




## Memorandum

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From Roy M. Fleming, Sc.D., Director, Research Grants Program  
Office of Extramural Coordination and Special Projects, NIOSH 

Subject Final Report Submitted for Entry into NTIS for Grant 1 R43 OH03437-01A1

To William D. Bennett  
Data Systems Team, Information Resources Branch, EID, NIOSH

The attached final report has been received from the principal investigator on the subject NIOSH grant. If this document is forwarded to the National Technical Information Service, please let us know when a document number is known so that we can inform anyone who inquires about this final report. Any publications that are included with this report are highlighted on the attached List of Publications. Thank you.

### Attachments

List of Publications  
Final Report

**FINAL PERFORMANCE REPORT  
(PHASE I)**

CDC/NIOSH  
Exposure Assessment Methods  
1 R43 OH03437-01A1

**Multiple Velocity Aerosol Sampling Inlets to Conform with Revised ACGIH Criteria**

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## Table of Contents

Title	1
Table of Contents	2
Significant Findings	4
Usefulness of Findings	4
Abstract	4
Background	5
Specific Aims	9
Procedures	9
Methodology	10
Results and Discussion	11
Conclusions	16
Literatures Cited	16

### List of Figures

Figure 1	Internationally harmonized size-selective criteria performance curves (ACGIH, CEN, and ISO).	5
Figure 2	Comparison of the respirable criteria and the penetration characteristics of two SKC cyclones at 2.6 lpm.	6
Figure 3a	Streamlines and particle trajectories for a typical impactor.	7
Figure 3b	Ideal efficiency curve and actual efficiency curve for a typical impactor.	8
Figure 4	Schematic diagram of a single impactor with three nozzle sizes.	8
Figure 5	Comparison of the measured collection efficiency of a prototype multi-nozzle impactor (with uniform jet velocities) and the ACGIH thoracic criteria.	9

Figure 6	Comparison of calculated collection curve for ASMI-t and the thoracic criteria curve.	11
Figure 7	Schematic diagram of ASMI-t and its electrical analog.	13
Figure 8	Distribution of particle deposition in the inlet with 5 $\mu\text{m}$ testing particles.	14
Figure 9	Collection efficiency of the ASMI-t.	15
Figure 10	Distribution of particle depositions at different particle sizes.	15
Figure 11	Comparison of ASMI-t performance with different orifice designs.	15

### **List of Tables**

Table 1	Design criteria for ASMI-t.	12
Table 2	Measurements of flowrate.	13

### **Appendix I Mechanical Design of ASMI-t**

Assembly	A-1
Body	A-2
Impactor substrate-and-orifice plug	A-3
Inlet	A-4
37 mm filter adopter	A-5
25 mm filter adopter	A-6

## **Significant Findings**

An array of single-stage multi-nozzle impactors (ASMI) with different jet velocities has been designed and tested in the phase I of this research project. The experimental data showed that the concept of ASMI could be used to develop the next generation of aerosol sampling inlets with penetration characteristics that approximate the revised ACGIH size-selective aerosol sampling criteria.

## **Usefulness of Findings**

ASMI, as a new concept for size-selective aerosol sampling inlets, will make contributions to the proper assessment of worker exposure to aerosol in the field. It will not only provide better overall cut-characteristics to comply with the revised ACGIH criteria, but also will be a relatively simple and inexpensive aerosol sampling inlet device.

## **Abstract**

A better evaluation of the hazard posed by airborne particles is possible if particles that do not contribute to the hazard are excluded from the airborne concentration analysis. Therefore, the criteria for the inhalable, thoracic and respirable fractions of airborne particles, proposed by Soderholm (1989), were adopted by the American Conference of Government Industrial Hygienists (ACGIH), the Comite European de Normalisation (CEN) and the International Standards Organization (ISO). However, currently available commercialized inlets, including cyclones and multi-nozzle impactors with uniform jet velocities do not comply with these revised criteria.

The primary objective of this research is to develop new aerosol sampling inlets. These inlets, using an entirely new concept, can comply with size-selective aerosol sampling criteria better than the inlets currently being used. A prototype array of single stage impactors with different jet velocities has been developed in the Phase I study. The experimental results show that the impaction collection performance of the new inlet meets the proposed expectations very well in the size range of testing particles, but particle losses in the inlet body were also found to be significant. The test results showed that some design modifications would improve the performance of this device. These modifications and further testing are beyond the scope of the current Phase I work.

## Background

For the hazard exposure assessment of aerosol particles, it is important to measure the mass concentration, while excluding particles that do not contribute to the hazard. The criteria for the inhalable, thoracic and respirable fractions of airborne particles proposed by Soderholm (1989) have now been adopted by the American Conference of Government Industrial Hygienists (ACGIH), the Comite European de Normalisation (CEN) and the International Standards Organization (ISO). However, the penetration characteristics of the inlets now available are not satisfactory. There is a clear need to develop new sampling inlets on air monitors that would simulate the aerosol penetration characteristics of the major functional components of the respiratory system as summarized in the ACGIH-ISO-CEN criteria.

The particle size selective TLVs can be expressed in three forms, e.g.,

- 1) *Inhalable Particulate Mass TLVs (IPM-TLVs)* for those materials that are hazardous when deposited anywhere in the respiratory tract.
- 2) *Thoracic Particulate Mass TLVs (TPM-TLVs)* for those materials that are hazardous when deposited anywhere within the lung airways and the gas-exchange region.
- 3) *Respirable Particulate Mass TLVs (RPM-TLVs)* for those materials that are hazardous when deposited within the gas-exchange region.

In 1989, Soderholm, Chair of the ACGIH Air Sampling Procedures (ASP) Committee, with the endorsement of the full ASP Committee, proposed modified particle size-selective sampling criteria for adoption by ACGIH, ISO and CEN. Three particulate mass fractions were redefined by him as illustrated in Figure 1.

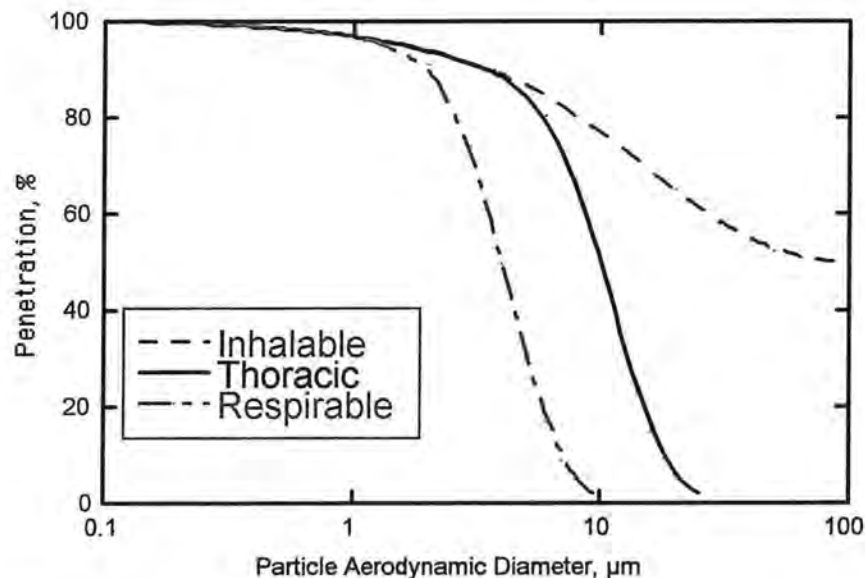


Figure 1. Internationally Harmonized Size-Selective Criteria Performance Curves (ACGIH, CEN, and ISO).

