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# **EMU CSC System Chamber Leak Rate Measurements**

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This document provides theoretical and experimental basis for the method (procedure and final formulas) to be used for measuring leaks in CSCs of the CMS Endcap Muon System. Section 1.4 gives a short summary of the procedure.

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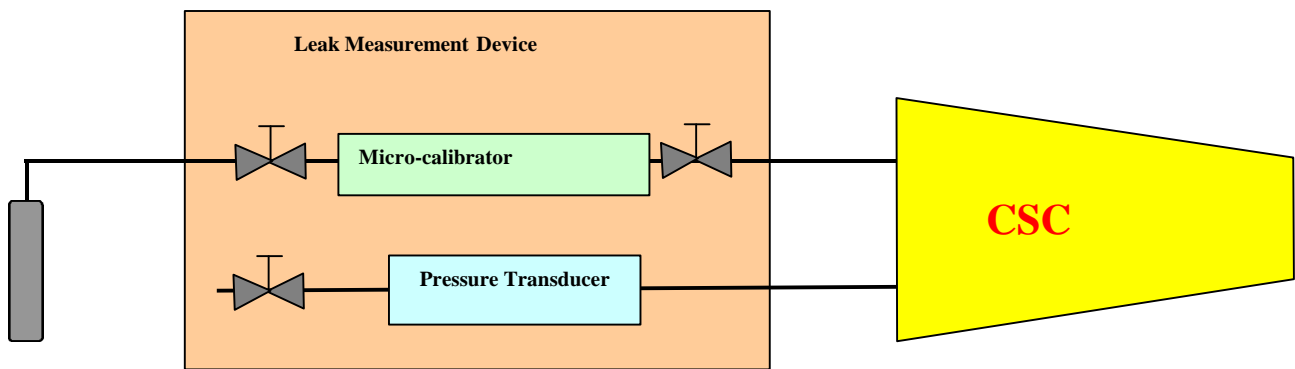
# 1. Measurement procedure

## 1.1 Requirements

The EMU system will have a recycling gas system with a fresh gas injection rate of the order of 10% of the entire system volume per day. Since the gas is expensive (due to presence of  $\text{CF}_4$ ), we desire to recuperate  $\text{CF}_4$  from the 10% of gas volume to be exhausted per day. To make it possible the leaks in the system should be much smaller, 1-2% per day. This explains the chosen specification: 2 cc/min for large ME234/2 chambers (193 liters) and 1 cc/min for all other smaller chambers (75-100 liters). These specifications translate to about 1.5% of gas losses per day.

The chambers will operate at overpressure up to 3.5 cm of water column equivalent. To allow for a safety margin, the tests are to be conducted at the initial overpressure of 3" (7.5 cm).

## 1.2 Leak rate measuring setup



## 1.3 Old gas leak measurement procedure

A chamber was pressurized by gas to 3" of water column equivalent. Then, using gas flow micro-calibrator of the leak measuring device, LMD, a constant gas flow rate equal to 2 cc/min (for ME234/2 chambers) was set and gas pressure inside the chamber was measured for a period of 15-20 minutes. If the overpressure was not decreasing during this period, this particular chamber was considered to be "good" with leak rate lower than the predefined limit. The lack of monitoring of atmospheric pressure and temperature changes resulted in insufficient accuracy and poor reproducibility of the measurements. That was the main reason to propose the new improved method of measuring chamber leak rates.

## 1.4 New gas leak measurement procedure

In addition to the leak measuring device, a weather monitoring device, with ability to measure the barometric pressure and ambient air temperature (also, humidity, which is currently, not used) is added. The new procedure is as follows:

- 1) Before measurements, a chamber has to have stayed in the room where measurements are to be done for at least 24 hours; the room should be air conditioned so the temperature stays constant within  $\pm 1^\circ\text{C}$  over a period of 24 hours.
- 2) The chamber is pressurized to 3 inches (7.5 cm) of water column equivalent and all gas flow regulators are shut off.
- 3) At the beginning and the end of  $24 \pm 1$  hour period, the following parameters are to be measured:
  - chamber-atmosphere overpressure,  $H_0$  and  $H_1$ ; the pressure transducer precision  $\sim 0.025$  mbar;
  - barometric pressure,  $B_0$  and  $B_1$ ; precision required 1 mbar or better;
  - ambient air temperature,  $T_0$  and  $T_1$ ; the change should not exceed  $1^\circ\text{C}$ ;
- 4) Based on these measurements, chamber leak rate is calculated as follows:

$$\frac{\Delta V}{\Delta t} (\text{cc} / \text{min}) \approx V_0 \left[ \frac{2 \Delta H + \Delta B}{B_0} \right] \frac{H_{\text{initial}}}{(H_{\text{final}} + H_{\text{initial}}) / 2} \frac{1}{\Delta t},$$

where  $V_0$  is the chamber volume,  $\Delta H = H_{\text{final}} - H_{\text{initial}}$  is the change in the chamber overpressure,  $\Delta B = B_{\text{final}} - B_{\text{initial}}$  is change in the atmospheric (barometric) pressure,  $B_0 = 1$  bar is the standard atmospheric pressure,  $\Delta t$  is the time between the final and initial measurements of the overpressure (recommended to be 24 hours).  $V_0$  is about 200 liters for ME234/2 chambers and about 100 liters for all the others (ME2/1, ME3/1, ME4/1 and ME1/2, ME1/3).

5) The maximum allowed leak is 2 cc/min for ME234/2 chambers and 1 cc/min for all others ( $\sim 10^{-5} V_0$  per minute).

6) The leak measured according to the formula given above and passing the spec will have an error (for large chambers) of less than  $\pm 0.5$  cc/min, which is mostly driven by temperature instabilities. The  $\pm 0.5$  cc/min estimate is based on the assumption that temperature stays constant during the entire time of measurements within  $\pm 1^\circ\text{C}$ . The error for the other chambers will be twice smaller.

