AN EVALUATION OF VACUUM EQUIPMENT
FOR COLLECTION OF ASBESTOS WASTE

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DISCLAIMER

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ABSTRACT

Nine industrial vacuum cleaners, suitable for the collection of asbestos waste, were evaluated and tested for the amount of asbestos fiber concentration in the exhausted air and the effects of increasing capacity on vacuum cleaner performance. An extensive work practice evaluation was performed on the units. Also, a comparison of three asbestos fiber counting methods (NIOSH Approved Method, Fibrous Aerosol Monitor, and Concentration Method) was conducted using one of the vacuum cleaners. The evaluation of the performance of three of the units was done using isokinetic sampling. The result of this research is the first step in establishing performance standards for industrial vacuum cleaners to be used in the collection of asbestos waste.

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I. INTRODUCTION

A. BACKGROUND OF THE RESEARCH

This research project evolved from the increasing national interest in asbestos as a health hazard. Asbestos has been widely used in American products principally due to its heat dissipative properties. The hazard to health occurs both in manufacture and use of the product.

Any casual reader of the popular press has learned of asbestos hazards in the school classroom where the material has been used as an ingredient in ceiling finishes. The gradual shedding of asbestos fibers from these ceiling surfaces was discovered and measured at significantly high levels in a few instances, while most levels were quite low. However, the threat to the health of school children in America comes closest to the heart and emotion of the public. An alarm of this type could send the Nation into a frenzy of replacing school ceilings.

The hazard of asbestos, however, is more pronounced in the industrial setting. Asbestos fibers are finely divided and are easily carried in the breathing air of unprotected workers. Early accounts of manufacturing processes suggest concentrations so heavy that one could not see across the width of a manufacturing building. Even in modern facilities, inspection by the naked eye reveals accumulation of fiber on structural members supporting the roof of the manufacturing plant. While in such plants the air appears clean of fiber, the accumulation of dust warns that the hazard is still present.

Unfortunately, hazardous levels of asbestos are invisible to the eye. Furthermore, the hazard is not discernable by any of the human senses and the typical diseased worker may not exhibit symptoms for periods as long as twenty years after exposure. This aspect of the asbestos hazard poses major difficulties in establishing health programs. Unless the worker cooperates in control strategies, exposures will not be reduced to an absolute minimum. Many workers express an unconcerned attitude and will not cooperate in protecting themselves or expressing a concern to management.

In view of worker attitudes and the properties of the substance, engineering controls are the preferred method for controlling asbestos hazards. Engineering controls take on a variety of forms but most generally involve some form of air cleaning. The most advanced manufacturing facilities (further discussed in a later section), enclose equipment and processes to capture airborne fiber and prevent the dispersion of fiber throughout the plant. These methods, if properly engineered and maintained, generally reduce exposures below the current health exposure limit (PEL of 2 fibers greater than 5 microns in length per cc of air). It is important to realize that the worker must again cooperate in operating these systems (e.g. closing entry portals, emptying accumulated fiber, servicing the control system, etc.) for the systems to operate effectively.

Despite the best engineering controls, some fiber residue will accumulate on plant surfaces (floors, walls, structural members, etc.). In other operations, asbestos residue is generated in maintenance and disposal operations. In removing insulation containing asbestos, (ceiling treatments, pipe insulation, etc.) as well as servicing friction products (especially brake shoes), fiber is dispersed in the breathing zone of nearby workers. These types of collection and disposal are not readily handled by air cleaning systems. For this type of collection and disposal, the portable vacuum cleaner has become a commonly used device.

The portable vacuum cleaner has been widely used by major asbestos manufacturers for many years. Most of these units are so-called "industrial" vacuum cleaners since they are more sturdily built and may have more sophisticated filtration systems. There is a wide variety of vacuum cleaners in use and the mode of operation, servicing, and performance testing (if any) varies considerably.

The basic vacuum cleaner is a relatively simple device. It consists of a flexible hose for collection, a canister to support the filtration system, contain accumulated waste, and a motor to provide negative pressure to operate the system. Beyond these essential basics, the individual design of systems varies considerably. The variation in design and performance of vacuum cleaners has motivated this research, especially relative to the collection and disposal of asbestos-containing waste.

The specific occurrence which stimulated this research was an announcement by NIOSH which specified the use of portable vacuum cleaners for collecting fiber-bearing wastes generated in brake relining operations. It was evident that this application of vacuum cleaners represented some unique and ponderous research problems. These problems included:

1. An extremely wide use of the units since brake relining is done in virtually every garage and service station in America.

2. The economic factor wherein the typical user of vacuum cleaners was likely to spend the minimum investment possible in obtaining a unit.

3. The absence of meaningful performance standards for vacuum cleaners of any type, especially units proposed for use in the disposal of asbestos waste.

The NIOSH announcement suddenly broadened the application of engineering controls in reducing the disease potential of asbestos fibers. Certainly, this application of vacuum equipment was far more complex than in the industrial setting where experience and capital investment had provided some of the better equipment available from vacuum cleaner manufacturers.

The Texas A&M research project began with two small, unfunded student research projects. The first project by Wilson (1), sought to test an off-the-shelf shop vacuum with pure asbestos fiber. This test protocol was somewhat severe since most clean up operations do not involve pure asbestos but involve another material with various percentages of asbestos fiber. (This principle has been adopted throughout this research as further discussed in later sections of the report.) In his approach, Wilson isokinetically sampled the exhaust stream of the unit under test after challenge with varied quantities of fiber. The samples were collected on a membrane filter and counted under a phase contrast microscope in accordance with the standard NIOSH method (2). This method of asbestos sampling and fiber-concentration analysis was used throughout this research.

While Wilson's research results were limited, several conclusions may be drawn:

1. The unit quickly loaded such that suction pressure reduced below usable levels although the canister was not filled to capacity.

2. The fiber entering the vacuum tended to "mat" on the filter media (a paper bag) thus reducing the operation time of the unit.

3. The exhaust stream of the vacuum contained potentially hazardous levels of asbestos fiber.

This initial study showed that a common shop vacuum was totally inadequate for collecting and containing asbestos fiber.

A later research project by Daniels (3), considerably amplified the results found by Wilson. In Daniels' research, a vacuum cleaner specifically designed for collecting and containing asbestos fiber was tested. This vacuum was designed and built by the Howard Forrest Company of Houston, Texas, for use on their line of industrial band saws. The Forrest Company markets band saws to specifically cut asbestos block materials for insulation and other applications. The cutting operation generates a high fiber concentration requiring the need for a control system. The Forrest Company investigated several units and solicited scientific studies by Mt. Sinai School of Medicine, but concluded that their inexpensive home-made design would function as adequately as the high-efficiency vacuum systems (4,5).

The testing of the Forrest vacuum cleaner was completed in Daniels' research. Until that time, the Forrest Company was marketing the unit without a laboratory test to effectively evaluate emissions in operation. This study took a completely different approach to the test protocol from the method used by Wilson. The necessity for a different approach is evidenced by examining the design of the unit. Essentially, the unit has no exhaust port common to a shop-type vacuum and emissions of asbestos can escape from any point on the 27 square foot filter bag. For this reason, Daniels used still air sampling and collected stationary samples at various heights above the floor at four points around the bag. A fifth sample was positioned directly above the bag suspended from the ceiling. All samples were operated by a common vacuum pump with critical orifices fitted in each line to insure known flow rates at each sample site. The test was conducted in a room about the size of a small office. The room was divided by a sheet of plastic to separate the tested vacuum cleaner from a mechanism designed to feed fiber into the inlet of the vacuum. The test protocol consisted of feeding a pre-weighed quantity of pure asbestos fiber into the vacuum unit at a constant rate for a fixed time period. During this period, the samples were operated continuously. Following shut down, the samples were analyzed using the standard NIOSH asbestos fiber count method.

The results of this research were more conclusive than Wilson's due to more extensive testing and a better performance by the vacuum cleaner. This vacuum did not clog with fiber preventing further use of the unit. Despite this improved performance, the unit was judged as unsatisfactory since fiber concentration at all sampling points were far higher than the current health standards.

The first standard for controlling exposure to airborne asbestos was recommended in 1938 by Dreesen. After a study of four asbestos textile plants. a tentative maximum limit for asbestos dust, determined by the impinger method, of five million particles per cubic foot (mppcf) was recommended by Dreesen (28).

From 1945 to 1970 the American Conference of Governmental Industrial Hygienists (ACGIH) recommended a threshold limit value (TLV) of five mppcf for asbestos dust. In 1968 and 1969 the TLV was lowered to 12 fibers/cc greater than five microns in length, or two mppcf. In 1970-71, the TLV was changed to five fibers/cc greater than five microns in length.

The current standard, which became effective on July 1, 1976 states that the 8-hour time-weighted average (TWA) for airborne concentration of asbestos dust to which employees are exposed shall not exceed two fibers/cc greater than five microns in length. Also, a ceiling value of 10 fibers/cc shall not be exceeded for airborne concentrations of asbestos dust during any period of time. Furthermore, a level of 0.1 fibers/cc (8-hour TWA) has been proposed. The determination of concentrations of airborne asbestos fibers are made by the USPHS/NIOSH approved Membrane Filter Method for Evaluating Airborne Asbestos Fibers.

The control of emissions is an important consideration to make when dealing with asbestos operations. Collection of asbestos waste by vacuum cleaning methods is an acceptable method as specified by NIOSH in the current Asbestos Criteria Document (39). The vacuum cleaning devices used for clean-up operations are usually portable and the exhaust air is discharged directly into the work area (29).

In the United States, no specific criteria has been established regarding performance or disposal procedure for vacuum cleaners used for asbestos waste control. The absence of such specifications may allow for improper operation of vacuum cleaners used for this purpose.

B. SCOPE

The results of Wilson's and Daniels' research were summarized in a proposal submitted to NIOSH for consideration. After extensive review and revision, the project was funded. The contract included four major tasks as follows:

- Literature review
- Plant visitations
- Laboratory research and
- Final report.

Each of these tasks will be briefly described and the results will be found throughout this report.

The literature review was planned to provide a summary of the research completed by others as well as locating any existing standards for vacuum performance in the collection and disposal of asbestos waste. This review included journal articles, books, reports, and manufacturers' literature. In addition to these standard sources, computerized searches were completed on several systems including NTIS and COMPENDEX.

The plant visitations were scheduled to provide a basic orientation to the asbestos industry and associated disposal methods in use. The visitations emphasized the use and effectiveness of portable vacuum cleaners for collection and containment of asbestos waste. Factors observed in these visitations included:

- Type and quantity of waste
- Asbestos content of waste
- Plant environmental conditions and
- Particle size distribution of waste.

The results of this task, in addition to an orientation to the scope of the disposal problem in industry, became a basis for laboratory test conditions such that the research was as representative as possible.

The laboratory research consisted of testing nine (9) vacuum cleaning units specifically designed for asbestos waste collection and disposal. The precise protocol is discussed in detail elsewhere in this report. Basically, the protocol is based upon the first efforts completed by Wilson and Daniels as well as the results of the field visitations.

II. LITERATURE REVIEW

A. INTRODUCTION

The literature review and field visitations were the first two tasks of the research project. These tasks were designed to provide a summary of other work in the collection and disposal of asbestos waste, as well as an orientation into various major types of asbestos products manufacturing to view the state of the art in vacuum cleaning.

B. VACUUM CLEANER TESTING

The review of journal articles, reports, and computerized data bases have produced limited results. Much of the current asbestos literature deals with interpretations of the hazards of asbestos fibers to humans and extensive debate regarding the current health standards. Relatively little of the literature is directed to engineering control methodologies. Specific literature appropriate to this project is cited throughout the text and is listed in the References section of the report. Only four accounts of vacuum cleaner testing by equipment manufacturers or others were discovered.

Four recent vacuum cleaner tests have been conducted for various purposes at different locations in the country. The most pertinent studies involved testing of a so called "high efficiency" vacuum unit designed specifically for the collection of asbestos waste. The first was funded by the American Cleaning Company of Addison, Illinois and performed by Clayton Environmental Consultants. This study was very similar to the laboratory research in this project in which air sampling was done within a small test room using brake dust containing asbestos fiber obtained from brake maintenance operations. The dust was vacuumed from a cardboard box and emissions from the vacuum unit measured. The results of this study are not publicly available but informal information reveals that the vacuum contained the asbestos-contaminated brake dust to an acceptable level.

Another study was performed by B.I. Caramella (6). This study was similar to the work done by Wilson in that sampling was conducted isokinetically from the exhaust stream of the test vacuum. This procedure was somewhat divergent from current occupational safety and health sampling methodology in that the protocol called for stack-type sampling apparatus. This apparatus differs considerably from the membrane filter method recommended by NIOSH which is used in virtually all asbestos surveys. Again, the results of this research have not been published; but, apparently extremely low concentrations of fiber were sampled in the exhaust stream.

Two additional studies were identified which attempted to test the performance of industrial vacuum cleaners. Neither of these studies used asbestos as a test medium or proposed to evaluate performance in asbestos collection. The first study sought to test the performance of each vacuum cleaner unit against dioctylpthalate (DOP). The DOP was generated and fed into the inlet hose of test units followed by sampling with a spectrophotometer to detect DOP leaks at various points in the unit. All testing was conducted in a clean room to eliminate background particulate which might interfere with DOP counts. The testing was similar to procedures used to test HEPA filters. The results of their research (unpublished) did not include any numerical data and units were rated as either satisfactory or unsatisfactory. Satisfactory units were those which had either no leaks or repairable leaks. Unsatisfactory units were those which showed unrepairable leaks or were fitted with inadequate filtration.

The second study of non-asbestos nature was located at Westinghouse Electronics Corporation, Baltimore, Maryland. This study sought to evaluate vacuum cleaners used to remove and collect microscopic debris in industrial clean rooms. The clean rooms were used for prevision assembly of electronic parts which could be contaminated by any particulate setting on parts. The study sought to determine if the vacuum cleaning units operated successfully in collecting dust and did not simply redistribute collected debris, through the filtration system, back into the clean room air. The test protocol consisted of simply following a unit through the clean room continuously monitoring the exhaust stream with an optical particle counter (ROYCO). Since the clean room air was essentially particle free, any significant counts of particles could be assumed to be leaking through the vacuum cleaner filtration system. This project was essentially an internal quality control study and hence no results were published.

C. ASBESTOS

The term "asbestos" is used to describe the family of hydrated silicate minerals that have one common property; they can be separated into fibers which are remarkably resistant to heat, weather, acids, alkalies, and other chemicals, and also possess high tensile strength. They are unusually flexible, and are the only mineral fiber that can be woven into cloth (7,8,9).

The known varieties of asbestiform minerals can be divided into two main classes on the basis of their crystal structure (serpentine and amphiboles). The sole member of the serpentine class is chrysotile asbestos, the most common form of the asbestiform minerals. About 95 percent of the asbestos used in the U.S. is chrysotile asbestos.

D. ASBESTOS-RELATED DISEASES

1. Asbestosis

Asbestosis (asbestos pneumoconiosis) was the first clearly demonstrated adverse affect of asbestos in man. It is a non-malignant fibrotic lung disease which may be caused by inhalation of asbestos fibers and a biological reaction to the deposition of those fibers in the respiratory system. Although asbestosis can occur throughout the lungs, it is most commonly found in the lower lobes, with both lungs usually affected (13).

2. Bronchogenic Carcinoma

Bronchogenic carcinoma is another disease that has been linked to asbestos exposure (16). While bronchogenic carcinoma can occur anywhere in the lungs it usually develops at the major junctions of the bronchioles in the central portion of the bronchial tree (17). It has also been reported that there is an increased risk of bronchogenic cancer among asbestos workers who smoke cigarettes (18,19).

3. Mesothelioma

A third asbestos related disease is mesothelioma, a rare form of cancer in the form of primary malignant tumors of the pleura and peritoneum, the linings of the pleural and abdominal cavities (20,21,22). Exposures of only a few weeks to the asbestos fibers have resulted in the disease. A unique feature of the disease is the long period, generally 20-30 years, between first exposure to asbestos and the appearance of a tumor.

III. FIELD VISITATIONS

The field visitations, as with the previous research by others, provided an important basis for the experimental design and equipment selection for test. Three major field trips were completed along with several shorter visitations to local brake/clutch servicing facilities. The major visitations included travel to an asbestos products plant, a friction materials plant, and an asbestos pipe plant. The most valuable visits were the friction products plant and the asbestos pipe plant. Both of these plants were engaged in major manufacturing of asbestos-based friction products. The asbestos products plant probably represents the highest level of asbestos control technology in the industry. The plant is extremely clean and is equipped with a variety of ventilation systems to control asbestos emissions. Raw asbestos was carefully stored in sealed containers and emptying of containers was performed under negative pressure in specially designed enclosures. At various points in production, wet processes were used to suppress the escape of asbestos into the plant air. Where necessary, employees used appropriate respiratory protection. Of interest to this research, several varieties of industrial vacuum cleaners were used to collect asbestos waste. The observations of these units may be summarized as follows:

1. A variety of units were in use, some antiquated.

2. The care and use of plant vacuum cleaners was not carefully controlled since units showed considerable wear and tear. A variety of vacuuming procedures (sweeping motions; tools used, etc.) were used with differing results.

3. The cleaning/filter replacement of vacuum units was not well established. Certain filters were never changed in a five year period. Other units showed excessive accumulation of waste.

The friction materials plant had a lower priority for control of asbestos emissions. Fiber accumulations were far more evident throughout the buildings. Considerable build up of fiber was observable on structural members in each building. Larger quantities of asbestos waste were seen accumulating from manufacturing processes and this waste was less frequently removed. Vacuum cleaners were also in use in the plant and the equipment appeared even more antiquated and in a worse state of repair. No policies were established for maintenance, filter replacement, or operation of units. Workers appeared to wear protective equipment only occasionally.

The asbestos pipe plant did not add any significant new observations to earlier visitations. The plant was quite clean as a result of company policy. This manufacturing process is considerably cleaner. Again, portable vacuum units were occasionally used, as in the friction product manufacturing plant.

The visitation to brake/clutch repair shops revealed some dust accumulation when friction plates were removed for replacement. This dust allegedly contains asbestos fiber and can be dispersed into the breathing zone of nearby workers. In the shops visited, no use of vacuum cleaners was observed and, in most cases, maintenance personnel stated a lack of awareness of any associated health hazard.

The few plant visitations completed in this research did not represent the full scope of uses of vacuum cleaners for collection and disposal of asbestos waste. These visitations did reveal a variety of units in use as well as potential problems in the industrial setting. After completion of this task, several additional applications of vacuum cleaner units became known, especially asbestos insulation removal. This includes removing pipe insulation, ceiling insulation, and even insulation from within the confines of a naval submarine.

The variety of manufactures of vacuum cleaning units (as well as applications discovered in the literature review along with plant visitations) suggested the major scope of this device is the controlling of health hazards. A number of manufacturers produce vacuum cleaners specifically for asbestos collection, the range of types and capabilities is reported elsewhere in this report. Furthermore, the applications are extensive. The absence of vacuum cleaner manufacturer standards as well as effective user practices can severely limit the potential benefits of these units in practice. This research, therefore, was dedicated toward establishing basic test parameters and methology, performance and test data, and observations as a basis for an industry wide program of standards and practice.

IV. TEST FACILITY AND EQUIPMENT

A. FACILITY AREAS

1. Feed Room

The feed room adjoins the test room and the two are isolated by a single wall (Figure 1). This isolation prevents any asbestos dust which has become airborne in the feed room (from the action of the asbestos hopper) from contaminating the test room air. The glass panel in the dividing wall allows for observation from one room to the next during testing.