The goal of obtaining air concentration data related to health hazards can be approached in several ways. Most of the samplers developed to satisfy them have been relatively simple two-stage devices that consists of a first stage inlet whose collection efficiency falls from very high to very low as the aerodynamic particle size decreases, and a second stage with a high collection efficiency for all particle sizes. Cyclones and multi-nozzle impactors have been most widely used as inlets, whereas filters have been used as the second stage in most two-stage samplers.

Cyclones are available in a wide range of flow rates, including miniature sizes for personal sampling. A cyclone removes particles larger than a desired size range from an air stream by particle inertia. The co-PI of this project, Dr. Fang, found in his previous study that both the SKC cyclones for 25mm filter cassette and SKC cyclones for 37mm filter cassette (SKC $\gamma$ ) were highly efficient for the removal of larger particles, and not efficient for smaller particles. The characteristic curve of SKC $\gamma$  cyclone shown in Figure 2 is much sharper than the curve of revised ACGIH criteria. Other investigators, (Ettinger et al. 1970; Blackman and Lippmann, 1974; Seltzer et al., 1971; Caplan et al., 1977; Liden 1993; Maynard and Kenny, 1995) also noted that the collection characteristics of other miniature cyclones are also sharper than that of the ACGIH criteria so that a perfect match is not possible. Since the mass concentration is contributed mainly by larger particles, hazard aerosol sampling using cyclones as inlet underestimates the mass concentration. Despite their limitations, cyclones are the most common inlets for respirable dust sampling currently used in the U.S.

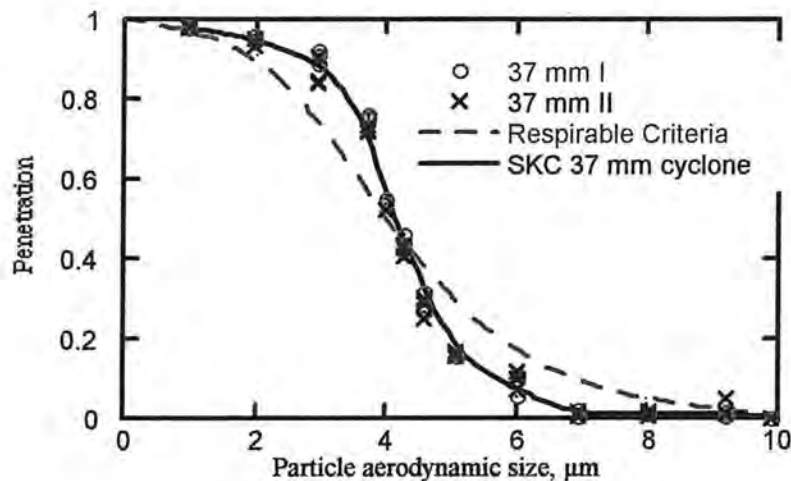


Figure 2. Comparison of the Respirable Criteria and the Penetration Characteristics of two SKC Cyclones at 2.6 lpm.

Inertial impactors are also used as inlets in hazard aerosol sampling. A typical inertial impactor consists of a nozzle and an impaction plate as shown in Figure 3a. The nozzle can be either round or rectangular. Particles in the stream having sufficient inertia will impact on the plate, and smaller particles will pass. An ideal particle classifier should collect all particles larger than a certain size and none of the smaller ones, which would correspond to the sharp ideal cut-off

illustrated in Figure 3b. Although the efficiency curve of a typical real impactor stage spans a range of particle sizes, it still has a good sharpness of cut. The theory of inertial impaction has been well developed (Marple and Liu, 1974; Marple and Willeke, 1976). The cut-off size,  $D_{p50}$ , is mainly determined by the sampling flowrate and the inlet nozzle size. A well designed impactor can be predicted as shown below for select flowrates and nozzle diameters:

$$St_{50} = \frac{\rho C V_0 D_{p50}^2}{9 \mu W} \quad (1)$$

where,  $\rho$  is the particle density;  $\mu$  is the fluid viscosity;  $W$  is the nozzle diameter for a round impactor or width for a rectangular impactor;  $C$  is the slip correction coefficient;  $V_0$  is the mean velocity of sample flow jet in the nozzle throat; and  $St_{50}$  is the Stokes number corresponding to 50% particle collection (cut-off size).

It has been found that  $St_{50}$  is nearly constant and relatively independent of the geometric features of the impactor and the Reynolds number ( $Re$ ) in the nozzle when  $Re > 100$  (Marple and Liu, 1974; Marple and Willeke, 1976; Fang, 1988). Therefore, desired cut-off sizes,  $D_{p50}$ , can be theoretically estimated.

a) Conventional Impactor

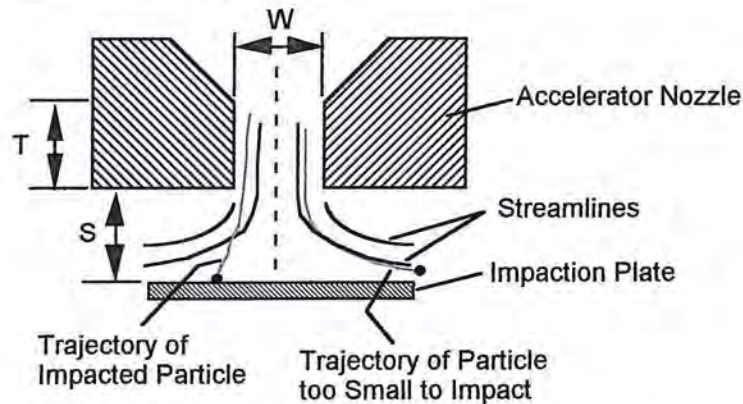


Figure 3a. Streamlines and particle trajectories for a typical impactor.

