NYSERDA Standard Operation Procedures for use of a Thermo Scientific 1405-D TEOM™ in a dilution tunnel with wood-fired stoves, hydronic heaters, and furnaces with calculations for grams PM emitted for EPA Independent Assessment Project

July 8, 2025

Note: This method does not include all of the specifications (e.g. equipment and supplies) and procedures (e.g., sampling and analytical) essential to its performance. Some material may be incorporated by reference from other measurement methods, therefore, to obtain reliable results, persons using this method should have a thorough knowledge of related test methods (e.g., NYSERDA Methods 5G-x and Integrated Duty Cycle)

Section 1. Introduction

This document covers operational procedures and calculations for use of the Thermo Scientific model 1405-D TEOM to measure continuous particulate matter (PM) concentrations from Residential Wood Heater Appliances with or without thermal storage in an ASTM E2515 dilution tunnel with a tunnel flow of at least 600 SCFM. The TEOM is a 2-channel inertial microbalance designed for ambient real-time PM measurements. It is a true continuous mass measurement method with a resolution of 0.01 µg (0.00001 mg). The output of the TEOM is 1-minute PM concentration in µg/m^3. This SOP also includes calculations that use 1-minute TEOM and wet tunnel flow data to report 1-minute PM emissions (in grams) for use in subsequent IDC phase and full-run calculations. The PM emission rate (g/h) is also reported, using run times calculated from minutes that have valid TEOM data, not the actual run or phase duration.

The version of the TEOM used here for measurement of PM in the dilution tunnel is the "Dichotomous" (dichot) 2-channel sampler without any inlet hardware or sample conditioning options such as "FDMS" (it ships with a virtual impactor and flow splitter that are not used). The TEOM operating parameters are highly configurable; for this application, flows, temperatures and timing parameters are changed from the normal ambient monitor settings. The second dichot TEOM channel is used as a co-located tunnel PM measurement for quality control purposes, similar to the paired filter trains used in ASTM E2515. There are no TEOM hardware modifications needed other than disconnecting the heater cable. Instrument manuals, Microsoft Windows instrument software, and related support information are available from the Thermo web site.[1] Technical support is available during eastern time business hours by calling Thermo Environmental Instruments at 866 282 0430.

Instrument Software

[1]The TEOM manual, revision of 15Feb2008, is referenced in this SOP, and is available here along with instrument software: https://www.thermofisher.com/order/catalog/product/TEOM1405D

Thermo provides two Microsoft Windows programs for the TEOM that can be obtained from the 1405 TEOM web page. "RPComm" (the serial port interface program) is used to display the last 15 minutes of data on a graph, download data, and quickly read all key operating parameters during a test run. It is also used to document the instrument settings. "ePort" (the ethernet interface program) is used to control the instrument remotely and to download data. Both programs can be used at the same time. Instrument control and data can be accessed remotely using any program that provides remote PC access such as Chrome Remote Desktop.

Instrument Installation.
The TEOM must be positioned close to the dilution tunnel sample port location, which must meet the requirements of EPA Method 1 or 1a. The length of the sample lines from the tunnel wall to the TEOM inlets must be no more than 18 inches. Consistent with ASTM E2515, samples are taken no more than 1 inch from the tunnel center line, and there must be at least 1 inch distance between the two sample line ends. Sample tubing must be conductive, either metal or conductive flexible tubing with ¼" ID. If metal tubing is used, care must be taken to prevent tunnel vibrations from causing excessive noise in the TEOM. A short piece of ¼" OD x 3/16" ID metal tubing must be used for insertion into the tunnel. All of the inlet tubing must be replaced or cleaned after every series of tests.

The TEOM is not heated. The laboratory temperature at the location of the TEOM must be kept sufficiently cool to keep the instrument's Case temperature reading from exceeding 32.2 ºC (90 ºF) for more than 10 minutes.

Filter loading can sometimes unexpectedly increase very rapidly, and the TEOM does NOT have any clear visual warning that the filter needs changing due to loading. The TEOM digital outputs (relay contact closures, page 3-31 of the TEOM manual) must be used to trigger an external audible alarm at ~115% filter loading, as shown in the alarm configuration instructions at the end of this SOP.

<u>Supplies and Parts needed for this test method:</u>
1405-D Dual channel TEOM without inlet, Thermo p/n 1405D-ANF
Teom filters, 6 to 8 per test, ordered from Thermo, p/n 57-007225-0020 (box of 20 filters)
Mass transducer calibration kit, Thermo p/n 59-008298 and 1 refill, p/n 59-008299 (optional)
Particle filter for zero-air tests and mass transducer calibration
3/8" OD conductive inlet tubing (metal or conductive plastic[2])
(2) 1/2" to 3/8" or 1/4" swage SS reducing union for inlet tubing
NIST-traceable mass flow meter for 0.40 to 3.30 lpm, accuracy of 2.0% or better, with resolution of at least 0.01 LPM, with a current calibration certificate.
Windows PC for RPComm (with a USB to serial port adaptor) and ePort (ethernet connection)
Filter change alarm parts: a DB25 male breakout connector, alarm, and alarm power supply (see details at end of this SOP).

[2]Available from Freelin-Wade, Static Dissipative 90A Plastic Tubing - 90A-452, p/n 1J-452-90-01

Note for mass transducer calibration filters.

If a semi-microbalance (0.01 mg resolution) is available and meets the calibration requirements for use in ASTM E2515, then calibration filters can be created by weighing a new TEOM filter in triplicate, twice on two different days. The range of these six weighings must not exceed 0.04 mg. The value to use is the average of all six weighings. Calibration filters must be stored in a TEOM filter box or petri dish, and stored in a sealed plastic bag with desiccant, with the balance information, dates of weighing, all six weights, and the average value to be used for K0 calibrations. A separate dedicated filter change tool is needed to avoid contamination of calibration filters. A red handle tool for this purpose comes with the mass transducer calibration kit.

Section 2. Routine Operation Procedures for Thermo 1405-D TEOM

This section is a summary of routine operating procedures.

A. Quality Assurance checks to be completed before and after each set of test runs:

1. Modify system settings as detailed in Section 8 (initial installation only).
2. Perform K0 mass transducer verification checks on both channels as detailed in Section 4 of this procedure.
3. Document the system settings listed below using the Thermo RPComm program to display and save the values to a text file. Instrument time (PRC390) is in Unix Epoch format (seconds since 1/1/70, valid through 2037). This example is at May 14, 2021 1:59:05 PM (instrument clock time, not UTC). TEOMA (left sensor) is PM2.5 and TEOMB (right sensor) is PM-coarse. K0 values are calibration constants specific to each TEOM mass transducer. Other key instrument operating parameters are always recorded in the data file and thus are not listed here.

