RESPIRATORY PROTECTIVE EQUIPMENT

PROGRESS REPORT

FOR

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by

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I

INTRODUCTION

Dust and gas masks and respirators have been an effective method under certain environmental conditions to reduce the inhalation of toxic aerosols. Under many conditions, however, their efficacy has been seriously questioned. It is the purpose of this study to evaluate over-all respirator performance on fine aerosols ($<0.2\ \mu$) and to develop equipment whereby a greater degree of respiratory protection may be assured with reliability for highly toxic atmospheres.

Present U. S. Bureau of Mines' specifications for the design and testing of respirators are based on dusts, fumes and mists from materials not significantly more toxic than lead. The increased use of higher toxicity materials requires that the performance of available devices be determined to assess their adequacy, and to determine the limitations to be placed upon their use. The toxicity levels with which we are concerned in nuclear processes are often several orders of magnitude more restrictive than the level for lead. To illustrate, non-radioactive beryllium is considered to be 100 times more toxic than lead, whereas the radioactive nuclides Pu-239, Po-210 and Sr-90 are respectively considered 5 million, 2 billion and 3 billion times more toxic on a weight basis. With exposures to these as possible contaminants, it is imperative that the controlling factors associated with the effective use of respirators be clearly defined and that the methods whereby they are used may be improved.

In addition, the possible leakage characteristics inherent in the nature of the face seal in half masks or even in full face masks raise concern as to whether the high efficiency filters now incorporated in ultra types are used anywhere near their accepted static test values obtained in existing performance schedules.

Leakage values previously obtained in this laboratory during World War II and elsewhere on half masks and full face masks indicate that the leakage values may range from 1 to 20 per cent on the half masks and from less than 1 to 5 per cent on full face masks, depending upon facial contours, suspension tension and conditions of wearing.

Considerable work has been done by Silverman, et al (1-8) on breathing requirements for military masks. These masks were, however, designed for protecting military personnel under combat conditions where comfort in daily use for normal occupations is not of primary concern.

Supplied air devices which are used for emergencies in Atomic Energy Commission installations consist of full face masks and demand valves which customarily require a portable supply cylinder or a self-generating canister such as the "Chemox". With positive pressure demand valves these devices can provide considerable protection beyond the filter types but their performance has not yet been evaluated for requirements as severe as outlined above.

The major objective of this respirator evaluation project is to study and evaluate existing devices and to modify them or develop new devices for respiratory protection against highly toxic radioactive and non-radioactive aerosols encountered in nuclear processes. Specifically, the following items are of principal concern in the achievement of the major objective.

1. A study should be made of the factors influencing respirator or protective breathing device performance. These factors include pulsating air flow, facial seal, valve leakage and sealing, comfort, filter media factors, resistance, visual field and interference with performance.
2. Initially, there should be developed an evaluation procedure for rating and qualifying personal protective equipment on wearers for determining their performance under conditions

comparable to exposure to highly toxic radioactive materials such as plutonium and non-radioactive materials such as beryllium.

3. An evaluation of existing types of respiratory protective equipment in the light of Atomic Energy Commission requirements must be conducted.
4. The development and an evaluation of a satisfactory maximum comfort minimum effort respiratory protective device for 8 hour daily use must be considered.

In essence, the scope of such a study should include:

A. An evaluation of respiratory factors influencing performance of respirators will include laboratory studies on a manikin and human beings.

The effects of pulsating flow on dynamic mask leakage and basic filter media efficiency are essentially unevaluated at present. Bench studies with a dynamic aerosol generator and breather pump (9) to provide pulsating air flow has been conducted by H. S. Jordan at the Harvard University School of Public Health (10). Preliminary results indicated that for a single particle size (approximately 1 μ) and a coarse fiber glass media, filter efficiency under conditions of pulsating flow at a given mean velocity could not be predicted from efficiency values obtained under steady conditions of flow. Efficiency values under pulsating flow conditions are higher at low mean velocities and lower at high mean velocities than values obtained at correspondingly steady state flow. An extension of the above studies to cover a wider particle size range and other media is indicated but will not be made in this study.

The immediate problem of interest to the AEC in this field was indicated as items (2) and (4) above and consequently the other two phases were considered as more basic than the applied research necessary for immediate field applications. If time and funds permit, items (1) and (3) will be investigated thoroughly.

The human studies will be directed towards the evaluation of dynamic leakage under typical conditions of use such as walking and performing sedentary tasks. The development of a dynamic method of evaluating leakage could determine the effects of facial seal, structural leakage, valve leakage and valve opening pressure.

Leakage has been largely determined in the past by chamber tests, although at present the U. S. Bureau of Mines is experimenting with a DOP peripheral seal test. The British at their Chemical Defense Center at Porton and our Chemical Corps Bacteriological Warfare Laboratory at Fort Detrick have developed a mask leakage evaluation using BG spores as a test aerosol and a cotton collector inserted in the mouth, or by use of an inner mask filter. Since this is a 1 μ average size suspensoid, it is not necessarily indicative of the penetration of smaller sizes and as another handicap the mask or mouth collector which must be worn imposes additional breathing resistance and alters mask conditions. The use of a gas or a submicron aerosol should therefore be more representative in quantitating leakage on a wearer. The aerosol used in this study is characterized by a geometric mean size (by count) of 0.2 micron with a geometric standard deviation of approximately 2.

The addition of hoses or appurtenances to the mask body for such tests imposes a condition which distorts actual wearing conditions and influences suspension, tension, weight, etc. Therefore, it is felt that a new and non-limiting procedure or device for rating performance during its actual wearing or use is necessary. It should also be noted that subjective reactions to leakage in a gas chamber are not entirely quantitative. Some differences will appear based on the sensory response of the subject. The need seems appropriate for the use of light weight, non-obstructive equipment which measures the aerosol intake (through leakage around the mask and through the filter) in a representative and proportional manner (during inhalation periods only). It may also be desirable to have a device which can appraise

leakage during exhalation only to determine valve performance, and possibly during both phases of respiration.

B. On the basis of past experience and development of the dynamic leakage method, it has been possible to develop an evaluation procedure for comparing existing devices. This evaluation procedure has been demonstrated to the U. S. Bureau of Mines personnel since they will eventually be responsible for the approval procedure and methods.

C. Development of a simple light weight positive pressure mask or protective shield device that can be worn without discomfort and which can have a light weight electric power operated blower or compressed air source with its own filter not limited to breathing capacities was one of the major objectives of this project.

The primary objective of this study we hope will, therefore, provide an improved means of respiratory protection for use in areas where materials more toxic than lead are used. To achieve this objective, new procedures and devices have been developed and will be discussed in this report. These include: development of a test method to evaluate respiratory protective equipment; evaluation of the effectiveness of some examples of existing equipment; development of devices for respiratory protection; and coordination of research efforts with other interested and responsible agencies.

II

DEVELOPMENT OF A TEST METHOD TO EVALUATE RESPIRATORY PROTECTIVE EQUIPMENT

In this development, we were guided by the tentative specifications set forth by the Subcommittee on Requirements, AEC Committee on Respiratory Protective Equipment, in their report of April 14, 1959. With respect to testing requirements, the primary specification of the AEC Committee was in essence that the over-all penetration should not be greater than 0.1 per cent for particles of 0.1 to 0.5 micron diameter. The complete report of the Subcommittee is attached as Appendix 1.

In addition to the Committee's specifications, it was necessary to develop a testing system that was light in weight and portable for field application. In the design of the equipment it was necessary to consider the following factors, each of which will be discussed in this report.

A. Development of an appropriate evaluation aerosol.
B. Method of aerosol generation.
C. Exposure chamber design.
D. Aerosol sampling system
E. Determination of respiratory air flow volumes.

Each of these factors will be discussed in the order given above.

A. Development of an Appropriate Evaluation Aerosol

As outlined in the introduction, the use of a submicron aerosol would permit the most representative quantitation of respirator leakage. The general characteristics desired in such an aerosol material are, a) the ability to generate an aerosol in the size range of 0.1 to 0.5 μ at adequate air concentrations, b) a detection sensitivity which will permit defining penetration of less than 0.1 per cent, c) low toxicity, and d) low cost.

Fluorescent pigments and dyes appeared to possess these minimum desirable characteristics so initial attention was given these materials. A number of pigments were acceptable but they required

moderately toxic and highly volatile solvents for solution and dispersal. These solvents presented manifold difficulties since they were not compatible with materials used in certain aerosol generators under study, their use resulted in exposure of the test subject to a moderately toxic vapor, and they presented a fire and explosion hazard.

Uranine, a commercial dyestuff previously used as a tracer in air pollution field work (11) possessed the same desirable characteristics without the liabilities inherent in fluorescent pigments. This di-sodium salt of fluorescein is readily soluble in water insuring compatibility with all generation and sampling equipment. It is considered non-toxic and has been used widely as an approved food color. Fluorescein is applied as a diagnostic aid in medicine. Intravenous administration of 3-4 ml. of a 20 per cent solution is used in the determination of circulation time. This technique can be repeated at intervals of several days without ill effects. Toxicological data presented on fluorescein demonstrates its low toxicity (12). It is assumed that the di-sodium salt of fluorescein will have similar properties.

Uranine is excited by light of 4400 to 5000 Å and emits at 5700-5900 Å. It can be detected in very low concentrations (10^{-9} g) using modified commercial instrumentation components. An initial survey using uranine WSS supplied by General Dyestuff Company, indicated that a submicron aerosol could be reliably generated. Aerosol generation will be discussed in the next section.

The instrumentation used in the analysis for uranine is shown in Figure 1. The light of the incandescent light source indicated at C is filtered by a Kodak Wratten Filter No. 47. The light causes the sample containing uranine located at D to fluoresce. The light emitted from the sample passes through a Kodak Wratten Filter No. 15 that is located in the sample holder housing unit at D. The intensity of this light, which is proportional to the content of uranine in the sample is measured by an RCA No. 1P21 photomultiplier tube (indicated

at A) in connection with an El-Dorado Photometer Model PH200 (shown at B).

This arrangement permits the detection of uranine concentrations as low as 10^{-9} grams per ml of water. As indicated in Figure 2, a linear relationship (on log-log paper) is obtainable in the concentration ranges of 4×10^{-9} g/ml to 2×10^{-6} g/ml. The calibration curve is reproducible within 5 per cent. Higher concentrations can be detected by diluting the specimens which contain 10 ml per sample.

The sensitivity of the analytical technique can be improved with the use of a more sensitive phototube and with a reduction of dark current in the tube. Detector dark current can be reduced by desiccating and refrigerating the detector. This improvement is not now needed since adequate sensitivity is available.

B. Method of Aerosol Generation

For the generation of particles with a mean size in the range of 0.1 to 0.5 μ, several commercially available nebulizers were tested using uranine as the aerosol. A summary of the experimental data is presented in Table 1.

The Dautrebande nebulizer produced an aerosol that was too small for our present studies. However, the Dautrebande nebulizer may be used in the future if particle sizes less than 0.1 μ are necessary.

The DeVilbiss nebulizer (under the conditions specified in Table 1) also produced a small aerosol which was, however, very heterogeneous. The standard deviation of the Devilbiss nebulizer aerosol was 6.7 when a midget impinger was used in series with the nebulizer. This high degree of heterogenity and the low geometric mean size made the DeVilbiss inadequate for our present studies.

Palmer and Kingsbury (13) have reported uniform aerosol production in the desired size range using a Vaponefrin nebulizer. In our tests (Runs 20 and 21 VN, Table 1) this generator produced an acceptable aerosol with an appropriate distribution when a 1 per cent uranine solution was used with a 4 psig generation pressure. Difficulty was encountered however, in obtaining a consistent geometric mean size under identical generating conditions. Apparently, the resolution used in the Palmer and Kingsbury study did not sufficientl identify the small particles in the background.

Table 1

Summary of Aerosol Generating Data

Run #	Nozzle Flow Rate in ml/min. of air at 70°F & 14.7 psig	Sol.Conc., in % wt.	Mg μ	σ	Mg' μ	Additional Equipment Modifying Particle Size Distribution
	Pen-i-sol (glass)					
1P	2460 ± 3% (est.)	1.0	0.26	3.06	11.2	No impinger
3P	2780	1.0	0.29	2.96	10.1	1 G-S *
6P	2140	0.6	0.27	3.5	27	"
5P	2780	0.6	0.14	3.06	6.0	"
13P	3650	1.0	0.06	1.74	0.215	2 G-S "
14P	3450	4.7	0.22	3.2	13.0	"
15P	3900	4.7	0.27	3.3	19.6	"
16P	3560	2.35	0.20	2.4	2.06	"
17P	3560	1.5	0.24	2.02	1.32	"
	Vaponefrin (glass)					
20VN	3380	1.0	0.46	2.7	9.7	No impinger
21VN	3380	1.0	0.23	2.85	6.5	1 G-S "
	DeVilbiss (plastic)					
5DV	6900	1.0	0.074	6.7	-	Midget impinger

Dautrebande $D_{30}1$ (plastic) Manufactured in Belgium.

Mg = 0.05 μ for soln. conc. 5% app. upper limit of device (frothing) and for 10 psig to 20 psig.

* Greenburg-Smith Impingers

The Pen-i-sol nebulizer consistently produced an aerosol with a geometric mean size (on a count basis) in the range of 0.14 to 0.29 μ. The conditions stated in Table 1 under Run 16P were selected, as the operating conditions for generating the aerosol in subsequent tests.

The aerosol generation technique finally adopted was based on the Pen-i-sol nebulizer. The generation procedure is shown in Photograph 1. A 2.35% solution of uranine is placed in the Pen-i-sol nebulizer indicated by the letter E. The pressure indicated by the gage at D, is set at 9.5 psig. The flow rate through the generator is approximately 3.5 l/m. The aerosol generated by the nebulizer is then passed through two impingers located at positions F and G where the larger size particles are removed from the air stream. Dilution air which has been dried and filtered is then metered at I and mixed with the aerosol at H. After additional mixing of the generated aerosol and dilution air in a second chamber, the diluted test aerosol is directed into the exposure chamber.