2. Asbestos Hopper

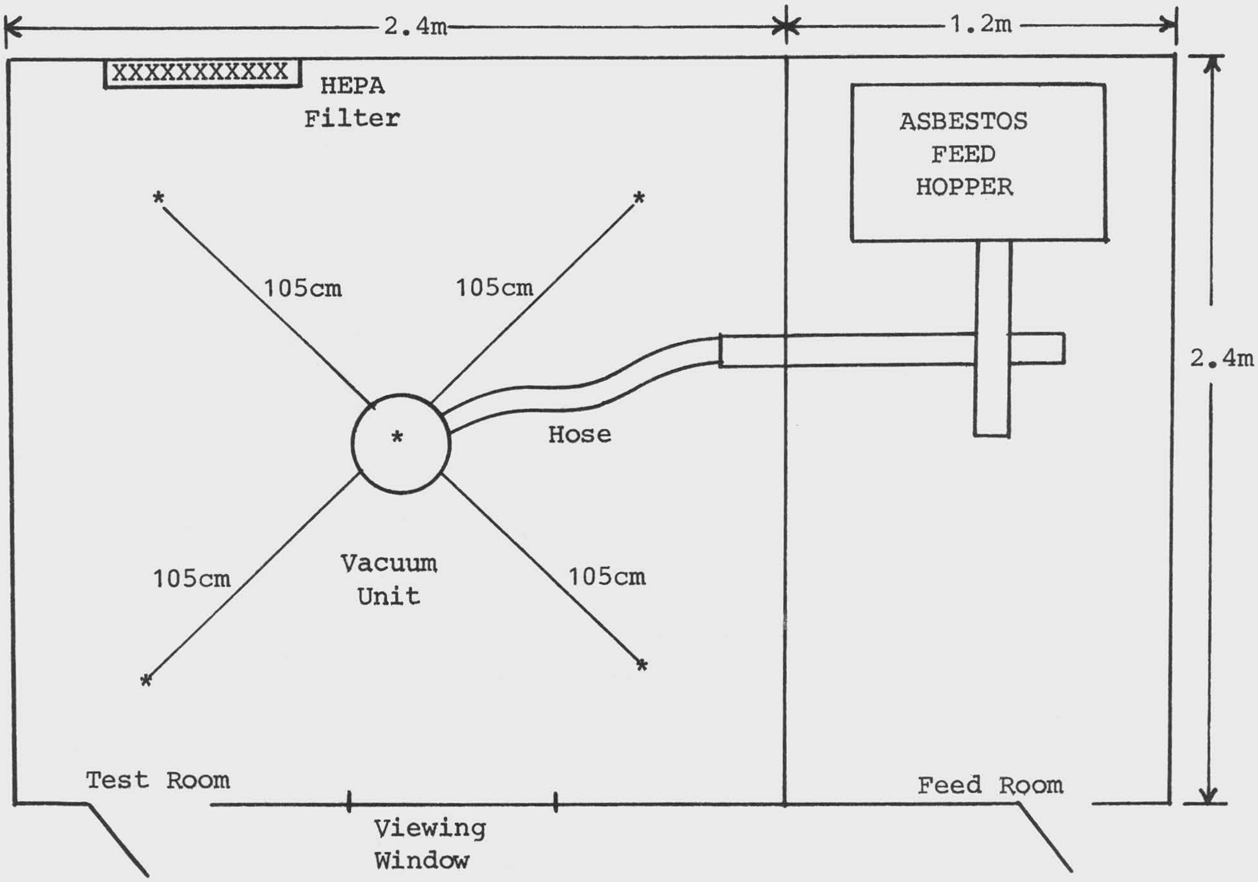
The asbestos hopper received several modifications before a design was found which could dispense the asbestos evenly and continually. The hopper is rectangular in shape with a cone-shaped opening at the bottom through which the asbestos is dispensed (Figures 1 and 2).

The hopper capacity is approximately seven kilograms when it is loosely loaded with chrysotile asbestos. Quantities above three kilograms of asbestos loaded in the hopper caused packing and increased the possibility of clogging or bridging, thus reducing the amount dispensed. Two and one-fourth (2.25) kilograms of chrysotile was fed into the hopper per test.

When loaded into the hopper as described above, the asbestos tends to bridge after only a small quantity of the material had fallen into the conveyance system under the hopper. To prevent this bridging phenomenon of the asbestos, a rotating grate was installed into the lower section of the hopper (Figure 2) to maintain the feeding by continually agitating the asbestos in the hopper. Also, an electrically powered vibrator (Figure 2) was mounted to the side of the hopper to help prevent the bridging tendencies by vibrating the walls of the hopper.

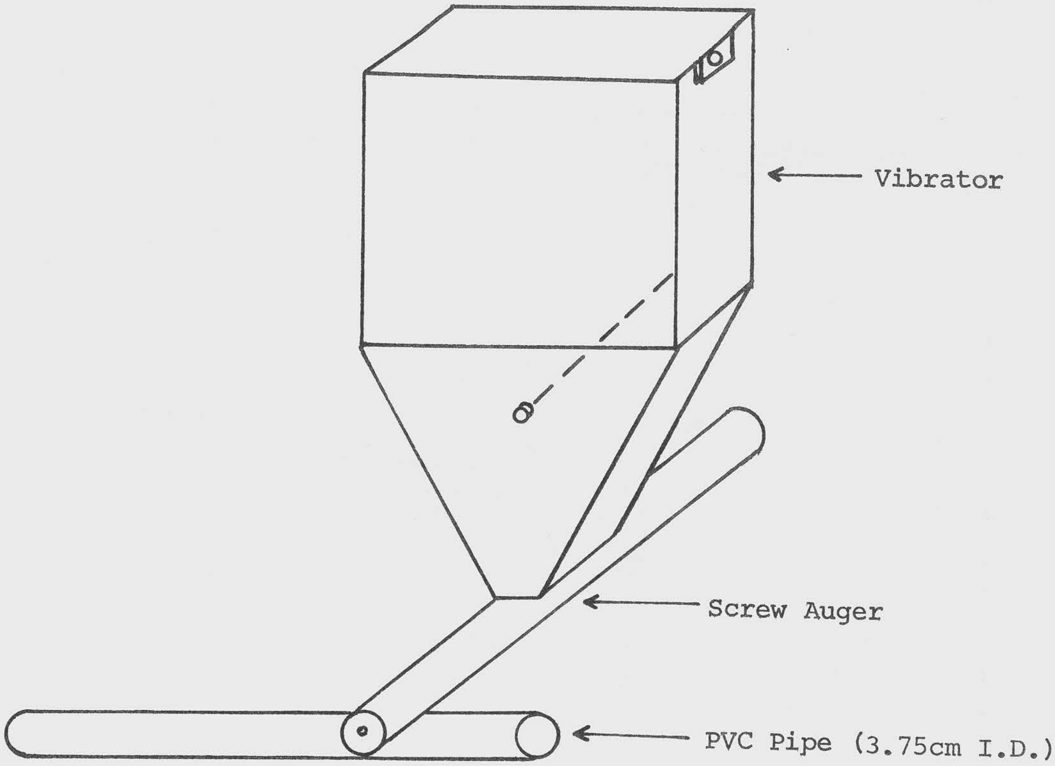
The grate is rotated by the same motor that turns the screw auger which is used to convey the asbestos. A chain and sprocket assembly unites the grate and auger and allows the motor to operate the two at the same rate.

The screw auger is enclosed in a section of clear plastic pipe and projects horizontally under the hopper. The screw auger is used to convey the asbestos falling from the hopper to the vacuum

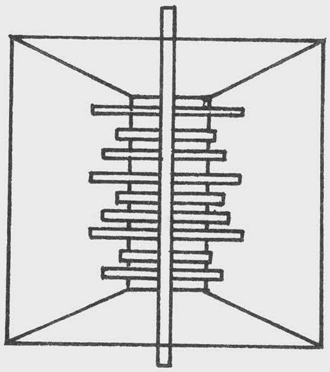


* Location of air sampling points

Figure 1. Test Facility



A. Side Projection View



B. Top View With Rotating Grate

Figure 2. Asbestos Feed Hopper

feed pipe (Figure 1). The clear pipe permits observation of the conveying operation and gives a quick check to see that the auger is turning properly. To avoid any jamming of asbestos, the rate of conveyance was set at a rate of 0.45 kg per minute of operation.

The screw auger deposits the asbestos into a clear plastic pipe that is perpendicular to and slightly below the screw auger. This pipe is termed the vacuum pipe and has an internal diameter of 4.4 cm. The back end is open to allow air to be drawn through this pipe by the vacuum unit, allowing the asbestos to be entrained in the rapidly moving air and conveyed into the vacuum unit. The vacuum pipe extends from the feed room through the adjoining wall and into the test room.

B. TEST MATERIAL

The material used in this research was Johns-Manville Product 7M-13 purchased from Thorpe Products of Houston, Texas. The number and letter "7M" are used to identify the length of the fibers of asbestos. The number "13" indicated that the grade of asbestos has low bulk and absorption. This product consisted of 100 percent chrysotile asbestos ($3MgO \cdot 2SiO_2 2H_2O$).

One hundred percent chrysotile was selected as the test material for two reasons. First, the literature review indicated that the form of asbestos used most in industry is chrysotile. Ninety-five percent of all the asbestos used throughout the world is chrysotile. Therefore, the type of asbestos most often associated with vacuum cleaner use would be chrysotile. Secondly, use of 100 percent chrysotile asbestos would produce a "worst case" situation. Although the use of 100 percent chrysotile in industry would be unusual, it was determined that this type asbestos allows for the examination of the vacuum cleaners under extreme conditions.

C. SAMPLING AND ANALYTICAL PROCEDURES

In the test room, the vacuum-unit hose is connected to the plastic vacuum pipe that extends through the wall from the feeder room. The vacuum unit exhaust port is positioned in the center of the test room. This positioning allows for a more symmetrical exhaust pattern in the test room, provided that the exhaust is uniformly discharged from the vacuum unit. (Some units have exhaust ports which are on one side of the unit which interrupts the exhaust pattern from being uniform within the test room - this is not a limitation of the unit, but a limitation of the test design.)

Five sample points were located in the test room at varying heights, in a circular pattern around the vacuum unit. The heights of the samples are as follows: 1.1, 1.2, 1.4, 1.5, and 2.0 meters. These heights were chosen to give a more complete analysis of greater area around the vacuum unit than would samples located at the same heights. The variety of sample heights would be able to account for more eddy currents that may have been present in the test room air.

The air sampling apparatus and methodology within the test room is designed to follow the recommended guidelines established by the NIOSH method for sampling of air suspected to contain asbestos fibers. The apparatus is as follows: five open-face filter cassettes consisting of a three-piece cassette with a 37mm, 0.8μm pore, AA filter with pad; five each, 2 liters of air per minute (2L/min) limiting orifices with metal adaptors for connecting to filter cassettes and tygon tubing. All tygon tubing from the five samples comes together in a single manifold which is connected to a vacuum pump with a rated capacity of 37 liters per minute. The pump is located on an overhead rack at a height of 2.4m. This positioning of the pump elevates all tubing so it does not become tangled with the vacuum unit and operations below.

Asbestos is an excellent filter medium and it improves the filtration efficiency of a filter once it has become loaded with asbestos. In this research, a small quantity of asbestos (2.27 kg) was used to challenge each vacuum unit. It was theorized that this amount would be sufficient to test a machine as to its ability to retain asbestos fibers before sufficient asbestos could load the filter and increase filtration efficiency.

To date the NIOSH approved phase-contrast microscopy technique is considered the best method of determining a concentration of airborne asbestos. Wedges of each sample filter are mounted on microscope slides and examined at 450X with a phase contrast microscope. Fibers longer than 5 microns with a length-to-width ratio of 3:1 are counted as asbestos. Varying microscope fields are counted, depending upon a rough estimate of the fiber concentration. Total fiber content is determined on the sample and the amount counted on a blank filter were subtracted from the total filter concentration. The result was divided by the air volume sampled (60 liters) to determine the average airborne velocity concentration.

D. AIR VOLUME ASSESSMENT

Since air volume is related directly to suction pressure (i.e. as suction pressure increases/decreases, air volume increases/decreases) and suction pressure is an important parameter to consider when evaluating performance, the instrument of choice was one that measured volume in terms of suction pressure.

The mercury vacometer, a device developed and manufactured by the Spencer Turbine Company of Windsor, Connecticut, was the instrument used to determine the suction pressure of the vacuum cleaners. The vacometer is a globe shaped device with two distinct openings. The first opening is an extension from the globe. This extension, called the hose inlet or inlet valve, is where the vacuum cleaner suction hose is attached. The second orifice is circular and located in the globe itself. This circular opening is covered by a rotatable ring which has two orifices of sizes 1/2 and 3/4 inches. This rotatable ring allows the variable sized orifices to overlap the opening in the globe, thus allowing the intake of air for the vacometer to pass through either a 1/2 or 3/4 inch opening.

A vacuum tap in the vacometer was connected to a mercury manometer with a length of tygon tubing. Thus, when a vacuum cleaner, which was connected to the mercury vacometer, was activated, a suction pressure reading was obtained from the mercury manometer.

After the suction pressure was found, it was used to determine the air volume. This was accomplished by using a graph which indicated the amount of air which passes through various sized, round, sharpe-edged orifices.

E. VACUUM UNITS

Nine industrial vacuum cleaners were tested during this research project, representing seven different manufacturers. Letters were sent to all manufacturers which could be identified as suppliers of vacuum cleaners for use in asbestos cleanup. All of the vacuum cleaners were loaned to Texas A&M University to be used in the various tests in this research project. Each manufacturer that supplied cleaners will be furnished copies of the test results in the final report.

The specifications of each vacuum cleaner are listed in Table 1. These specifications are intended to aid in the selection of a vacuum cleaner, based primarily on size, capacity, power and filter configuration.

It was not the intent of this research project to compare one vacuum cleaner against another and make evaluations concerning the most effective cleaners. Therefore, the manufacturer's name and model numbers of the units have been purposely omitted from this report.

Table 1. Specifications of vacuum cleaner test units.

Unit	"A"	"B"	"C"	"D"	"E"
Tank size	62 l	58 l	20 l	69 l	62 l
Capacity	42 l	29 l	15 l	42 l	36.5 l
Size					
Height	80cm	80cm	45cm	105cm	72.5cm
Width or diameter	50cm	45cm	30cm	80cm	60cm
Length			45cm		
Weight	32kg	27kg	11kg	60kg	30kg
Motor size	1.5HP	1.1HP	1/3HP**	3@1/3HP**	3 HP
Power (volts/amp)	115/10	115/6	115/4.4	115/4.4	115/6.3
Suction pressure @ 3/4"	2.3"Hg	1.7"Hg	1.4"Hg	2.1"Hg	3.8"Hg
Volume (Q) @ 3/4"	44CFM	37CFM	33CFM	42CFM	58CFM
Noise					
2m	72db	82db	74db	80db	88db
4m	71db	78db	72db	77db	84db
Filters (number)	3	5	4	3	3
Filters (type)					
1	Paper*	Paper	Paper	Cloth	Paper
2	Cloth	Cloth(2)	Cloth	Cloth	Nylon
3	Fiber-glass	Fiber-glass	Cloth	High Effi-ciency	Cloth
4		High Effi-ciency	Fiber-glass		
Hose					
Length	2.1m	3.2m	*	3.0m	4.9m
Diameter	3.75cm	3.75cm		4.4cm	3.75cm

*Not supplied with unit.
**Estimate.

Table 1. Specifications of vacuum cleaner test units (continued).

Unit	"F"	"G"	"H"	"I"
Tank size	65 l	25 l	33 l	62 l
Capacity	54 l	23 l	30 l	31 l
Size				
Height	165cm	75cm	95cm	113cm
Width or diameter	90cm	35cm	50cm	60cm
Length				90cm
Weight	82kg	14kg	40kg	68kg
Motor size	3 HP	1.0HP	1.0HP**	1.5HP**
Power (volts/amp)	230/8.4	115/6	115/12	220/9
Suction pressure @ 3/4"	3.5"Hg	2"Hg	2.5"Hg	1.5"Hg
Volume (Q) @ 3/4"	55CFM	40CFM	48CFM	33CFM
Noise				
2m	82db	80db	79db	78db
4m	79db	76db	76db	76db
Filters (number)	2	3	4	2
Filters (type)				
1	Cloth	Paper	Paper	Cloth
2	High Effi-ciency	Nylon	Nylon	High Effi-ciency
3		Cloth	Cloth	
4		Foam Rubber	High Effi-ciency	
Hose				
Length	1.8m	*	*	*
Diameter	5.0cm			

*Not supplied with unit.
**Estimate.

V. TEST 1 - INITIAL EVALUATIONS

A. EXPERIMENTAL PROCEDURE

Two personnel were required to conduct the testing (one to attend to the feed room and one to attend to the test room).

Each vacuum unit underwent an individual check before it was tested to assure that the filtration system was intact and the assembly met manufacturer's specifications.

1. Feed room preparation

    a) All electrical power to drive motor and the vibrator was off.

    b) The switches to each of the above was turned to "on" position. (This procedure allowed for all electrical equipment to be started simultaneously, including the test room equipment.)

    c) Asbestos hopper was loaded with 2.27 kg of chrysotile asbestos.

    d) Personnel exit door was closed.

2. Test room preparation

    a) The test room floor and walls were mopped to remove as much extraneous dusts as possible from test room. Mopping was done several hours before a test was performed to allow the humidity to return to ambient level.

    b) Suction pressure of the vacuum unit was measured prior to being challenged with the 2.27 kg of asbestos.

    c) A vacuum unit was then placed in the center of the test room and the hose was connected to the plastic feed pipe protruding through the wall from the feed room. (All electrical power was off but equipment was plugged in and all switches were in the "on" position on the sample pump and vacuum unit.)

    d) One (1) filter cassette was placed at each fixed sample point (5 locations) and the covers were all removed.

e) The door was closed and sealed with tape.

f) Temperature and relative humidity readings were made and recorded.

g) All electrical power was turned on and testing was conducted for 30 minutes.

h) All electrical power was turned off.

i) Temperature and relative humidity readings were recorded again.

j) Test room was entered and all filter cassettes were closed and removed.

k) Suction pressure of the unit was measured again while the unit contained asbestos.

B. RESULTS

The results of this study are presented in Figure 3, which is a plot of the fiber concentrations per cubic centimeter versus the specific sampling points. The mean value of the five sample points is also included. Curves are shown for each vacuum cleaner which was tested in this phase of the research project. Not all of the available vacuum units which were available were tested in this part of the study because it was felt that the data to be gained would not justify the cost, since the capacity tests would yield much of the same data.

C. CONCLUSIONS

Based on fiber counts obtained from each vacuum unit when challenged with 2.27 kg of chrysotile asbestos, conclusions as to a numerical ranking or rating of vacuum cleaner performance cannot be documented. All of the units yielded counts well below the OSHA limit of 2.0 fibers/cm^3 as long as the units retained their integrity and were serviced correctly. However, all of the units would have difficulty in meeting the proposed standard of 0.1 fibers/cc.

From the fiber count results the vacuum units could be divided into two groups (pass and fail) with regard to the current OSHA standard. All units would be in the pass group with the possible exception of unit "A". While unit "A" appears to have the lowest counts from the graph, numerous failures of the unit would relegate this vacuum cleaner to the marginal, or fail classification.