7) If the final overpressure  $H_{\text{final}}$  is less than 1 inch (2.5 cm) of water column equivalent, the formula given above will result in a measurement failing the spec, unless the barometric pressure correction brings it down. The actual leak in this case may have been substantially larger than the one that would be given by the formula (see discussion in section 2.3)\*. In the case of  $H_{\text{final}}$  being less than 1 inch, the leak measurement is to be repeated. If the test fails two times in a row, the leak is to be identified and fixed.

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\* The closer  $H_{\text{final}}$  to zero, the large error is; at  $H_{\text{final}}$  equal to 1", the error is still small  $\sim 0.1$  cc/min

## 2. Leak rate calculation

### 2.1 Gas equation

Chamber at time  $t_0$



**Initial chamber state:**  
 **$P_0, V_0, T_0, m_0, B_0, H_0$**

Chamber at time  $t_1$



**Final chamber state:**  
 **$P_1, V_1, T_1, m_1, B_1, H_1$**

$P$ —absolute pressure inside a chamber (not measured)

$V$ —inner gas volume of a chamber (not measured);

note that chambers bulge under overpressure and, therefore, the gas volume is not constant;

$T$ —temperature of gas inside a chamber (assuming it is constant from plane to plane and equal to ambient temperature)

$m$ —mass of gas inside a chamber (not measured)

$B$ —absolute atmospheric (Barometric) pressure

$H=(P-B)$ —overpressure in a chamber (usually measured in height of water column equivalent).

We can treat chamber gas as ideal, which obeys the ideal gas equation. Then, one can write equations for initial and final state of gas inside the chamber:

$$P_0 V_0 = \frac{m_0}{m} R T_0 \quad \text{and} \quad P_1 V_1 = \frac{m_1}{m} R T_1$$

Combining these two equations gives:

$$\frac{P_0 V_0}{m_0 T_0} = \frac{P_1 V_1}{m_1 T_1}, \quad (1)$$

where  $V_1 = V_0 + \Delta V$ ,  $T_1 = T_0 + \Delta T$ , and  $m_1 = m_0 + \Delta m$

Also, note that  $P_0 = B_0 + H_0$  and  $P_1 = B_1 + H_1$ , from where:  $P_1 - P_0 = B_1 + H_1 - B_0 - H_0 = \Delta B + \Delta H$ , and, finally:

$$P_1 = P_0 + \Delta B + \Delta H$$

By substituting values of  $P_1, V_1, T_1, m_1$  in equation (1), one gets:

$$\frac{P_0 V_0}{m_0 T_0} = \frac{(P_0 + \Delta H + \Delta B)(V_0 + \Delta V)}{(m_0 + \Delta m)(T_0 + \Delta T)} \quad (2)$$

and

$$\frac{(m_0 + \Delta m)(T_0 + \Delta T)}{m_0 T_0} = \frac{(P_0 + \Delta H + \Delta B)(V_0 + \Delta V)}{P_0 V_0} \quad (3)$$

and

$$\left(1 + \frac{\Delta m}{m_0}\right) \left(1 + \frac{\Delta T}{T_0}\right) = \left(1 + \frac{\Delta H}{P_0} + \frac{\Delta B}{P_0}\right) \left(1 + \frac{\Delta V}{V_0}\right) \quad (4)$$

Assuming that all increments are small and, also,  $P_0 \approx B_0$ , one can re-write, keeping only first order terms:

$$1 + \frac{\Delta m}{m_0} + \frac{\Delta T}{T_0} \approx 1 + \frac{\Delta H}{B_0} + \frac{\Delta B}{B_0} + \frac{\Delta V}{V_0} \quad (5)$$

From where, the leak can be estimated as:

$$\frac{\Delta m}{m_0} \approx \frac{\Delta H}{B_0} + \frac{\Delta B}{B_0} + \frac{\Delta V}{V_0} - \frac{\Delta T}{T_0} \quad (6)$$

Therefore, in the *approximation* that the leak rate was constant during the time of measurements<sup>1</sup>, the leak per unit of time is

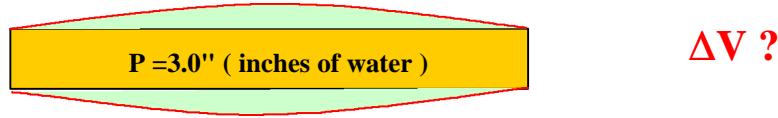
$$\frac{\Delta m}{m_0} \frac{1}{\Delta t} \approx \left[ \frac{\Delta H}{B_0} + \frac{\Delta B}{B_0} + \frac{\Delta V}{V_0} - \frac{\Delta T}{T_0} \right] \frac{1}{\Delta t} \quad (7)$$

We will be measuring leak rate in units of gas volume at normal conditions (i.e.,  $\Delta m/m = \Delta V/V$ ) per min and taking leak rate to be a positive number when a chamber does leak. Correspondingly, equation (7) will be modified as follows:

$$\frac{\Delta V}{\Delta t} \approx V_0 \left[ \frac{\Delta H}{B_0} + \frac{\Delta B}{B_0} + \frac{\Delta V}{V_0} + \frac{\Delta T}{T_0} \right] \frac{1}{\Delta t} \quad (8)$$

## 2.2 Chamber volume variations due to overpressure

Chamber panels do not provide sufficient rigidity, and outer panels bulge between support points under overpressure.



