Good Laboratory Practice in Particle Measurement Calibration: Cascade Impactor[†]

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Abstract

A laboratory often is faced with the task of calibrating particle inertial classifiers or investigating how instruments, or systems, respond to particles of specific sizes. Since, over time, multiple technicians may be involved in the calibrations, it is imperative that the procedures be uniform. For this purpose, "Good Laboratory Practice" (GLP) procedures as outlined in Code of Federal Regulations (CFR), Volume 21, Part 58 can be followed.

There are three main features of GLP that can be employed in calibrations with particles. They are: 1) all equipment that are used for measuring flow rates, pressure, volume, etc. are calibrated to NIST traceable standards, 2) a calibration protocol is written, and 3) Standard Operating Procedures (SOPs) are defined for all steps of the calibration process. The SOPs include management structure, document control, data handling, procedures for training personnel, calibration of the equipment, and the actual calibration for the device in question.

Although these GLP procedures are applied to nearly all calibrations performed in our laboratory, this paper will emphasize procedures suitable for the calibration of inertial classifiers, specifically cascade impactors.

Keywords: aerosol, calibration, particle, GLP, impactor

Introduction

It is necessary to have instruments that are accurately calibrated when measuring the size distribution and concentration of aerosol particles. Often the supplier of the instruments will provide calibration curves with the instruments. However, there are times when a calibration has to be performed in a laboratory. This may be during the course of developing a new instrument, or an independent calibration (other than that supplied by the manufacture) of a specific unit.

In the Particle Calibration Laboratory (PCL) at the University of Minnesota we have performed many of these types of calibrations. One such calibration was the archival calibration of the Next Generation Pharmaceutical Impactor (NGI) (Marple et al., 2003; Marple et al. 2004). Although all laboratories attempt

to use proper laboratory practices in their work, the PCL found that it was necessary to have a specific written procedure (protocol), which is followed through a set of Standard Operating Procedures (SOPs) so that the results of a calibration will be independent of the person doing the calibration. If the protocol and SOPs are followed, any person doing the calibration will take the same steps.

The procedures that were developed for our laboratory follows closely those outlined by the US Pharmacopoeia "Good Laboratory Practice for Nonclinical Laboratory Studies" (GLP) Code of Federal Regulations (CFR), Volume 21, Part 58. Some variations had to be made to these procedures to accommodate particle calibration of instruments, which we call Good laboratory Practice (GLP) for Particle Instrument Calibration.

In this paper, the GLP procedures that are followed to perform a calibration in the PCL are presented in detail. Since it is not possible to cover the calibration of the many different instruments used to analyze aerosol particles employing a wide variety of principles, the paper will reduce its scope to the calibra-

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tion of inertial classifiers, such as inertial impactors, cyclones, virtual impactors and body impactors. To further narrow the scope of the paper, the subject of the calibration will be a wide-range cascade inertial impactor covering the particle size distribution range from 20 μm at the upper stage to 0.05 μm at the last stage.

For readers not familiar with inertial impactors, a schematic is shown in **Fig. 1** of a cascade impactor, which consists of a series of stages. Each stage consists of a nozzle that directs a jet of particle-laden air at an impaction plate. Large particles will have enough inertia to slip across the air streamlines and strike the impaction plate. Smaller particles that do not strike the plate will proceed to the next stage where their inertia is increased due to a smaller nozzle that provides a higher velocity to the flow. Some of these smaller particles will impact on this second stage. Particles not collected here will proceed to the next stage where the nozzle is smaller and the process is repeated through all of the stages with each stage increasing the jet velocity. The net result after a known quantity of air has passed through the cascade impactor is the separation of the particles by aerodynamic size onto the various impaction plates.

The separation of the particles at each stage is characterized by the particle collection efficiency curve at each stage, where the particle collection efficiency for any particle size is defined as the fraction of particles passing through the stage nozzle(s) that are collected on the impaction plate (Marple et al., 2001). The experimentally determined collection efficiency curves for a typical cascade impactor are shown in **Fig. 2**.

Although the most important result of the calibration is the defining of the particle collection efficiency curves, it is also possible to determine particle inter-stage losses. Interstage losses are particles collected on surfaces other than the impaction plate.