Since all units performed satisfactorily when compared to the present TLV with regard to exhaust emitted fibers, the criteria

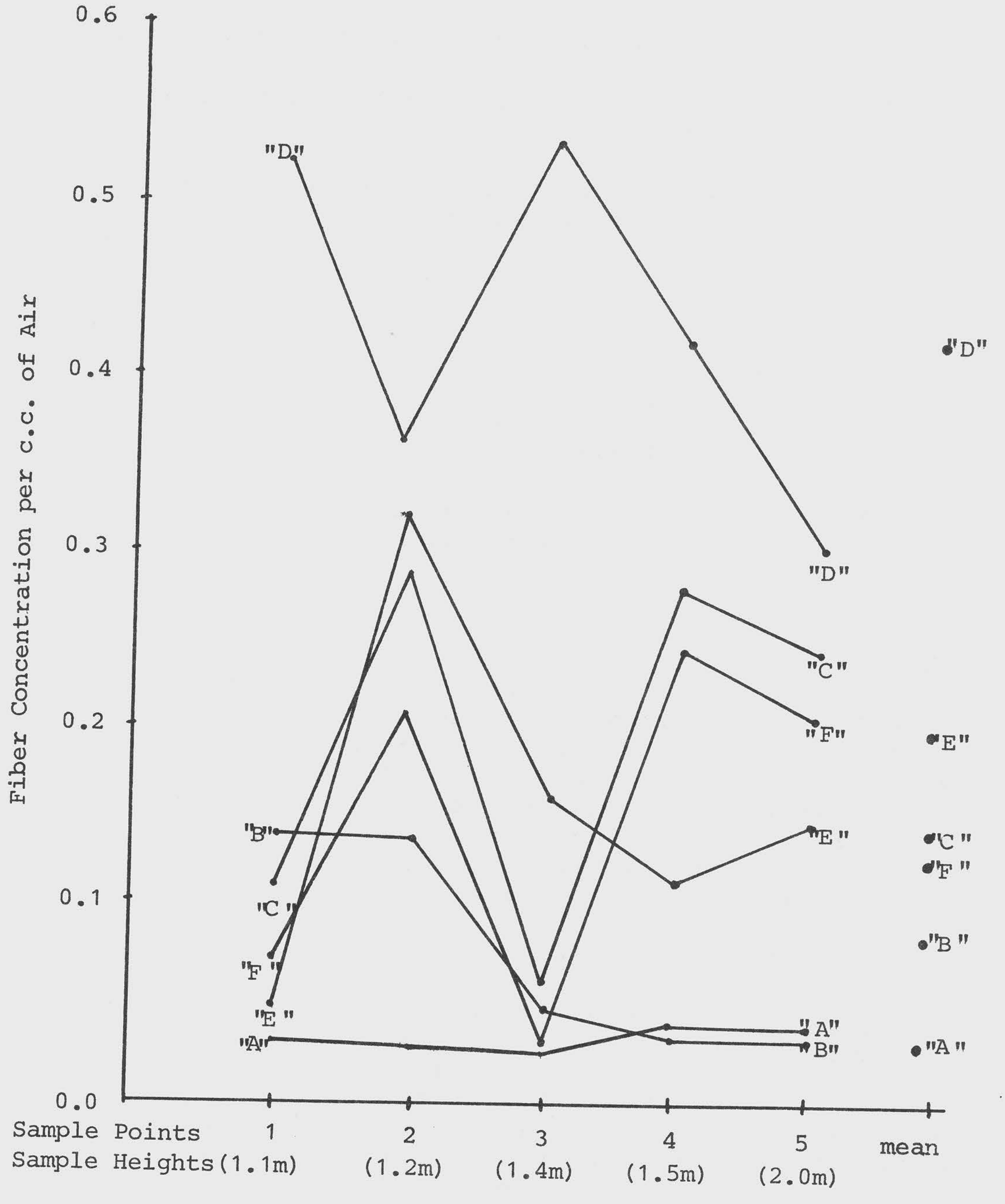


Figure 3. Plot of Fiber Concentrations vs. Sample Points for 2.27kg Asbestos Test Using Vacuum Cleaners "A", "B", "C", "D", "E", and "F".

which should ultimately determine "pass" or "fail" should be such things as reliability and ease of maintenance and serviceability. Both are discussed further under the work practice considerations portion of this report.

VI. TEST 2 - EFFECTS OF CAPACITY ON VACUUM CLEANER PERFORMANCE

A. PROCEDURE

This test was conducted to determine effects on the performance of industrial vacuum cleaners when the manufacturer's specified capacity was approached, obtained, or exceeded. The evaluation of the vacuum cleaner's performance was based on two measurements. The first was a measurement of the amount of asbestos fibers that were present in the exhaust air of each cleaner. Compliance with the current OSHA standard for airborne asbestos concentration was the basis for performance acceptance or rejection. Samples of the vacuum discharge air were collected simultaneously at two locations positioned on each side of the vacuum cleaner being tested. Asbestos fibers in the vacuum cleaner discharge air were collected on membrane filters and evaluated for determination of asbestos concentrations.

The second measurement method was the determination of suction pressure. The suction pressure for each vacuum cleaner was measured before, during, and after each test run.

When a vacuum cleaner was ready to be tested, it was placed as near as possible to the center of the test room. The vacuum inlet hose was connected to the conductor pipe, which extended from the feeder room through the divider wall. Because a positive pressure exists in the test room when a vacuum is operated, a High Efficiency Particulate Air (HEPA) filter was placed in the back wall of the test room. This allowed for the dissipation of the positive pressure in the room while preventing the escape of airborne asbestos fibers that may have been present in the discharge air.

In order to sample the discharge air of the vacuum cleaners for the presence of asbestos fibers, the system developed in the earlier tests was used. The major component of the system consisted of a vacuum pump manifold, 1/4" i.d. tygon tubing, flow limiting orifices, and membrane filters contained in sample cassette holders.

The vacuum pump was mounted on a platform 8 feet from the test room floor. In this position, the pump was out of the way and helped minimize the amount of tygon tubing leading to the sampling positions.

A manifold was designed to allow the collection of up to five simultaneous samples around the test room using only a single vacuum pump. Because of the cost involved in laboratory counting and sizing of sample filters, only two sample positions were used to collect samples of the vacuum cleaner discharge air (see Figure 4). These positions remained stationary throughout the sample collection of all nine vacuum cleaners. Both sample positions were separated from the center of the room, and the center of the vacuum cleaner, by a distance of 42 inches at a height of 4 and 5 feet, respectively. The cassette sample holders were located on specially constructed support stands. These stands were constructed of 2" x 2" lumber and each stand was securely anchored to the floor. Sample stand I, for sample position I, stood 5 feet in height, while sample stand II, for sample position II, stood 4 feet in height.

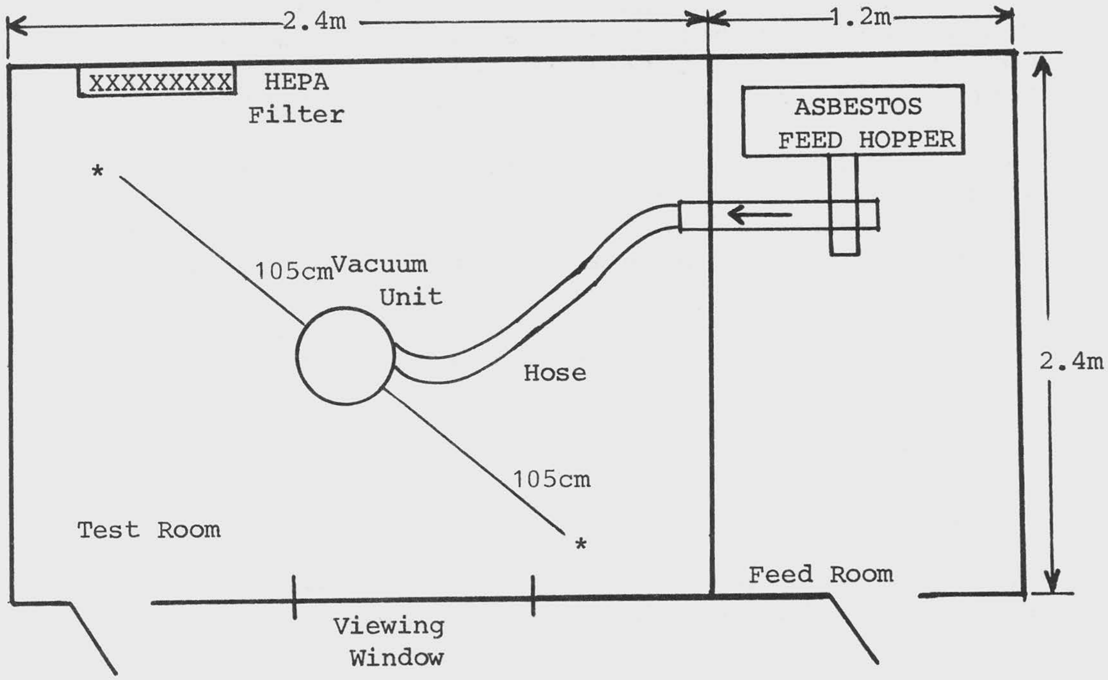
Samples were collected on 37mm 0.8μ pore size, Millipore AA membrane filters backed by a support pad. A 3-piece cassette holder contained a filter and pad. The outlet of the holder was attached to the sample end of the tygon tubing. Sample collection was carried out using the "open face" method, as recommended by NIOSH. After the sampling period had been completed, the cassette holder was reassembled to protect the sample from being contaminated.

B. RESULTS

1. General Discussion

When each vacuum was tested, it was operated until 125% of the manufacturer's specified capacity was obtained or the cleaner broke down. A breakdown was defined as the point when vacuum cleaner performance was no longer within design specifications. The performance of a vacuum cleaner was declared "down" if the suction pressure was so low that asbestos would not be pulled through the conductor pipe or if the presence of asbestos in the exhaust air was such that it was visible. Therefore, complete data collection was not possible for all units.

The integrity of the vacuum cleaner is an important aspect that was considered. Although a cleaner may appear to perform well, an internal breakdown can easily result in an exposure when the unit is cleaned out. It was found that on every occasion in which a paper bag was ruptured or was not present, the inside of the unit was thoroughly covered with asbestos. Any attempt to clean out the machine had to be done very slowly, and still it was impossible not to agitate the asbestos fibers. Other exposures occurred when the asbestos stuck to the bag surface and would drop to the floor when the bags were removed from the tank. Thus, the integrity of the cleaner was considered to be an important parameter in preventing employee exposure. Therefore, when these or any other type of breakdown occurred, the testing was immediately stopped and any performance evaluation



* Location of air sampling points

Figure 4. Test Facility Showing Location of Sample Points (*).

was made upon the data collected before the termination of the test.

2. Discussion of Collected Data

A measurement of the change in the vacuum cleaner's suction pressure was made on each cleaner that was tested. A relationship between the vacuum cleaner suction pressure and air velocity was recognized. This relationship is represented graphically in the plot of the suction pressure vs. percent capacity. Figures 5 and 6 illustrate this relationship. Only the curves for vacuum unit "D" are presented as all the units which were tested yielded similar results.

Figure 7 is a plot of the fiber concentrations which were counted at each capacity mark. Two samples were taken at each capacity and the average of these were used in plotting the results. It can be noted that although there is a great deal of variation in the readings, all points are well below the TLV value of 2.0 fibers/cc greater than 5μ in length. This variation is probably due to the accuracy of the counting method at these extremely low fiber concentrations.

Unit "A" is not included in the graph because failure occurred on each run before the capacity could be attained. The capacity of this unit should be reduced, or the design modified in order to meet the unit's specifications.

The large class-2 units were not included in this test because of the large amounts of asbestos which would have been required in order to reach the 100% and 125% capacity quantities.

C. CONCLUSIONS

The calculated airborne fiber concentrations were all far below the OSHA standard of 2 fibers/cc. This is especially important because 100 percent chrysotile was used to produce a "worst case" situation. Under normal conditions, materials introduced into the vacuum cleaners would contain a lesser percentage of asbestos, reducing the amount of asbestos escaping from the cleaners; thus, even lower airborne fiber concentrations values would be expected.

The suction pressure of each vacuum cleaner dropped considerably as each cleaner's capacity was approached and/or exceeded. The drop in suction pressure was visibly evident in all vacuum cleaners and was such that the specified capacity of one unit could not be exceeded in the second run.

Although vacuum cleaner integrity may not have been a direct effect on the performance of a vacuum cleaner, it can play an important role in preventing employee exposure. In all instances

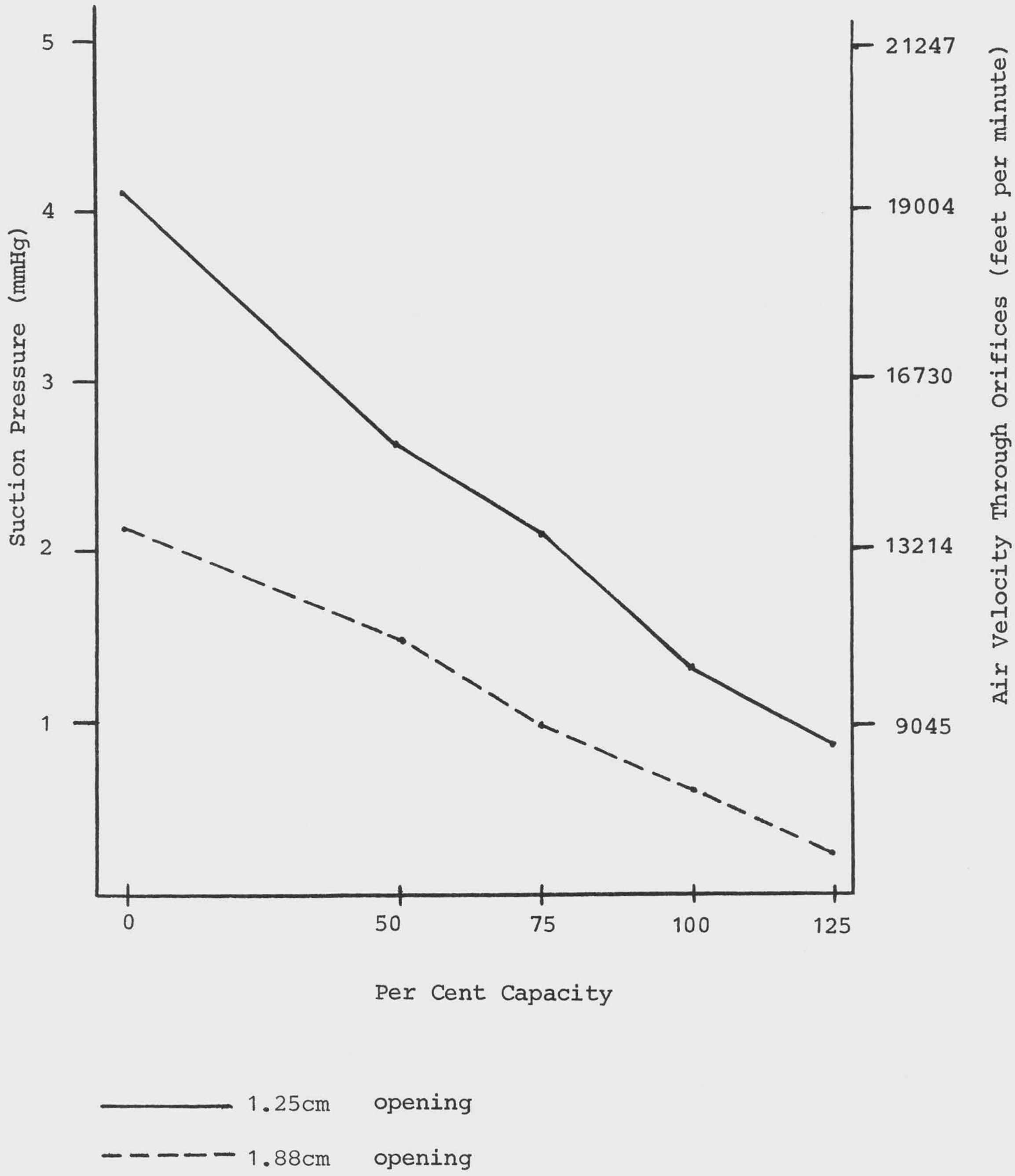


Figure 5. Typical Plot of Suction Pressure vs. Percent Capacity (Test I), (Unit "D").

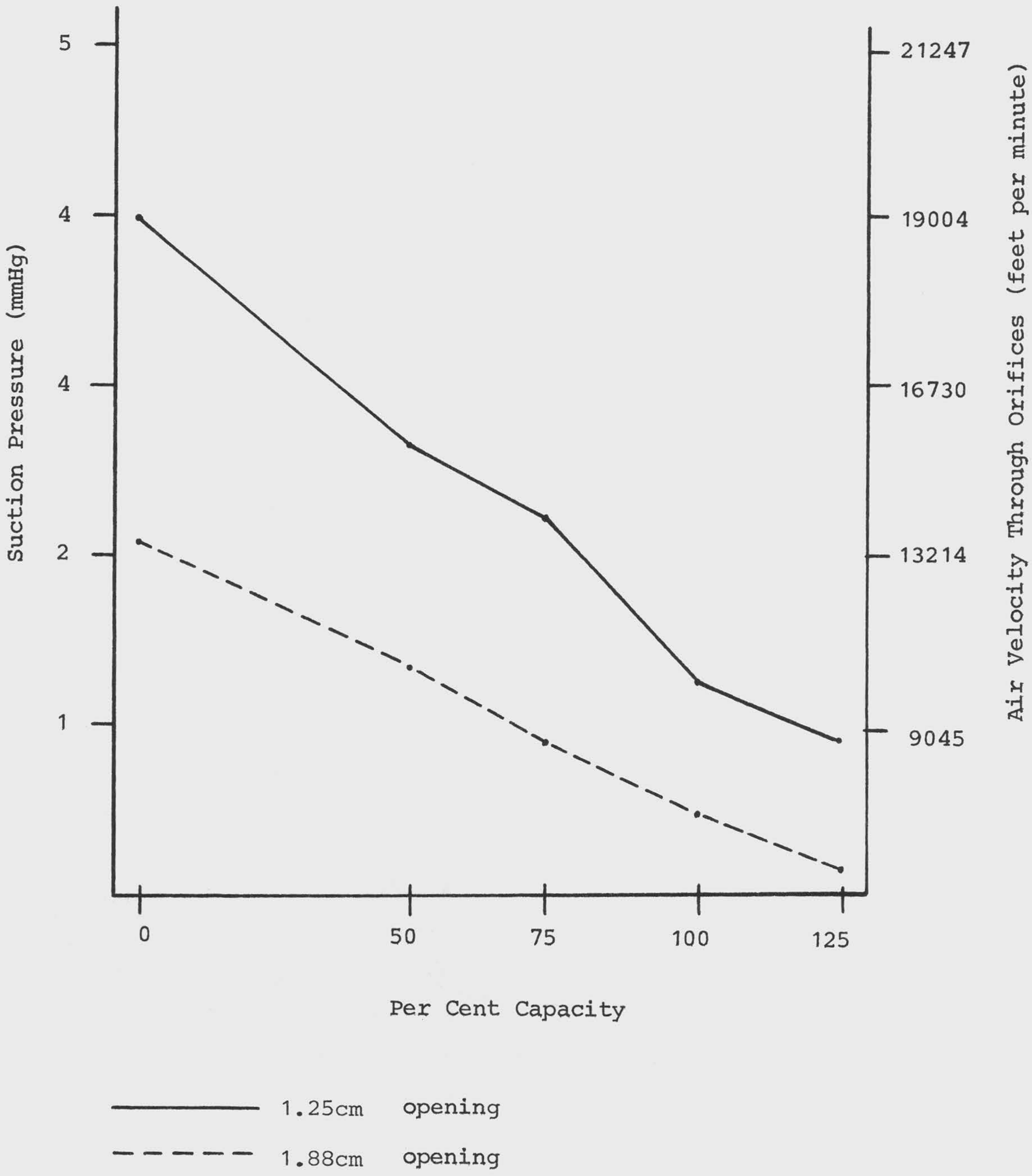


Figure 6. Typical Plot of Suction Pressure vs. Percent Capacity (Test II), (Unit "D").