Obviously, change in the chamber volume will be proportional to over-pressure:

$$\frac{\Delta V}{V_0} \approx k \frac{\Delta H}{B_0} \quad (9)$$

To estimate how a chamber deforms under overpressure, we have done the following experiment. An ME234/2 chamber was quickly (during about 20 minutes so that changes in atmospheric pressure  $\Delta P$  and temperature  $\Delta T$  were negligible) filled at some gas flow rate up to  $\Delta H=3''$  and time of filling was measured. Amount of gas entered was estimated as

$$\Delta m = (\text{gas flow rate}) \cdot (\text{time}) \cdot \rho = (3.0 \text{ liters}) \cdot \rho \quad (10)$$

$$\Delta m/m = ((3.0 \text{ liters}) \cdot \rho) / ((200 \text{ liters}) \cdot \rho) = 1.5 \cdot 10^{-2} \quad (11)$$

At the same time,  $\Delta H/P = 7.5 \text{ mbar} / 1 \text{ bar} = 7.5 \cdot 10^{-3}$

The only way to accommodate the difference (see equations (7) and (9)), is to take  $k \approx 1$ .

Measurements done with a ME4/1 chamber, gave exactly the same value for  $k \approx 1$ . This is not a surprise since small and large chambers have about the same span of unsupported panels and, therefore, one should expect the same relative effects.

<sup>1</sup> This is a good approximation only for small leaks. See discussion of errors in the section 3.

To crosscheck these results, we measured panel bulging directly. The results and measuring scheme are shown on pictures below.

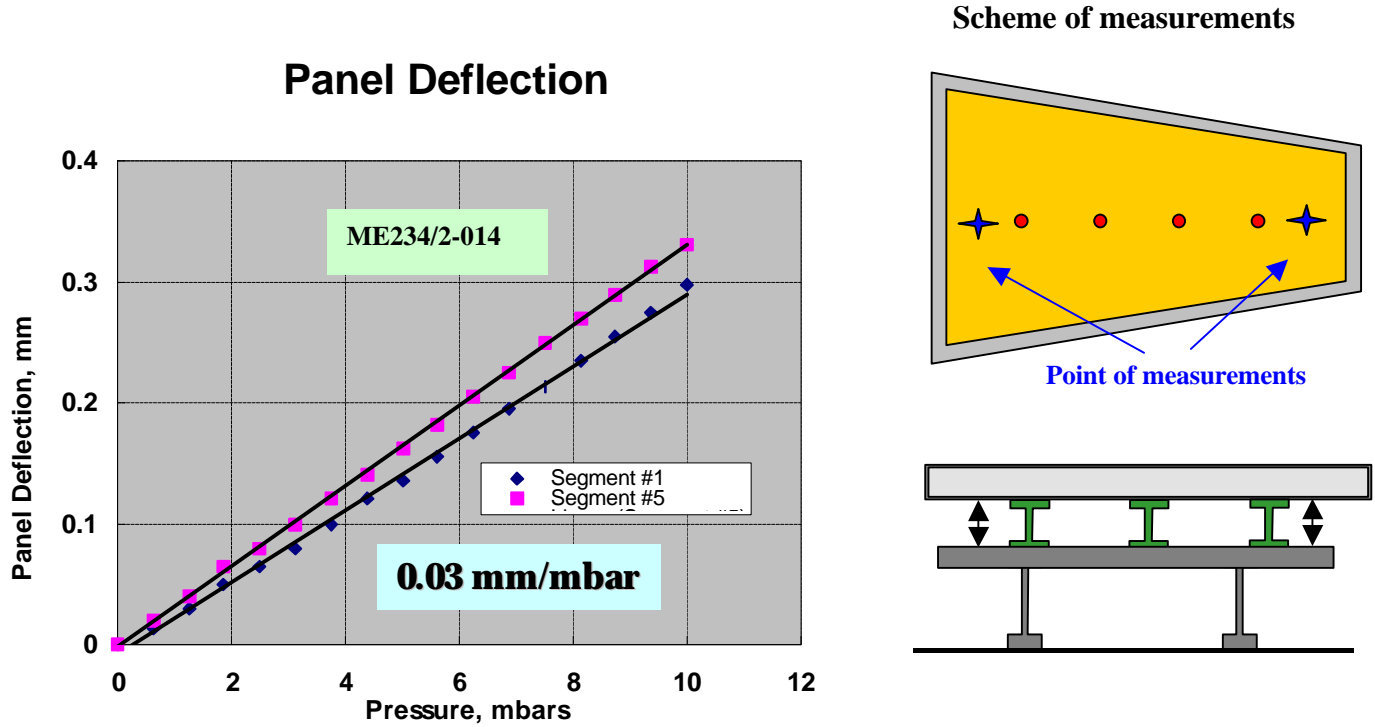


Figure on the right shows the actual setup. Panels are fixed along the chamber perimeter and at four points (red circles) along the chamber axis. Two blue stars are places where the measurements of panel bulging were done. Plot on the left shows the results. One can see that deflection (and therefore, chamber volume) linearly depends linearly on the applied pressure, which confirms eq. (9). At 7.5 mbar (3" water) panel deflection was about 0.20-0.25 mm.

From Eq. (9), one can easily estimate what a mean deflection  $\delta$  averaged over the entire chamber surface should be:

$$k \frac{\Delta H}{B_0} \approx \frac{\Delta V}{V_0} \approx \frac{2 A d}{V_0}, \quad (12)$$

where  $A \approx 3 \text{ m}^2$  is a panel area and factor accounts for deflection of top and bottom panels. From eq.(12), the estimate for mean deflection is

$$d \approx \frac{\Delta H}{B_0} \frac{V_0}{2 A} \approx 0.0075 \cdot \frac{0.2 \text{ m}^3}{2 \cdot 3 \text{ m}^2} \approx 0.25 \text{ mm}, \quad (13)$$

which agrees quite well with direct measurements.