PRC	Name	Value
1	serial number	1405A247642010
2	instrument firmware version	1.74
3	instrument model	TEOM 1405-D
4	Instrument model variant	Dichot
28	system wait time	0
35	mass average time	30
74	average temperature set point	20.0
75	standard temperature set point	20.0
76	average pressure set point	1.00
77	standard pressure set point	1.00
78	volumetric flow control	1
79	mass conc reporting	1
91	bypass flow mass set point	0.00
259	TEOMA K0	15317
343	TEOMB K0	17551
390	instrument time	1621000745
392	MRMC average time	30

407	TEOMA mass constant A	0.00
408	TEOMA mass constant B	1.00
409	TEOMB mass constant A	0.00
410	TEOMB mass constant B	1.00

It is possible to simply record all TEOM parameters by clicking on the "Select All Registers" icon, read them, and then click on the "save" button.

B. Routine procedures before every test run to be conducted 1-2 hours prior to testing.

1. Check the TEOM time display and set as needed to be within 5 seconds of the laboratory master clock time. Changing the time causes an instrument reboot and loss of up to an hour of data - see notes section below. Using RPComm, verify and document that the 1-minute data records are being recorded with time-stamp seconds between :00 and :05 (seconds between :30 and :59 will cause problems with the TEOM data processing). If they are not correct, reboot the instrument and check that data are being properly stored after the top of the next hour. Alternatively, do a routine reboot at least 1-hour before the start of each test run; this still requires a check with RPComm after the top of the hour that data are being stored after the reboot.

2. Before installing new TEOM filters, perform a leak test and flow check on both TEOM channels using the procedures in Section 3 of this SOP. The leak test net results must be no greater than 0.10 lpm. The flow checks must be performed with a traceable calibration standard. If either measured flow is greater than 2.0% different than the reported flow on the TEOM display, a flow calibration must be performed and documented using the procedures in Section 3.

3. Teom Initial filter change.
Install a clean filter for each channel before each test run and put two clean filters on the storage pins inside the sensor. See Section 5 for the filter change procedure, including confirmation of proper operation after the filter change.

C. Operation During Testing

1. Before initiating the test, run the TEOM while sampling dilution tunnel air with tunnel flow for at least 10 minutes. The change of pressure in the tunnel can cause a large transient TEOM response which would invalidate the data for several minutes.

2. TEOM filter changes during a test run must be done when any of the following conditions are met, using the "Advanced" filter change mode and the procedure in Section 5. Filters for both channels must always be changed at the same time. The display PM2.5 concentration will read zero after a filter change until the top of the next hour (data are being recorded, just not displayed).

Note: Changing filters more often than required should be avoided if possible since it can affect the reported PM values.

Planned filter changes: when these are done depends on the type of device being tested. For cordwood appliances, filters are changed sufficiently in advance of loading the next cordwood fuel charge to allow the TEOM to stabilize after completion of the filter change procedure, and ensures that valid data are available when the next fuel charge is loaded.

Cordwood stoves: Near the end of load 2 when ~70 to 75% of the fuel charge has been burned, and also near the end of load 3 when ~80% of the fuel charge has been burned.
Pellet stoves: No planned changes.
Cordwood hydronic heaters: when ~80% of load 2 has been burned.
Pellet hydronic heaters: Half-way through phase 4 (no heat load), approximately 20 to 25 minutes after phase 4 starts, but ONLY if the filter loading exceeds 40% on either channel at this point in the test. Otherwise, no planned changes.
Cordwood furnaces: When ~80% of the first fuel load is burned (near end of phase 3).

Note: Planned changes are guidelines to minimize filter changes during periods of high PM emissions, but there may be situations where they can not be followed. An example of this: some cordwood hydronic heaters may not reach 80% of load 2 burned before L3; in this case TEOM filters are changed during phase 4, between 10 and 30 minutes before L3.

Avoiding unnecessary filter changes: If an unplanned change for a cordwood appliance is required before the target fuel charge burned is reached, the subsequent planned change can be skipped if filter loading is low when the target fuel charge is reached. Low is defined as: TEOM filter mass loading < 300 µg **AND** filter loading < 20% [as read from the Teom display]. If either of these limits are exceeded for either TEOM channel, change the filters as planned unless experience with the appliance being tested has shown another unplanned change during the test run is unlikely.

Unplanned filter changes:
a. Percent loading reaches 115% for either TEOM channel.
b. When the sample flow drops more than 5% of the flow setpoint for either channel.

Note: (a) will not normally trigger a filter change on a low-emitting device, and (b) should never occur without (a) unless there is a problem with the pump. Note that filter "plugging" does not end the test run – it triggers a filter change and the run continues.

Proper operation of the TEOM must always be confirmed after a filter change as detailed in the Section 5 filter change procedure. Detailed information on performing filter changes during testing is provided in Section 5 of this document.

Note that if the flow starts to drop from the setpoint before 115% is reached, that is an indication of a vacuum pump problem. Vacuum is usually between 0.20 and 0.35 atm as read on the "System Status" TEOM display screen. If it exceeds 0.40 atm, the pump must be serviced.

3. At the end of the test, perform external leak and flow checks on both channels as detailed in Section 3 and record the results. For valid test results, post-test leak checks must be no more than 0.15 lpm, and flow checks must be within 4.0% of the TEOM flow reading.

4. Download the test data using either the Thermo ePort software (preferred), RPComm, or to a USB thumb drive. Note: the data format may be different depending on how the data are downloaded (if used, the TEOM data template is based on downloading data using the ePort software but with minor changes can be used with RPComm data).

   Notes:

   - The instrument "Status" code is not normally used for data validation since with no heaters errors are always shown.

   - When the TEOM is first turned on or rebooted, no data are recorded until the top of the next hour. Other than after a reboot, data will be recorded even when no concentration data is displayed on the screen, such as after a filter change.

   - **After EVERY instrument power on or Reboot:** confirm data are being recorded after the top of the hour. Occasionally the TEOM doesn't store any data after a reboot, even though all operational parameters are normal and concentrations are reported to RPComm and the TEOM display. If this occurs, Stop and Start the instrument to start data storage. A filter change using the Wizard is a Stop and Start cycle.

