NASA
TM
X-53881
c.1

N70-37495

MONITORING AIRBORNE PARTICULATE CONTAMINATIO.

T. W. Lewis

12 September 1969

NATIONAL TECHNICAL INFORMATION SERVICE

Distributed . . . 'to foster, serve and promote the nation's economic development and technological advancement.'

U.S. DEPARTMENT OF COMMERCE

NASA TECHNICAL
MEMORANDUM

REPORT NO. 53881

MONITORING AIRBORNE PARTICULATE CONTAMINATION

By T. W. Lewis
Manufacturing Engineering Laboratory

September 12, 1969

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

INTERNAL NOTE R-ME-IN-67-1

was changed to TM X-53881 on September 12, 1969

MONITORING AIRBORNE PARTICULATE CONTAMINATION

by

T. W. Lewis

George C. Marshall Space Flight Center
Huntsville, Alabama

ABSTRACT

This report describes the test program conducted by the Manufacturing Engineering Laboratory to determine the accuracy of the instrumentation and to establish an operational coefficient of correction for the Valve Clinic electronic particle monitoring system.

NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER

NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER

INTERNAL NOTE R-ME-IN-67-1

MONITORING AIRBORNE PARTICULATE CONTAMINATION

By

T. W. Lewis

MANUFACTURING ENGINEERING LABORATORY
RESEARCH AND DEVELOPMENT OPERATIONS

ACKNOWLEDGEMENT

This document is based on a progress report on Valve Clinic Electronic Particle Monitoring System Instrumentation, prepared by Alvin Perkins and L. Lewis Berry, R-ME-DP.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

LIST OF ILLUSTRATIONS (Concluded)

LIST OF TABLES

LIST OF TABLES (Concluded)

INTERNAL NOTE

MONITORING AIRBORNE PARTICULATE CONTAMINATION

SUMMARY

The sizing and counting of the particulate contamination by microscopic examination of a membrane filter through which a known volume of sampled air has been passed is a long, tedious, time-consuming procedure. While this examination cannot be eliminated because of the important clues visual examination gives regarding the possible sources of contamination, the requirements for the number of samples taken can be substantially reduced by the substitution of automatic samplers. The automatic electronic airborne particulate contamination monitoring system, which is now installed in the clean room complex of the Valve Clinic, gives a continuous readout of the relative level of the airborne contamination.

The instruments respond well and are sufficiently sensitive to disclose variations in the contamination levels in the rooms.

There are at least two ways in which these instruments may be improved. The first is by lowering the height of the sampling probe to bench level. The second is by installing an alarm system that will give warning when the upper level of contamination is being approached.

NOTE: Two metric units have been used in this report that are not specified in the International System. The first is the liter but since this is a very common measure of volume there are no objections anticipated.

The second is the micron, which is generally used in the measurement of particulate contamination. The IS units indicate that the prefix to be used for one millionth is "micro." The micron is one millionth of a meter. Prefixing "meter" with "micro" we have "micrometer" which might be confusing because it is a word normally associated with various types of instruments for measuring minute distances. For this reason the micron has been used in this report to indicate a distance equivalent.

INTRODUCTION

In response to the indication of a need for an instrument to automatically monitor the airborne particulate contamination in the Manufacturing Engineering Laboratory's Valve Clinic, the Illinois Institute of Technology Research Institute, in Chicago, Illinois, after having been awarded a contract, developed a monitoring system consisting of three mobile sampling consoles, one for each of the three rooms in the Valve Clinic clean room complex, and one data center, located outside the clean rooms, where all the data is printed out on a tape.

The sensing and sizing of the airborne particulate contamination is accomplished by utilizing the light scattering principle, but these instruments include many new and unique features in the optical and electronic systems. Extraneous signals are minimized by precision machining to obtain an exceptionally light tight cover and by several light controlling and absorbing devices. Improved electronic devices and circuits were incorporated as well. Since there were multiple sensing devices feeding information into one central data center and since it was desirable to have continuous records of all three rooms, it was necessary to include a memory circuit in the electronics so that the categorized counts could be stored until printout time. This stored information is then printed out at pre-set time intervals on a tape. The time at the end of the sampling period is printed out first, and then the channel number is printed out in the left hand column, followed by the number of particles counted in that size category in the right hand column. There are six size classifications reported for each sampler. There is an option of selecting from eleven different size ranges. Actually there are six possible selections of size ranges to choose from in each of two classifications, but the sixth range on the smaller classification is equal to the first range on the larger classification, leaving eleven different size ranges from which to choose. The size ranges vary from one-half or five-tenths micron (0.5μ) to four microns (4.0μ) on range one of the small classification to sixteen microns (16μ) to one hundred twenty-eight microns (128μ) on range six for the large classification.

This information can be printed out in time intervals which may be set at two, five, ten, twenty, thirty or sixty minutes as indicated on the dial. This would be equivalent to 120, 300, 600, 1200, 1800 or 3600 second intervals. The total volume of air drawn into the sampling probe is three quarters of a cubic foot per minute or 0.75 cubic feet per minute (0.354 liters per second). The volume of air actually scanned is determined by the slit selected and may be

0.0076 cu. ft. per minute or 0.035 liters per second
0.0302 cu. ft. per minute or 0.143 liters per second
0.1175 cu. ft. per minute or 0.555 liters per second
0.424 cu. ft. per minute or 2.001 liters per second.

METHOD OF MEASUREMENT AND TESTING

The accepted standard method of measuring the airborne particulate contamination has been the microscopic examination of a membrane filter through which a known volume of the sample air has been passed. This method is limited because the smallest size particle that can be counted - using incident light - is five microns (5μ). The size ranges that have been counted in our laboratory have been five to twenty-five microns (5-25μ), twenty-five to fifty microns (25-50μ), fifty to one hundred microns (50-100μ), and greater than one hundred microns ($>100\mu$). Fibers which are greater than one hundred microns have been classified separately.

This accepted standard was modified for the purposes of this study, however, in order to adjust the microscopist's count so that it might agree more closely with the instrumental counts. A microscopist can differentiate only between five micron measurement increments utilizing our present equipment and methods. Accordingly, the microscopist counted particles in the five to twenty-five micron (5-25μ) range, in the twenty-five to forty-five micron (25-45μ) range and in the forty-five to one hundred micron (45-100μ) range, in order to have counts in the size range as near as practical to the size ranges counted by the instruments.

The instruments were adjusted to count in the five and six tenths to forty-five micron (5.6-45μ) range. This was accomplished by setting and calibrating them in the larger size category by placing the "calibrate voltage" switch in the "low" position and the range selector switch in position "three" (3). The instruments then counted in the following size ranges (in microns):

5.6	to	8.0
8.0	to	11.0
11.0	to	16.0
16.0	to	22.0
22.0	to	32.0
32.0	to	45.0 .

For the series, and side by side tests, the microscopist examined, sized, and counted the particles on all the filter instead of counting and sizing the particles on one tenth of the filter and multiplying by ten, in the hope that this would give a more exact count. The particles sized from five to twenty-five microns (5-25μ) were reported and those between twenty-five and forty-five microns (25-45μ) were also reported.

In the same intervals of time, the counts on the instrument were determined by adding the counts on the first four channels to give the total counts between five and six tenths and twenty-two microns (5.6-22μ) and the last two channel counts were added to give the total counts between twenty-two and forty-five microns (22-45μ).

NOTE: In order to minimize variations, a large number of samples was taken and the sampling time intervals were relatively long. In addition, the over-all averages of the results were taken, thus effectively integrating the wide variations.

The Valve Clinic electronic particle monitoring system instrumentation which was installed in April 1966 has been evaluated using two methods. The first method was a day-to-day general observation of the system in operation, its ability to register contamination and its problem areas. The second method was a specific test program to determine its accuracy in measuring contamination and to establish an operational coefficient of correction.

In the day-to-day operation of the particle counter, it was observed that when high or low numbers were printed on the data center tape, the degree of contamination was proportional to these numbers. When extensive packaging of parts, an operation known to produce excessive contamination, was being conducted, the data center printed higher numbers than when personnel were working on valves or simply walking by the sampler. On one occasion the filter in one of the ceiling air inlets broke down. When one of the samplers was moved within approximately twenty feet of the inlet, the data center count increased. The data count continued to increase progressively as the sampler was moved nearer the inlet. From these observations, it was concluded that the system definitely responds proportionately to the relative degree of airborne particulate contamination.

The specific test program consisted of three basic types of tests: series, side by side, and daily monitoring. The filter impingement system was selected as a standard for comparison of the new system to determine the accuracy because it is the only acceptable particle monitoring method presently approved by MSFC.

The series test was critical, and the results show the accuracy of the automatic system to monitor the Valve Clinic Clean Room contamination. The series test consisted of monitoring air contamination in one of the Valve Clinic clean rooms by connecting a membrane filter assembly in series with the automatic system so that the same air samples are monitored by both methods. To accomplish this test, a membrane filter assembly (Fig. 1) was installed in the flow tube of the automatic sampler downstream and adjacent to the intake tube where the air is sampled. Figures 2 and 3 show the installation of this membrane filter assembly. This assembly consisted of two elements because no single dark-colored membrane element with sufficient flow was available. The automatic system viewed 56.6 percent of the intake air flow whereas 100 percent of the intake air flow went through the membrane filter assembly. The contamination on the membrane filters was counted microscopically in accordance with ARP 743, except that the total impingement area of the filter was counted instead of a statistical randomly selected number of grid squares on the filter. Figures 4 - 9 and Table I show the graphic and summary chart results of this test.

The series test results show:

a. The automatic system registered more contamination than was filtered out and counted under the microscope in the low range, 5 to 25 microns.

b. The automatic system registered less contamination than was filtered out and counted under the microscope in the high range, 25 to 100 microns.

c. Considering the overall range of 5 to 100 microns, the automatic system registered 23.6 percent more contamination than was filtered out and counted under the microscope.

The side by side test was conducted to obtain more test data to clarify the results of the original limited side by side calibration test conducted by IITRI as stated in the report IITRI-C6071-8. The side by side test consisted of monitoring the air contamination in one of the Valve Clinic clean rooms by the customary filter impingement method and the automatic system. Three- and four-hour air samples were obtained in the same vertical position and at the same height. Figure 10 shows a picture of the test arrangement used for this test. The graphic and summary chart results of this test are shown in Figures 11 through 16 and Table II.

The daily monitoring test was conducted to compare the daily clean room particle counts taken by the filter impingement method with those taken by the automatic system. The filter impingement samples were taken in accordance with ARP 743 once a day in the horizontal position and at a height of approximately thirty-six inches. The automatic system samples were taken in the vertical position continuously for the eight-hour work shift at a height of sixty-one inches. Figures 17 and 18 show the methods used for taking the daily filter impingement sample and the probe sample for the automatic electronic sampler, respectively. Test data for the daily monitoring test is displayed graphically in Figures 19 through 33 and a summary of the results is shown in Tables III, IV, and V.

The results of the daily monitoring test show:

a. There is more contamination close to the processes at the work bench level than at sixty-one inches from the floor.

b. The automatic system monitors the airborne contamination of the clean room. The filter impingement method monitors the combination of the clean room contamination and the contamination produced by the processes.

c. The height, position and location are influencing factors in sampling the clean room for contamination.

A calibration record of each sampler has been maintained during the test program and is shown in graph form in Figure 34. Samplers A and B reached their maximum calibration voltage setting during the month of August and sampler C reached its maximum setting in September. The sensing lamps in each sampler were then realigned in order to bring the calibration voltage back in range. A continuous record of the calibration settings is being maintained by R-ME-DP for future study and analysis.

During this program, the verbal coordination of the individual settings and location of each sampler in the clean room complex with the numbers printed on the data center tape were found to be insufficient. To correct this problem, a log sheet (Fig. 35) is being maintained at the data center.

CALCULATIONS

Calculation of data center tape reading into particles per cubic foot:

$$\text{Particles per cubic foot} = \frac{\text{data center tape count}}{\text{air flowrate x sample time in minutes}} .$$

Derivation of the operational coefficient of correction:

a. Series test accuracy correction: 76.4%A.
the automatic system count in particles per cubic foot.

The letter A represents the automatic system count in particles per cubic foot.

b. Conversion of corrected automatic system count in particles per cubic foot at 61 inches high to equivalent filter impingement count in particles per cubic foot at 61 inches high:

(1) Side by side test ratio of the corrected automatic system counts in particles per cubic foot at 61 inches high to the filter impingement method count in particles per cubic foot at 61 inches high:

$$\frac{2.627}{0.392} = 6.702A$$

(2) Equivalent filter impingement method count in particles per cubic foot at 61 inches high:

$$(76.4\%A)\ \left(\frac{1}{6.702}\right) = 0.112A$$

c. Conversion of equivalent filter impingement count in particles per cubic foot at 61 inches high to equivalent filter impingement count in particles per cubic foot at 36 inches high.

(1) Ratio of the daily monitoring test assembly room filter impingement count in particles per cubic foot at 36 inches high to the side by side test filter impingement method count in particles per cubic foot at 61 inches high:

$$\frac{21.956}{0.392} = 56$$

(2) Equivalent filter impingement count in particles per cubic foot at 36 inches high:

$(0.112A)\ (56) = 6.27A$

Operational coefficient of correction: 6.27A.

CONCLUSIONS AND RECOMMENDATIONS

This automatic airborne particulate contamination monitoring system continuously monitors the air in the three different clean rooms and not only provides a record, but, with a minimum time lag, indicates the degree of contamination present.

There are two recommendations for improving the system: (1) lower the sampling probe to work bench height; and (2) install an alarm system which will notify all concerned when a critical level of contamination has been reached.

Because the present sampling probe is so much higher than the working level at bench height where most of the work is being done and where the membrane filter sample is taken for microscopic examination, it was determined that the readout from the automatic monitoring system had to be multiplied by a factor to agree with the microscopic count over the overall range of five to one hundred microns (5-100μ).

The data from this report confirms that the monitoring system could be improved by lowering the sample probe to the work bench level.

Until such time as additional information can be obtained, the instrumental data showing the number of particles per cubic foot may be multiplied by a factor of 6.27 in order to obtain an equivalent contamination count at work station height and location.

The second recommendation would eliminate the possibility that an observer might miss detecting a critical rise in the count level. A visual or audible alarm that would warn the operators when a critical level of contamination had been reached would be a great improvement. This alarm should be provided with a fail-safe system that would indicate when the detection system was not operating. The alarm system would have to be adjustable so that it could be adapted to different contamination levels for the different particle ranges.

TABLE I. SERIES TEST SUMMARY CHART

PARTICLE SIZE RANGE IN MICRONS		AUTOMATIC SYSTEM		FILTER IMPINGEMENT METHOD		RATIO AVERAGE (AUTOMATIC/FILTER IMPINGEMENT)
Automatic	Filter Im-pingement	Average Particle Count Per Cubic Foot	Percent of Average Total Particles Counted	Average Particle Count Per Cubic Foot	Percent of Average Total Particles Counted	
5.6-22	5-25	5.106	98.7	3.440	82.1	1.210
22-45	25-45	0.059	1.1	0.656	15.7	0.118
45-91	45-100	0.011	0.2	0.091	2.2	0.343
TOTAL		5.176	100.0	4.187	100.0	1.236

TABLE II. SIDE BY SIDE SUMMARY CHART

PARTICLE SIZE RANGE IN MICRONS		AUTOMATIC SYSTEM		FILTER IMPINGEMENT METHOD		RATIO AVERAGE (AUTOMATIC/FILTER IMPINGEMENT)
Automatic	Filter Im-pingement	Average Particle Count Per Cubic Foot	Percent of Average Total Particles Counted	Average Particle Count Per Cubic Foot	Percent of Average Total Particles Counted	
5.6-22	5-25	3.340	97.2	0.210	53.6	18.090
22-45	25-45	0.069	2.0	0.087	22.2	0.824
45-91	45-100	0.029	0.8	0.095	24.2	0.407
TOTAL		3.438	100.0	0.392	100.0	9.536

TABLE III. DAILY MONITORING TEST ASSEMBLY ROOM

PARTICLE SIZE RANGE IN MICRONS		AUTOMATIC SYSTEM		FILTER IMPINGEMENT METHOD		RATIO AVERAGE (AUTOMATIC/FILTER IMPINGEMENT)
Automatic	Filter Im-pingement	Average Particle Count Per Cubic Foot	Percent of Average Total Particles Counted	Average Particle Count Per Cubic Foot	Percent of Average Total Particles Counted	
5.6-22	5-25	3.070	97.2	15.700	71.5	0.196
22-45	25-45	0.065	2.1	5.470	24.9	0.012
45-91	45-100	0.022	0.7	0.786	3.6	0.028
TOTAL		3.157	100.0	21.956	100.0	0.144

TABLE IV. DAILY MONITORING TEST PACKAGING ROOM

PARTICLE SIZE RANGE IN MICRONS		AUTOMATIC SYSTEM		FILTER IMPINGEMENT METHOD		RATIO AVERAGE (AUTOMATIC/FILTER IMPINGEMENT)
Automatic	Filter Im-pingement	Average Particle Count Per Cubic Foot	Percent of Average Total Particles Counted	Average Particle Count Per Cubic Foot	Percent of Average Total Particles Counted	
5. 6-22	5-25	0. 692	77. 5	14. 320	75. 5	0. 483
22-45	25-45	0. 200	22. 4	4. 220	22. 2	0. 047
45-91	45-100	0. 001	0. 1	0. 430	2. 3	0. 003
TOTAL		0. 893	100. 0	18. 970	100. 0	0. 047