In the following section a nine-step calibration protocol is presented, which if followed, will provide the same result independent of the researcher doing the calibration. The result of this calibration will be the experimental determination of the particle collection efficiency curve for each stage of a cascade impactor.

General Procedure for Calibration of an Inertial Impactor

The first step in performing a GLP calibration is to write a protocol for the calibration. The basic components of a protocol are as follows:

Fig. 1 Schematic diagram of a cascade impactor.

Fig. 2 Collection efficiency curves for a typical cascade impactor.

1. Purpose – Why and for whom is the calibration being performed?
2. Scope – Is the calibration being performed on a single unit or multiple units?
3. Objects to calibrate – This states what stages are to be calibrated, including any inlets, pre-separators, after filter sections and interstage loss determination.
4. Measurement matrix – This outlines the number of data points to be taken to define a stage efficiency curve (usually 3, 5 or 7 data points)

and about what percent efficiency these data points should be taken (usually at 5, 16, 40, 50, 60, 84 and 95% collection efficiency for seven point calibrations or some subset of these for fewer data points, but always one data point should be near the 50% collection efficiency). Also, the flow rate(s) and the precision of the flow rates should be defined here.

5. Validation of Ancillary Equipment – Each piece of equipment that is used for the calibration needs to be validated prior to the calibration being performed. This validation process is called Installation Qualification (IQ) as is a set of procedures to show that the equipment, once installed, is operating properly. The ancillary equipment includes:

- a. flow rate measuring devices
- b. pressure measuring devices
- c. fluorometer
- d. Aerodynamic Particle Sizer (APS)
- e. Optical Particle Counter (OPC)

After IQ is completed the equipment needs to be checked on a regular basis during the calibration to ensure that it has not gone out of specification. This process is called Operational Qualification (OQ). An example validation (IQ and OQ) for the flow rate measuring equipment is given in Appendix A.

6. Methodology – This is the section that describes the actual calibration of the impactor. This defines the aerosol generator (usually a vibrating orifice aerosol generator (VOAG) for particles in the size range from 0.6 to 20 μm or a differential mobility analyzer (DMA) for particles in the size range of 0.02 to 0.6 μm) to be used in the calibration, and the material that will be used for the aerosol (usually oleic acid with a uranine fluorescent dye tracer for liquid particles or ammonium fluorescein for solid particles). Also defined in this section is the detection method to be used to determine the fraction of particles collected on the various surfaces. To fulfill this step, a number of Standard Operating Procedures (SOPs), listed in **Table 1**, must be followed. The details of the calibration procedure that must be described in this step of the protocol are quite voluminous, and has been moved to its own section following the last step (Step 9) of the protocol and titled “Methodology for calibration of an inertial impactor (Protocol step 6 continued)” so as not to overwhelm this list of protocol steps.

7. Data analysis – The particle collection efficiency data for each particle size at each stage taken in Step 6 must be analyzed to construct a particle collection efficiency curve and the 50% particle collection efficiency value (D_{p50}) for each stage. The data is also analyzed to determine the uncertainty of the data points and the corresponding uncertainty of the D_{p50} value.
8. Data report – The data report will include tables of collection efficiency versus particle aerodynamic diameter for each stage at each flow rate and all uncertainty values. In addition, this report must have a complete description of the impactor, including measurements of all nozzles and jet-to-plate distances. Large nozzle diameters can be measured using pin gauges but smaller nozzles need to be measured by optical methods. Automated optical measurement systems may have to be used if there are a large number of nozzles on a stage. All nozzle diameters measured should be included in the data report, along with the average, standard deviation, and minimum and maximum sizes. The report will also include a comprehensive description of the test methodology, including diagrams of the relevant apparatus used in the calibration, together with the actual test conditions (i.e., laboratory temperature, relative humidity, flow rate, barometric pressure).
9. Recording and retention of information - Experimental measurements, together with related observations, will be recorded and dated in a hard-back laboratory notebook with numbered pages. This notebook will be retained as part of the master file, together with hard copies of any relevant ancillary measurement data (e.g. APS, OPC) originally stored on computer. Hard copies of any calibration certificates and related documentation pertaining to ancillary equipment used in the calibration will also be retained in the master file.

Methodology for calibration of an inertial impactor (Protocol step 6 continued)

Two methods, the VOAG and DMA, are used to calibrate impactors in the size range of 0.02 μm to 20 μm . The methodology (Step 6 of the above protocol) must describe these methods in detail.

