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INVESTIGATION OF PARTICULATE EMISSIONS FROM OIL-FIRED RESIDENTIAL HEATING UNITS

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INVESTIGATION OF PARTICULATE EMISSIONS FROM OIL-FIRED RESIDENTIAL HEATING UNITS

by

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ABSTRACT

Two residential oil-fired heating units (a warm-air furnace and a boiler) were fired in the laboratory while Bacharach smoke and filterable particulate emissions were measured at several excess-air levels for both cyclic and steady-state runs. In addition, particle-size distributions were measured during runs on the boiler to determine if particle-size variations might help explain the lack of correlation between smoke and particulate emissions, based on earlier field measurements.

One unit was found to produce essentially no excessive smoke or particulate on startup; smoke one minute after startup was equal to steady-state smoke, and particulate emissions for cyclic and steady-state firing were equal. The second unit produced high smoke on startup (relative to the steady-state smoke) and produced higher particulate emissions for cyclic runs than for steady-state runs, suggesting that this unit had a significant "on puff" on startup.

It was determined that particulate emissions varied with excess air in the same pattern as smoke number, being higher at low excess air levels for both units. Correlations between smoke and particulate emissions appeared practical for individual units firing at specific operating conditions. However, the data did not suggest that a general correlation between smoke and filterable particulate emissions exists for cyclic operation. For the two units examined here, particle-size distributions indicated that over 80 percent of the particles were below 1.0 micron and that the particle-size distributions were nearly identical for all runs.

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INVESTIGATION OF PARTICULATE EMISSIONS FROM OIL-FIRED RESIDENTIAL HEATING UNITS

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OBJECTIVE

The objective of this limited laboratory study was to investigate the relationship between particulate emissions and excess air and the relationship between particulate emissions and Bacharach smoke number from oil-fired residential heating units.

BACKGROUND

Battelle-Columbus has conducted a two-year field study of emissions from 33 oil-fired residential heating units and 13 commercial boilers[(1,2)*]. During the course of that study, gaseous emissions (CO, hydrocarbons, SO_2, and NO_x) were measured at many different operating conditions. However, due to the time and cost associated with particulate sampling, data were collected on particulate emissions at only a few operating conditions. Consequently, several questions remained unanswered after completion of the field study. These questions included:

(1) What is the relationship between particulate emissions and excess air? (During the field study, particulate emissions were measured at only one excess-air level for each burner condition.)

(2) Is there a relation between particulate emissions and Bacharach smoke number? (The field study data showed no satisfactory correlation between particulate emissions measured during cyclic operation and smoke measured near the end of a 10-minute "on" time, as normally measured by burner servicemen.)

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* References are given on page 16.

(3) Do particle-size variations explain the lack of suitable correlation between particulate emissions and smoke reading?

(4) How much do transients at startup and shutdown contribute to particulate emissions?

In an effort to obtain data that might answer some of the above questions, the American Petroleum Institute and the U.S. Environmental Protection Agency sponsored this laboratory study to measure particulate emissions, smoke, and particle size while firing two residential oil-fired heating units at several operating conditions.

APPROACH

Battelle's approach to this study was to install two typical oil-fired heating units within the laboratory and to fire these units at a range of conditions while collecting data on filterable particulate emissions, Bacharach smoke, and particle-size.

Heating Equipment Studied

The two heating units that were selected for this study were intended to be representative of different types of oil-fired heating units: a warm-air furnace and a hot-water boiler. The furnace was equipped with a light-weight ceramic combustion chamber liner and a conventional gun burner, while the boiler was equipped with a heavy refractory (firebrick) liner and a flame-retention gun burner. The specific units were as follows:

Unit 36*

Up-flow oil furnace with ceramic-felt liner and 1.0 gph conventional high-pressure gun burner. (This unit was identified as Unit 35 in the Phase II studies[2].

Unit 37*

Dry base, vertical fire-tube steel boiler with a dense cast-refractory combustion chamber and a 1.0 gph high-pressure, flame-retention-type oil burner with 3450 rpm motor.

* Unit numbers were continued sequentially from numbers used in the Phase I and II reports. Unit 36 was given a new number as the air damper had been modified since it was run as Unit 35.

The units were equipped with solenoid shut-off valves (nondelay type) to eliminate possible variations due to pump shut-off.

To increase the variety of equipment included in this study, the burner was interchanged and one run was made with the flame-retention burner firing in the warm-air furnace. The combination of the flame-retention burner firing in the warm-air furnace is identified as Unit 38.

Measurement Techniques and Equipment

Measurement techniques and equipment used in conducting this study were identical to those described in Reference 2 with the following exceptions:

(1) NO and NO_x were not measured as most of the data from the field study showed fairly consistent levels of NO_x emissions from oil-fired residential heating units.

(2) A back-up filter was used on the EPA particulate sampling train to catch any material not collected by the first filter. Particulate weights are based on the sum of the mass collected on the two filters.

(3) The material collected in the impingers of the EPA particulate sampling train was not dried and weighed, as the interest was in correlation with filterable particulate.

(4) For the runs on the first units examined (Units 36 and 38), fiberglas filters were used in the EPA sampling train [as specified by the EPA Method 5 procedure(3)]. However, due to problems associated with the hygroscopic nature of the fiberglas filter and its fragility, silver filters were used for runs on Unit 37. (Silver filters were used for the Phase I and Phase II field studies.)

Particle Sizing

Particle-size measurements were made for six runs in Unit 37 using the Battelle Cascade Impactor. The design of the impactor is based on the principle of particles in a moving aerosol impacting on a slide placed in the air stream. The impactor classifies particles in the range of 0.25 - 16.0 microns into seven categories. If a particle is sufficiently large it will impact on the first stage; the smaller particles will continue to travel around the slide to subsequent stages. The jet diameter of each succeeding stage decreases. Thus, the particle will increase in velocity for various stages until it obtains sufficient inertia to impact as illustrated in Figure 1[4].

Procedure. Flue-gas was sampled from the center of the stack. For the sampling done for this study, a 5/8-inch-diameter sample probe about 20 inches in length (from probe tip to impactor inlet) was used, It had a 90-degree, 6-inch radius bend such that the probe tip pointed upstream. The impactor was operated horizontally and was heated to stack gas temperature (about 400 F) prior to probe insertion in the stack. Sampling at the required 12.5 liters per minute was initiated immediately on probe insertion into the stack. Due to the small particle size measured in some preliminary runs, it was decided that the particle size was so low as to not require isokinetic sampling and so sampling was conducted at greater than isokinetic velocities. (Also, the very low gas velocities in the stack would have required an excessively large nozzle to obtain isokinetic sampling.) Sampling times were 30 and 60 minutes. The impactor slides were covered with a disk of 2-mil stainless steel shim stock so that the entire glass slide did not have to be weighed. Immediately after sampling, the impactor slides were removed and returned to a constant temperature and humidity room to equilibrate and for weighing.

Conditions at Which Measurements Were Made

Particulate emissions and smoke were measured at a range of excess-air levels for two types of runs: cyclic runs with repeated cycles of 10-min on and 20-min off cycles (the same cycle as used in the field program) and steady-state runs at thermal equilibrium. In addition, CO_2, O_2, CO, and HC were continuously monitored for all runs and particle-size measurements were made during steady-state runs on Unit 37.

Particulate emissions for the cyclic runs were collected during the firing portion of six cycles, giving one hour of sampling during burner operation. To assure obtaining samples during startup and shutdown puffs, sampling was initiated about 30 seconds before burner startup and was continued until about 30 seconds after burner shutdown. For the steady-state runs, sampling was begun about 30 minutes after startup and was continued for about two hours. Smoke readings were taken at the 1-, 2-, 3-, 5-, 7-, and 9.5-minute points during the 10-minute "on" period for cyclic runs and at the 10-, 30-, 50-, 70-, and 100-minute points for the steady-state runs.

The fuel fired during this investigation was identical to the No. 2 reference fuel oil used during the field study[1,2].

COMMENTS ON FILTER MEDIA

The particulate emission measurements in this study were complicated by the problems associated with weighing the very small quantities of particulate accumulated on the filters during these experiments with residential oil burners having relatively low particulate emission levels. For example, for most of the runs, three hours of sampling during cyclic operation (one hour of firing time) or two hours sampling during steady-state operation resulted in collection of less than 10 mg of particulate; for many runs, less than five mg of particulate was collected. Moreover, no filter is completely satisfactory when attempting to measure these small quantities of materials as indicated by the following:

- Fiberglas filters (as required by EPA Method 5) are highly hygroscopic, are somewhat fragile, and contain significant impurities which make them less suitable for detailed chemical analyses of particulate catch.

- Quartz filters (compared to fiberglas) contain lesser quantities of background elements but are even more fragile and also are hygroscopic.

- Silver filters are rugged and, essentially, not hygroscopic. However, the silver does react with sulfur compounds to a greater extent than fiberglas.

Fiberglas filters were chosen initially for use in conducting the measurements for this study, primarily because of their being specified by the EPA Method 5 for sampling large sources. However, weighings of fiberglas filters from runs on Units 36 and 38 sometimes produced negative values for filter catch. These negative values were attributed to one of two causes: (1) the hygroscopic nature of the filter, or (2) the loss of small pieces of filter that stick to the glass filter holder or break off when the filter is removed at the completion of the run.

At this point it was decided that the silver filters should be used for runs on Unit 37, even though there was the possibility of reaction with sulfur. Hence, silver filters were used as the filters for the Unit 37 runs and as back-up filters for the particle-size runs on the same unit.

RESULTS

Data Summary

Tables 1 and 2 give detailed data resulting from this investigation. Table 1 lists operational conditions and emissions. Table 2 gives detailed smoke data. The data presented in these tables are plotted in Figures 2 through 15, and their significance is discussed below.

Smoke Versus Time During Cycle

For the cyclic runs, smoke readings were taken at the 1-, 3-, 5-, 7-, and 9.5-minute points in the 10-minute "on" period. These data are plotted in Figures 2 and 3 for runs in Unit 36 and 37, respectively. For Unit 36, the smoke readings during the first few minutes of the cycle were usually high; that is, this unit had an appreciable start-up transient. The CO_2 and O_2 data indicated a richer flame (compared to steady state) immediately after startup of this unit, probably related to nozzle characteristics. In contrast, the 1-minute smoke

TABLE 1. SUMMARY OF EMISSIONS AND EMISSION FACTORS

	Operational Data: Firing Cycle	CO_2, %	O_2, %	Excess Air, %	Smoke No. at 9.5 or 10 min.	Stack Temperature, F	Emission Data, Dose Average, ppm: CO	HC	Filterable Particulate Loading,[a] mg/sm(3): F[e]	F+P[f]	Emission Factors, lb/1000 gal: CO	HC	Filterable Particulate: F[e]	F+P[f]
Unit 36	10/20[b]	9.7	7.5	54	0.3	611	10.2	1.9	5.4	6.5	1.54	0.16	0.71	0.85
		11.0	5.6	37	0.3	610	11.1	3.2	6.7	7.3	1.49	0.25	0.79	0.86
		12.1	4.2	25	0.3	596	11.8	4.2	7.8	9.1	0.45	0.29	0.82	0.95
		12.3	3.9	23	0.5	579	10.7	2.0	8.7	10.8	1.29	0.14	0.90	1.12
		12.3	3.8	23	0.6	595	10.8	2.9	14.6	16.2	1.30	0.20	1.53	1.70
		12.9	3.3	18	0.3	567	11.1	1.9	8.6	11.3	1.29	0.13	0.86	1.13
		13.3	2.6	14	3.0	551	17.9	2.2	30.7	33.6	2.01	0.14	2.99	3.27
		13.6	2.3	12	4.0	542	37.4	2.4	38.0	42.9	4.12	0.15	3.67	4.09
Unit 37	10/20	11.3	5.8	35	0.2	580	25.9	7.0	2.7	4.0	3.44	0.53	0.31	0.46
		11.7	5.0	30	0.8	546	24.5	3.5	3.3	5.8	3.12	0.76	0.37	0.66
		11.8	4.6	28	0.5	547	23.0	3.5	3.4	5.4	2.89	0.25	0.37	0.58
		11.8	4.5	27	0.7	543	25.3	2.6	3.5	12.4	3.16	0.19	0.39	1.39
		12.0	4.4	26	0.7	528	28.8	2.4	3.2	9.1	3.56	0.17	0.34	0.97
		12.3	4.0	23	1.5	540	26.9	3.1	3.6	17.9	3.25	0.21	0.38	1.89
		12.9	3.2	18	(5.4)[c]	529	65.7	2.8	9.3	24.8	7.59	0.19	0.93	2.48
Unit 38	10/20	12.5	3.8	22	0.3	570	17.5	3.0	(d)	9.7	2.09	0.20	--	0.90
Unit 36	steady-state	9.7	7.6	55	0.3	630	8.0	<1.0	3.8	7.2	1.22	<0.09	0.51	0.97
		11.0	5.9	38	0.3	624	8.0	<1.0	5.3	5.6	1.08	<0.08	0.61	0.64
		11.9	4.3	26	0.3	610	10.0	<1.0	2.7	4.3	1.24	<0.07	0.29	0.47
		12.3	4.0	23	0.5	593	12.0	<1.0	7.1	8.2	1.21	<0.07	0.73	0.84
		12.2	3.9	23	0.3	582	12.0	<1.0	2.0	2.4	1.45	<0.07	0.21	0.25
		12.8	3.4	19	0.7	580	10.0	<1.0	3.4	3.5	1.17	<0.07	0.34	0.35
		13.3	2.7	15	1.8	566	11.0	<1.0	6.2	8.7	1.24	<0.06	0.59	0.83
		13.5	2.4	13	4.0	560	11.0	<1.0	10.3	13.3	1.22	<0.06	0.98	1.27
Unit 37	steady-state	11.3	5.8	35	0.2	584	18.0	1.1	3.0	4.2	2.39	0.08	0.34	0.47
		11.8	5.0	29	0.7	547	22.0	<1.0	4.2	9.8	2.79	<0.07	0.45	1.06
		11.9	4.6	27	0.7	552	20.0	<1.0	3.6	4.8	2.50	<0.07	0.39	0.57
		11.8	4.5	27	0.9	550	20.0	<1.0	3.6	9.9	2.50	<0.07	0.39	1.07
		12.0	4.4	26	1.0	552	22.0	<1.0	3.7	5.3	2.72	<0.07	0.39	0.56
		12.3	3.9	23	2.3	542	27.0	<1.0	4.4	7.6	3.25	<0.08	0.45	0.78
		12.9	3.3	18	5.8	538	52.0	<1.0	12.5	23.5	6.03	<0.07	1.25	2.35
Unit 38	steady-state	12.5	3.7	21	0.3	590	11.0	<1.0	(d)	1.3	1.31	<0.07	--	0.14

(a) Background levels were measured and found to be less than 0.25 mg/sm^3.

(b) Cycle of 10 minutes on and 20 minutes off.

(c) Data at 7 minutes.

(d) Negative value obtained, considered as zero when determining total filterable particulate.

(e) Filter catch only.