   - When the time is changed, the instrument reboots (after many seconds of being hung, with no information on the screen). When it reboots, no data are recorded until after the top of the next hour (see above).

   - TEOM PM concentrations are in micrograms per cubic meter, at EPA STP (20.0 ºC and 1.00 atmosphere) with the instrument configuration used in this procedure. Filter mass loading is reported in micrograms, with a resolution of 0.01 micrograms (10^{-8} grams).

Section 3. Leak and Flow Checks and Flow Calibration for the 1405-D TEOM

A traceable flow standard capable of reporting flow at standard conditions and with a resolution of at least 0.01 LPM must be used for all leak and flow checks and all flow calibrations. All leak and flow checks and all flow calibrations must be documented. Facing the front of the dichot TEOM, the left channel is PM2.5 (TeomA) and the right channel is PM-coarse (TeomB). TEOM sample flows are normally 1.00 LPM for both channels. If the device under test has emissions

high enough to require excessive filter changes (more than 2 additional changes), a flow of 0.50 LPM can be used for subsequent test runs. Flows can not be changed during a test run.

Leak Checks

A leak test measures the net flow as reported by the TEOM's flow sensors with inlets closed off. Leak checks must be done for both channels before the start and after the end of every test run. The TEOM leak test flow readings must be corrected for the TEOM flowmeter's zero offsets. To conduct a leak check, follow the procedures below or use the Leak Check Wizard (page 3-4 of the 1405-D manual):

1. With the TEOM warmed up for at least 30 minutes, turn off or disconnect the pump from the rear of the instrument. Wait 1 minute and read the TEOM reported flow for both channels. This is the flowmeter zero reading.
2. Close off the inlets to the TEOM sample train.
3. Turn on or connect the TEOM pump.
4. Wait one minute and read the flows reported by the TEOM for both channels.
5. The leak test results are the difference (net value) between the reading without and with flow.
6. The leak test net value must be no greater than 0.10 lpm pre-test, and 0.15 lpm post-test. All leak test results must be documented.
7. Open the inlet to the TEOM sample train.

Flow Checks.

The TEOM sample flows for each channel must be set to 1.00 lpm. If the device under test has emissions high enough to require excessive filter changes, flows down to 0.50 lpm can be used. The TEOM must be warmed up for at least 30 minutes before checking or adjusting the sample flows. The sample flows must be measured at the sample train inlet with an external NIST-traceable flow mass flow meter. Before a test run, measured flows must be within 2.0 % of the flow as indicated on the TEOM display for each of the two channels. If this flow check fails, a flow calibration must be performed. The flow check limit after a test run is 4.0 %; if it is greater than 4.0 %, the test run is not valid. All flow checks must be documented. Note that large changes (>5 °C) in lab temperature may change the TEOM flow calibration by a few percent.

Flow Calibrations.

Flows must be calibrated for each channel with a NIST-traceable mass flow meter with at least 0.01 LPM resolution, using the TEOM wizard at Service, Calibration, Flow Calibration (page 5-41 of the Dichot TEOM manual); select "Direct Flow Device" (not FTS). If the flow meter standard T is different from 20 °C, that standard T value must be used to adjust data to 20 °C during data processing. Flow calibrations and checks must be documented. A Flow Check must be performed immediately after every flow calibration.

Flow Calibration Troubleshooting.

When a Flow Calibration fails, power-cycle the instrument and then use RPComm to report the "flow offset" and "flow span" parameters (PRC 228, 229 for TeomA, and PRC 312, 313 for TeomB). If they are not close to 0 and 1 respectively, reset the instrument's flow calibration to 0

and 1 by doing a flow calibration routine but just selecting "next" without entering any flows. Once those are reset, perform a normal flow calibration and then record the new offset and span parameters.

NOTE: In buildings where heavy electrical equipment is operated, the actual TEOM flows might be unstable even though the reported flow appears to be stable. This can cause erratic and poor agreement in the PM between the two TEOM channels. For that reason it is recommended to use a constant voltage power supply for this instrument rather than a direct 120VAC wall outlet. A ferroresonant-based power conditioner is recommended; it provides voltage regulation, noise and harmonics filtering, spike suppression, and galvanic isolation.

Section 4. TEOM Mass Transducer K0 Check Procedure for the 1405-D TEOM

The mass transducer K0 (calibration factor) checks described here must be done before and after each set of test runs. A set is usually the three to five IDC runs required for wood heater certification purposes; for research use a set could be more runs. A set of tests is not valid until it is bracketed by valid K0 checks.

K0 Checks

K0 checks (verifications) confirm the calibration factor for the tapered element mass transducer in use by the TEOM by weighing a clean TEOM calibration filter of known mass (nominally 0.09 grams) as supplied by Thermo or measured by the lab as noted in Section 1 of this protocol. To prevent contamination of calibration filters, the red filter change tool must only be used with calibration filters, and the black filter change tool must never be used with the calibration filters

K0 verifications must be done before and after every set of test runs using the K0 Wizard. See page 5 53 of the Dichot TEOM manual. Verify that the K0 values in use by the instrument are the same as the values on the mass transducer sticker, and document the serial number of the mass transducer. The PM2.5 K0 is on the left, and the PM-coarse K0 is on the right. The transducer serial number is on the far right in the example below; the last four digits are the YYMM of manufacturer. If either of the K0 values in use are different than the original values, the date(s) of calibration and the values currently in use must also be recorded.

Record the calibration filter ID, the calibration date, and the average mass value of the calibration filter. Document the results of each K0 check with an ePort screenshot of the result as shown below; note that the percent difference reported here is the absolute value, not the signed value. If results are greater than 2.0% different from the values currently being used by the TEOM, or if the signed difference in the K0 % error between the two dichot TEOM channels is greater than 2.0%, repeat the check. If repeated checks fail either of these criteria, repeat the check with a second calibration filter. If either of the differences above still exceed 4.0%, the K0 check has failed, and all tests performed since the last valid K0 check result are invalid.

If either of the 2.0% difference limits above can not be met, the K0 values in the instrument must be changed from the manufacturer's value supplied with the instrument, but this must not be done without clear and robust evidence such as multiple calibrations with multiple filters that the K0 values are out of tolerance. The new values must be documented and stored with the instrument for future reference.

K0 Verification Results

The K0 Verification Wizard has completed successfully. The instrument will be put in Run mode when this wizard is finished.