TABLE V. DAILY MONITORING TEST LABORATORY

PARTICLE SIZE RANGE IN MICRONS		AUTOMATIC SYSTEM		FILTER IMPINGEMENT METHOD		RATIO AVERAGE (AUTOMATIC/FILTER IMPINGEMENT)
Automatic	Filter Im-pingement	Average Particle Count Per Cubic Foot	Percent of Average Total Particles Counted	Average Particle Count Per Cubic Foot	Percent of Average Total Particles Counted	
5.6-22	5-25	1.300	98.0	10.570	70.6	0.123
22-45	24-45	0.026	1.9	3.830	25.6	0.007
45-91	45-100	0.001	0.1	0.570	3.8	0.002
TOTAL		1.327	100.0	14.970	100.0	0.089

TABLE VI. VALVE CLINIC AUTOMATIC PARTICLE MONITORING SYSTEM
SAMPLER SETTING LOG

	SAMPLER A						SAMPLER B						SAMPLER C					
Date	Room Loc.	Plug No.	Range Setting	View Vol. No.	Voltage Calib.	Channel Readout Numbers	Room Loc.	Plug No.	Range Setting	View Vol. No.	Voltage Calib.	Channel Readout Numbers	Room Loc.	Plug No.	Range Setting	View Vol. No.	Voltage Calib.	Channel Readout Numbers