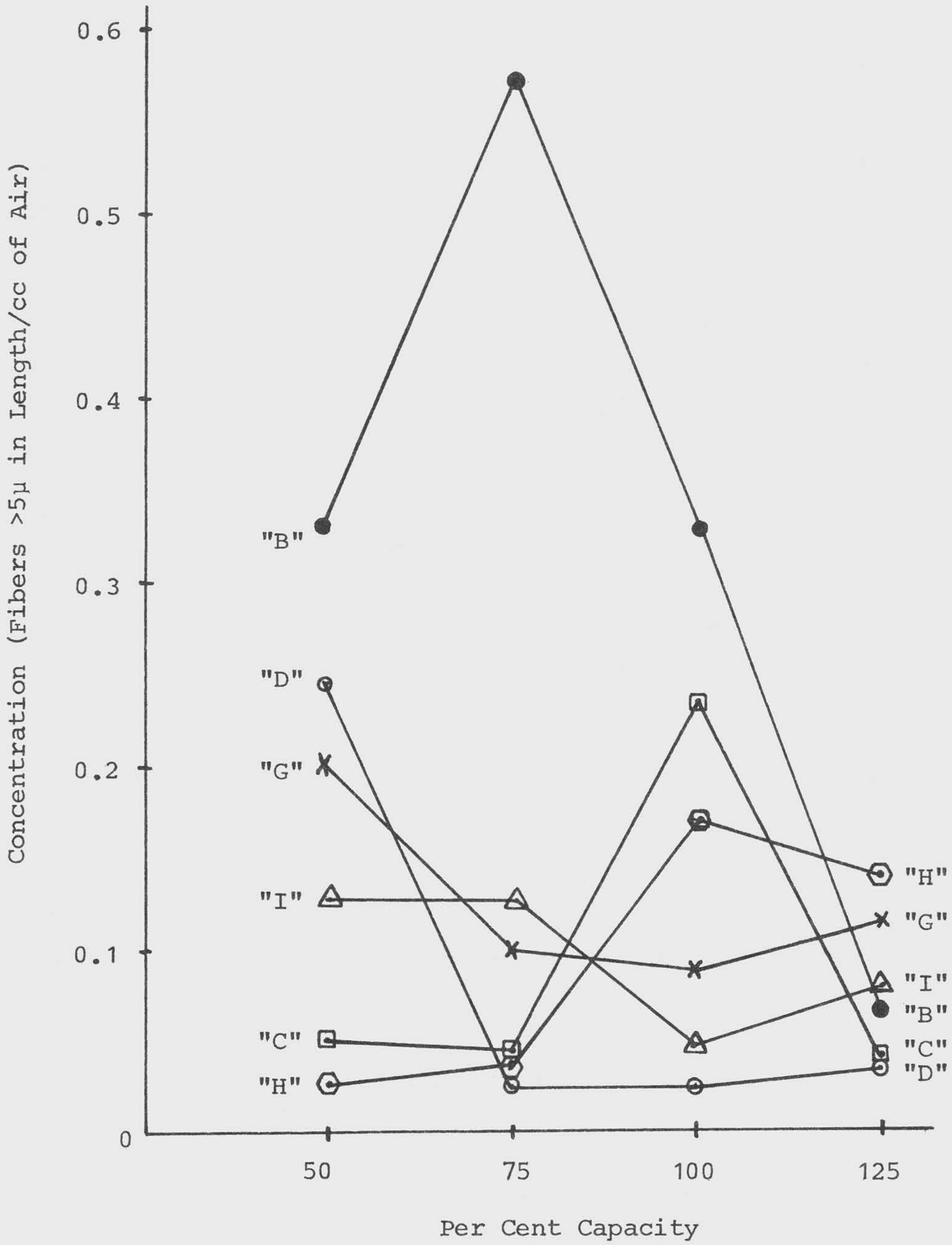


Figure 7. Plot of Fiber Concentration vs. Percent Capacity for Vacuum Units "B", "C", "D", "G", "H", and "I".

in which a disposable paper bag burst during a test, subsequent clean up of the vacuum cleaner was difficult and the asbestos that escaped from the broken bag became airborne when attempting to remove the damaged bag. The absence of asbestos fibers in the exhaust air of a vacuum cleaner in which a bag had burst is believed to be due to the extensive filtering system incorporated into the vacuum cleaners. Thus, an internal breakdown would probably not be evident until the vacuum cleaner is opened for cleaning.

To summarize, the effect of capacity on vacuum cleaner performance is not evident in the fiber concentration of the air exhausting from the vacuum cleaners that underwent complete testing. This indicates that the ability of the vacuum cleaners to contain the entrapped asbestos, even in the event of an internal failure such as a bag rupture, is within design specifications. The effect of capacity on vacuum cleaner performance is evident in the change in suction pressure. This effect is a decrease in the ability of the vacuum cleaner to pick up the asbestos as the percentage of asbestos inside the cleaner increases. All of the vacuum cleaners except one were able to contain 25% more than their specified capacity without internal problems, failure of the filtering system, or total loss of suction pressure.

VII. WORK PRACTICE EVALUATIONS OF VACUUM TEST UNITS

A. EVALUATION OF VACUUM CLEANER "A"

1. Construction (See Figure 8)

This unit consists of a motor and housing, canister, and wheel carriage which clamps onto the canister. Two internal metal rings are held in position between the motor housing and canister rim. Three latches hold this assembly together. Filters are mounted onto the internal rings. The first ring above the canister rim holds the primary filter, a cotton satine bag which connects to the internal ring by means of an elastic band installed in the bag which is stretched over a lip on the ring. The second ring holds the final filter, a FG pad (fiberglass). This filter is held in position by two wire mesh screens.

2. Filtering System

a) The satine bag is the initial point of filtration for any dusts being drawn into the vacuum unit. The cotton satine bag collects dusts on its exterior surface.

b) The secondary filter, the FG pad, functions to filter out any dusts penetrating the cotton satine bag.

3. Comments

One weakness of this unit involves the breakdown of the filtration system. Upon pick-up of dusts, the cotton satine will have a mat of asbestos dust build-up on its exterior surface. This dust build-up sometimes causes the cotton satine bag to pull loose from the retaining ring. The elastic band is not sufficient to keep the cotton satine bag in place. Large quantities of dusts by passing the cotton satine bag will not be retained by the fiber-glass pad. This fact has been demonstrated in several tests. As a result, large amounts of dusts were released into the exhaust air.

This system as received for testing is not sufficient to control asbestos dusts. One possible means of improvement would be to include a disposable filter bag as the primary filter before the cotton satine bag. This would still not be fool-proof for re-taining asbestos dusts. In the event that the disposal paper bag ruptures, the same series of events that occurred before the paper bag was installed would occur and asbestos would be released in the exhaust air in large quantities.

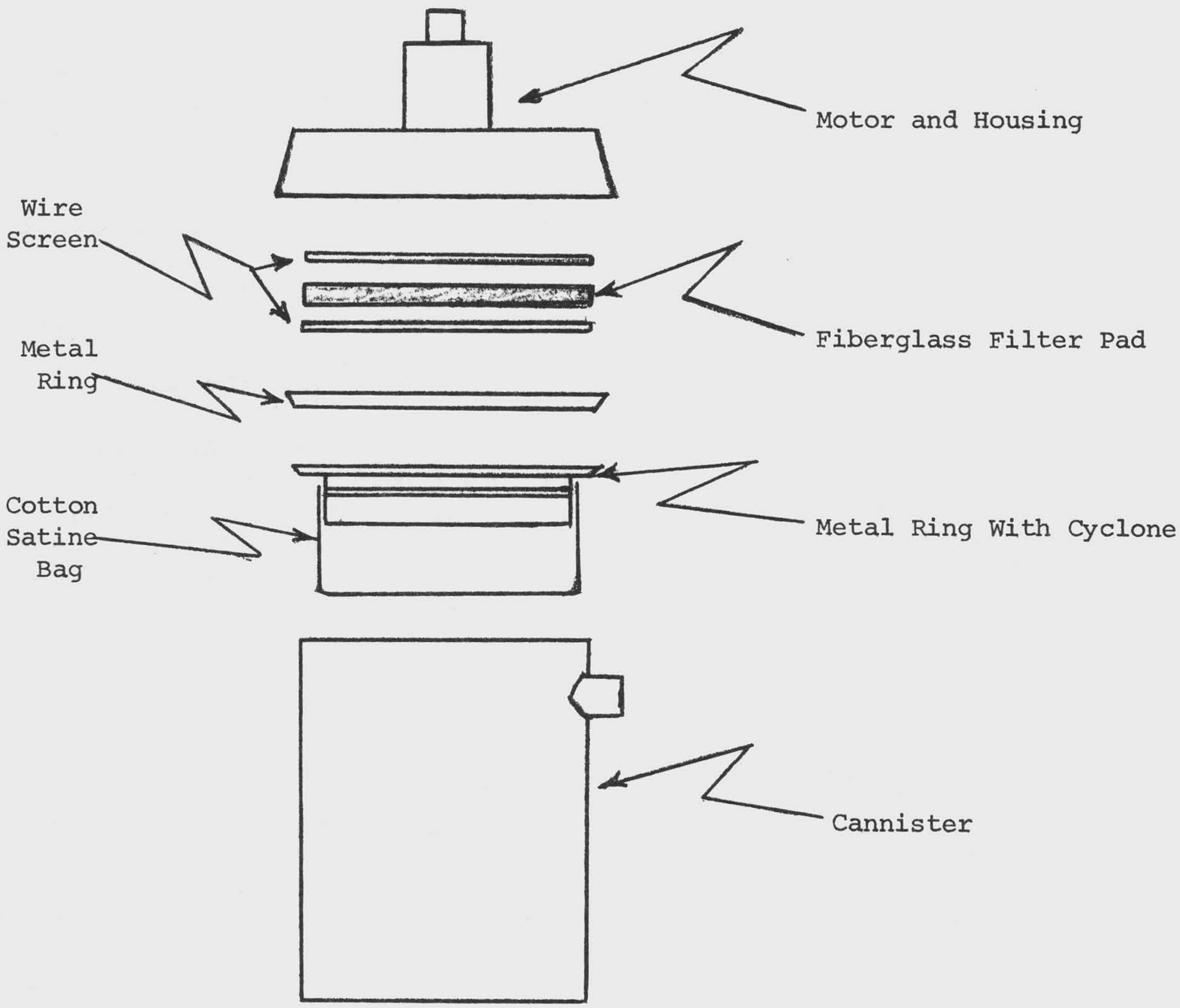


Figure 8. Diagram of Unit "A"

As received for testing, the vacuum unit had no operating or servicing instructions supplied. Upon request for detailed operating instructions, a parts list and assembly diagram was sent along with a brochure on accessory parts and attachments. No explicit instructions were ever supplied. One of the brochures received listed that a disposable paper bag was available, but none was ever supplied.

4. Serviceability

Serviceability is defined as the removal of all wastes from the vacuum unit and the restoration of the filtration system and interior of the unit to conditions resembling original conditions.

This unit, as supplied, is difficult to service if asbestos laden dusts have been vacuumed. The primary problem is how to contain and dispose of the dusts which have been collected in the bottom of the canister. Some aid is offered by the fact that the canister can be removed from the wheel assembly. If plastic bags are supplied or are available, they may be slipped over the rim of the canister and the dust emptied into the plastic bag.

The cotton satine bag still will need to be thoroughly cleaned since asbestos dusts will be caked on the exterior surface. If asbestos dust is visible on the inside of the bag it may need to be washed gently to restore it. This washing is unfortunate as it may cause undue wear on the cotton satine bag. The FG filter pad should be replaced if any dust is detected in the area between the cotton satine bag and the FG pad.

5. Recommendations

In tests conducted with the unit, visible clouds of asbestos were released in the exhaust indicating a severe breakdown of the filtration system. A disposable paper bag used as the primary filter would improve this system. If a paper bag was installed, then possibly the cotton satine would function successfully as a secondary filter. A better alternative would be to redesign the cotton satine filter to a level that is doesn't contribute to the failure of the system. The final filter, the FG pad, should be redesigned to offer greater filtration efficiency, or an absolute filter used as a substitution.

6. Summary

The basic unit design is comparable with other units designed for asbestos collection but the filtration system and ease of serviceability are inadequate. Also, specific operating and servicing instructions should be supplied with each unit.

B. EVALUATION OF VACUUM CLEANER "B"

1. Construction (See Figure 9)

The vacuum consists of a motor housing, 15 gallon canister with a complex filtering system, and a wheel carriage. The motor housing contains one 1.1 horsepower, 6 ampere, motor. It is held in place on the vacuum cleaner by two latches mounted directly opposite each other on the upper perifery of the canister. An absolute filter (6 1/2" X 6 3/4" X 6") is bolted directly to the intake side of the motor housing. There are two rubber seals between the absolute filter and the motor housing. This absolute filter has a metal enclosure around four sides allowing only one inlet at the bottom of the filter. A fiberglass pad (6 1/2" X 6 3/4" X 1/2") is held over the inlet to the absolute filter by means of a wire screen. The wire screen is held in place over the inlet side of the absolute filter by two long, thin springs attached to the absolute filter's metal enclosure. A cloth filter is mounted to a metal rim by a 1/2" metal band and a rubber gasket is seated snugly around the lip of the metal rim. The lip of the metal rim is seated on top of the vacuum cleaner canister and the rubber gasket serves as a seal between the motor housing and the canister. A paper filter slips over the rim of the canister underneath the rubber gasket and protrudes into the canister. A disposable paper filter bag is connected to the intake port of the canister. An optional addition to this vacuum system is a plastic bag placed underneath the filter bag. This is made possible by the 11 1/2" intake port inside the canister.

2. Filtering System

Because this vacuum cleaner was developed specifically to be used in asbestos waste disposal, a highly efficient (but complicated) filtering system was developed for this unit. The filtering system consists of five filters. These include three primary filters, a secondary filter, and a high efficiency air filter (absolute filter).

The primary filtering system consists of a 7.5 gallon disposable paper filter bag, a paper protection filter, and a cloth filter bag. The secondary filtering system consists of a double impaction prefilter (a fiberglass filter pad). The fiberglass filter is attached underneath the absolute filter.

3. Comments

This vacuum cleaner is a highly efficient unit. One design feature was found inadequate in this vacuum system; the number and quality of the motor housing latches are not sufficient to guarantee a proper seal between the canister and the motor housing. This would not cause any problems if the motor housing is placed on the canister properly, due to the suction pressure

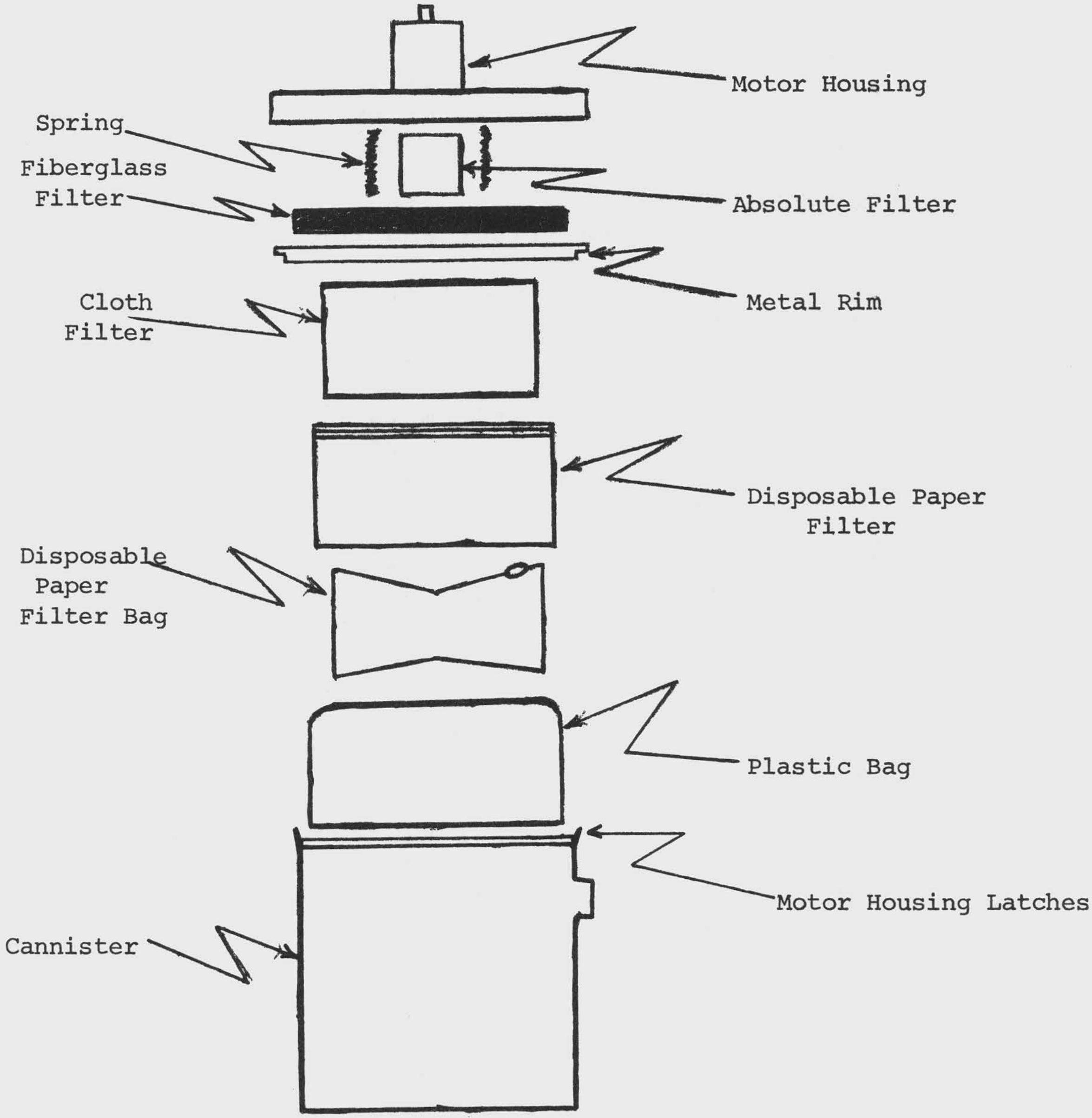


Figure 9. Diagram of Unit "B"

between the canister and motor housing. However, if the motor housing was inadvertently latched to the canister improperly or if one of the two motor housing latches were to fail, a possible hazardous dust exposure could arise.

4. Serviceability

Routine servicing of the unit was found to be relatively rapid. The paper filter was easily folded into the plastic bag along with the disposable paper filter bag. The plastic bag was secured and simply disposed. This method of disposal of the asbestos wastes was one of the most efficient methods encountered.

Restoring this vacuum unit to its original condition was found to be fairly tedious because of the number of filters in the vacuum system. In general use, each of the filters would not require changing or cleaning every time the disposable filters were removed; but, this would be recommended in such cases as filter overloading or after prolonged use. The cloth filter bag was found most difficult to remove from the metal rim due to the metal band attachment. Each time the cloth bag was removed the band became less efficient. Another problem with this unit is also due to the number of filters in the vacuum system. Even in routine servicing, there is the potential of leaving a filter out of the vacuum cleaner. This can be prevented by educating the vacuum cleaner operator by means of a simple check list.

5. Recommendations

One or two more motor housing latches should be added to the canister. All of the latches should be of a better quality than those that are now on the system.

The cloth filter band should be designed to allow the removal of the cloth filter.

A set of simple filter placement directions should accompany each vacuum unit, possibly written directly onto the vacuum cleaner canister.