PM-2.5 (left) TEOM:
K0: 14523.0 Audit K0: 14592.7
Percent difference: 0.48
Initial frequency: 344.6019
Final frequency: 248.6712

PM-Coarse (right) TEOM:
K0: 15825.0 Audit K0: 15871.9
Percent difference: 0.30
Initial frequency: 364.9168
Final frequency: 260.5874

Section 5. Filter Change Procedure for the 1405-D TEOM

The TEOM measures the pressure drop across the filter as % of maximum (115 %), and is shown on the instrument display screen. A clean filter has a loading of about 5 % at 1.00 lpm. Teom filter lifetime will vary widely depending on the PM concentrations and nature of the smoke being sampled. Under typical sampling conditions, lifetime is an hour or more with concentrations in the 20 to 50 mg/m^3 range, but at very high PM concentrations (several hundred mg/m^3), filter lifetime may be less than 30 minutes. With care, filter changes can be done such that only 3-4 minutes of data are lost. A video showing the TEOM filter change procedure is on the Thermo TEOM web page. This video does not use the "Advanced User Mode" that is required by this SOP, but is useful for training purposes. The Dichot TEOM manual has illustrated procedures for filter changes starting on page 5-6.

Performing successful filter changes in short order is paramount to improved data quality with this test method. It is strongly advised to practice filter changes to gain experience with this process, and also learn to recognize a filter change that is not fully seated or a sensor latch that is not fully closed, and to quickly remedy such a situation during a live test.

Note: Both TEOM filters must always be changed at the same time, even if only one channel triggers a filter change event.

Filter change procedure.

The following are filter handling procedures that must be followed:

A. Unused clean filters must be stored in the original box and plastic bag, with the silica gel desiccant in the bag.
B. Two clean filters must always be stored inside the mass transducer on the posts provided.
C. Filters must only be handled with the black filter change tool.

Minimize the time the mass transducer is open to reduce the time needed to re-stabilize temperatures after the filter change.

1. The filter change menu can be located by choosing Service, Maintenance, Replace Filter. Select the "Advanced" option, and then Next to proceed. This turns off the oscillating element which makes filter seating easier.

2. Open the TEOM cabinet door, open the box of clean filters, and open the mass transducer. Remove the old filters by sliding the filter tool onto the filter and pulling straight out. Do not twist the tool (to prevent damage to the glass tapered element).

3. For each channel, pick up a new filter that has been stored inside the mass transducer with the tool. Position it directly over the tapered element and push the filter on gently. Once the filter is on, remove the tool from the filter and fully seat the filter by pushing firmly straight down on the filter with the bottom of the tool with approximately two pounds of force for at least two seconds (see the TEOM manual and video for more information). The filter should have a small amount

of horizontal play when this is done; if not, the filter may be wedged between the tapered element and the side of the opening for the element. Store two new filters on the posts inside the mass transducer (this equilibrates them to the sensor temperature).

4. Close the mass transducer, replace the filter box cover, and close the cabinet door. Restart the TEOM by completing the filter change wizard with Next, Finish. The TEOM is not restarted until the Wizard is closed with "Finish", and the Maintenance screen is shown.

5. Proper operation of the TEOM must always be confirmed after a filter change. Proper operation for both channels is verified using the TEOM's PM2.5 and PM-Coarse display (PM-10 is not used) using the checks below.

1-minute after the filter change is completed:
a. Frequencies for both channels must be greater than 200 Hz.

5-minutes after the filter change is completed:
b. Filter mass values for both channels must be within 10 µg of each other.
c. Noise values for both channels must be small (< 2 µg), or if larger because of high PM concentrations, within 15% of each other.

	PM-2.5	PM-Coarse
MC (µg/m³):	0.00	8.66
30-Min MC (µg/m³):	0.00	0.00
1-Hr MC (µg/m³):	0.00	0.00
2-Hour value (µg/m³):	0.00	0.00
12-Hr MC (µg/m³):	0.00	0.00
24-Hr MC (µg/m³):	0.00	0.00
Total mass (µg):	0.07	0.11
Filter loading:	3.68 %	5.51 %
Frequency:	257.9879 Hz	270.8600 Hz
Noise:	0.028 µg	0.129 µg

If the filter change fails, the filter may need to be reseated, or the sensor latch may not be closed properly. Repeat the filter change "advanced" procedure and take the filter off and re-seat it. Push it on firmly with the back of the filter tool and make sure the sensor is properly closed and latched. If the problem persists after another 5 minutes, repeat the procedure with another new filter. Invalid data from a failed filter change must be manually removed from the 1-minute data since the TEOM reports it as valid data (operating mode = 3 or 4).

Note: the PM2.5 concentrations on the TEOM display will read 0.0 after a filter change until the top of the next hour. When valid data are being collected, the RPComm graph will indicate PM2.5 concentration, and the "Total Mass" on the TEOM display will read something other than "0.00" for both channels, and with similar mass values.

Section 6: TEOM Data Storage and Download

The TEOM must be set to store data every 60 seconds. There is storage for more than a year of data at this storage interval. Data can be downloaded while the TEOM is running.

Data are usually downloaded with the ePort software, with the "use old column names" option unchecked. If needed, data can also be downloaded to a USB thumb drive or with the RPComm TEOM software, but the data format may change. The TEOM raw data file is in .CSV format for importing into a spreadsheet.

The TEOM must be configured to record data parameters as follows. There is a limit of 20 stored parameters (not including the Date and Time, which are always recorded).

0. Date, Time (the end of the 1-minute interval)
1. Operating mode (0 to 4)
2. PM-2.5 raw MC
3. PM-Coarse raw MC
4. PM-2.5 total mass
5. PM-Coarse total mass
6. Case temperature
7. Cap temperature
8. PM-2.5 flow rate
9. PM-2.5 air tube temperature
10. PM-2.5 TEOM filter load
11. PM-2.5 TEOM filter pressure
12. PM-2.5 TEOM noise
13. PM-2.5 TEOM frequency
14. PM-Coarse flow rate
15. PM-Coarse air tube temperature
16. PM-Coarse filter load
17. PM-Coarse TEOM noise
18. PM-Coarse TEOM frequency
19. Vacuum pump pressure
20. System status

The key parameters for data validation are:

1. Date and Time – reported as the end of the 1-minute interval.
2. Mode – must be 3 or 4 for valid data.
3. PM2.5 raw and PM-Coarse raw Mass Concentration in $\mu g/m^3$. A zero value or a repeating value for Mass Concentration indicates no data. Concentrations are always reported even when they are invalid; this requires manual review of the data to remove

invalid PM concentrations based on the parameters listed below.