### b) Efficiency Curve

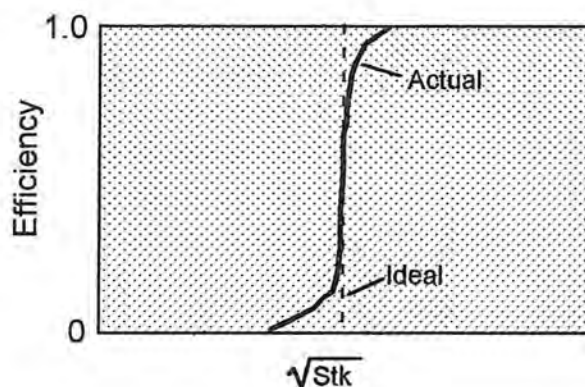


Figure 3b. Ideal efficiency curve and actual efficiency curve for a typical impactor.

However, conventional inertial impactors have penetration characteristics that are much sharper than the size-selective criteria. A design procedure was developed so that the penetration characteristics of single stage inertial impactors can be designed to approximate penetration curves of criteria (Marple, 1977; Willeke, 1978; Marple and McCormack, 1983; Fang and Lippmann, 1995). This design procedure involves use of different nozzle sizes in a parallel flow arrangement, as shown in Figure 4. Since the pressure drops across all of the nozzles are the same, each nozzle will have the same jet velocity but a different particle cut-off size, depending upon the size of the nozzle. The combination of penetration characteristics will then be a function of the size and number of the nozzles used and the total flowrate through the nozzles.

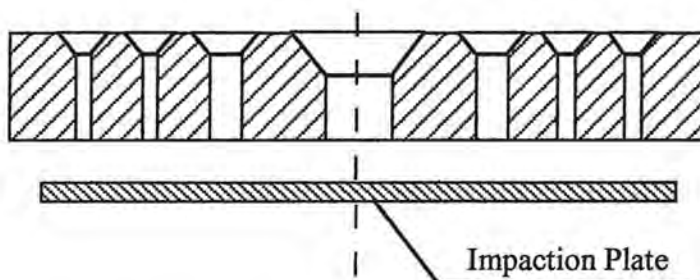


Figure 4. Schematic Diagram of a Single Impactor with three nozzle sizes.

Although the multi-nozzle impactors with uniform jet velocities are able to match the cut-off sizes of the ACGIH criteria and to comply with the penetration characteristics very well for larger particles, they failed to comply with the criteria at small particle sizes. The characteristics of this type thoracic inlets have been experimental determined by Dr. Fang as shown in Figure 5. The jet velocity and the Reynolds Number of the smallest nozzles are substantially low. Marple (1970), through his theoretical study, pointed out that the performance of inertial impactors becomes worse when jet Reynolds Number falls below 100.

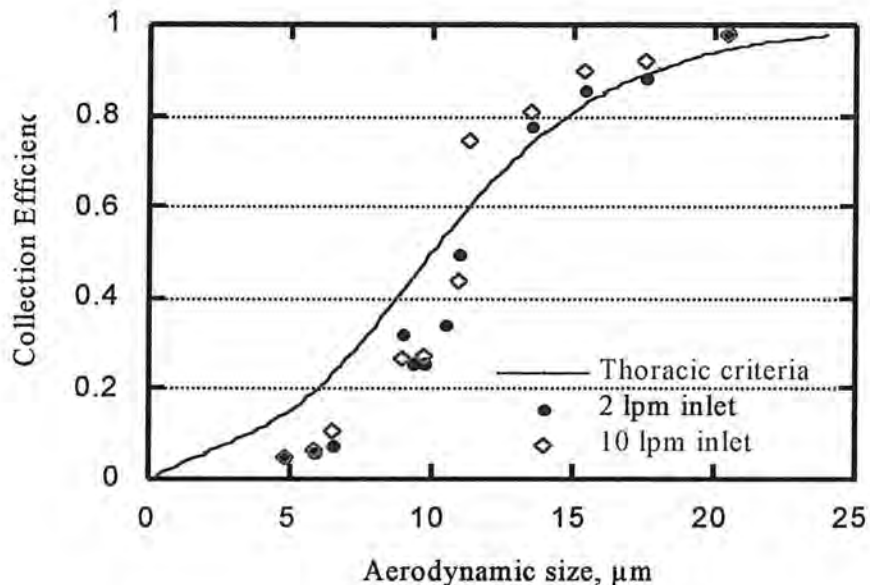


Figure 5. Comparison of the measured collection efficiency of a prototype multi-nozzle impactor (with uniform jet velocities) and the ACGIH thoracic criteria.

### Specific Aims

The specific aims of the Phase I study are:

- 1) To develop an array of single stage multi-nozzle impactors (ASMI) with different jet velocities as prototypes of an entirely new inlet design for aerosol sampling. The new design uses fewer small nozzles and additional metering orifices to substantially increase jet velocity and Reynolds number ( $Re$ ) in the small nozzles. As a result, the performance of the inlets is superior to those of pre-existing designs.
- 2) The new inlets will plug into both 37 mm and 25 mm filter cassettes and remove oversize particles according to the ACGIH-ISO-CEN criteria.

### Procedures

Based on the limitations of time and finance in the Phase I, feasibility study, we only developed a protocol ASMI-t for the ACGIH thoracic criteria. The protocol ASMI-t consists of three individual impactors connected with a pump in parallel. The reasons for choosing the thoracic criteria are: 1) there is no thoracic inlet currently commercially available; 2) the investigators have

previous experience in the development of thoracic inlets; and 3) the thoracic criteria, which are very similar to EPA's PM<sub>10</sub> criteria, may have the best commercial prospects.

The design phase included the experimental determination of: 1) the optimum geometric parameters of three individual impactors; 2) the optimum operating conditions of ASMI-t; 3) the precision of flow control by the metering orifices; 4) particulate penetration characteristics; and 5) Sampling artifacts, such as the particle loss.

## Methodology

### Device Design

Based on the previous studies, a new and innovative inlet has been developed. The new inlets are basically an array of single stage multi-nozzle inertial impactors with different jet velocities. The new design can use fewer small nozzles and additional metering orifices to substantially increase jet velocity and Reynolds number in the small nozzles. Therefore, the performance of the small nozzles can be improved.

### Calibration

The calibration of the ASMI-t was done with monodisperse spherical particles in a wide size range. The vibrating orifice monodisperse aerosol generator (VOAG-1, Model 3050, TSI) was employed to generate monodisperse uranine (2%) tagged oleic acid aerosols (Berglund and Liu, 1973). The resulting uranine (2%) tagged oleic acid aerosols have geometric standard deviations less than 1.10. The sizes of the aerosols generated by the vibrating orifice generator were calculated from the equation for the conservation of mass,

$$D_p = \left( \frac{6QC}{\pi f} \right)^{1/3} \quad (2)$$

where,  $Q$  = liquid flow rate through orifice (cm<sup>3</sup>/sec)  
 $C$  = volumetric concentration of the solute in the solution (cm<sup>3</sup>/cm<sup>3</sup>)  
 $f$  = frequency of vibrating orifice (sec<sup>-1</sup>)

The aerodynamic size of the generated particles,  $D_{ae}$ , can then be obtained from the geometric size  $D_p$  by the following equation:

$$D_{ae} = D_p \sqrt{\rho_p} \quad (3)$$

where  $\rho_p$  is the particle density and is 0.895 g/cm<sup>3</sup> for oleic acid.