6. Summary

The vacuum cleaner is a highly efficient vacuum system. With a few minor changes, it could be one of the better low volume systems available.

C. EVALUATION OF VACUUM UNIT "C"

1. Construction (See Figure 10)

a) Ovoid canister with wheels
   1) wire frame

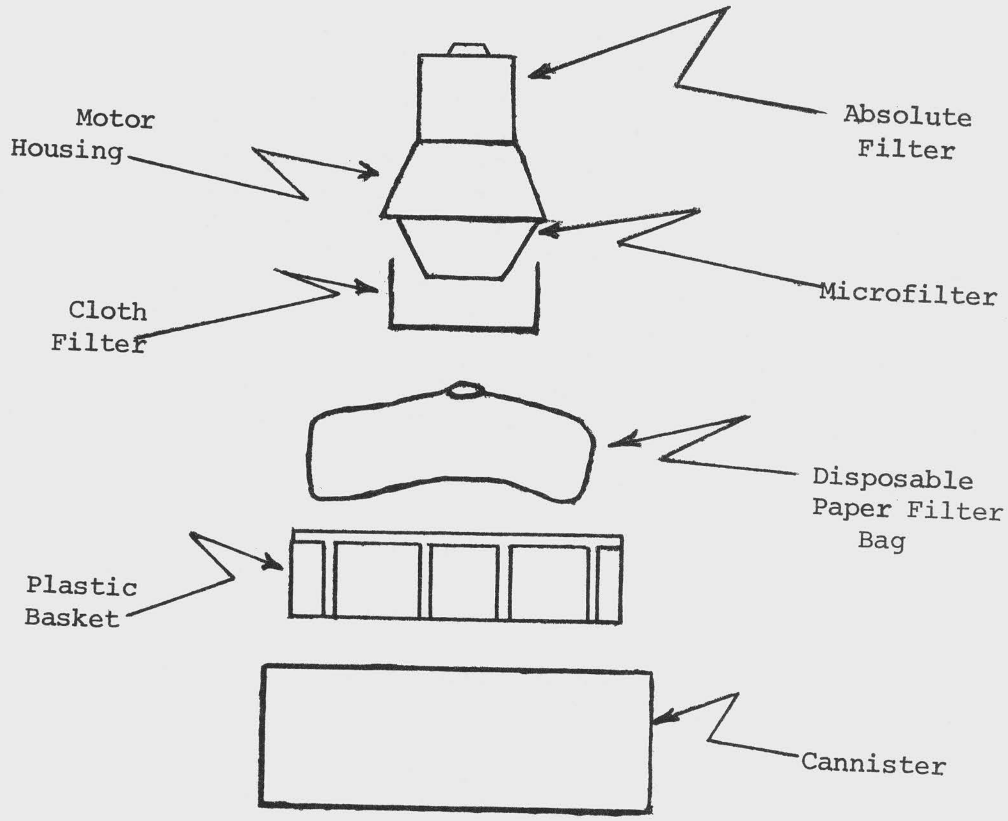


Figure 10. Diagram of Unit "C"

2) plastic retaining ring
3) primary filter - disposable paper bag

b) Motor housing with secondary cloth filter
c) Motor with tertiary and quarternary filters.

The canister and motor housing clamp together by means of two clamps, with a rubber seal at this joint. A metal frame rests in the bottom of the canister and supports a paper bag and plastic retainer. The plastic retainer rests over the paper bag and holds it down in the canister. A permanent secondary cloth filter is mounted in the motor housing, protruding down into the canister. The motor mounts into the motor housing by means of bayonnet-type locks. An elastic-rimmed cotton filter fits over the lower portion of the motor frame. A final filter is mounted on the exhaust side of the motor and is known as the exhaust filter.

2. Filtering System

The overall filtration system consists of four filters; three on the intake side of motor, one on the exhaust side. The primary filter is a disposable paper bag, while the secondary filter is a cloth filter permanently mounted to the motor housing. A tertiary filter (microfilter) consists of a cloth filter removable from motor frame, and an exhaust filter is mounted externally on the exhaust side of the motor. A summary of the filter materials and surface areas of the filters is listed below:

Filter	Material	Surface Area
1	paper	3800 cm^2
2	cloth	1850 cm^2
3	cloth	200 cm^2
4	fiberglass	3200 cm^2

This filtration system is designed to give a large filtration area to allow for a smooth and even airflow through the filters.

3. Serviceability

As long as the paper bag filter maintains its integrity, the serviceability is clean and quick. If the bag ruptures due to overloading, or any other reason, serviceability becomes more tedious and hazardous.

Once the unit has been separated into two parts, canister and motor housing with motor, the paper bag, which is easily removed, contains the majority of the collected waste. The secondary cloth filter can be shaken into a plastic bag to prevent most of the dusts from becoming airborne. The microfilter is easy to remove and can be shaken clean also. The exhaust filter is not cleaned, but is replaced after a certain period of time depending on the use and levels of asbestos collected. All filters and parts are easily accessible.

4. Recommendations

The stated capacity is an area that poses a potential problem. Operators have no way of accurately knowing when the capacity is reached or exceeded. In previous testing, the primary filter integrity was destroyed at levels below the stated capacity of the unit. It was concluded that the stated capacity was not an accurate representation of the true capabilities of this unit as operated.

5. Summary

The filtration system is thorough and adequate. Serviceability is easy and quick. Actual capacity is easily exceeded, however, back-up filters prevent any appreciable escape of fibers until the unit is serviced.

D. EVALUATION OF VACUUM CLEANER "D"

1. Construction (See Figure 11)

This unit is a larger than normal, yet still portable, vacuum cleaner. Its body is a canister 26 inches wide and 22 inches tall. A beveled motor head is bolted directly onto the canister, consisting of 3, one-horsepower motors. A smaller canister, 25 X 11 inches, is attached to the bottom of the body of the vacuum. There is a rubber seal between the two canisters. The smaller canister is used for the collection of waste. It is designed to drop down by pulling up on a metal bar located at the foot of the vacuum. A metal retaining ring, used to hold a plastic bag in place to collect the waste, is found inside the smaller canister.

2. Filtering System

There are two types of filters on this unit. The first is a large cloth bag found inside the canister body. A large rod is attached to it which is used as a manual shaking mechanism to remove any loose particles from the cloth bag. The second filtering system is a set of three absolute filters found on the exhaust ports of the vacuum motors.

3. Serviceability

Routine servicing of the unit was found to be relatively easy. The main filter was shaken and the smaller canister removed. The metal retaining ring was removed from the canister and the plastic bag was tied off and properly disposed. A new plastic bag and the retaining ring were replaced.

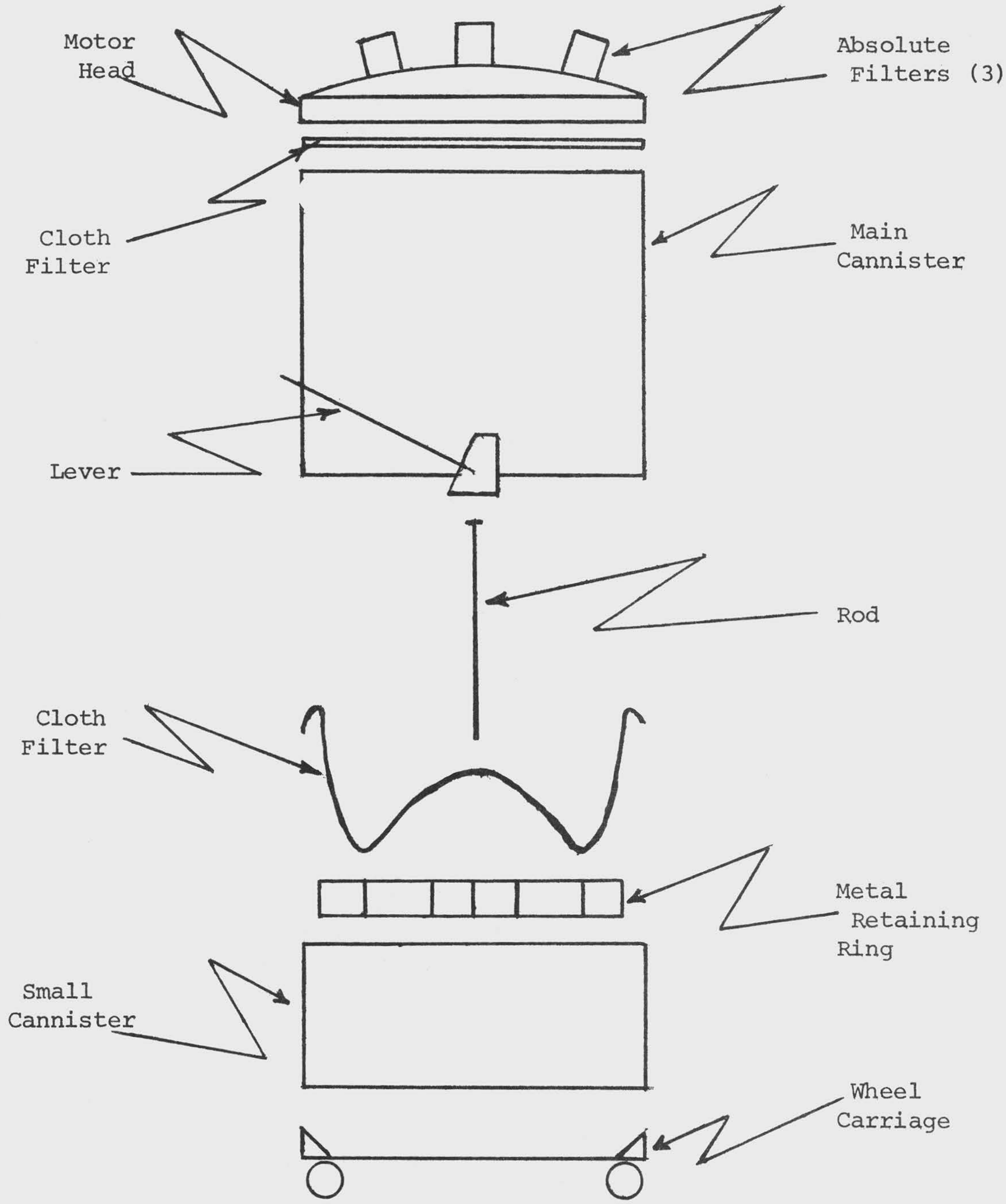


Figure 11. Diagram of Unit "D"

4. Comments and Recommendations

A small amount of asbestos was lost (possibly causing personal exposure) when the retaining ring was removed from the small canister.

5. Summary

The unit is an efficient vacuum system. Because of its size, it would not be recommended for areas with limited space requirements.

E. EVALUATION OF VACUUM UNIT "E"

1. Construction (See Figure 12)

The unit consists of a 16 gallon canister placed on a wheel carriage. A motor housing containing three 1-horsepower, 6.3 ampere motors, is held in place at the top of the unit by three latches uniformly distributed around the top of the canister. A dual-purpose rubber seal is placed between the canister and the motor housing. Inside the canister, the rubber seal holds one filter to the lip of a wire cage. Another filter is stretched over the wire cage and held in place by a wire ring, thus preventing collapse while in use. The filter held in place by the rubber seal is loosely placed over the first filter. Underneath the second filter and at the bottom of the canister, a 9.5 gallon disposable paper bag is held in place over a 1-1/2" inlet hose adapter by means of a rubber diaphram.

2. Filtering System

This unit has a three-part filtering system:

a) the primary filter is the disposable paper filter bag;
b) the secondary filter is a water and fire resistant outer-filter, termed "never-clog filter"; and
c) the final filter is a cotton bag. As previously mentioned, this filter is stretched over a metal cage and held in place by a retaining ring.

3. Comments

By virtue of the relatively low fiber counts, the design and construction of this unit is an efficient vacuum unit in the collection of asbestos dust. The only design feature that was determined as needing improvement on this unit is that of the latches which hold the motor housing in place. These motor housing latches are not adequate to determine proper placement of the motor housing on the rubber filter seal. This would not cause any problems if the motor housing is placed on the rubber

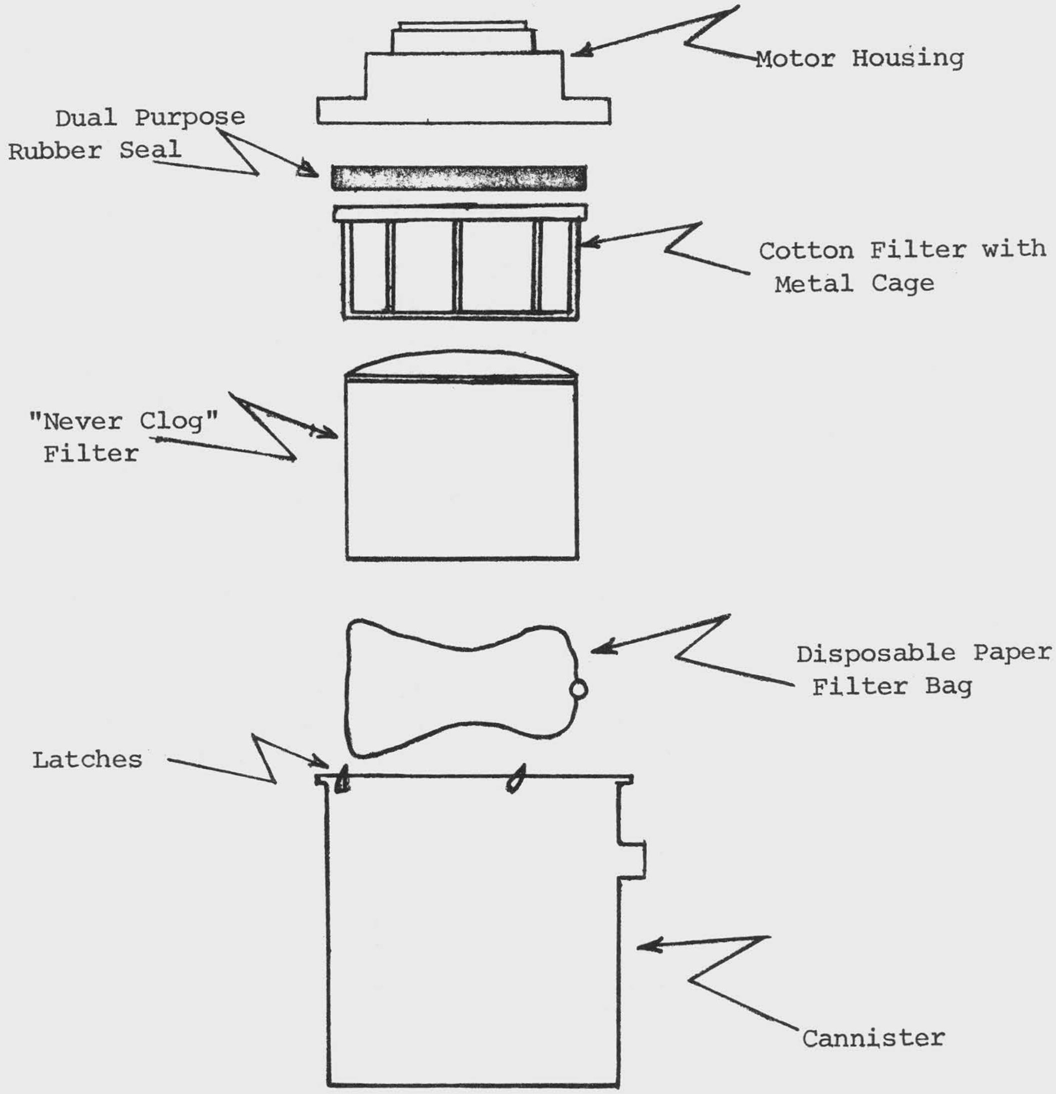


Figure 12. Diagram of Unit "E"

seal properly, due to the suction pressure between the canister and motor head. If the motor housing is not properly placed on the rubber seal, the seal between the canister and the motor head would be inadequate and a possible asbestos exposure could arise. In all fairness it would be difficult, but not impossible, to place the motor head on the vacuum unit improperly because of the large width of the rubber seal. Proper use and maintenance instructions should be supplied with each vacuum system.

4. Serviceability

In cleaning and restoring this unit into its original condition, two problems were encountered. First, the vacuum unit was tested both with and without the primary filter (i.e. the disposable paper bag). While this made no significant differences in the asbestos fiber counts, it did make a considerable difference in the servicing of the vacuum cleaner. With the filter bag in place, the asbestos waste was rather simple to dispose by simply removing the filter bag. But, in attempts to increase the capacity of the vacuum unit, the filter bag was removed and cleaning became a major problem. The removal of the loose asbestos from the bottom of the canister was of primary importance and usually created a greater dust hazard.

Another problem was that of the small cotton filter. Each of the secondary filters (the cotton filter and the "never-clog" filter) were removed and cleaned between tests. The "never-clog" filter was fairly simple to remove and clean but because of the way it was attached to the metal cage, the cotton filter became increasingly difficult to remove and clean, as the wire ring became less efficient with use.

5. Recommendations

The basic design of the unit was good. A more efficient means of latching the motor housing to the vacuum cleaner canister should be developed as should a better way of retaining the cotton filter to the metal cage. Because of servicing problems, this vacuum should not be used without a filter bag when cleaning up asbestos waste.

6. Summary

The unit is a relatively good low volume vacuum system. Of the canister type units, this unit was sufficiently easy to service.

F. EVALUATION OF VACUUM CLEANER "F"

1. Construction (See Figure 13)

This unit was unique among the vacuum units tested. The frame is of a heavier construction than the other units, and is

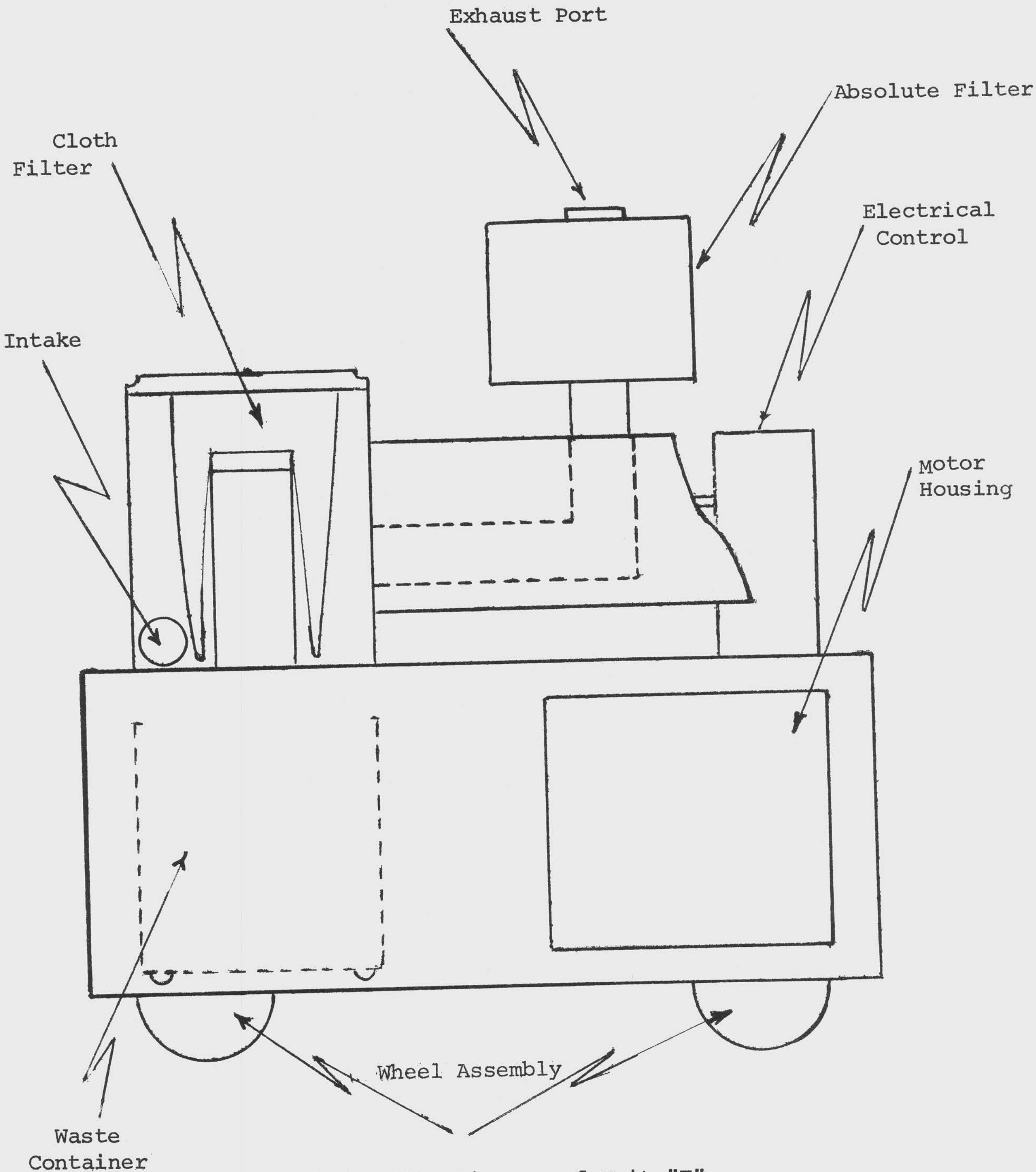


Figure 13. Diagram of Unit "F"

rectangular in shape and mounted on 4 wheels. The overall heavy construction indicates the consideration given by designers for the type of environment the unit would be subjected to.

