TI 176B Flow Rate Audit Calculations

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1.0 PURPOSE AND APPLICABILITY

This standard operating procedure (SOP) describes the procedures for calculating the values necessary for performing a final flow rate audit on an IMPROVE aerosol sampler. These calculations may be done prior to arriving at the site, if the elevation, the audit device calibration equation, and the temperature are known. Air Quality Group personnel frequently perform these calculations on a computer prior to going out in the field.

2.0 RESPONSIBILITIES

2.1 Field Specialist

The field specialist shall:

- Train field technicians to audit IMPROVE aerosol samplers.
- Oversee the calculations required for flow rate audits, if done in Davis.
- Approve and file the audit device calibration equation.
- Maintain an accurate database of site location and elevation.
- Approve the sampler audits and calibration equations.

2.2 Field Technician

The field technician shall:

- Prepare an audit device for use in the field.
- Calculate the values required to perform a final flow rate audit.
- Keep accurate records of the calculations and audit values.
- Audit the sampler at the site.

3.0 REQUIRED EQUIPMENT AND MATERIALS

The equipment required to prepare a final flow rate audit form includes the following:

- Blank final flow rate audit sheet
- Scientific calculator
- Audit device with a verified calibration equation
- Elevation of the site to be audited

4.0 METHODS

This section covers the theory behind sampler calibration and audits, and the methods and equations used to generate the audit forms.

4.1 Theory Behind Sampler Calibration and Audit Procedures

4.1.1 Critical Orifice Calibration

The flow rate through each module of the IMPROVE sampler is maintained by an adjustable critical orifice, located between the filter and the pump. (Prior to the summer of 1994, instead of adjustable orifices, the IMPROVE network used small brass fittings with a range of orifice sizes that could be slightly enlarged or decreased in the field.) As long as the pressure after the orifice is than 52% of the pressure in front of the orifice, the air flow will be critical, that is, limited by the speed of sound and will not be affected by small changes in pump performance.

The mass flow rate is constant at all points in the system, but the volume flow rate increases as the pressure of the air decreases when the air passes through different stages. The concentration depends on the volume of ambient air, so we are concerned with the volume flow rate through the inlet. Since there is negligible pressure drop across the inlet, this is equal to the volume flow rate at the cyclone. This volume flow rate at the cyclone determines the cutpoint of the cyclone. The pressure will decrease as the air passes through the filter. If the pressure drop is ΔP, then the inlet flow rate is (1- ΔP) times the flow rate at the front of the critical orifice.

The flow rate through a critical orifice depends on the geometry of the orifice (primarily the diameter) and the absolute temperature of the air at the front of the orifice. We will assume that this temperature is the same as the ambient temperature. The flow rate at the critical orifice differs from the inlet flow rate because of the pressure drop as the air passes through the filter. We have chosen to express all calibrations relative to a common temperature, 20°C. The equation for the inlet flow rate is

$$Q = Q_o * \left(1 - \frac{\Delta P}{P}\right) * \sqrt{\frac{T + 273}{293}} \ , \qquad \text{(TI176B-1)}$$

where Q_o is a constant and $\Delta P/P$ is the relative decrease in pressure before the orifice. The pressure drop ΔP is produced primarily by the filter, either because of the pressure drop of a clean filter or because of filter loading. To account for the pressure drop of the clean filter, each critical orifice is adjusted during calibration to give the desired flow rate with a typical clean filter appropriate for the module. The important pressure quantity is the variation, δP, about the nominal pressure drop of the clean filter used in calibration, ΔP_{nom}:

$$\delta P = \Delta P_{nom} - \Delta P \qquad \text{(TI176B-2)}$$

If δP is associated with variation in the clean filter, it can be either negative or positive, and will affect the measurements before and after collection equally. If the variation is caused by filter loading; δP will be positive and affect only the final flow rate measurement. For this reason we average the two readings.

The annual mean temperatures for all the IMPROVE sites, based on the weekly temperature measurements is 15°C. In order to have the mean annual flow rate at 22.8 L/min, the critical orifices are adjusted to provide a flow rate of 23 L/min at 20°C with a typical filter in the cassette. The constant Q_o in Equation A1-2 is then given by

$$Q_o = 23.0 * \left(1 - \frac{\Delta P_{nom}}{P}\right)^{-1} , \qquad \text{(TI176B-3)}$$

The nominal flow rate is set at 19.1 L/min at 20°C for the Wedding PM_{10} inlet, and at 17.8 L/min for the Sierra-Anderson PM_{10} inlet.