(f) Filter catch plus probe wash (reported as "filterable" particulate in reports covering Phases I and II)

TABLE 2. SMOKE DATA

	Operational Data				Smoke, Bacharach Number									
	Firing Cycle	CO_2, %	O_2, %	Excess Air, %	1 min	3 min	5 min	7 min	9.5 min	10 min	30 min	50 min	70 min	100 min
Unit 36	10/20[a]	9.7	7.5	54	0.3	0.3	0.3	0.3	0.3					
		11.0	5.8	37	0.7	0.6	0.3	0.3	0.3					
		12.1	4.2	25	2.9	0.6	0.3	0.3	0.3					
		12.3	3.9	23	1.9	0.6	0.5	0.5	0.5					
		12.3	3.8	23	4.3	1.0	0.7	0.6	0.6					
		12.9	3.3	18	7.9	1.7	1.0	1.0	0.3					
		13.3	2.6	14	8.1	5.4	3.9	3.0	3.0					
		13.6	2.3	12	8.3	4.7	4.8	4.1	4.0					
Unit 37	10/20	11.3	5.8	35	0.2	0.2	0.2	0.2	0.2					
		11.7	5.0	30	0.8	0.8	0.8	0.7	0.8					
		11.8	4.6	28	0.6	0.6	0.5	0.5	0.5					
		11.8	4.5	27	1.0	1.0	0.9	0.7	0.7					
		12.0	4.4	26	1.0	0.9	0.8	0.8	0.7					
		12.3	4.0	23	1.9	1.7	1.6	1.5	1.5					
		12.9	3.2	18	5.2	5.4	5.4	5.4	--					
Unit 38	10/20	12.5	3.8	22	0.3	0.3	0.3	0.3	0.3					
Unit 36	Steady state	9.7	7.6	55						0.3	0.3	0.3	0.3	--
		11.0	5.9	38						0.3	0.3	0.3	0.5	0.3
		11.9	4.3	26						0.3	0.3	0.3	0.3	0.3
		12.3	4.0	23						0.5	0.5	0.5	--	--
		12.2	3.9	23						0.3	0.3	0.3	0.3	0.3
		12.8	3.4	19						0.7	0.6	0.6	0.7	--
		13.3	2.7	15						1.8	2.1	2.1	2.1	2.1
		13.5	2.4	13						4.0	3.9	4.0	4.1	--
Unit 37	Steady state	11.3	5.8	35						0.2	0.2	0.2	0.2	0.2
		11.8	5.0	29						0.7	0.8	0.7	0.7	--
		11.9	4.6	27						0.7	0.7	0.6	0.7	0.7
		11.8	4.5	27						0.9	0.8	0.8	0.9	0.8
		12.0	4.4	26						1.0	1.0	1.0	1.0	1.0
		12.3	3.9	23						2.3	2.2	2.3	2.3	2.2
		12.9	3.3	18						5.8	5.8	5.6	5.4	--
Unit 38	Steady state	12.5	3.7	21						0.3	0.3	0.3	0.3	0.3

(a) Cycle of 10 minutes on and 20-minutes off.

readings for Unit 37 were nearly as low as the steady-state values and, hence, it appears that this unit stabilizes relatively quickly from a cold start. The shorter start-up transient for Unit 37 was somewhat unexpected in that it was the unit having the heavier refractory combustion chamber and, thus, was expected to have slower temperature response. The excellent start-up properties of Unit 37 are apparently due to superior burner design and/or nozzle characteristics.

Smoke Versus Excess Air

Figures 4 and 5 show plots of Bacharach smoke number versus air for runs with Units 36 and 37, respectively. Data plotted in these figures are 9.5-minute smoke data for the cyclic runs and 100-minute smoke data for the steady-state runs. By the 9.5-minute point in the cyclic runs, the smoke levels were essentially equal to the steady-state values.

Both units demonstrated low smoke at relatively low excess air levels. Units 36 and 37 reached No. 1 smoke at about 18 and 26 percent excess air (12.9 and 12.0 percent CO_2), respectively. No field units from the Phase II study exhibited smoke levels as low as No. 1 Bacharach at such low excess-air levels. (Data at lower excess-air values were obtained on Unit 37 during these runs than when this unit was investigated during the Phase II study; this was accomplished by modifying the air gate to reduce leakage in the closed position.)

For Unit 38, the flame-retention burner from Unit 37 firing into the furnace, a 0.3 smoke number was obtained at 22 percent excess air. This smoke reading agrees more with the observed smoke versus excess air characteristics of the Unit 36 data than with that for Unit 37. The flame-retention burner produced low start-up smoke at relatively low excess air when fired in the furnace (0.3 smoke number at both 1.0 minute and steady state), similar to its performance when fired into the boiler.

Particulate Emissions Versus Excess Air

Figures 6 and 7 show plots of filterable particulate emissions (probe wash plus filter) versus excess air for runs on Units 36 and 37, respectively. Figures 8 and 9 show similar plots but based on filter catch alone, which is the portion of the total particulate catch that should relate best to smoke data. Particulate emissions were collected using the EPA Method 5,* but only filterable particulate was dried and weighed.

For Unit 36 (Figures 6 and 8), particulate emissions were appreciably less for the steady-state runs than for the cyclic runs, suggesting that cycling (probably startup) contributes significant quantities of particulate to particulate measurements "integrated" over the cycle. The ratio of cyclic particulate to steady-state particulate was nearly four to one at low excess air; this ratio decreased as excess air was increased so that, at 40 to 50 percent excess air, cyclic particulate emissions were less than twice the level of steady-state emissions.

The difference in particulate emissions between the cyclic and steady-state runs is attributed to particulate generated during burner startup and shutdown. Hence, for this unit, it appears that the startup and shutdown "puffs" contribute between 30 and 75 percent of the particulate emissions measured while operating a burner on a 10-minute-on/20-minute-off cycle. Because this unit also exhibited high smoke levels during startup, it is concluded that high startup smoke may be an indication of high levels of particulate emissions during startup.

Both cyclic and steady-state particulate emissions increased significantly as excess air was reduced below 20 percent.

For Unit 37 (Figures 7 and 9), the cyclic and steady-state runs produced about the same particulate emission levels at given excess air levels. These data, combined with the low smoke early in the cyclic runs,

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* Silver filters were used for runs on Unit 37; whereas, EPA Method 5 specified fiberglas.

suggest that start-up transients are minor for this unit. Again, both cyclic and steady-state particulate emissions increased significantly as excess air was reduced below about 20 to 30 percent.

The filter loadings and particulate emissions for runs on both units are in the same range of values as the data from the Phase I and II field studies[1,2].

Particulate Loading Versus Smoke

Figures 10 and 11 show the correlations between filterable particulate loading (probe wash plus filter catch) and the 9.5-minute smoke reading for cyclic runs or 10-minute smoke reading for steady-state runs for Units 36 and 37, respectively. Figures 12 and 13 show similar data for filter catch alone (without probe wash). For both units, there is considerable scatter of data below No. 1 smoke, but a correlation between particulate emissions and smoke appears practical above this smoke level for a given unit operating on a given cycle.

Figures 10 and 11 show that, for both units, the cyclic runs gave a different correlation between filterable particulate emissions and smoke than did the steady-state runs. Figures 12 and 13 show that the correlations between filter catch and smoke number for the steady-state run for Unit 36 and both runs for Unit 37 were similar. However, the cyclic run for Unit 36 produced a quite different correlation.

Figure 14 shows the correlation between particulate based on filter catch only and smoke at the 1.0-minute point for cyclic runs in both units. The correlations between particulate emissions and smoke for Units 36 and 37 are more nearly similar when the 1.0-minute smoke reading is used as the data base. However, there is considerable scatter in these data for Unit 36.

Comparing the cyclic-run results shown in Figures 10 and 11, it can be seen that Unit 37 emitted less particulate at a No. 5 smoke than did Unit 36 at a No. 2 smoke. This illustrates the difficulty of controlling air pollution emissions from residential heating by basing regulations on smoke reading alone.

Figure 15 shows particulate emissions plotted against smoke number (at 9.5 minutes) for cyclic runs and for steady-state runs for all three units. The data are too few to draw certain conclusions about a general relationship of particulate emissions and smoke. The scatter in the data do not suggest that a strong correlation between particulate emissions and smoke exists for the total of the cyclic data from these two units. It appears that different start-up characteristics of the two units are the primary factor preventing correlation of smoke number and particulate emissions. This helps to explain why such correlations were not possible with the field data from Phases I and II. However, within limits of the available data, Figure 15 does show a fairly definite relationship between steady-state particulate emissions and smoke.

Particle Size

Figures 16 through 21 show plots of particle-size distribution for samples collected by a Battelle Cascade Impactor during six steady-state runs on Unit 37 with excess air ranging from 18 to 35 percent. Runs were made at smoke levels from 0.2 to 5.8 Bacharach smoke numbers, with duplicate samples collected during each run. All runs were for 60 minutes except Runs B in Figures 16 and 21 which were for 30 minutes. A particle specific gravity of 2.0 was assumed for calculating the cutoff particle size for each impactor stage.

These data indicate that 80- to 90-weight percent of the particulate was below 0.25 microns in size, even with the higher smoke levels. Little difference in particle-size distribution is evident for the various runs.

An electron-microscope examination of selected particulate filters was made to provide an alternative determination of particle size (an optical microscope cannot see below about 0.25 microns). Figures 22 through 29 show electron microscope photographs as follows:

- Figure 22 - 1000X view of a fiberglas filter with collected particulate (Unit 36 run at 14 percent excess air)
- Figures 23-24 - 1000X and 5000X views of clean (unused) silver filters
- Figures 25-29 - 20X, 100X, 500X, 1000X, and 5000X views of silver filters with collected particulate (Unit 37 run at 23 percent excess air).

Although these electron-microscope photographs (particularly Figures 25 through 28) show the presence of some large particles, Figures 22 and 29 suggest that a significant portion of the collected material is well below one micron in particle size. The possible presence of agglomerations makes determination of the size of individual particles difficult. However, these photographs appear to confirm the fact that most of the particles emitted by the furnace and boiler were quite small, below one micron, placing them within the respirable size range which is considered to be below about 3.5 microns[5,6].

CONCLUSIONS

Although the conclusions of this investigation must be considered in the context of data limited to only two units, the following conclusions can be made:

- Filterable particulate emissions vary with excess air in approximately the same manner as smoke readings; that is, particulate emissions are relatively low at high excess air and increase significantly as excess air is reduced. Thus, smoke readings are indicative of particulate emission trends for a given unit and operating condition.

- Correlations of particulate emissions and smoke appear possible for given operating cycles for particular units and possibly for different units at steady-state conditions. However, data for cyclic conditions of the two units examined do not suggest that a general relationship between particulate emissions and smoke exists when considering more than one unit, primarily due to differences in start-up characteristics. This observation confirms the results of the Phase I and II studies where no general relationship between particulate emissions and smoke was found.

- A greater difference between cyclic and steady-state particulate emissions was observed for the unit that had high start-up smoke than for the unit that did not have high start-up smoke. Hence, high start-up smoke appears to be an indicator of the startup contributing a disproportionately large quantity of particulate emissions.

- Particle-size distribution did not change significantly for a given unit as excess air and smoke were varied.

- Particle-size measurements indicated that most particulate emitted by these units was below one micron, and in the respirable range. (The respirable range is not precisely defined but is roughly below 3.5 microns.)

Additional Information Needed

Although the results do not show a firm correlation between particulate emissions and smoke when different cycles and equipment are considered, the results show that there is a trend toward lower particulate emission with lower smoke numbers. Thus, if the desired particulate emission control level falls in the range of data observed for low smoke number values, the smoke number might be used as a satisfactory control. To do this, it would be necessary to accumulate considerably more data on the relationship between smoke number and particulate emission for a large number of oil-fired units under different operating conditions.

The following information that is presently not available would contribute to a better understanding of this subject:

- Particulate data versus excess air and smoke for a variety of burners and applications
- Effect of nozzle firing-rate characteristic on starting (including consideration of nozzle temperature)
- Cycles other than 10-on and 20-off, especially shorter cycles
- Effect of pump cut-off characteristics
- Particulate characterization versus particle size

  Chemical composition: carbon, hydrogen, and nitrogen contents and polycyclic organic matter (POM).
- Effect of filter material on particulate measurement (reaction of silver filters with sulfur).

This latter work would be justified only if particulate emissions from domestic oil-fired equipment are considered to be a significant contribution in the overall particulate abatement problem.

REFERENCES

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(2) Barrett, R. E., Miller, S. E., and Locklin, D. W., "Field Investigation of Emissions from Combustion Equipment for Space Heating". This report is identified as API Publication 4180 (available from API); PB-223148 (available from NTIS); and as EPA Publication EPA-R2-73-084a, all June, 1973.

(3) "Standards of Performance for New Stationary Sources", Federal Register, Vol. 36, No. 139, Part II, pp 24876-24895, December 23, 1971.

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(5) Dunmore, J. H., Hamilton, R.J., and Smith, D.S.G., "Instrument for the Sampling of Respirable Dust for Subsequent Gravimetric Assessment", J. Scientific Instruments, 41, 669 (1964).

(6) Lippman, M., and Harris, W. B.,"Size-Selective Sampling for Estimating 'Respirable' Dust Concentrations", Health Physics, 8, 155 (1962).

