EPA-450/3-76-002
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MODEL VALIDATION AND TIME-CONCENTRATION ANALYSIS OF THREE POWER PLANTS

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Waste Management
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

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MODEL VALIDATION AND TIME-CONCENTRATION ANALYSIS OF THREE POWER PLANTS

by

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Publication No. EPA-450/3-76-002

ABSTRACT

This report presents an analysis of the EPA Single Source Model using SO_2 concentration and meteorological data collected in the vicinity of three Ohio Power Plants: J. M. Stuart, Muskingum River, and Philo. The model predicts the upper percentile of the frequency distribution of 1-hour and 3-hour concentrations reasonably well. Concentrations over the remainder of the distribution are significantly underpredicted, due in part to the errors in the determination of background concentrations. The second highest 24-hour concentrations tend to be underpredicted by the model except at the Philo plant, where the model is less likely to account properly for terrain influences. Also investigated during this study were the frequency distributions of peak 1-hour to average 3-hour and peak 1-hour to average 24-hour concentration ratios. Statistics of these distributions were found to vary little from one plant to the next.

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ACKNOWLEDGMENTS

The key data used in carrying out this study were made available to GCA/Technology Division by the Dayton Power and Light Company, the Ohio Power Company, and the American Electric System. Project direction and guidance were given by Mr. Russell Lee of the Source-Receptor Analysis Branch, Monitoring and Data Analysis Division, EPA, Durham, North Carolina, who served as Project Officer, and by Mr. Michael Lazaro from the EPA Region V Office.

SECTION I

INTRODUCTION

BACKGROUND

Reliable tools for the estimation of SO_2 concentrations downwind from large power plants are urgently needed to guide environmental and energy related policy decisions. Most mathematical dispersion models for the prediction of SO_2 concentrations provide estimates for averaging times which are either very short (up to 1 hour) or very long (seasonal or annual). For example, the plume parameters given by Turner[1] and developed principally from earlier work of Pasquill, Cramer, and Gifford are based on experimental data much of which was collected over 10- and 30-minute periods. Power law relationships by which concentrations from point sources are linked to time are generally considered to be valid only over averaging times which range from a few minutes to perhaps 1 or 2 hours. National ambient standards for SO_2, however, include standards for annual and 24-hour time periods. The method currently favored for estimating 24-hour concentrations is to average concentrations that have been predicted for the component 1-hour periods. A second method, based on the development of peak-to-mean ratio statistics, has been suggested by Montgomery, Carpenter, and Lindley.[2] To date, very few sets of field data have been used to test the adequacy of either estimation technique.

PURPOSE OF STUDY

The purpose of this study was twofold:

1. To conduct validation studies of an EPA concentration model designed to estimate concentrations due to a single source for averaging times of 1 hour, 24 hours and 1 year, with emphasis on the 24-hour value.

2. To analyze time-concentration relationships of measured air quality data in the vicinity of a large elevated point source, paying special attention to the ratios of 1-hour to 3-hour and 1-hour to 24-hour concentrations.

The analytical procedures were to parallel those used by Klug[3] and Montgomery et al.[2] in their analysis of TVA data.

SUITABILITY OF POWER PLANT DATA

J. M. Stuart Site and Plant Description

The J. M. Stuart plant is located in Southwestern Ohio on the Ohio River, about 9 kilometers Southwest of Manchester, Ohio, and 4 kilometers East of Maysville, Ohio (see Figure 1). The plant occupies a position centered in the Ohio River Valley about 700 meters from the valley walls on either side. A detailed map of the plant, the SO_2 monitoring sites, and the surrounding towns is given in Figure 2. The elevation of the top of the valley above the bottom is about 115 meters, so the 244 meter stacks rise about 130 meters above the surrounding countryside. The data used in this study were collected during the 1-year period from January 1, 1973 to December 31, 1973. During this period, the plant consisted of four identical coal-fired boilers with a generating capacity of 610 megawatts each. However, one boiler was down for repairs during the entire year so that the total generating capacity was only 1830 megawatts, the yearly average being 1318 megawatts, or 72 percent of the maximum. Further characteristics of this plant can be found in Table 1.