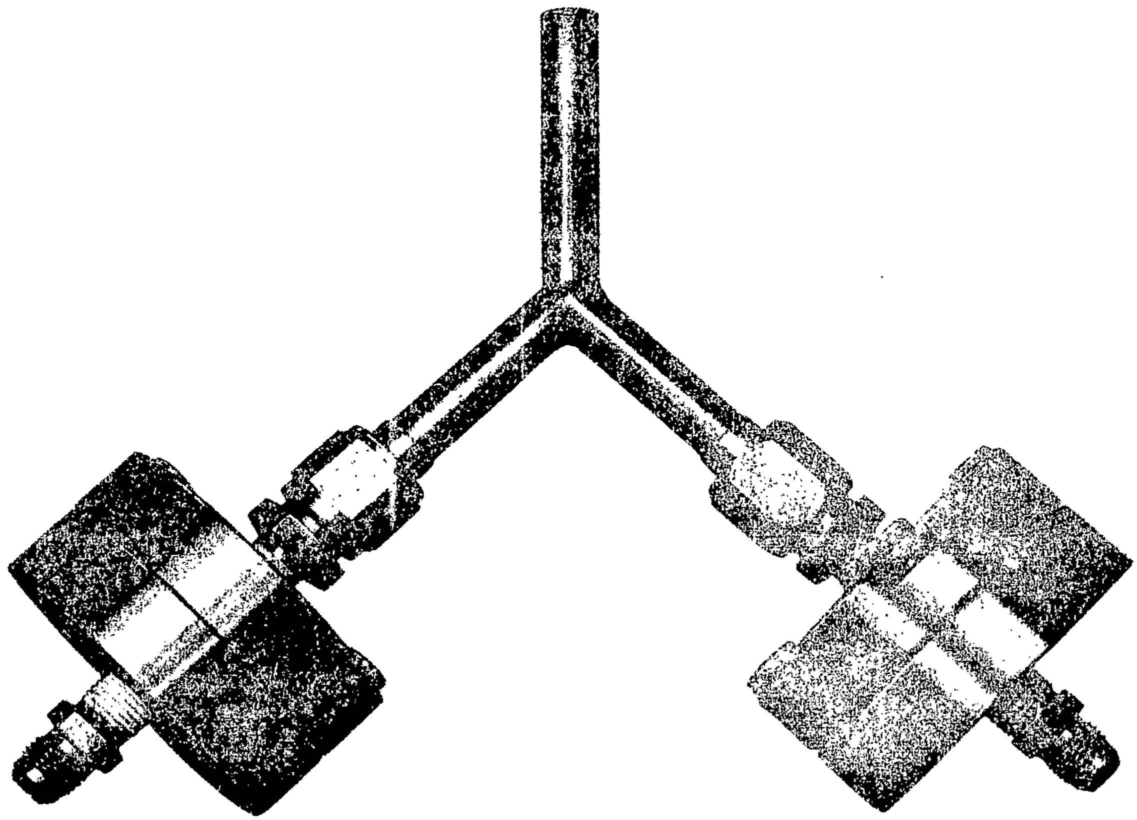

FIGURE 1. MEMBRANE FILTER ASSEMBLY - SERIES TEST

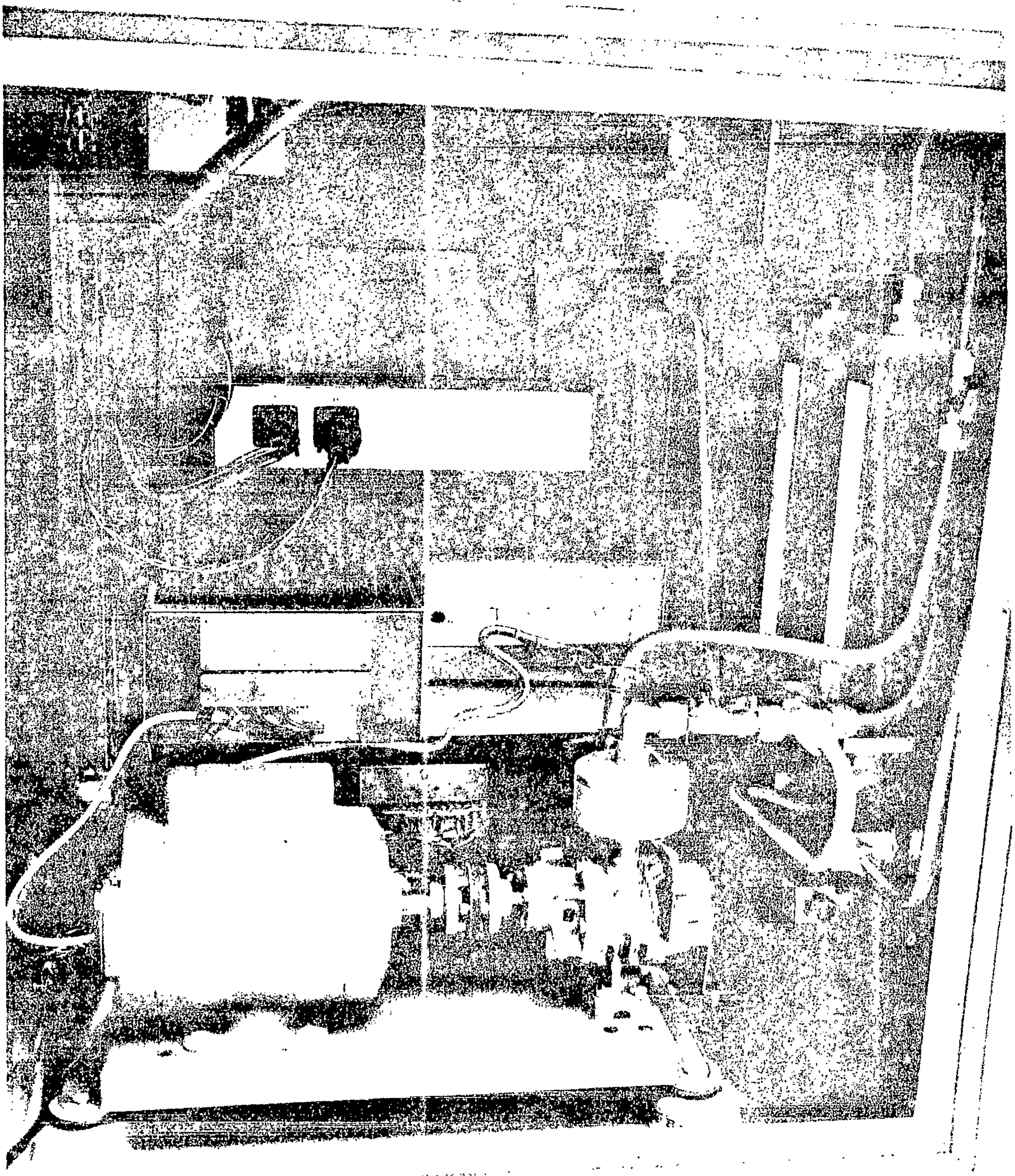

FIGURE 2. VIEW INSIDE SAMPLER PRIOR TO INSTALLATION OF SERIES TEST MEMBRANE FILTER ASSEMBLY

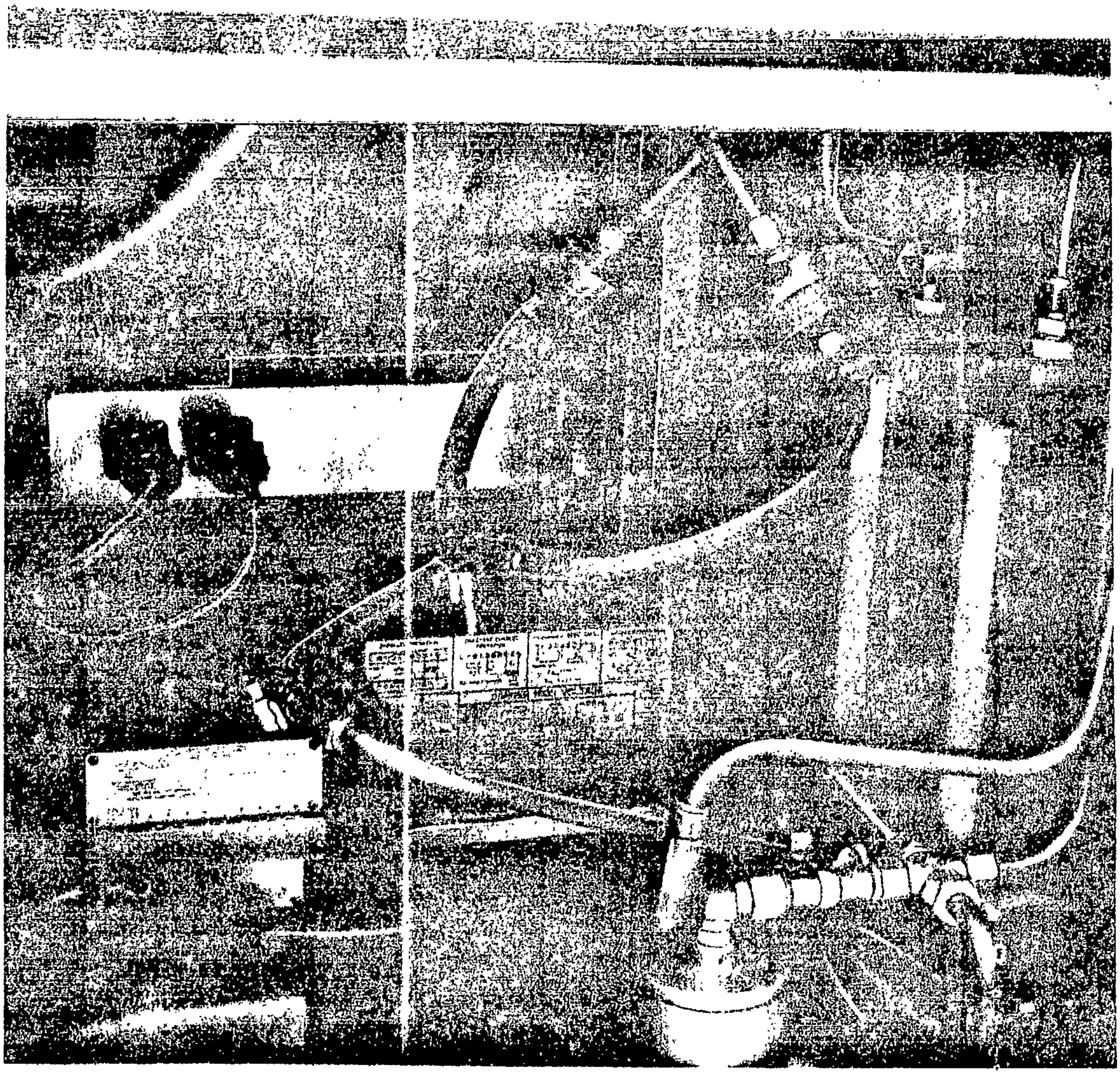

FIGURE 3. VIEW INSIDE SAMPLER AFTER INSTALLATION OF SERIES TEST MEMBRANE FILTER ASSEMBLY

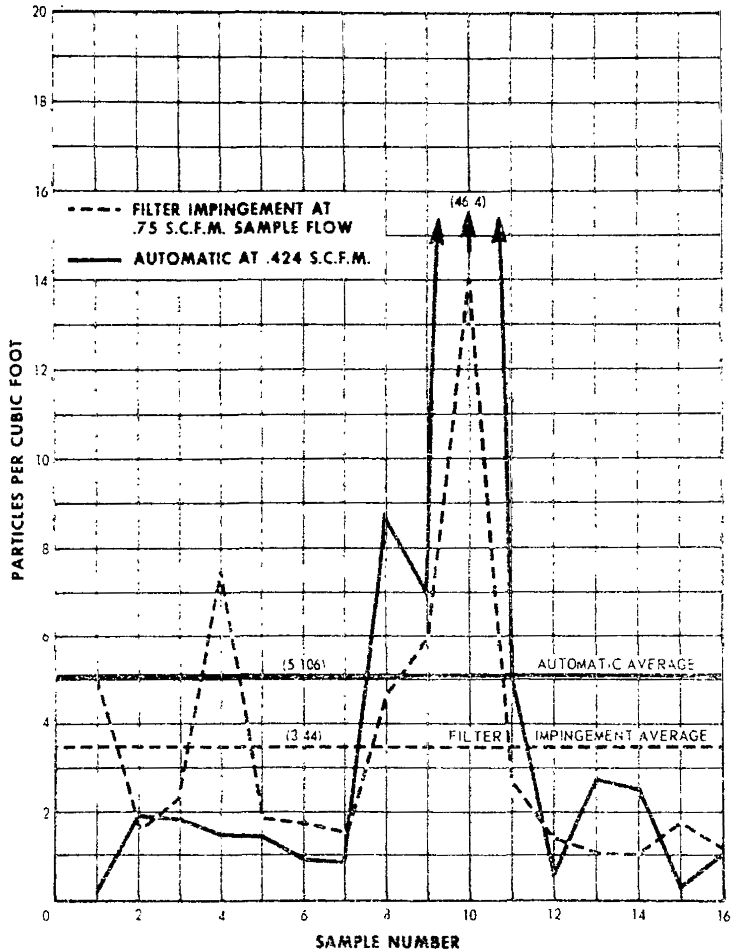

FIGURE 4. COUNTER VERSUS FILTER IN SERIES
COUNTS: 5 TO 25 MICRONS

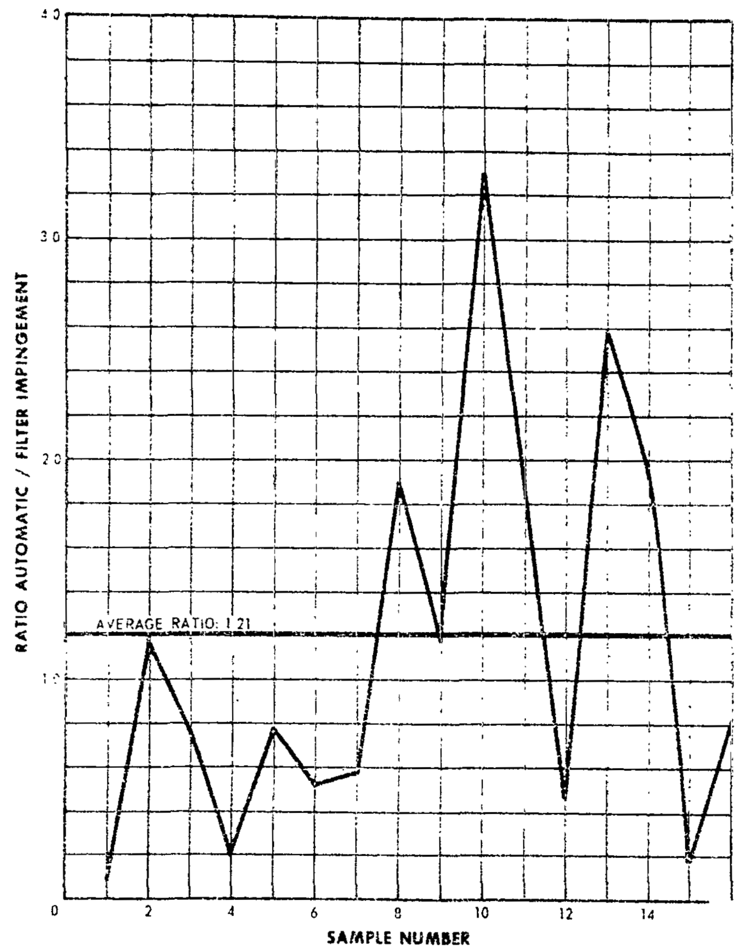

FIGURE 5. COUNTER VERSUS FILTER IN SERIES
RATIOS: 5 TO 25 MICRONS

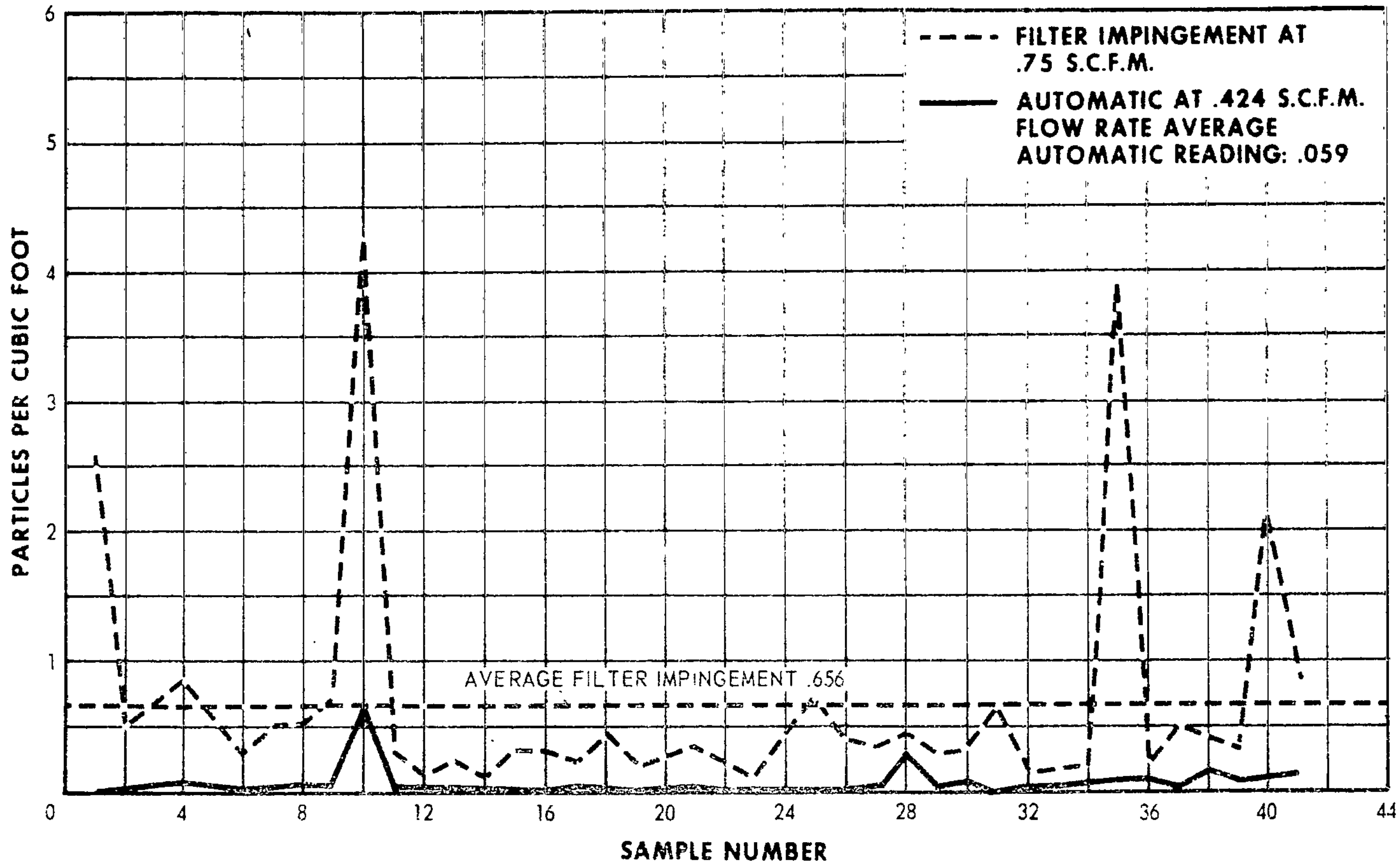

FIGURE 6. COUNTER VERSUS FILTER IN SERIES COUNTS: 25 TO 45 MICRONS