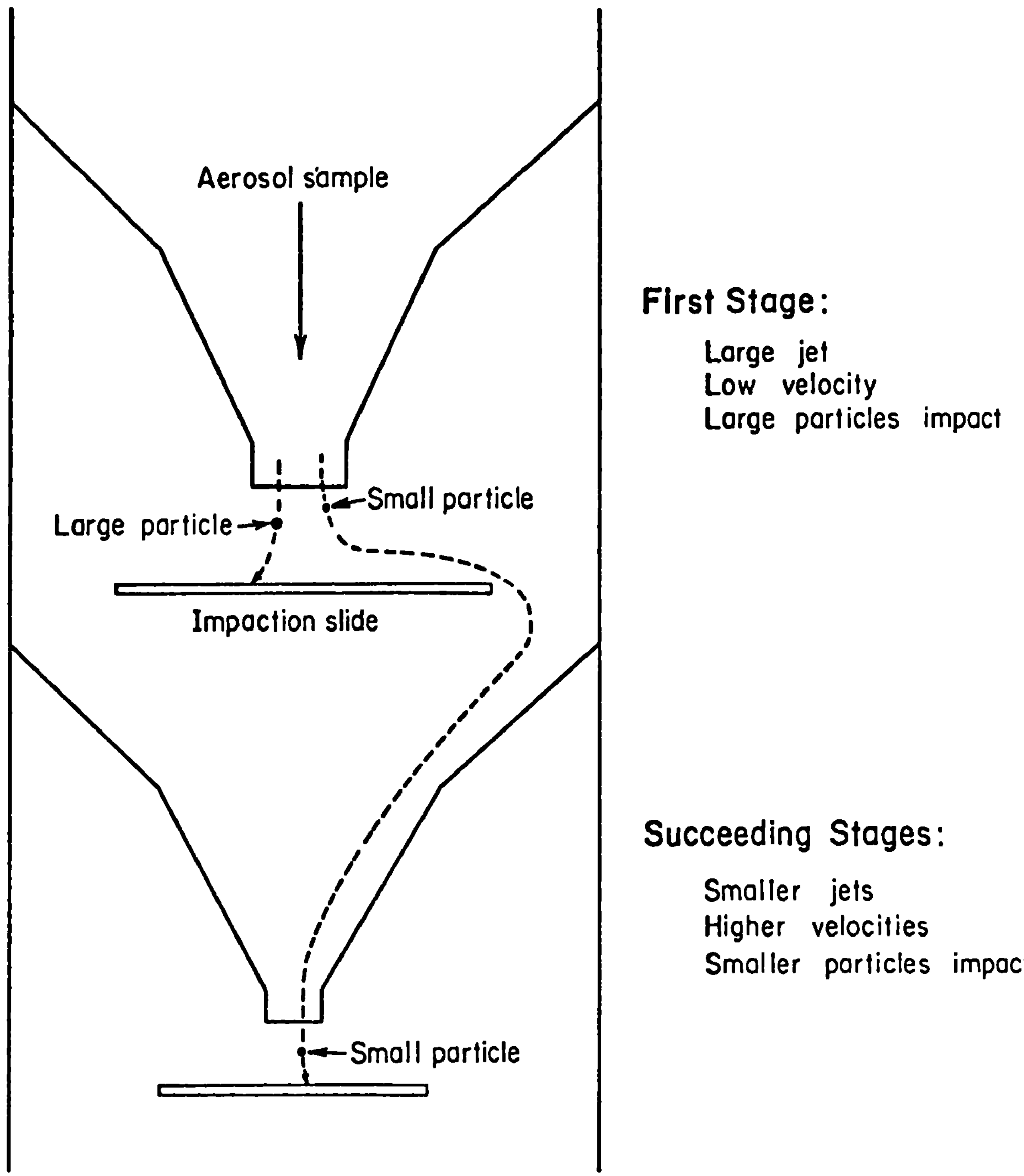


FIGURE 1. SCHEMATIC DIAGRAM SHOWING PRINCIPLE OF THE CASCADE IMPACTOR

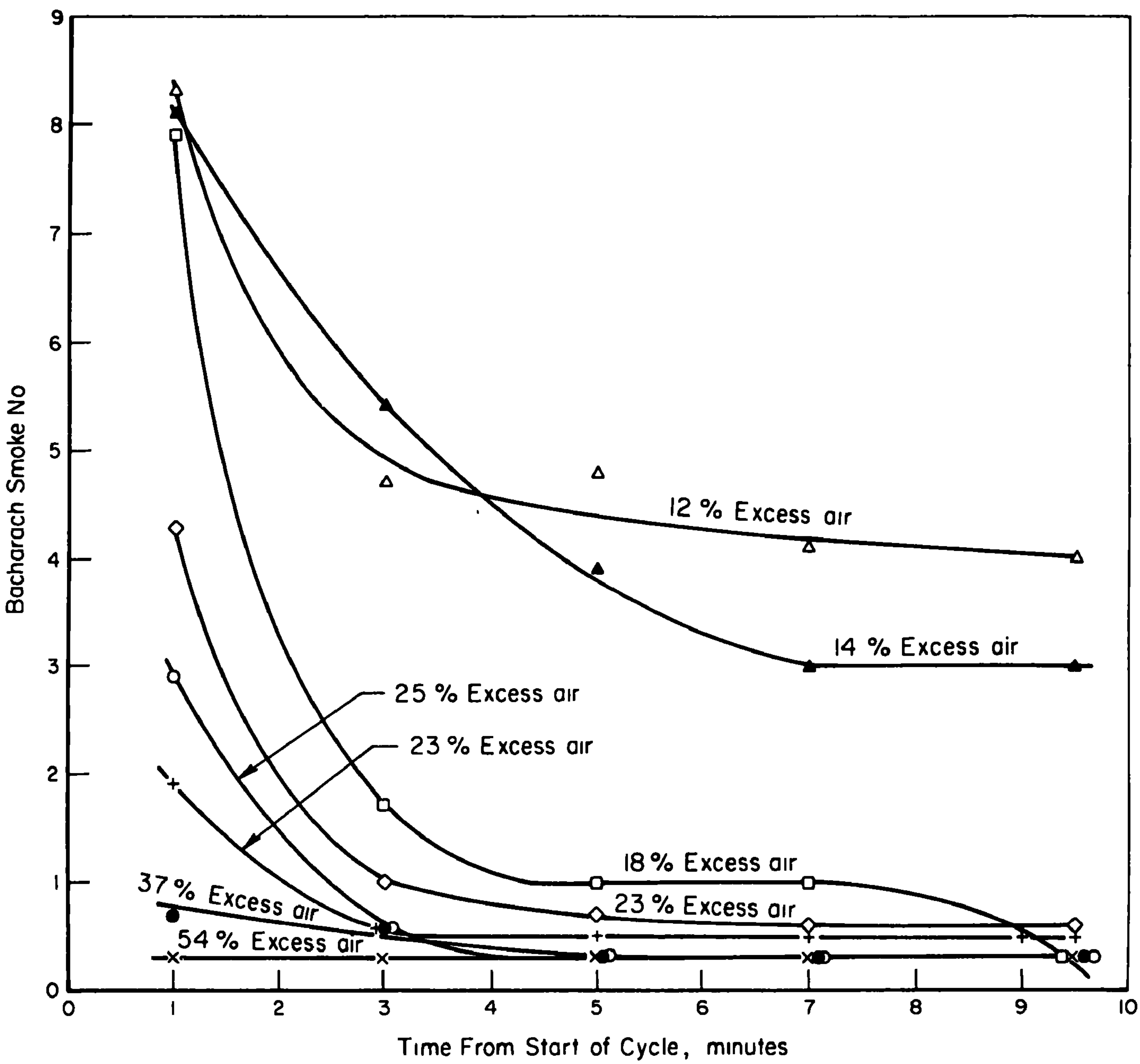


FIGURE 2. SMOKE VERSUS TIME DURING CYCLE - UNIT 36

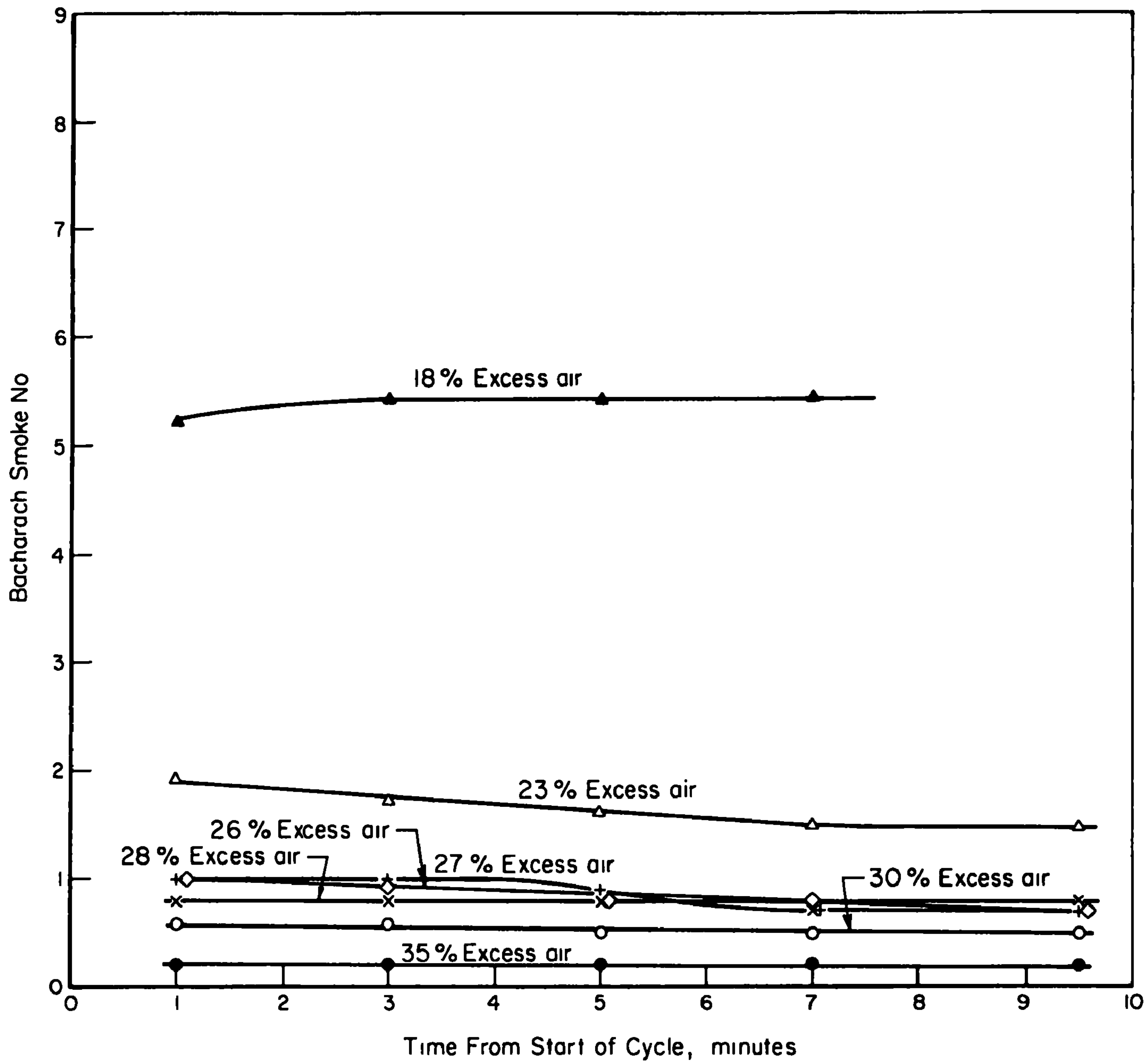


FIGURE 3. SMOKE VERSUS TIME DURING CYCLE – UNIT 37

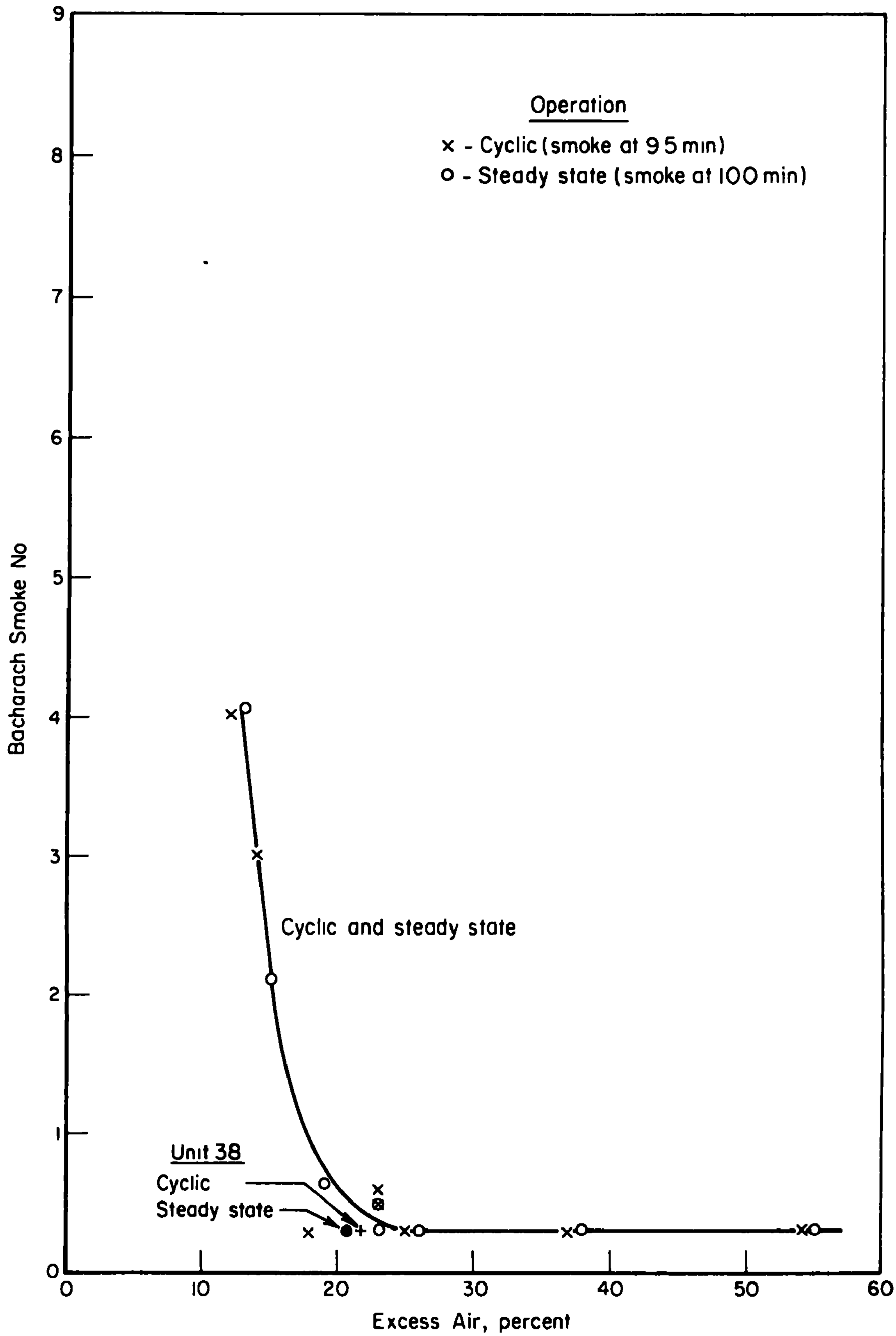


FIGURE 4. SMOKE VERSUS EXCESS AIR - UNIT 36

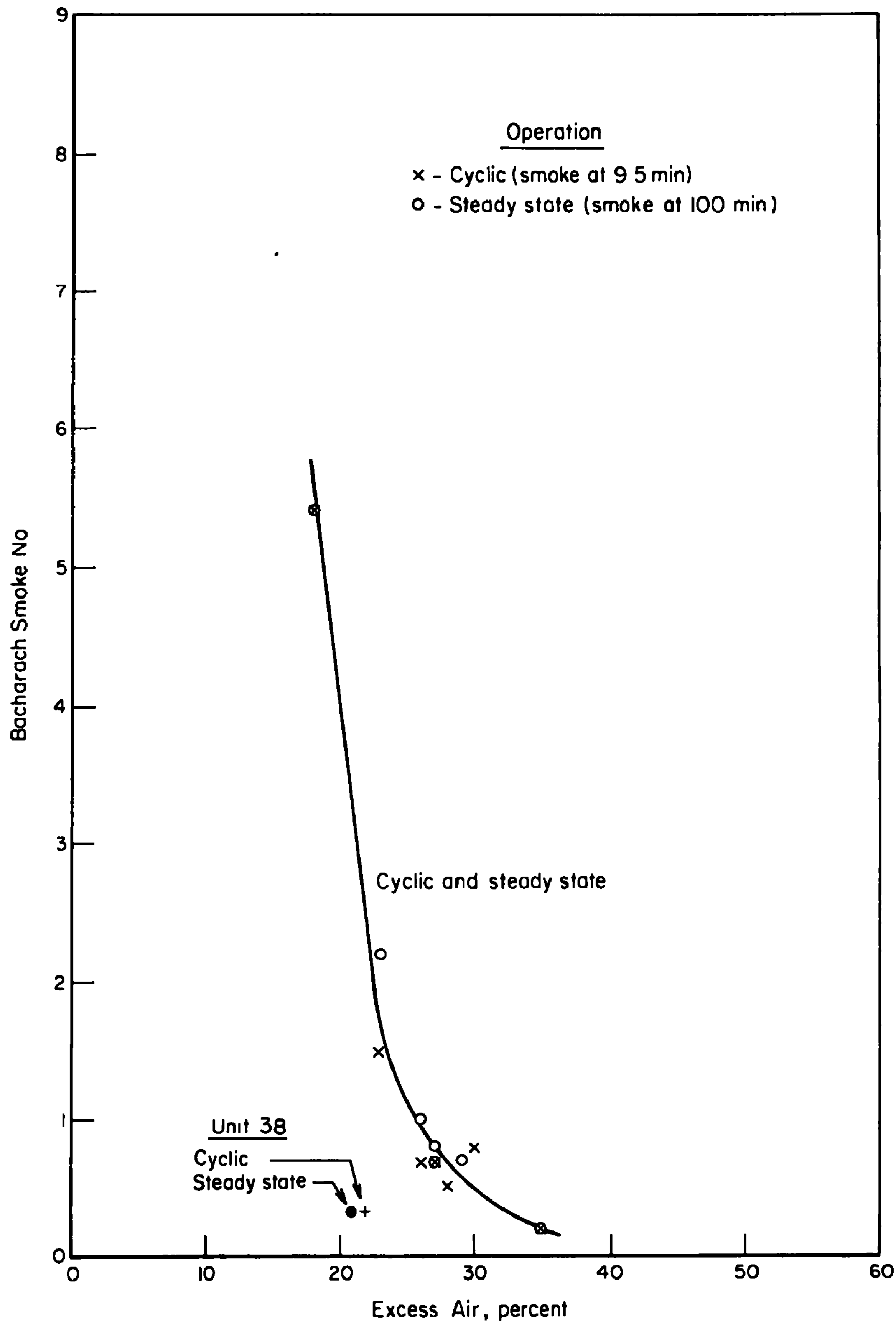


FIGURE 5. SMOKE VERSUS EXCESS AIR – UNIT 37

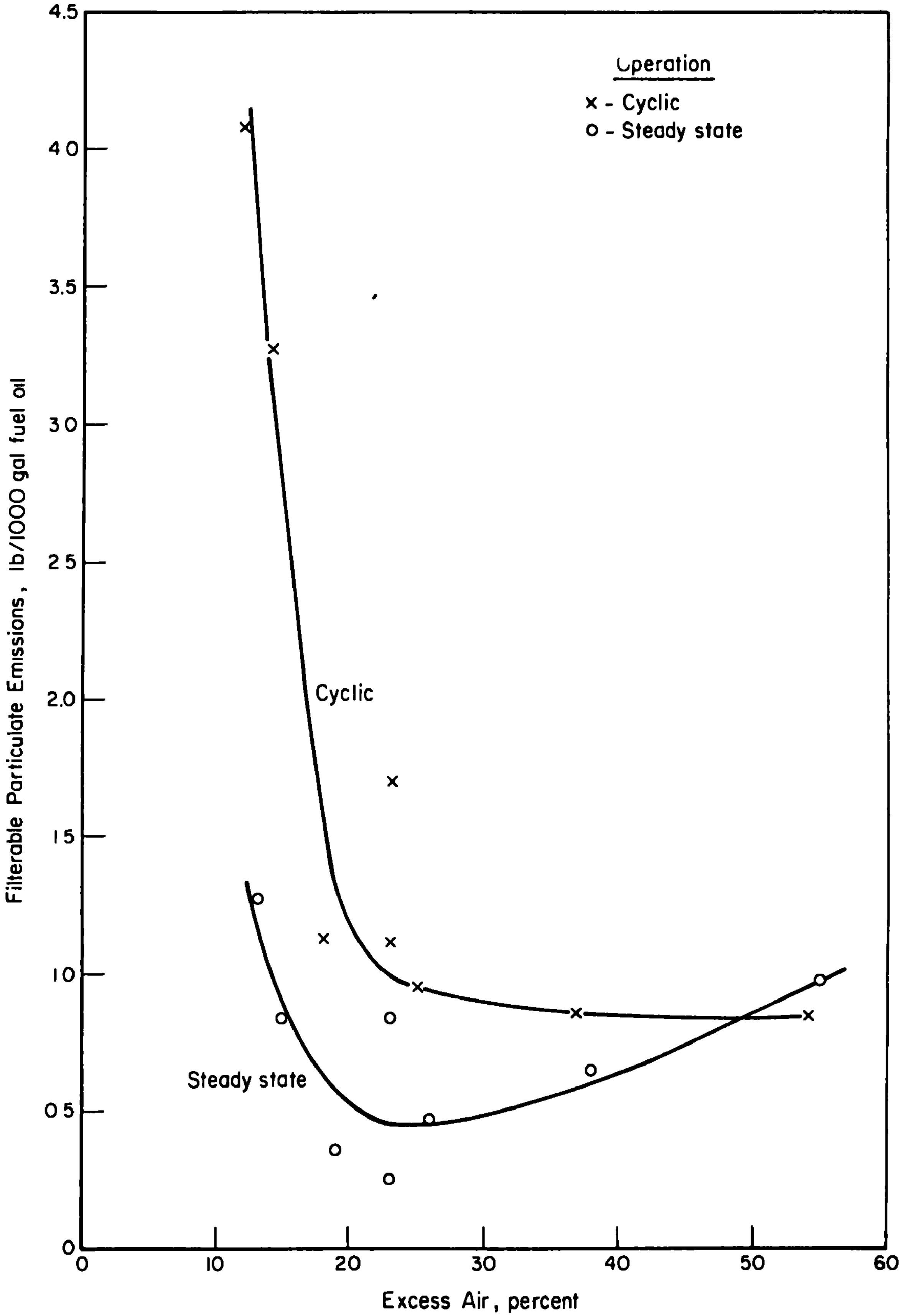


FIGURE 6. FILTERABLE PARTICULATE EMISSIONS VERSUS EXCESS AIR - UNIT 36

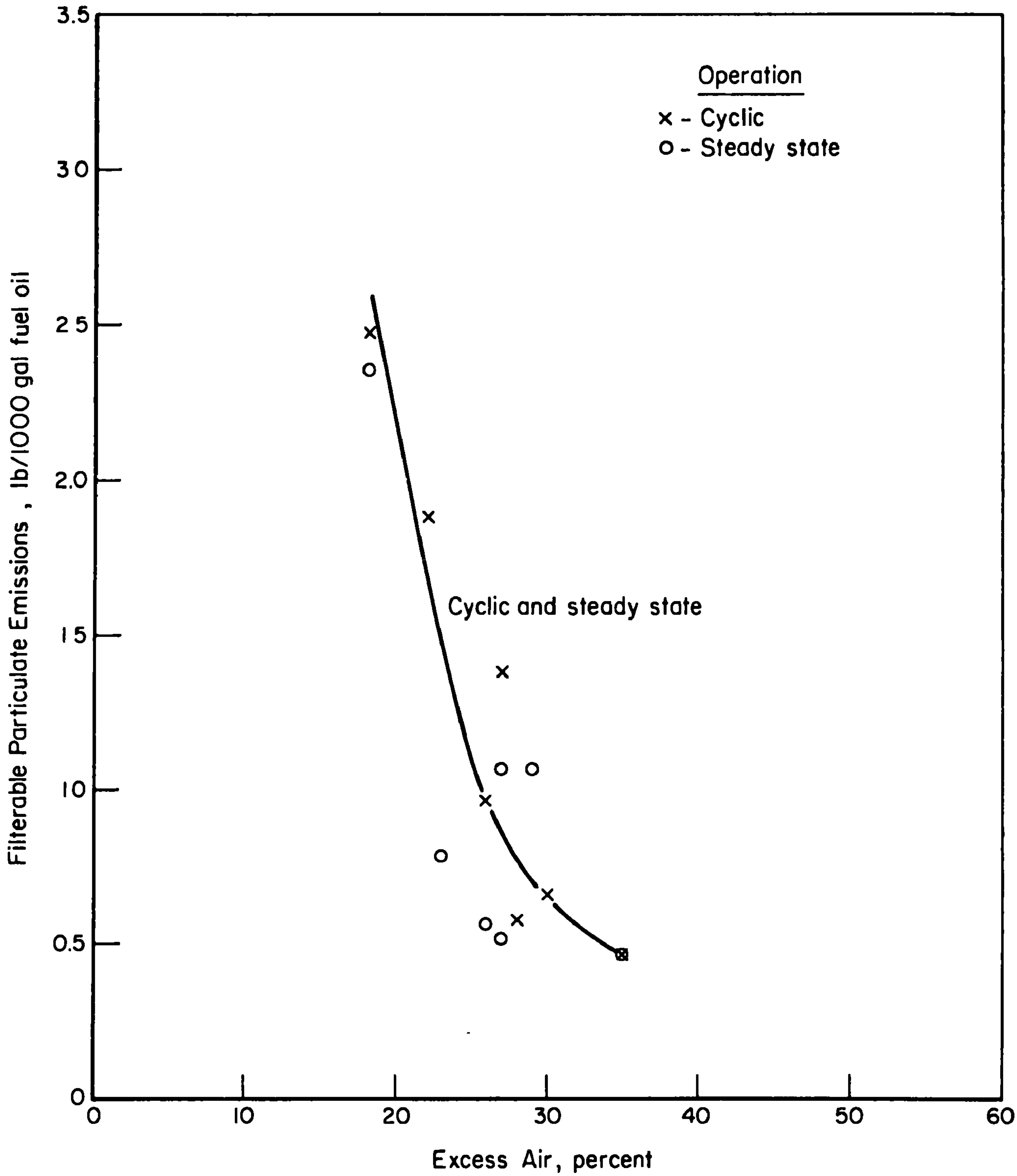


FIGURE 7. FILTERABLE PARTICULATE EMISSIONS VERSUS EXCESS AIR - UNIT 37

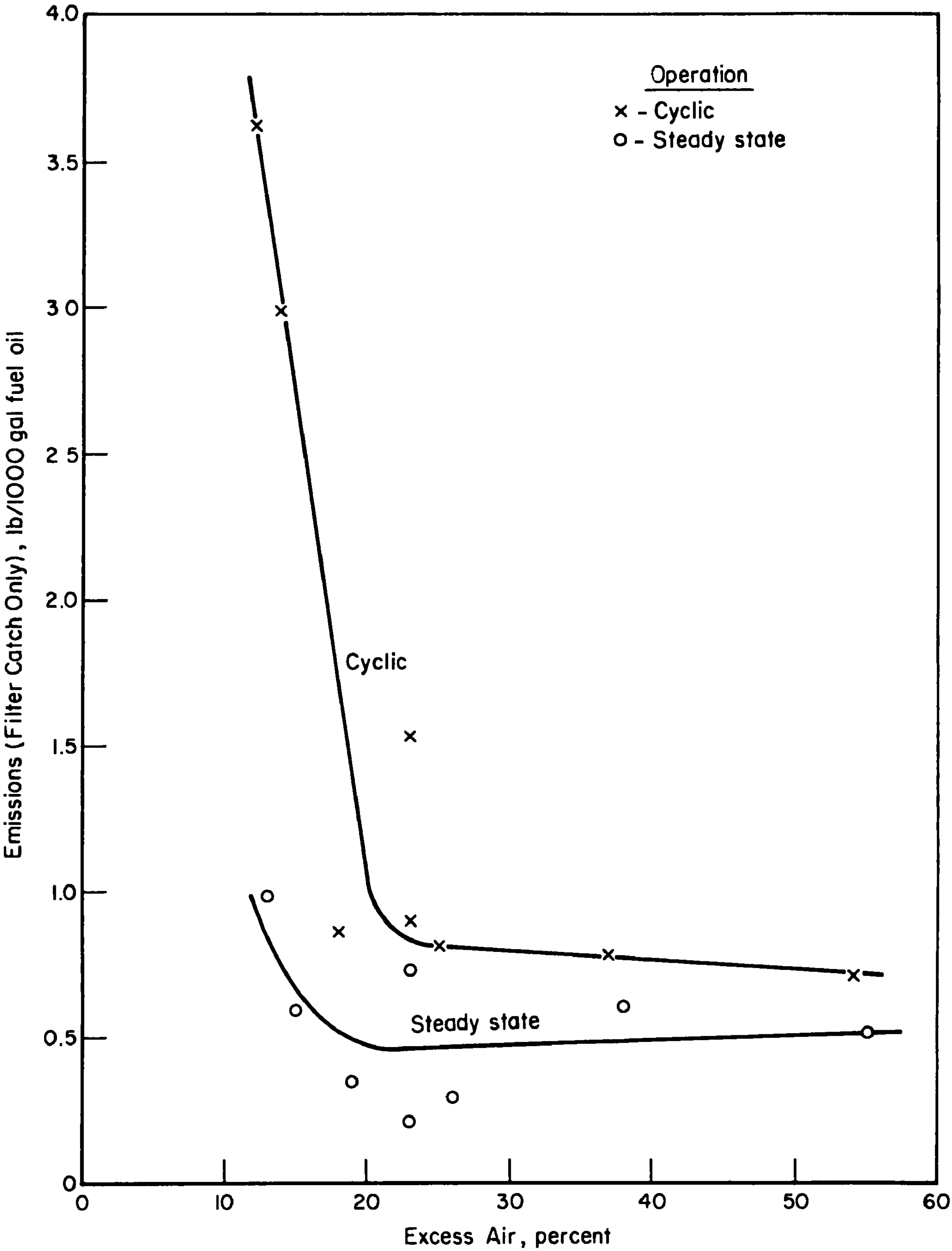


FIGURE 8. FILTER CATCH VERSUS EXCESS AIR – UNIT 36

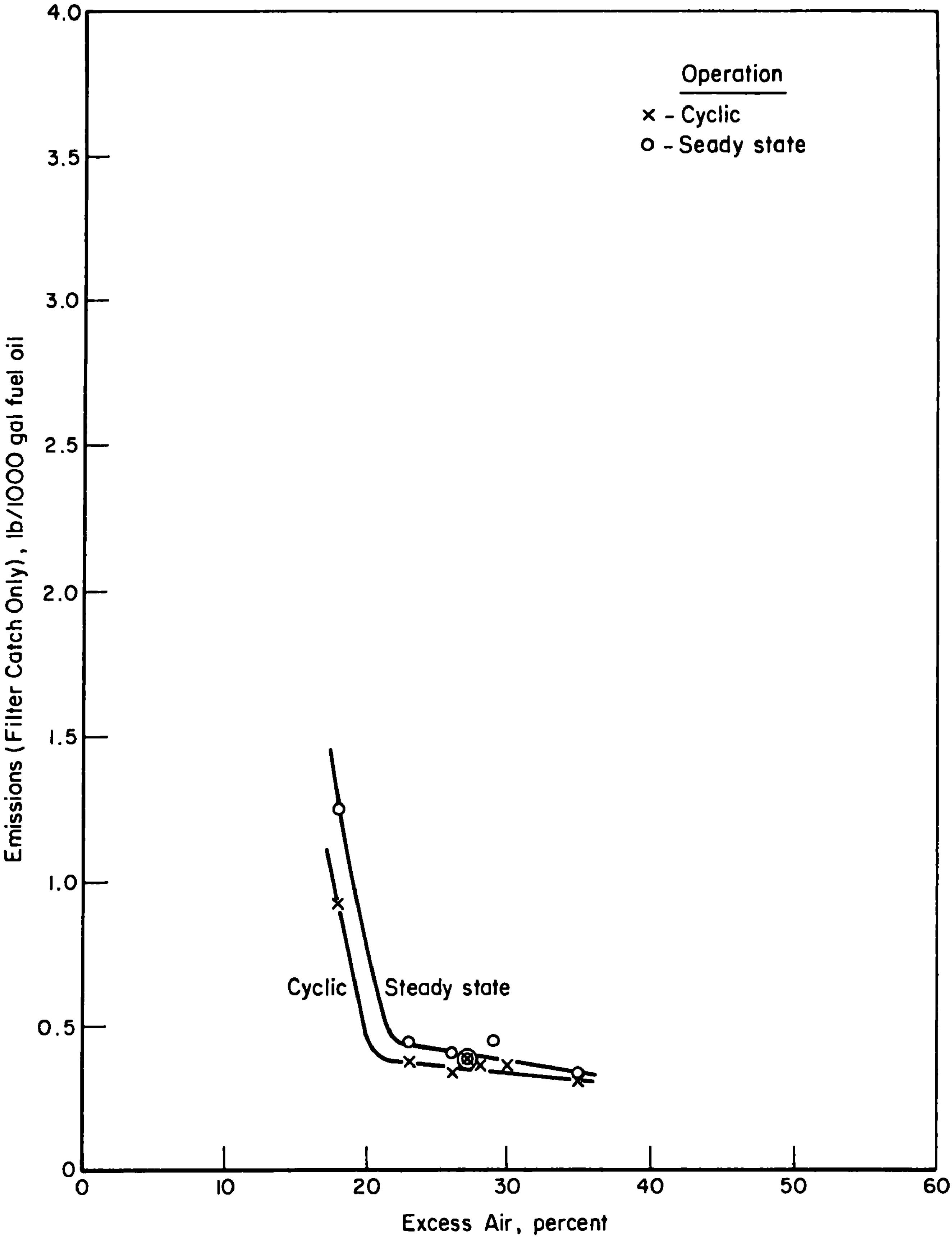


FIGURE 9. FILTER CATCH VERSUS EXCESS AIR - UNIT 37

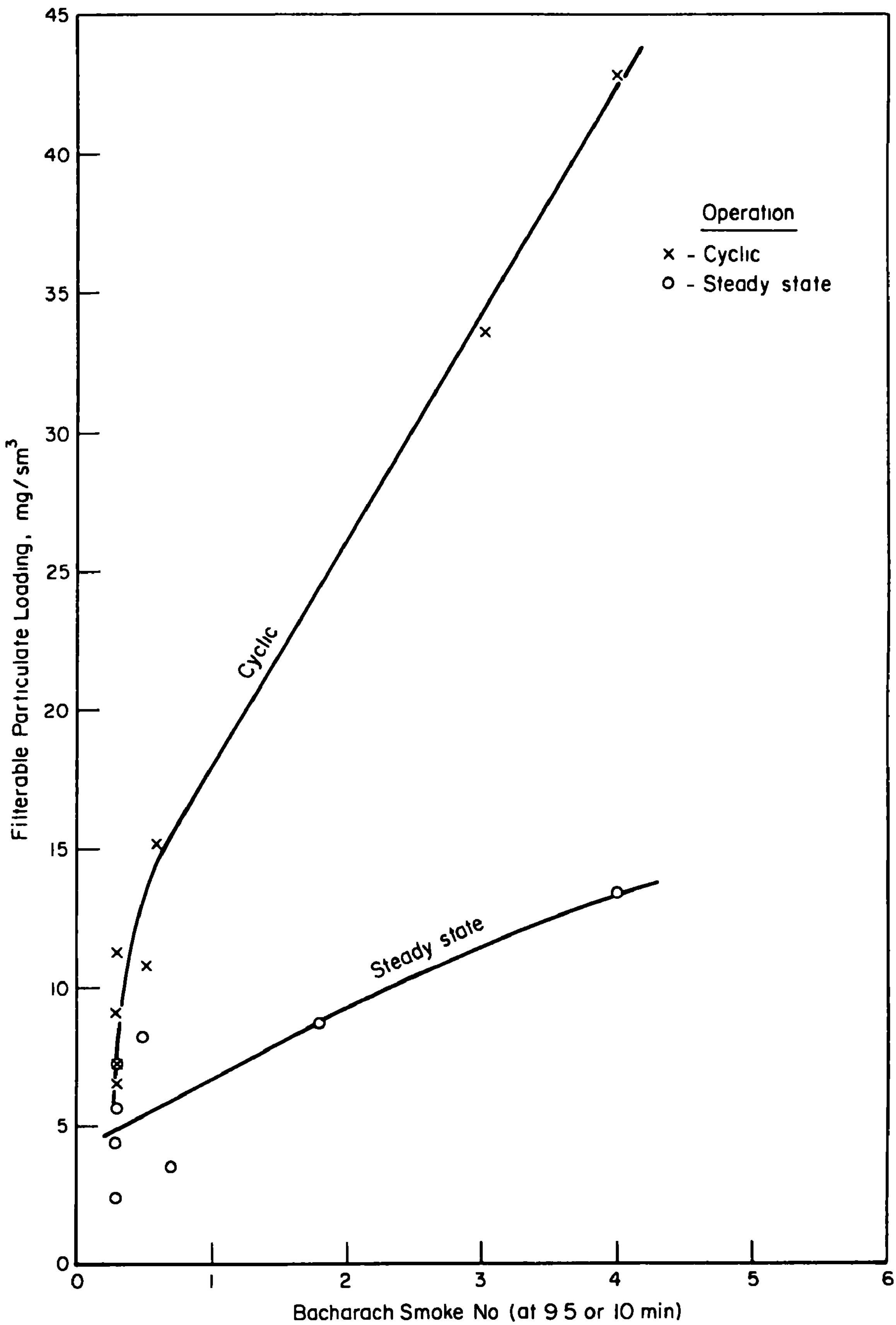


FIGURE 10. FILTERABLE PARTICULATE LOADING VERSUS SMOKE – UNIT 36