The unit can be best described by examining the basic areas separately:

- a) frame with motor and electrical circuitry (see diagram);
- b) filtration system:
  - 1) cloth filter bag
  - 2) absolute filter (optional);
- c) waste container - detachable metal container mounted on wheels.

2. Filtering System

The initial point of filtration is a large cloth filter. This cloth filter attaches to a lid which is held in place by the suction pressure generated when the motor is operating. When the unit is shut down the lid can be raised and the cloth filter shaken.

Before the air is filtered, it is channeled through a cyclone where the bulk of the airborne fibers are removed from the air.

When an absolute filter (optional equipment) is mounted on the exhaust port, it becomes the final filter. The unit used in this series of tests was equipped with the optional absolute filter.

3. Serviceability

This unit was easily serviced. The design of the waste-collection container made removal of the asbestos from the unit simple and expedient.

The bulk of the asbestos waste was deposited into the waste container, which can be removed from the housing and rolled away. From this waste container, the asbestos can be easily loaded into disposable plastic bags.

When the unit is initially deemed ready for service, the cloth filter is gently shaken while the waste container is still in place. After a few minutes have elapsed to allow for fiber settling, the waste container can be removed. Once the emptied waste container is reattached to the housing, the servicing is complete and the unit is ready for operation.

4. Recommendations and Conclusions

As tested, the unit has only two filters. This is fewer than any other unit tested. Even so, no reduction in filtration capabilities was observed. By having fewer filters, the servicing of the unit becomes a simple operation.

The unit is simple, yet functional with serviceability quickly and easily performed. One exception to this unit's overall evaluation is the lack of specific maintenance and operating instructions.

VIII. EVALUATION OF VACUUM UNIT PERFORMANCE BY ISOKINETIC SAMPLING

A. INTRODUCTION

Several different aerosol sampling methods are in use today. Though each of these procedures are valid methods of determining particular concentrations in air, results produced by one method often do not correlate with those of other methods under similar test conditions. The state of the aerosol must be considered when choosing a sampling procedure with respect to the air stream velocity, relative concentration of particulates, chemical and physical nature of the gaseous system, and the possibility of time dependent variations.

Isokinetic sampling is a method of sampling in which the flow of the air sample into the sampling device has the same flow rate and direction as the ambient atmosphere. An isokinetic condition allows the difference in concentration and size distribution between the original aerosol and the sample size to be as small as possible. To sample isokinetically, the air to be tested must be moving through a defined area.

No applicable standard for the use of vacuum cleaners for the asbestos industry is available today, though vacuum cleaning is specified as the preferred method of removing asbestos waste. Various studies have been completed on various vacuum units using different sampling methods. Isokinetic sampling is considered by some to be a more reliable method of testing vacuum cleaners than the still air sampling tests described in other sections of this report.

Due to the differences in design and construction of the exhaust system of each vacuum unit, the initial test procedure (Test 1) would have to be altered if an isokinetic sampling technique was used to conduct all the tests in this research project. Therefore, isokinetic testing was not used. The objective of this test was to evaluate the feasibility of sampling for asbestos fiber emissions from industrial-use vacuum cleaners with the use of an isokinetic sampling chamber. This chamber was developed to incorporate the majority of portable vacuum units available to industry today and allowed for a uniform isokinetic sampling technique for most of these vacuum units. Because of size limitations only three units were tested ("C", "B" and "E").

B. ISOKINETIC SAMPLING TEST

The manufacturer's operating guidelines were followed stringently during the test procedure, and the units were tested with 100 percent chrysotile asbestos to simulate the worst possible work conditions. In order to maintain a uniform test procedure, five pounds of asbestos were used in each test. The test procedure was repeated a total of two times with each unit tested. After each test, each of the filters and bags were changed as required in the operator's instruction manuals.

A chamber was developed to funnel the exhaust air from each of the vacuum systems in order to sample isokinetically. This chamber was of 18 gauge aluminum in three sections, as shown in Figure 14. The first section used a cylinder, three feet in diameter and three feet tall which was large enough to incorporate each of the vacuum units while maintaining a minimum of dead air space. This was important to prevent the heavier asbestos fibers released from the test vacuum cleaner from falling out of suspension before it was removed from the chamber. A door was cut into the cylinder in order to place each of the portable vacuum cleaners inside the test chamber.

The second portion of the chamber was a 36-by 4-inch reducing coupling which measured two feet from top to bottom. The inside of this section, as with the total system, was impervious so that only a minimum of asbestos was collected on the sides of the chamber. The third section was a 3-inch found duct made of P.V.C. plastic pipe, 50 inches in length, to serve as a stack. The chamber funnels the exhaust air out of this stack. This size stack was chosen because it was sufficient to allow for a representative sample, but not so small as to permit the linear flow rate within the system to be prohibitively high to work with while using the highest velocity vacuum cleaner.

Approximately ten diameters (75cm) from the base of the stack, a six point pitot traverse was run before and after each test to determine a reference air velocity pressure. The air velocity was monitored throughout each of the tests with a hot wire anemometer to enable immediate adjustment of flow through the sampling system to accommodate the isokinetic sampling procedure. Although continuous pitot traverse measurements may have been used to assure isokinetic sampling, it was felt that the hot wire anemometer was simpler to use without reduced accuracy. As required in isokinetic sampling, the temperature and humidity of the sampled air was monitored constantly.

The development and accurate monitoring of the sample train was the most difficult aspect of the research. First, the development of a properly-designed sample probe was of major importance. It was placed in the stack approximately 100cm from the top of the reducing coupling. From the sample probe, the air was

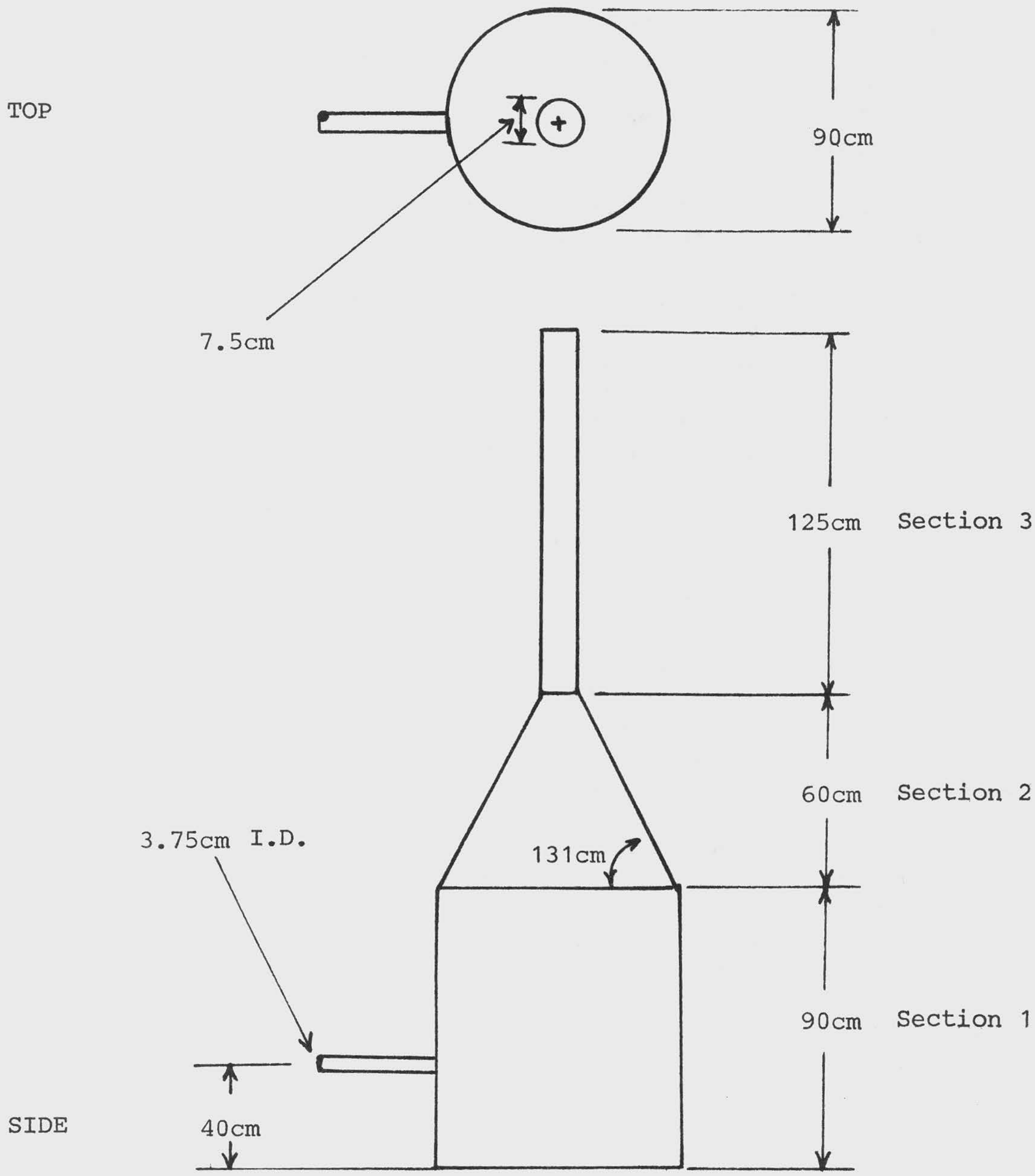


Figure 14. Isokinetic Test Chamber

filtered through a closed face 37mm, 0.8μ micron pore size, Millipore aerosol field monitor. Three extra center extensions were added to the filter cassette to act as a plenum. Next, in the sample train, a Gilmont Flowmeter No. F1500 was used to determine the proper adjustments necessary to match the sample air velocity with the duct air velocity. A dry gas meter was used to measure the volume of the air sampled. This was essential in order to match the same volume of air sampled in the still air sampling procedures (60 liters).. Air was drawn through this sampling train by means of a vacuum pump. A flow control valve was incorporated into the sample train immediately before the vacuum pump in order to make the proper corrections in the isokinetic sampling procedure.

The asbestos was induced into the system through the asbestos hopper which was used in the other vacuum cleaner tests. The filters were sent to an accredited laboratory for counting and analysis by the standard counting method.

C. RESULTS AND CONCLUSIONS

The objective of this test was threefold: 1) to develop a chamber with which the majority of industrial-use portable vacuum cleaners may be tested isokinetically for the release of asbestos fibers; 2) to isokinetically test vacuum units under similar circumstances; and 3) to determine if there was a difference in an isokinetic sampling procedure and the still air sampling procedure that was used in the other vacuum cleaner tests in this research project.

The data from this test is tabulated in Table 2. When compared with the results of the still air studies under the same experimental conditions, it was concluded that there was no significant difference between the results of the two different sampling techniques. Additional information concerning the isokinetic test of vacuum cleaners is contained in an unpublished thesis by Grabowski (38).

Table 2. Asbestos fibers per cc of air.

	Isokinetic Study		Still Air Study	
Vacuum	Test 1	Test 2	Test 1	Test 2
Unit "C"	0.25	.05	.17	.04
Unit "B"	.05	.01	.093	.078
Unit "E"	.17	.16	.42	.245

IX. CONCLUSIONS AND RECOMMENDATIONS

A. GENERAL CONCLUSIONS

This research represents a first step in establishing a performance documentation for industrial vacuum cleaners used for the collection of asbestos waste. Prior to this project, no research sought to compare the performance of more than one vacuum cleaner against a common test regimen. While this research did not provide a quantitative ranking of performance, it did provide qualitative results. Several approaches to the design of vacuum cleaner systems were examined and qualitatively compared. This comparison is the most important result of the project since it provides a basis of knowledge for the potential consumer of these systems. Manufacturers do not possess comparative data to judge the relative performance of their units either for sales appeals or for improvements in design.

The major weakness of this project, as well as any project attempting to use actual asbestos, was the measurement of fibers in the vacuum cleaner exhausts. It has been shown that the best asbestos fiber counting procedures among microscopists and among samples reflect a 30% variation in results (36). This degree of variability completely masks any slight differences in fiber emission between units.

These results, however, do not suggest that testing of units for asbestos waste disposal should not or cannot be done. The health hazards posed by asbestos fiber is so great that testing is imperative, even in view of known variables in standard analytical techniques. The testing should be performed as a routine procedure by manufacturers and eventually a standard test method should be established by an appropriate agency (e.g. NIOSH, ANSI, ASTM).

Any manufacturer testing should include several tests. All filter materials used should receive a rating for particulate collection. This rating is common for HEPA filters where the rating is stamped on the side of the filter at the time of manufacture. Beyond HEPA filters, however, other cloth and paper materials should be comparatively tested and rated before adoption into the design of the system. Furthermore, the general sealing and fitting of the unit deserves considerable scrutiny. All units should be subjected to a careful quality control inspection and the manufacturers should consider a DOP test to search for leaks which should be sealed before shipment of the unit. Any significant or regularly recurring leaks should lead to an evaluation of the design of the unit.

Work practices is a major area where the manufacturer should employ research effort. Many units reflect less than optimal human factors design. The units are bulky, difficult to move, and require awkward positioning to service the unit. Servicing is the area most ignored by manufacturers. Yet, this area is critical to the continued safe operation of the unit in the field. Manufacturers provide little, if any, guidance on servicing and this procedure is assumed to be common knowledge. Certainly the servicing of the unit is critical in overall performance and the user should have some guidelines on when and how to service the unit as well as when the unit may not be operating properly.

Only one manufacturer provides a mechanism for alerting the user to the need for servicing (manometer). Beyond this, the vacuum cleaner industry has failed to adopt a standard or a device for measuring air flow. The "Vacometer" used in this research is the only mechanism routinely used by a manufacturer for air flow measurement. This mechanism, however, is subject to error and has not been adopted for use by other manufacturers.

The establishment of a manufacturers' association in this industry could be an important step in producing quality control standards and test methods. The absence of such an association has resulted in the need for this research and any followup research. Hopefully, the results of this research will suggest the need for a manufacturers' association with special attention to quality control standards in both manufacturing and field use.

This research has represented a great challenge to the project staff. Numerous research questions arose and were resolved as the project progressed. It is important to acknowledge the assistance of manufacturer representatives in this process. Without this assistance, the quality of results would have been adversely affected. The many variables and research questions resulting from this research represent a foundation and basis for further needed efforts.

Engineering controls are viewed as a major method of providing health and safety for the worker in a reliable way without reliance on cooperation by the individual worker. The industrial vacuum cleaner is an important element in engineering control of asbestos fiber. This research has shown that these units can represent as much of a hazard as a help. Certainly, these systems deserve continuing attention both by the research and manufacturing communities.

B. DESIGN CONSIDERATIONS

1. Classification of Basic Designs

The units tested varied in weight from approximately 15 kg to approximately 80 kg (empty weight) with capacities ranging from approximately 20 liters to 70 liters. Because of this wide range in size and capacity, a basic classification system was needed for comparing the various units on an equal basis. For the purpose of this research, the following system was proposed for portable vacuum cleaner units:

Class 1 - small canisters (capacities of approximately 20 to 30 liters with disposable bag filters).

Class 2 - large units (capacities over 30 liters with non-disposable filters).

2. Discussion of Designs

a) Class 1: The small canister class includes 6 of the units available for study: "A", "B", "C", "E", "G", and "H". These units are in this class because of their canister size and because the primary filter in each is a disposable paper bag. Unit "C" is the smallest unit in this class with a canister volume of approximately 21 liters. The volume of the disposable filter bag varies with each unit. Unit "C" has a rated capacity of 19.25 l., unit "B" uses a filter bag rated at 28.85 l., unit "E" bag is rated at 36.5 l., and unit "A" is rated at 44.25 l. (See Table 1.) These capacity ratings are manufacturers' specifications and not data generated from this research.

Another design similarity within this class is the means by which the units are disassembled. The motor and its housing are all mounted over the canister and held in place by quick-release latches.

The differences in the units in Class 1 is primarily with the secondary, tertiary, and quaternary filters (if present). All the units have a cloth filter as the secondary filter, but the basic designs vary. On one unit, the secondary cloth filter is mounted on a wire frame which holds the filter stationary and allows a large surface area to be exposed to the dust-laded air. Another unit has the cloth filter hanging loosely into the canister body from a supporting rim. Other units use a cloth filter that is mounted over a rim and held in place by means of an elastic band sewn into the filter.

Three of the units tested have tertiary filters, two of the units have fiberglass pads. Only one unit in this class has a quaternary filter. See Table 1 for the filter.

Two of the units in Class 1 have handles mounted on the canister which aid in controlling these units. The internal surface of the canister is smooth and unobstructed on three of these units. One unit has several bolts protruding into the canister area. This canister surface should be as smooth and unobstructed as possible since paper bags containing asbestos will fill this area and the bolts would tend to tear the bags.

b) Class 2: The large-bodied units differ in appearance from Class 1 markedly and they also differ in appearance from each other. They are portable in the sense that they are mounted on wheels or rollers and can be moved about easily. However, their weight and bulkiness limit their portability to one primary location. It would be difficult to move them from one building to another.

The entering dust-laden air in these units is filtered initially by a large surface area cloth filter. This filter is non-removable and is designed to be shaken periodically to restore it. One unit has an external plunger-shaker to facilitate the removal of the asbestos waste. In one unit, a cover must be lifted and the exposed filter shaken by hand. All units in this class were equipped with high efficiency filters as the final filter. These units have the capacity to collect larger volumes of asbestos (50 to 70 liters, estimated).

These units have a canister (which is removable) into which the filtered asbestos is collected. One of the units has a wire frame under which a plastic bag can be placed to aid in disposal.

3. Design Recommendations

a) Class 1: It is recommended that each unit in this class be equipped with a tear-resistant disposable paper bag. The volume of this bag should be stated and this data should be available to the consumer.

The secondary filter should expose as much surface area as possible. Also, it should be securely held in place. If it becomes laden with asbestos and falls from its mounts due to the weight, the filtration reliability will be lost. A wire frame is recommended as the optimum design to which the cloth filter should be securely mounted. A minimum of three (3) clamps should be used to secure the lid to the body of the unit.