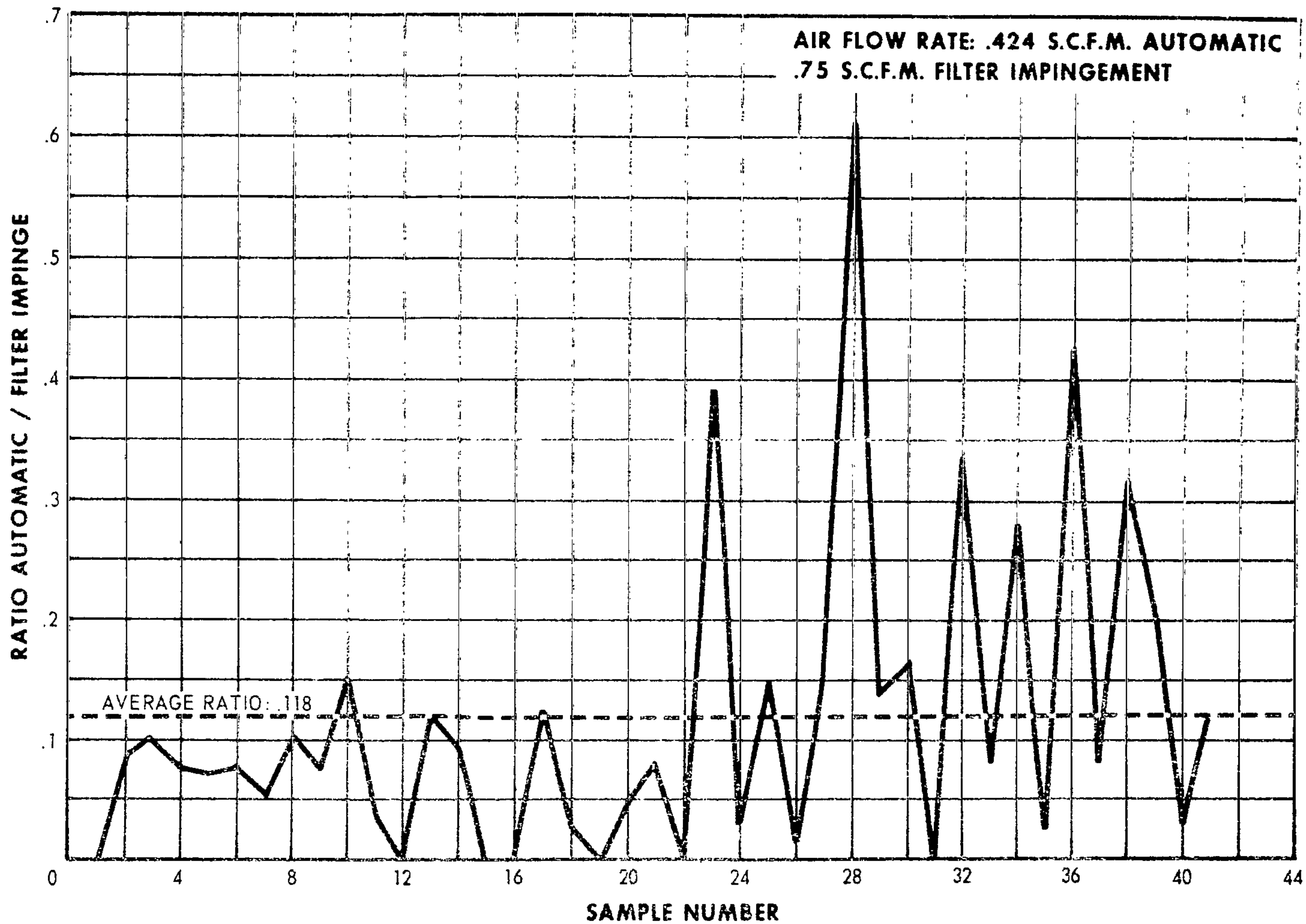

FIGURE 7. COUNTER VERSUS FILTER IN SERIES RATIOS: 25 TO 55 MICRONS

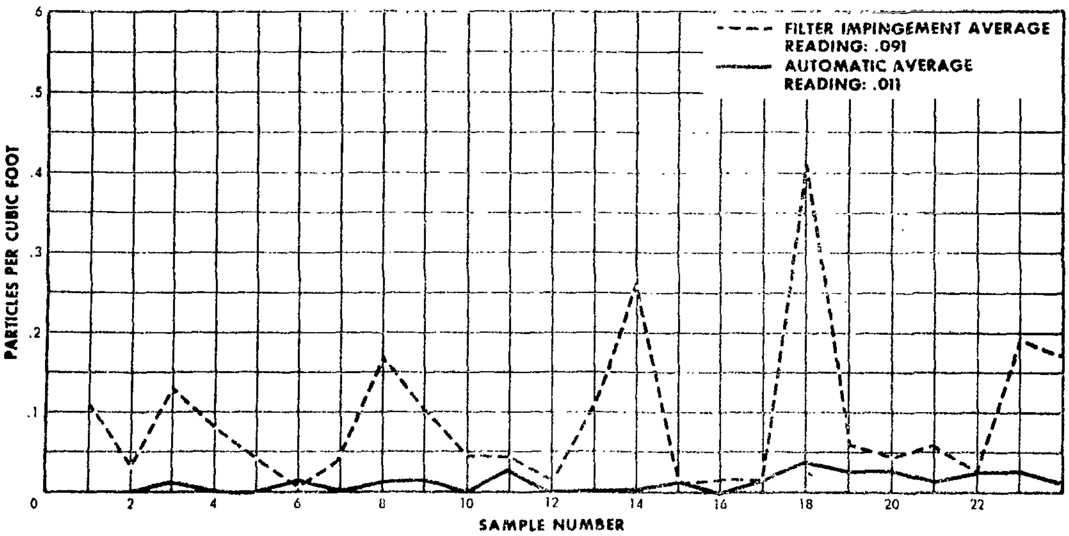

FIGURE 8. COUNTER VERSUS FILTER IN SERIES COUNTS: 45 TO 100 MICRONS

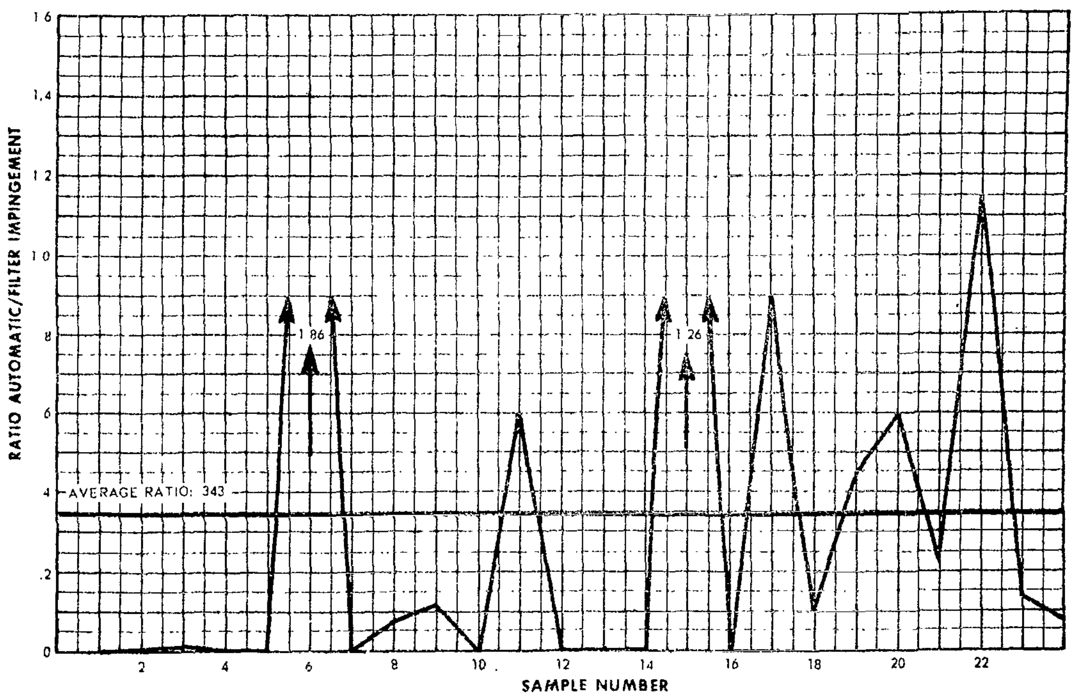

FIGURE 9. COUNTER VERSUS FILTER IN SERIES RATIOS: 45 TO 100 MICRONS

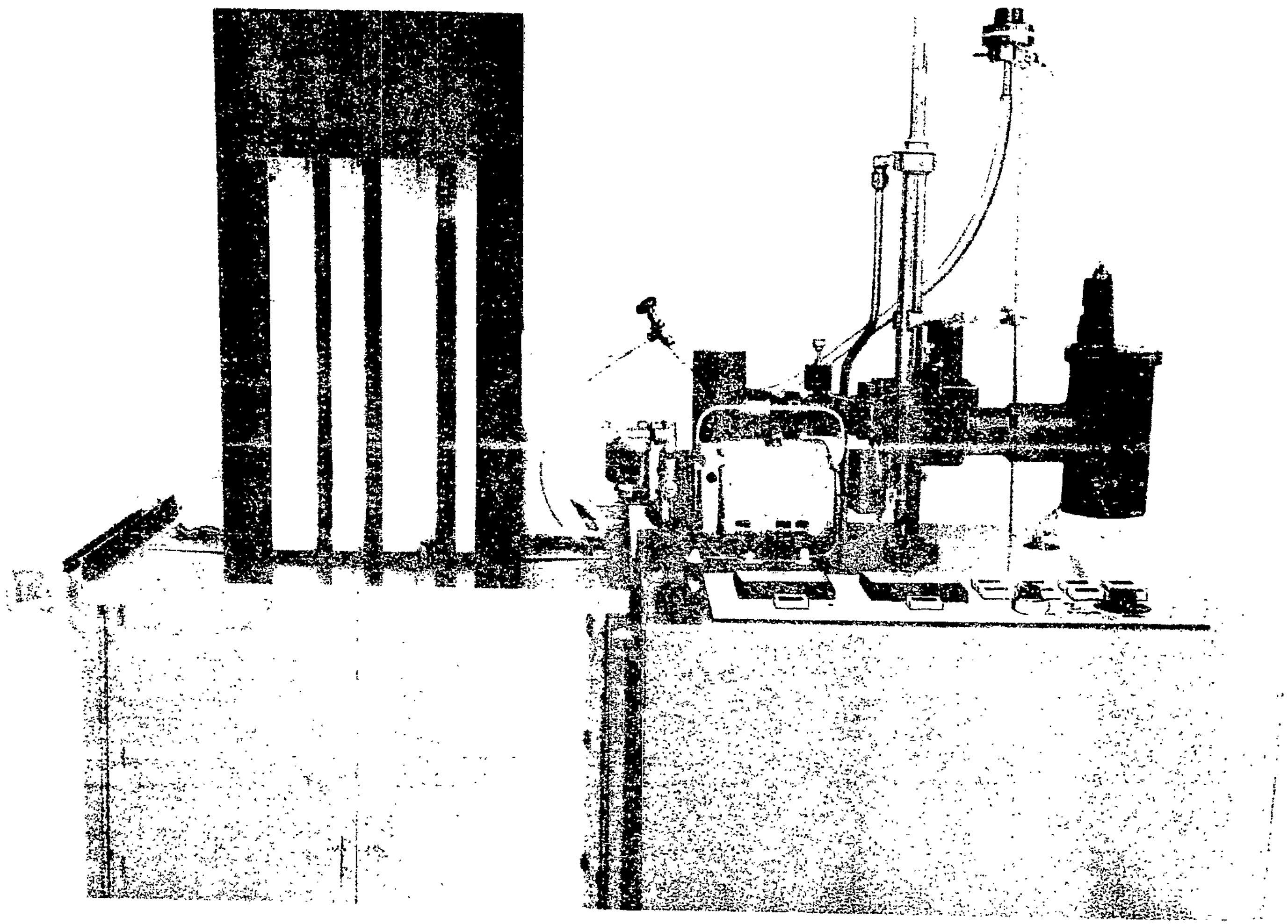

FIGURE 10. SIDE BY SIDE TEST ARRANGEMENT

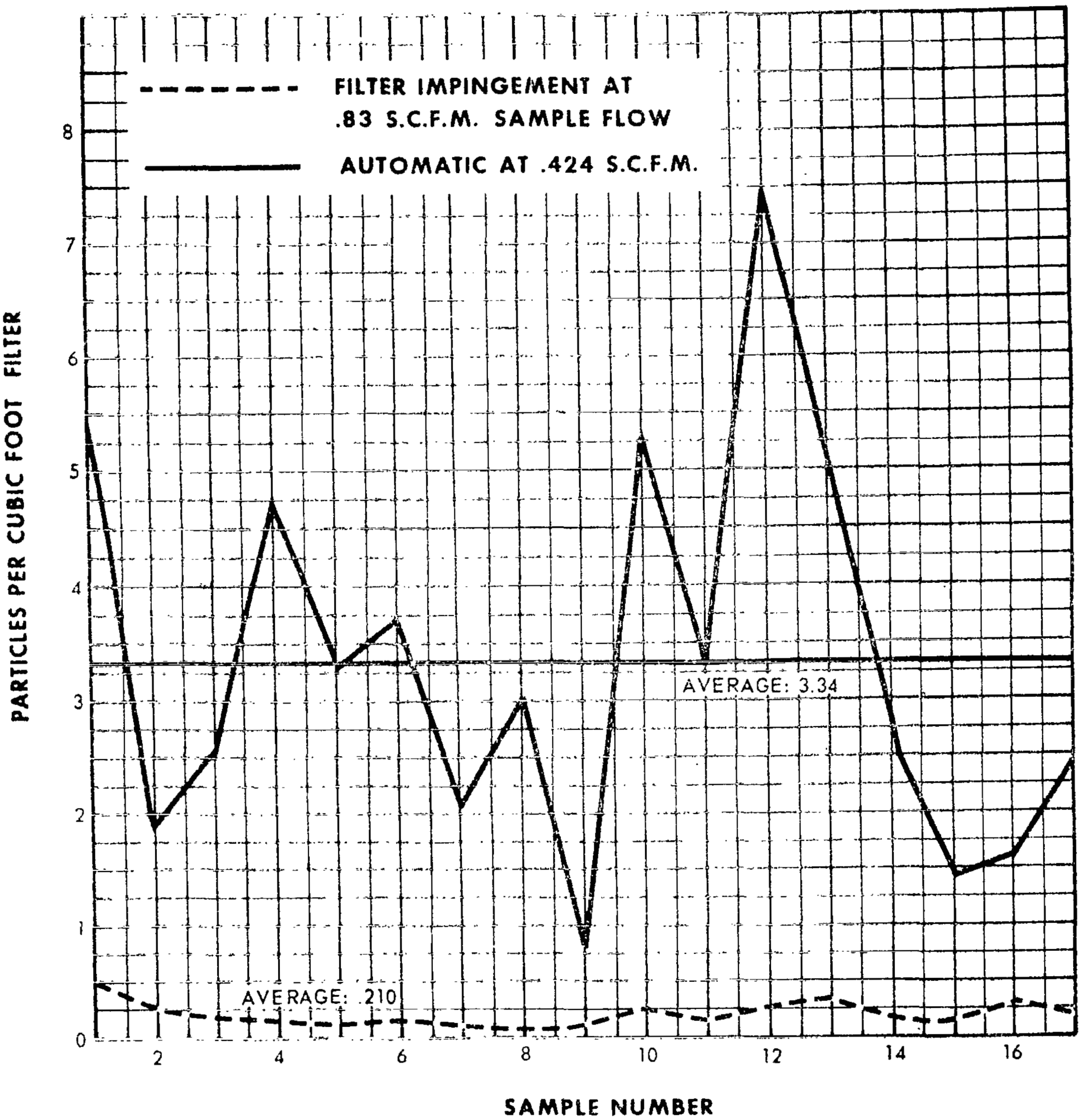

FIGURE 11. COUNTER VERSUS FILTER SIDE BY SIDE COUNTS:
5 TO 25 MICRONS

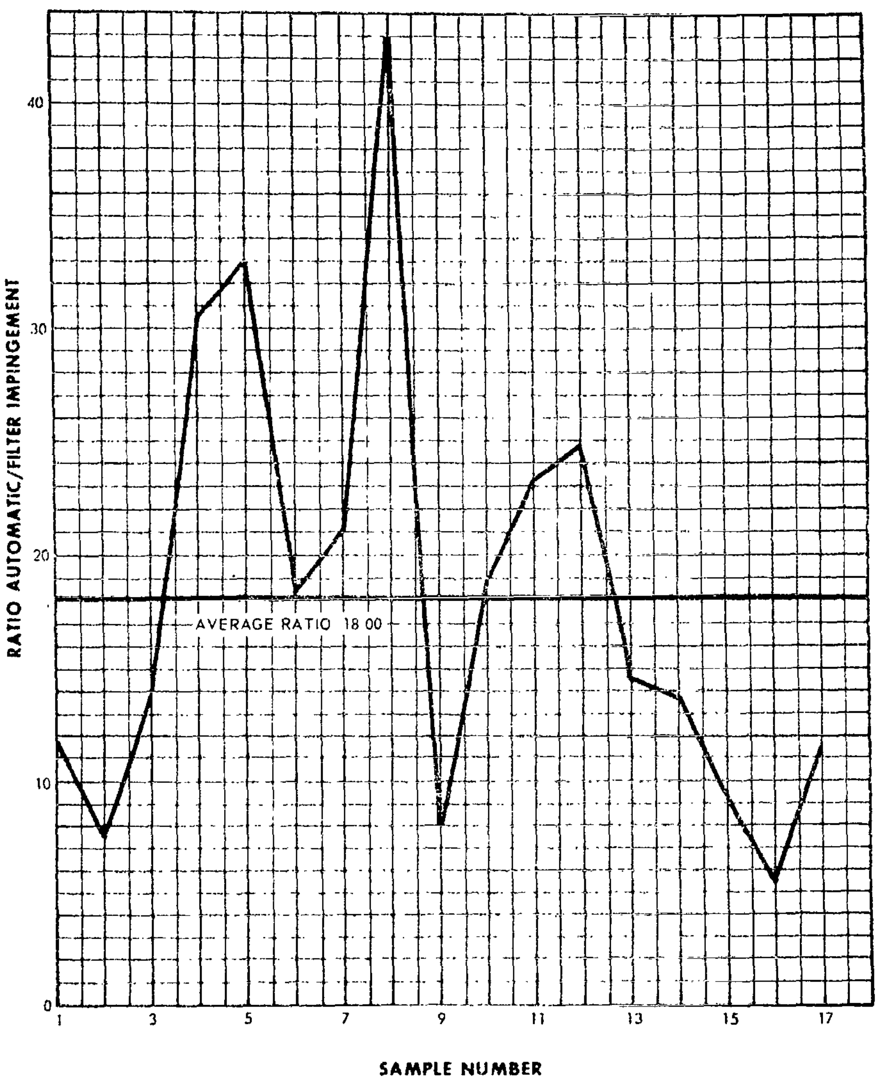

FIGURE 12. COUNTER VERSUS FILTER SIDE BY SIDE RATIOS:
5 TO 25 MICRONS