## 2.3 Final formulae and error analysis.

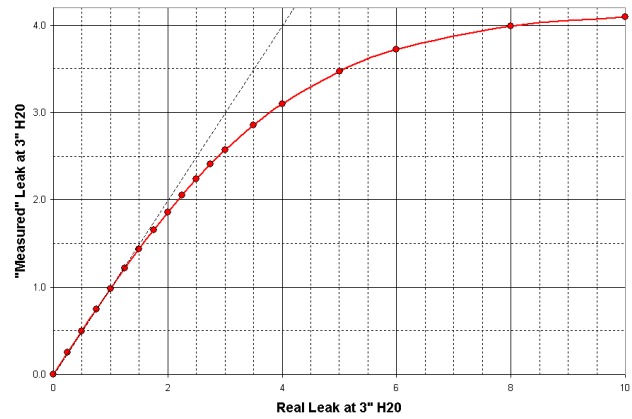
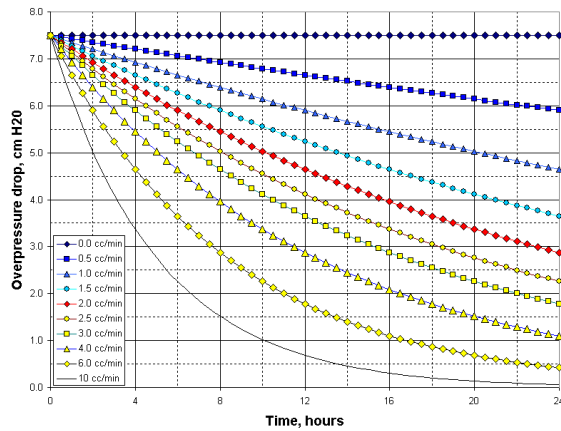
By combining Eq.'s (8) and (9), one gets for the final expression:

$$\frac{\Delta V}{\Delta t} \approx V_0 \left[ \frac{(1+k)\Delta H + \Delta B}{B_0} + \frac{\Delta T}{T_0} \right] \frac{1}{\Delta t}, \quad (14)$$

Small leaks are expected to be proportional to overpressure  $H$ . Since  $H$  changes during the measurements, the leak obtained with Eq.(13) will be referred to some average  $H$ , for which we will take the arithmetical average  $\langle H \rangle = (H_0 + H_1)/2$ . To make all measurements referenced to one overpressure of 3" of water column equivalent, the result should be correspondingly rescaled:

$$\frac{\Delta V}{\Delta t} \approx V_0 \left[ \frac{(1+k)\Delta H + \Delta B}{B_0} + \frac{\Delta T}{T_0} \right] \frac{H_0}{(H_0 + H_1)/2} \frac{1}{\Delta t}. \quad (15)$$

The assumption that we can take the arithmetical average  $\langle H \rangle = (H_0 + H_1)/2$  is an approximation that may not be valid if the overpressure dropped substantially. Assuming that the leak rate is proportional to the overpressure (and assuming that there were no changes in temperature and barometric pressures), one would expect that the level of overpressure depends on time as shown on the left figure below (the curves labeled according to leak rates at 3" overpressure for ME23/2 chambers):



As will be described below, the measurements will have to be performed over period of 24 hours. Taking mathematical average implies that, to evaluate the slope of curves at time  $T=0$ , one takes a slope of a straight line between the initial and final overpressures, which would yield correct results only for leak rates up to  $\sim 3$  cc/min. To make this statement more quantitative, the plot on the right above shows the "measured" leak calculated according to our approximate formula (15) and the real leak. At a leak rate of 2 cc/min, the error is only 0.1 cc/min; at 3 cc/min—the error is already 0.4 cc/min. Once the "measured" leak is 3 cc/min or larger, all one can tell that the leak is larger than 4 cc/min. To get a better accuracy for large leaks, the measurements would have to be conducted over shorter time, but the accurate measurements of large leaks are, strictly speaking, not what we want. Looking at the plots, one can derive a recommendation that if the observed overpressure at the end is less than 1" of water column equivalent, one has to find and fix a leak.

In addition to these errors related to approximations we make, there might be significant errors due to temperature and barometric pressure changes, if not correctly taken into account. Indeed, typical pressure changes of a period of 24 hours are around 0.1" of Hg column, or ~3.4 cm of H<sub>2</sub>O (and sometimes substantially, e.g., 3 times, larger). Obviously the barometric pressure changes cannot be neglected. Assuming that time between two measurements  $\Delta t$  is 24 hours (see discussion below), *the leak measurement error due to errors in measuring the barometric pressure* of about 0.03" of Hg column, or 1 mbar (a typical barometer, e.g., the ones currently used at FNAL, UF, UC), can be easily estimated from eq. (16) and is:

$$\varepsilon(\Delta V/\Delta t) \sim (200 \text{ liters}) \cdot (1 \cdot 10^{-3}) / (60 \cdot 24 \text{ minutes}) \sim 0.14 \text{ cc/min.} \quad (16)$$

*The error in leak measurement due to errors in measuring the overpressure H* of about 0.01" of H<sub>2</sub>O column equivalent (pressure transducer precision), or 0.025 mbar, is negligible:

$$\varepsilon(\Delta V/\Delta t) \sim (200 \text{ liters}) \cdot 2 \cdot (0.025 \cdot 10^{-3}) / (60 \cdot 24 \text{ minutes}) \sim 0.007 \text{ cc/min.} \quad (17)$$

As will be shown in section 3, temperature stabilization in a chamber is a long (many hours) process. Therefore, the change in ambient temperature does not necessarily reflect the change in temperature inside the chamber under the tests. Therefore, we require measurements to be done in a reasonably air-conditioned room where temperature fluctuations are not much larger than 1° C and over long time  $\Delta t \sim 24$  hours. This will allow one to neglect *the temperature-dependent term, with its contribution estimated to be less than*:

$$\varepsilon(\Delta V/\Delta t) \sim (200 \text{ liters}) \cdot (1^\circ/293^\circ) / (60 \cdot 24 \text{ minutes}) \sim 0.5 \text{ cc/min.} \quad (18)$$

Making measurements at exactly the same time one day apart will further reduce the sensitivity due to possible day-night temperature variations, if any.