Substituting Equation TI176B-3 into Equation TI176B-1, and assuming there is no variation in atmospheric pressure at the site, the flow rate is given by

$$Q = 23.0 * \left(1 - \frac{\delta P}{P - \Delta P_{nom}}\right) * \sqrt{\frac{T + 273}{293}} , \qquad \text{(TI176B-4)}$$

An orifice meter consists of a restriction in the air path and a device to measure the pressure drop across the restriction. Three orifice meters are used in the IMPROVE network, all using magnehelics to measure the pressure drop. The audit devices consists of an assembly that fits into the base of the inlet tee of the fine modules and at the base of the inlet stack or the PM10 module. For the fine modules, the assembly stops the normal flow through the inlet. For all modules, the air flow must pass through a calibrated orifice in the assembly. The audit devices are calibrated at Davis using a spirometer. The fine modules use a system orifice meter based on the restriction produced by the cyclone. The PM10 module uses an orifice meter located between the filters and the pump.

The flow rate through an orifice meter depends on the pressure drop across the restriction and the square root of the density of the air:

$$Q = Q_1 \, (\delta P)^{\beta} \sqrt{\frac{P_o}{P}} \; \sqrt{\frac{T + 273}{293}} \qquad \text{(TI176B-5)}$$

where Q_1, β, and P_o are constants. For laminar flow, $\beta = 0.5$. We express Equation TI176B-5 in parameterized form using the magnehelic reading, M, for the pressure drop:

$$Q = 10^{a} \, M^{b} \sqrt{\frac{P(\text{sea level})}{P(\text{site})}} \; \sqrt{\frac{T + 273}{293}} . \qquad \text{(TI176B-6)}$$

We have arbitrarily defined all pressures relative to the standard pressure at sea level and all temperatures relative to 20°C. Thus, the parameters, a and b, are always calculated relative to 20°C and Davis. The value of b should be similar to that of β, around 0.5. The advantage in expressing the parameters relative to sea level is that all modules should have parameters with similar values independent of the site elevation.

Thus, Equation TI176B-6 can be written

$$Q = 10^{a}\, M^{b}\, F(\text{elev})\; f(T) \qquad \text{(TI176B-7)}$$

Where F(elev) and f(T) are in the form shown below. F(elev) is described more fully in Section 4.1.2.

$$F(\text{elev}) = \sqrt{\frac{P(\text{sea level})}{P(\text{site})}} \qquad f(T) = \sqrt{\frac{T+273}{293}}\ .$$

Because the PM10 orifice meter is located after the filter, where the air density is lower than the inlet density, the inlet flow rate does not follow Equation TI176B-5. Using the equation for an orifice meter and Equation TI176B-1, the equation for the inlet flow rate is

$$Q = Q_2\, (\delta P)^{2\beta} \left[F(\text{elev})\right]^2 f(T)\ , \qquad \text{(TI176B-8)}$$

where Q_2 and β, are constants. The temperature behavior is the same as for the meters in the fine modules, but the pressure/elevation relationship is different. We can use Equation A1-7b with the limitation that the a parameter will vary with site elevation. This is acceptable as long as we perform the calibration at the sampling site. The procedures are significantly simplified by using the same parameterized equation for all orifice meters. Note that the b parameter is approximately 1.0 for the PM10 meter, compared to 0.5 for the fine modules.

4.1.2 Ambient Pressure Corrections

The ambient pressure enters into the equations for UCD audit devices and the system magnehelic as the square root of the pressure. Because of the difficulties of measuring the ambient pressure at each sample change, we have chosen to use an average pressure based on the elevation of the site. The actual pressure is used only in calibrating the audit devices at Davis.

Based on the 1954 tables of Treworth, the pressure at an elevation Z feet can be expressed by

$$P = P_o \exp\left[-\left\{\frac{Z}{27674} + \left(\frac{Z}{87317}\right)^2\right\}\right]\ , \qquad \text{(TI176B-9)}$$

where P_o is the standard pressure at sea level.