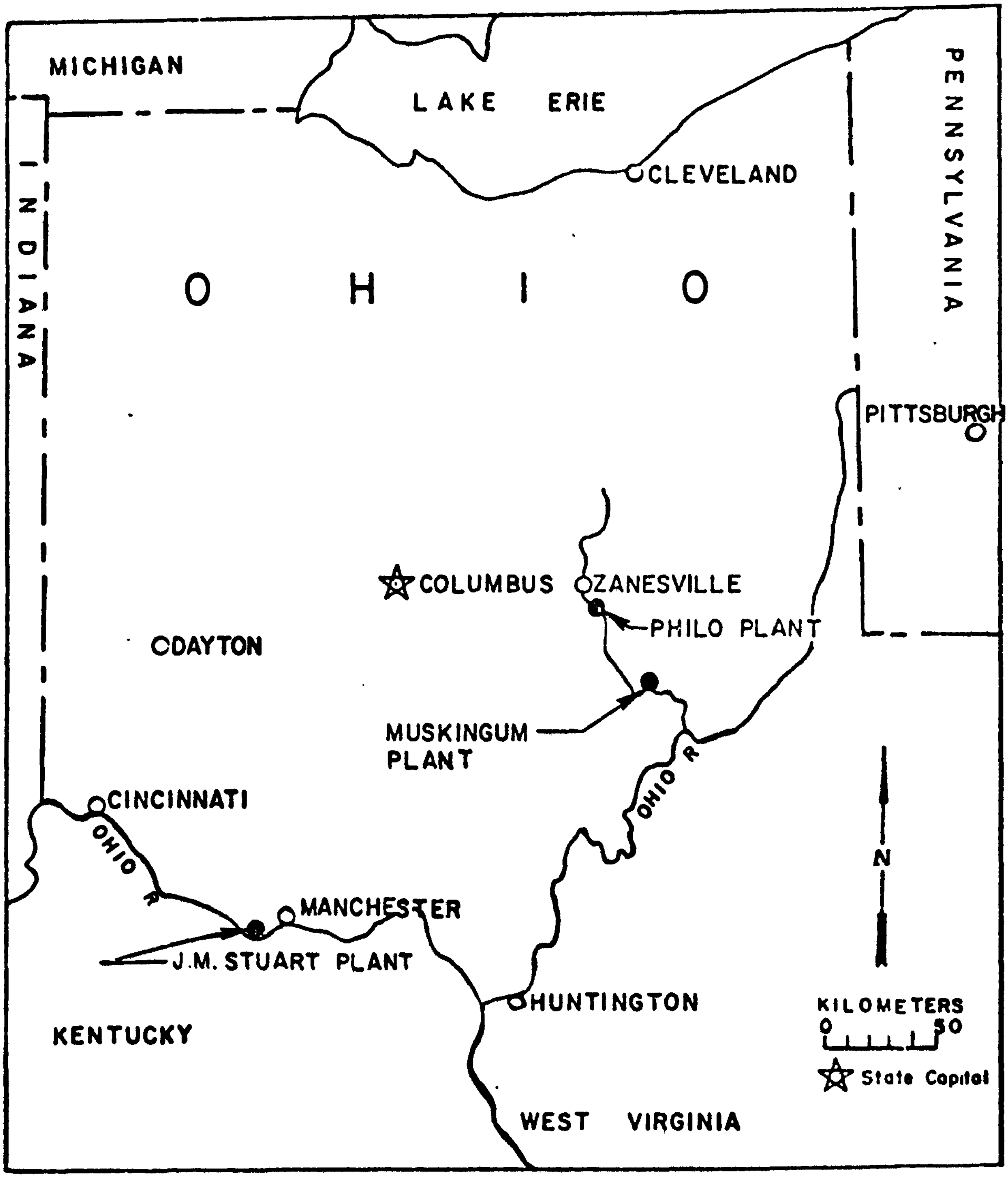

Figure 1. Map of Ohio and surrounding states showing location of J. M. Stuart Plant, Philo Plant, and Muskingum River Plant