After dropping  $\Delta T$  term, the final expression becomes:

$$\frac{\Delta V}{\Delta t} \approx V_0 \left[ - \frac{(1+k)\Delta H + \Delta B}{B_0} \right] \frac{H_0}{(H_0 + H_1)/2} \frac{1}{\Delta t} \cdot^* \quad (19)$$

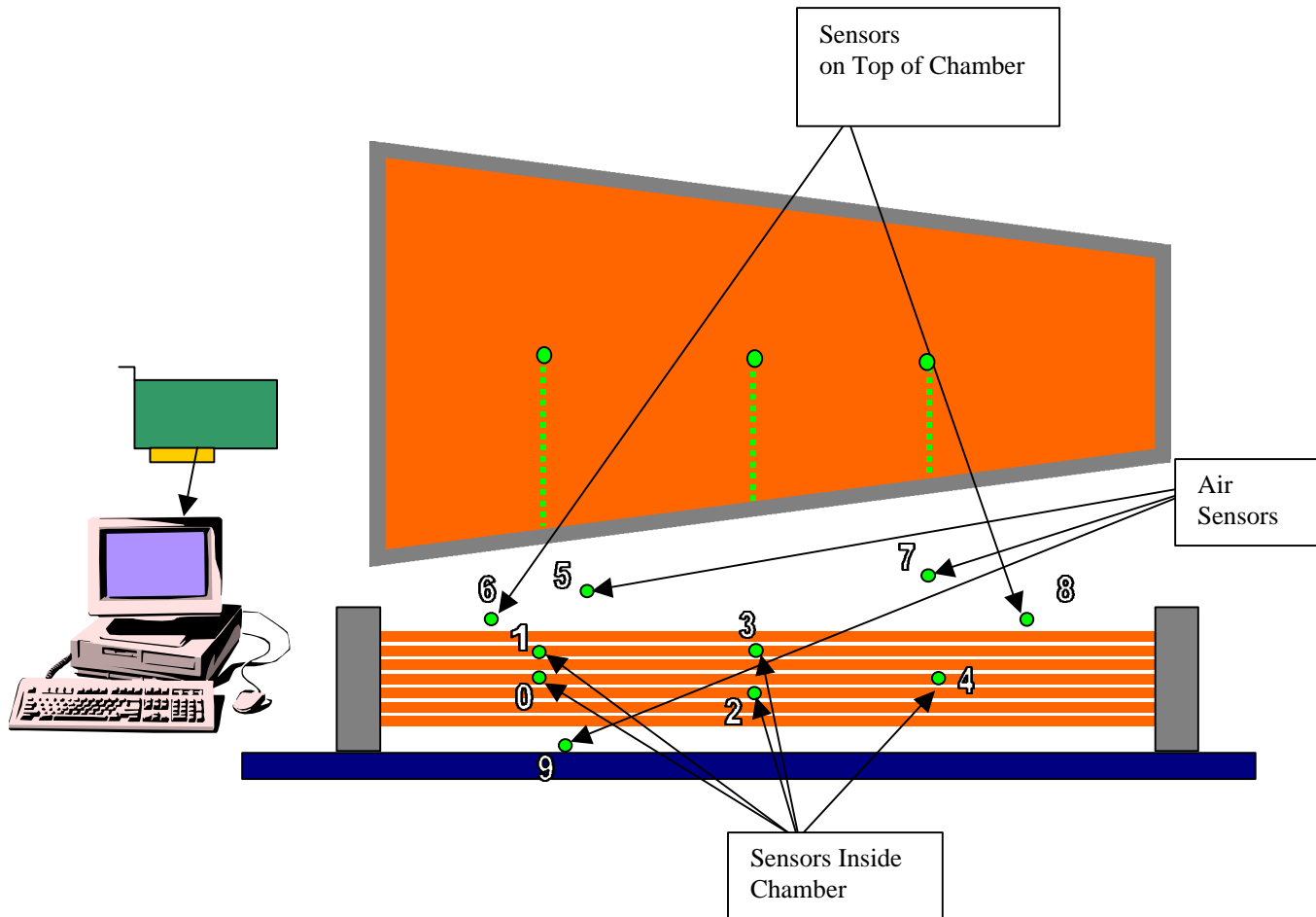
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\* For ME234/2 chambers ( $V_0=193$  liters),  $k \approx 1$ ,  $H_0=3''$ , the formula (17) can be modified to the one to be used on the production floor:

$$\begin{aligned} \frac{\Delta V}{\Delta t} (\text{cm}^3 / \text{min}) &\approx -(200,000 \text{ cm}^3) \frac{2\Delta H (" \text{H}_2\text{O}) + 13.6\Delta B (" \text{Hg})}{400 (" \text{H}_2\text{O})} \frac{6 (" \text{H}_2\text{O})}{H_0 (" \text{H}_2\text{O}) + H_1 (" \text{H}_2\text{O})} \\ &\approx -3000 \frac{2\Delta H (" \text{H}_2\text{O}) + 13.6\Delta B (" \text{Hg})}{H_0 (" \text{H}_2\text{O}) + H_1 (" \text{H}_2\text{O})} \frac{1}{\Delta t} \end{aligned} \quad (20)$$