It is convenient to define an elevation factor that is the square root of the pressure at sea level divided by the pressure at the site. This factor is expressed as

$$F(\text{elev}) = \sqrt{\frac{P_0}{P(\text{site})}} = \exp\left[\frac{1}{2}\left\{\frac{Z}{27674} + \left(\frac{Z}{87317}\right)^2\right\}\right] \qquad \text{(TI176B-10)}$$

The values of nominal P and F(elev) as a function of elevation are given in Table 1.

Table 1 Elevation Factor vs. Elevation

elev	F(elev)	P
0	1.000	29.92
100	1.002	29.81
200	1.004	29.70
300	1.005	29.60
400	1.007	29.49
500	1.009	29.38
600	1.011	29.28
700	1.013	29.17
800	1.015	29.07
900	1.016	28.96
1000	1.018	28.85
1100	1.020	28.75
1200	1.022	28.64
1300	1.024	28.54
1400	1.026	28.44
1500	1.028	28.33
1600	1.030	28.23
1700	1.031	28.13
1800	1.033	28.02
1900	1.035	27.92
2000	1.037	27.82
2100	1.039	27.72
2200	1.041	27.62
2300	1.043	27.51
2400	1.045	27.41
2500	1.047	27.31
2600	1.049	27.21
2700	1.050	27.11
2800	1.052	27.01
2900	1.054	26.91
3000	1.056	26.81
3100	1.058	26.72
3200	1.060	26.62
3300	1.062	26.52
3400	1.064	26.42
3500	1.066	26.32
3600	1.068	26.23
3700	1.070	26.13
3800	1.072	26.03
3900	1.074	25.94

elev	F(elev)	P
4000	1.076	25.84
4100	1.078	25.74
4200	1.080	25.65
4300	1.082	25.55
4400	1.084	25.46
4500	1.086	25.36
4600	1.088	25.27
4700	1.090	25.17
4800	1.092	25.08
4900	1.094	24.99
5000	1.096	24.89
5100	1.098	24.80
5200	1.100	24.71
5300	1.103	24.61
5400	1.105	24.52
5500	1.107	24.43
5600	1.109	24.34
5700	1.111	24.25
5800	1.113	24.16
5900	1.115	24.07
6000	1.117	23.97
6100	1.119	23.88
6200	1.121	23.79
6300	1.123	23.70
6400	1.126	23.62
6500	1.128	23.53
6600	1.130	23.44
6700	1.132	23.35
6800	1.134	23.26
6900	1.136	23.17
7000	1.138	23.08
7100	1.141	23.00
7200	1.143	22.91
7300	1.145	22.82
7400	1.147	22.74
7500	1.149	22.65
7600	1.152	22.56
7700	1.154	22.48
7800	1.156	22.39
7900	1.158	22.31

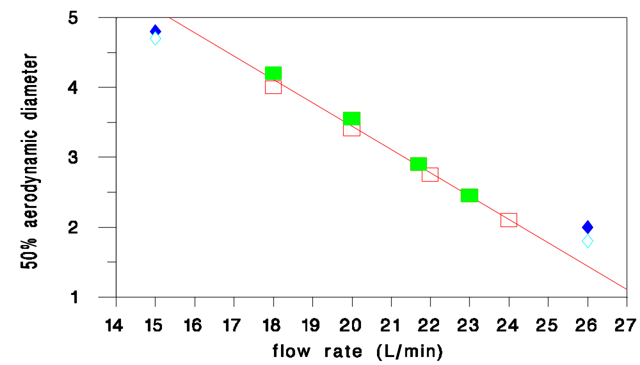
elev	F(elev)	P
8000	1.160	22.22
8100	1.163	22.14
8200	1.165	22.05
8300	1.167	21.97
8400	1.169	21.88
8500	1.172	21.80
8600	1.174	21.72
8700	1.176	21.63
8800	1.178	21.55
8900	1.181	21.47
9000	1.183	21.38
9100	1.185	21.30
9200	1.187	21.22
9300	1.190	21.14
9400	1.192	21.06
9500	1.194	20.98
9600	1.197	20.90
9700	1.199	20.82
9800	1.201	20.73
9900	1.204	20.65
10000	1.206	20.57
10200	1.211	20.42
10400	1.215	20.26
10600	1.220	20.10
10800	1.225	19.94
11000	1.230	19.79
11200	1.234	19.64
11400	1.239	19.48
11600	1.244	19.33
11800	1.249	19.18
12000	1.254	19.03
12200	1.259	18.88
12400	1.264	18.73
12600	1.269	18.59
12800	1.274	18.44
13000	1.279	18.29

4.1.2 Cut Point Calculations for IMPROVE Cyclones

The sampler calibration procedure both allows accurate determination of the volume of ambient air sampled, and of the cut point of the sampled aerosols. IMPROVE samplers are designed to provide a nominal 2.5 µm cut point, meaning it efficiently removes particles from the air stream larger than 2.5 µm in aerodynamic diameter.