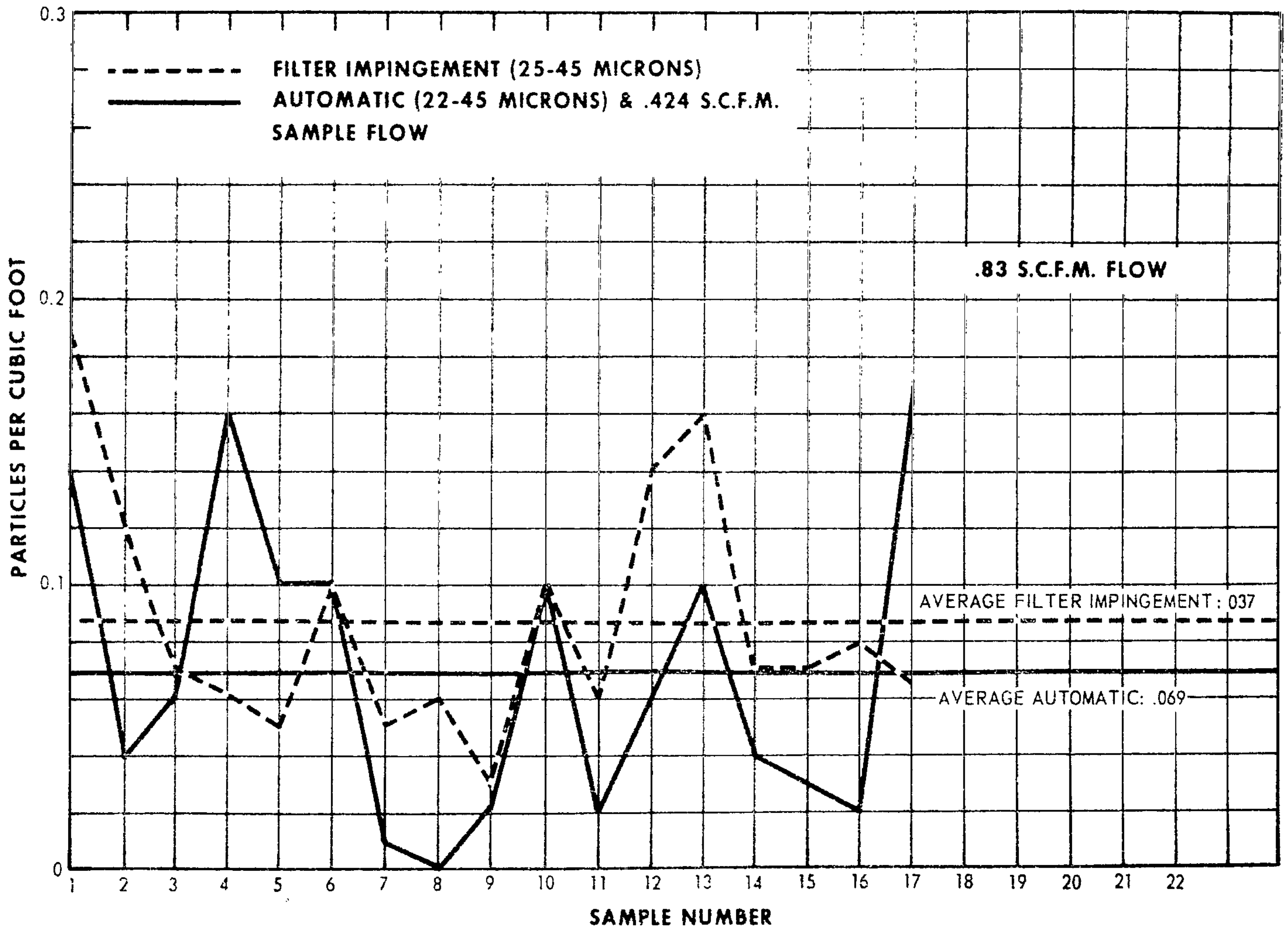

FIGURE 13. COUNTER VERSUS FILTER SIDE BY SIDE COUNTS: 22 TO 45 MICRONS

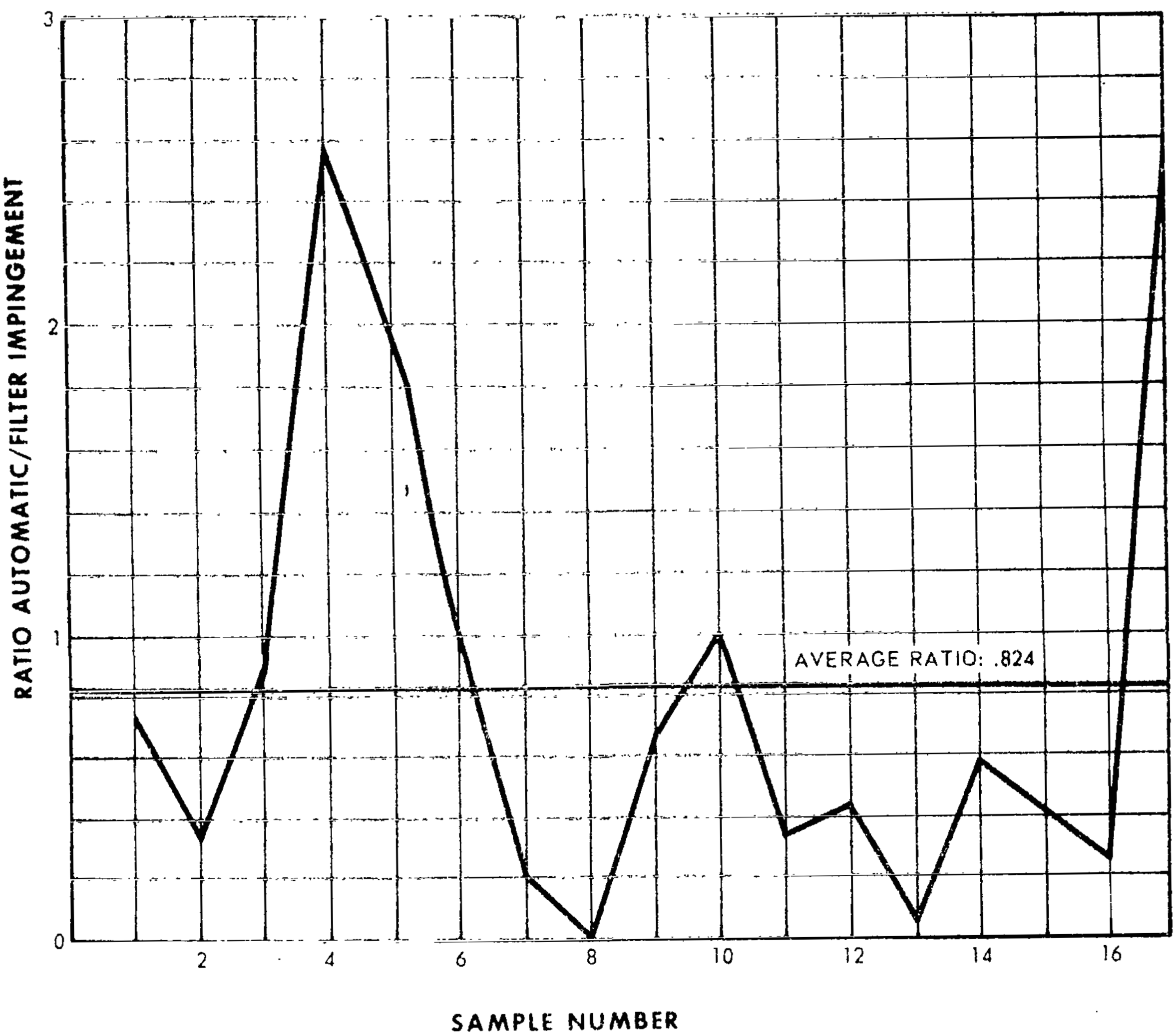

FIGURE 14. COUNTER VERSUS FILTER SIDE BY SIDE RATIOS: 25 TO 45 MICRONS

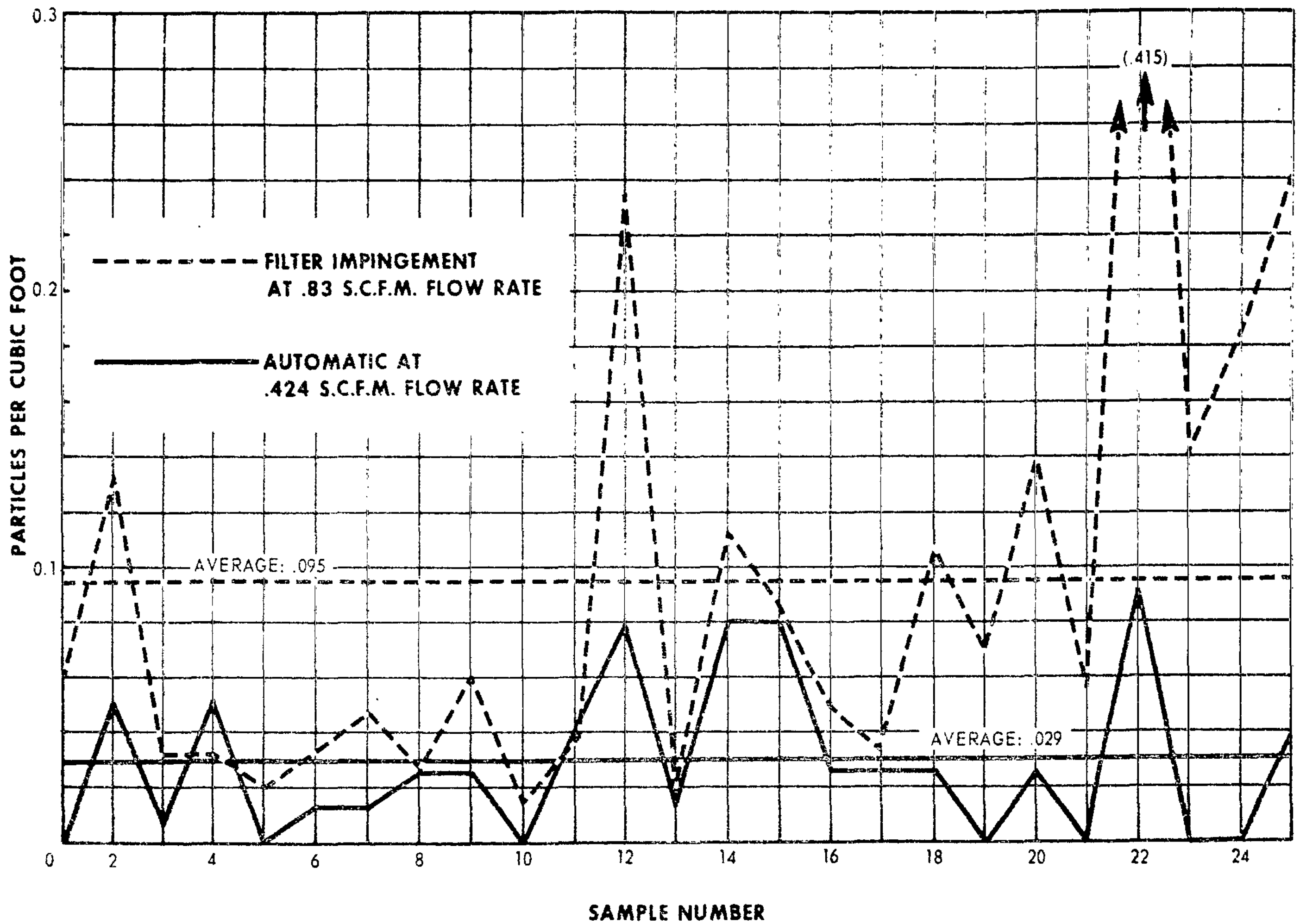

FIGURE 15. COUNTER VERSUS FILTER SIDE BY SIDE COUNTS:
45 TO 100 MICRONS

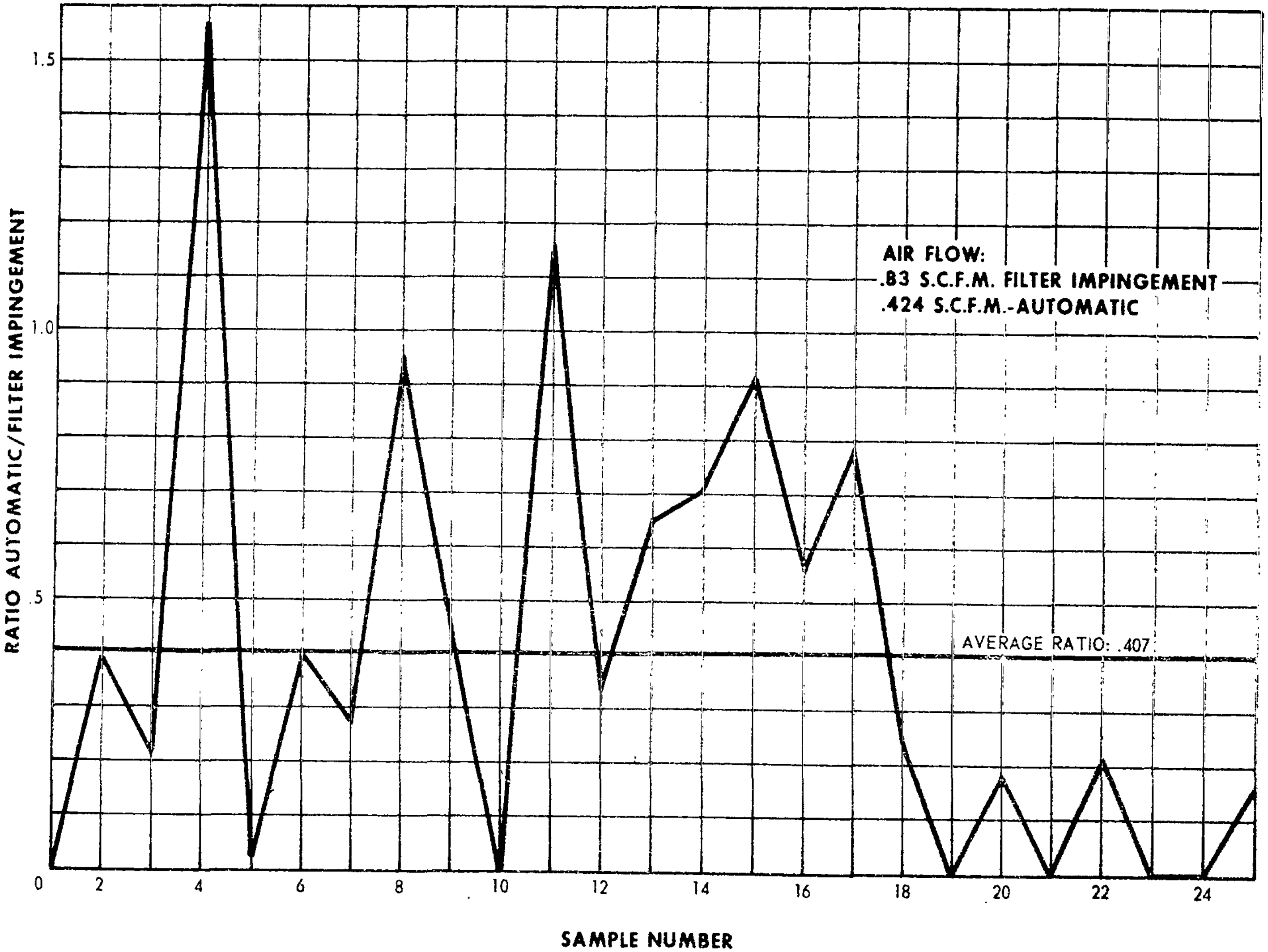

FIGURE 16. COUNTER VERSUS FILTER SIDE BY SIDE RATIOS: 45 TO 100 MICRONS

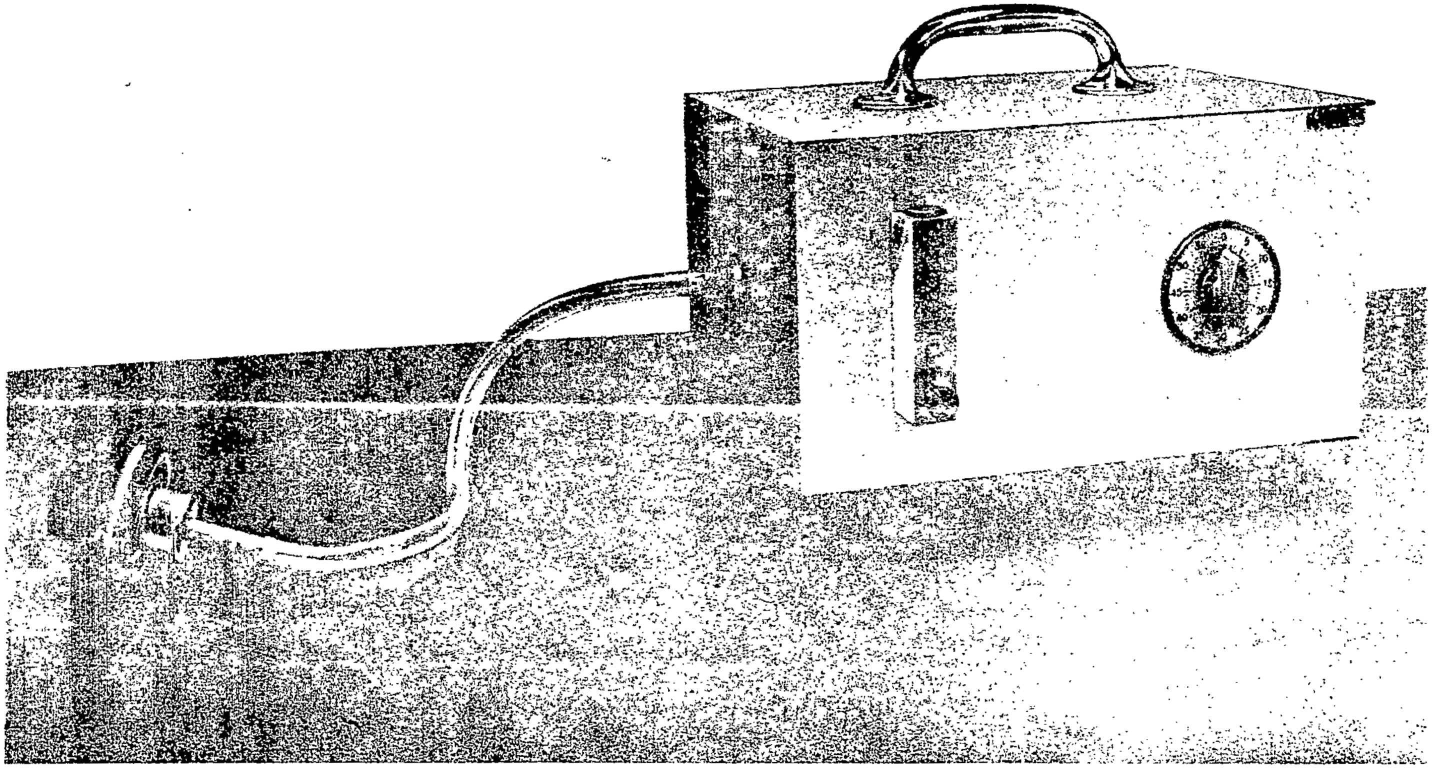

FIGURE 17. DAILY MONITORING FILTER IMPINGEMENT EQUIPMENT

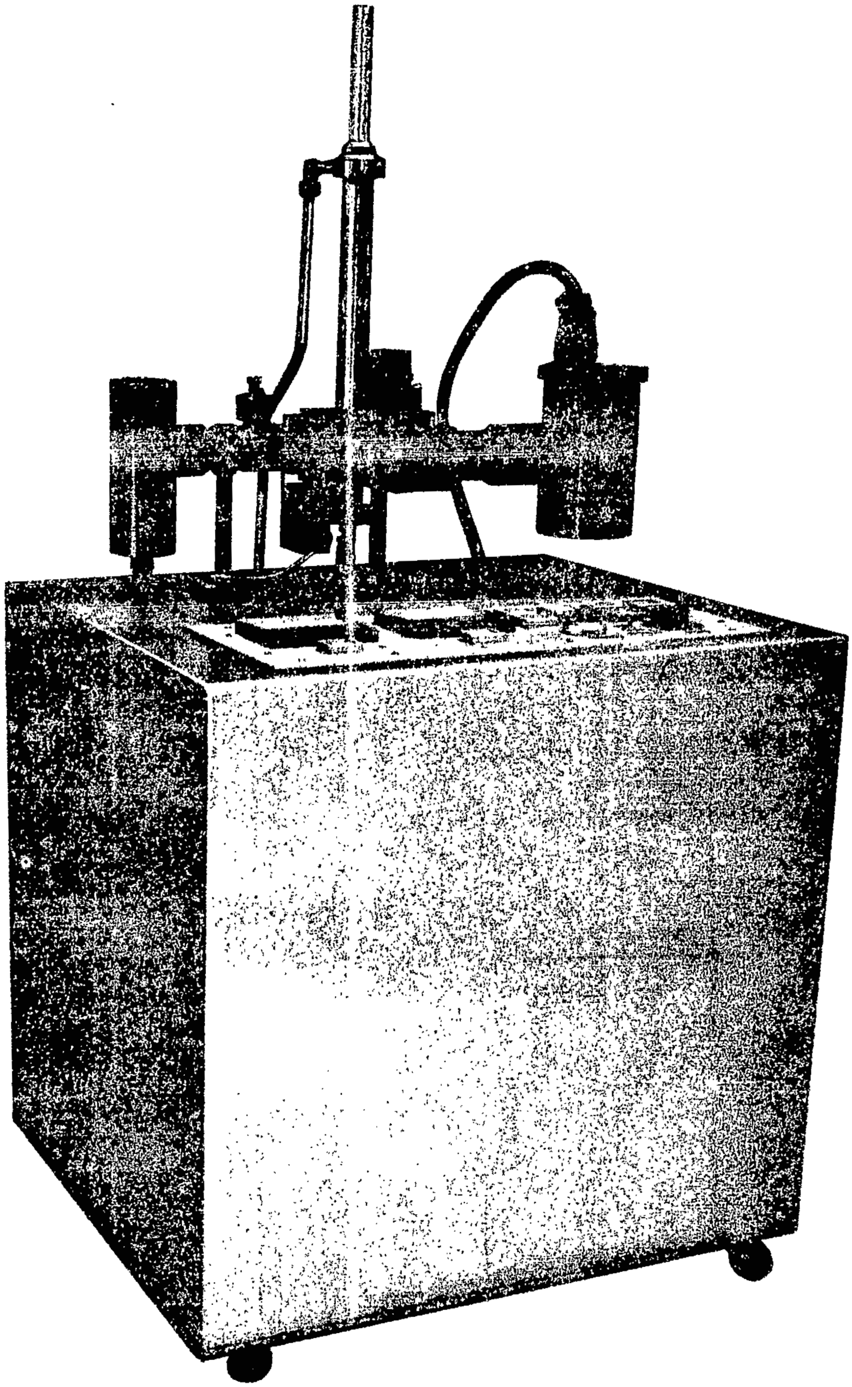

FIGURE 18. AUTOMATIC ELECTRONIC SAMPLER

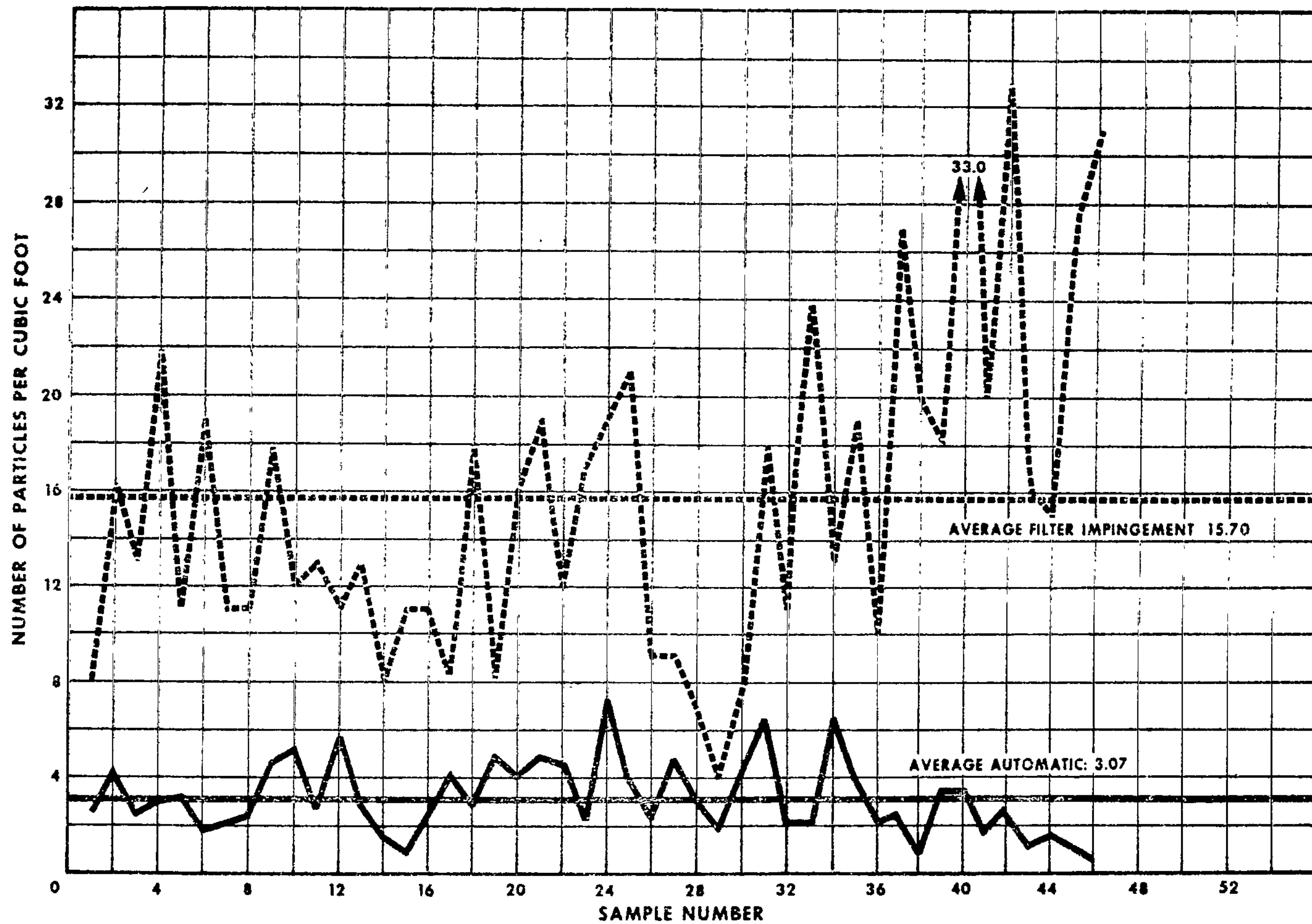