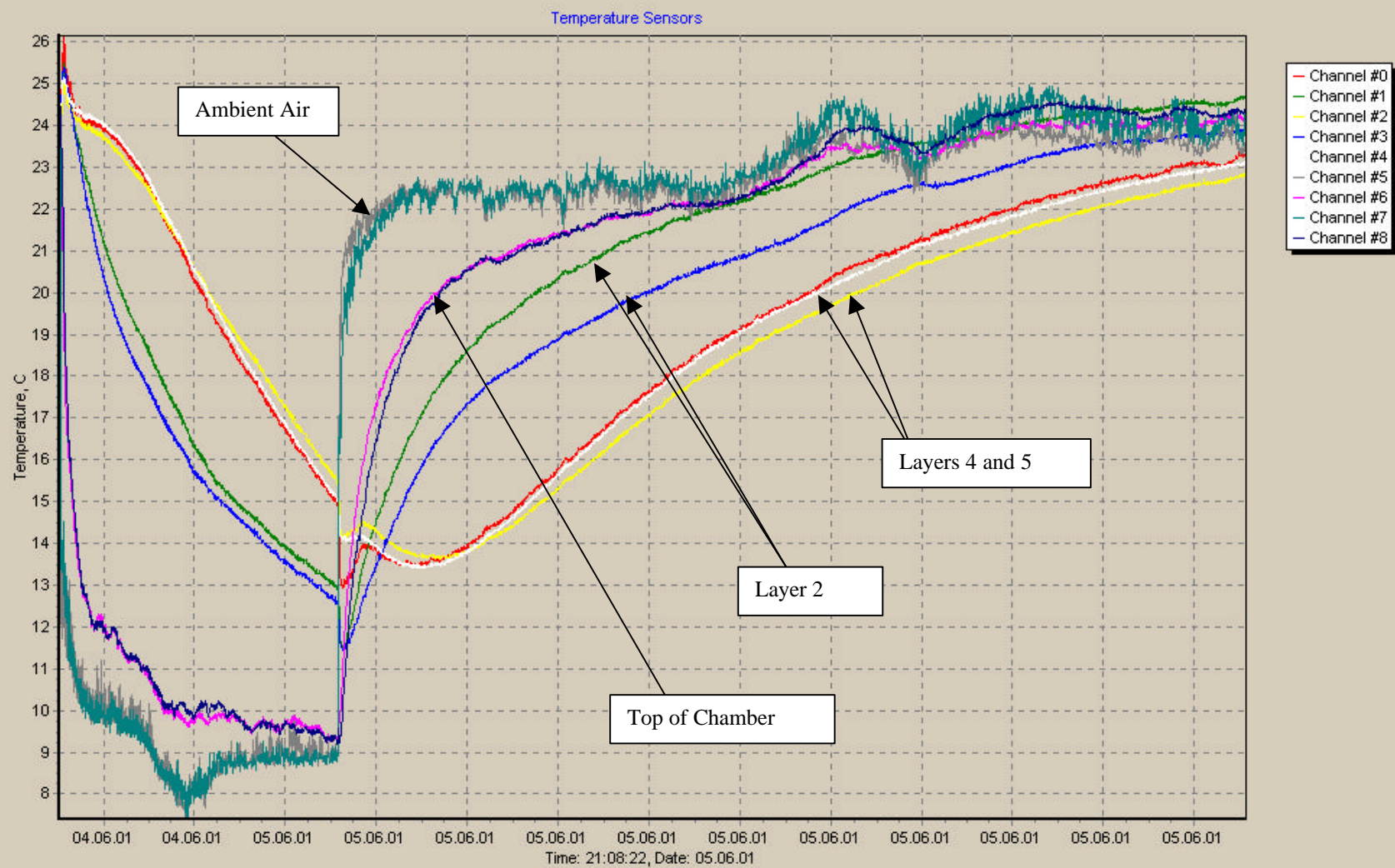
### 3. Chamber temperature stabilization