The charge-neutralized aerosol was simultaneously sampled by the inlets and collected by either impactor plates or downstream filters. The deposited oleic acid-uranine particles were then recovered by sonicating the filters and plugs separately in a bath with distilled water buffered with

0.1 N ammonia hydroxide ( $\text{NH}_4\text{OH}$ ). The mass concentration of oleic acid-uranine in each sample solution was determined using a calibrated fluorometer. All experiments were replicated three times or more (when uncertainty remains too large for adequate analysis) at each condition to ensure the accuracy of the measurement.

## Results and Discussion

### *Design of Impactors*

The ASMI-t developed in this study consists of an array of single stage multi-nozzle impactors with different jet velocities. The new technique uses additional metering orifices to control flowrates of three different sizes of impactor nozzle arrayed in a single stage. The design, as shown below, will: 1) increase jet velocities and Reynolds numbers and, therefore, enhance the performances of the inlets; and 2) reduce the number of jets dramatically, compared to conventional multi-jet inlets

To simulate the penetration characteristics, three different nozzle sizes were chosen so that each nozzle size approximates a part of the penetration curve. The flowrate for each group of nozzles was designed to be equal, i.e. one third of the sampling flowrate. One design is illustrated in Figure 6 for simulation of the thoracic penetration curve which has a nominal cutoff size of  $10\ \mu\text{m}$ , the midpoints of each portion of the thoracic collection curve (collection efficiency = 1 - penetration efficiency) are  $15.4$ ,  $10.0$  and  $5.4\ \mu\text{m}$ , respectively. The nozzle sizes and numbers were calculated with Equation 1. The resulting designs are tabulated in Table 1.

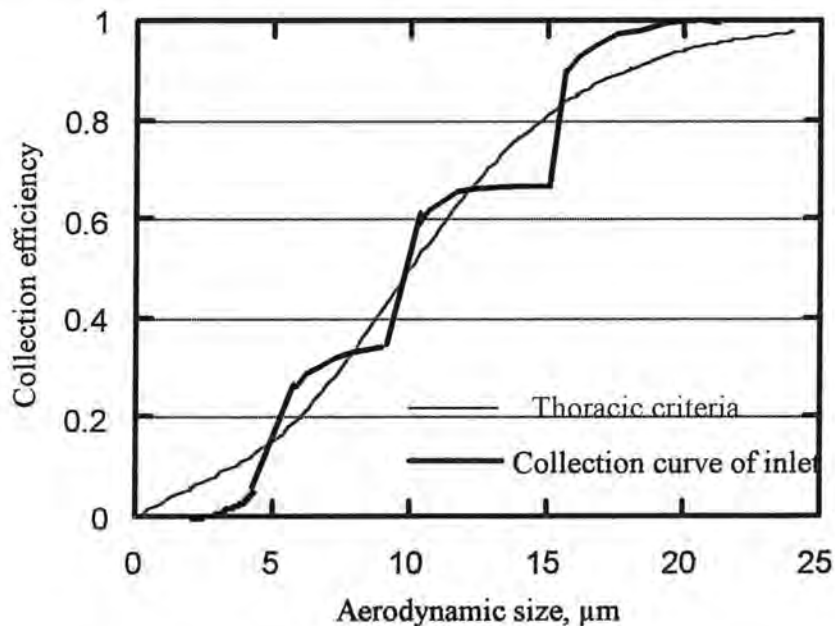


Figure 6. Comparison of calculated collection curve for ASMI-t and the thoracic criteria curve.

**Table 1. Design Criteria for ASMI-t**

Cutoff size ( $\mu\text{m}$ )	no. of nozzles	Nozzle size (cm)	Velocity (cm/sec)	Re
<u>Different velocity design</u>				
15.4	1	0.441	72.6	211
10.0	1	0.331	129	282
5.4	2	0.124	233	267

The mechanical designs for the prototype ASMI-t units are given in Appendix I. O-rings were used for sealing between cylindrical body surfaces. Connection tubing was specially designed to use as a tool for measuring the flowrates through each impactor unit.

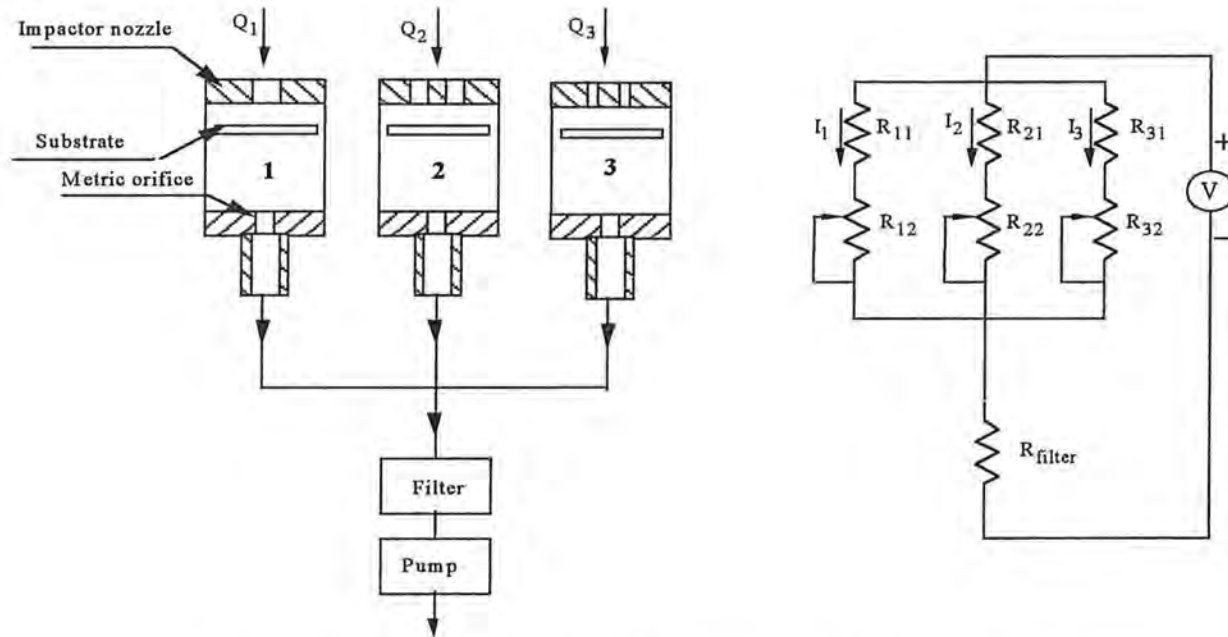


Figure 7. Schematic diagram of ASMI-t and its electrical analog.