VOAG Method of Particle Generation and use as a Calibration Aerosol

Monodisperse particles of a desired size will be generated with the VOAG (Berglund and Liu, 1973) and passed through a multiplet reduction impactor (MRI) to remove all multiplet particles consisting of two or more coalesced primary particles. The impactor being calibrated will subsequently sample the aerosol that now contains only primary particles. The impactor will be assembled with all stages installed preceding and including that being calibrated. **Fig. 3** illustrates the calibration arrangement, showing the location of the VOAG and ancillary equipment with respect to the impactor. The after filter can be located immediately downstream of the stage being calibrated.

An Aerodynamic Particle Sizer[®] aerosol spectrometer (APS[®], model 3310, TSI, Inc.) will be used to sample the particle stream immediately before and after the measurement with the impactor to verify that the particles are monodisperse, since its size resolution is $0.02 \mu\text{m}$ at $1.0 \mu\text{m}$ and $0.03 \mu\text{m}$ at $10 \mu\text{m}$ aerodynamic diameter. This instrument will NOT be used to provide measurements of particle size for the purpose of defining the stage D_{50} value. Particle size will be determined from the operating variables of the VOAG.

The impaction plate of the stage being calibrated and the after filter will be washed separately with known quantities of 0.001 N aqueous solutions of sodium hydroxide, and the concentration of the uranine dye in the resulting solutions will be assayed using a fluorometer.

Fig. 3 Schematic diagram of the calibration setup using the vibrating orifice aerosol generator method.

DMA Method of Particle Generation and use as a Calibration Aerosol

A polydisperse aerosol, predominantly in the sub-micron size range, will initially be generated using a Collison-type pneumatic atomizer. This aerosol will subsequently be passed through a Kr-85 neutralizer to reduce the electrical charge on the particles and then the particles are size-classified using a differential electrical mobility analyzer (DMA), producing a monodisperse aerosol at the outlet (Liu and Pui, 1974). This aerosol will be subsequently sampled by the impactor to be calibrated, which will be assembled with all stages installed preceding and including the stage being calibrated. **Fig.4** illustrates the calibration arrangement, showing the location of the DMA and ancillary equipment with respect to the impactor. The impactor will be modified to provide a sample port downstream of the stage being calibrated. This modification will NOT affect the calibration, since the airflow pathway through the stage being calibrated will be unaffected. The CPC will be connected to this sample port. A modified impaction plate that provides a jet-to-plate distance of at least 50 nozzle

Fig. 4 Schematic diagram of the calibration setup using the differential mobility analyzer method.

diameters ($S/W \geq 50$) will be placed in the stage being calibrated to allow for a jet-to-plate distance large enough so that particle impaction will not occur. The number of particles counted with the CPC for a pre-determined sample period, depending on particle concentration, will be used as the upstream count. A standard impaction plate will then replace the modified impaction plate and the measurement repeated to obtain the downstream count. The collection efficiency for that stage at the particle size being generated will be defined by comparing upstream and downstream counts. A Laser Aerosol Spectrometer (Model HS-LAS, PMS, Inc., Boulder, CO) will be used to sample the particle stream immediately before and after the measurement to verify that the particles are monodisperse. This instrument will NOT be used to provide measurements of particle size for the purpose of defining the stage D_{50} value; this measurement will be determined from the operating variables of the DMA.

Uncertainty Analysis

The primary result of an impactor calibration is the particle collection efficiency versus aerodynamic particle diameter curves. Thus, the uncertainty in the generated particle size and the uncertainty of the measured particle collection efficiency values must be determined. These uncertainty calculations will depend on the type of particle generation system that is used and the method used to determine the fraction of particles collected at each stage.

If the VOAG is used to generate particles, the uncertainty values in each term of the fundamental equations that define the generated particle size must be determined by experimentation. For example, the flow rate of the liquid through the vibrating orifice of

the VOAG is one term in the equation for the generated particle size. Multiple measurements (at least three measurements) of this liquid flow rate must be measured and the standard deviation of the measurements used as the uncertainty of the liquid flow rate. In like manner, the uncertainty of all terms in the fundamental equation of the calculation of the particle size must be determined. Then a propagation of error technique, such as the Root-Sum-Square method, must be used to determine the effect of these individual uncertainties on the calculation of the uncertainty of the particle size generated. A similar analysis is used to determine the uncertainty of the particle size for the DMA method of generating aerosols.