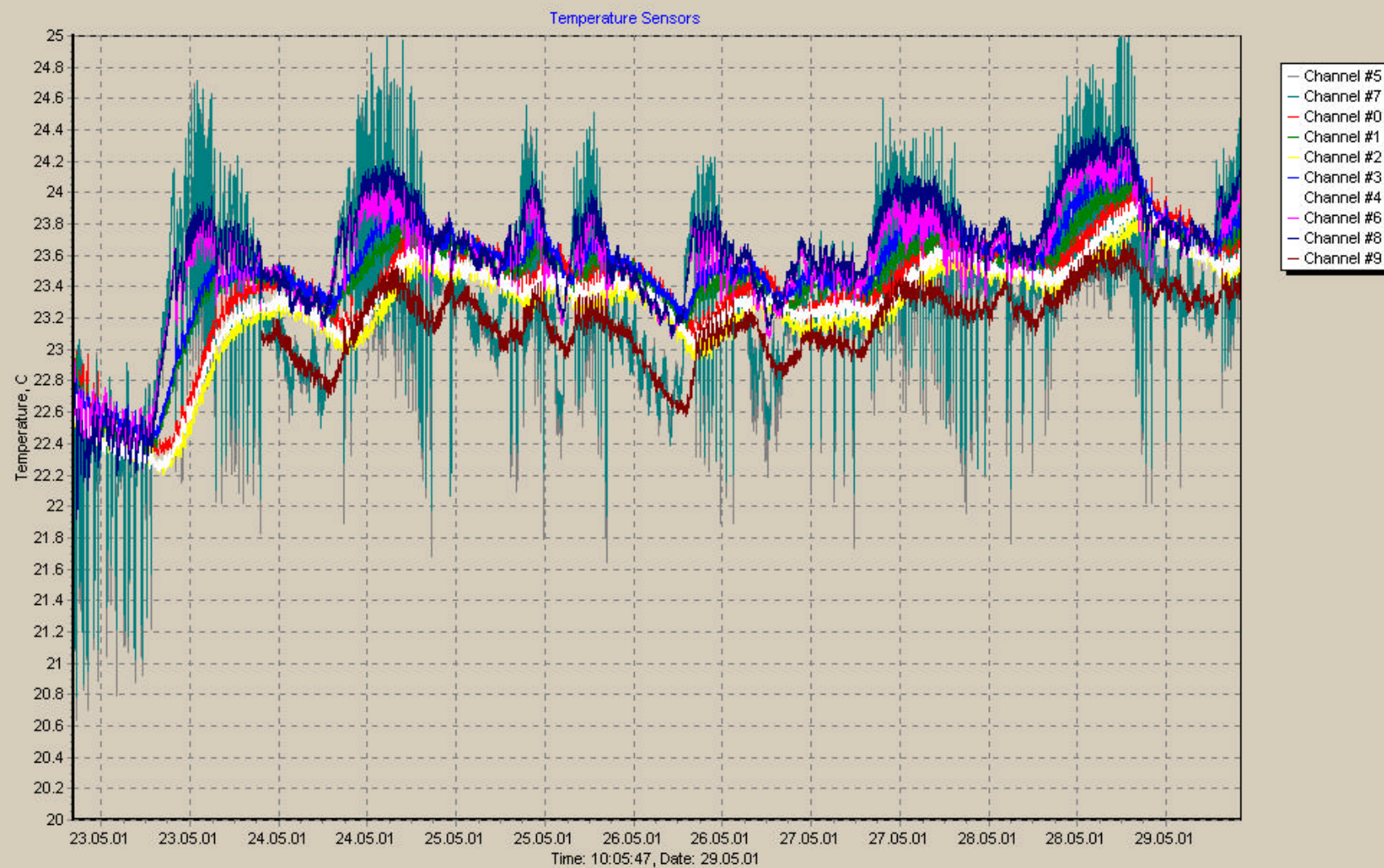


To measure a temperature inside the chamber, five holes (#0 to #4) of 3 mm diameter were drilled in polycarbonate core of the panels and the temperature sensors were installed. Sensors #6 and #8 were attached to the surface of the chamber, sensors #5 and #7 were set above the chamber and one sensor (#9) underneath it to measure air temperature.

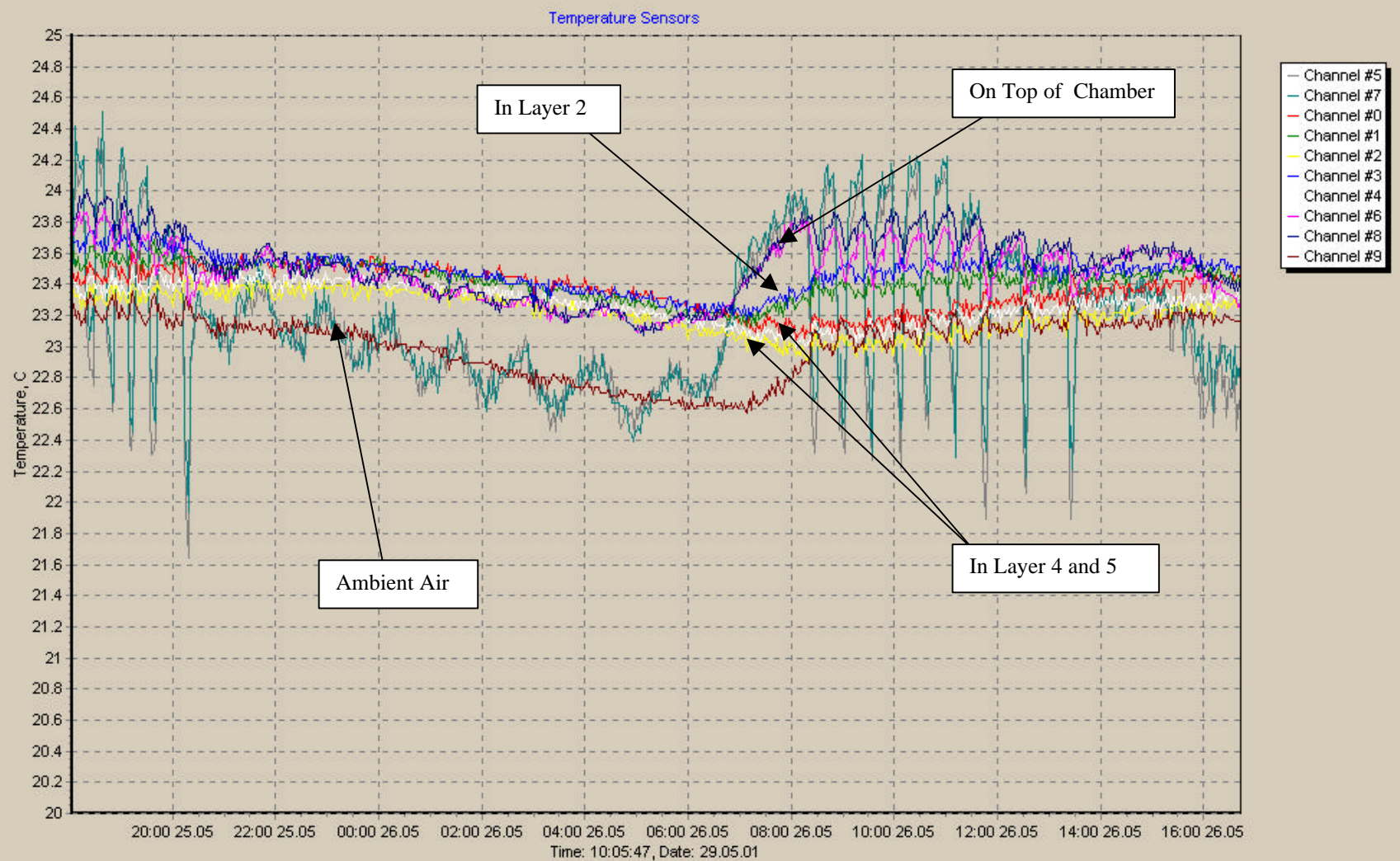
Temperature stabilization inside the chamber was measured for 1 day. The chamber was first moved out of the building for about 6 hours and then brought back into the building for the rest of the test time. Inside building temperature was 24°C, outside was 9°C. As a response to the changed ambient air, temperature inside the chamber was changing exponentially. Changing rate strongly depends on layer's location. Results of measurements are below. One can see that for innermost layers it takes as long as 24 hours to come in equilibrium with the ambient air temperature.

Two plots to follow the next one show results obtained in a 6-day long test aimed to verify the actual conditions in the building with a common conditioning system. One can see that temperature inside a chamber stayed well within 1°C span. One can also see the obvious advantage of doing leak measurements during exactly 24 hours, i.e. at the same time of the day. Day-night temperature variations would not contribute as much in this case.