FIGURE 19. COUNTER VERSUS FILTER DAILY MONITORING COUNTS:
5 TO 25 MICRONS

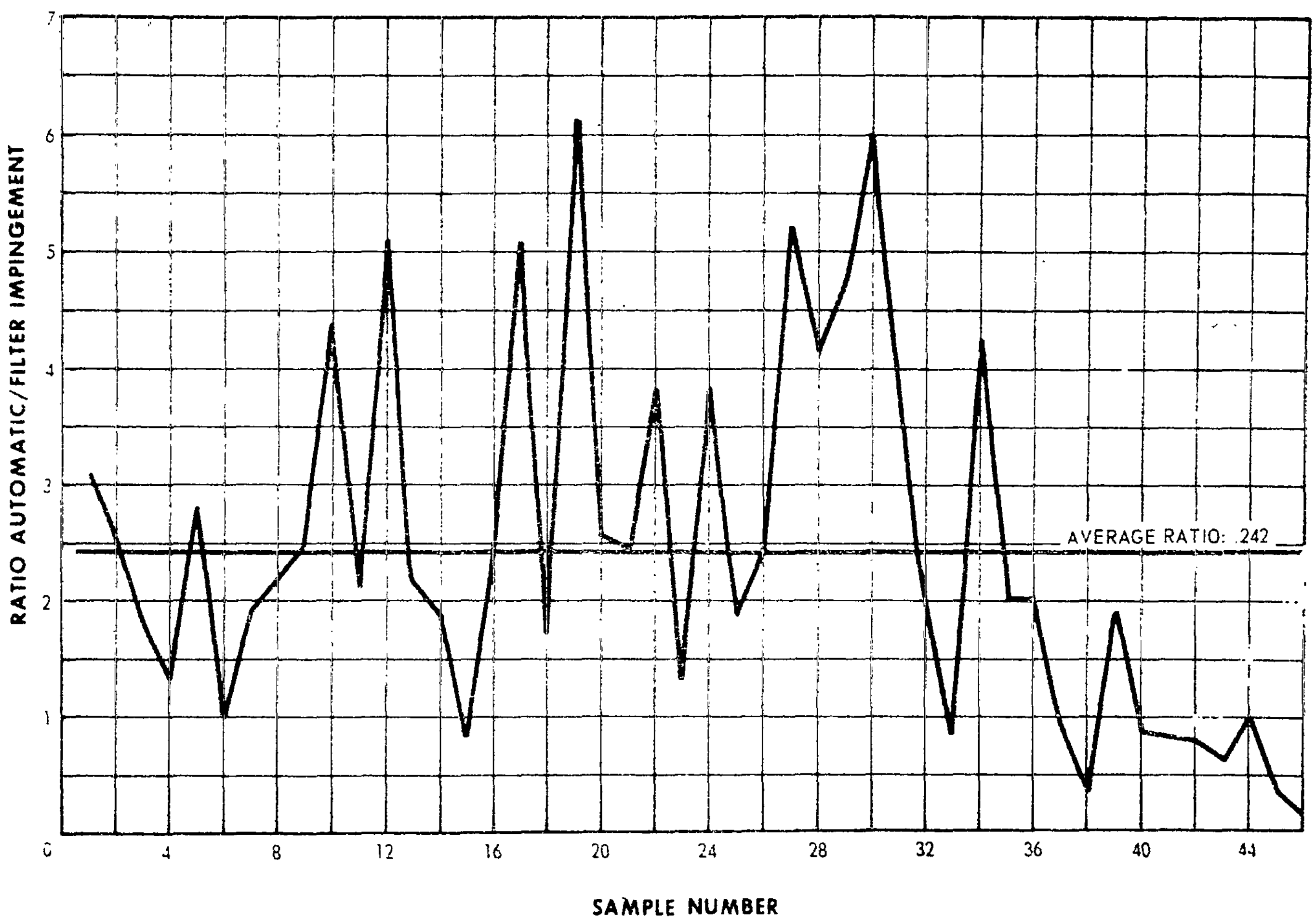

FIGURE 20. COUNTER VERSUS FILTER DAILY MONITORING RATIOS: 5 TO 25 MICRONS

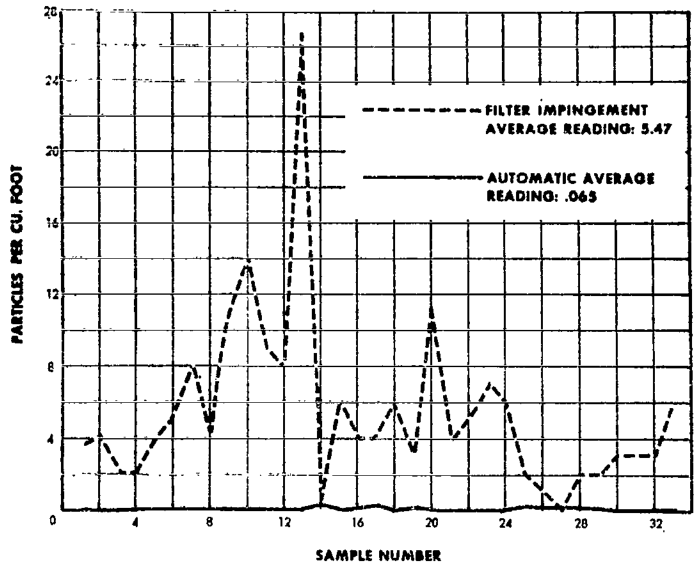

FIGURE 21. COUNTER VERSUS FILTER DAILY MONITORING COUNTS: 25 TO 45 MICRONS

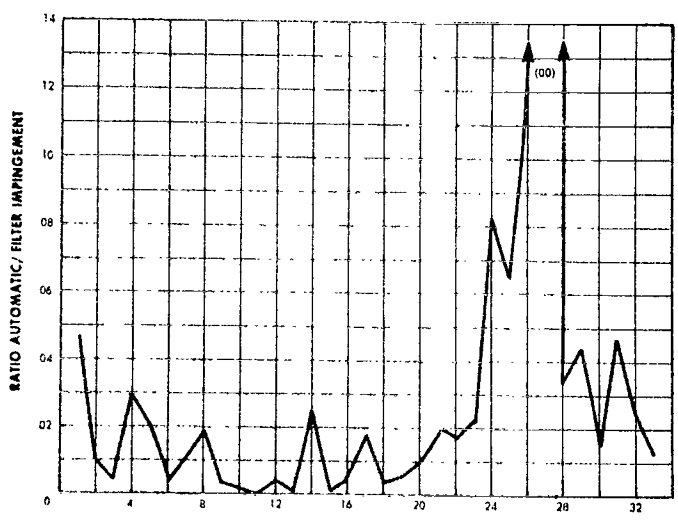

FIGURE 22. COUNTER VERSUS FILTER DAILY MONITORING RATIOS: 25 TO 45 MICRONS

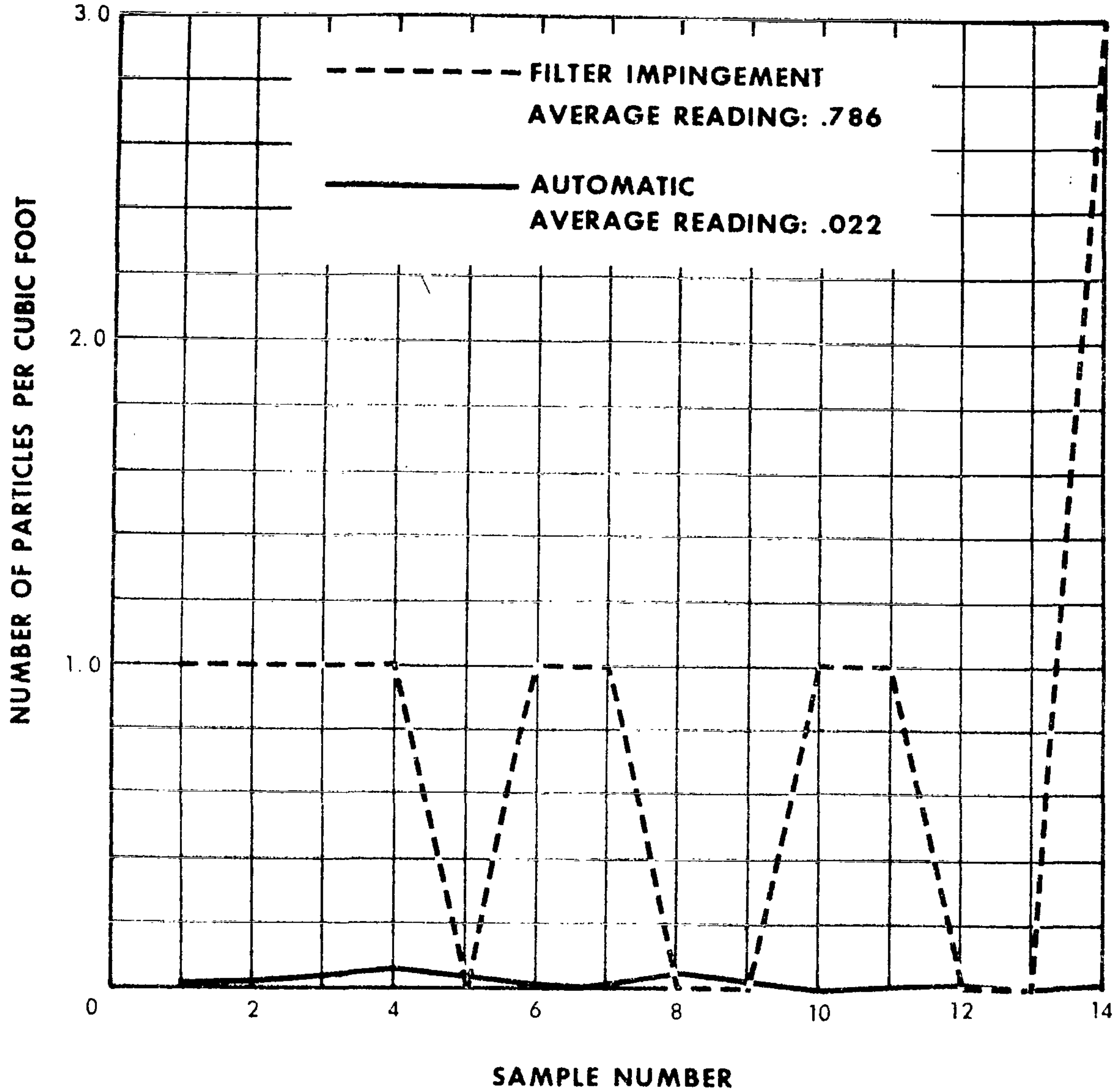

FIGURE 23. COUNTER VERSUS FILTER DAILY MONITORING COUNTS: 45 TO 100 MICRONS

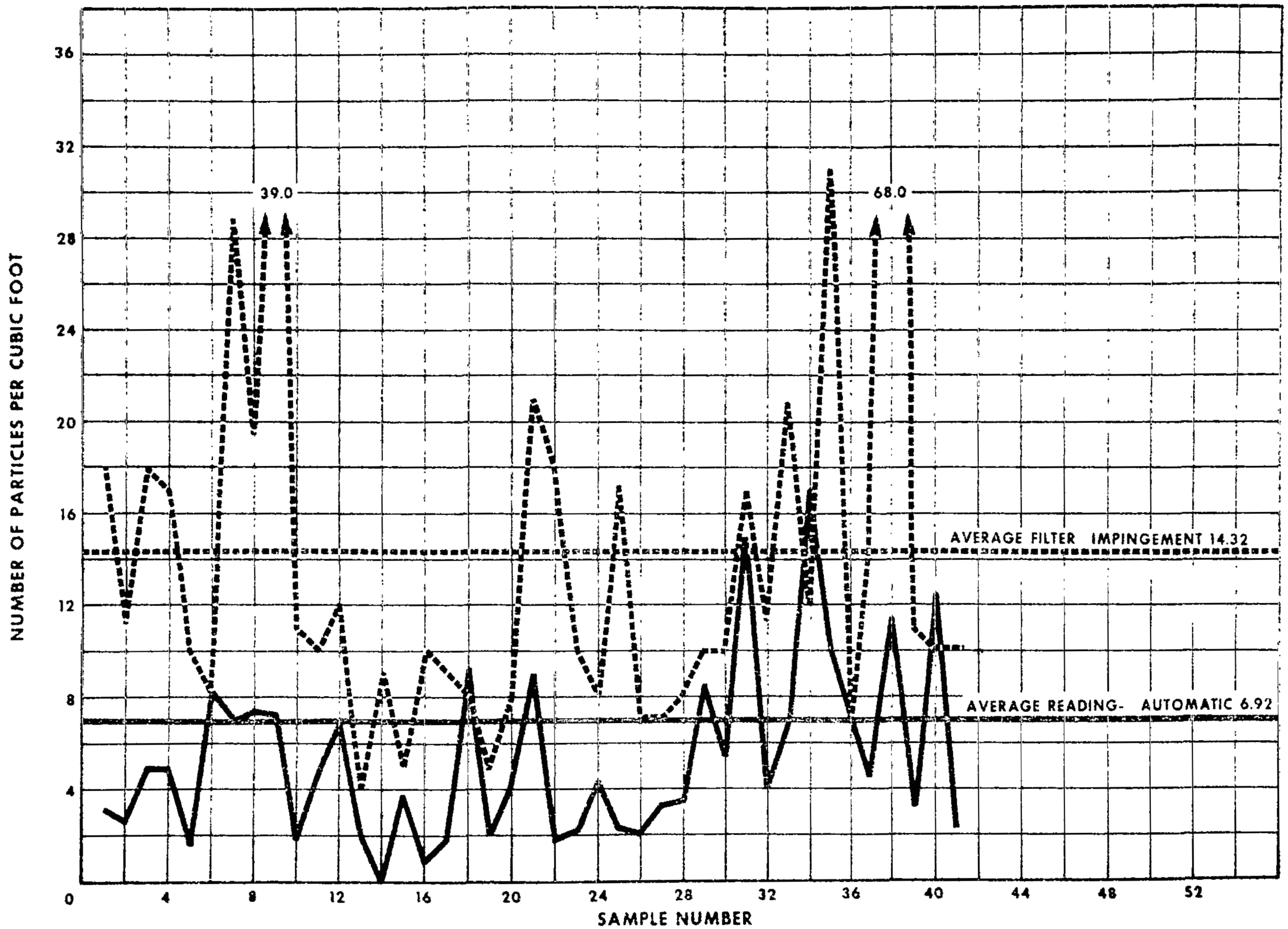

FIGURE 24. COUNTER VERSUS FILTER DAILY MONITORING COUNTS: 5 TO 25 MICRONS (PACKAGING ROOM)