Particle size analysis of the aerosol supplied to the helmet was conducted by the collection of the aerosol on carbon coated electron microscope screens. The collected aerosols were viewed under the electron microscope and sizing was obtained from the electron-micrographs. A typical particle size distribution curve is presented in Figure 3 for the aerosol within the helmet under the normal operating conditions as previously stated.

C. Exposure Chamber

In order to expose a man wearing a respirator to the test aerosol while in a work situation an exposure chamber with certain unique design features was required. The exposure chamber, in order to perform its basic function, must provide a known concentration of aerosol to the breathing zone of the subject. The second requirement of the chamber design was that it permit exposure of the subject without surrendering his mobility to perform various work activities

during the test program. In addition, the chamber must be so designed as to permit various connections to the respirator, provide full vision for the subject, and allow the removal of the test aerosol. This latter feature seemed especially desirable with the sensitive analytical procedure in use since trace contamination of laboratory equipment could result in erroneous test results.

An exposure chamber incorporating the basic design features listed above was designed and is shown in Figure 4. The helmet platform (A) is the main structural part. The platform is designed to permit the rapid assembly of two concentric and transparent cylinders (B). The aerosol is introduced through two ports (C) and distributed by impaction plates (D) in a shallow plenum (E). The aerosol then passes through an open cell polyurethane pad (F) which insures homogeneous distribution of aerosol in the chamber. From the exposure zone the aerosol is exhausted through the annulus formed by the two plastic cylinders. Connectors for tubing leads to the respirator are provided for easy access as shown at (G). A chamber prototype in test position is shown in Photograph 2.

The uniformity of distribution of aerosol within the chamber was evaluated by sampling with Millipore filters using the samplers to be described in a subsequent section of the report. Concentrations of aerosol varied less than 10 per cent within the chamber. The normal concentration of uranine generated as described in the section on aerosol generation was 3-4 mg uranine/cu.m. This concentration permits the detection of respirator leakages of less than 0.1 per cent.

D. Aerosol Sampling System

A Millipore filter type HA was chosen as the filter for collection of uranine. Sample holders were required for the exposure helmet and the respirator. The design requirements for the respirator sample holder were rigid. The sampler must permit the taking of a representative air sample inside the respirator without interfering with normal use of

the respirator by the subject. A small sampler was required to insure that there would be no mechanical interference with the respirator fit. Weight consideration was necessary so that the designed suspension of the respirator would not be modified. Either of these conditions would present unrealistic test conditions.

Miniature plastic filter holders were originally developed for sampling, however, the filter seal was not absolute. The final sampler design is shown in Figure 4. This sample, slightly larger than a nickle and weighing only 6 gms. has an aluminum body and a integral hypodermic needle. A screw top insures a tight filter seal so that "by-passing" does not occur. In setting up for a test the hypodermic needle is pushed from the inside of the respirator through the rubber frame. The chamber sampler, identical to the respirator sampler is clipped to the inside of the chamber. Catheter tubing is used to attach the sampler to the suction source.

For representative tests the respirator sample should be taken only during inhalation. A pressure sensing device to direct respirator sampling during inhalation was developed based on a Fisher-Porter Precision Calibrator. The manufacturer's description of this unit is given below.

> "The Model 32CA110 Precision Comparator is a precise pneumatic comparing device designed to sense the value of some unknown pressure to one side of a diaphragm separating a chamber while a monitored pressure is applied to the other side of the diaphragm. At the point of equilibrium an electric contact is opened to actuate some indicating device, and the unknown pressure is determined from the value of the monitored pressure."

The precision calibrator was modified by removing the bias spring and locating the diaphragm in a vertical plane. One side of the unit was open to atmosphere and the other connected to the respirator void by means of a hyopdermic needle inserted through the frame. With correct orientation of the diaphragm the unit becomes a pressure sensing device with sensitivity of 0.01 to 0.02 "H_2O. During inhalation the diaphragm is displaced, completing a direction circuit and

opening an electric valve in the respirator sampling line. As exhalation is initiated the diaphragm moves to open the direction circuit and close the respirator sampling valve. The duration of each inhalation period is recorded on an integral timer which records the total sampling time. The helmet sampler is continuously sampling during the test. The total air volume sampled from both samplers is determined from total sampling time and flow rate through a critical orifice in the sampling line. The calibration of the helmet sampler critical orifice is shown in Figure 7. A similar calibration is available for the respirator sampler. A schematic of this sampling technique is shown in Figure 6.

E. Determination of Inspiratory Air Flow Volumes

A method of measuring the inspiratory air flow of test subjects under working conditions was developed. The design requirements were that the device predict the minute volume within ± 10 per cent and that it not interfere with the normal use of the respirator by the subject.

A simple device acceptable for field use was developed based on existing instruments (14, 15). The device, shown in Figure 8, provides a parallel air path of high resistance to the main path through the respirator filter or cartridge. The flow in this aliquoting path is in fixed ratio to total respiratory flow for a given respirator and filter design.

The parallel air flow path shown in Figure 8 consists of a hypodermic needle inserted in the mask, a solenoid operated valve directed by the pressure sensing device which opens only during inhalation, a capillary resistance, and a soap film spirometer which acts as a flow integrating device. During the inhalation phase the valve opens and an aliquot of air passes through the capillary into the respirator. The soap film spirometer defines this air volume. Since the air path is closed during exhalation the soap film moves

stepwise progressing only during inhalation. Measurement of a single inhalation or average breathing volume is therefore possible.

As an example, the calibration curve for the determination of the flow rate through the respirator as a function of the pressure drop across a test respirator with respect to flow through the aliquoter is presented in Figure 9. The relationship of the flow rates through three commercially available respirators with respect to flow rate through the aliquoter are presented in Table 2.

Table 2

Relationship of Respirator to Aliquoter Flow Rates

Test Respirator	Flow Rate Through Respirator* l/min
X No. 1	$2.31 \times 10^3 Q_A$
X No. 2	$2.23 \times 10^3 Q_A$
X No. 3	$2.23 \times 10^3 Q_A$
	$3.81 \times 10^3 Q_A$
Z No. 1	$3.43 \times 10^3 Q_A$
Z No. 3	$3.72 \times 10^3 Q_A$
Y No. 3	$2.70 \times 10^3 Q_A$

* Where Q_A is the flow rate through the aliquoter in ml/min.

III

EVALUATION OF THE EFFECTIVENESS OF EXISTING RESPIRATORY PROTECTIVE EQUIPMENT

Present studies have involved the testing of half face masks or respirators produced by Mine Safety Appliances, American Optical Company and the Willson Company. Tests have included the measurement of air resistance to inhalation and the penetration of the aerosol through respirators worn by the manikin and human subjects.

A. Inspiratory Resistance of Various Respirators

The resistance to air flow (inhalation) of representative samples of the respirators have been determined under conditions of air flows ranging from less than 20 lpm to approximately 85 lpm as presented in Figures 9, 10, and 11. The resistance to inhalation at a flow rate of 85 lpm for these respirators are listed in Table 3.

Calibration data to determine the flow rate through the aliquoter for a given flow rate and corresponding pressure drop through the respirators was presented in Figures 9, 10, 11 and Table 2. It may be noted that the flow rate through the aliquoter is approximately 0.03 to 0.05 per cent of the flow rate through the respirator.

The resistance values presented in Table 3 are in all cases greater than those specified by the AEC Committee on Respiratory Protective Equipment. For "Comfort", the Committee recommended that the maximum resistance to air flow at 85 lpm be; for inhalation, 1.25" H_2O and for exhalation, 0.75" H_2O.

B. Penetration of Aerosol with Respirator Sealed to Face of Manikin

The results of the tests with a variety of respirators sealed to the face of a manikin are summarized in Tables 4 and 5. The first series of tests as indicated in Table 4 was conducted at a steady flow rate through the X No. 3 respirator. The average penetration was approximately 0.25 per cent under the conditions stated above. Using the breather pump set for a flow rate of 36.3 lpm as indicated in Table 5, the penetration of the aerosol through the respirators sealed

Table 3

Resistance to Air Flow (Inhalation) in Respirators

Respirator Manufacturer	Resistance, at 85 Liters/minute	
	Inches of Water	Millimeters of water
X No. 1	2.19	56
X No. 2	2.28	58
X No. 3	2.28	58
Z No. 1	1.33	34
Z No. 2	1.47	37
Z No. 3	1.36	35
Y No. 3	1.88	48

Table 4

Summary of Aerosol Penetration
Through
Respirators on Manikin

Respirator X No. 3	Under Condition of Steady Flow 20 Liters/minute
	Penetration Through Respirator, in Per cent
Test No. 1	0.19
Test No. 2	0.31
Test No. 3	0.24

NOTE: Conditions of Test: Manikin tests were conducted with the respirators sealed to the face of the manikin. In each case the flow rate was 36.3 liters per minute (622 mkg. cam).

Table 5

Summary of Effect of Pulsating Flow
on
Penetration Through Respirator

Respirator Manufacturer	Penetration Through Respirator, in Per Cent
X No. 1	0.089
X No. 1	0.098
X No. 1	0.059
X No. 2	0.240
X No. 2	0.305
X No. 2	0.328
Z No. 1	3.61
Z No. 1	4.53
Z No. 1	4.38
Y No. 3	0.096
Y No. 3	0.098
Y No. 3	0.107

NOTE: Conditions of Test: Manikin tests were conducted with the respirators sealed to the face of the manikin. In each case the flow rate was 36.3 liters per minute (622 mkg. cam).

to the face of the manikin varied considerably with respect to the type of respirator used. The Z respirator which had relatively good air resistance characteristics displayed relatively poor collection characteristics. The X No. 1 which had approximately the most undesirable air resistance characteristics displayed the best collection characteristics of those tested. On the basis of performance and comfort, the Y No. 3 respirator rated the most acceptable under test conditions.

C. Penetration of Aerosol with Respirator on Human Subjects

The results of pulsating flow tests with human subjects wearing the respirators under conditions of sedentary breathing are presented in Table 6. The effects of bad face fitting of the respirator were noted during two tests. Bad face fitting increased the normal penetration by an estimated factor of 10. The Z respirators were, as in the case of the manikin tests, a factor of 10 less effective in the collection of the test aerosol.

Table 6

Summary of Aerosol Penetration
Through
Respirators Worn by Human Subjects

Respirator Manufacturer	Breathing Rate, in Liters/minute	Aerosol Penetration Through Respirator in Per Cent	Comments
X No. 2	15.4	0.163	
X No. 2	24.9	3.49	Poor fit.
X No. 2	20.9	0.211	
X No. 2	14.4	0.352	
Z No. 2	19.2	0.216	
Z No. 1	10.2	2.75	
Z No. 1	10.2	1.23	
Z No. 2	-	37.4	Impossible to fit.

NOTE:
Conditions of Tests: Tests were conducted under conditions of sedentary breathing with respirator fixed tightly to the head.

IV

DEVELOPMENT OF NEW RESPIRATORY PROTECTIVE EQUIPMENT

As indicated in the introduction, the design, development and testing of new respiratory protective equipment is essential to provide more comfort and effectiveness in the proposed use of respirators for highly toxic aerosols. Two approaches in the development of new equipment have been used to achieve the above objective. Both respirator designs, Harvard-AEC Mark I and Mark II are directed at the reduction or elimination of the in-leakage of toxic materials which may occur between the edge of respirator and the face of the wearer.

A. Design of Harvard-AEC Mark I: Semi Full Face Respirator with Filtered Positive Air Supply

The Mark I respirator has been designed to provide a sufficient supply of filtered air to the wearer so that a positive pressure exists in the mask at all times. This design eliminates in-leakage by maintaining at all times a positive pressure within the respirator with respect to the ambient atmosphere. More freedom in filter design is permitted by this approach since air flow resistance is no longer a factor of comfort with the use of a forced filter air supply. The air flow characteristics of the ultra filter used in the X respirator and a special Chalk River canister were evaluated and are presented in Figure 12. The pressure drops across the above filters at 3 cfm, the design flow rate for Mark I are 3.2 and 1.65 inches of H_2O, respectively. The ultra filter pressure drop at the design flow rate would be prohibitive if a forced air supply were not provided.

The supply blower requirements for both the Mark I and Mark II units are:

(1) Weight - 5 to 10 pounds.
(2) Size - convenient size to carry on belt or shoulder harness.
(3) Noise - quiet operation and low vibration.
(4) Power - DC motor drive with disposable battery.
(5) Cost - power cost should be less than 10 ¢ per hour.

The Harvard-ABC Mark I unit design requirements are such that the blower should supply 3 cfm at 1 inch of water resistance. Since a suitable motor-blower set was not commercially available, a unit had to be designed and developed. A centrifugal wheel element appeared to be the most applicable type of air mover for this application. Small light weight DC motors that are suitable for this application were found to be available. Initially, fan designs were fabricated from sheet metal. Since a wide range of designs were considered, it appeared desirable to cast the fan elements in plastic with later machining to the exact design desired. This technique proved quite successful. The sequence of operations that are involved are described below:

1. Fabrication of wood pattern of the basic fan element design.
2. Form mold with Dow Corning Silastic RTV 881 or 882. These materials are silicone rubber potting compounds which cure at room temperature.
3. Cast fan elements using an epoxy resin formulation reinforced with fiberglas cloth. The epoxy resin used in our work was Ren Laminating Mix Resin RP 1710A and Hardener RP 1710A, Ren Plastics, 5322 South Cedar Street, Lansing, Michigan.
4. Conduct required machining on cast fan.

Fabrication of centrifugal fan designs was accelerated by the use of vacuum forming techniques for plastic blower housings and details. A large number of miniature DC motors were tested to determine their suitability in these applications.

