panel portion of the gas circuits).

Recall equation 9:

$$\frac{dV}{dt} = \frac{11V}{1000}\frac{dP}{dt}. \tag{26}$$

We can take credit for the fact that tubes in real operation will be operating at only 10 mbar of over-pressure (not 30 mbar as tested), so the mass-flow leak rate is reduced by a factor of 3. Our criteria for the pressure drop then gives the following mass-flow leak rate for one gas circuit:

$$\begin{aligned} \frac{dV}{dt} &= \frac{11 \cdot 24 \cdot 4000\,\mathrm{cc}}{3 \cdot 1000}\frac{0.018}{\mathrm{min}} \qquad (27) \\ &= 6.3\,\mathrm{cc/min/circuit} \qquad (28) \end{aligned}$$

If all of the circuits leak at this rate, one side of a large panel will leak 38 cc/min into the aluminum box (where it is diluted with the N2 purge gas and aspirated to a flammable gas sensor).

The same criteria applied to the small panel result in the same fractional volume leakrate. In other words, a small panel side will leak less than 14 cc/min.

The total leak rate summed over all panels is therefore less than 3600 cc/min (5.2 m^3/day).

8 Conclusions

1. The Iarocci tubes arrive certified to be leak tight at a level of $6.7 \cdot 10^{-2}$ cc/min.

2. We cannot reliably guarantee this level of certification with a pneumatic test. But, with a QA criteria that we can achieve, we can guarantee that the entire MuID leaks no more than 5.2 m^3/day.

9 Conversion Factors

This is a table of pressure unit conversions for reference:

	mbar	**mm H_2O**	**atm**	**mm Hg (Torr)**	**psi**	**mm Gauge Oil**
mbar	1	10	9.8692×10^{-4}	0.75006	0.0145	12.08
mm H_2O	0.1	1	9.8692×10^{-5}	0.075006	0.00145	1.208
atm	1013.25	10132.5	1	760.00	14.696	12246.67
mm Hg (Torr)	1.333	13.33	0.001316	1	0.0193	16.083
psi	68.948	689.48	0.0680	51.72	1	833.33
mm Gauge Oil	0.0826	0.826	8.15×10^{-5}	0.0620	0.00120	1

Table 1: To convert a pressure value from a unit in the left hand column to a new unit, multiply by the factor appearing in the column in the new unit.