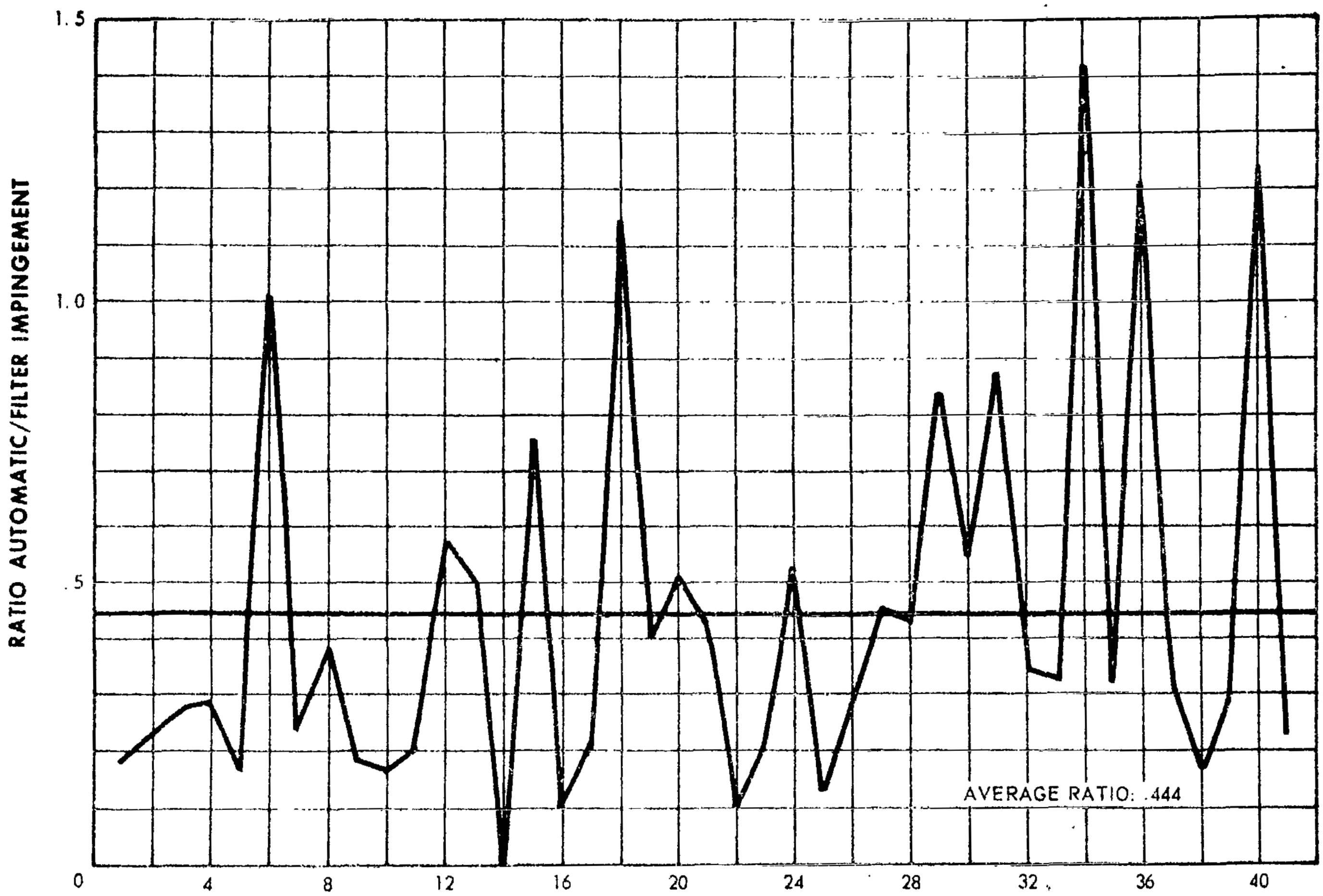

FIGURE 25. COUNTER VERSUS FILTER DAILY MONITORING RATIOS:
5 TO 25 MICRONS

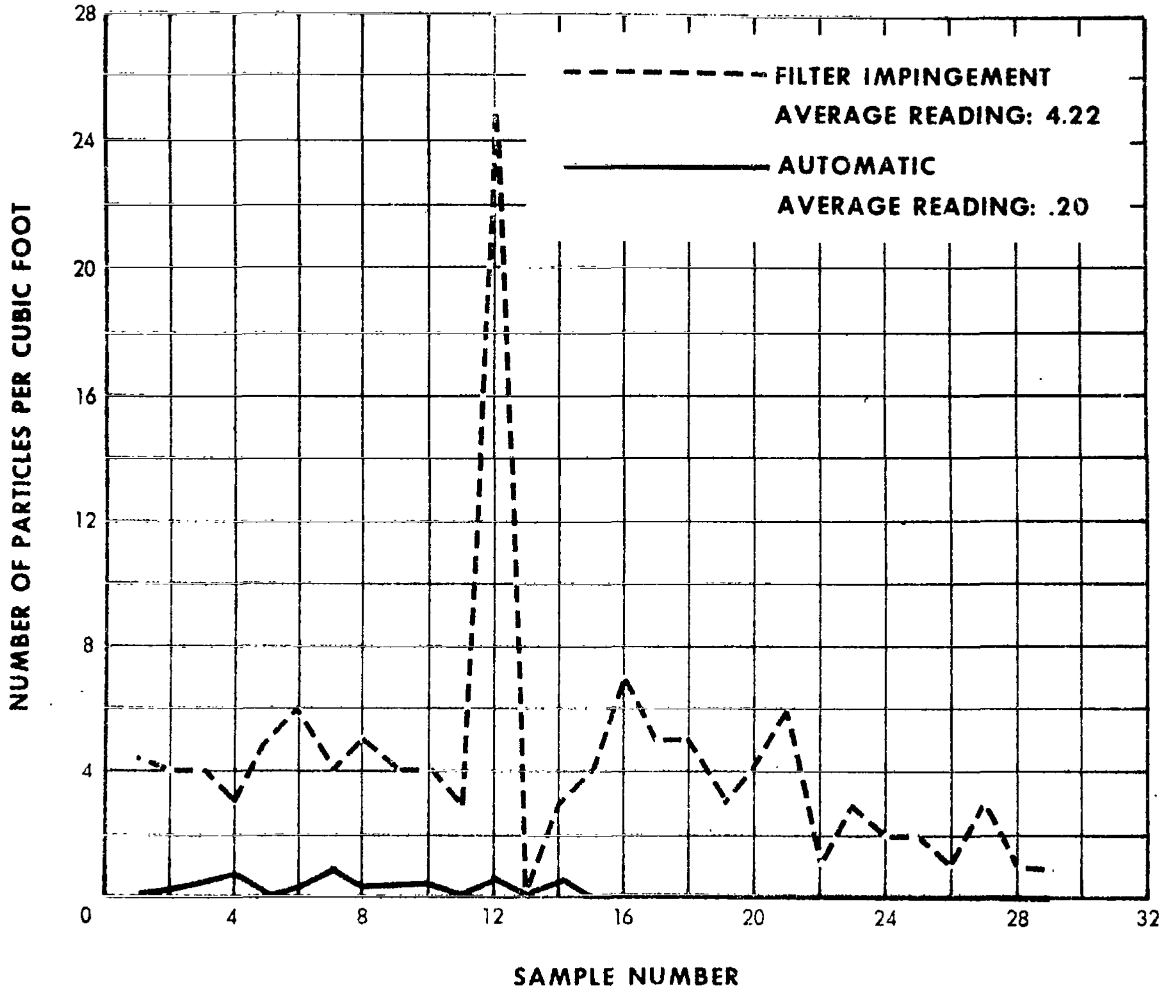

FIGURE 26. COUNTER VERSUS FILTER DAILY MONITORING COUNTS: 25 TO 45 MICRONS

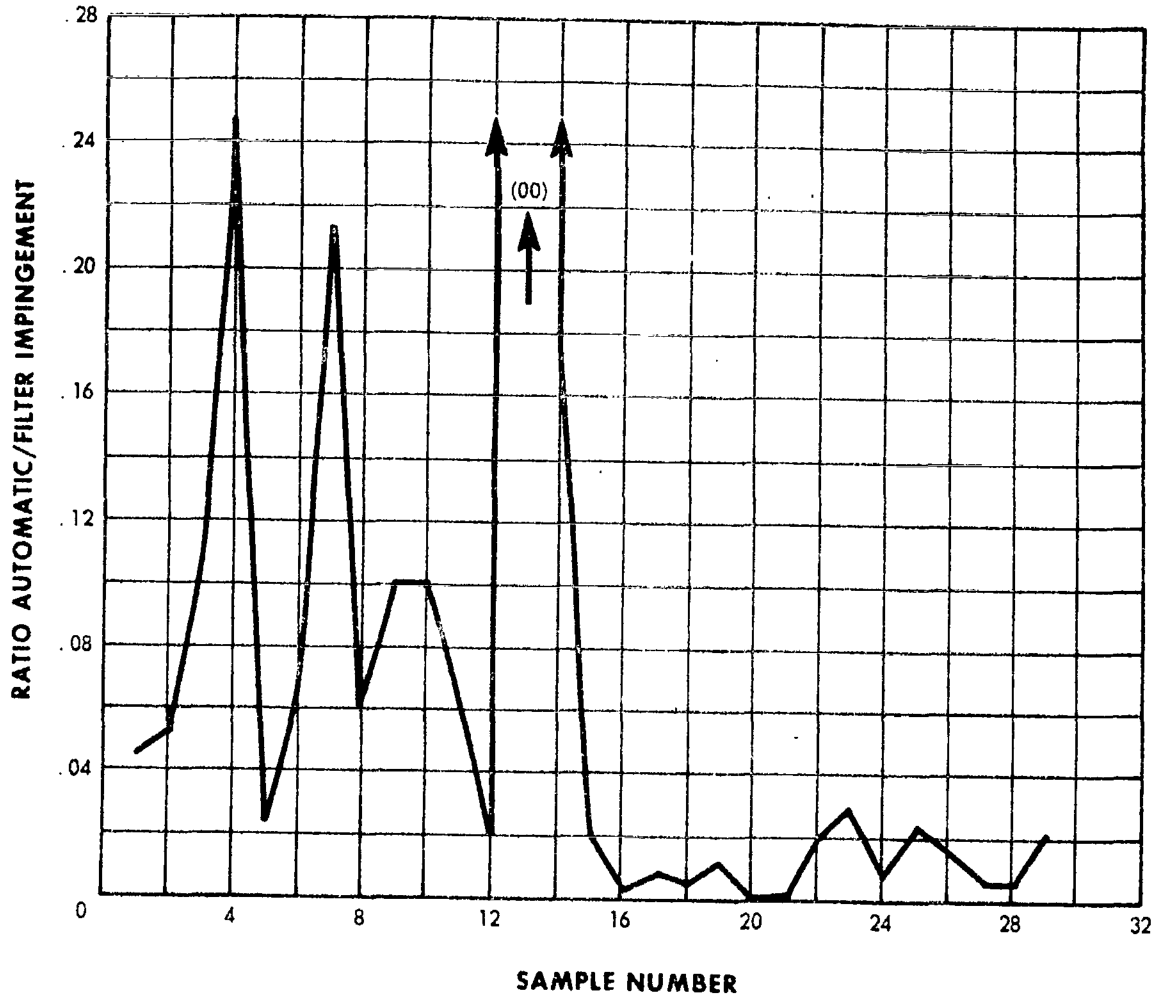

FIGURE 27. COUNTER VERSUS FILTER DAILY MONITORING RATIOS: 25 TO 45 MICRONS

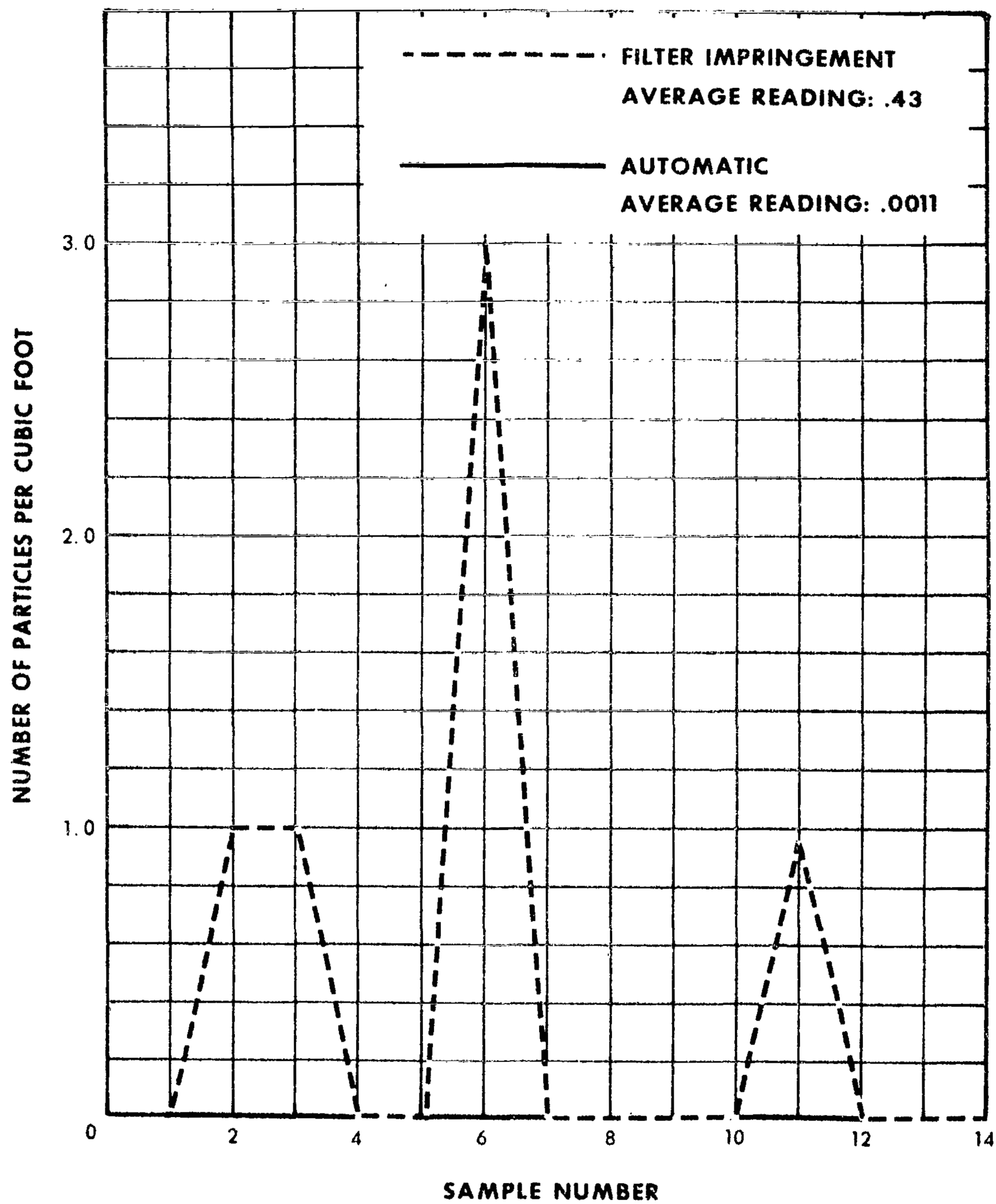

FIGURE 28. COUNTER VERSUS FILTER DAILY MONITORING COUNTS: 45 TO 100 MICRONS

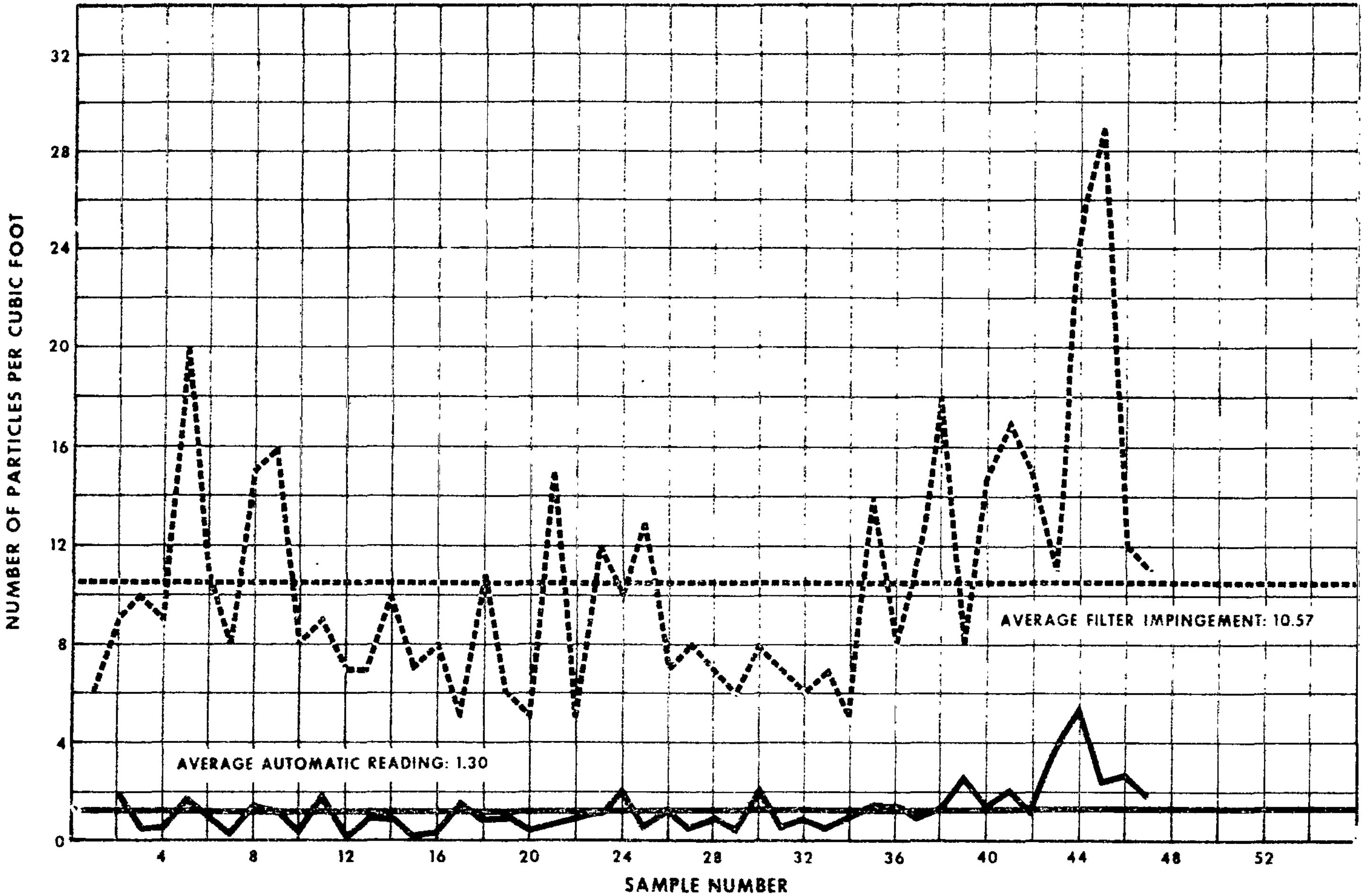

FIGURE 29. COUNTER VERSUS FILTER DAILY MONITORING COUNTS: 5 TO 25 MICRONS (LABS)