The two motor-blower designs that showed the most promise are illustrated in Photograph 3. The Delco #5067043 motor drives a 2½ inch diameter plastic fan. A 2 inch diameter fan is powered by the Cramer PB 8202. Performance data on these fans are presented in Tables 7 and 8, and Figures 13 and 14.

The Delco unit requires a 12 volt battery source with an initial current drain of 400 milliamperes. Two Burgess Model TW1, 6 volt dry batteries are used to power this unit. The service life of the batteries on this application is 16 hours based on a discharge of 4 hours per day. Since the unit cost of these batteries is $1.63 the hourly cost for such operations is approximately 20 cents.

The Cramer unit is powered at 6 volts with an initial current drain of 1000 milliamperes. Two TW1 3 are used because of the high current drain. Based on the same intermittent discharge of 4 hours per day, the service life of such a power pack is approximately 10 hours. The corresponding power cost is 33 cents per hour.

The total weight of the power pack for each unit of the Delco and Cramer models is 6.5 pounds. The over-all dimensions of the battery pack are 5-3/8 x 5-3/4 x 4-15/16 inches. The Delco unit is considered the more desirable unit because of its greater capacity, more efficient operation and longer battery life.

Plastic models and metallic forms of the Mark I and Mark II respirators are shown in Photographs 4 and 5. The Mark I models are on the left-hand side of the photographs. A schematic diagram of the complete Mark I and Mark II units is presented in Figure 15.

B. Design of Harvard-AEC Mark II: Positive Edge Seal Respirator with Supplementary Supply

The above Cramer unit is being modified to supply 1 cfm at 1 inch of water on a 3 volt system. It is believed that with these lower requirements, a compact, light weight unit with relatively low power costs can be achieved.

At the present time, a positive displacement blower is being developed for both Mark I and Mark II applications. The efficiency of this unit should be much higher than the efficiency obtained with the centrifugal fans.

Table 7

Blower Performance Test, Cramer PB 820Z, Wheel #2

Setup	Total Head, "H_2O	Static	Velocity	Power Consumption E_{VDC}	I_{ma}	Speed RPM	Q CFM	Shaft Hp	Air Hp	Mechanical Efficiency Per Cent
Blocked Entry	1.35	1.35	0	5.4	980	9300	0	.0021	0	0
Direct to Balloon	.4	.40	.05	5.2	1100	6750	4.55	.0023	.00032	14.0
Direct to Spirometer	.58	.55	.03	5.0	1090	7300	3.44	.0022	.00031	14.3
Orifice A	.91	.90	.01	5.0	1050	7800	2.0	.0021	.00029	13.8
Orifice B	1.20	1.20	0	5.0	980	8750	.51	.0020	.00009	4.5

Where: (1) Total head = static head + velocity head
Max. Q of 2 cfm in 1 inch diameter pipe $h_v = .01$

(2) Shaft hp = $\frac{30(E \times I)}{746}$ $\quad E = \frac{\text{Output}}{\text{Input}} = \frac{2\pi \ TN}{\frac{33,000}{\frac{EI}{746}}}$ = 27 per cent

E motor = 30 per cent

From data sheet .25 oz-in., .24 z, 26 v, 9000 rpm

(3) Air hp = $\frac{QHt}{6350}$

(4) Mechanical efficiency blower = $\frac{\text{Air Hp}}{\text{Shaft Hp}}$

Table 8

Blower Performance Test, Delco #5067043, Wheel #6
12 V Operation

Setup	H_t. "H_2O	Power Consumption E_{VDC}	Power Consumption I_{ma}	Speed RPM	Q CFM	Shaft Hp	Air Hp	Mechanical Efficiency Per Cent
Blocked Entry	1.9	11.3	340	8400	0	.00206	0	0
Direct to Balloon	.62	11.3	480	6950	6.5	.00291	.000635	21.8
Direct to Spirometer	.82	11.3	460	7250	5.0	.00279	.000646	23.2
Orifice A	1.48	11.3	400	7850	2.90	.00243	.000676	27.8
Orifice B	1.72	11.3	340	8200	.75	.00206	.000203	9.9

Where: (1) Shaft Hp = $\frac{.40\ (E \times I)}{746}$

(2) Air Hp = $\frac{Q\ Ht}{6350}$

(3) Mechanical Efficiency Fan = $\frac{\text{Air Hp}}{\text{Shaft Hp}}$

COORDINATION OF RESEARCH EFFORTS WITH MUTUALLY INTERESTED AGENCIES

In December 1959, Mr. J. J. Fitzgerald visited the Health and Safety Activity, Bureau of Mines, to review the classical techniques of respirator testing and evaluation, and to present the proposed uranine aerosol generation and sampling techniques developed for the Harvard University study. Mr. Perzak of the Bureau of Mines visited this laboratory during the week of February 7, 1960 and reviewed the respirator evaluation technique. A later follow-up visit was made by Messrs. Pearce, Watson, and Perzak on May 4, 1960 to obtain additional information to determine if the Bureau would adopt the evaluation procedure.

Mr. J. J. Fitzgerald visited the University of Rochester in December, 1959 and reviewed the respiratory protection problems at this site with Mr. R. Wilson. In a later discussion with Dr. J. N. Stannard and Mr. R. Wilson, attention was given available respiratory protection, influence of particle size on respirator efficiency, and the bio-assay-exposure relationship in a work population wearing respirators.

An initial proposal of this project, the conduct of in-plant evaluation of respirators during normal operations, was discussed on several occasions with Mr. H. Schulte, Los Alamos Scientific Laboratory. The designed portability of the present sampling equipment will permit on-site testing with minimal interference to the subject. A packaged unit for AEC site use in testing respirator usage is to be constructed and it is hoped that the first application will be made by August, 1960.

Mr. Neil, Chalk River, visited Harvard University on other matters and at this time we briefly discussed the evaluation program and the features of advanced respirator design. A follow-up visit was made by Mr. Leslie Silverman and Mr. J. J. Fitzgerald. At that time we obtained a Chalk River respirator to evaluate at Harvard.

VI

RESEARCH IN PROGRESS AND FUTURE PLANS

The efficiency of the MSA, Airline Respirator at flow rates of 1 to 4 cfm is being determined under sedentary and working conditions using the manikin and human studies. The results of the tests to date are included in Table 9.

From the data presented in Table 9, the following comments can be made.

1. Under working conditions, an air supply of at least 4 cfm is required to keep the degree of penetration less than 1 per cent.

2. Under inhalation conditions of approximately 36 liters per minute the penetration can be maintained at levels less than 0.03 per cent.

3. The intake of material with an air supply of 4 cfm was increased by a factor of approximately 2.5 when conditions were changed from sedentary to 4500 ft. lbs. per minute. All other conditions were held constant.

4. The reduction in penetration as a function of air supply using the same subject in each case could be expressed as an exponential function.

Additional data will be collected to determine the relationship between the supply air flow rate and the degree of penetration under various conditions of use.

Future plans involve the use of the sampling system in operational areas. Discussions have been held with operational personnel to achieve this goal.

The new respiratory protective equipment described in Section IV will be tested in the laboratory and under operational conditions.

Table 9

Penetration of Airline Respirators at Various Supply Volumes

Supply Air CFM	Sedentary Conditions				Working Conditions (4500 ft. lbs/min)	
	Run #	Manikin % Penet.	Subject	Humans % Penet.	Manikin % Penet.	Humans % Penet.
1	1	0.0025	A	0.091	-	-
	2	0.00645				
2	1	0.0220	A	0.0179		
	2	0.0118	B	0.030		
	3	0.0069	C	0.0115		
3	1	0.00595	A	0.00404	3.97	Not enough supply air.
	2	0.00363			3.12	
4		-	D	0.0127	2.58	0.0309
						0.0082
						0.0259

APPENDIX I

AEC COMMITTEE ON RESPIRATORY PROTECTIVE EQUIPMENT

REPORT OF THE SUB-COMMITTEE ON REQUIREMENTS

REQUIREMENTS FOR RESPIRATORY PROTECTIVE EQUIPMENT FOR USE AS PROTECTION AGAINST ATMOSPHERES CONTAINING SIGNIFICANTLY MORE TOXIC THAN LEAD PARTICULATES*

The Atomic Energy Commission Committee on Respiratory Protective Equipment has herein synthesized certain objective requirements for respiratory protective devices to assist users, vendors, and manufacturers in understanding what characteristics and features are desired in such equipment to most fully meet customer requirements for safe, comfortable, and functional equipment. The specifications that follow do not set forth the complete requirements for the respiratory protective devices included but are intended to accentuate certain features that warrant special consideration. These specifications represent the considered opinions of 23 AEC contractors, based on their experiences with such equipment.

I. MASKS AND RESPIRATORS - MECHANICAL FILTER AND CHEMICAL ADSORBANT

A. FULL-FACE MASKS

1. Performance(1): Over-all penetration(2) of the device shall be less than 0.10%. Any specific device (or a size series thereof) shall provide fits that will assure no greater than the stated penetration for at least 95% of the wearers, regardless of race or sex. The 5% not achieving the stated protection shall be identified by some measurable facial or personality criterion.

2. Comfort:

a. Maximum resistance to airflow, at 85 liters per minute; inhalation = 1.25" H_2O, exhalation = 0.75" H_2O.

b. Maximum weight of complete facepiece, including cartridges, etc. = 1.25 lbs. Center of gravity should be as close to the face as possible to minimize neck fatigue.

c. Device should be capable of being worn for two 4-hour periods daily without objectionable discomfort, such as "pain spots," etc.

d. Cartridges, canisters and other projections should be so located that, for 90% or more of the wearers, unrestricted freedom of head movement is provided.

e. The face-piece should incorporate a "chin-cup" to minimize movement of the mask.

f. The device should incorporate features that will permit utilization of corrective or protective spectacles without increasing penetration beyond the permissible maximum or adversely affecting the other stated criteria.

*The following specifications pertain to the components of the respiratory equipment that actually provide respiratory protection; viz., mask and respirator facepieces, etc., but do not include the requirements for supplementary components such as bottled gas supplies, air-supply piping systems, pumps, etc.

3. Vision:

a. Use of the device should not restrict normal binocular vision more than 30%, based on tests on several representative individuals.

b. Lens, for beta radiation protection, should have a minimum density of 500 mg/cm^2.

c. The lens should meet approved standards for safety lens material issued by the National Safety Council.

d. Air inlets should minimize lens fogging.

4. Exhalation and Inhalation Valves:

Check valves shall be present at the inlet and outlet ports.

5. Decontamination:

a. Device must be capable of being decontaminated 50 times by being washed in mild soap for 15 minutes at 120°F and sterilized without functional impairment.

b. The device should be capable of being completely disassembled and assembled using a minimum of common hand tools or special tools provided by the manufacturer.

c. The device should have a smooth interior and exterior finish, incorporating design features which eliminate cracks, wrinkles, pits and overlapping parts. Canvas or other absorbant materials should not be used.

6. Standardization: Where possible, facepiece components should be standardized to permit interchangeable use of filters, cartridges, canisters or supplied air.

B. RESPIRATORS AND HALF-MASKS

1. Performance:(1) Over-all penetration(2) of the device shall be less than 1.0%. Any specific device (or a size series thereof) shall provide fits that will assure no greater than the stated penetration for at least 95% of the wearers, regardless of race or sex. The 5% not achieving the stated protection shall be identified by some measurable facial or personality criterion.

2. Comfort:

a. Maximum resistance to airflow, at 85 liters per minute; inhalation = 1.25" H_2O, exhalation = 0.75" H_2O.

b. Device should be capable of being worn for two 4-hour periods daily without objectionable discomfort, such as "pain spots," etc.

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(1) Based on tests performed with a gas and/or a standardized homogeneous particulate aerosol in the size range 0.1 μ - 0.5 μ diameter and with pulsating airflows.
(2) Over-all penetration implies the combined penetration from all sources such as the filter medium, face seal leakage, leakage by valves, speaking diaphrams, etc.

c. Cartridges, canisters, and other projections should be so located that, for 90% or more the the wearers, unrestricted freedom of head movement is provided.

d. The device should incorporate features that will permit utilisation of corrective or protective spectacles without increasing penetration beyond the permissible maximum or adversely affecting the other stated criteria.

3. Exhalation and Inhalation Valves: Check valves shall be present at the inlet and outlet ports.

4. Decontamination:

a. Device must be capable of being decontaminated 50 times by being washed in mild soap for 15 minutes at 120°F and sterilized without functional impairment.

b. The device should be capable of being completely disassembled and assembled using a minimum of common hand tools or special tools provided by the manufacturer.

c. The device should have a smooth interior and exterior finish, incorporating design features which eliminate cracks, wrinkles, pits and overlapping parts. Canvas or other absorbant materials should not be used.

5. Standardisation: Where possible, facepiece components should be standardised to permit interchangeable use of filters, cartridges, canisters or supplied air.

APPENDIX II

QUALITATIVE EVALUATION OF FACE SEAL LEAKAGE

The total penetration resulting from all avenues of entry, as well as the periphery only, of a contaminant into the respirator void is defined by the procedure described in this report. It is reasonable to accept the concept that a major portion of the total penetration will be leakage at the face seal. For this reason qualitative odor or sensory tests of respirator fit (exposure to isoamyl acetate, ammonia, phosgene) have been the primary methods for evaluating gross respirator penetration. This type of test does not, however, give reliable and reproducible assessment of actual leaking. In this study attention has been given to more definitive methods of evaluating gross facial seal.

A number of techniques, all briefly described below, have been utilized for determining facial seal in addition to the quantitative approaches already described in this report.

1. The subject wearing the test respirator inspires, the inlet is blanked off and the subject holds his breath. The initial static suction is noted and a suction versus time plot is obtained. Rapid decay of suction indicates face seal leakage, presuming the balance of the respirator has integrity. The major drawbacks to this technique are the reliance on the subject to cooperate and quantitative assessment is difficult because excess resistances are created.