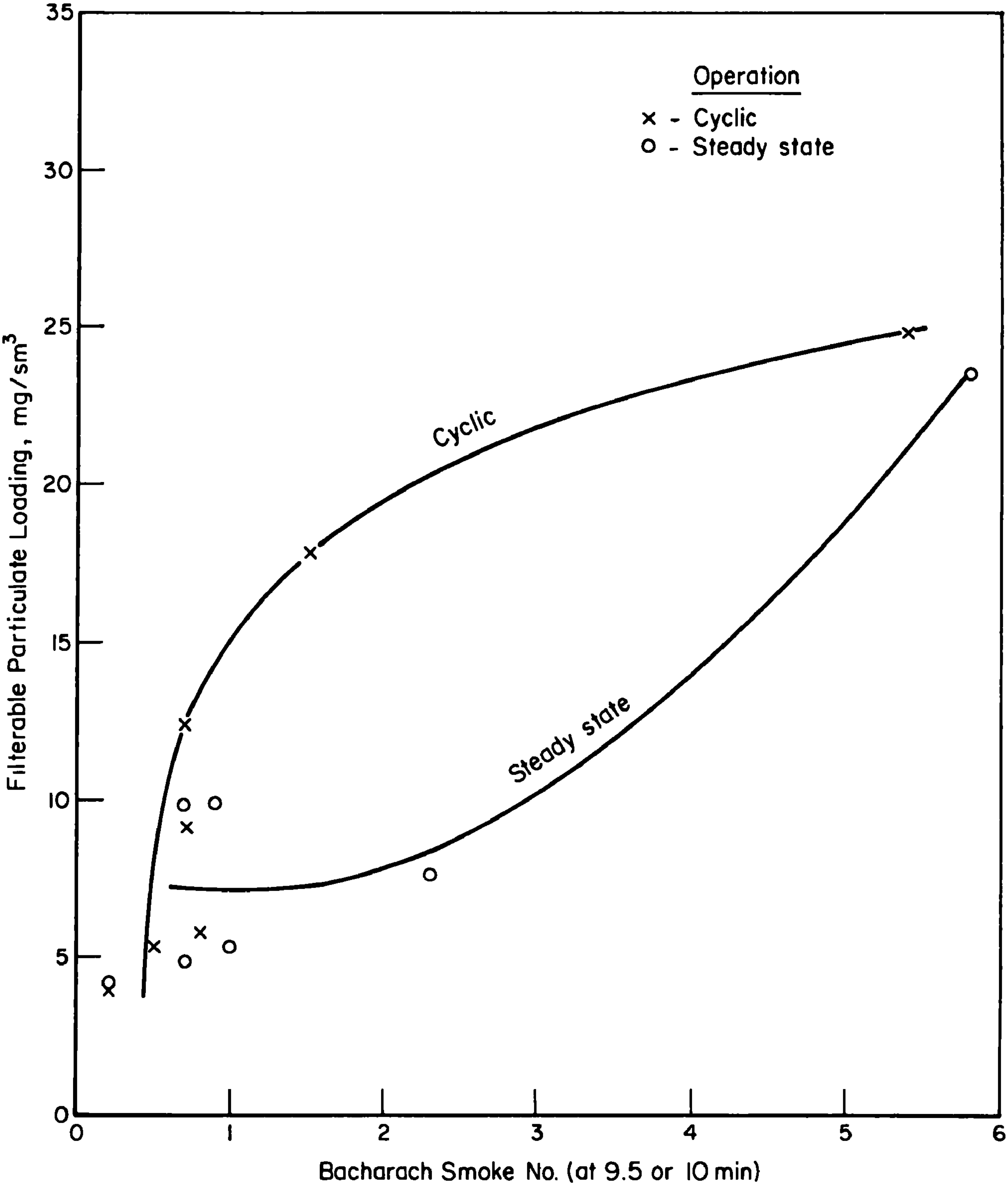


FIGURE 11. FILTERABLE PARTICULATE LOADING VERSUS SMOKE - UNIT 37

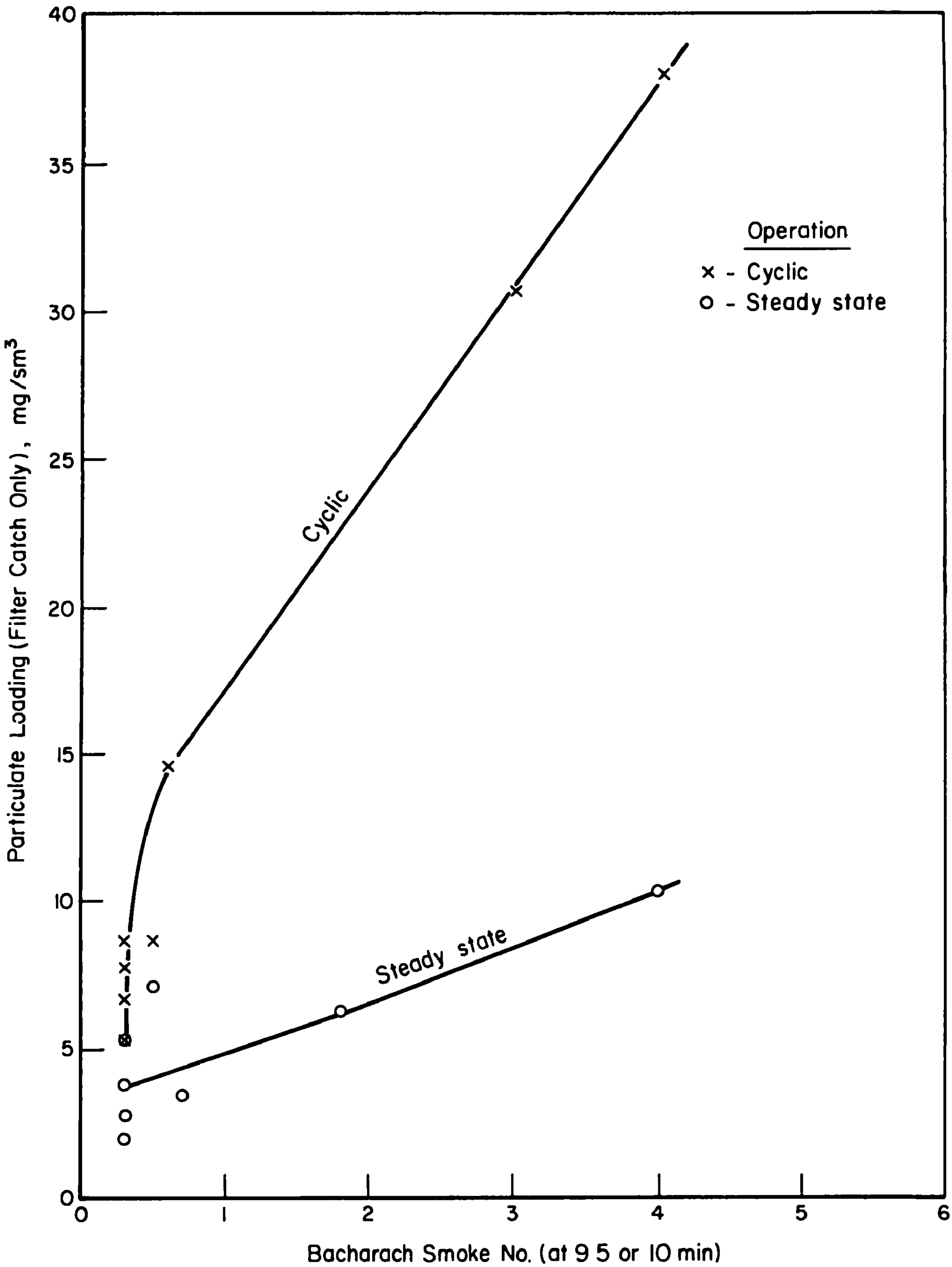


FIGURE 12. PARTICULATE LOADING (BASED ON FILTER CATCH) VERSUS SMOKE – UNIT 36

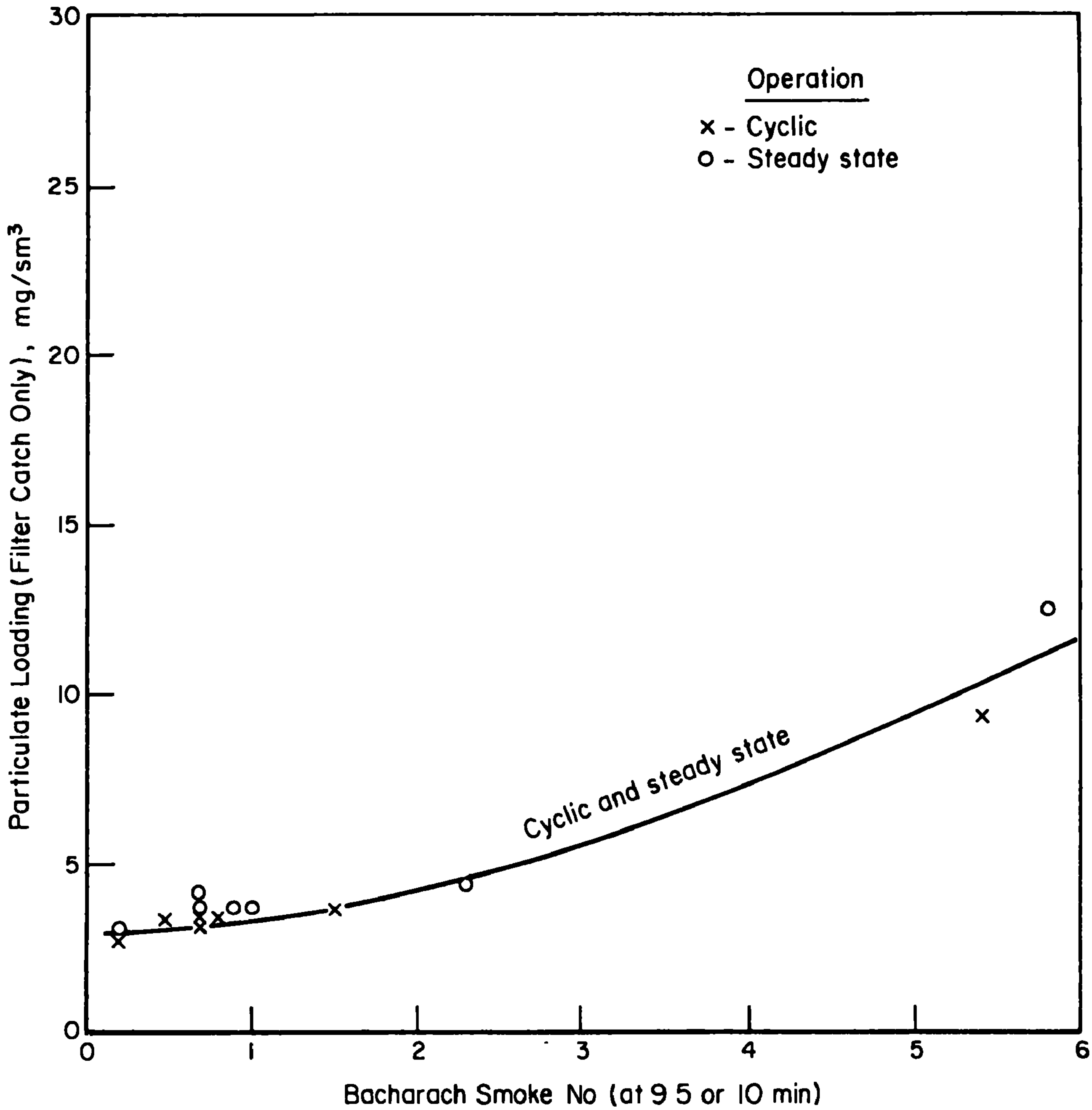


FIGURE 13. PARTICULATE LOADING (BASED ON FILTER CATCH) VERSUS SMOKE - UNIT 37

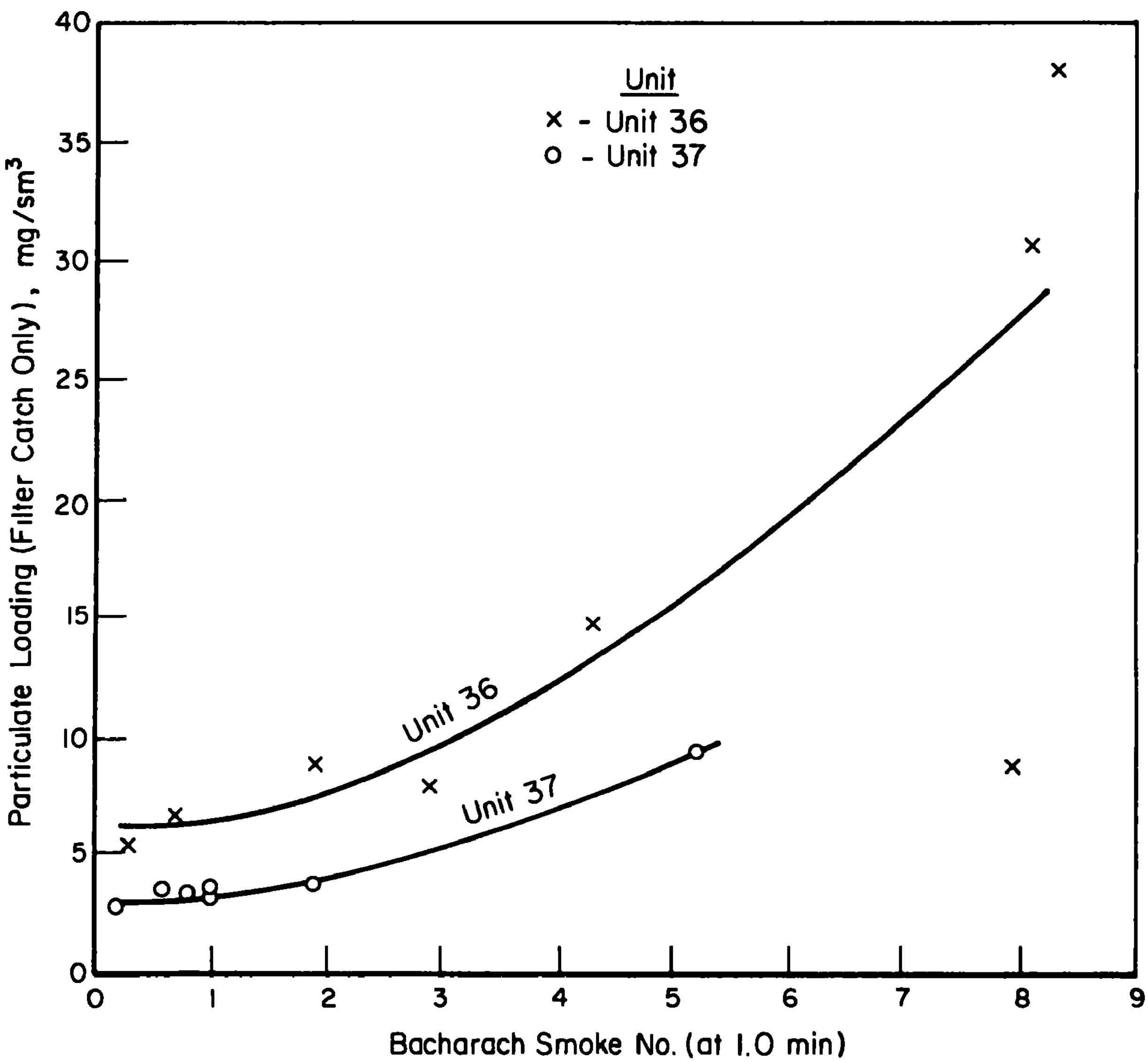


FIGURE 14. PARTICULATE LOADING (BASED ON FILTER CATCH) VERSUS SMOKE AT 1.0 MINUTE FOR CYCLIC RUNS

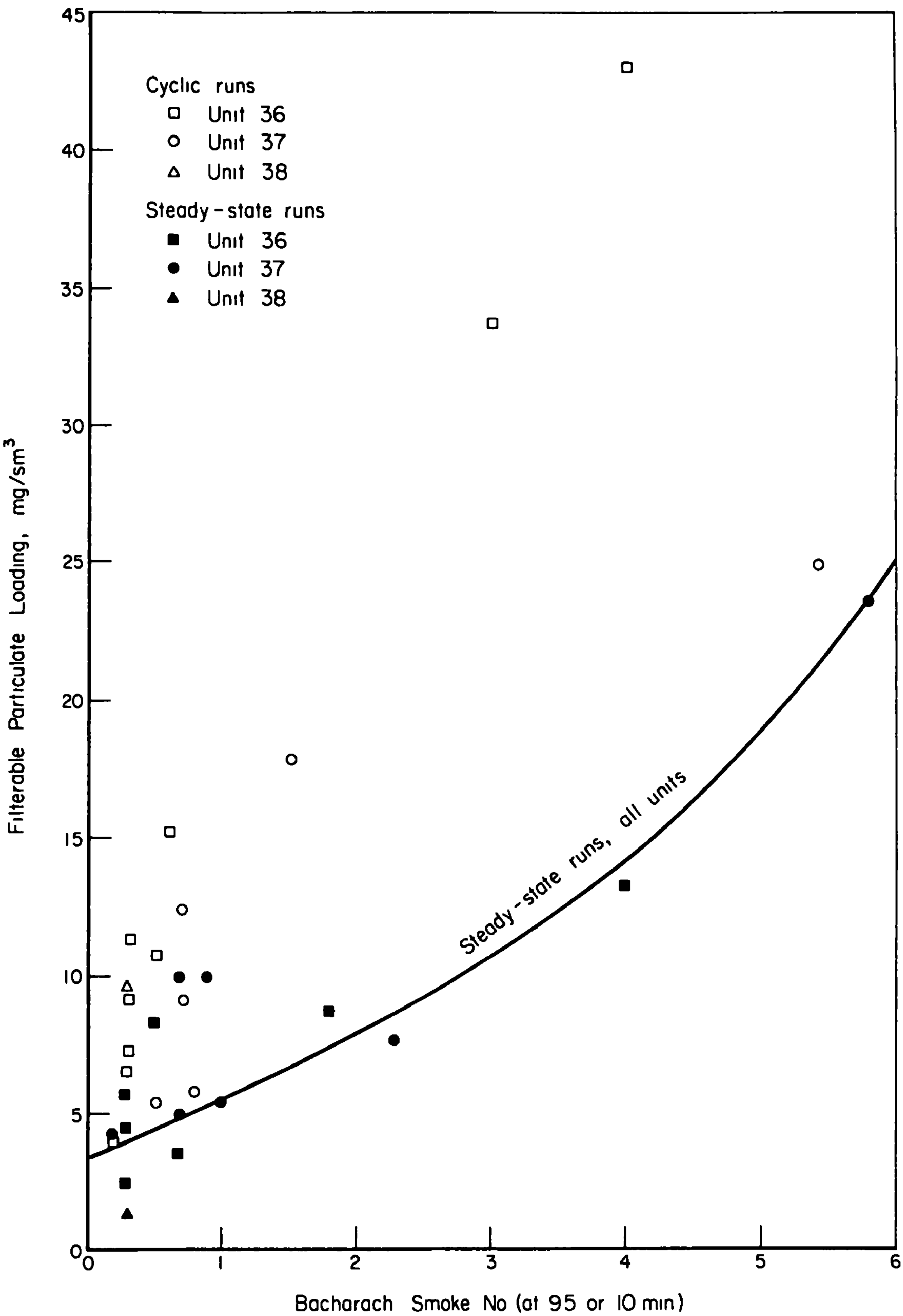


FIGURE 15. FILTERABLE PARTICULATE LOADING VERSUS SMOKE – CYCLIC OPERATION OF UNITS 36 AND 37

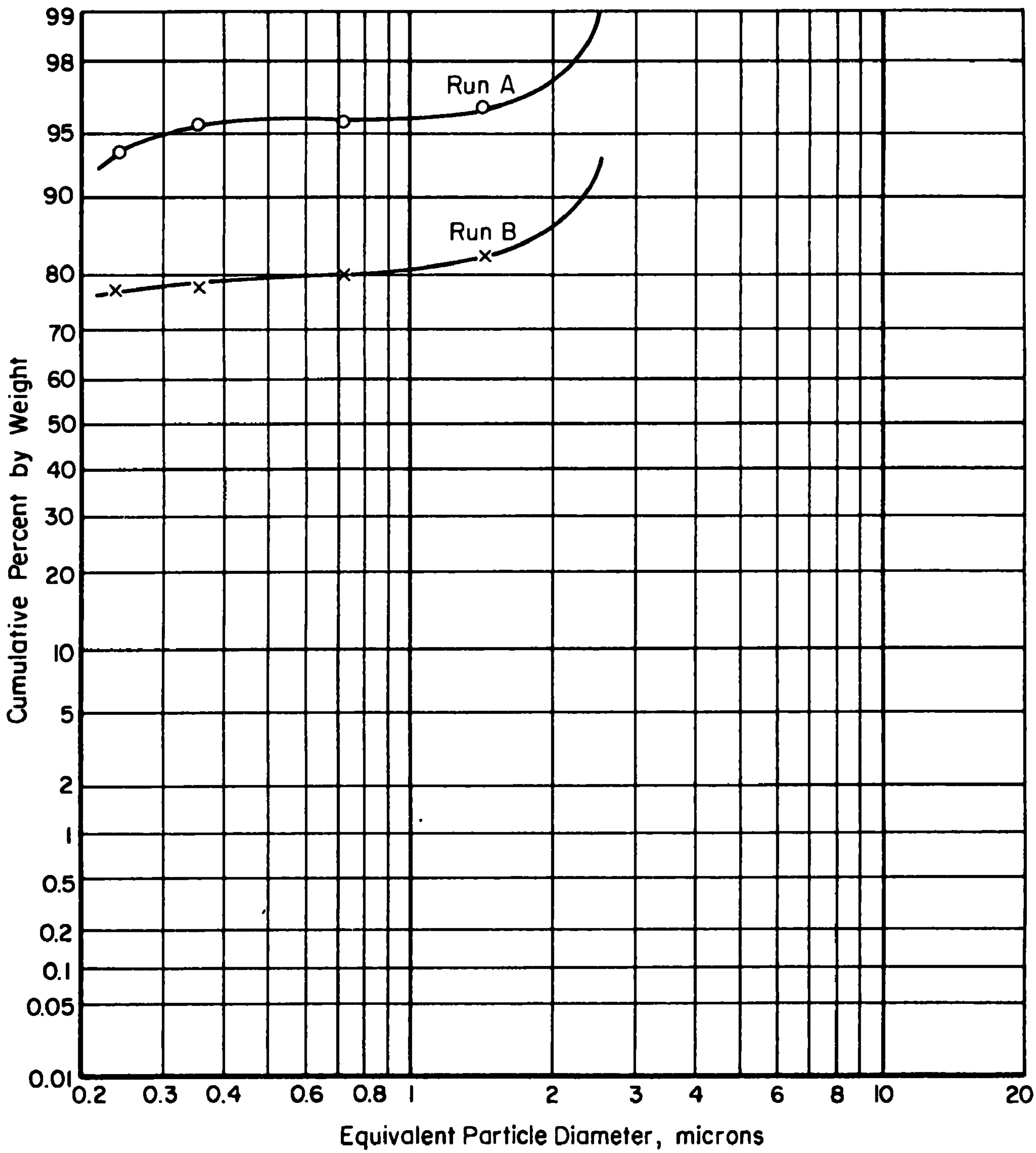


FIGURE 16. PARTICLE-SIZE DISTRIBUTION FOR UNIT 37 AT 35 PERCENT EXCESS AIR

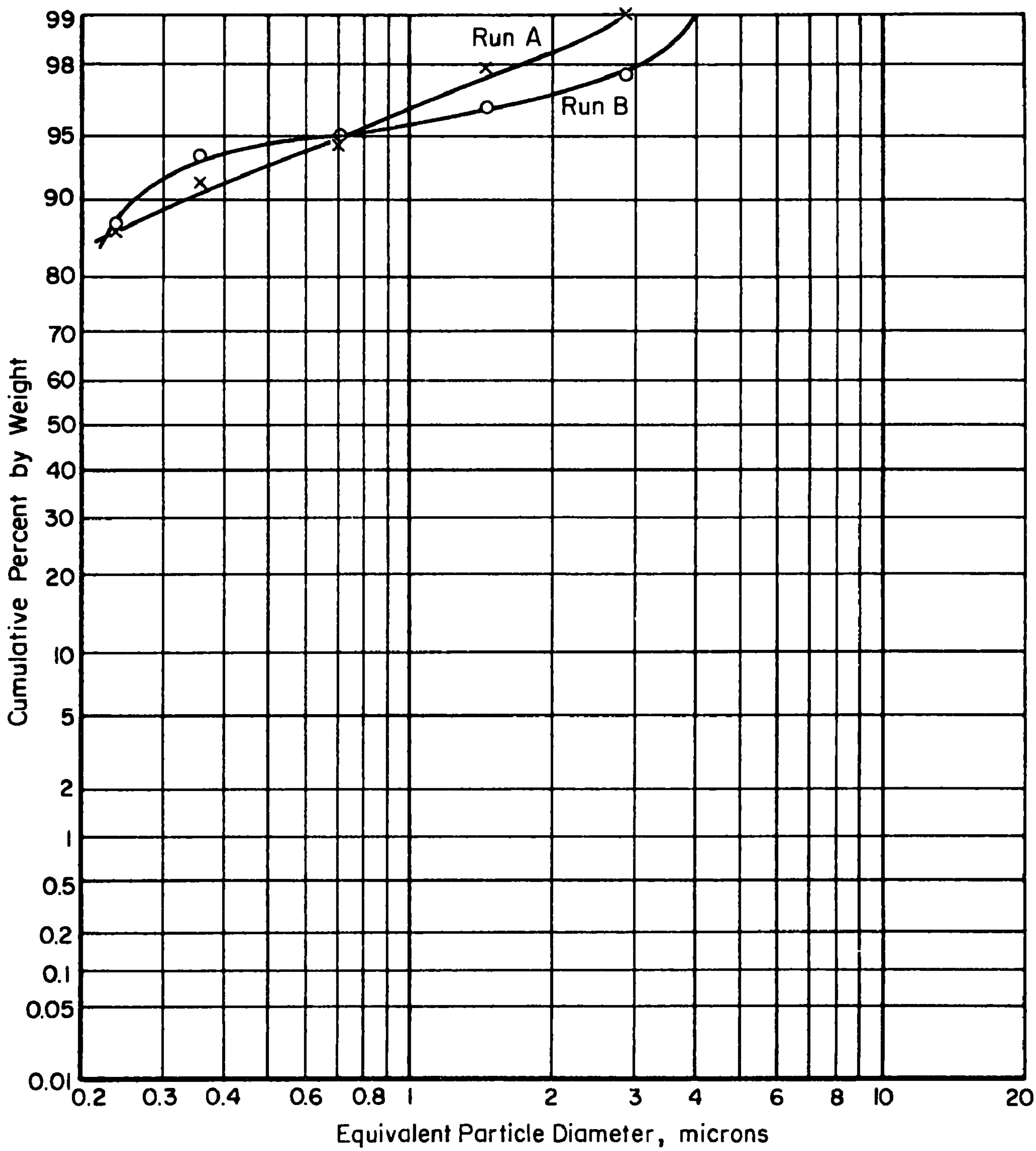


FIGURE 17. PARTICLE-SIZE DISTRIBUTION FOR UNIT 37 AT 29 PERCENT EXCESS AIR

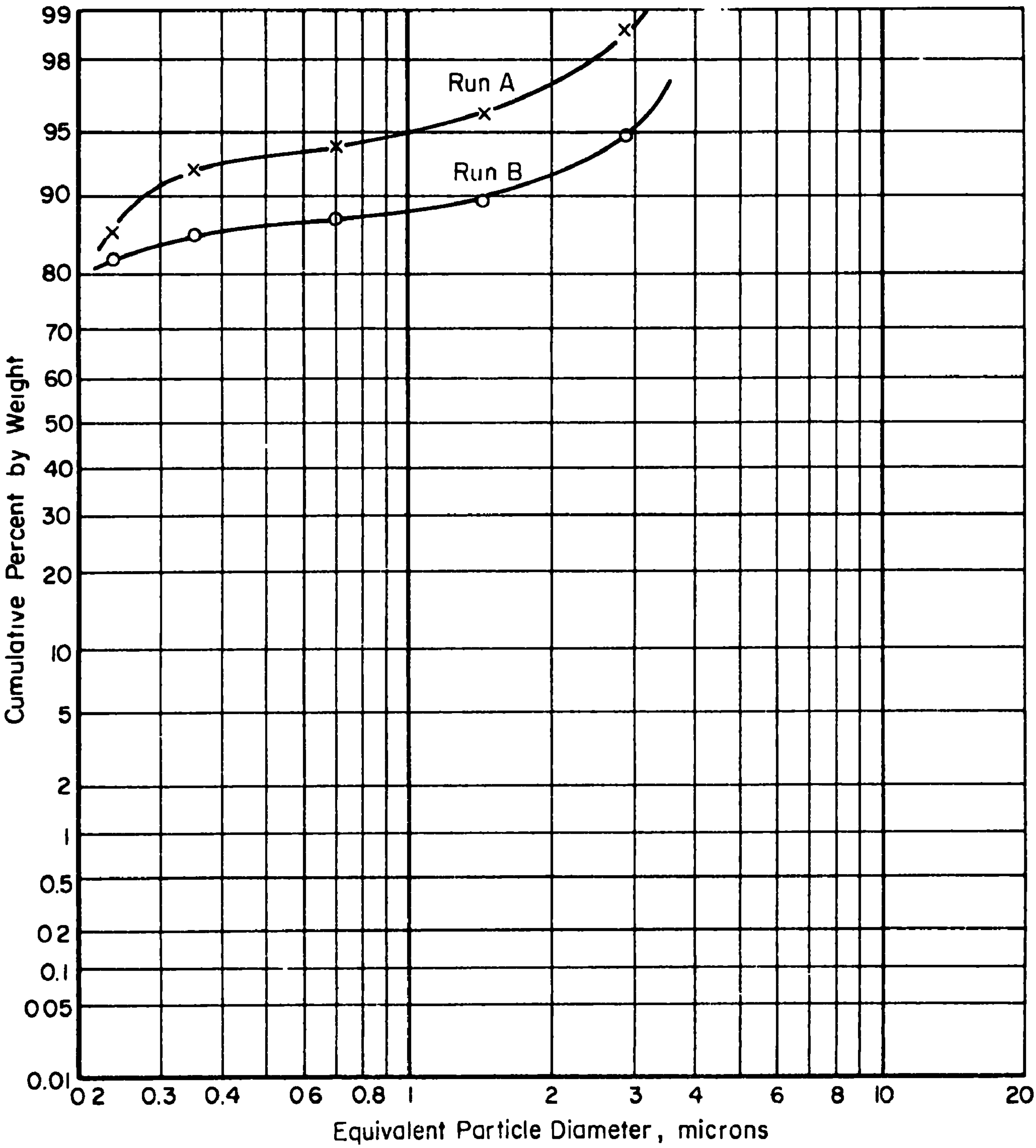


FIGURE 18. PARTICLE-SIZE DISTRIBUTION FOR UNIT 37