Different Velocity Flow System

The protocol ASMI-t consists of three individual impactors connected with a pump in parallel. The new technology for size-selective air sample can be illustrated schematically in Figure 7 and explained with the electrical analogy. Three different size groups of nozzles are arranged in parallel. In order to obtain the same flow rate through each group of nozzles, additional metering

orifices were used to control the flow resistance. The particles passing through the inlet can be collected by a filter. The situation is quite like Ohm's law in electric-circuit theory. The electric circuit shown in Figure 7 consists of three lines in parallel. Each line has two resistors in series,  $R_{11}$  and  $R_{12}$ ,  $R_{21}$  and  $R_{22}$ , and  $R_{31}$  and  $R_{32}$ , respectively. It is assumed that the  $R_{11}$ ,  $R_{21}$  and  $R_{31}$  are different and given, and the  $R_{12}$ ,  $R_{22}$  and  $R_{32}$  are adjustable. The resistance of the filter is presented with  $R_{\text{filter}}$  in series. By adjusting  $R_{12}$ ,  $R_{22}$  and  $R_{32}$ , we can obtain  $R_{11}+R_{12} = R_{21}+R_{22} = R_{31}+R_{32}$ . With Ohm's law, then we have  $I_1 = I_2 = I_3$ .

To our inlet system as shown in Figure 7, the numbers and diameters of impactor nozzles were determined by impactor theory. By adjusting the diameters of metering orifices, the flowrates through each impactor can be close to equal, i.e.,  $Q_1 = Q_2 = Q_3$ . Our design criteria for the differences among three flowrates are within 3%.

**Table 2. Flow calibration data**

Average flowrate, ml/min				
Group I	Plug 1	Plug 2	Plug 3	Error
	654.9	655.8	653.9	< 0.5%
	227.8	224.2	226.8	< 1.0%
	978.6	979.6	978.7	< 0.2%
Group II	Plug 1	Plug 2	Plug 3	Error
	655.2	655.5	654.5	< 0.2%
	428.6	430	427.6	< 0.5%
	898.1	907.3	895.6	< 1.0%
Group III	Plug 1	Plug 2	Plug 3	Error
	981.2	979.9	980.17	< 0.2%
	694.9	693.9	693.7	< 0.2%
	296.5	294.2	295.5	< 0.2%

### Flowrate Calibration

A key point for this development is to assure the flowrates passing through all three impactors are equal. These flowrates are controlled by the metering orifice in the plug. The nominal diameter of the metering orifice is 1 mm. However, the actual size may deviate due to manufacturing errors. Three plugs in each group must be carefully chosen and evaluated according to our design criteria. For quality assurance, 20 substrate-and-orifice plugs of designed impactor were fabricated for selection of the matching groups. Three groups of plugs were selected from these 20 plugs. The differences of all three groups of plugs used in following studies are within 1%, which is much better than the design criteria, 3% (Table 2).

### Penetration Characteristics

We started the calibration of ASMI-t with 5  $\mu\text{m}$  particles and found that the experimental data of particle deposition efficiency in plugs significantly exceeded the values of the theoretical prediction by using Equation 1. Tremendous efforts were made then to discover the reason causing this difference. When we collected depositions on impaction substrates with Q-tips instead of dipping the whole plug into the solution to recover the particle depositions, particle losses inside the plug body were discovered. Figure 8 shows the distributions of average particle deposition on impaction substrates, filters, and loss in plugs. The particle loss counts about 50% of the total deposition for 5  $\mu\text{m}$  particles.

To determine the performance characteristics of the inlets as well as the correlation between the particle loss and the particle sizes, we measured particles collected on substrates and in plug bodies separately. Figure 9 shows the collection characteristics of ASMI-t corresponding to a particle size range of 2  $\mu\text{m}$  to 10  $\mu\text{m}$ . For comparison, the thoracic criteria curve was also plotted in Figure 9. The results show that the impaction collection efficiency of the ASMI-t agree with the expectations very well in the size range of testing particles. However,, the total collections prior to the filter are high due to particle loss in plugs.

Figure 10 shows the distributions of particle collections at various particle sizes. Portions of particle loss in plugs are in a range of 30-50%, and are independent to particle sizes.

Careful examinations revealed that the major particle loss is in the metering orifice area, especially on the inner surface of the orifice. Two measures were made to reduce particle losses in plugs: 1) increase orifice diameter from 1 mm to 2 mm; and 2) reduce orifice length from 0.06 inch to 0.025 inch.

Experimental data illustrated in Figure 11 show that both methods could decrease particle losses and increase filter collection. To meet the expectations, further modifications of the orifice, such as sharp edged orifice, are also needed.

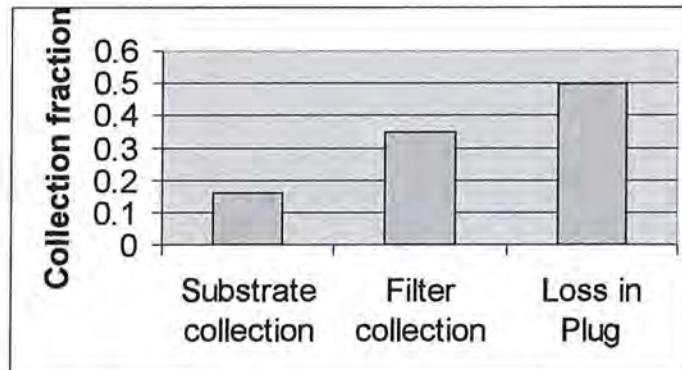


Figure 8. Distribution of particle deposition in the inlet with 5 $\mu\text{m}$  testing particles.

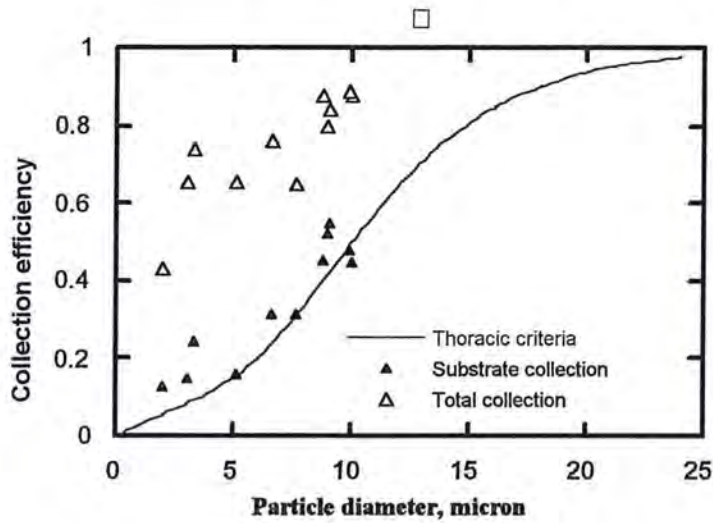


Figure 9. Collection efficiency of the ASMI-t.