## 4. Conclusions: the leak measurement procedure

- To measure leaks in large ME234/2 CSCs with accuracy of 0.5 cc/min, a room with stable ambient temperature is required. The temperature variations typically should not exceed  $\sim 1^\circ\text{C}$  over the time of measurements. Under these conditions the inside chamber temperature could be treated as constant and calculations can be performed without temperature correction. Same conditions will imply an accuracy of 0.25 cc/min for chambers of the smaller types.
- To stabilize temperature inside chamber after transportation and before starting measurements, a minimum time period of 24 hours is required.
- Set the initial overpressure in a chamber at 3 inches (7.5 cm) of water column equivalent and observe its drop over 24 hours (to minimize some day-night temperature variations, the time of the measurements is recommended to be  $24 \pm 1$  hours).
- Atmospheric pressure at the beginning and at the end of the measurements is to be recorded (with precision of 1 mbar or better). The effect of barometric pressure changes is to be taken into account in calculations of the chamber leaks.
- Formula to be used in calculations of the chamber leak is as follows:

$$\frac{\Delta V}{\Delta t} (\text{cc} / \text{min}) \approx V_0 \left[ \frac{2 \Delta H + \Delta B}{B_0} \right] \frac{H_{\text{initial}}}{(H_{\text{final}} + H_{\text{initial}}) / 2} \frac{1}{\Delta t},$$

where  $V_0$  is the chamber volume,  $\Delta H = H_{\text{final}} - H_{\text{initial}}$  is the change in the chamber overpressure,  $\Delta B = B_{\text{final}} - B_{\text{initial}}$  is change in the atmospheric (barometric) pressure,  $B_0 = 1$  bar is the standard atmospheric pressure,  $\Delta t$  is the time between the final and initial measurements of the overpressure (recommended to be 24 hours).  $V_0$  is about 200 liters for ME234/2 chambers and about 100 liters for all the others (ME2/1, ME3/1, ME4/1 and ME1/2, ME1/3).

- The maximum allowed leak is 2 cc/min for ME234/2 chambers and 1 cc/min for all others ( $\sim 10^{-5} V_0$  per minute).
- If the final overpressure  $H_{\text{final}}$  is less than 1 inch (2.5 cm) of water column equivalent, the formula given above will give results failing the spec. The actual leak in this case may have been substantially larger than the one given by the above formula.

## APPENDIX:

### Chamber Assembly Traveler

#### Chamber Leak Test Measurements

Completed

- 10.14 Turn the Main Valve to begin the flow. The Microcalibrator should read 10ccm. To pressurize the chamber, increase the gas flow by turning the Flow Adjustment Valve until the mechanical flowmeter reads its full value of 130 ccm. The chamber pressure should immediately begin increasing. Within a 10-15 minutes the pressure should read 2.9 inches. When it does, reduce the flow rate gradually so that the target pressure of 3.00 inches is gradually approached ☐
- 10.15 Close the bottle, pressure regulator valve, and microcalibrator valve. ☐
- 10.16 Turn the main valve to gas flashing position to drop the pressure on the manometer to 0 (backside of LMD) and then turn main valve to close position. ☐
- 10.17 Wait for 5 minutes before starting the measurements. Using the weather station device for measurements of atmospheric pressure, temperature and humidity. ☐
- 10.18 Leak test the chamber for 16-24 hours. Record a few measurements at the beginning and at the end of the leak test measurements at intervals of 1-2 hours. Record data in the table below. ☐

#	Chamber Pressure (P) inch, Water	Barometric Pressure (B) inch, Hg	Temperature F°	Humidity %	Time t h/min	Date day
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						

**Note(s):**

**The final chamber pressure data must be higher than 1" (2.5 mbar) at the end of measurements. Temperature must not be more than + -2° F (± 1° C), during measurements.**

10.19 Calculate leak rate in accordance with the formula below.

$$\text{Leak rate (cm}^3\text{/min)} = \frac{3000 (2\Delta P + 13.6 \Delta B)}{(\Delta P_{\text{final}} + \Delta P_{\text{initial}}) \Delta t}$$

Where:  $\Delta P = P_{\text{initial}} - P_{\text{final}}$ , chamber pressure in inch water,  
 $\Delta B = B_{\text{initial}} - B_{\text{final}}$ , barometric pressure in inch Hg  
 $\Delta t = t_{\text{final}} - t_{\text{initial}}$ , minutes,

10.20 Record result of the leak rate calculation in the table below.

Leak rate, cm <sup>3</sup> /min	Date

**Note(s):**

**Leak Flow Rate MUST be less than 2.0cm<sup>3</sup>/min.**

10.22 If leak rate is higher than 2.0cc/min start procedure for definition of leak location using a leak detector. Record results of leak investigation below.

Remarks: \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

10.23 When leak is fixed, repeat leak test measurements. Record a few measurements at the beginning and at the end of the leak test measurements at intervals of 1-2 hours. Record data in the table below.

#	Chamber Pressure (P) inch, Water	Barometric Pressure (B) inch, Hg	Temperature F°	Humidity %	Time T h/min	Date day
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						

**Note(s):**

**The final chamber pressure data must be higher than 1" (2.5 mbar) at the end of measurements. Temperature must not be more than  $\pm 2^{\circ}\text{F}$  ( $\pm 1^{\circ}\text{C}$ ), during measurements.**

- 10.24 Calculate leak rate in accordance with formula (see 10.19). Record result of the leak rate calculation in the table below.

Leak rate, $\text{cm}^3/\text{min}$	Date

**Note(s):**

**Leak Flow Rate MUST be less than  $2.0\text{cm}^3/\text{min}$ .**

Remarks: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

\_\_\_\_\_  
 Technician(s)

\_\_\_\_\_  
 Date

- X** 10.25 Verify all Section 10.0 steps have been properly completed and signed off and the panel is acceptable for further processing.

\_\_\_\_\_  
 Lead Person

\_\_\_\_\_  
 Date