4. PM2.5 and PM-Coarse total mass – the mass loading on the TEOM filter in µg since the last instrument reset, filter change, or Stop/Start cycle. A zero value indicates no data.
5. PM2.5 and PM-Coarse flow rate – Flow is lpm.
6. PM2.5 and PM-coarse TEOM filter load – filter loading as % of maximum.
7. Case temperature, in degrees C. Cap and Air Tube temperatures are not normally used for validation.
8. PM2.5 and PM-coarse "Noise" is a mass transducer stability metric; the concentration-normalized value should normally be less than 0.2 µg but can briefly be higher when there are large rapid changes in concentration or very PM high concentrations.
9. Agreement between the full-run PM2.5 and PM-coarse channel PM unadjusted concentration data meets the QC criteria of 7.5%.

Section 7. Data Validation and Calculations

TEOM PM concentration data are recorded every 60 seconds; this is the average of six 10-second measurements. Data validation is performed on this 1-minute TEOM data. PM emissions (grams) are calculated from 1-minute PM concentration and wet tunnel flow data. Results in grams are summed up to longer intervals for reporting use as required. A valid test run must have at least 85% data capture for each burn phase.

Data Validation

One-minute TEOM PM concentration data for each channel are valid only when all of the following parameters are met:

1. Flow reported by the instrument is within 5% of the flow setpoint (between 0.950 and 1.050 lpm for 1 lpm)
2. Operating mode (not system status): 3 or 4
3. Noise: 3-minute tunnel PM running average of (100 x noise / concentration) is < 0.20 µg
4. Case temperature: no higher than 32.2 °C (90 °F).
5. Concentration is not 0.00
6. Total Mass is not 0.00
7. Concentration is different from the preceding 1-minute interval.
8. For a valid minute of test data, at least one channel of Tunnel PM data must be valid.

Items 5, 6, and 7 are usually covered by item 2 (Mode) but there can be cases such as a failed filter change where mode indicates valid data but some of these parameters indicate invalid data. In this case invalid data must be manually removed as described in the data processing and validation spreadsheet instructions. Data that might be of questionable quality but pass all of these validation criteria should be retained. If they are influential at the phase data level, they should be flagged for possible review.

When a filter change is done during a test run, the TEOM data may skip a time interval. The time sequence during a filter change must be examined using the data processing and validation spreadsheet and corrected if needed.

Since the "wait time" is set to 0 to minimize data loss after a filter change, the TEOM never invalidates any data. Thus the data must always be reviewed and validated manually using the criteria above and the data processing and validation spreadsheet. One-minute intervals during the test run that do not have valid data are represented as empty spreadsheet cells for those intervals. Any longer interval calculated from the 1-minute data (such as a burn-phase) must have at least 85% of the possible 1-minute values. Example: a 40 minute phase must have at least 34 minutes of valid 1-minute data to be valid.

Note that negative TEOM PM concentration data can occur when there is substantial mass on the TEOM filter and PM emissions become very low, typically near the end of a burn phase. The filter can lose mass when this occurs, and that results in negative PM being reported. Any 1-minute data less than zero is set to zero during data processing; this is the final result. For comparison purposes only, data are also reported with negative values retained; these data are not used for reporting purposes.

<u>TEOM Run validation parameters.</u>

The %D of run-average PM for the entire run from the PM concentration data for the two channels is calculated as follows:
%D = 100* (PM2.5 – PM-C) / (PM2.5 + PM-C)/2
The absolute value of %D must be no more than 7.5% for a run to be valid. Exceedances of this limit with valid TEOM data are usually due to poor tunnel mixing, not TEOM performance from flow or mass transducer calibrations or leaks. Note that this calculation is <u>not</u> equivalent to the dual train comparison calculation in ASTM E2515 Section 11.7 of 7.5%: 100*train1/(average of train1 and train2).

<u>Calculations.</u>

The final product of this SOP is 1-minute, phase average, and run average PM emissions in grams, where the data record time is the start of the 1-minute interval. The number of minutes with valid PM data are also reported for each phase for use with IDC g/h calculations. An interim product of this SOP is valid 1-minute TEOM PM concentration in $\mu g/m^3$. That and wet tunnel flow data are then used to calculate emissions (g) at 1-minute intervals. 1-minute grams * 60 gives g/h, which is used for real-time emission rate time-series QC plots. Missing data minutes are left as missing; no data interpolation or fill-in is performed, and minutes with negative data are set to 0. The TEOM test run-time is less than the actual test run-time due to

missing data from filter changes. Emission rates, emission factors and other metrics that use PM mass emissions are calculated in Section 13 of the IDC protocol.

TEOM PM concentration calculations

The 1405-D TEOM does not report the actual PM-coarse channel (TeomB) concentration because it is designed for use with a dichotomous sampler virtual impactor inlet system. The PM concentrations for the PM-Coarse channel is calculated as follows:

PM-Coarse raw MC * (16.67/PM-Coarse flow).

For 1.00 lpm flow, the calculation is:

PM-Coarse channel ($\mu g/m^3$) = 16.67 * PM-Coarse raw MC.

Note: The dichot TEOM software does not do the correction for fine-channel PM that would normally be present in the coarse channel. This simplifies the PM-Coarse channel correction to the form shown above.

The PM2.5 TEOM channel does not need any additional calculations.

Valid 1-minute TEOM data require only one channel of data.

Calculation of PM grams emitted

The validated 1-minute PM concentrations and wet tunnel flow (not ASTM E2515 "dry" flow) are used to calculate 1-minute grams PM emitted and g/h. Phase or full-run grams values are calculated by summing the 1-minute grams emission data over the time period of interest. Calculations of other phase or full-run test results such as grams/kg are covered in the IDC operation and fueling SOP. Note that the time interval used to calculate average phase or full-run g/h values is the number of valid TEOM data minutes, not the number of actual minutes of the test phase or full run. Thus run times for TEOM data will be less than the actual run time of the test when there are missing TEOM data minutes due to filter changes or other causes.

The dilution tunnel flow rate used to calculate PM emissions at 1-minute intervals (below) is without the tunnel water vapor correction used in equation 3 in ASTM E2515-11 ("1-Bws", or 0.98). For calculations in this SOP, ASTM E2515 compliant "dry" tunnel flow data can be used as an input. They are then multiplied by 1.02041 to get the original "wet" flow.