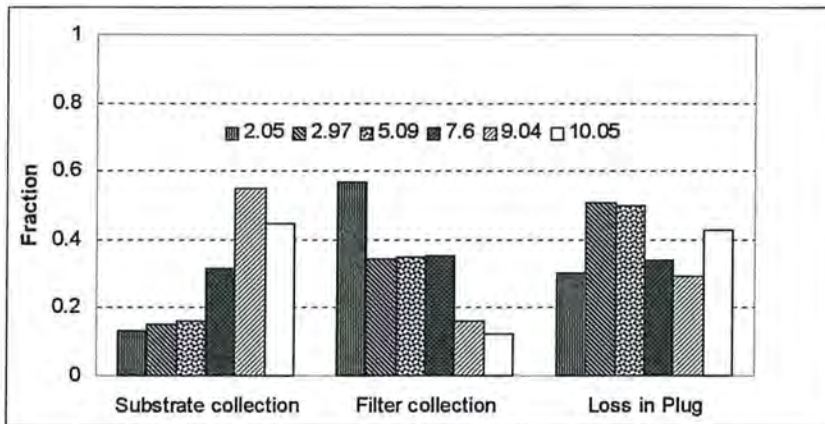


Figure 10. Distribution of particle depositions at different particle size.

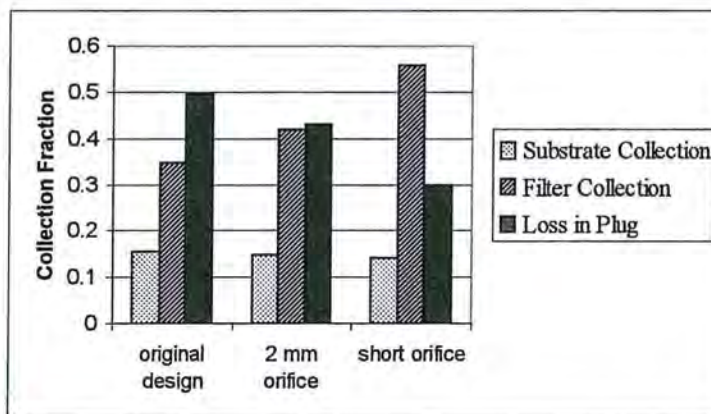


Figure 11. Comparison of ASMI-t performances with different orifice design.

## Conclusions

ASMI-t, a multiple velocity aerosol sampling inlets to conform to revised ACGIH criteria, has been developed in this Phase I research. The experimental results of impaction collection meet the expectations in the size range of testing particles. This means the idea of a single stage multiple velocity impactor is feasible. The filter collections, however, are much less than the expectations because of 30-50% particle loss in plug bodies. Improvements have been made by increasing orifice diameter and reducing orifice length. Significant improvement can be made if more time and funds are available.

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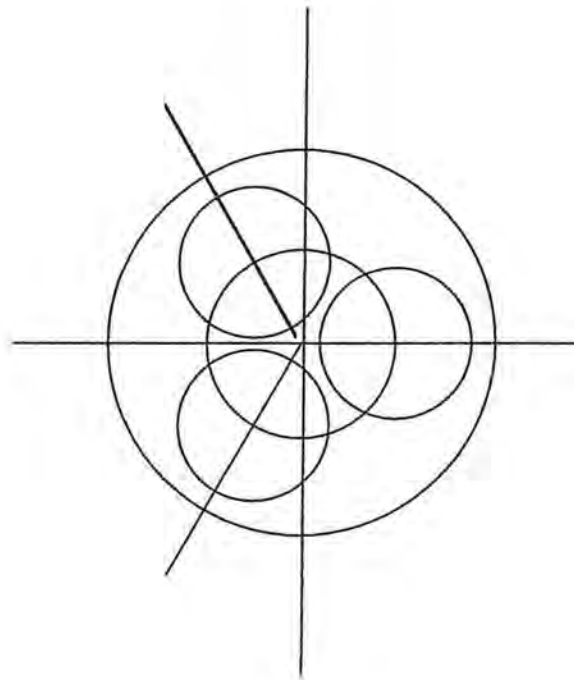
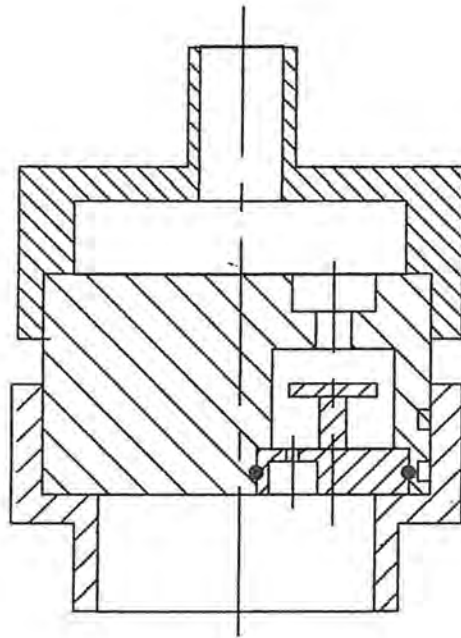
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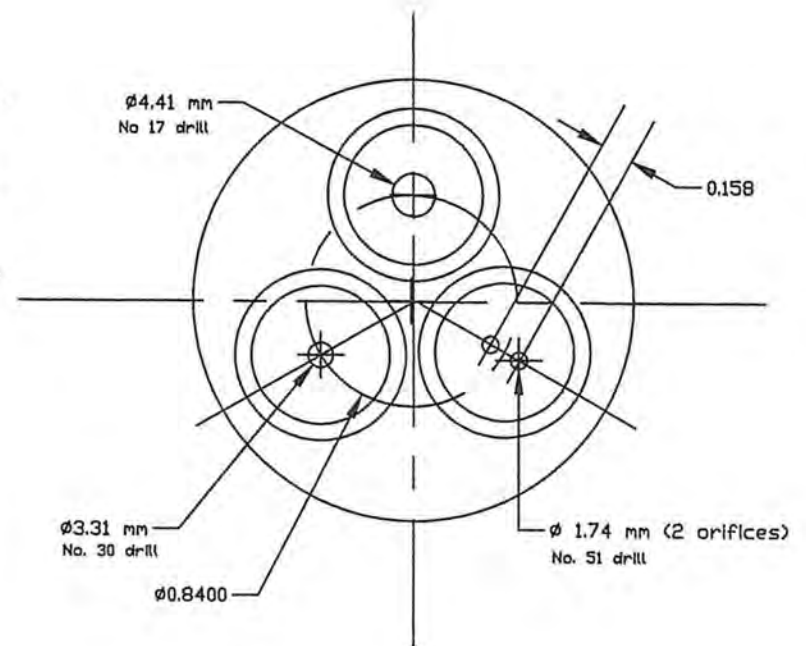
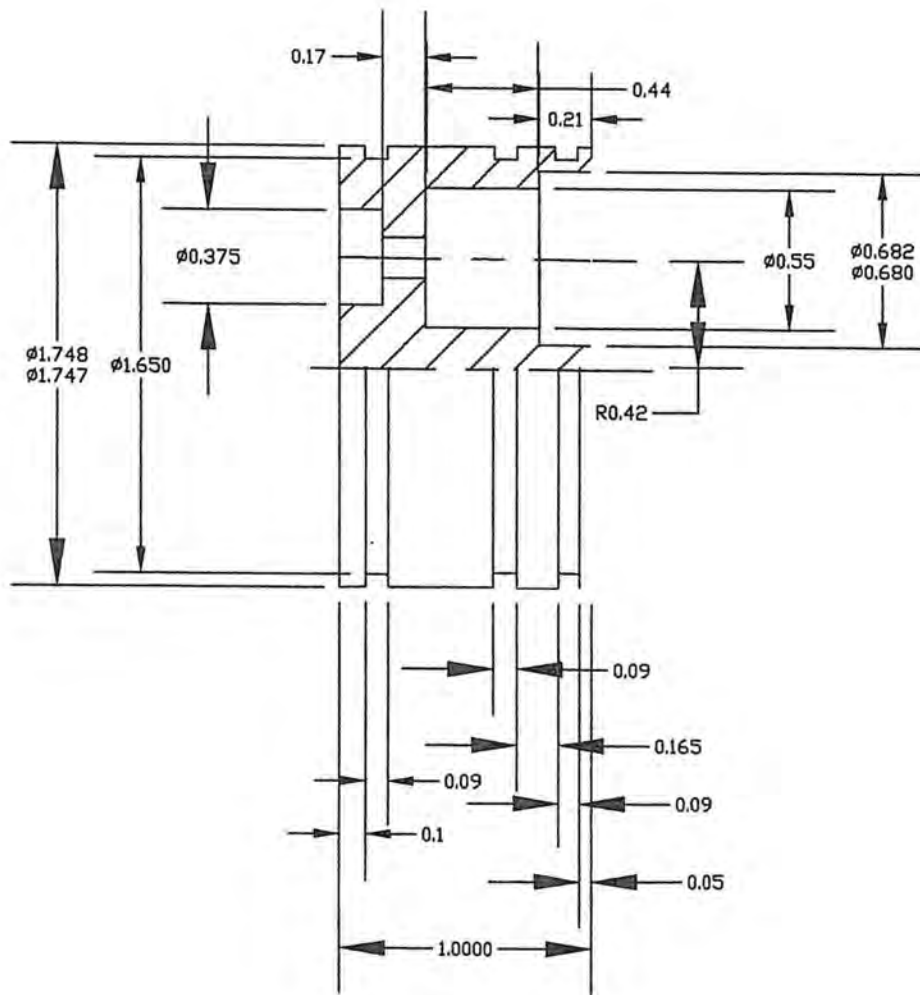
## Appendix I