The collection efficiency of the IMPROVE cyclone was characterized at the Health Sciences Instrumentation Facility at the University of California at Davis. The efficiency was measured as a function of particle size and flow rate using two separate methods: PSL and SPART. Both use microspheres of fluorescent polystyrene latex particles (PSL) produced by a Lovelace nebulizer and a vibrating stream generator. The PSL method analyzed these by electron micrographs, while the SPART method analyzed them by a Single Particle Aerodynamic Relaxation Time analyzer. The aerodynamic diameter for 50% collection, d_{50}, was determined for each flow rate. The relationship between diameter and flow rate is shown in Figure 1. The solid symbols are from PSL and the open symbols from SPART.

Figure 1 Relationship between 50% Aerodynamic Diameter and Flow Rate for the IMPROVE Cyclone.



The best-fitting straight line in Figure 1 is based on measurements for both methods for flow rates between 18 and 24 L/min. The equation is:

$$d_{50} = 2.5 - 0.334 * (Q - 22.8) \qquad (176B\text{-}11)$$

with a correlation coefficient of $r^2 = 0.991$. In order to maintain a constant cutpoint of 2.5 µm, it is necessary to maintain a constant volume flow rate of 22.8 L/min.

Variations in temperature with site and season affect the collection cutpoint but not the volume calculation. The mean annual d_{50} will be slightly lower at warm sites than at cold. Saguaro (22° C) would have an annual d_{50} of 2.4 µm, while Denali (2°C) would have a d_{50} of 2.7 µm. For a given site, the mean d_{50} in summer will be lower than in winter. For example, based on historical records, the d_{50} at Davis would vary between 2.4 µm in midsummer and 2.6 µm in midwinter. At the highest maximum temperature recorded at Davis (34°C), the d_{50} would drop to 2.2 µm.

The Table 2 gives the variation in flow rate Q and d_{50} as a function of temperature, using Equations 176B-4 and 176B-11, with δP zero.

Table 2 Flow Rate and 50% Aerodynamic Diameter vs. Flow Rate.

T(°C)	-20	-10	0	10	20	30	40	50
Q (L/min)	21.4	21.8	22.2	22.6	23.0	23.4	23.8	24.1
d_{50} (µm)	3.0	2.9	2.7	2.6	2.4	2.3	2.2	2.1

Because the flow rate is measured before and after each sample, variations in ΔP also affect the collection cutpoint more than the volume calculation. The decrease in flow rate because of filter loading is accounted for in the volume calculation by averaging the values before and after collection. In general, filter loading is not a problem. For a typical western site, Canyonlands, the mean final flow rate over a recent 12-month period was 1% lower than the mean initial value. (The precision for reading the gauges is approximately 2%.) For a heavily loaded eastern site, Shenandoah, the difference of means was 3%. In the worst case, the flow rate dropped 15%; this increased the cutpoint from 2.3 µm to 3.5 µm.

The mean measured flow rates for the 49 sites of the IMPROVE network for the annual period from June 1991 to May 1992 indicate that in practice the combination of temperature and δP produce only a small variation in flow rate. The standard deviation at each site ranged from 0.2 L/min to 1.2 L/min, corresponding to standard deviations in d_{50} of 0.1 to 0.4 µm. In addition, the flow rate for all samples was close to the target value of 22.8 L/min. The mean flow rate was 22.5 ± 0.6 L/min, corresponding to d_{50} of 2.6 ± 0.2 µm.

4.2 Procedures to Calibrate the IMPROVE Aerosol Sampler

The final audit calculations, though done on the computer for existing sites, are listed in detail in the following section. These calculations ensure the sampler is, on average, running at the appropriate ambient flow rate. The form for final site audits follows in Figure 1. The following procedures describe the pre-audit calculations.