AT 27 PERCENT EXCESS AIR

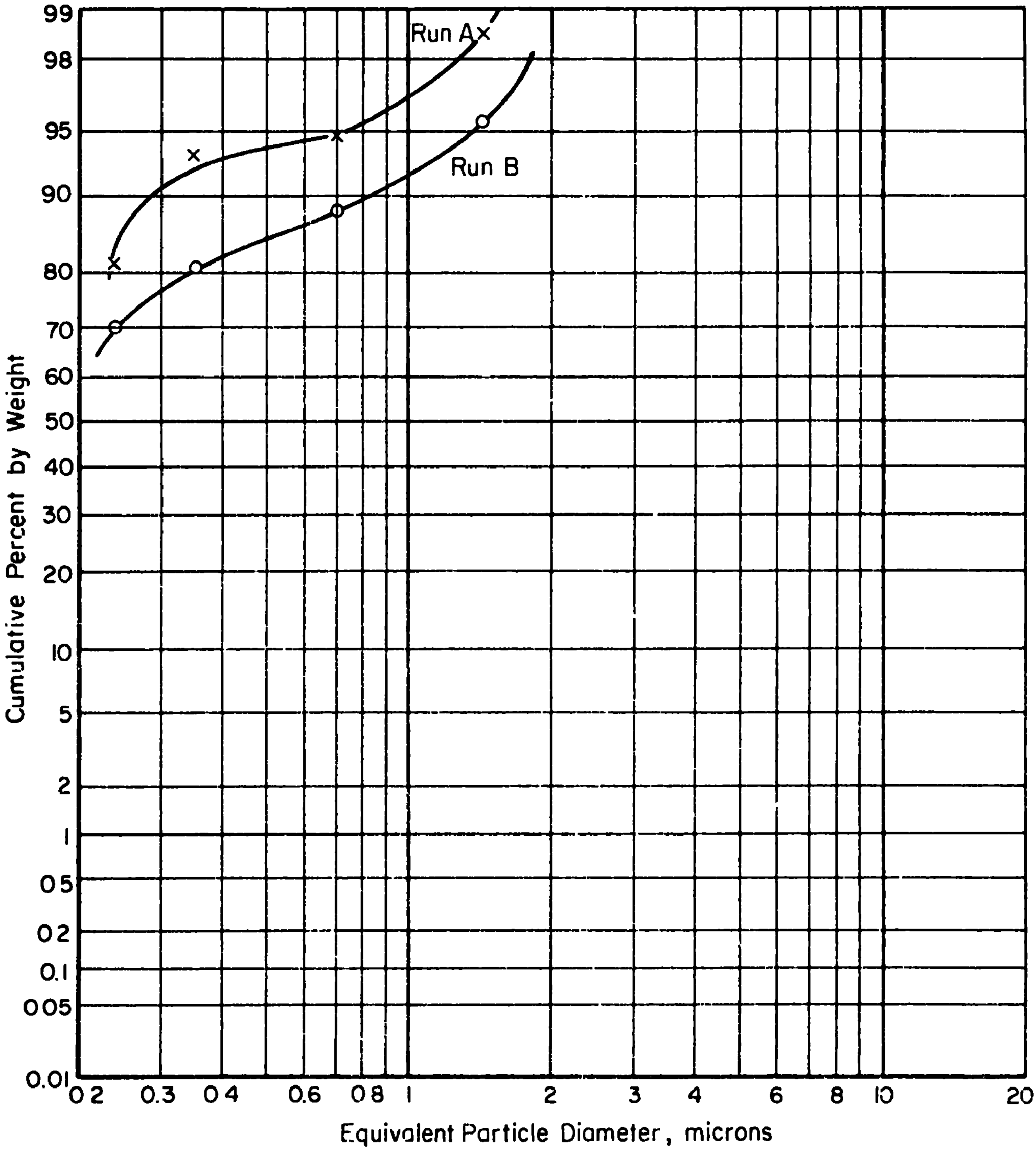


FIGURE 19. PARTICLE-SIZE DISTRIBUTION FOR UNIT 37 AT 26 PERCENT EXCESS AIR

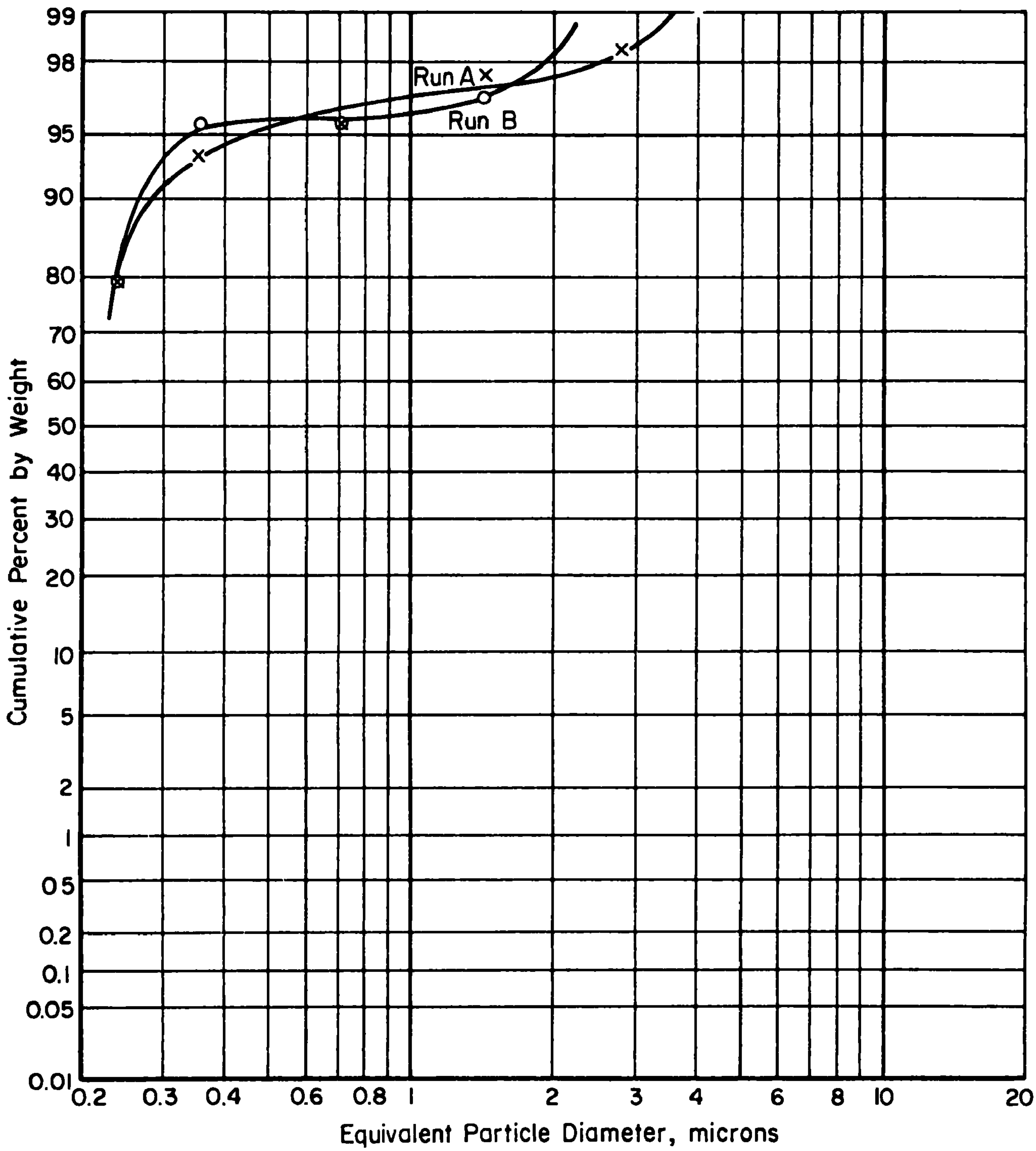


FIGURE 20. PARTICLE-SIZE DISTRIBUTION FOR UNIT 37 AT 23 PERCENT EXCESS AIR

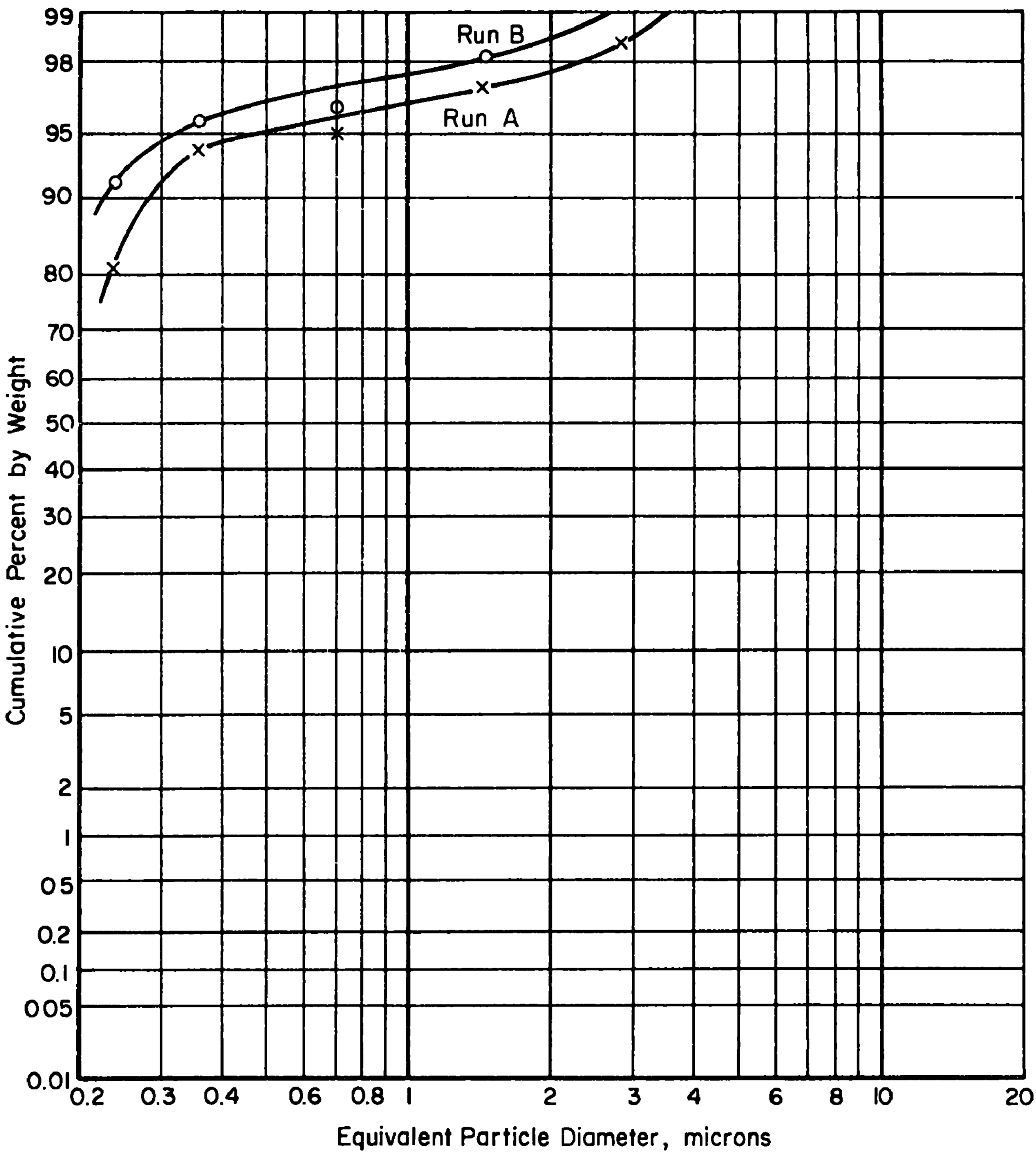
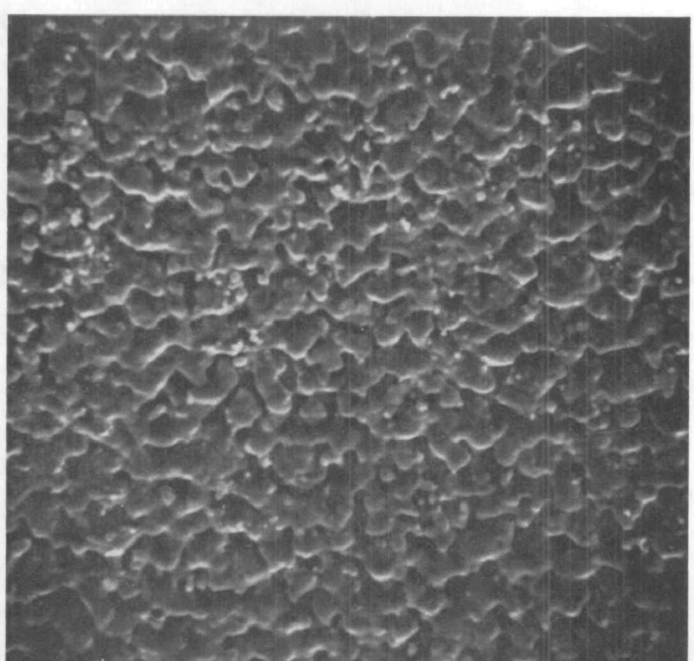


FIGURE 21. PARTICLE-SIZE DISTRIBUTION FOR UNIT 37 AT 18 PERCENT EXCESS AIR

1000X

Scale: →||← 1 Micron

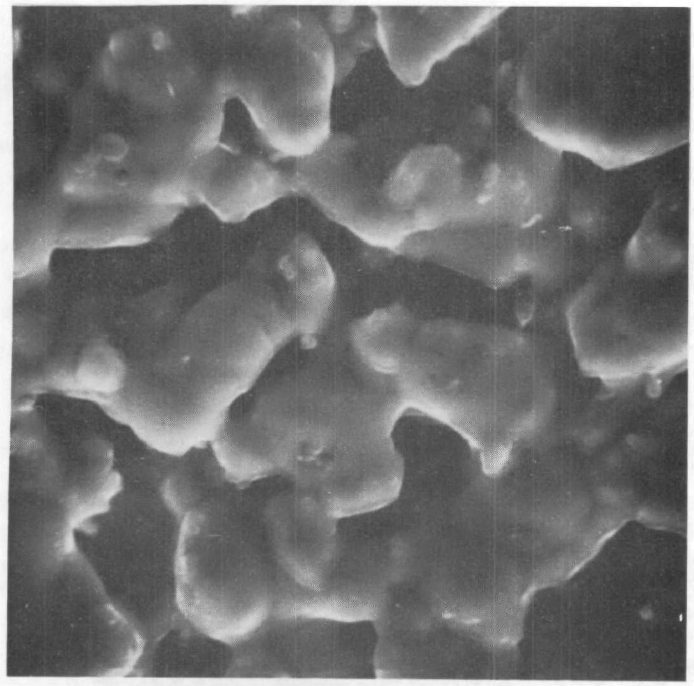
FIGURE 22. PARTICULATE ON FIBERGLASS FILTER



1000X

Scale: →||← 1 Micron

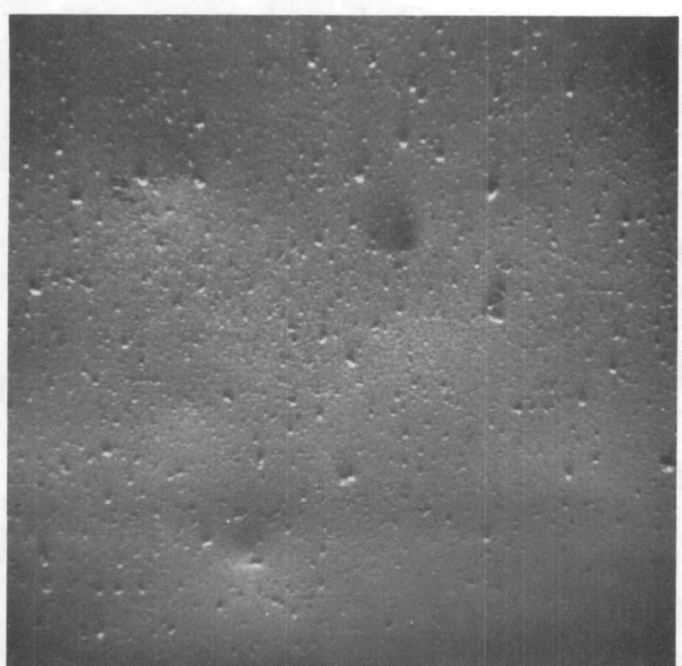
FIGURE 23. CLEAN SILVER FILTER



5000X

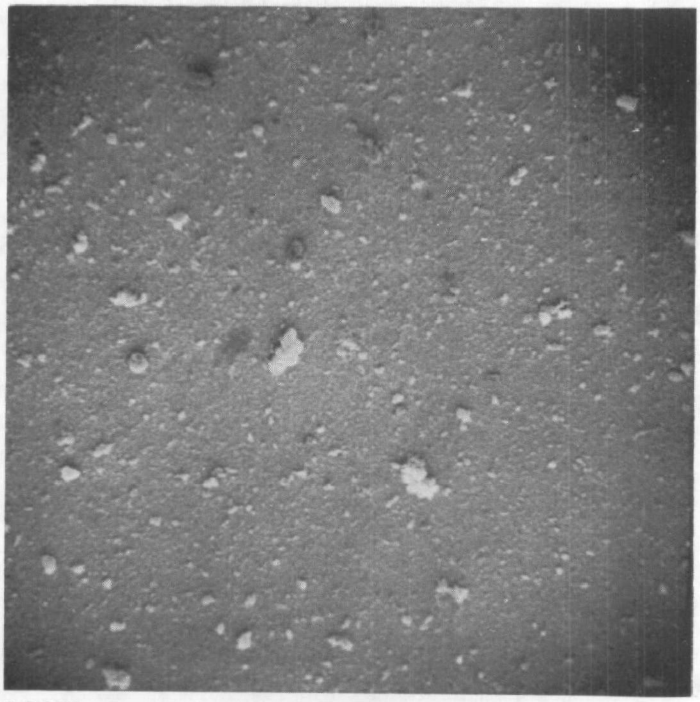
Scale: →| |← 1 Micron

FIGURE 24. CLEAN SILVER FILTER



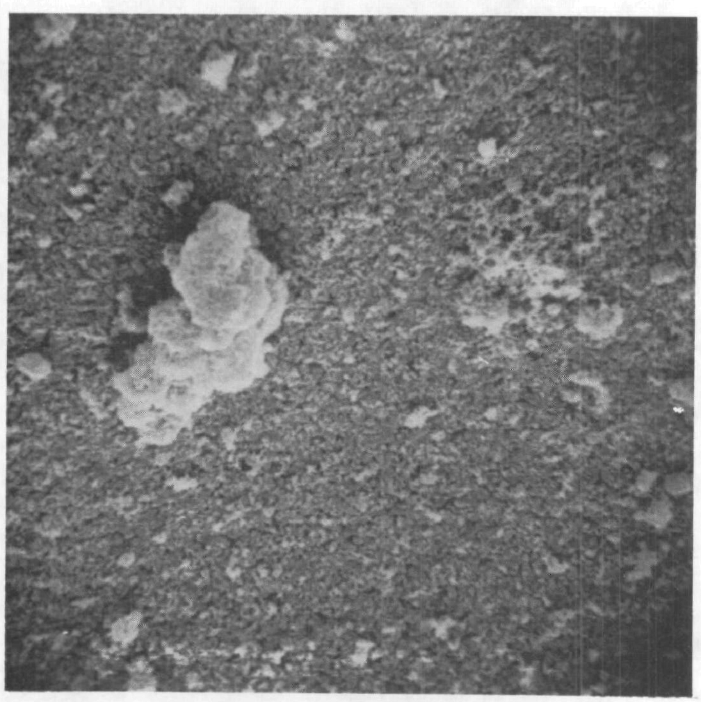
20X

FIGURE 25. PARTICULATE ON SILVER FILTER



100X

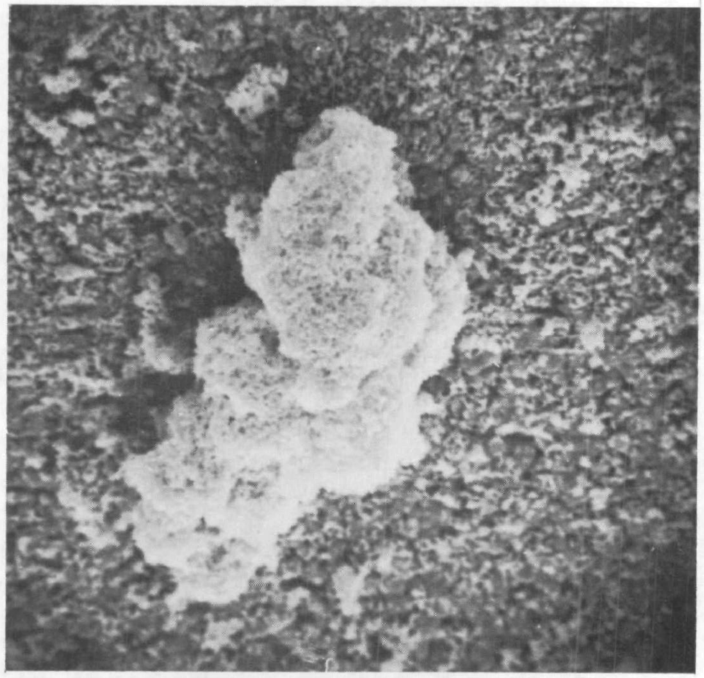
FIGURE 26. PARTICULATE ON SILVER FILTER



500X

Scale: →|← 1 Micron