The final 1-minute TEOM PM concentrations and 1-minute wet SCFM tunnel flows are converted into 1-minute grams as follows:

g = 2.8317^-8 * (tunnel flow in wet SCFM) * (TEOM PM concentration in $\mu g/m^3$)

NOTE: ASTM E2515 tunnel flow has a correction for 2% water vapor that must be removed for the TEOM grams calculation shown above that uses "wet" tunnel flow. The TEOM sample flow

is wet (not dried, no E2515 2% correction), and thus the tunnel flow must also be "wet". If ASTM E2515 "dry" tunnel flow is reported by the test lab, multiply the "dry" tunnel flow x 1.02041 to get "wet" flow for use with Teom emission calcs.

For use in plotting 1-minute time-series of emission rates, g/h = g*60

Missing TEOM data from filter changes or other reasons are never filled in – they are left as missing, effectively excluding those minutes from the test duration. For IDC calculation of run metrics that use grams PM emitted, when there are missing TEOM data minutes the TEOM run duration for calculations is limited to the number of valid TEOM data minutes, which will be fewer than the actual test run time.

TEOM data processing templates (Optional)

There are two Excel data templates that can be used to process data. Their use is optional but they provide a way to perform calculations that are compliant with this TEOM protocol and related test protocols to provide final mass emissions data products.

1. "TEOM data template" performs calculations and provides QC screening plots. The output is valid PM concentration for both channels, for both unadjusted (negative data left in) and adjusted (1-minute negative data set to 0) concentrations.
2. "TEOM grams per phase template" uses the output of the "TEOM data template" PM concentrations, tunnel flows, phase run times and other test run data to calculate emissions by phase. Note that if tunnel flow is already on a "wet" basis, the column for ASTM tunnel flow should be left blank; it is only used if tunnel flow data uses the ASTM E2515 correction for water vapor.

These two templates are self-documenting with comments.

Section 8: TEOM Configuration Changes for Fast Response, High PM Concentrations and Cold Filter Temperatures, and List of TEOM Parameter Configuration Values.

These settings are for the 1405-D TEOM as used in this application that are different from instrument default settings. See the 1405-D manual for detailed information on how to change these values.

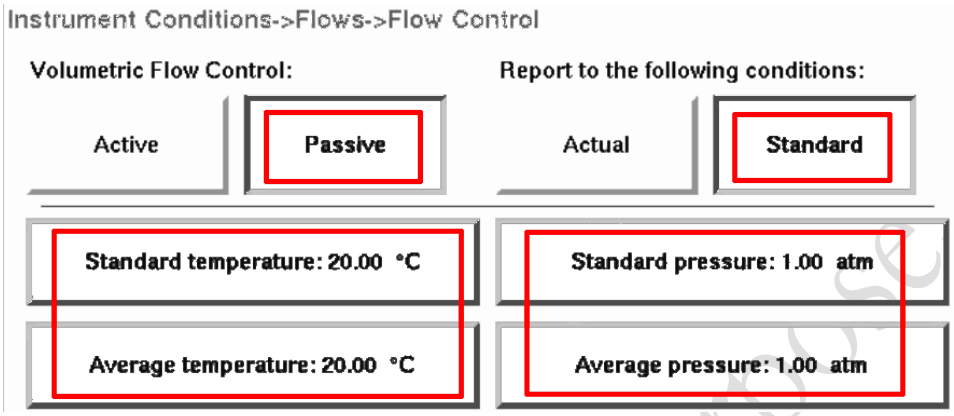
1. For both channels (TEOMA and TEOMB), confirm that all of the "Mass Constants" A and B factors are set as follows: The 3 "Mass Constant A" values are set to 0.0, and the 3 "Mass Constant B" values are set to 1.00.

2. Change system signal filtering and wait time settings:
Mass Avg time from 300 to 30 seconds
MR-MC (Mass Rate/Mass Conc) Avg time from 300 to 30 seconds

System Wait Time from 1800 to 0 seconds (disabled)

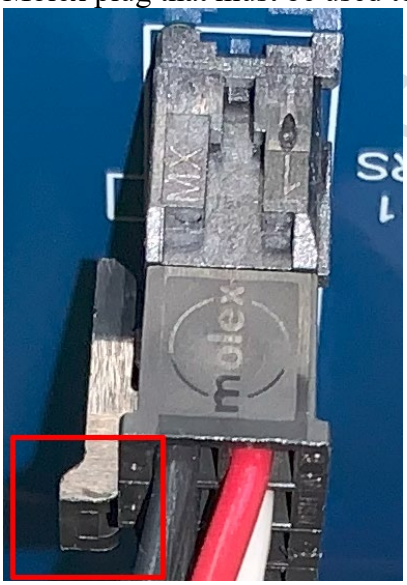
3. Change the sample flow from 3.00 to 1.00 lpm for the PM2.5 channel, and from 1.67 to 1.00 lpm for the PM-Coarse channel. Change the bypass flow to 0.00.

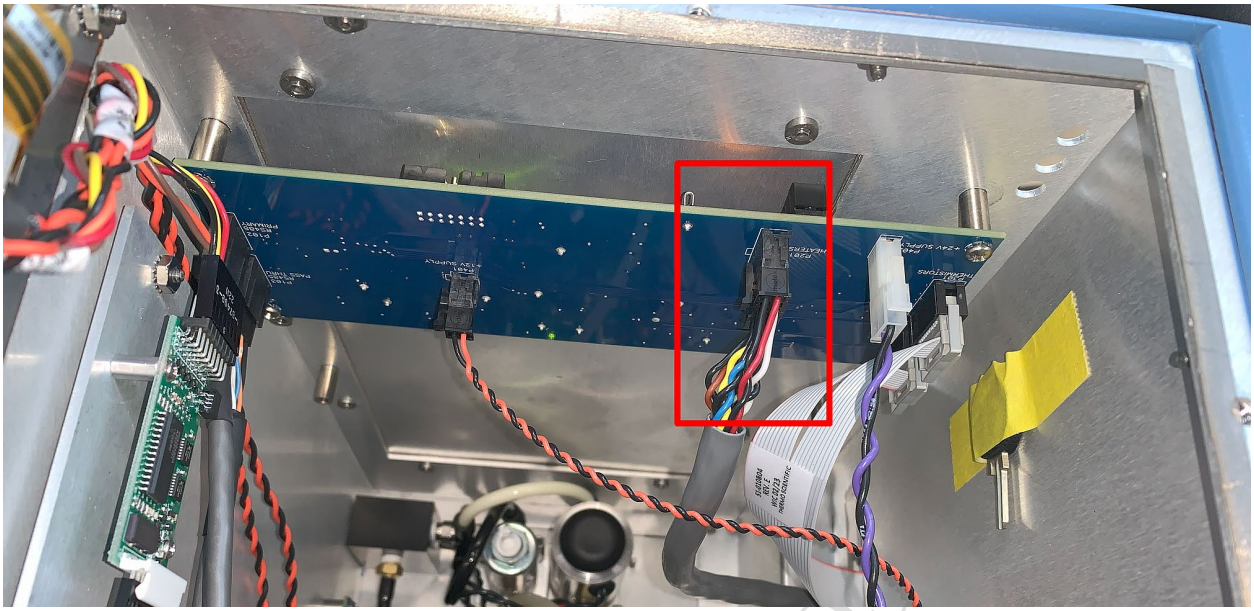
4. Set the Flow Control to Passive, and Reporting conditions to Standard. Change T/P values to 20.0 (Std) and 20.0 (Avg) °C and 1 atm Std. and Avg. pressure as shown below.