This technique can also be applied to all terms that are used to calculate the particle collection efficiency for each determination of the collection efficiency. However, triplicate determinations of the collection efficiency can be made for each particle size for each stage and the standard deviation of the collection efficiencies used as the uncertainty in the collection efficiency instead of using a propagation of errors method.

Application of SOPs

To follow the GLP and implement the calibration protocol, a number of SOPs were written. Each time the calibration protocol is applied to an impactor calibration these SOPs must be followed. Some of the SOPs are only applied periodically as the need arises, some are applied at the beginning of each calibration day, and some are applied for each experimental calibration run that produces data.

Table 1 provides a list of SOPs followed for the calibration of a cascade impactor. Some of the SOPs are for training of lab personnel, some are for calibration of ancillary equipment to be used in the actual impactor calibration, and some are for the calibration itself. The SOPs for each of the particle generation techniques were also written.

Table 1 SOPs for calibration of cascade impactors

SOPs for Management of Calibration

1	DOCUMENT CONTROL (how to handle instructional manuals, certificates and other calibration documents)
2	MANAGEMENT OF LABORATORY AND TRAINING OF TECHNICAL STAFF (program management structure, training responsibility and handling of training records)
3	HANDLING OF DATA (how data should be recorded and handled and where it should be kept)
4	DOCUMENT CHANGE CONTROL (defines what SOPs will be changed and who will approve and sign them)

SOPs for Performing Calibration with VOAG

5	VOAG, DAILY OPERATION
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6	VOAG, PARTICLE CALIBRATION
7	VOAG, CALIBRATION OF THE FREQUENCY GENERATOR
8	VOAG, CALIBRATION OF THE LIQUID SYRINGE PUMP
9	APS, DAILY OPERATION
10	DATA TRANSFER FROM THE APS
11	FLUOROMETER, DAILY OPERATION
12	CALIBRATION OF FLUOROMETER
13	MRI SETUP
14	URANINE, WEIGHING FOR CALIBRATING FLUOROMETER
15	PREPARATION AND HANDLING OF A LIQUID SOLUTION OF SODIUM HYDROXIDE IN WATER WITH A CONCENTRATION OF 0.001 N
16	PREPARATION AND HANDLING OF LIQUID SOLUTIONS OF URANINE AND SODIUM HYDROXIDE IN WATER BY VOLUME AND DILUTIONS
17	PREPARATION AND HANDLING OF LIQUID SOLUTIONS OF OLEIC ACID AND URANINE IN METHANOL: PARENT SOLUTION CONTAINING 5.0 PERCENT NON-VOLATILES BY VOLUME AND DILUTIONS

SOPs for Performing Calibration with DMA

18	OPERATION OF EVAPORATOR/CONDENSOR
19	OPERATION OF CPC
20	OPERATION OF DMA
21	CALIBRATION OF DMA
22	OPERATION OF LASER AEROSOL SPECTROMETER (LAS)
23	CALIBRATION OF LASER AEROSOL SPECTROMETER (LAS)
24	COLLISON-TYPE ATOMIZER OPERATION- DOS
25	CALIBRATION OF DMA LAMINAR FLOW METERS
26	VERIFICATION OF DMA MAGNEHELIC PRESSURE GAUGES
27	CALIBRATION OF DMA ROTAMETER
28	CALIBRATION OF DMA EXCESS FLOW CRITICAL ORIFICES
29	PREPARATION AND HANDLING OF LIQUID SOLUTIONS OF BIS (2-ethylhexyl) SEBACATE IN 2-PROPANOL PARENT SOLUTION CONTAINING 10 PERCENT SOLUTE BY VOLUME AND DILUTIONS