2. Aerosol dispensing cans of Zyglo Penetrex Penetrant (Magnaflux Corporation, New York 36, N.Y.) produces particles readily visible in an ultra-violet lamp irradiation. This aerosol is applied around the mask as worn by the subject. After the respirator is removed the subject is removed to a dark room and the seal area is fluoresced with a suitable ultra-violet light source. If the facial seal is satisfactory, a discrete parting line will be noted as in the Bureau of

Mines coal dust procedure. If leakage occurs, fluorescence is noted inside the facial seal boundary. This test is felt to be more convenient and certainly more discriminating than the early coal dust technique.

3. Freon gas is fed to the seal area with a probe and the presence of Freon is sensed in the respirator cavity by sampling at the exhalation valve with a General Electric Type H-2 Leak Detector. In this test the respirator must be filled with a charcoal canister to remove the Freon from the primary air.

4. The Bureau of Mines DOP test consists of exposure to a dioctyl pthalate (DOP) liquid aerosol. Prefiltered air is fed through a supply port to the respirator. Exhaust air from the respirator is monitored for the presence of the contaminant. This test requires modification of the respirator and involves the use of a liquid aerosol.

LITERATURE CITED

1. OSRD No. 1222 - Inspiratory Air Flow Measurements on Human Subjects with and without Resistance, dated January 1, 1943; by Silverman, Lee, Lee, Drinker and Carpenter.

2. OSRD No. 1864 - The Characteristics of Inspiratory and Expiratory Valves, dated August 1, 1943; by Silverman, Lee and Lee.

3. OSRD No. 3526 - Inspiratory Resistance of U. S. Army C. W. S. Gas Masks with Static and with Dynamic Air Flow, dated March 15, 1944; by Silverman and Lee.

4. OSRD No. 4229 - End Point Breathing Rate Studies, dated August 1, 1944; by Silverman, Lee, Lee, Brouha, Lt. Whittenberger (MC), Lt. Stiff (CWS), Byrne, Jr., and Smith.

5. OSRD No. 5338 - A Portable Instrument for Measuring Respiratory Air Flows under Field Conditions, dated June 1, 1945; by Silverman Plotkin, Lee, and Smith.

6. OSRD No. 5339 - A Study and an Evaluation of Inspiratory and Expiratory Resistances for Protective Respiratory Equipment, dated May 1, 1945; by Silverman, Lee, Yancey, Amory, Barney and Lee.

7. OSRD No. 5496 - Measurements of Inspiratory Air Flow on Soldiers Performing Various Field Operations, dated July 1, 1945; by Silverman, Plotkin and Lee.

8. OSRD No. 5732 - Inspiratory and Expiratory Air Flow Measurements on Human Subjects with and without Resistance at Several Work Rates, dated August 1, 1945; by Silverman, Lee, Plotkin, Amory and Yancey.

9. Wilson, M. E. and Harrod, D. C.: Development of Mechanical Breather for Evaluation of Respiratory Equipment, AMA Archives of Industrial Health:561-566, 1956.

10. Jordan, H. S.: The Effect of Pulsating Stream Flow on the Efficiency of Filtration by a Fibrous Mat. M.E. Dissertation, Harvard University (1958).

11. Robinson, E., MacLeod, J. A. and Lapple, C. E.: A Meteorological Tracer Technique Using Uranine Dye, J. Meteor. 16:63, 1959.

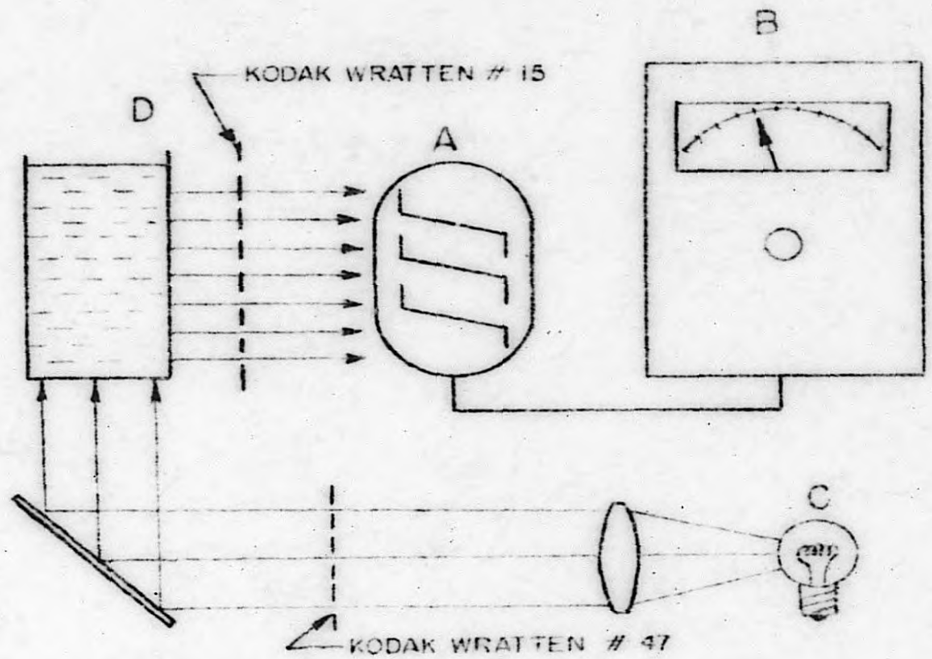
12. Goodman, L. S. and Gilman, A.: The Pharmacological Basis of Therapeutics, The MacMillan Co., New York, 1955.

13. Palmer, F. and Kingsbury, S. S.: Particle Size in Nebulized Aerosols, Am. J. Pharm. 124:112, April, 1952.

14. Silverman, Leslie, et al: United States, Patent No. 2,738,669 (1952).

15. Silverman, Leslie: United States, Patent No. 2,742,897 (1954).

FIGURE I - ANALYSIS OF URANINE IN SAMPLE



FLUORESCENCE OF URANINE SOLUTIONS VS. URANINE CONCENTRATIONS

(LOG. SCALES)

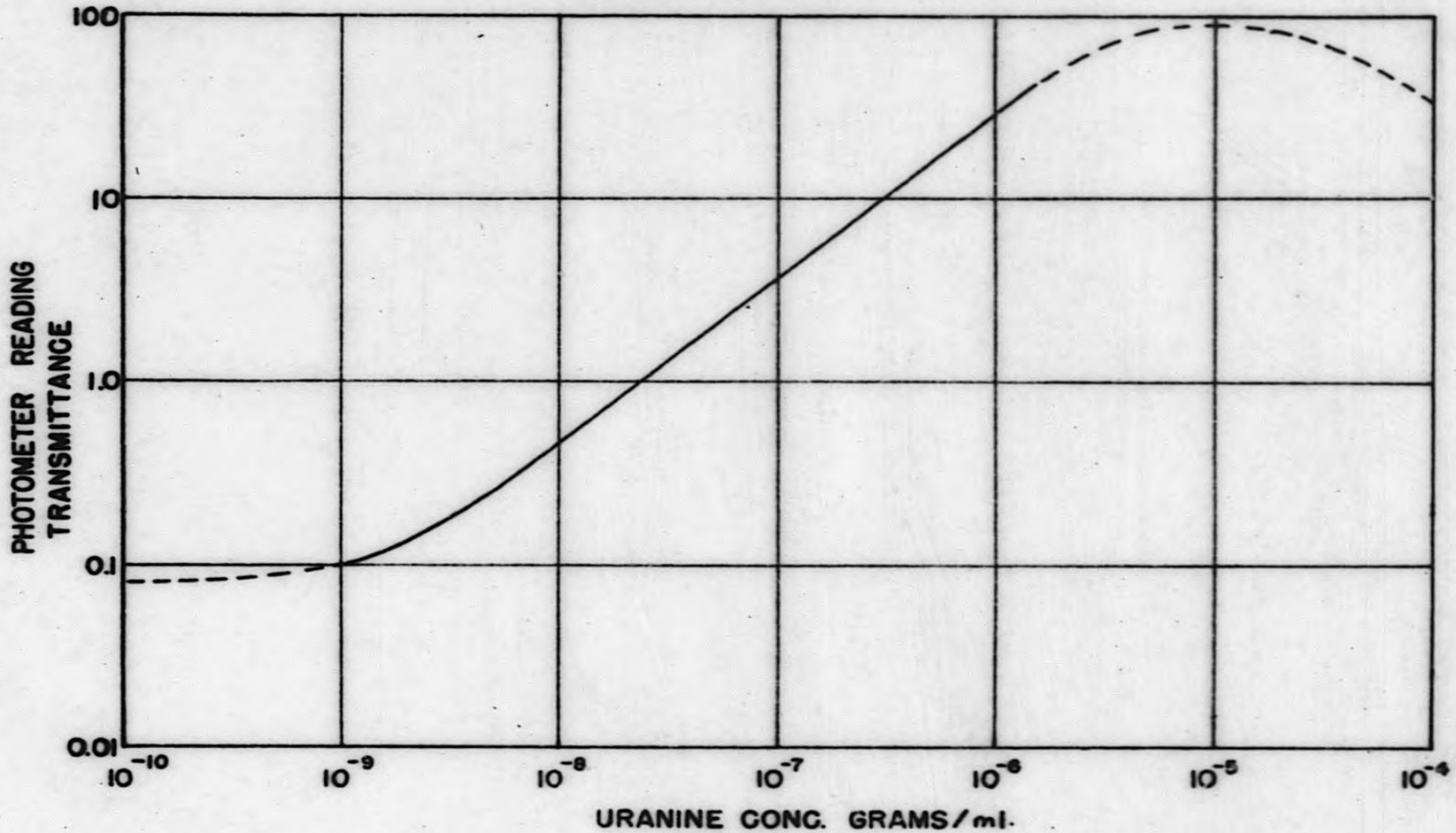


FIGURE 2

AEROSOL SIZE DISTRIBUTION CURVE IN THE HELMET
2.35% URANINE, 2 G-S IMPINGERS

$M_g = 0.20\mu$ $\sigma = 2.4$ $M_g' = 2.06\mu$

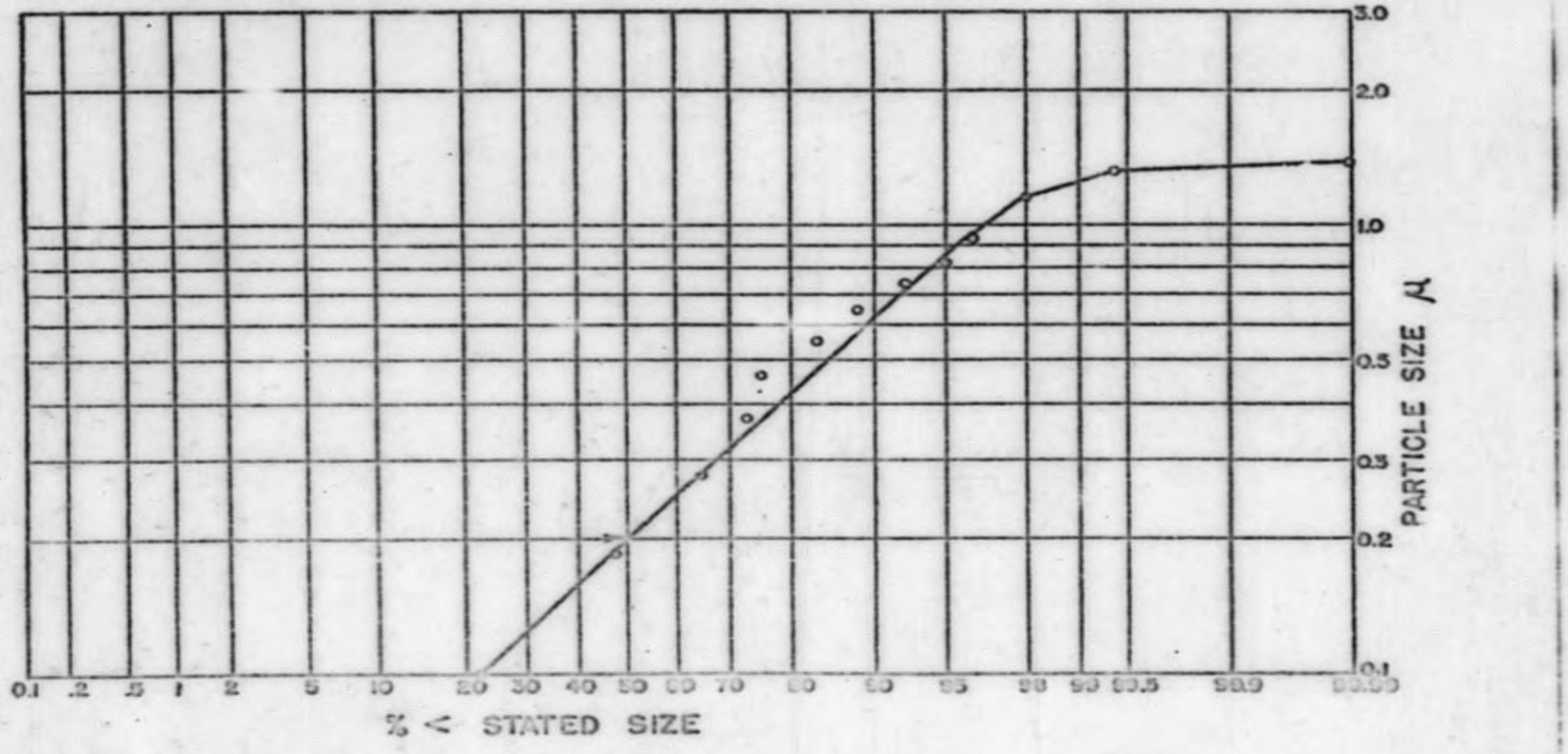
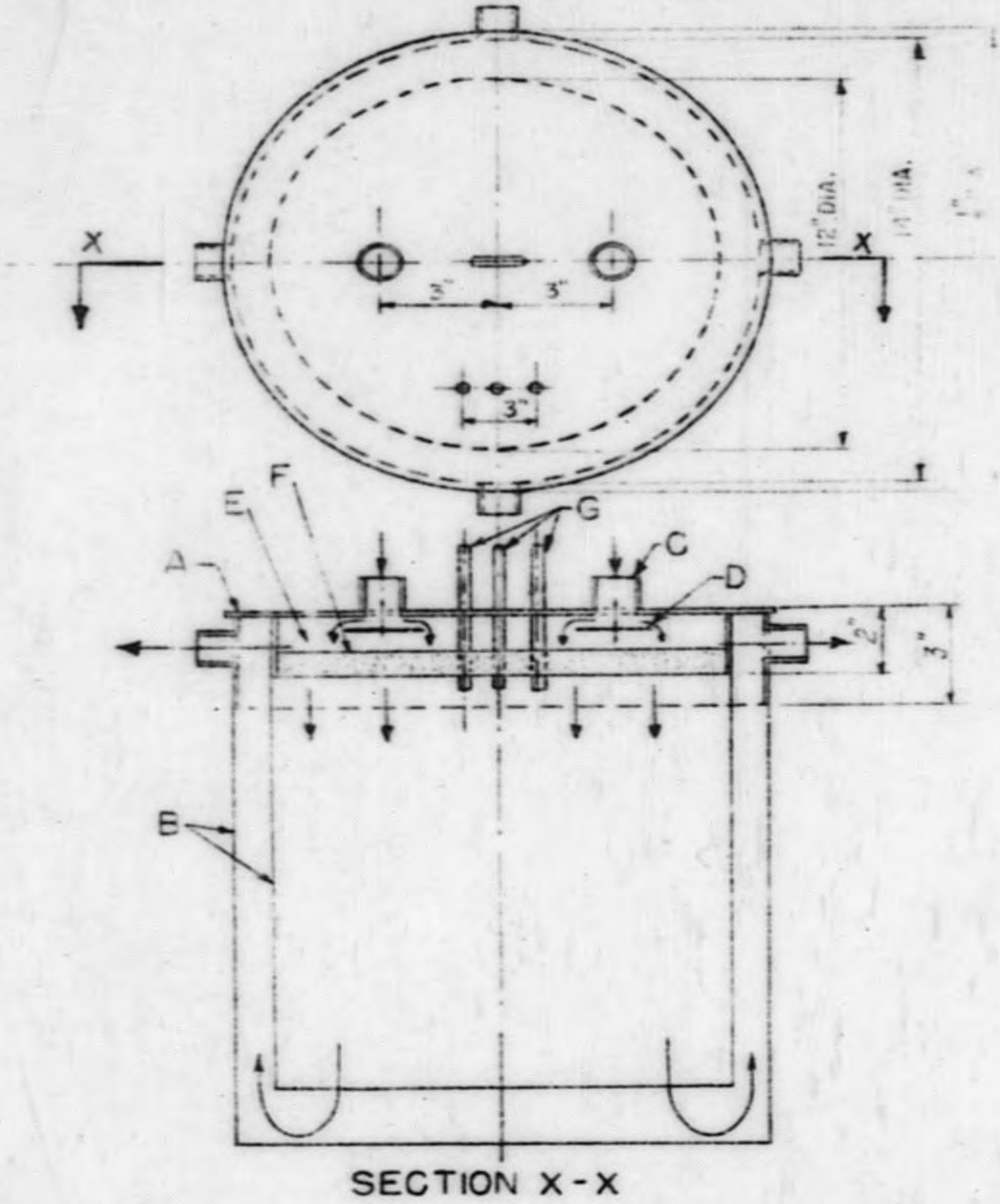