FIGURE 27. PARTICULATE ON SILVER FILTER



1000X

Scale: →||← 1 Micron

FIGURE 28. PARTICULATE ON SILVER FILTER

5000X

Scale: →| |← 1 Micron

FIGURE 29. PARTICULATE ON SILVER FILTER

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1 REPORT NO. EPA-650/2-74-026	2.	3 RECIPIENT'S ACCESSION NO.
4 TITLE AND SUBTITLE Investigation of Particulate Emissions from Oil-Fired Residential Heating Units		5 REPORT DATE March 1974
		6 PERFORMING ORGANIZATION CODE
7 AUTHOR(S) R. E. Barrett, D. W. Locklin, and S. E. Miller		8 PERFORMING ORGANIZATION REPORT NO.
9 PERFORMING ORGANIZATION NAME AND ADDRESS Battelle, Columbus Laboratories 505 King Avenue Columbus, Ohio 43201		10 PROGRAM ELEMENT NO. 1AB015; ROAP 21AFE-07
		11 CONTRACT/GRANT NO. 68-02-0230 (Task 9)
12 SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development NERC-RTP, Control Systems Laboratory Research Triangle Park, NC 27711		13 TYPE OF REPORT AND PERIOD COVERED Final
		14 SPONSORING AGENCY CODE
15 SUPPLEMENTARY NOTES		