6. Change the Data Storage interval to 60 seconds.

7. The TEOM heater cable must be carefully disconnected from the front heater control board located inside the left cabinet door (with the display). There is a latch on the left side of the Molex plug that must be used to release it:





A complete list of 1405-D TEOM Settings that are modified from instrument defaults are shown below. TEOMA is the PM2.5 (left) channel, and TEOMB is the "Coarse PM" (right) channel. Temperature settings do not need to be changed when the heater cable is unplugged.

PRC*	Description	Value	Unit	Notes
12	storage interval	60	Sec	
28	system wait time	0	Sec	Always reports data
35	mass average time	30	Sec	See also PRC392 (MRMC Avg)
48	case T Set	33.0	ºC	
59	cap T Set	33.0	ºC	30 can be used if needed
74	average T	20.0	ºC	For reporting PM at 20 ºC
75	standard T	20.0	ºC	For reporting PM at 20 ºC
76	average P	1.00	ATM	For reporting PM at 29.92 "Hg
77	standard P	1.00	ATM	For reporting PM at 29.92 "Hg
115	TEOMA air tube T Set	33.0	ºC	30 can be used if needed
227	TEOMA flow rate Set	1.00	lpm	PM2.5 flow
311	TEOMB flow rate Set	1.00	lpm	PM-coarse flow
119	TEOMB air tube T Set	33.0	ºC	30 can be used if needed
392	MRMC average time	30	Sec	See also PRC35 (Mass Avg)
407	TEOMA mass constant A	0.0	µg/m^3	Intercept
408	TEOMA mass constant B	1.00		Slope
409	TEOMB mass constant A	0.0	µg/m^3	Intercept
410	TEOMB mass constant B	1.00		Slope

* TEOM Program Register Code

1405-dichot TEOM filter change alarm setup.

This configuration uses the TEOM contact closure ("digital") outputs, and triggers alarms when either Teom channel exceeds the filter loading threshold. The male DB25 connector goes on the TEOM USER I/O connector. See pages 3-31 to 3-33 of the dichot TEOM manual.

Any kind of low voltage alarm can be used, typically a 6 to 12 volt DC alarm. The TEOM interface is only a contact closure - it does not supply any alarm power, so an external alarm power supply must be used.

Parts needed.

1. DB25-male breakout connector, such as Mouser p/n 651-2761622, Phoenix Contact p/n 2761622
https://www.mouser.com/ProductDetail/Phoenix-Contact/2761622/?qs=p6trItWzfMXZ%2FKY9Mkeclg%3D%3D or equivalent. Thermo p/n 102562-00 is a DB25 male connector that goes to a DB25 breakout board where you can connect alarm and power wires.

2. A low DC voltage alarm (24 volts).
IDEC Illuminated buzzer, p/n HW1Z-P1F2PQ4R or equivalent.
Mouser 199-HW1ZP1F2PQ4R
https://www.mouser.com/ProductDetail/IDEC/HW1Z-P1F2PQ4R?qs=OlC7AqGiEDn8cZ9vi1aUlw%3D%3D

3. 24V DC power supply for alarm
CUI p/n SWH15-24-NB-P5, Mouser 490-SWH15-24-NB-P5 or equivalent.
https://www.mouser.com/ProductDetail/CUI-Inc/SWH15-24-NB-P5?qs=sGAEpiMZZMvasLKgtn5bIYKP6QZl6QwdfPQDyoQEpbARJhi%252BIN8IBg%3D%3D

Alarm wiring.
DB25 pins 12 and 13 both go to DC power positive
DB25 pin 24 and 25 both go to alarm positive power connection
DC power negative to alarm negative power connection

1405-dichot Teom contact closure alarm config:

Settings->Analog & Digital Outputs->Contact Closure

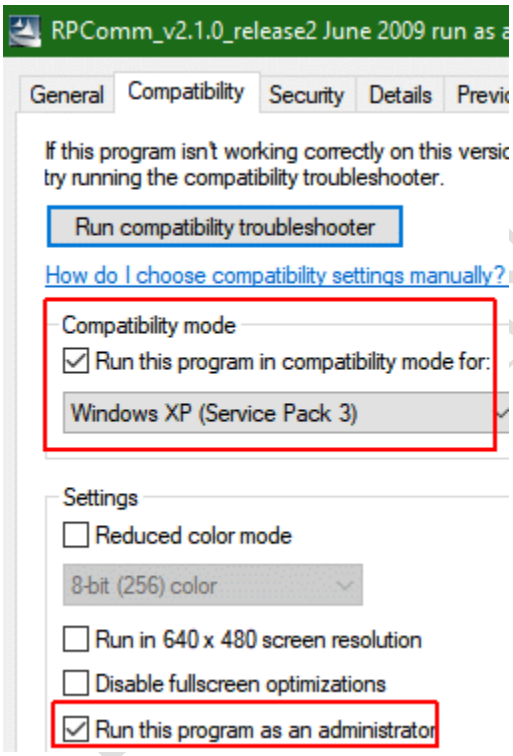
	Instrument Variable:	Compare Operator:	Compare Value:
#1:	PM-2.5 TEOM filter load	>	115.00
#2:	PM-Coarse TEOM filter load	>	115.00

Installation of RPComm on Windows 10

RPComm must be run in a 32-bit (x86) version of Windows; it will not run in 64-bit Windows. It will not run in Windows 11, since that is only available as a 64-bit version. If Windows 11 must be used, then RPComm can be run in a virtual Windows 10 machine using Oracle Virtual Box. https://www.virtualbox.org/

1. The account you install it from must have administrator rights.

2. Right-click on the executable file for the RPComm install program, and on the compatibility tab enable settings for "Compatibility mode" (XP SP3) and "Run as administrator". If these two compatibility settings are not available as shown in the screenshot below, you may not have administrator rights. RPComm may install and start, but it will crash when you try to use it.