FIGURE 3

FIGURE 4 – EXPOSURE CHAMBER



SECTION X-X

FIGURE 5 - SAMPLE HOLDER

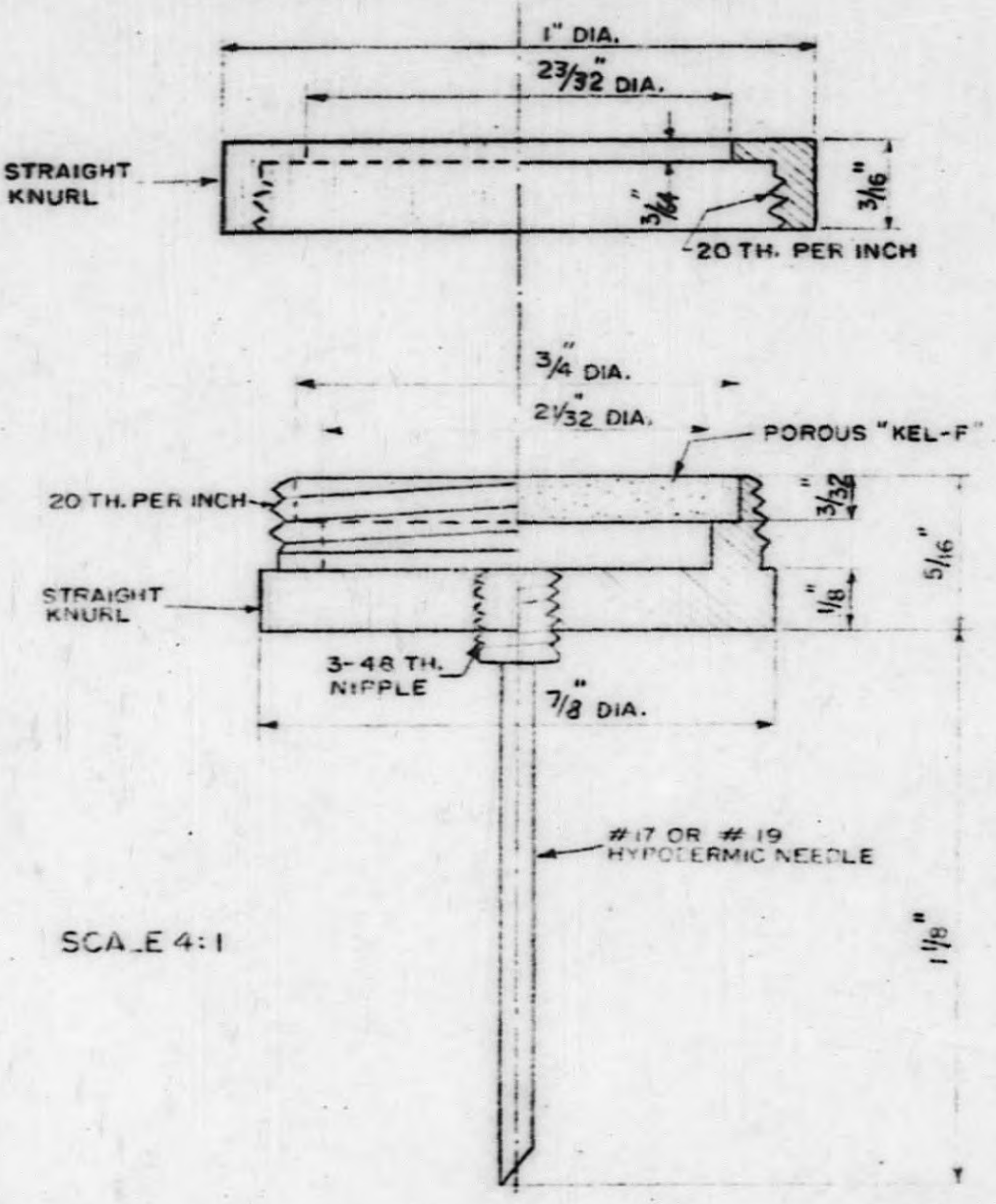
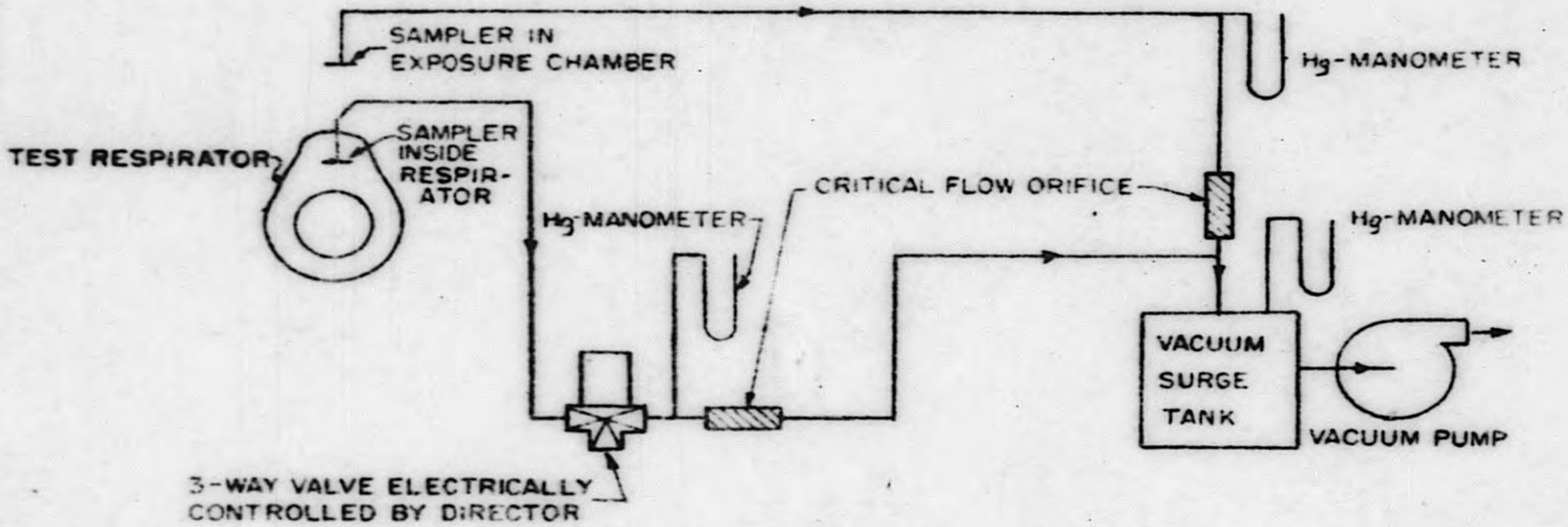