If the primary and secondary filter are of sound design, a fiberglass pad should be sufficient as the final filter. If greater filtration efficiency is demanded, then a high efficiency filter could be installed in place of the fiberglass pad. One unit has a silk filter on the filtration side of the cloth filter. This silk filter serves to collect the majority of fibers and debris escaping the paper bag. It also protects the cloth filter from damage and wear. A silk filter is recommended as a means of prolonging the life of the cloth filter and increasing the long-term efficiency of the filtration system.

As long as the units were properly assembled and the various filters remained in place, all of the units in this class had fiber emissions in the exhaust well below the current standards. The three most significant problem areas with the units in this class are summarized below:

1) Several dramatic failures (test room completely engulfed with asbestos dust in the air) were the result of the disposable paper bags rupturing, for one reason or the other. The quality of the paper bags, when used for disposal of asbestos waste should definitely be increased and controlled in order to minimize failures of this nature.

2) Cloth bag filters which are held in place by elastic bands tend to slip off when the bag gets full. Several failures of this type were observed during the capacity test program. Each resulted in asbestos spreading throughout the unit and sometimes into the exhaust air, creating hazardous conditions for the maintenance personnel. The method of attaching the cloth bag should be redesigned in a more reliable manner.

3) The configuration of the filters, and lack of proper instructions on some units made it easy to leave out a primary filter or attach the filters improperly. Several failures of this nature were experienced and will be discussed further in the "Work Practice" recommendations.

b) Class 2: The cloth filter is necessary as a primary filter. This filter should be as inaccessible as possible to the operator during servicing of the unit to prevent unnecessary exposure from fibers present on the filter. Therefore, the external plunger-shaker is recommended.

An externally-mounted high efficiency filter is recommended as the final filter. This filter should have a long operating life and a large internal effective surface area.

One limitation of the Class 2 designs tested was the lack of protection afforded to the cloth filter. Since the cloth filter is the primary filter and will be exposed to a variety of compounds, the life of this filter is of unknown and probably varied duration. No solution to this potential problem is known at present.

Two of the three units tested in this class have 220 volt power requirements. This limits the portability of the units in most applications. The power requirements should be clearly stated on the unit when it is greater than the standard 115 volt supplies.

All of the units tested in this class were efficient and performed satisfactorily so far as the fiber counts exhausted were concerned.

The prime area of concern centers around the protection of the cloth filters and servicing of the vacuum cleaners.

C. WORK PRACTICE CONSIDERATIONS

The ease of serviceability of the units varied considerably. Factors influencing the ranking of unit service were:

1) presence of maintenance or serviceability instructions or manual,
2) housekeeping problems created by servicing,
3) exposure to service and maintenance personnel,
4) accessibility of filters,
5) potential for human error in replacing filters,
6) time required to service, and
7) accuracy required in replacing filters.

In all cases, the manufacturer's specifications and instructions (if available) were followed in the use and service of the vacuum cleaners.

The larger units (Class 2) were the easiest to service. They were also superior in factors (2) and (6) (lack of housekeeping problem and shortest time to service) listed above.

Units which would rate a satisfactory or good rating with respect to serviceability become marginally rated units when the primary filter (paper bag) ruptured or tore, creating a number of problem areas.

In order to minimize problems created by the omission of a filter or incorrectly assembling of the various filters, consideration should be given to a simple, effective filter system that is as fool-proof as possible in so far as human error is concerned. Researchers who participated in the testing were highly educated and motivated individuals; yet a number of mistakes were made in placing the filter into their proper positions. In all cases, the errors adversely affected the performance of the units, in some cases significantly. The maintenance and service personnel would not be expected to be as motivated, nor probably appreciate the magnitude of the hazards of asbestos waste, and therefore would be expected to commit more mistakes than the researchers who conducted the tests.

Specific recommendations in the areas of work practice or serviceability are listed below:

1) The development of complete and exact operating instructions for all vacuum cleaners used for the collection of asbestos waste. This instruction manual should be included with all asbestos vacuum cleaners. The presence of explicit and complete

vacuum cleaner assembly, operating, and care instructions could greatly enhance the effectiveness of any vacuum cleaner.

2) Evaluation of vacuum cleaners under actual working conditions during operation in an asbestos environment. This may give a more practical assessment of employee exposure to asbestos fibers.

3) Educational programs for those employees that use vacuum cleaners for the control of asbestos. The importance of proper vacuum cleaner operation, assembly and waste disposal cannot be overstated due to the extremely dangerous potential of asbestos.

D. SELECTION OF THE PROPER VACUUM CLEANER

The selection of the proper vacuum cleaner for the collection of asbestos waste should depend on the following factors, but not in any particular order of preference:

1) size and weight of unit,
2) mobility requirements,
3) effectiveness of unit (containment of asbestos fiber),
4) capacity of unit,
5) reliability of unit,
6) suction pressure,
7) work practice considerations,
8) power requirements, and
9) price of unit.

Two of the units tested ("C" and "G") were extremely small units and could be used in confined spaces such as submarines and other limited-space areas. The remaining Class 1 units were middle sized units, similar to the common shop or garage vacuum cleaners. As mentioned previously, the remaining units (Class 2) were large, bulky units with a more limited range as far as portability is concerned. Size would, therefore, be of prime consideration depending on the actual application of the units.

Since all of the units performed satisfactorily, unless an internal failure occurred, the next consideration should probably be a unit whose design minimizes human error and maximizes reliability. It may well be that maintenance personnel will be exposed to greater risks than the hazards associated with emissions from the exhaust of the units. For this reason, serviceability and other work practice considerations should be given a high priority when selecting the proper vacuum cleaner.

E. SYSTEM OF DETERMINING FIBER CONCENTRATION

For testing of this nature where no human operators are present, the method of collection and analysis should possibly not depend on one measurement system. A practical area-monitoring system could be used in conjunction with the present NIOSH-approved phase-contrast method (or possibly as a substitute for the NIOSH-approved method if deemed acceptable).

A direct-reading area monitor would provide quicker results and allow for more adjustments to be made to the testing procedure. Also the two measuring systems could be compared as to similarity of counts. An overall evaluation could be made of several methods. If another method is found to be more reliable, then further studies could be conducted to determine the feasibility of incorporating it as an additional "approved" method, especially in the lower fiber concentrations. It was difficult to distinguish between the various units in the extremely-low-concentration environments.

F. RECOMMENDATIONS FOR FURTHER RESEARCH

This research effort suggests the need for a manufacturers' association and an operating charter which includes a provision for research on vacuum cleaner performance. Thus, the formation and adequate funding of such an association is one of the leading recommendations of this project. Given the existence of this group, or any other interested party, there are several key issues which must be addressed including:

1) The test facility - should a large room be used or a small enclosure providing better control of exhaust streams?

2) The challenge medium - is pure asbestos the best challenge medium and, if so, which size and what quantity? If not pure asbestos, what mixture or combination should be used?

3) The test method - is fiber counting the best method or should another approach be attempted (e.g. optical particle counting, DOP testing, etc.)?

4) The analytical method - is the NIOSH method most effective or the ashing method recommended by Esmen (36), or perhaps a gravimetric method?

5) The sampling period - is a 30 minute period adequate or is a long term (8 hours) or other intermediate period more effective?

6) The selection of units - which units should be tested and should they be classified (large, small, high efficiency, low efficiency, etc.)?

7) The classification of units after testing - is a rating justified and how should this rating be reported (in literature, brochures, or on the unit proper)?

8) A work practice - what recommendations should be made regarding operation and handling the unit with emphasis on servicing?

9) Industry-wide performance standards - what suction pressure, air flow, filtration efficiency, or other parameters should be adopted?

10) Field instrumentation - what type of instrument(s) should be developed or adopted to measure performance including motor rpm, volatage demand, etc.?

11) Air flow measurement - should a more accurate "vacometer" or other air flow measuring devices be developed?

Nearly all of these questions are interrelated and will affect any future research. If asbestos is adopted as the challenge material, the project is constrained by the state-of-the-art of fiber counting. If DOP is used, the applicability of results (beyond leak testing) to other materials is subject to debate. The test facility is a necessary foundation to the applicability and repeatability of any results.

Many of these questions were addressed in this research, but the answers were not definitive. It appears that the first course of action is the establishment of an advisory group composed of representatives of each interested area (e.g. manufacturers, users, etc.) as well as standards associations (ASTM, ANSI). These latter associations provide a mechanism for the orderly establishment of a consensus standard. This research project is a challenge to manufacturers to assume the initiative to further carry on with this research and establish guidelines which will provide an effective and reliable control mechanism to efficiently collect and dispose of asbestos waste while protecting the health of the worker.

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Appendix A. Fibrous Aerosol Monitor Evaluation

A. Introduction

The NIOSH-approved method of sampling and counting was used to determine the level of asbestos fibers escaping from the vacuum units tested. Alternate techniques for fiber enumeration are available and the usefulness of one technique was tested in this study.

The GCA Corporation's Fibrous Aerosol Monitor (FAM) was chosen as the alternate method and was used to determine asbestos levels emitted from one vacuum unit (33,34,35,39). Also, the change of fiber concentration within the test room over varying lengths of time was monitored with the FAM. Simultaneous sampling was performed with the NIOSH-approved method to provide some level of comparison between the two methods.

B. Principles of Operation

The FAM is a prototype instrument developed and tested recently in a joint industry and government project. The FAM is a light-scattering particle counter, yet it differs from other light scattering particle counters due to its specificity for fibrous-shaped particles.

The principle on which the FAM operates is based on two properties of fibrous-shaped particles; (1) electrostatic properties, and (2) light-scattering properties. A continuously flowing sample stream (1 - 2.5 l/min, variable) of air is subjected to a high intensity rotating electric field and concurrent illumination by a parallel beam of monochromatic light. The flow stream should remain fixed at 2.0 l/min.

The rotating electric field aligns incoming fibers perpendicular to the direction of flow and causes the fibers to oscillate. The oscillating fiber is illuminated by the beam of monochromatic light and the incident light is scattered characteristically by the oscillating fiber. The scattered light is detected by a photomultiplier detector and the signal is amplified. Varying particle length will produce varying scattered light intensity. The minimum length of fibers detected (and counted) by the FAM can be controlled by adjusting the ratio control and amplitude control on the face of the FAM. Minimum fiber detection length is approximately 2μm.

C. Advantages and Disadvantages

The FAM is capable of giving realtime results whereas the NIOSH-approved method requires significant time delays before results can be obtained. No variability is present from human interpretation of fiber counts. The FAM will give visual readout of fiber concentration. Also, a strip-chart recorder can be attached to continually record signals and counts from the FAM. When studying processes or equipment such as vacuum cleaners for levels of emission, the FAM is extremely useful. The FAM has not been designed to monitor breathing zone air of workers; therefore, the amount of asbestos fibers being inhaled by a worker cannot be directly estimated, only fibers present in a given area can be determined.

D. Testing Procedure

1. Methodology

A sample stand was positioned in the test room as depicted by Figure 15. The sample stand held 3 sample heads as depicted in Figure 16. These heads could be located at any of 5 positions depicted in Figure 16. The sample height was 1.2 meters. One sample was connected with the FAM by means of 0.9 meters of tygon tubing. The flow of the air sample stream was calibrated by means of soap bubble buret. The flow was set at 2 l/min. The remaining 2 samples were connected to an electric pump by means of 1.5m of tygon tubing. Limiting orifices were located in line behind the filters and the flow rate was calibrated at 2.0 l/min with a soap bubble burette.

As in previous tests, a vacuum unit was located in the center of the room and connected to the feed pipe from the feed room (see Figure 1).

The FAM was located outside of the test room with the connecting sample tubing running through a hole in the test room wall.

2. Investigative Procedure

a) Walls and floor of test room were thoroughly mopped to remove as much extraneous dust as possible.

b) 2.27 kg of chrysotile asbestos were loaded into feed hopper.

c) Test room door was taped shut, all power was turned on, and vacuum cleaner and feed hopper were started simultaneously.

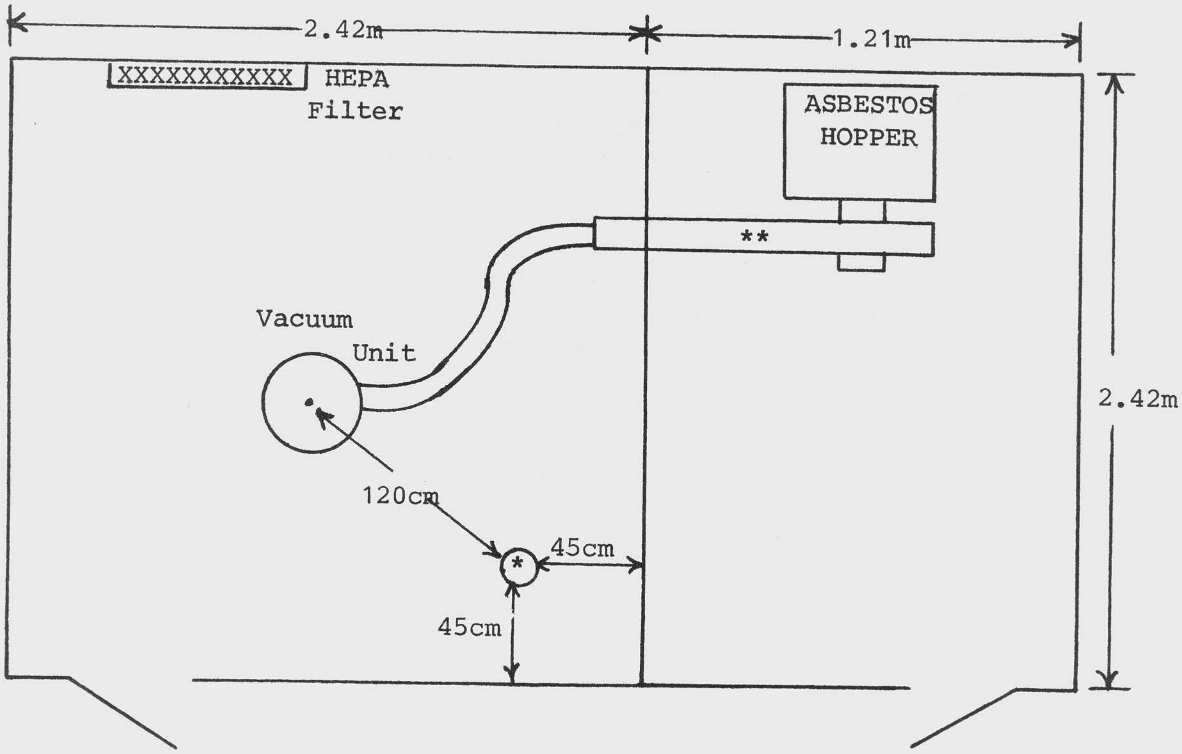
d) 10 minute monitoring periods begun with FAM (simultaneously with vacuum and feed hopper start-up).

e) For various ranges of fiber concentrations, as monitored by the FAM, both methods sampled for 10 minute periods. Range 1: 1.25 fibers to 0.25 fibers/cm^3; and Range 2: 0.25 fibers to 0.05 fibers/cm^3.

f) At end of 10 minute period of Range 2 all power shut off. Test room entered and NIOSH method samples covered and removed.

g) Steps a-f repeated 8 times.

h) NIOSH method samples were sent to the same laboratory



* Location of sample holder

** Asbestos feed rate: 0.6kg/minute

Figure 15. Test Room, Showing Location of Sample Holder

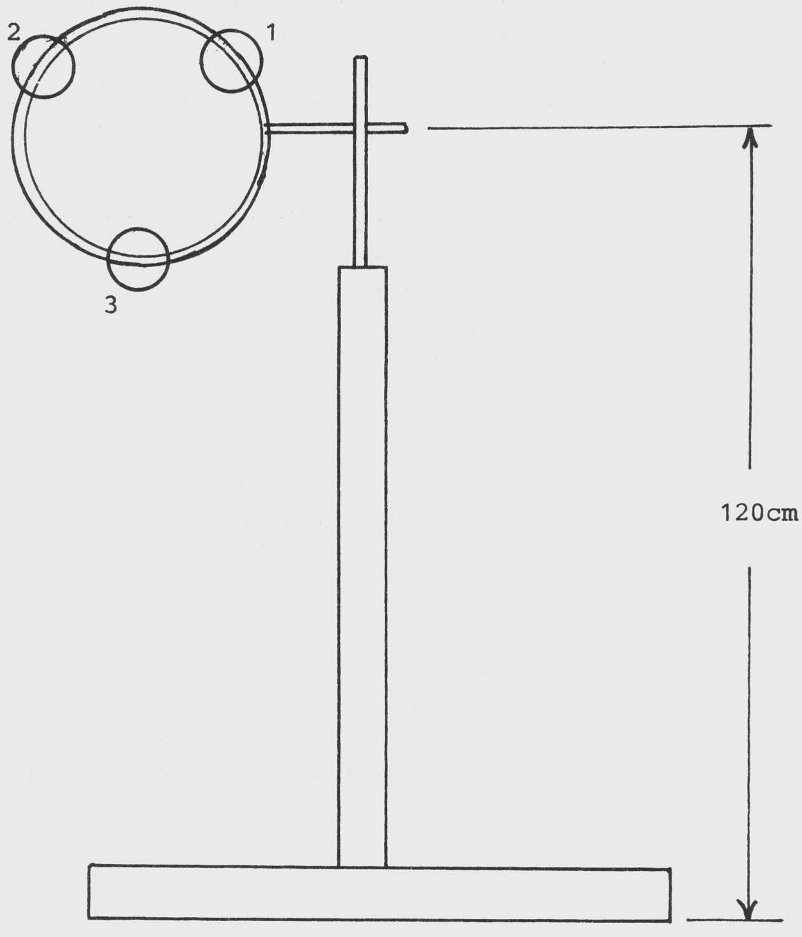


Figure 16. Sample Holder With Three Heads

which was used for the analysis of the other tests in this research project.

i) Concentration method samples were sent to a laboratory which specialized in this method of counting.

j) Data from all three counting methods were tabulated and plotted for further analysis.

E. Results

The results of this study are presented in Figures 17 through 18. Graphs of each counting method are presented for comparison. Each method was studied under high and low ranges of fiber concentration. Range 1 varied from 0.5 fibers/cm^3 to 1.25 fibers/cm^3. Range 2 was from 0.05 fibers/cm^3 to 0.25 fibers/cm^3.

Because the fiber counts were expected to be higher using the FAM, a third counting method was utilized for a third point of comparison. Data were taken simultaneously and counted by the three different methods. A tabulation of the data is found in Table A-1.

The third method used was the Fiber Concentration Method (36) which was developed especially for low airborne fiber concentrations. The samples for this method were sent to a laboratory which specialized in this method of fiber counting.

F. Conclusions

The fiber counts obtained by the three different methods varied significantly. The counts from the Fibrous Aerosol Monitor were higher on 16 of the 18 different samples taken. On most instances, the FAM gave results which were higher by a factor of approximately four times. FAM obtained values were much more consistent, as expected, since they were controlled.

Use of the Fibrous Aerosol Monitor shows definite possibilities; however, more research is needed at the present time. Definite conclusions from this study cannot be made in so far as the comparison of the three counting methods are concerned. Additional information in this research area can be found in a Master's thesis by E. Studinka (37).