SOPs for Calibration and Operation of Ancillary Equipment

30	CALIBRATION OF REFERENCE PRESSURE GAUGE
31	CALIBRATION OF MANOMETER
32	OPERATION OF BAROMETER
33	CALIBRATION AND OPERATION OF DRY GAS FLOW METERS
34	CALIBRATION AND OPERATION OF PRESSURE TRANSDUCER
35	OPERATION OF SARTORIUS MODEL BP120S WEIGHT BALANCE
36	OPERATION OF SARTORIUS MODEL L610 WEIGHT BALANCE
37	OPERATION OF CAHN MODEL 31 MICROBALANCE
38	OPERATION OF TEMPERATURE AND RELATIVE HUMIDITY PROBE
39	CALIBRATION OF IMPACTOR FLOW
40	CALIBRATION AND OPERATION OF BUBBLE FLOW METER
41	OPERATION OF COLLISON-TYPE ATOMIZER- PSL
42	SILICA GEL DESICCANT

SOPs for General Laboratory Operations

43	LABORATORY ENVIRONMENTAL CONDITIONS
44	LABORATORY WATER SUPPLIES
45	LABORATORY CONSUMABLES EXCLUDING WATER
46	CLEANING OF GLASSWARE
47	CLEANING THE IMPACTOR
48	CLEANING OF APPARATUS

49	GLASSWARE HANDLING
50	STORAGE AND HANDLING OF CHEMICALS
51	LABELING OF CHEMICALS
52	USE OF TUBING AND CONNECTORS

A typical SOP is shown in Appendix B. The front page provides the title, date, and sign-off sheet for the author, study director and external reviewer. The page also lists the SOP title, document number, revision and if it supersedes any previous SOP. The next page lists the purpose, scope, safety requirements, responsibility and the action of the SOP in step-by-step instructions. As can be seen from Appendix B, the SOPs are written in great detail.

Conclusion

A Good Laboratory Procedure has been presented that governs the calibration of aerosol instruments. To simplify the description of the procedure, the procedure has been aimed at the calibration of one specific type of aerosol instrument, a cascade impactor. With very few changes in the protocol the procedure could be applied to the calibration of any inertial classifier. With further modifications the procedure could be applied to any aerosol-analyzing instrument. Although the procedure can theoretically be applied to any instrument, it is best suited for routine calibrations of rather standard instruments. For these types of applications, by following a well-defined protocol that is supported by detailed Standard Operating Procedures, calibrations can be performed on aerosol instruments with confidence that the calibration

results will be independent of the researcher doing the calibration. This assumes, however, that they are conscientious laboratory technicians.

References

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APPENDIX A- VALIDATION OF ANCILLARY EQUIPMENT EXAMPLE

A.1 FLOW RATE MEASUREMENTS (VOAG- AND DMA-BASED PROCEDURES)

A.1.1 IQ:

Two dry gas meters (Model R-315, Rockwell International), maximum flow rate of 315 cubic-feet/hr (149L/min) (index 1/10 cubic-foot per revolution), will be flow certified for accuracy, before the start of the archival calibration of the NGI. This procedure will be performed by an external contractor (Energy Economics, Dodge Center, MN) using a Prover A #3079 certified using a NIST traceable one cubic-foot bottle AMCO #163, (NIST #4199).

Two bubble flow meters (model Gilibrator-2 with flow cell P/N 20826-S, Sensidyne, Clearwater, FL) with an operating flow rate range from 0.020L/min to 6L/min will be calibrated for accuracy by Sensidyne, before the start of the impactor calibration. This company uses a film flow meter MCL-103 as its primary standard traceable to NIST, as described in circular #602.

A.1.2 OQ:

A Rockwell dry gas meter will be used as a secondary standard to verify that the volumetric flow rate at the entry to the induction port of the NGI is within the specified limits (Sect. 4). The initial calibration of this 'test' dry gas meter will be checked at the end of the impactor calibration and the dry gas meter will be deemed to be within specification if its accuracy limits is within $\pm 1.0\%$ in the range from 30 to 100 L/min

A second (local reference) Rockwell dry gas meter will be used as an in-house secondary standard. This flow meter will be used for NO other purpose but to perform a weekly flow calibration check of the 'test' dry gas meter to be used for the calibration of the impactor in the range from 30 to 100 L/min. The 'test' dry gas meter will be deemed to be operating within specification if the difference between its indicated flow rate and that of the local reference dry gas meter is within $\pm 1.0\%$.

A Gilibrator model-2 bubble flow meter will be used as a secondary standard to verify that the laminar flow meters associated with the DMA are operating within specification. The initial calibration of this 'test' bubble flow meter will be checked at the end of the archival calibration exercise and the flow meter will be deemed to be operating within specification if its accuracy has remained within $\pm 1.0\%$ in the flow rate range of interest.