FIGURE 6 - AEROSOL SAMPLING SYSTEM



CALIBRATION OF HELMET SAMPLER ORIFICE VS. UPSTREAM PRESSURE

$P_2 < 0.53 P_1$ $\quad Q = 1.805 + 0.0625 P_1$

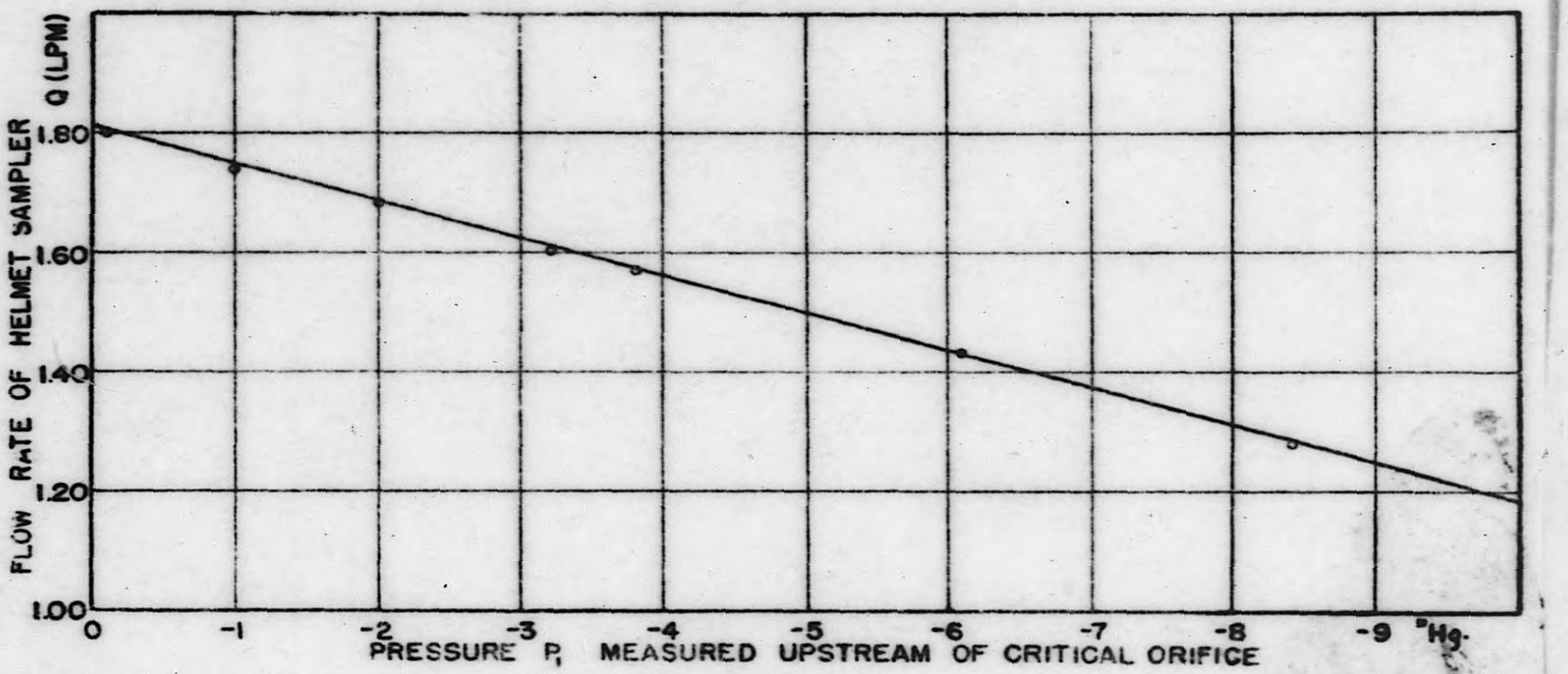


FIGURE 7

FIGURE 8- INSPIRATORY AIR FLOW VOLUME INDICATOR

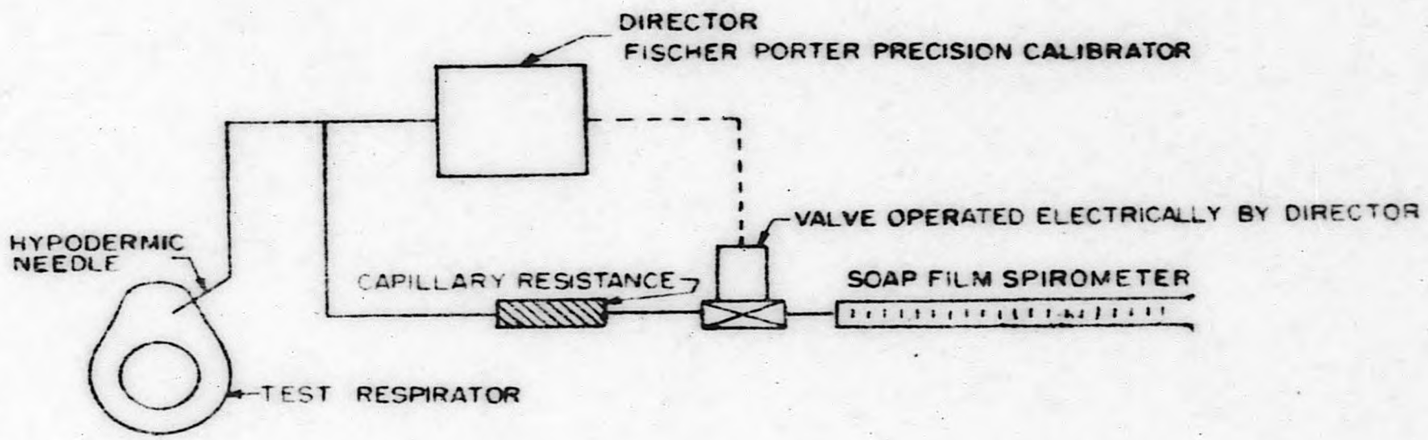


FIGURE 9 - ALIQUOTER CALIBRATION, X No.1 RESPIRATOR

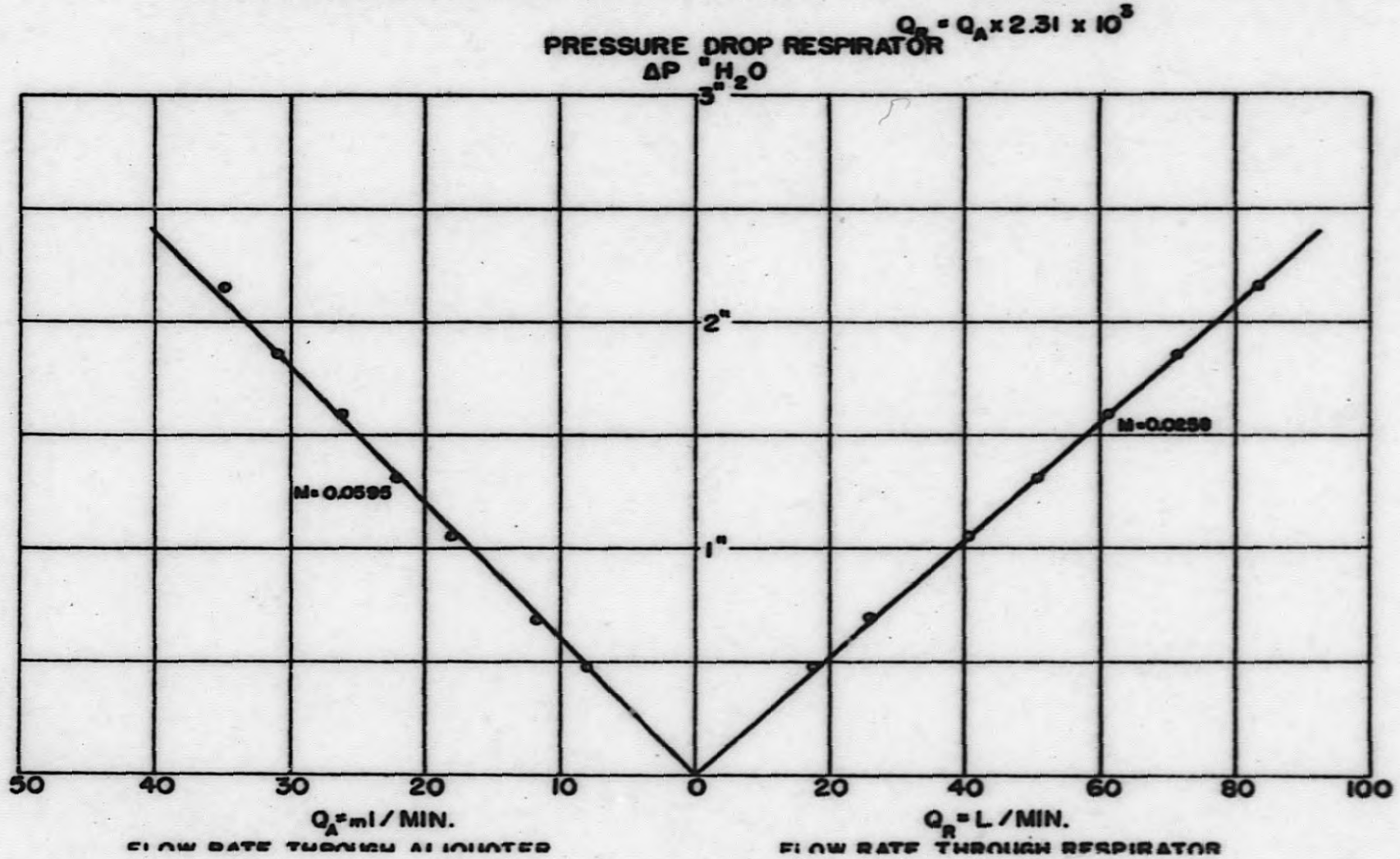


FIGURE 10 - ALIQUOTER CALIBRATION, Z No.1 RESPIRATOR

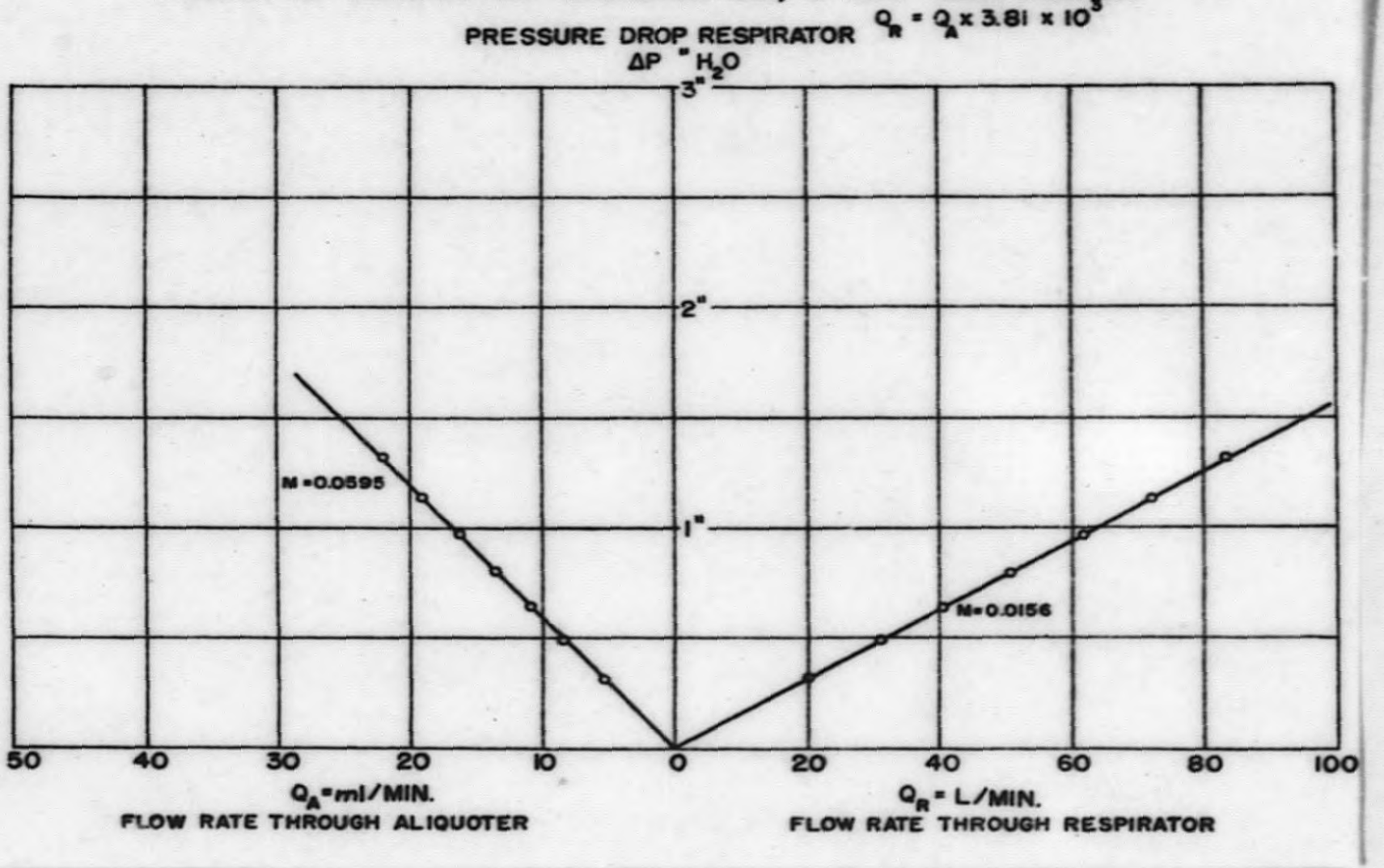
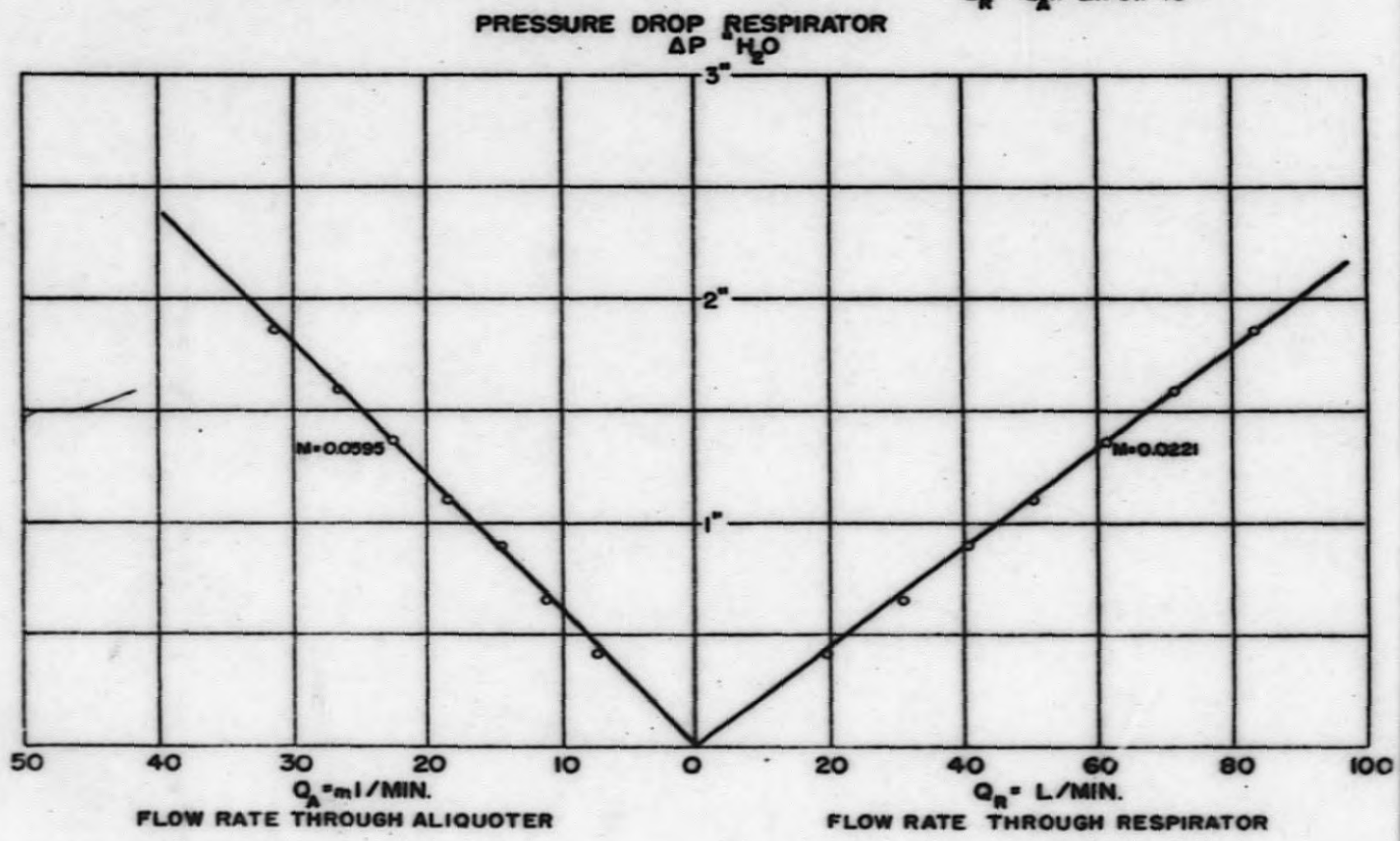