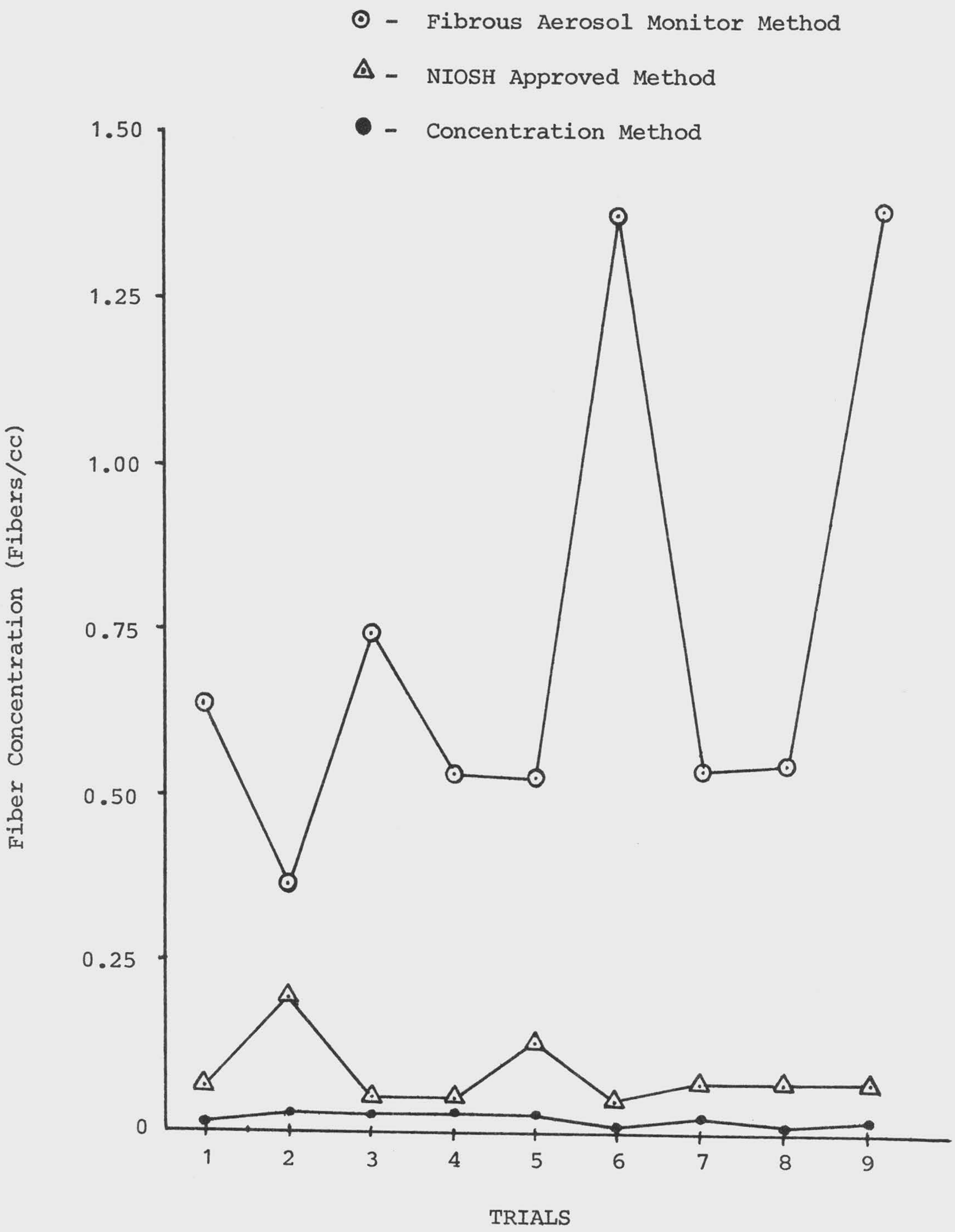


Figure 17. Plot of Fiber Concentrations vs. Trials for F.A.M. Method, NIOSH Method, and Concentration Method, Range (0.5 fibers/cm^3 to 1.25 fibers/cm^3)

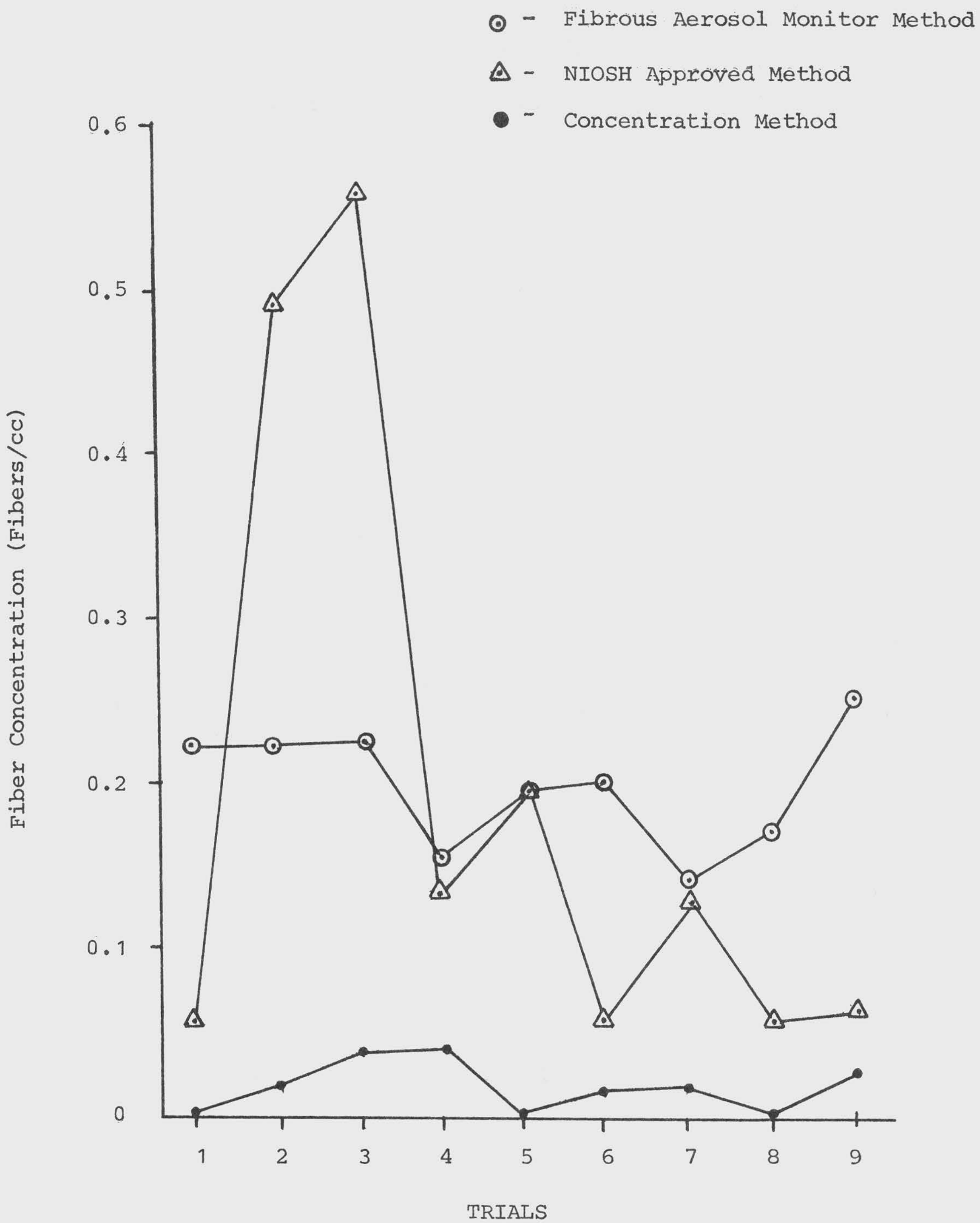


Figure 18. Plot of Fiber Concentration vs. Trials for F.A.M. Method, NIOSH Method, and Concentration Method, Range 2 (0.05 fibers/cm^3 to 0.25 fibers/cm^3)

Table A-1. Fiber Concentrations for Fibrous Aerosol Monitor Method and NIOSH Approved Method and Concentration Method

	Sample No.	FAM	Concentration	NIOSH
	1	0.67	0.007	0.06
	2	0.34	0.022	0.18
	3	0.74	0.015	<0.05
	4	0.54	0.022	<0.05
Range 1	5	0.52	0.015	0.12
	6	1.38	0.007	<0.05
	7	0.56	0.022	0.06
	8	0.58	0.007	0.06
	9	1.40	0.022	0.06
	1	0.22	0.007	0.06
	2	0.22	0.015	0.49
	3	0.23	0.030	0.55
	4	0.16	0.030	0.12
Range 2	5	0.19	0.007	0.19
	6	0.20	0.015	<0.05
	7	0.14	0.015	0.12
	8	0.17	0.007	<0.05
	9	0.25	0.022	0.06

Appendix B. Selected Excerpts from the USPHS/NIOSH Membrane Filter Method for Evaluating Airborne Asbestos Fibers (TR-84)

A. Scope

This method describes the equipment and procedures for collecting, mounting, sizing and counting asbestos fibers on membrane filters in the evaluation of breathing zone samples of airborne asbestos fibers.

The method has been successfully applied using 37mm Millipore AA filters and small battery-operated personal sampling pumps at a flow rate of 1.0 to 2.5 liters per minute for time periods of 15 to 150 minutes at concentrations of 1 to 20 fibers (longer than 5 microns) per cubic centimeter. Large deviations from these conditions may result in filters with either too few or too many fibers, which will yield air concentration estimates of low statistical precision and accuracy.

This method considers only fibers with a length to width ratio of 3 to 1 greater and a length greater than 5 microns.

B. Summary

The sample is collected by drawing air through a membrane filter by means of a battery-powered personal sampling pump. The filter is transformed from an opaque solid membrane to a transparent, optically homogeneous gel. The fibers are sized and counted by phase contrast microscope at 400-450X magnification.

C. Interferences

All particulates with a length to width ratio of 3 to 1 or greater and a length greater than 5 micrometers should, in the absence of other information, be considered to be asbestos fibers and counted as such.

D. Optical Equipment

1. Microscope body with binocular head.
2. 10X Huygenian eyepieces are recommended. Other eyepieces can be substituted if necessary.
3. Koehler illumination (preferably built in and having provisions for adjusting light intensity).

Prepared by Nelson A. Leidel, Stephen G. Bayer and Ralph D. Zunwalde, NIOSH, 11/73.

4. A Porton reticle is recommended. Others such as the Patterson Globe and Circle can be substituted, if necessary.
5. Mechanical stage.
6. Abbe or Zernike condenser fitted with phase ring (or Hiene) with a numerical aperture (N.A.) equal to or greater than the N.A. of the objective.
7. 40-45X (N.A. 0.65 to 0.75) positive phase contrast achromati objective.
8. Phase-ring centering telescope or Bertrand lens.
9. Green filter, if recommended by microscope manufacturer.
10. Stage micrometer with 0.01mm subdivisions.

E. Filter Mounting Equipment

Experience has shown that certain equipment is useful for efficient sample mounting. The following items are recommended for extracting and mounting a portion of the filter onto the microscope.

1. Microscope slides: 2.5 by 7.5 cm (1-inch by 3-inches) glass slides are most commonly used. Sample number, data, initials, etc., can be conveniently written on a frosted end slide.
2. Cover slips: Cover slips are a necessary part of the slide mount and optical system. The shape should be appropriate for the size of the filter wedge. The appropriate cover slip depends upon the objective to be used. Ordinarily objectives are optically corrected for a H1 1/2 (0.17 millimeter) thickness cover slip. Improper cover glass thickness will detract from the final image quality.
3. Scalpel: A scalpel is needed to remove a portion of the filter to be examined. A number-ten curved blade scalpel works very well.
4. Tweezers: A pair of fine-tipped tweezers is used to remove the membrane filter slice from the field monitor and place it upon the slide.
5. Lens tissue: To insure cleanliness, use of a lint-free lens tissue is recommended. This tissue should also be used for wiping mounting tools and for cleaning slides and cover slips.
6. Glass rod or spatula: A spatula or fire-polished glass rod is needed to spread the mounting solution on the slide.

7. Wheaton Balsam bottle: This special glass container has a glass top which prevents contamination of the mounting solution. A glass rod is included for dispensing the solution.

F. Reagents

Chemicals should be reagent grade, free from particles and color, conforming to the specifications of the Committee on Analytical Reagents of the American Chemical Society, where such specifications are available.

1. Dimethyl Phthalate
2. Diethyl Oxalate

G. Safety Precautions

Avoid getting the mounting solution on the skin. Wash skin with soap and water if contact occurs.

H. Calibration and Standardization

1. Portion Reticle - The asbestos fiber count procedure consists of comparing fiber length by comparison with calibrated circles, and counting all fibers greater than 5 micrometers in length within a given counting field area. It is recommended that a Porton reticle be used for this purpose. The Porton reticle is a glass plate inscribed with a series of circles and rectangles. The square on the left, divided into six rectangles, is defined as the counting field.
2. Placement in Eyepiece - The Porton reticle is placed inside the Huygenian eyepiece where it rests on the field-limiting diaphram. The reticle should be kept clean, since dirt on the reticle is in focus and will complicate the counting and sizing process. For mounting in other eyepieces such as a Ramsden, a mounting collar must be used.
3. Stage Micrometer - The Porton reticle cannot be used for counting until it has been properly calibrated with a stage micrometer. Most stage micrometer scales are approximately two millimeters long and are divided into units of one hundredth of a millimeter or ten micrometers.
4. Microscope Adjustment - Follow the manufacturer's instruction while observing the following guidelines:
   a) The light source image must be in focus and centered on the condenser iris or annular diaphram.
   b) The object for examination must be in focus.
   c) The illuminator field iris must be in focus, centered on the sample, and opened only to the point where the field of view is illuminated.
   d) The phase rings (annular diaphram and phase-shifting elements) must be concentric.
5. Portion Reticle Calibration Procedure - Each eyepiece objective-reticle combination on the microscope must be calibrated. Should any of the three be changed (disassembly, replacement, zoom adjustment, etc.) the combination must be re-calibrated. Calibration may change if interpupillary distance is changed. For proper calibration, the following procedure should be followed closely. With a 10X objective in place, place the stage micrometer on the mechanical stage, focus, and center the image. Change to the 40-45X objective and adjust the first scale division to coincide with the left boundary of the Porton reticle. Count the number of divisions between the

left and right boundaries of the long horizontal dimensions of the largest rectangle, estimating any portion of the final division. This measurement represents 200 L units and one divides the measurement by 200 to find "L". The large rectangle is 100 L units long on the short vertical dimension. The calculated "L" is inserted into the formula $D=L(2^N)$ where "N" is the circle number (indicated on the reticle) and "D" is the circle diameter. Since the circle diameters vary logarithmically, every other circle doubles in diameter. For example, number three is twice the diameter of number one; number four is twice the diameter of number two. When the circle's sizes have been determined, the counting field area consisting of the left six smaller rectangles can be calculated from the relation 10,000 L^2. This completes the reticle calibration for this specific objective-eyepiece-reticle combination.

I. Procedure

1. Mounting - A very important part of the sample evaluation is the mounting process. This process involves a special mounting medium of prescribed viscosity. The mixture must be stirred periodically until the filters have dissolved and a homogeneous mixture is formed. The normal shelf life of the mounting solution is about 6 months. Twenty milliliters of mounting solution will prepare approximately 300 samples.
2. Sample Mounting - Cleanliness is important. A dirty working area may result in sample contamination and erroneous counts. The following steps should be followed when mounting a sample.
   a) Clean slides and cover slips with lens tissue. Lay the slide down on a clean surface with the frosted side up. It is a good practice to rest one edge of the cover slip on the slide and the other edge on the working surface. By doing this, you keep the bottom surface (the one which contacts the filter) from becoming contaminated.
   b) Wipe all the mounting tools clean with lens tissue and place them on a clean surface (i.e. lens tissue). When mounting a series of filters, the scalpel should be wiped clean before cutting each sample.
   c) Using a glass rod which is supplied with the Wheaton balsam bottle, apply a small drop of mounting solution onto the center of the slide. It may be necessary to adjust the quantity of solution used or the size of the wedge. The correct amount will result in the solution extending only slightly beyond the filter boundary. If the quantity is greater than this, adverse particle migration will occur.
   d) With the spatula or a supplemental glass rod, spread the mounting media into a triangular shape. The size of this triangle should coincide with the dimension of the filter wedge.

e) Separate the middle and bottom sections of the field monitor case to expose the fragile filter. Cut a triangular wedge from the center to the edge of the filter using the scalpel. The size of the wedge should approximate one eighth of the filter surface.
f) Grasp the filter wedge with the tweezers in the outer area of the filter which was clamped between the monitor case sections. Do not touch the filter with your fingers. Place the wedge, sampled side up, upon the mounting medium.
g) Pick up the cover slip with the tweezers and carefully place it on the filter wedge. Once this contact has been made, do not reposition the cover slip.
h) Label the slide with the sample number and current date before proceeding to the next filter.
i) The sample should become transparent after about 15 minutes. If the filter appears cloudy, it may be necessary to press very lightly on the cover slip. This is rarely necessary.
j) Discard the sample mount after 3-days if it has not been counted. Crystals which appear similar to asbestos fibers may begin to grow at the mounting media/air interfaces. They seldom present any problems if the slide is examined before 3 days. In any case, stay away from the filter's edges when counting and sizing.

3. Counting and Sizing - Finding and inspecting counting fields. Place the mechanical stage and position the center of the wedge under the objective lens and focus upon the sample. Nearly all of the particulates (particles and fibers) will be found in the upper 10 to 15 micrometers of the filter surface. When counting and sizing, continual use of the fine focus control is required to insure that nothing is missed. Start counting from one end of the wedge and progress along a radial line to the other end (count in either direction from circumference to wedge tip). Random fields are selected, without looking into the eyepieces, by slightly advancing the slide in one direction with the mechanical stage control.
4. Achieving Comparable Results - Size only fibers with a length to width ratio greater than or equal to 3:1.
Count only fibers greater than 5 micrometers in length. (Be as accurate as possible in accepting or rejecting fibers near this length). Measure curved fibers along the curve to estimate total length.
Count as many fields as necessary to yield a total count of at least 100 fibers. Exceptions: a) count at least twenty fields even if you count more than 100 fibers and b) stop at 100 fields even if you haven't reached 100 fibers.
Select the field of view without looking through the microscope's eyepieces to eliminate unconsciously selecting "heavy" or "light" areas.
The fields are selected along the entire length of a radial line running between the outside perimeter and the tip of the wedge.

When an agglomerate (mass of material) covers a significant portion of the field of view (approximately 1/6 or greater) reject the field and select another. (Do not include it in the number of fields counted.) However, report the fact as it may have meaning to sampling or medical personnel. Bundles of fibers are counted as one fiber unless both ends of a fiber crossing another can be clearly resolved. For fibers that cross either one or two sides of the counting field, the following procedure is used to obtain a representative count. First, arbitrarily select; a) the left and bottom sides and; b) the upper and lower left corners of vertical direction as "decision aids".
Then count any fiber greater than 5 micrometers in length, but only if the fiber:
a) lies entirely within the counting area, or
b) crosses the left or bottom sides, or
c) crosses the upper or lower left corners, or
d) crosses both the top and bottom sides.
Reject and do not count all other fibers.

J. Calculations

1. Calculation of Airborne Concentration - Asbestos fiber airborne concentration may be calculated from the following formula:

$$C = \frac{(F - B\ (W)}{(A)\ (V)}$$

Where:

C = Airborne fiber concentration in fibers greater than five micrometers in length per cubic centimeter of air.
F = Average fiber count in fibers greater than 5 micrometers in length per field.
B = Average fiber count of blank(s) or control filter(s) in fibers greater than 5 micrometers in length per field. (It is subtracted to eliminate the error or background contamination.)
W = $855 mm^2$ for 37mm diameter filter (the portion of the Millipore filter which is exposed when mounted in the field monitor case, i.e., the effective filter area).
A = The area of the counting field of a calibrated reticle expressed in mm^2/field.
V = Total air volume collected through filter expressed in milliliters.

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