### Mechanical Design of ASMI-t

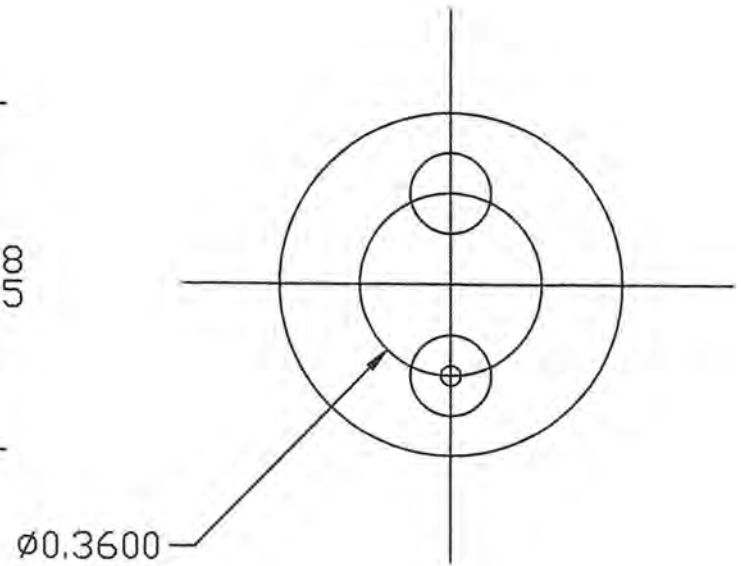
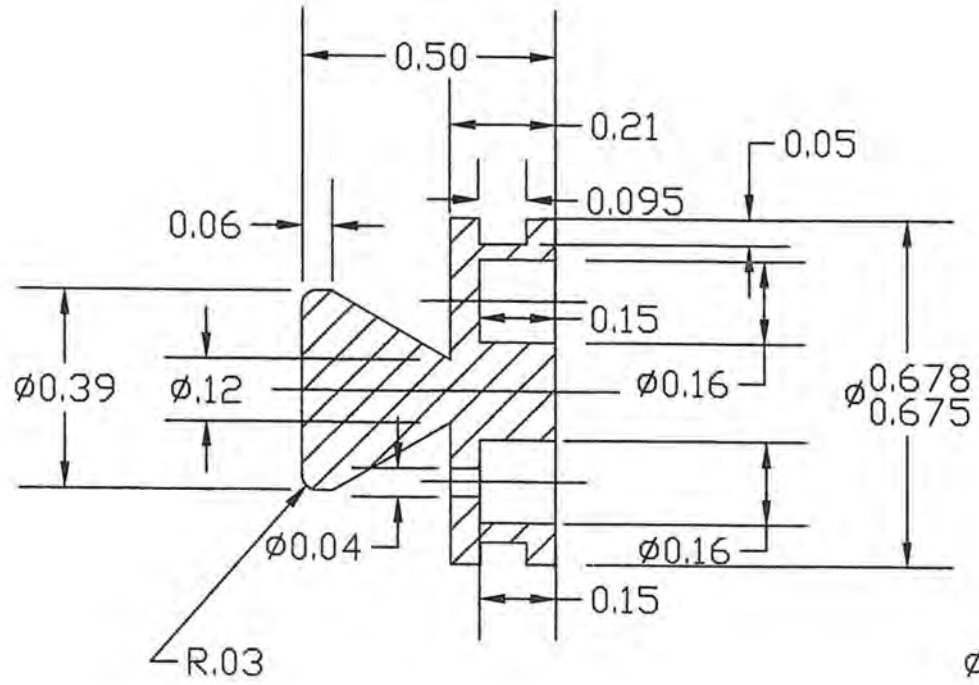
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37 mm filter adopter	A-5
25 mm filter adopter	A-6