FIGURE II–ALIQUOTER CALIBRATION, Y No.1 RESPIRATOR

$Q_R = Q_A \times 2.70 \times 10^3$



PRESSURE DROP ΔP VS. FLOW RATE Q FIGURE 12
FOR A) MSA ULTRA FILTER CR 73927 C
B) CHALK RIVER CANISTER

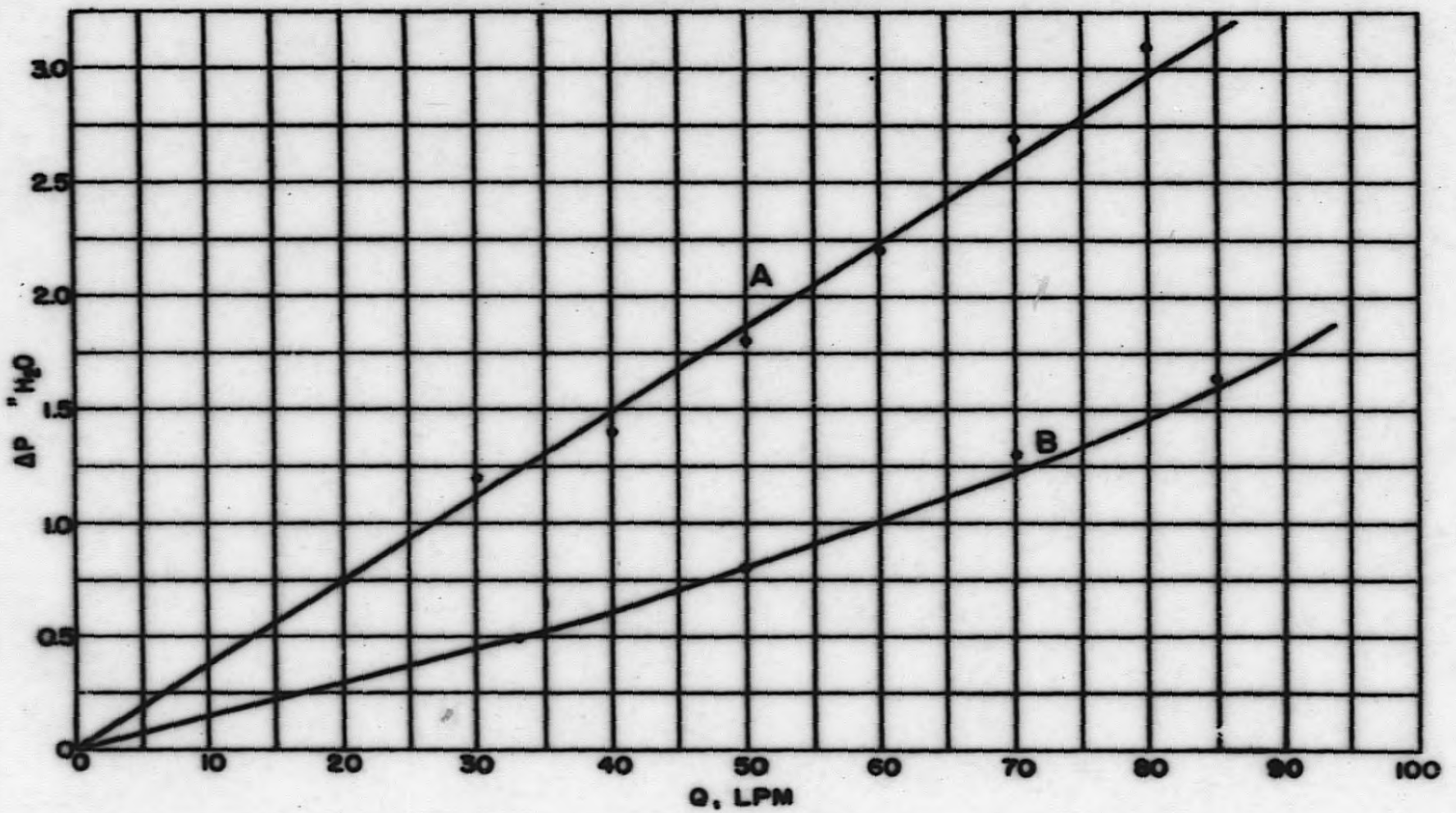
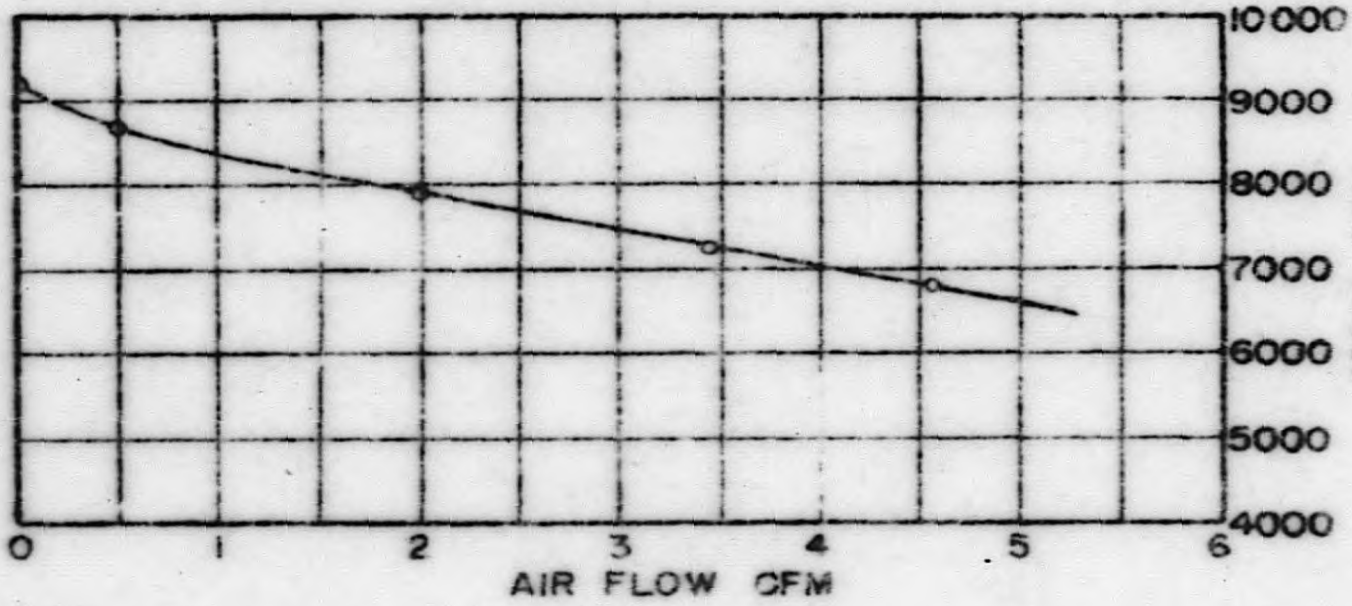


FIGURE 13
BLOWER PERFORMANCE
CRAMER PB 820 Z,
WHEEL # 2



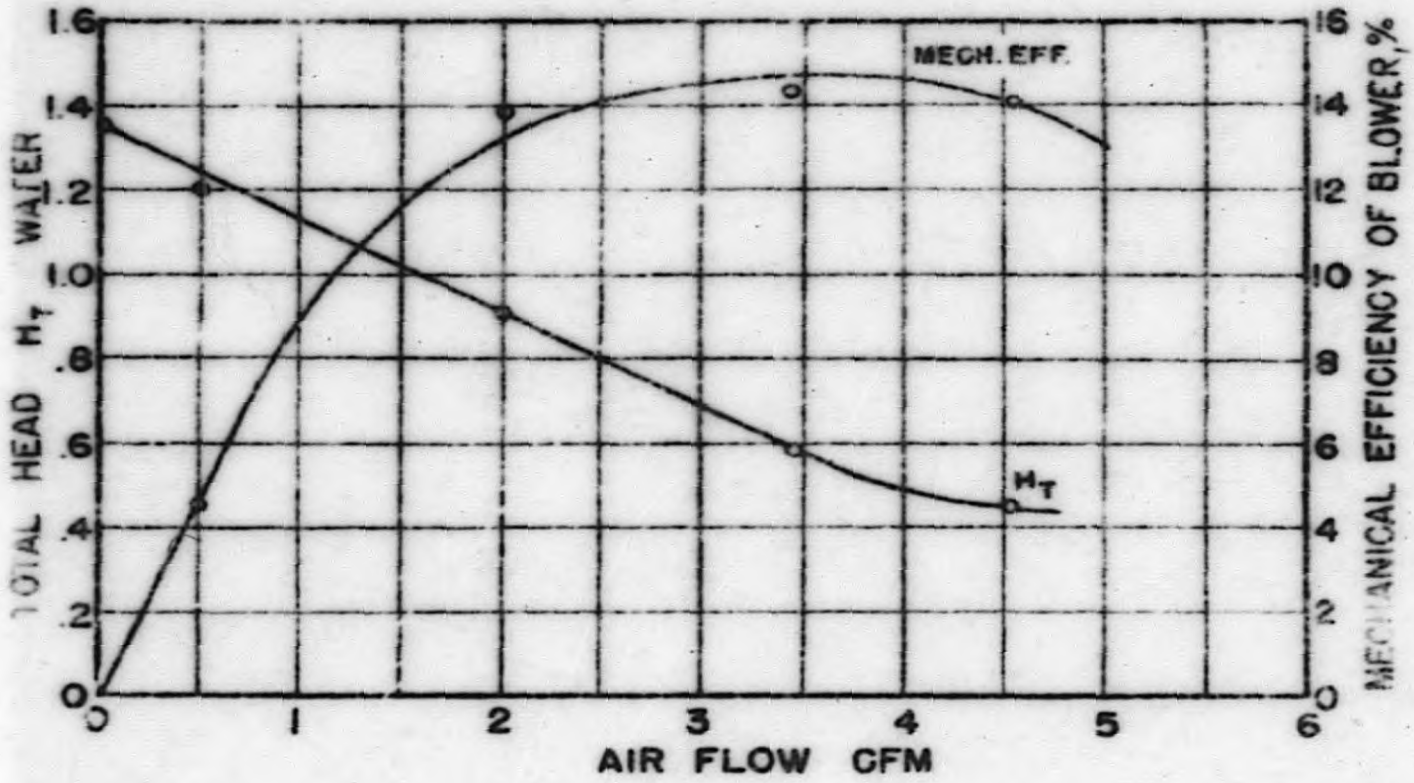
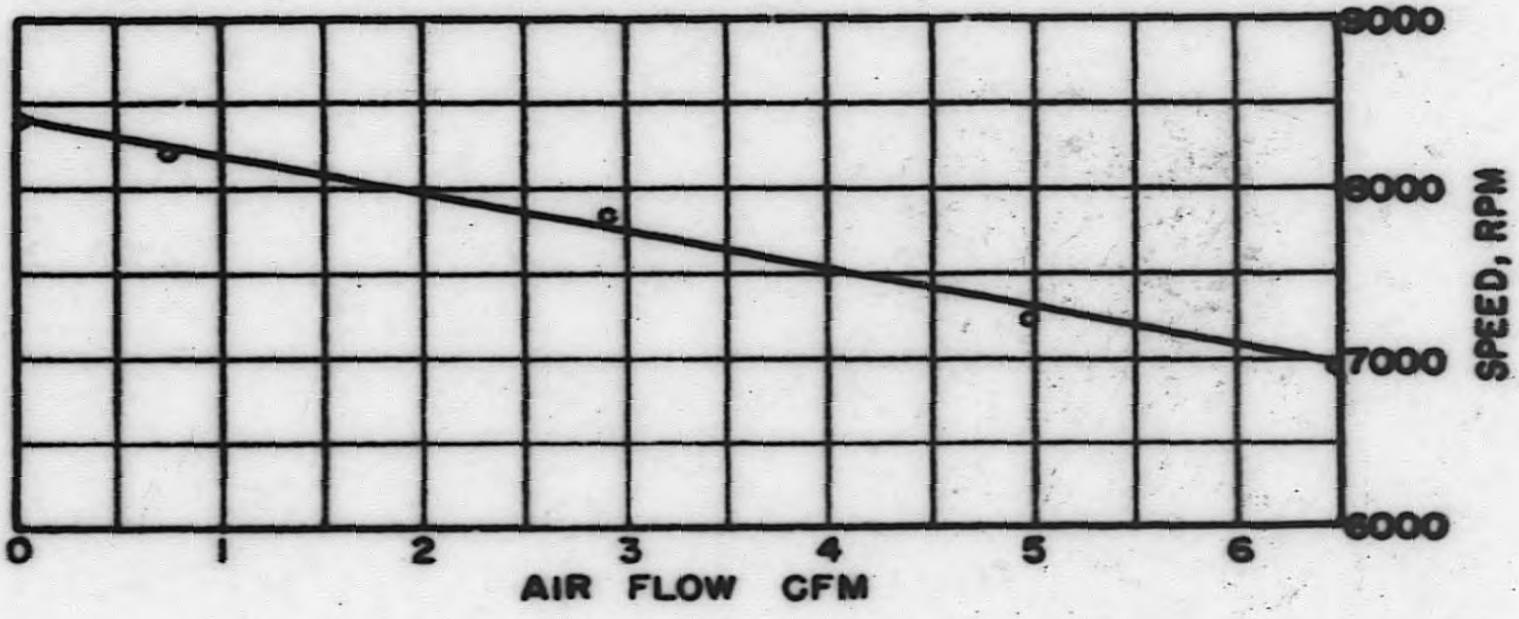