16 ABSTRACT

The report gives results of a laboratory study of two residential oil-fired heating units, a warm-air furnace and a boiler. Bacharach smoke and filterable particulate emissions were measured at several excess-air levels for both cyclic and steady-state runs. Particle-size distributions were also measured during boiler runs to determine if particle-size variations might help explain the lack of correlation between earlier smoke and particulate emission field measurements. One unit produced essentially no excessive smoke or particulate on startup; 1 minute after startup, smoke was equal to steady-state smoke; and particulate emissions for cyclic and steady-state firing were equal. The second unit produced a startup smoke higher than its steady-state smoke, and higher particulate emissions for cyclic runs than for steady-state runs, suggesting that this unit had a significant "on puff" on startup. Particulate emissions varied with excess air in the same pattern as smoke number, higher at low excess air levels for both units. Correlations between smoke and particulate emissions appeared practical for individual units firing at specific operating conditions. However, a general correlation between smoke and filterable particulate emissions does not appear to exist for cyclic operation. For the two units, particle-size distributions were nearly identical for all runs and indicated that over 80 percent of the particles were below 1.0 micron.

17 KEY WORDS AND DOCUMENT ANALYSIS

a DESCRIPTORS		b IDENTIFIERS/OPEN ENDED TERMS	c COSATI Field/Group
Air Pollution	Stoichiometry	Air Pollution Control	13B, 07D
Soot	Measurements	Stationary Sources	11G, 14B
Smoke	Particle Size Distribution	Particulate Emissions	21B
Oil Burners	Boilers	Residential Heating Units	13A
Combustion	Furnaces	No. 2 Oil	
Smoking	Carbon Monoxide	Oil Fired	07B
	Hydrocarbons	Cyclic Operation	07C

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