A second (local reference) Gilibrator model-2 bubble flow meter will be used as an in-house standard. This flow meter will be used for NO other purpose but to perform a weekly flow calibration check of the 'test' bubble flow meter to be used in the calibration of the impactor. The 'test' bubble flow meter will be deemed to be operating within specification if the difference between its indicated flow rate and that of the local reference bubble flow meter is within 2.0% in the flow rate range of interest.

APPENDIX B - STANDARD OPERATING PROCEDURE

TITLE: FLUOROMETER, CALIBRATION
DOCUMENT: SOP-020
REVISION: 1.0
SUPERSEDES: NONE

IMPACTOR CALIBRATION PARTICLE CALIBRATION LABORATORY

UNIVERSITY OF MINNESOTA

	NAME	SIGNATURE	DATE
AUTHOR			
STUDY DIRECTOR			
EXTERNAL REVIEWER			

STANDARD OPERATING PROCEDURE

FLUOROMETER, CALIBRATION

PARTICLE CALIBRATION LABORATORY
UNIVERSITY OF MINNESOTA

DOCUMENT: SOP-020

PAGE: 1 OF 2

REVISION: 1.0

SUPERSEDES: NONE

PURPOSE: Calibration of fluorometer.

SCOPE: Impactor calibration

SAFETY: Use personal safety protection appropriate to chemicals.

RESPONSIBILITY: Operator/Supervisor

ACTION:

INITIAL TURN-ON AND DARK CURRENT SUBTRACTION

- 1) Familiarize yourself with the Aminco Fluorometer Instruction Manual.
- 2) Ensure that cell adaptor and lamp cover are in place.
- 3) Insert primary and secondary filter holders.
- 4) Set PHOTOMETER switch to off (out) position (twist counterclockwise and release) to disconnect meter.
- 5) Set MULTIPLIER switch to 100 (keep MULTIPLIER FINE ADJUST control turned fully clockwise to maximize meter sensitivity).
- 6) Set BLANK ADJUST switch to LOW.
- 7) Set DAMPING switch to OFF.
- 8) Remove cell adapter, turn cell adapter so that solid side is toward the PM tube and replace cell adapter cap.
- 9) Turn POWER switch to HV (high voltage). Power indicator light is indicating that PM tube is now active.
- 10) Allow at least 30 minutes for instrument to stabilize and record time.
- 11) Depress PHOTOMETER switch and lock (quarter twist clockwise). Meter is now connected to microphotometer's measuring amplifier.
- 12) Turn MULTIPLIER switch to different sensitivity settings until a needle deflection is noted. Adjust the BLANK ADJUST FINE control until the meter indicates zero. Continue to reset the MULTIPLIER switch and adjust the BLANK ADJUST FINE control until the MULTIPLIER switch is set to 0.1 (most sensitive position) and the meter indicates zero. The instrument is now zeroed and PM tube dark current subtracted.
- 13) Turn POWER switch to ON position.
- 14) Turn PHOTOMETER switch to off.

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CALIBRATION

Note: when changing cell adapter, filters, or aperture plates, the high voltage must be removed from the PM tube by setting the Power switch to the ON position. Extraneous light striking the PM tube could cause tube fatigue. When changing samples, the PHOTOMETER switch MUST be in the off (out) position.

- 15) Prepare sample and blank solutions and add to clean cuvettes.
- 16) Select the aperture and 47B as primary filter. Place in primary filter holder.
- 17) Select 2A-12 as secondary filter and place in secondary filter holder.
- 18) Remove cell adaptor cap and remove cell adaptor.
- 19) Insert cuvette with blank into cell holder and replace cell adapter cap.
- 20) Set POWER switch to HV.
- 21) Set MULTIPLIER switch to the 0.1 position. Subtract the meter indication to zero with the BLANK ADJUST controls as follows:
 - A. Set BLANK ADJUST COARSE to LOW position.
 - B. Adjust BLANK ADJUST FINE control to obtain zero meter indication.
- 22) Set PHOTOMETER switch to off position.
- 23) Set aperture to 1-hole position and insert into primary filter holder.
- 24) Select the calibration standard solutions to cover the