FIGURE 14
BLOWER PERFORMANCE
DELCO # 5067043



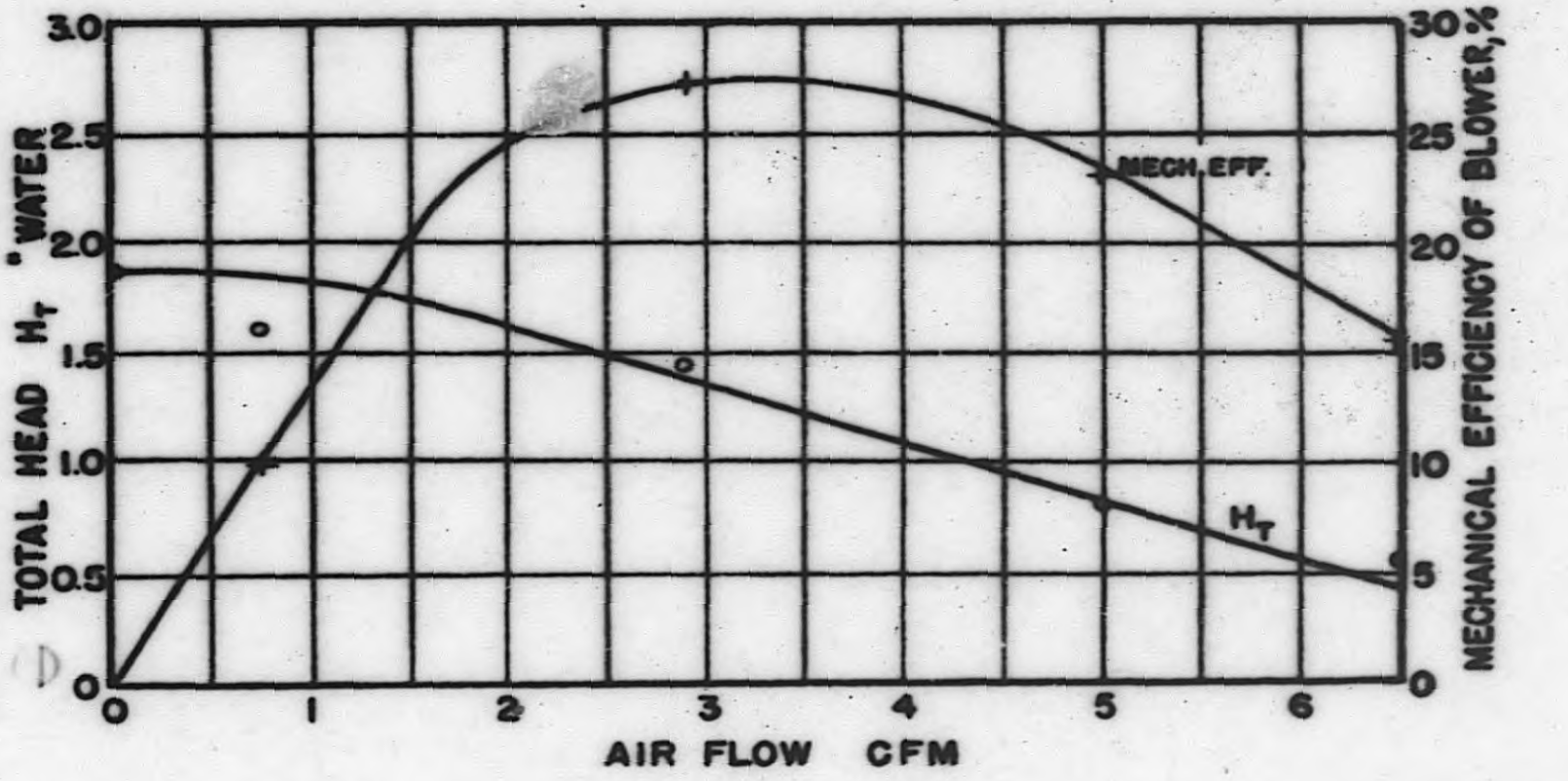
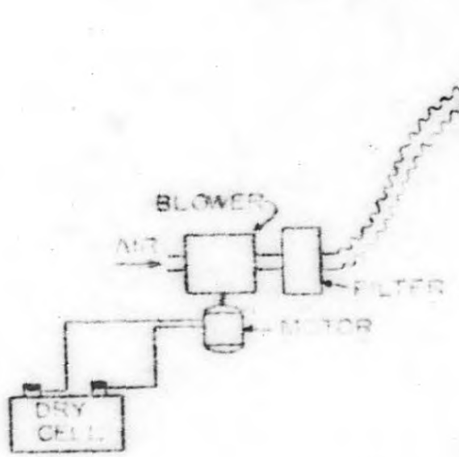
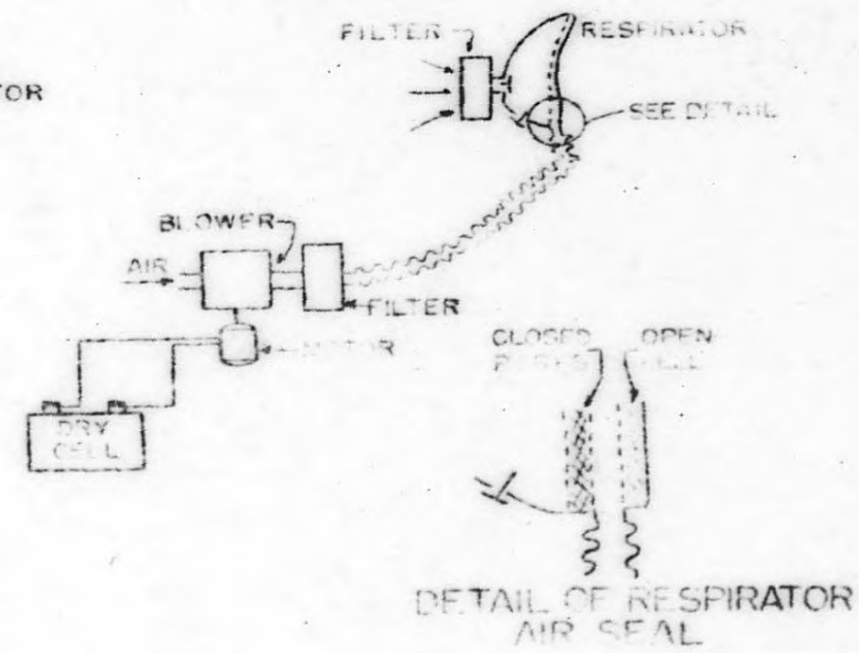


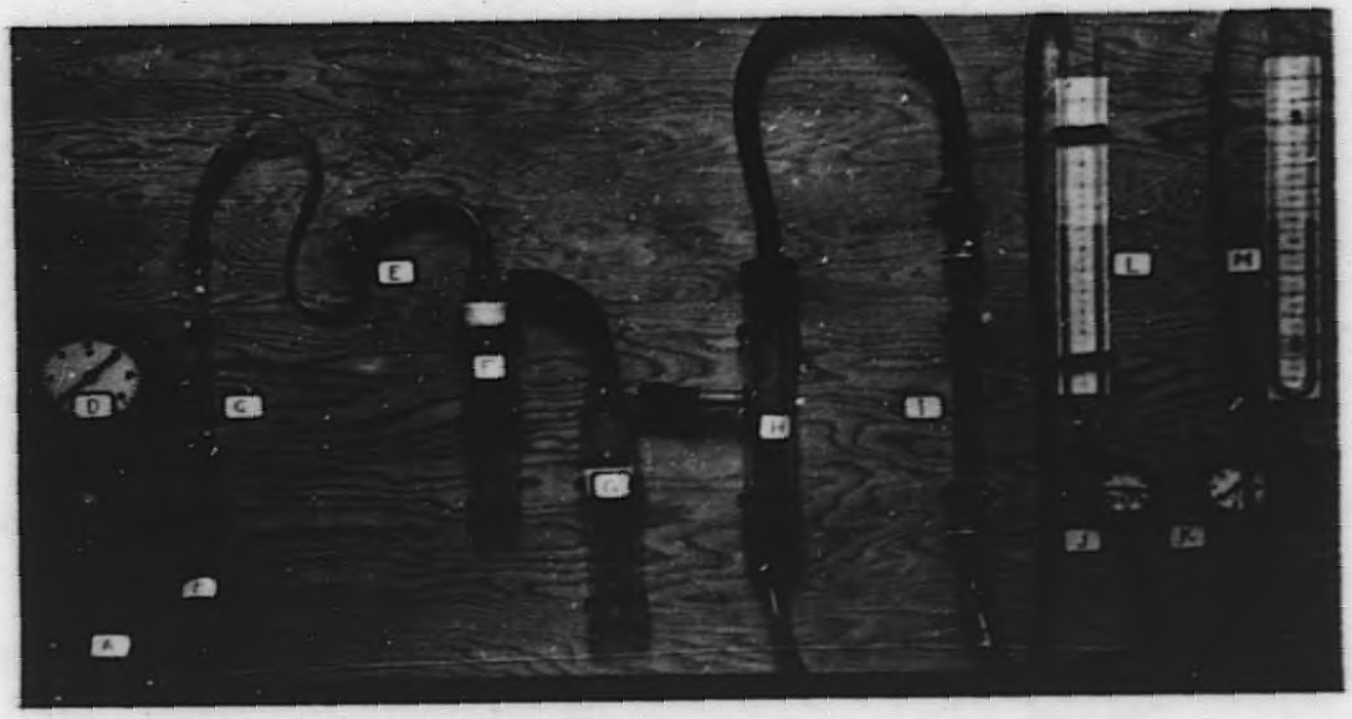
FIGURE 15
RESPIRATOR DESIGN

MARK I

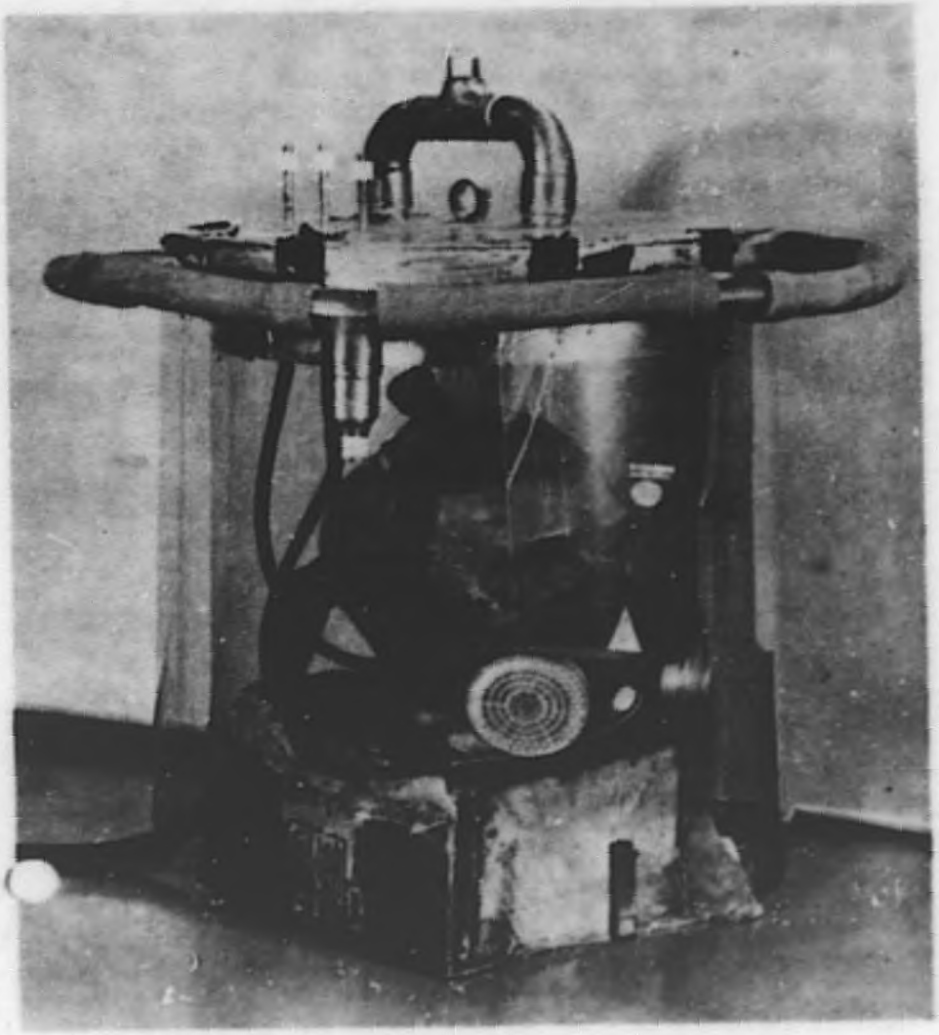


MARK II





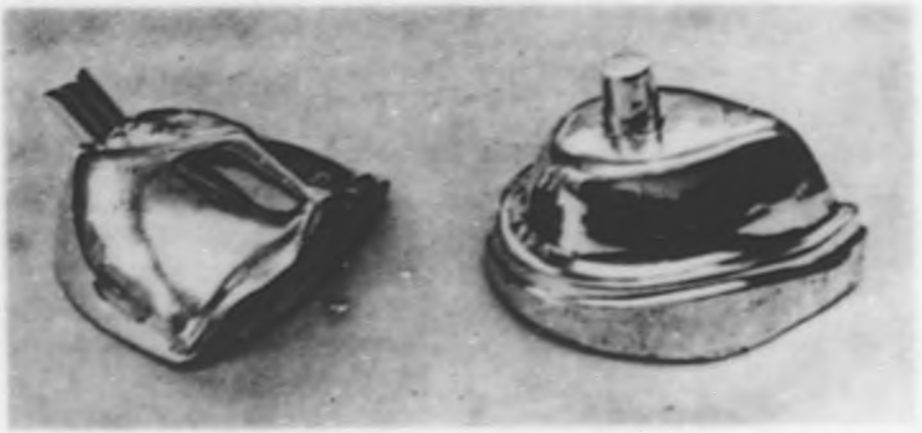
PHOTOGRAPH 1.
Aerosol generating system



PHOTOGRAPH 2. Exposure chamber

PHOTOGRAPH 3. **Delco and Cramer supply units**

PHOTOGRAPH 4. **Models of Harvard-AEC Mark I and Mark II respirators**



PHOTOGRAPH 5. **Metallic vacuum forming molds for Harvard-AEC Mark I and Mark II respirators**