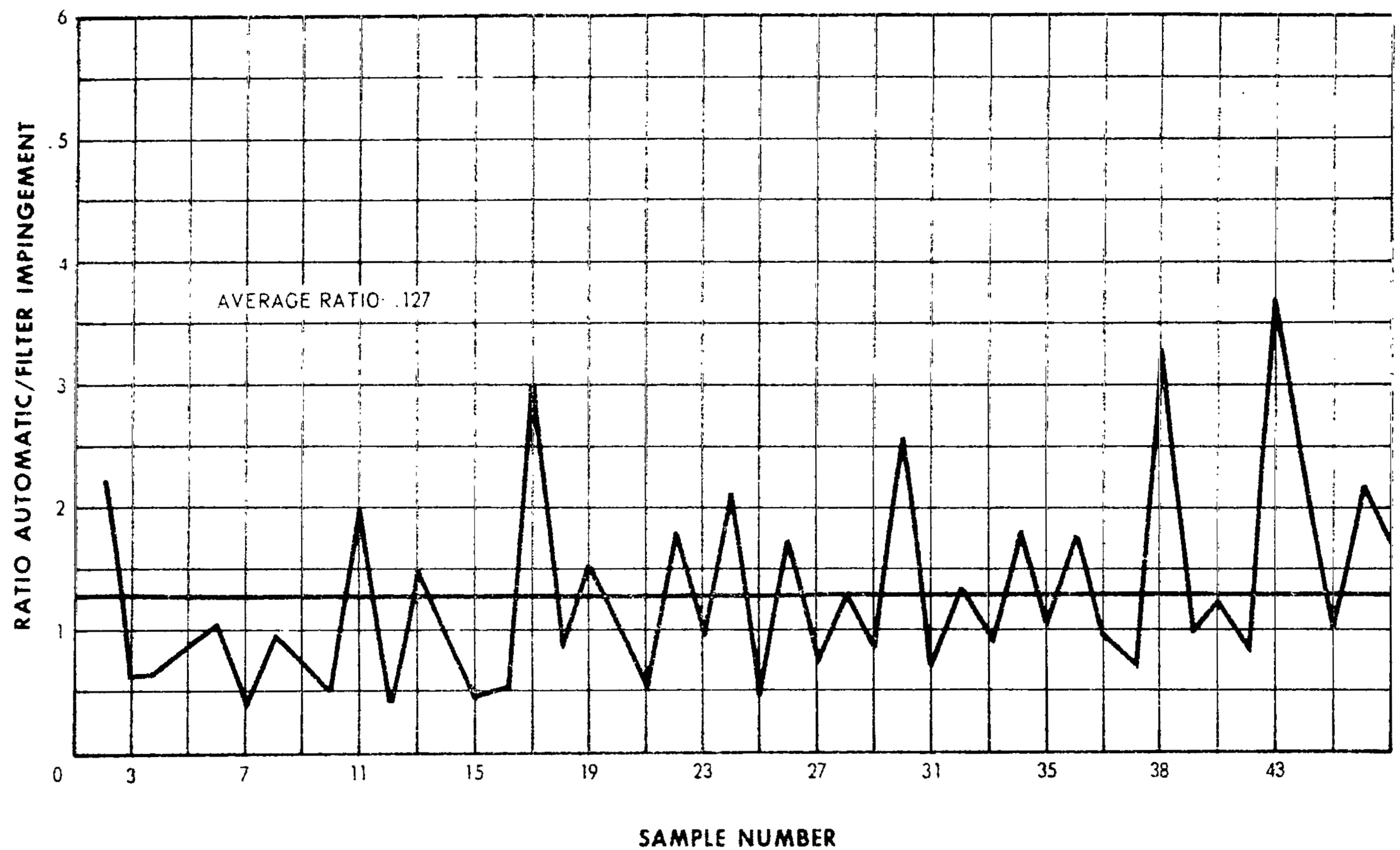

FIGURE 30. COUNTER VERSUS FILTER DAILY MONITORING RATIOS: 5 TO 25 MICRONS

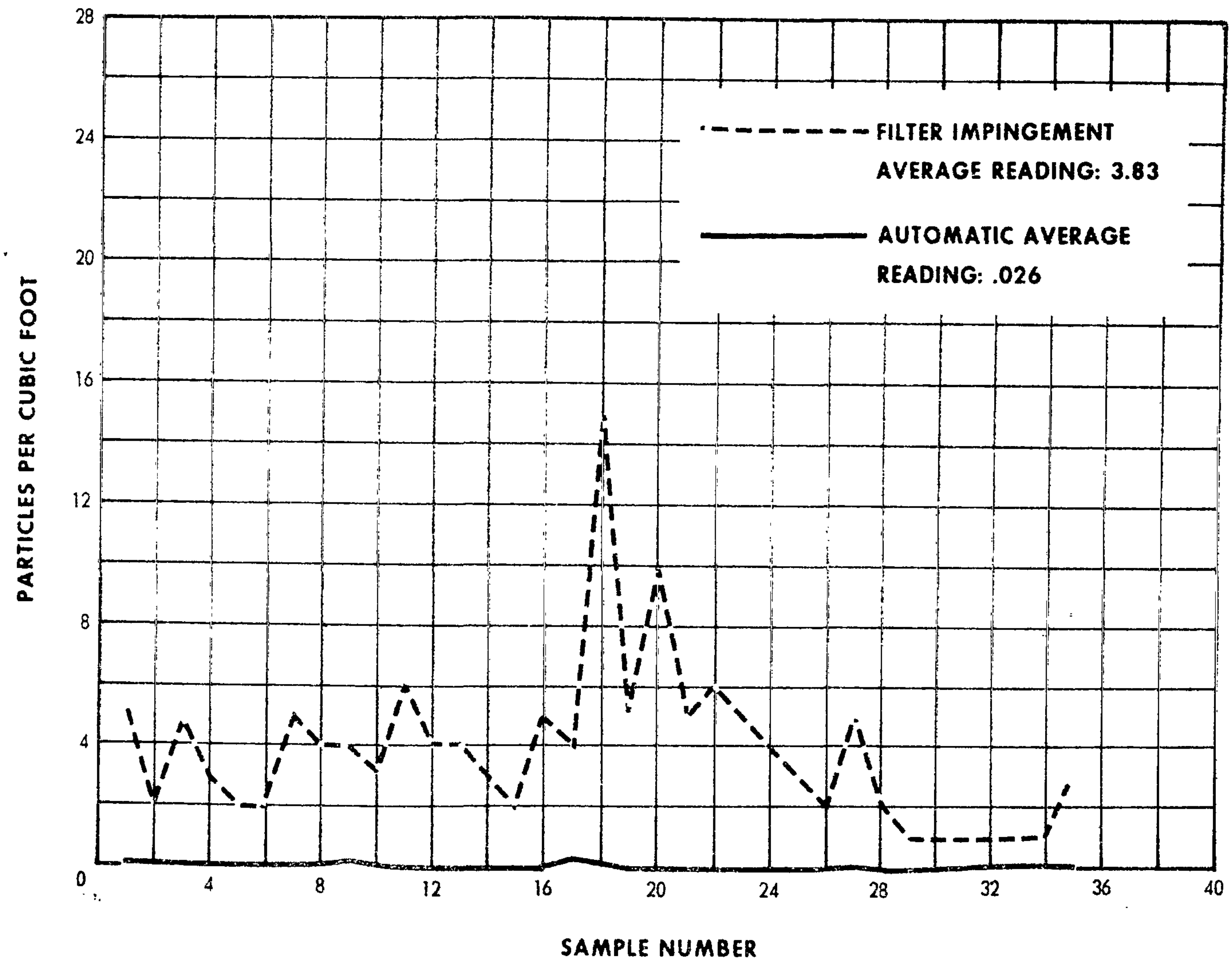

FIGURE 31. COUNTER VERSUS FILTER DAILY MONITORING COUNTS: 25 TO 45 MICRONS

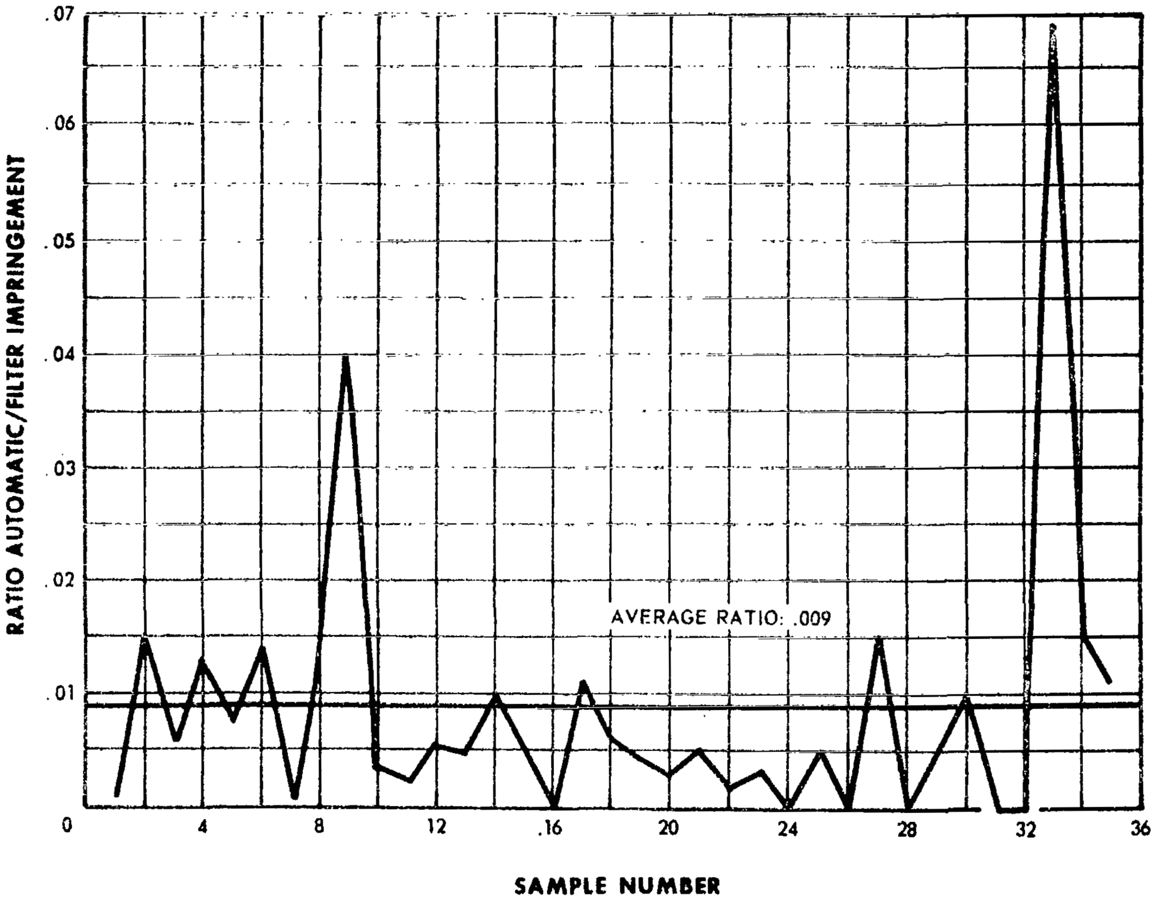

FIGURE 32. COUNTER VERSUS FILTER DAILY MONITORING RATIOS: 25 TO 45 MICRONS

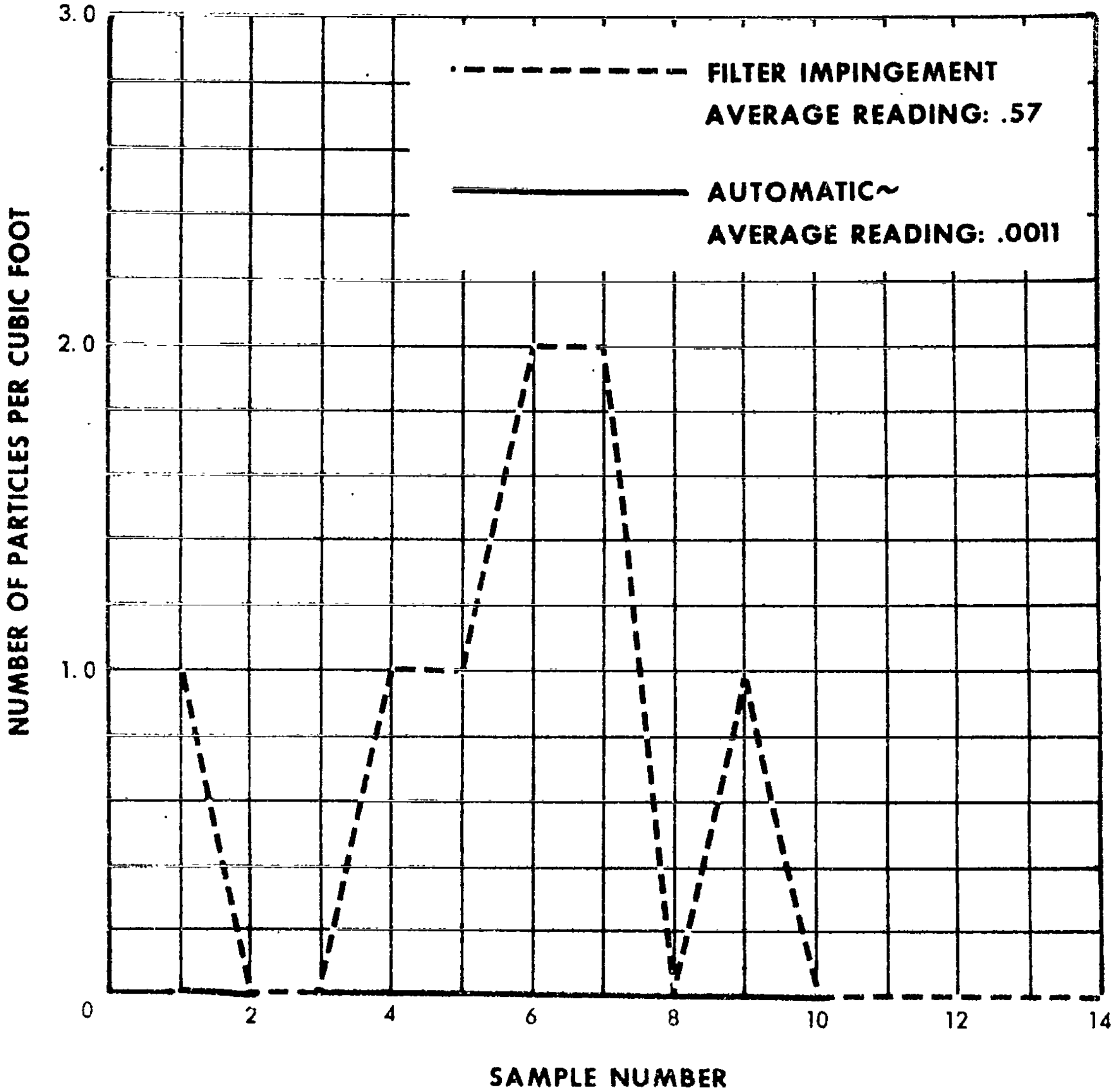

FIGURE 33. COUNTER VERSUS FILTER DAILY MONITORING COUNTS: 45 TO 100 MICRONS (LAB)

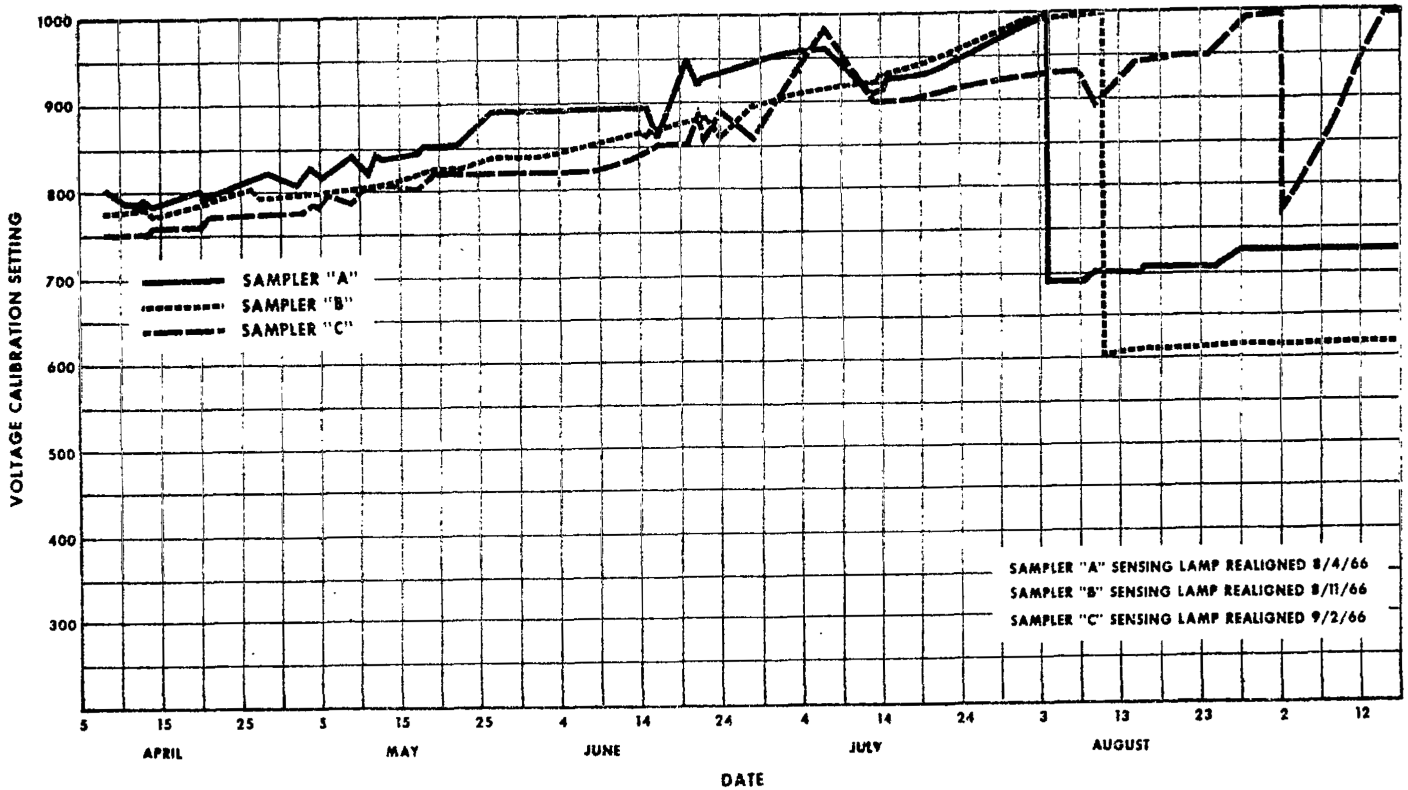

FIGURE 34. INSTRUMENT CALIBRATION VOLTAGE VERSUS DATE - VOLTAGE INCREASED AS LAMP BRILLIANCE DECREASED

APPROVAL R-ME-IN-67-1

PROGRESS REPORT ON VALVE CLINIC ELECTRONIC PARTICLE MONITORING SYSTEM INSTRUMENTATION

By T. W. Lewis

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

W. A. Wilson

W. A. WILSON
Chief, Methods Development Branch

J. R. Williams for

J. P. Orr
Chief, Manufacturing Research and Technology Division

for

Werner R. Kuers
Director, Manufacturing Engineering Laboratory