- complete range of the fluorometer. Fill the cuvettes with the calibration solutions.
- 25) Insert the lowest concentration standard solution into cell holder and replace cell cap.
 - 26) Adjust meter sensitivity with MULTIPLIER switch, as required, and record meter indication in laboratory notebook (Note: Do not change the BLANK ADJUST FINE control during sample measurements as this will change the zero reference point. The MULTIPLIER switch can be set to different sensitivities as required).
 - 27) Repeat steps 24 and 25 for the remaining solutions.
 - 28) Insert cuvette with blank into cell holder and repeat step 25 to ensure that the meter indication is still zero. If it is not, re-zero and repeat steps 24 through 26.
 - 29) Change the aperture from the 1-hole position to the 2-hole position and repeat steps 23 through 27. Once this is done replace the aperture 2-hole position to the 4-hole position and repeat steps 23 through 27.
 - 30) Use linear regression analysis program to determine the R-squared value for each of the aperture settings.
 - 31) If the R-squared value is greater than or equal to 0.9998 for any of the aperture settings, the fluorometer is deemed to be linear and it can be used for taking measurements. Print out copy of entries made in linear regression analysis program and attach to laboratory notebook.
 - 32) If the R-squared value is less than 0.9998 any of the aperture settings, allow an additional 30 minutes for stabilization of the electronics (record time) and repeat calibration. If the R-squared value is still less than 0.9998, allow an additional 30 minutes (record time) for stabilization and repeat calibration. If the R-squared value is still less than 0.9998 the fluorometer cannot be used and the operator must refer to the Study Director for advice in accordance with SOP-003.

Author's short biography

Virgil A. Marple, Ph.D.

Virgil Marple is a Professor of Mechanical Engineering in the Particle Technology Laboratory of the Mechanical Engineering Dept at the University of Minnesota. Most of his research in the past 37 years has been in the area of aerosol physics and particle technology. He received his BSME from the University of Minnesota in 1962, his MSME from the University of Southern California in 1965, and his Ph.D from the University of Minnesota in 1970. Much of his research has been in the development of instrumentation to measure the size distribution and concentration of aerosol particles, as well as devices to generate these aerosols. In particular, he is known for his pioneering work in impactor design and development. This work has spanned the range from the first CFD analysis of the impactors in 1970 to the development of commercial cascade impactors, such as the Marple Personal Impactor, the Microorifice Uniform Deposit Impactor, and the Next Generation Pharmaceutical Impactor. In 1988 he was awarded the first American Association for Aerosol Research David Sinclair Award in recognition of sustained outstanding work in Aerosol Science and Technology. From 1970 to 2000 he has been involved in the study of CWP (black lung) in the coal mining industry, developing instrumentation, performing field studies as well as laboratory evaluation of samplers. He has been a consultant on aerosol problems to numerous companies, and is currently director of the Particle Calibration Laboratory, a laboratory dedicated to high quality particle calibration of inertial classifiers using "Good Laboratory Practice" techniques. He can be reached at marple@me.umn.edu.

Bernard A. Olson, Ph.D.

Bernard Olson is a research associate in the Particle Technology Laboratory of the Mechanical Engineering Department at the University of Minnesota. He received his BSME, MSME, and Ph.D. from the University of Minnesota. For the past 20 years his research has been in the design and testing of numerous aerosol sampling instruments. Most recent research projects include: Development of a Calibration Reference Device for Use with Test Standard ANSI/ASHRAE 52.2-2007, Method of Test to Evaluate Field Performance of Commercial Kitchen Ventilation Systems, Navy Prototype Aerosol Inlet Design and Fabrication, the Development of a Standard Test Method for Grease Particle Capture Efficiency of Commercial Kitchen Filters and Extractors (ASTM Standard 2519-05), Design of a 2.5 μ m Cut Pre-Classifier for the EPA Vehicle Exhaust Particulate Mass Measurement Module, Archival Particle Calibration of the Next Generation Pharmaceutical Impactor (NGI), and Development of a Micro-orifice Uniform Deposit Impactor with Cut Sizes Down to 10 Nanometers (Nano-MOUDI). He is currently the manager of the Particle Calibration Laboratory at the University of Minnesota's Mechanical Engineering Department. He can be reached at olso0209@umn.edu.