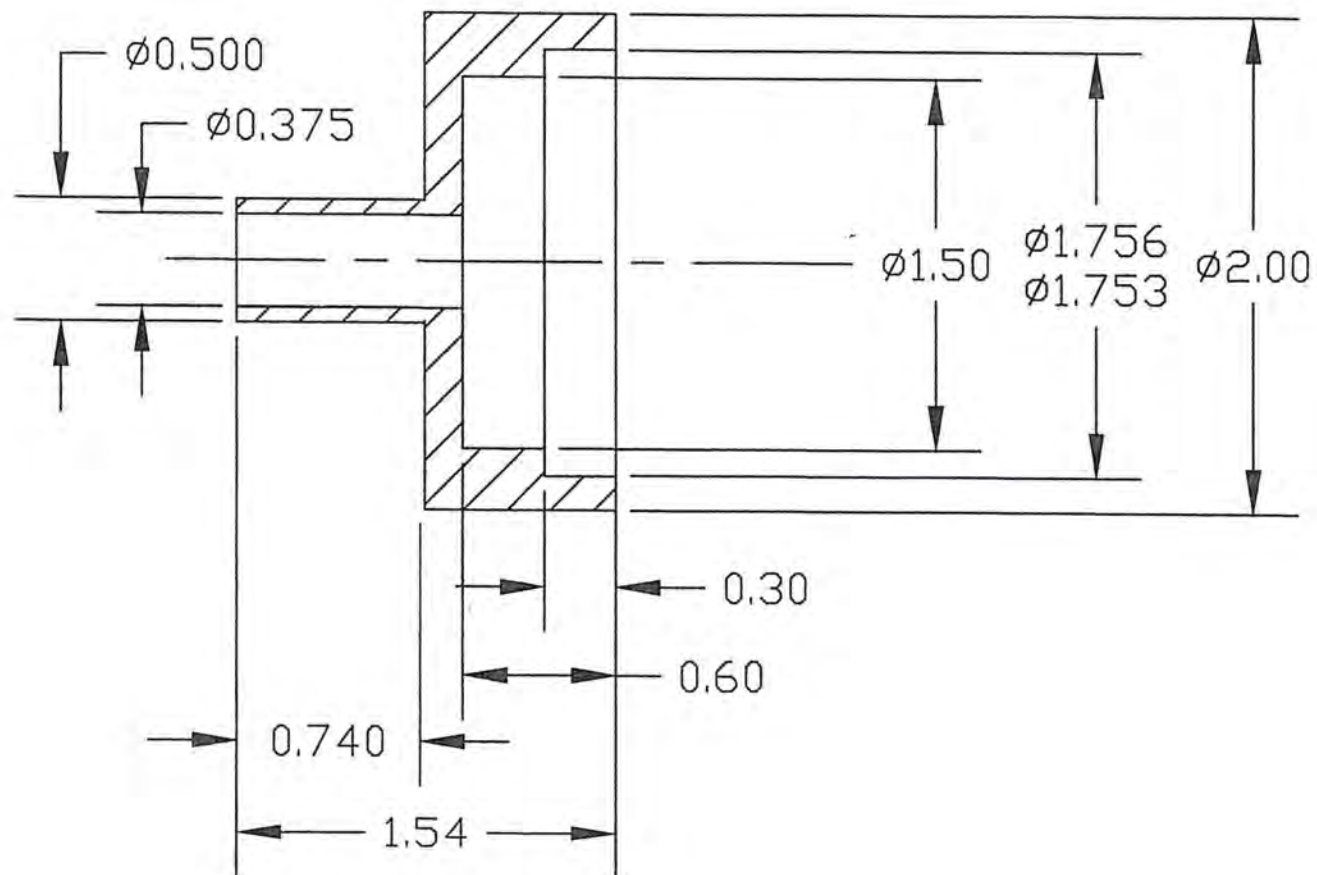
A-2



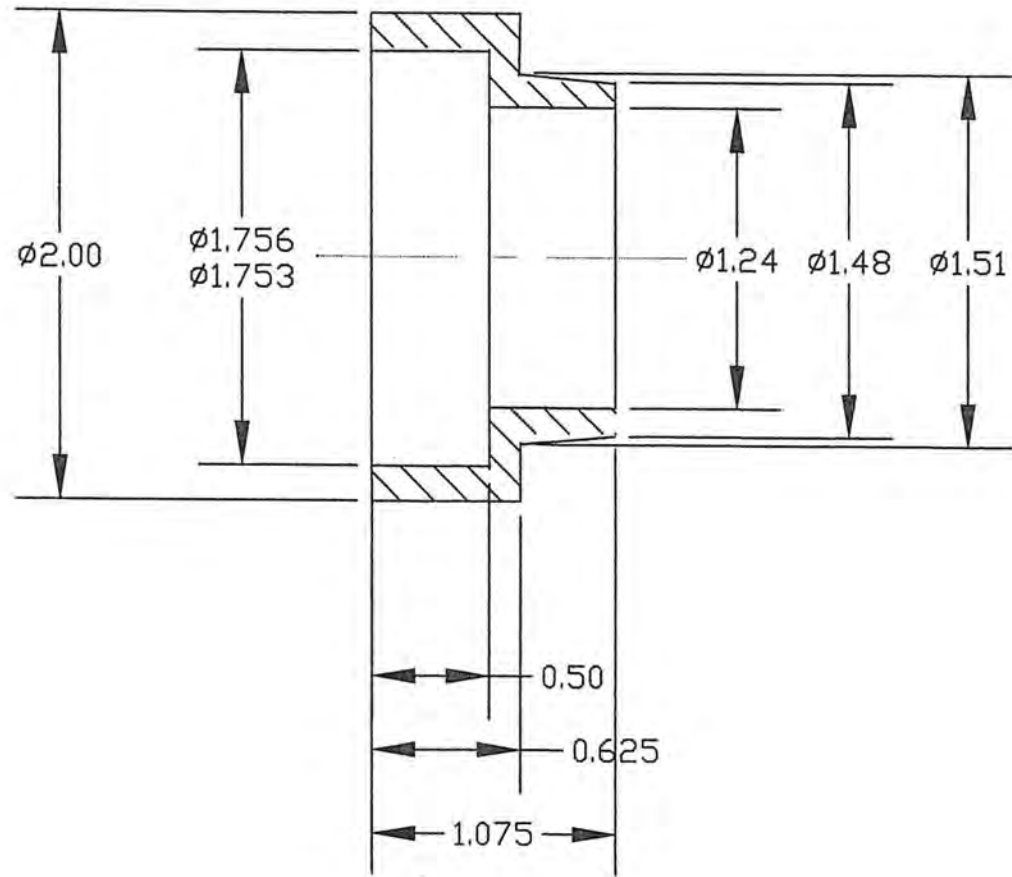
A-3



A-4



A-5



A-6