When asked where to install the program, do not put it in "C:\Program Files (x86)\ ". Use a location such as "C:\Thermo\RPComm\" . It is recommended to create a Windows restore point or system backup before attempting to install RPComm. It is very old software, and things may go wrong that are not readily recovered from.

After installing but before running RPComm:

RPComm needs a TEOM parameter file that matches the firmware version installed on the TEOM. This file is included in the firmware update zip file on the 1405 web page – it is not included in the RPComm install package. Download the firmware update zip file, open it, and copy the "RP14051.74.txt" file (or other RP14051.nn.txt file that matches the firmware version in use) to the location where RPComm is installed, such as "C:\Thermo\RPComm\" . Then rename that file to remove the ".txt" filename extension to make the filename "RP14051.74".

Note: you may need to disable the Windows File Explorer option to "Hide extensions for known file types". By default they are hidden for known extensions like ".txt".

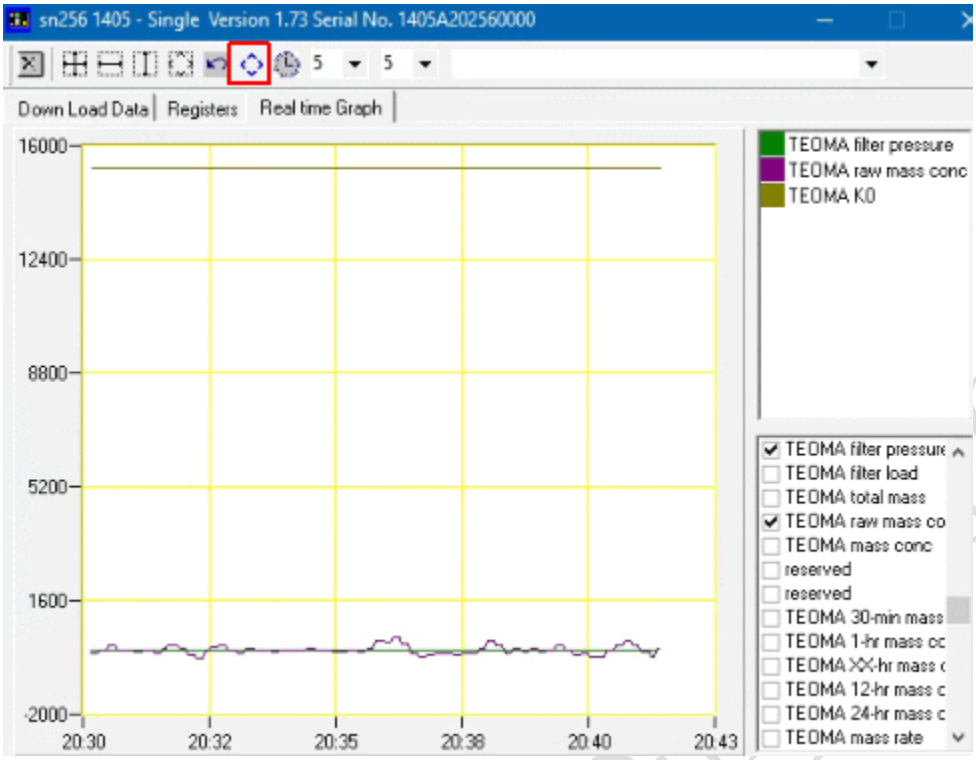
Once installed, RPComm.exe must be set to use the "XP SP3" and "Run as an administrator" compatibility settings as shown above.

Using RPComm.

Multiple TEOMs can be accessed from a single instance of RPComm. To rename a connection in the main RPComm window, single-click it.

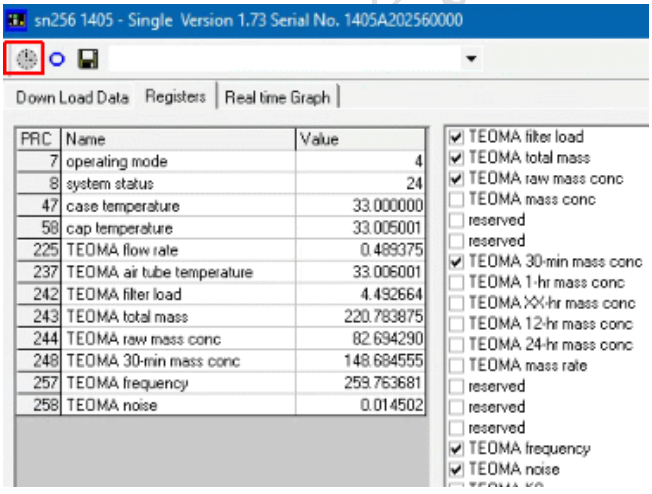
Below are screenshots showing how to use RPComm. These examples are from a single channel Teom.

For the TEOM plots, put a 0 [filter P] and a ~15,000 value [K0] to anchor the scale, and the raw mass conc:



The icon circled in red auto-scales it as needed beyond these 2 values. You can also put TEOMB raw mass conc on the plot, but it's 16.7 times too low (at 1 lpm flow).

For the Register tab, set it to list key parameters - this is the only way to get a quick look at everything that matters for proper operation:



The icon circled in red refreshes the values. There is no auto-refresh in this screen. This example is from a single channel TEOM. The "Select All Registers" icon can be used to easily document all instrument settings.

Using ePort

The ePort program is used to download data and provides a remote control interface to the instrument. The ePort program must be installed from an administrator account, and the installation program must also be "run as administrator". Once installed, the program must be "run as administrator". Detailed ePort instructions start on page 3-10 of the dichot TEOM manual. Note that the current version of ePort (Version 4) no longer has the "Find Instrument" option; instruments must be added to ePort manually as detailed in the TEOM manual, or Version 3 should be used.

ePort uses an ethernet connection on the local area network (LAN). It can only connect to computers on the same LAN subnet. If access is needed from a remote computer, PC remote access software must be used, such as Chrome Remote Desktop. RealVNC Viewer is available for Windows, iOS and Android; it allows viewing the TEOM screen when all devices are on the same LAN. https://www.realvnc.com/en/connect/download/viewer/