1. At the top of the final audit log sheet, record the site name, the date, the sampler serial number (located on the lower left inside the controller or A module).
2. Record the elevation of the site above sea level, the elevation correction factor f_{elev} = [Pressure(Davis) / Pressure(site)]$^{1/2}$ (pressure in "Hg), and the name of the field technician performing the audit.
3. Record the audit device number, the audit device calibration equation constants, and the current temperature. Note that the audit device constants, a_o and b_o are printed on a sticker on the face of the audit device.
4. Calculate the audit device reading for nominal flow at 20°C for the A, B, and C modules M_o(A,B,C). Recall that Q_o = 23 lpm, as recorded on the A, B, and C module calibration tables. Record the calculated value in the space provided.
5. Calculate the audit device reading for nominal flow at 20°C for the D module, M_o(D). Recall that Q_o = 19.1 lpm for a Wedding style PM_{10} inlet, and Q_o= 16.9 lpm for a Sierra style PM_{10} inlet. Record the calculated value in the space provided to the right of the equation.
6. Record the nominal flow rate at 20°C, Q_o, and the audit device reading, M_o in the first two columns of the top row of the respective audit tables for the A, B, C, and D modules.
7. Calculate Q_1, Q_2, and Q_3 for each module (A, B, C, and D) and record the values in the spaces provided. Recall, as shown on the form,
   Q_1= 0.95*Q_0, Q_2= 0.90*Q_0, Q_3= 0.85*Q_0
8. Calculate M_1, M_2, M_3 using the equation for M_o above the calibration tables, but substituting in Q_1, Q_2, and Q_3 respectively for Q_o. Record the values for each module in the spaces provided in the audit tables for each module.
9. This completes the pre-audit calculations. Final flow rate audits, as described in SOP 176, may proceed, using the values calculated in this worksheet.

Figure 2 Flow Rate Audit Form

Site Name:______________ Date of Audit: ____/___/__ Sampler Serial #________________

elevation________ F(*elev.*)_______ (from Table) Field Technician: _____________________

Audit Device # _________ Audit Constants: a_o = _________ b_o = _________ T_______°C

audit mag. reading for nom flow: $M_o = \frac{Q_o}{F_{(elev)}} {\frac{1}{10^{a_o}}}^{1/b_0}$ M_o(**A, B, C**) = ______ M_o(**D**) = __________

A Module: Q_o = 23 lpm

Flow Rate at sea level, 20°	Audit Device	System Magnehelic	System Vac. Gauge
Q_o	M_o=		
Q_1=0.95*Q_o	M_1=		
Q_2=0.90*Q_o	M_2=		
Q_3=0.85*Q_o	M_3=		
Magnehelic: r²=___________ log(flow) = + * log(M)			
Vacuum Gauge: r²=___________ flow = + * (G)			
Nominal flow @ site (sys.):		mag. zero:	max. vac.:

B Module: Q_o = 23 lpm

Flow Rate at sea level, 20°	Audit Device	System Magnehelic	System Vac. Gauge
Q_o	M_o=		
Q_1=0.95*Q_o	M_1=		
Q_2=0.90*Q_o	M_2=		
Q_3=0.85*Q_o	M_3=		
Magnehelic: r²=___________ log(flow) = + * log(M)			
Vacuum Gauge: r²=___________ flow = + * (G)			
Nominal flow @ site (sys.):		mag. zero:	max. vac.:

C Module: Q_o = 23 lpm

Flow Rate at sea level, 20°	Audit Device	System Magnehelic	System Vac. Gauge
Q_o	M_o=		
Q_1=0.95*Q_o	M_1=		
Q_2=0.90*Q_o	M_2=		
Q_3=0.85*Q_o	M_3=		
Magnehelic: r²=___________ log(flow) = + * log(M)			
Vacuum Gauge: r²=___________ flow = + * (G)			
Nominal flow @ site (sys.):		mag. zero:	max. vac.:

D Module: Wedding (19.1) ☐ Sierra (16.9) ☐

Flow Rate at sea level, 20°	Audit Device	System Magnehelic	System Vac. Gauge
Q_o	M_o=		
Q_1=0.95*Q_o	M_1=		
Q_2=0.90*Q_o	M_2=		
Q_3=0.85*Q_o	M_3=		
Magnehelic: r²=___________ log(flow) = + * log(M)			
Vacuum Gauge: r²=___________ flow = + * (G)			

Nominal flow @ site (sys.):	mag. zero:	max. vac.: