LA-UR 74-1035

1974

Conf-740807--6

PERFORMANCE OF MULTIPLE HEPA FILTERS AGAINST PLUTONIUM AEROSOLS*

Manuel Gonzales
John C. Elder
Harry J. Ettinger

Aerosol Section, Industrial Hygiene Group
Health Division
Los Alamos Scientific Laboratory

PREPRINT FROM

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

* Work supported by the U. S. Atomic Energy Commission.

PERFORMANCE OF MULTIPLE HEPA FILTERS AGAINST PLUTONIUM AEROSOLS*

Manuel Gonzales, John C. Elder, and Harry J. Ettinger

Aerosol Section, Industrial Hygiene Group
Health Division
Los Alamos Scientific Laboratory

*Work performed under the auspices of the U. S. Atomic Energy Commission.

PERFORMANCE OF MULTIPLE HEPA FILTERS AGAINST PLUTONIUM AEROSOLS*

M. Gonzales, J. Elder and H. Ettinger
Health Division
Los Alamos Scientific Laboratory
University of California
Los Alamos, New Mexico 87544

Abstract

Performance of multiple stages of High Efficiency Particulate Air (HEPA) filters against aerosols similar to those produced by plutonium processing facilities has been verified as part of an experimental program. A system of three (3) HEPA filters in series was tested against $^{238}PuO_2$ aerosol concentrations as high as 3.3×10^{10} d/s-m^3. An air nebulization aerosol generation system, using ball milled plutonium oxide suspended in water, provided test aerosols with size characteristics similar to those defined by a field sampling program at several different AEC plutonium processing facilities. Aerosols have been produced ranging from 0.22 µm activity median aerodynamic diameter (amad) to 1.6 µm amad. The smaller size distributions yield 10 to 30% of the total activity in the <0.22 µm size range allowing efficiency measurement as a function of size for the first two HEPA filters in series. The low level of activity on the sampler downstream of the third HEPA filter (~0.01 c/s) precludes aerosol size characterization downstream of this filter. For the first two HEPA filters, overall efficiency, and efficiency as a function of size, exceeds 99.98% including the <0.12 µm and the 0.12 to 0.22 µm size intervals. Efficiency of the third HEPA filter is somewhat lower with an overall average efficiency of 99.8% and an apparent minimum efficiency of 99.5%. This apparently lower efficiency is an artifact due to the low level of activity on the sampler downstream of HEPA #3 and the variations due to counting statistics. Recent runs with higher concentrations, thereby improving statistical variations, show efficiencies well within minimum requirements.

I. Introduction

Most AEC facilities use multiple stages of HEPA filters to provide the necessary level of control associated with the release of radioactive particulates. While emission standards have not been established for radioactive particulates, AECM 0524 [1] has been interpreted to require that emission concentrations be controlled so that effluent concentrations at the boundary between controlled and uncontrolled areas does not exceed specified limits without any credit for atmospheric diffusion and dilution between the point of discharge and the boundary. This extremely conservative interpretation limits the release of plutonium to 6×10^{-14} µCi/ml, as measured at the point of discharge. Some operations involving plutonium will generate exhaust air streams with concentrations as high as 10^{-5} µCi/ml just upstream of the building air cleaning system [2] and to reduce this contaminant concentration to that specified by AECM 0524, the building air cleaning system must provide a decontamination factor of approximately 10^9.

*Work supported by the U. S. Atomic Energy Commission

To satisfy this requirement, multiple stages of HEPA filtration have generally been used, and these are quality controlled tested to assure a media efficiency ≥ 99.97% against 0.3 μm monodisperse dioctyl phthalate (DOP) [3].

Because of the potential problems associated with handling and installing these filters [4], most designs assume that the installed filters will perform at a somewhat lower level (99.9 to 99.95%) [5, 6, 7] with this performance level confirmed by in-place testing the entire system with 0.8 μm polydisperse DOP aerosols[8,9].

While these concepts are generally accepted for a single stage HEPA filter, unresolved problems are introduced by the need for multiple filter stages to provide the decontamination factors of 10^9 required to satisfy the previously noted conservative interpretation of AECM 0524. While filtration theory predicts that 0.3 μm aerodynamic diameter aerosols are the most difficult to remove[10], and the 99.97% quality control efficiencies will be exceeded by the first HEPA filter, and at least satisfied by back-up filters, substantiating experimental data does not exist for the specific problem at hand. In addition, existing multiple HEPA filter system designs generally do not permit routine testing to assure that efficiencies for each bank continuously satisfy or exceed 99.9%, nor do the existing test methods provide sufficient sensitivity to confirm decontamination factors (over several HEPA filters in series) of 10^9.

To guarantee the adequacy of existing HEPA filter systems or designs which do not permit routine in-place testing of each successive stage, it is necessary to provide assurance that the filter media will perform against plutonium aerosols at the levels suggested by theory, and monitored by DOP quality control tests on individual filters. To provide this information, an experimental program was initiated to (1) define size characteristics of the source terms from the major AEC operations using plutonium; (2) simulate these aerosols under laboratory test conditions; and (3) define the performance of multiple stages of HEPA filters against these laboratory aerosols. The possibility of obtaining similar information via a field test program was considered, but this approach was discarded since existing HEPA filter systems handling large quantities of plutonium do not permit testing of individual stages, and it would not be possible to distinguish between plutonium aerosol penetration due to the inadequacy of the media in successive stages (due to changes in the aerosol size characteristics) in contrast to leaks around the filters, due to improper installation.

II. Field Sampling--Source Term Characterization

Field sampling to determine Pu particle size characteristics and alpha activity concentration was performed immediately up-stream of the exhaust HEPA filters at five locations: two each at Mound Laboratory and Rocky Flats Plant, and one at LASL. These locations were selected to monitor Pu aerosols produced by typical research and production operations utilizing both ^{238}Pu and ^{239}Pu. Samples were obtained during the most active periods of the working day, when activity concentrations could be termed "worst normal" and most source

operations would be normally contributing plutonium aerosols to the process ventilation system. Many variables were expected to affect size characteristics and activity concentration, resulting in a range of these parameters for each facility. The relationship between some of these variables and the individual sampling sites are summarized in Table I. The predominant chemical form at each plant was reported to be PuO_2, although a detailed chemical analysis of each sample was not performed.

Aerodynamic diameter was considered the significant aerosol parameter of concern in preference to physical (microscopic) diameter since inertial impaction is the chief mode of particle collection by HEPA filters operating at rated capacity [10]. Activity median aerodynamic diameter (amad) is a convenient unit because it is not affected by changes in isotopic ratio, particle shape, or particle density. Particle size characteristics were determined by radiometric analysis of each of the nine stages of Andersen impactors (eight impaction stages plus backup membrane filter). Errors due to possible rebound of particles were minimized by covering the impaction surface with filter media.

Table II summarizes the results of this field sampling program in terms of the mean values of amad and geometric standard deviation (σ_g). Detailed analysis of the individual sampling results[11] shows that the two fabrication facilities have aerosols with amad's ranging from 2 to 5 μm; the two research and development facilities indicate amad's ranging from 1 to 4 μm; and the recovery facility consistently shows a sub-micron aerosol with a typical amad of 0.3 to 0.5 μm. This recovery facility (location 11) also produces aerosols as small as 0.1 um amad, has the highest activity concentration, and constitutes the most difficult air cleaning problem.

III. Performance of Multiple HEPA Filters

A. Experimental Procedures

A two-module laboratory test system was designed and constructed to permit testing three HEPA filters in series, using ^{238}Pu test aerosols with size characteristics similar to those defined by the field sampling program. HEPA filter efficiency would be determined in terms of gross plutonium activity passing each filter as well as a function of aerosol size. Figure 1 shows the first module, a 9 ft. glove box housing the aerosol generators, (1); sampler #1, (2); and HEPA filter #1, (3). Each test HEPA filter has a design flow rate of 0.012 m^3/s (25 cfm) and its construction and filtration velocity is identical to the typical 0.472 m^3/s (1000 cfm) units used in most air cleaning systems. The only difference is that the 0.472 m^3/s (1000 cfm) units are generally open faced, while the test filter is designed for in-line installation with 2-inch pipe nipples at each end. Figure 2 shows the second module and its major components which consists of sampler #2 (4) immediately upstream of HEPA filter #2 (5); sampler #3 (6) immediately upstream of HEPA filter #3 (7); sampler #4 (8) downstream of HEPA filter #3; and a vacuum pump (9).

Samplers #1, #2 and #3 are dual samplers simultaneously collecting a gross membrane filter sample for aerosol concentration, and an Andersen impactor sample for measuring aerosol aerodynamic size characteristics. The gross filter measurements determine overall HEPA filter efficiencies, while impactor data are used to calculate HEPA filter efficiency as a function of plutonium aerosol aerodynamic size. Sampler #4 consists of nine 2-inch open face glass fiber filters (Figure 3) and is designed to filter all the exhaust air. This was required because of the very low levels of activity existing at this point which preclude impactor measurements to define aerosol size characteristics downstream of the third HEPA filter.

To obtain sufficient activity downstream of the third HEPA filter in series it was calculated that an activity concentration of $\sim 10^{10}$ to 10^{11} d/s-m^3 had to be produced by the aerosol generating system. This high activity level upstream of the first HEPA filter resulted in activity levels collected on the first impactor which are virtually impossible to handle with the counting facilities available. To circumvent this problem, a sample dilution system was designed to draw a relatively small sample 2.33×10^{-5} m^3/s (0.05 cfm) at the sampling probe, to be diluted with 4.48×10^{-4} m^3/s (2.95 cfm) filtered air. Even so, samples obtained from this first sampler required preparation of extensive serial dilutions prior to counting. Andersen impactors located downstream of the first and second HEPA filters did not need dilution systems because the activity concentration at those positions are sufficiently low. A gross filter sampler was used at each location, concurrently with the Andersen samplers, to monitor total aerosol concentration. Sampling times varied for each sampling position with one minute being sufficient for position number one (upstream of first HEPA filter) and up to two hours for position number three (downstream of second HEPA filter). With these gross differences in sampling times, it was necessary to take several samples at position number one during each run to monitor the degree of variation in aerosol generator output as a function of time.

Several plutonium aerosol generating methods were investigated before choosing the modified ReTec nebulizer[12]. Modification entailed enlarging holes in the cap and jet to twice their original size to provide a threefold increase in aerosol output, from $\sim$300 µl/min to $\sim$900 µl/min at 3.45×10^5 pascals (50 psig) operating pressure. The generator solution reservoirs were constructed of brass to a capacity of 70 ml to allow generation times up to one hour per loading, O-ringed for elimination of leaks and Teflon coated to minimize wall losses. Six of these nebulizers attached to a central duct (Figure 4), with a generator solution concentration of up to 8.0 mg/ml $^{238}PuO_2$ suspended in water, yielded the plutonium aerosol concentrations required to test three HEPA filters in series.

To keep the suspension well stirred and achieve a constant aerosol output, the reservoirs were partially immersed in an ultrasonic bath throughout the aerosol generation run. Because the aerosol was produced from a water suspension, care was exercised to assure that all water was dried from the particles before arriving at the samplers and the first HEPA filter. This required supplying heated air at the system air inlet, raising the temperature of the system air about 10°C.

To approximate plutonium aerosols with 0.1 to 5 μm amad's measured under field conditions, $^{238}PuO_2$ powders were dry ball milled for various time intervals and suspended in water to a concentration of 2.5 -8.0 mg/ml. Ultrasonic agitation of the suspension broke up agglomerates, and addition of anionic surfactant kept the suspensions well dispersed. Selective ball milling provided some control of size characteristics over the range of interest with some limitations at either end. By adjusting the ball milling time, it was possible to produce aerosol with amad's ranging from 0.7 to 1.6 μm, with σ_g's ranging from 2.1 to 2.9. Even with extensive dry ball milling, it was not possible to produce an aerosol with an amad smaller than 0.7 μm. However, these aerosols contained a significant fraction of particles smaller than 0.4 μm, which is the smallest size fraction which can be characterized by the Andersen impactor operated at its normal sampling rate of 0.48×10^{-3} m^3/s (1 cfm).

To provide aerosols similar to those measured at the chemical processing facility (location 11; amad ranging from 0.1 to 1.0 μm) a centrifugal ball mill was used to mill various batches of $^{238}PuO_2$ for varying time intervals. Smaller sizes could be attained because of higher rate of energy input. Milling was carried out using a carrier liquid to reduce agglomeration. Initially, ethanol was used, but high pressures generated within the mill enclosure necessitated a change to water as the carrier liquid. Additional problems were encountered as a result of alpha activity breaking down the water to H_2, O_2, and H_2O_2, again creating high pressures and explosive mixtures within the mill jar. A continuously vented mill enclosure was developed to eliminate these problems. The new milling procedures yielded aerosol amad's ranging from 0.22 μm to 0.66 μm for milling times ranging from 44 to 167 hours. Though not reaching the desired 0.1 μm amad, these size distributions yield 10 to 30% of the material in the size range of interest, i.e., <0.22 μm.

The previously described sampling system ahead of each HEPA stage was modified to allow impactor sampling at 1.42×10^{-3} m^3/s (3.0 cfm). As previously utilized in the field sampling program at location 11, operation of these impactors at higher flow rates shifts the effective range of particle size classification downward to include the lower limit of the range of interest (0.1 μm). Calculated and experimentally measured effective cutoff diameters[13] for 1.42×10^{-3} m^3/s (3.0 cfm) flow rates are in adequate agreement to permit characterization of the test aerosol using this technique.

B. Test Results

For the plutonium aerosols produced through dry ball milling (amad range of 0.7 to 1.6 μm), overall HEPA filter efficiencies determined by gross filter samples for each filtration stage are detailed in Table III and summarized in Table IV. HEPA filter stages are numbered 1-3 with stage 0 representing the aerosol concentration and size characteristics upstream of HEPA filter #1. Aerosol size characteristics in terms of amad and σ_g generally decrease at succeeding stages. Activity concentrations upstream of HEPA #1 ranged between 10^9 to 2.3×10^{10} d/s-m^3. As expected, filter efficiency is highest

for the first stage, but the measured HEPA filter efficiencies remain well within the present minimum AEC performance guidelines for each stage[14]; i.e., 99.95% for first stages and 99.8% for succeeding stages. In fact, the second HEPA filter efficiency always exceeds 99.99%.

Minimum efficiency noted for the third stage is slightly below the 99.8% guideline. This is due to statistical problems encountered with count rates below .01 c/s downstream of the third HEPA filter, and counting problems due to gaseous contaminants from radon-thoron daughters. Contamination probably accounts for the two tests indicating an efficiency less than 99.8%. Greater confidence in third HEPA stage efficiencies was obtained using longer run times with greater aerosol concentration (10 mg/ml), and longer counting times, allowing a minimum of one week for decay of gaseous contaminants. These modifications to the original test procedure have resulted in consistently higher efficiencies for the third HEPA filter (for the last seven test runs), and indicate that a third HEPA filter in series will satisfy existing AEC guidelines[14].

Table V shows HEPA filter efficiencies as a function of aerosol aerodynamic size. The first column denotes the impactor stages for an 8-stage impactor plus a backup filter (MF #2). The next column gives the impactor particle collection interval for each stage in μm. Mean efficiencies of HEPA filters #1 and #2 are well above the minimum criteria, and actually exceed the DOP quality control requirement of 99.97% for all size intervals characterized by the impactor. Although impactor data downstream of HEPA #3 are not available, the efficiencies reported for HEPA #3 are essentially against particles <1.1 μm aerodynamic diameter, with particles <.43 μm aerodynamic diameter accounting for approximately 40% of the total activity.

Based on the field data obtained at location 11, the need for characterizing HEPA filter performance for aerosols as small as 0.1 μm was indicated. As previously detailed, wet centrifugal milling provided plutonium aerosols with amad's as small as 0.22 μm, with a significant fraction of the aerosol smaller than 0.22 μm. Overall HEPA filter efficiencies against these aerosols are detailed in Table VI, and summarized in Table VII. The first and second stages were all well within minimum criteria guidelines[14], with the minimum measured efficiency for each of the first two filters in series of >99.98%. HEPA filter #3 in the series shows an average efficiency of 99.84, with a minimum efficiency of 99.50%, significantly lower than HEPA #1 or #2. However, these lower efficiencies are probably an artifact, and can be attributed to poor count statistics at sampler #4 downstream of HEPA #3. More recent tests (last 8 tests in Table VI) having higher initial aerosol concentrations, thereby increasing the challenge aerosol to HEPA filter #3, show efficiencies exceeding the minimum criteria guidelines.

Table VI also shows that aerosol size distributions do not change significantly with subsequent filter stages, in contrast to the observation previously noted with larger plutonium test aerosols. The σ_g

is decreased somewhat, indicating an aerosol with a narrower size range downstream of successive HEPA filters. However, these minor aerosol size variations suggest that the aerosol challenging the third HEPA filter is comparable to that for the second HEPA, and filter performance for these filters should be the same.

Efficiency of the first and second HEPA filters in series as a function of size was also well within minimum requirements. A typical computer print-out is reproduced as Table VIII. This shows the HEPA filter efficiency as function of particle size; the combined protection factor (HEPA's #1 and #2) as a function of particle size for the first two HEPA's; filter efficiency based on gross MF-1 filter samplers upstream and downstream of each HEPA; and the overall protection factors for two or three HEPA's in series. For all tests completed, protection factors for two HEPA's in series ranged from 1.6×10^8 to 1.7×10^{11} against aerosols 0.22 to 0.66 μm amad, while for three HEPA's the protection factor ranged from 2.1×10^{12} to 4.7×10^{13}. Table VIII shows these protection factors to be 1.97×10^{10} and 2.35×10^{13}. Overall efficiencies based on total Andersen impactor activity agreed quite closely with the overall efficiencies as given by the gross MF-1 filter samplers. Aerosol concentrations for these runs have ranged from 3.3×10^9 d/s-m^3 up to approximately 1.9×10^{10} d/s-m^3. The closer the initial aerosol concentration is to 1.9×10^{10} d/s-m^3, the fewer are the low level counting problems associated with the sampler downstream of HEPA #3.

Summary

Recent effort in the area of test methods and efficiency studies on multi-bank HEPA filter systems has been prompted primarily by a need to specify design requirements of air cleaning systems for several new plutonium processing plants. Primary interest lay in attaining decontamination factors above 10^9, and establishing test methods to permit routine efficiency testing of each stage. In the absence of experimental data to substantiate individual stage efficiency against an actual plutonium aerosol, a laboratory study was initiated using $^{238}PuO_2$ as the test aerosol. A field study preceding the laboratory phase determined the source term at three AEC plants for typical plutonium processing operations in terms of aerosol size characteristics and activity concentrations. It was against similar aerosols that efficiency of a three stage HEPA test system was evaluated.

Aerosol size characteristics in terms of amad and σ_g of the generated aerosol and the aerosol passing the first two stages were determined by Andersen 8-stage cascade impactor samples. Efficiency of each stage was provided by gross samples on membrane filters. Quality of the HEPA filter installation was removed as a variable by utilizing fully enclosed, quality control tested filters. Aerosols of $^{238}PuO_2$ ranging from 0.22 μm to 1.6 μm amad were generated upstream of the three stage system in activity concentration as high as 2.3×10^{10} d/s-m^3. Measured HEPA filter efficiencies remained high for all three stages and was, as expected, highest for the first stage. Mean efficiencies by stage, including values obtained against 0.22 μm amad, were as follows:

first stage, 99.99+%; second stage, 99.99+%; and third stage, 99.84%. Several early tests indicated stage 3 efficiencies below the 99.8% guideline (99.49% minimum) but these observations have been considered artifacts after improved test methods resulted in efficiencies consistently above 99.8%. The tests show that second and third stages do not suffer gross efficiency loss for plutonium aerosol as small as 0.22 μm amad.

This study was done under idealized conditions to assure that only aerosol penetration, and not leakage around the filter media was monitored. Therefore, proper installation of good, quality control tested HEPA filters is of prime importance to achieve the protection factors determined by this study.

Acknowledgement

The cooperation, guidance and assistance of the following people in completing the field sampling program and initiating the laboratory program are gratefully acknowledged: D. G. Carfagno and W. H. Westendorf, Monsanto Research, Mound Laboratory; W. D. Kittinger and E. A. Putzier, Dow Chemical, Rocky Flats Plant; and C. E. Klatt and F. Miley, Los Alamos Scientific Laboratory.

References

1. AEC Appendix 0524, Standards for Radiation Protection, (Nov. 1968).

2. Ettinger, H., J. Elder, M. Gonzales: Performance of Multiple HEPA Filters Against Plutonium Aerosols, Progress Report for period Jan. 1 through June 30, 1973. Report LA-5349-PR, (July 1973).

3. U. S. Army Chemical Corps and U. S. Navy Bur. Ships: Filter Units, Protective Clothing, Gas Mask Components and Related Products: Performance-Test Methods. Report MH-STD-282, (May 1956).

4. Gilbert, H. and J. H. Palmer: High Efficiency Particulate Air Filter Units, Report TID-7023, (Aug. 1961).

5. Panchuk, F. and W. Rachuk: Filter Testing Program Atomic Energy of Canada Limited. Proceedings of the 9th AEC Air Cleaning Conference, CONF. 660904, pp. 979-1020, (Sept. 1966).

6. Proceedings of the 8th AEC Air Cleaning Conference: In-Place Filter Testing, Round Table Session, Report TID-7677, pp. 433, (1963).

7. Collins, J. T., Jr.: Criteria for High Efficiency Filter Installations at the National Reactor Testing Station, Report IDO-12045, pp. 30-31, (Dec. 15, 1965).

8. Burchsted, C. A. and A. B. Fuller: Design Instruction and Testing of High Efficiency Air Filtration Systems for Nuclear Application, ORNL-NSIC-65, (Jan. 1970).

9. ANSI Standard N101.1, Efficiency Testing of Air Cleaning Systems Containing Devices for Removal of Particles, (1972).

10. Chen, C. Y.: Filtration of Aerosols by Fibrous Media, Chemical Review, 55, 595, (1955).

11. Ettinger, H., J. Elder, M. Gonzales: Performance of Multiple HEPA Filters Against Plutonium Aerosols, Progress Report for period July 1 through Dec. 31, 1972. Report LA-5170-PR, (Jan. 1973).

12. Manufacturer's Bulletin, ReTec Development Laboratory, Portland, Oregon.

13. Hu, J. N. H.: An Improved Impactor for Aerosol Studies - Modified Andersen Impactor, Envir. Sci. and Tech., 5, #3, 251, (1971).

14. HEPA Filtration Guidelines (draft), AEC Division of Operational Safety, and Division of Engineering and Construction, (Dec. 9, 1971).

TABLE I

SUMMARY OF OPERATING CONDITIONS AT EACH SAMPLING LOCATION

Location	Operations	Isotope	Prefilter[c] Efficiency	Relative Quantities Handled
00	R & D	Both	Unknown	Small
04	R & D	238	High[a]	Moderate
08	Fabrication	238	High[a]	Moderate
11	Recovery	239	Unknown[b]	Large
14	Fabrication	239	Unknown	Large

[a] Routine monitoring and replacement.

[b] Probably unreliable due to presence of high concentrations of corrosive acid vapors.

[c] Prefilter is small HEPA located at glove box.

TABLE II

MEAN Pu AEROSOL SIZE CHARACTERISTICS* AND ACTIVITY CONCENTRATION

Location	Type	Isotope	amad (μm)	σ_g	Activity Concentration d/s-m^3
00	R & D	Both	1.9	2.1	2.0×10^2
04	R & D	238	2.9	3.0	2.0×10^3
08	Fabrication	238	4.1	1.7	1.0×10^3
11	Recovery	239	0.5	3.9	1.5×10^5
14	Fabrication	239	2.6	2.9	2.7×10^4

*Assuming particle diameters are lognormally distributed.

TABLE III

OVERALL HEPA FILTER EFFICIENCY

Run	HEPA Filter Stage	Plutonium Aerosol amad (μm)	σ_g	Activity Concentrations d/s-m^3	HEPA Filter Efficiency
P2-1	0	0.7	2.26	2.80×10^9	
	1	0.6	1.50	9.60×10^3	99.99+
	2	0.7	1.8	2.38×10^{-1}	99.99+
	3	--	--	1.20×10^{-3}	99.49*
P2-3	0	1.3	2.94	2.12×10^9	
	1	0.59	1.6	5.17×10^3	99.99+
	2	0.57	1.84	8.63×10^{-2}	99.99+
	3	--	--	CONTAMINATED	
P2-4	0	1.3	2.7	1.86×10^9	
	1	0.45	2.04	5.55×10^3	99.99+
	2	0.46	2.54	4.04×10^{-2}	99.99+
	3	--	--	CONTAMINATED	

*Probable contamination from radon-thoron daughters.

TABLE III (continued)

OVERALL HEPA FILTER EFFICIENCY

Run	HEPA Filter Stage	Plutonium Aerosol amad (μm)	σ_g	Activity Concentrations d/s-m^3	HEPA Filter Efficiency
P2-5	0	0.65	2.2	5.04×10^{9}	
	1	0.64	1.6	9.22×10^{4}	99.99+
	2	0.55	1.4	1.68	99.99+
	3	--	--	CONTAMINATED	
P2-6	0	0.75	2.7	4.36×10^{9}	
	1	0.59	1.6	6.25×10^{4}	99.99+
	2	0.51	1.5	1.39	99.99+
	3	--	--	7.67×10^{-4}	99.94
P2-7	0	1.02	2.70	1.68×10^{9}	
	1	0.64	1.70	7.52×10^{3}	99.99+
	2	0.43	1.31	7.69×10^{-2}	99.99+
	3	--	--	1.67×10^{-4}	99.78
P2-8	0	0.79	2.51	1.24×10^{9}	
	1	0.67	1.74	2.35×10^{4}	99.99+
	2	0.56	1.47	2.50×10^{-1}	99.99+
	3	--	--	1.21×10^{-3}	99.52*
P2-9	0	0.84	2.07	5.17×10^{9}	
	1	0.45	1.93	8.10×10^{4}	99.99+
	2	0.42	1.66	2.07	99.99+
	3	--	--	5.77×10^{-4}	99.97

*Probable contamination from radon-thoron daughters.

TABLE III (continued)

OVERALL HEPA FILTER EFFICIENCY

Run	HEPA Filter Stage	Plutonium Aerosol amad (μm)	σ_g	Activity Concentrations d/s-m^3	HEPA Filter Efficiency
P2-10	0	0.80	2.09	7.34×10^{9}	
	1	0.52	1.67	1.04×10^{5}	99.99+
	2	0.36	1.79	2.15	99.99+
	3	--	--	4.02×10^{-4}	99.98
P3-1	0	0.71	2.12	1.59×10^{10}	
	1	0.66	1.58	3.34×10^{5}	99.99+
	2	0.42	1.79	8.79	99.99+
	3	--	--	9.64×10^{-4}	99.99
P3-2	0	0.77	2.18	2.14×10^{10}	
	1	0.61	1.65	3.78×10^{5}	99.99+
	2	0.60	1.40	1.12×10^{1}	99.99+
	3	--	--	7.80×10^{-4}	99.99+
P3-3	0	1.45	2.79	7.30×10^{9}	
	1	0.82	2.00	1.99×10^{5}	99.99+
	2	0.50	1.60	2.57	99.99+
	3	--	--	9.36×10^{-4}	99.96
P3-4	0	0.78	2.55	7.31×10^{9}	
	1	0.57	1.75	8.39×10^{4}	99.99+
	2	0.50	1.65	1.37	99.99+
	3	--	--	3.71×10^{-4}	99.97

TABLE III (continued)

OVERALL HEPA FILTER EFFICIENCY

Run	HEPA Filter Stage	Plutonium Aerosol amad (μm)	σ_g	Activity Concentrations d/s-m^3	HEPA Filter Efficiency
P3-5	0	0.80	2.54	2.28×10^{10}	
	1	0.58	1.69	2.12×10^{4}	99.99+
	2	0.49	1.49	3.31×10^{-1}	99.99+
	3	--	--	3.22×10^{-4}	99.90

TABLE IV

OVERALL HEPA FILTER EFFICIENCY

HEPA Filter Stage	Range of Size amad (μm)	σ_g	Efficiency Range (%) Min.	Mean	Max.
1 *	0.70 - 1.6	2.07 - 2.9	99.99+	99.99+	99.99+
2 *	0.45 - 0.82	1.5 - 2.04	99.99+	99.99+	99.99+
3 **	0.36 - 0.70	1.31 - 2.54	99.49	99.86	99.99+

*Total of 14 test runs.

**Total of 11 test runs.

TABLE V

HEPA FILTER EFFICIENCY AS A FUNCTION OF AEROSOL SIZE

Sampling Impactor Stage Number	Aerodynamic Diameter Range μm	Mean Efficiency (%)	
		HEPA #1	HEPA #2
0	>11	99.999	99.999
1	7.0 - 11	99.999	99.996
2	4.7 - 7.0	99.999	99.999
3	3.3 - 4.7	99.999	99.998
4	2.1 - 3.3	99.999	99.999
5	1.1 - 2.1	99.999	99.999
6	0.65 - 1.1	99.997	99.998
7	0.43 - 0.65	99.997	99.998
MF#2	<0.43	99.998	99.997
OVERALL	-	99.998	99.998

TABLE VI

HEPA FILTER EFFICIENCY

Run	HEPA Filter Stage	Plutonium Aerosol amad (μm)	σ_g	Activity Concentrations d/s-m^3	HEPA Filter Efficiency(%)
P4-1	0	0.31	2.87	8.06×10^{8}	
	1*	0.31	2.01	3.79×10^{3}	99.99+
	2*	0.40	1.69	6.19×10^{0}	99.98+
	3	--	--	3.67×10^{-4}	99.94
P4-2	0	0.37	2.46	1.42×10^{9}	
	1**	--	--	4.90×10^{3}	99.99+
	2	0.34	1.65	0.10×10^{0}	99.99+
	3	--	--	4.33×10^{-4}	99.50

* Broker backup filter.
**Broken backup filter - no activity.

TABLE VI (continued)

HEPA FILTER EFFICIENCY

Run	HEPA Filter Stage	Plutonium Aerosol amad (μm)	Plutonium Aerosol σ_g	Activity Concentrations d/s-m^3	HEPA Filter Efficiency(%)
P4-3	0	0.38	2.51	3.26×10^{9}	
	1	0.37	1.76	2.90×10^{3}	99.99+
	2	0.36	1.68	6.86×10^{-2}	99.99+
	3	--	--	2.98×10^{-4}	99.55
P4-4	0	0.34	3.00	4.06×10^{9}	
	1	0.36	1.99	2.78×10^{4}	99.99+
	2	0.34	1.89	1.47×10^{-1}	99.99+
	3	--	--	9.23×10^{-5}	99.92
P4-5	0	0.66	3.28	5.22×10^{9}	
	1	0.38	2.10	6.52×10^{3}	99.99+
	2	0.39	2.09	9.95×10^{-2}	99.99+
	3	--	--	3.30×10^{-4}	99.63
P4-6	0	0.48	3.76	9.14×10^{9}	
	1	0.44	1.69	2.21×10^{3}	99.99+
	2	0.42	1.66	5.01×10^{-1}	99.99+
	3	--	--	1.81×10^{-4}	99.60
P4-7	0	0.48	2.98	4.74×10^{9}	
	1	0.47	1.96	2.60×10^{4}	99.99+
	2	0.42	1.68	2.08×10^{-1}	99.99+
	3	--	--	1.95×10^{-4}	99.89

TABLE VI (continued)

HEPA FILTER EFFICIENCY

Run	HEPA Filter Stage	Plutonium Aerosol amad (μm)	σ_g	Activity Concentrations d/s-m^3	HEPA Filter Efficiency(%)
P4-8	0	0.47	3.26	6.29×10^{9}	
	1	0.48	1.70	2.11×10^{4}	99.99+
	2	0.41	1.69	1.81×10^{-1}	99.99+
	3	--	--	6.23×10^{-5}	99.96
P4-9	0	.36	3.17	3.56×10^{9}	
	1	.40	1.85	4.12×10^{3}	99.99+
	2	.37	2.00	4.04×10^{-2}	99.99+
	3	--	--	1.29×10^{-4}	99.64
P4-10	0	.44	3.06	1.07×10^{10}	
	1	.53	2.28	1.66×10^{6}	99.99+
	2	.42	1.72	5.83×10^{1}	99.99+
	3	--	--	4.23×10^{-3}	99.99+
P4-11	0	.43	3.36	1.94×10^{10}	
	1	.47	2.36	1.94×10^{6}	99.99
	2	.39	1.86	6.49×10^{1}	99.99+
	3	--	--	3.87×10^{-3}	99.99+
P4-12	0	.33	3.56	1.38×10^{10}	
	1	--	--	1.09×10^{5}	99.99+
	2	.15	1.93	1.07×10^{1}	99.99
	3	--	--	9.67×10^{-4}	99.99

TABLE VI (continued)

HEPA FILTER EFFICIENCY

Run	HEPA Filter Stage	Plutonium Aerosol amad (μm)	σ_g	Activity Concentrations d/s-m^3	HEPA Filter Efficiency(%)
P4-13	0	.27	3.86	1.04×10^{10}	
	1	--	--	9.29×10^{4}	99.99+
	2	.20	2.5	9.15×10^{0}	99.99
	3	--	--	6.11×10^{-4}	99.99+
P4-14	0	.22	2.59	1.68×10^{10}	
	1	--	--	2.54×10^{5}	99.99+
	2	.28	2.34	1.41×10^{1}	99.99+
	3	--	--	1.10×10^{-3}	99.99+
P4-15	0	.26	3.20	1.12×10^{10}	
	1	.29	2.18	$9.1[illegible] \times 10^{4}$	99.99+
	2	--	--	$1.[illegible]9 \times 10^{1}$	99.98
	3	--	--	1.14×10^{-3}	99.99
P4-18	0	.37	3.16	9.29×10^{9}	
	1	.30	2.52	4.23×10^{4}	99.99+
	2	.22	2.50	2.90×10^{0}	99.99+
	3	--	--	1.69×10^{-4}	99.99+
P4-19	0	.32	3.65	5.40×10^{9}	
	1	.30	2.10	1.08×10^{5}	99.99
	2	.28	2.44	1.31×10^{1}	99.98
	3	--	--	3.25×10^{-4}	99.99

TABLE VII

SUMMARY OF HEPA FILTER EFFICIENCY

HEPA Filter Stage	Pu Aerosol amad Range (μm)	HEPA Filter* Efficiency (%) Minimum	Avg.	Maximum
1	0.22 - 0.66	99.99+	99.99+	99.99+
2	0.29 - 0.53	99.98+	99.99+	99.99+
3	0.15 - 0.42	99.50	99.86	99.99+

*Total of 17 experimental runs.

TABLE VIII

MULTIPLE HEPA FILTER EFFICIENCY RUN NUMBER P4-7

RATIO CONCENTRATION ANDERSEN TO CONCENTRATION MF1

SAMPLE LOCATION	ONE	TWO	THREE
RATIO	1.2662	1.2038	1.0907

ECD*	INDIVIDUAL FILTER EFFICIENCIES BY CASCADE IMPACTOR STAGES: FILTER 1	FILTER 2	PROTECTION FACTOR FILTER ONE AND TWO: FILTER 1 & 2
>5.40	99.999954	100.000000	.20397E.13
5.40	99.999950	100.000000	.18518E.13
3.39	99.999951	100.000000	.19279E.13
2.30	99.999886	99.999903	.45993E.12
1.54	99.999674	99.999915	.17018E.12
.96	99.999070	99.998994	.10935E.11
.44	99.999264	99.999188	.16597E.11
.22	99.999645	99.998973	.28075E.11
.12	99.999748	99.998957	.39029E.11
SUM	99.999478	99.999170	100.000000

TOTAL FILTER EFFICIENCY AS GIVEN BY MF 1 FILTERS AND FINAL STAGE FILTERS

FILTER 1	FILTER 2	FILTER 3
99.999451	99.999056	99.890966

PROTECTION FACTORS AS GIVEN BY FILTER COLLECTIONS

FILTER 1+2= .19681E+11 FILTER 1+2+3= .23456E+14

*Effective cutoff diameter.

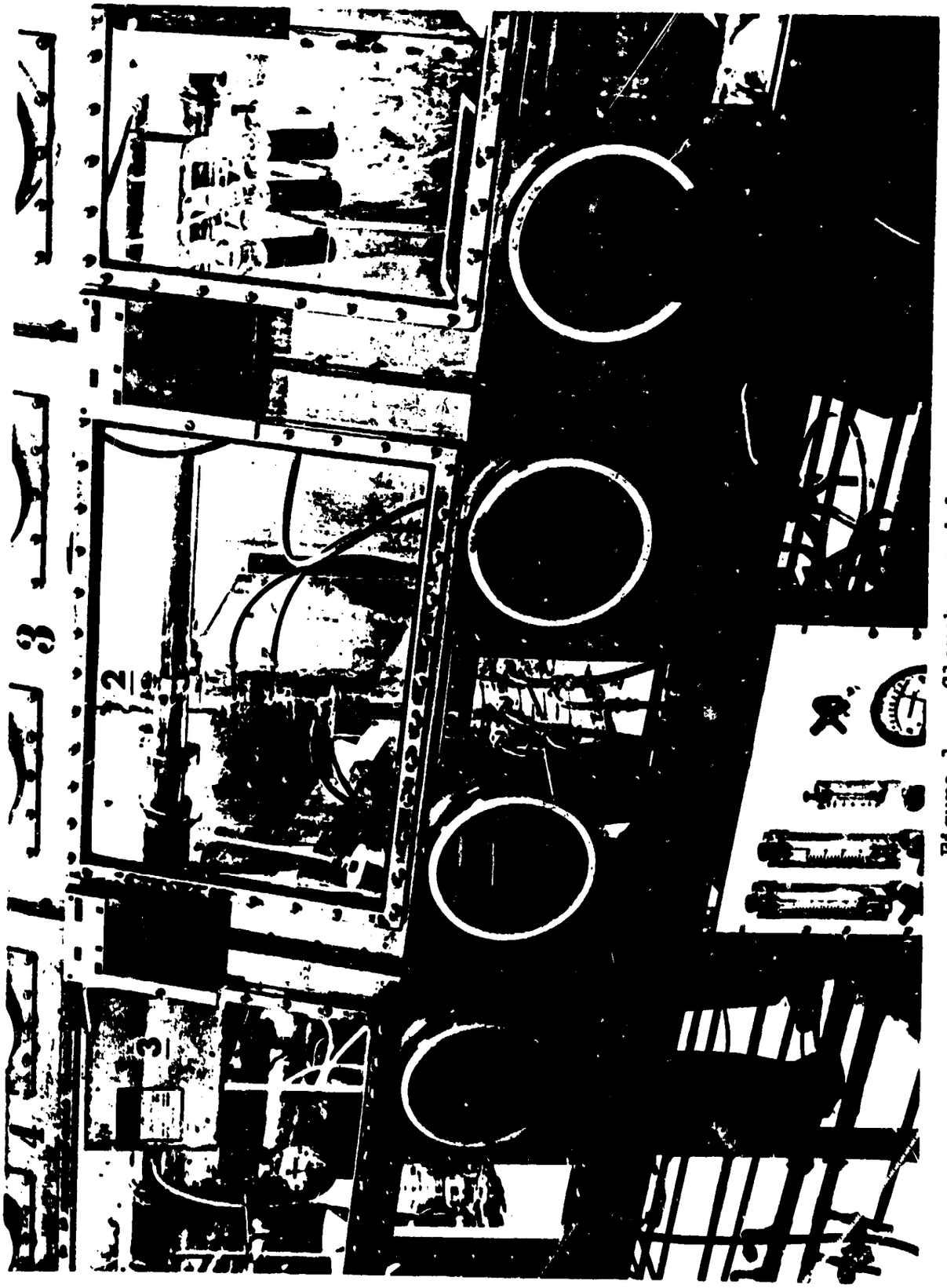

Figure 1. Glovebox module.

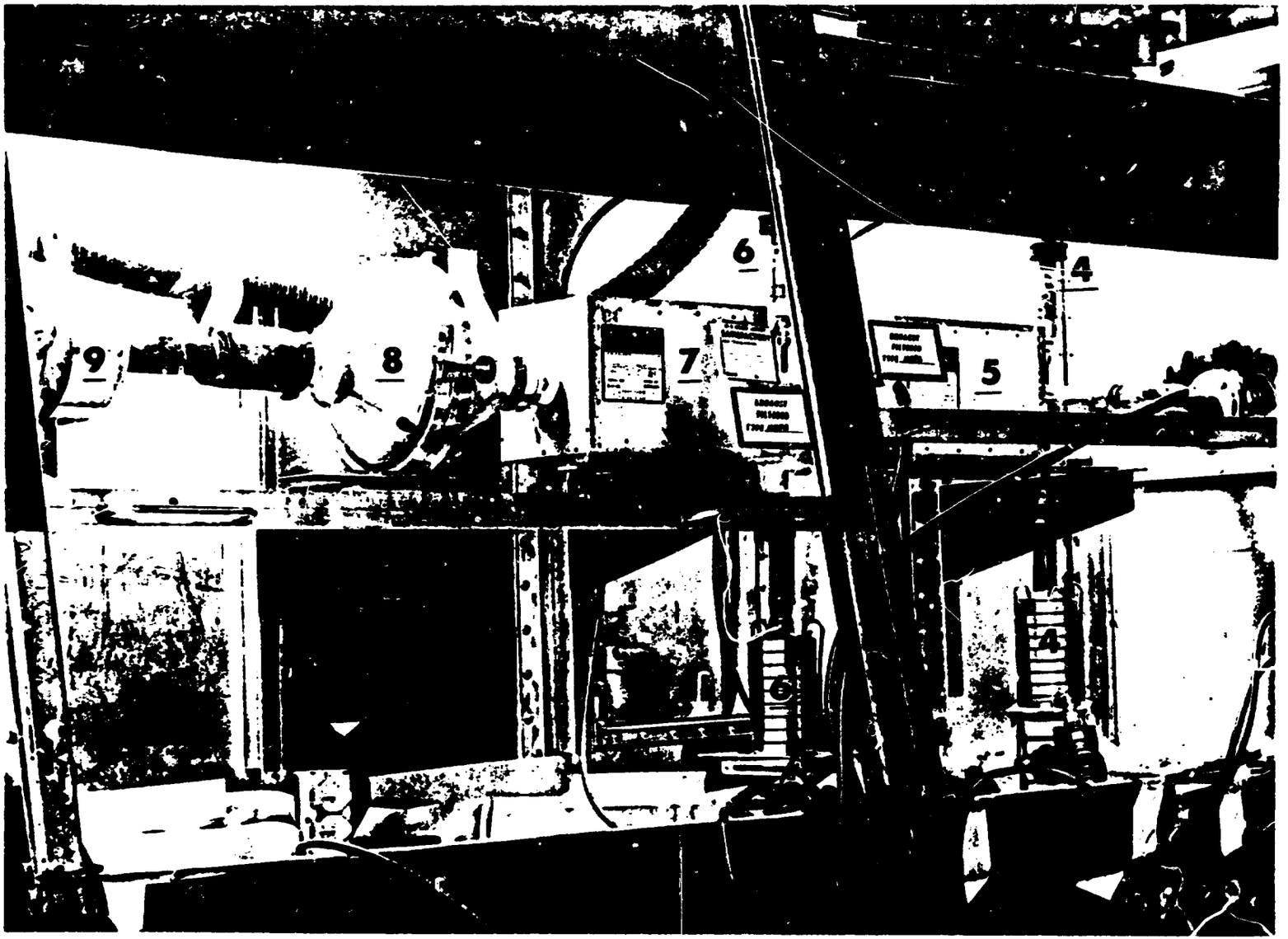

Figure 2. Hood module.

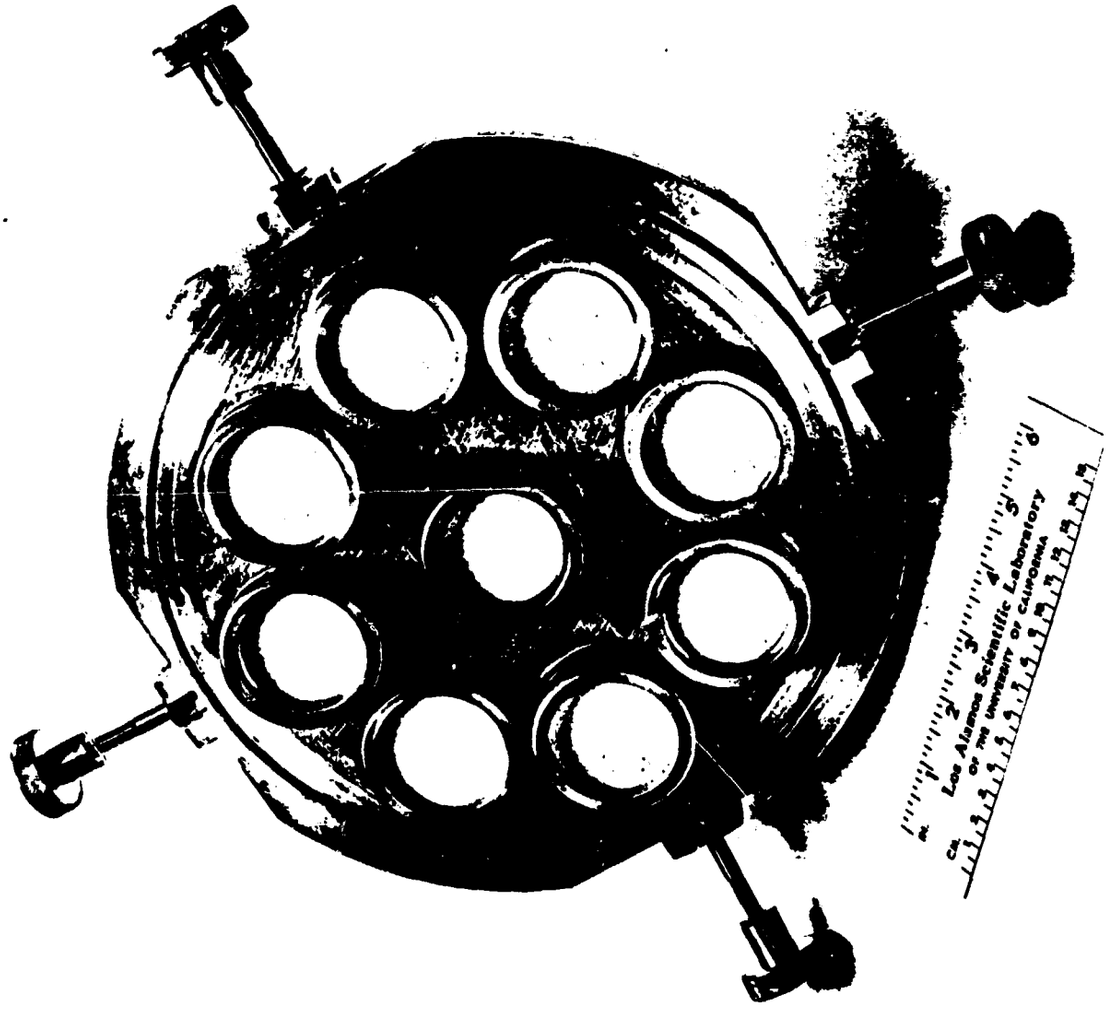

Figure 3. Sampler #4.

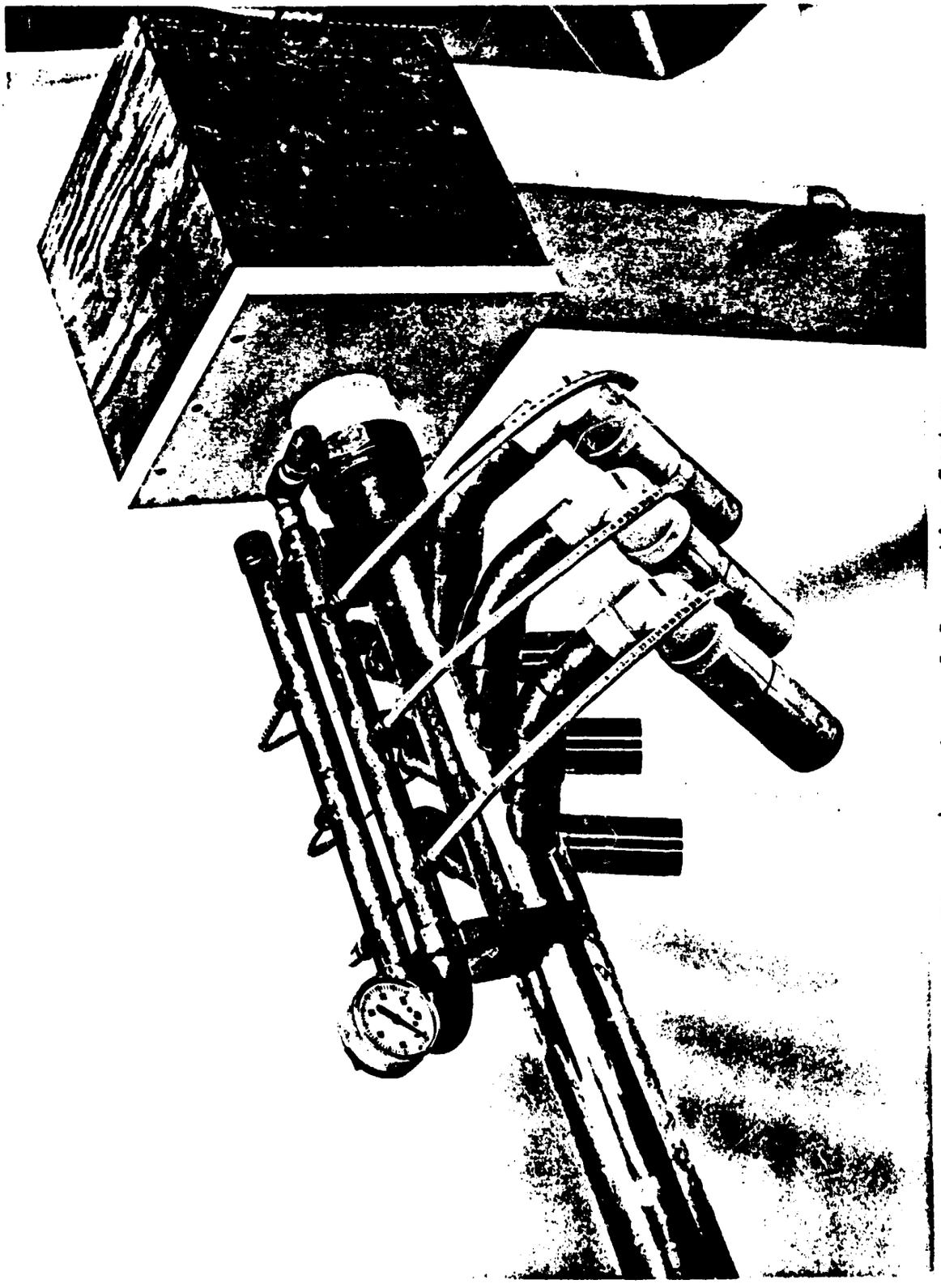

Figure 4. Aerosol Generation System.