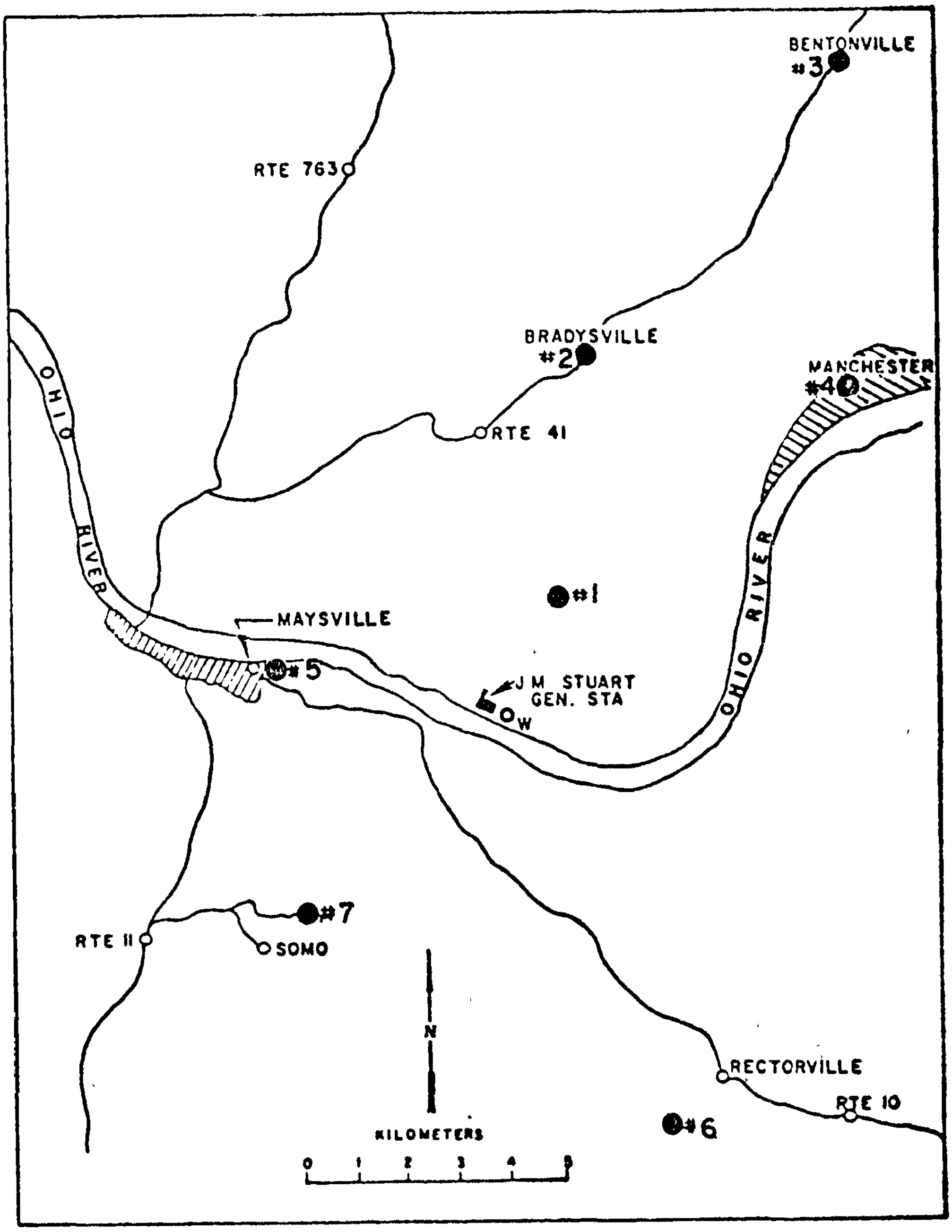

Figure 2. Sketch of the J. M. Stuart Plant area showing **locations** of seven automatic SO_2 monitoring stations

Table 1. PLANT CHARACTERISTICS

Characteristic	Plant					
	Stuart	Muskingum		Philo		
	Four similar stacks	Stack 1	Stack 2	Stack 4	Stack 5	Stack 6
Stack height (M)	244	251	251	81	81	84
diameter (M)	6.0	7.6	6.7	5.2	3.9	2.6
velocity (M/S)	22.2	28.5	24.8	4.5	7.7	29
temperature (°K)	373	430	425	458	458	433
Number of boilers per stack	1 each	4	1	2	2	1
Generating capacity:						
Maximum per stack (MW)	610	876	591	166	166	125
Average per stack (MW)	(each) 439	748	487	114	128	84
Plant total (MW)	2440	1467		457		
Plant average (MW)	1318	1235		326		

Muskingum Site and Plant Description

The Muskingum Plant is located in Southeastern Ohio on the Muskingum River about 6 kilometers Northwest of the Town of Beverly. Figure 1 shows the geographical location of the Muskingum Plant in relation to the major cities in Ohio and Figure 3 shows a detailed map of the plant, the SO_2 monitoring sites, and the surrounding towns. The plant is situated in the Muskingum River Valley and is roughly centered about 500 meters from the valley walls to the north and south. During 1973 the plant consisted of five coal-fired units feeding into two stacks. The boiler capacities and stack parameters for its two stacks are listed in Table 1. Stack 2 is approximately 640 meters to the southwest of Stack 1. The top of the valley rises about 75 meters above the bottom, so the 251 meter stacks stand about 185 meters above the surroundings.

Philo Site and Plant Description

The Philo plant is located in eastern Ohio on the Muskingum River in the town of Philo, which is about 11 kilometers to the southeast of Zanesville, Ohio. The geographical location of the Philo plant in relation to the major cities in Ohio is indicated in Figure 1. Figure 4 shows a detailed map of the plant, the SO_2 monitoring sites, and the surrounding towns. The plant is located in the Muskingum River Valley and is roughly centered about 500 meters from the valley walls to the east and west, although the valley widens to the north. The three stacks are relatively low in comparison to the other two plants, since they are approximately 82 meters high and rise about 11 meters above the top of the valley walls.

Overview of J. M. Stuart Plant Monitoring Program

There are seven sulfur dioxide monitoring stations which comprise the monitoring network. These are shown on the map in Figure 2 and their elevations, distances, and bearings from the plant are listed in Table 2.

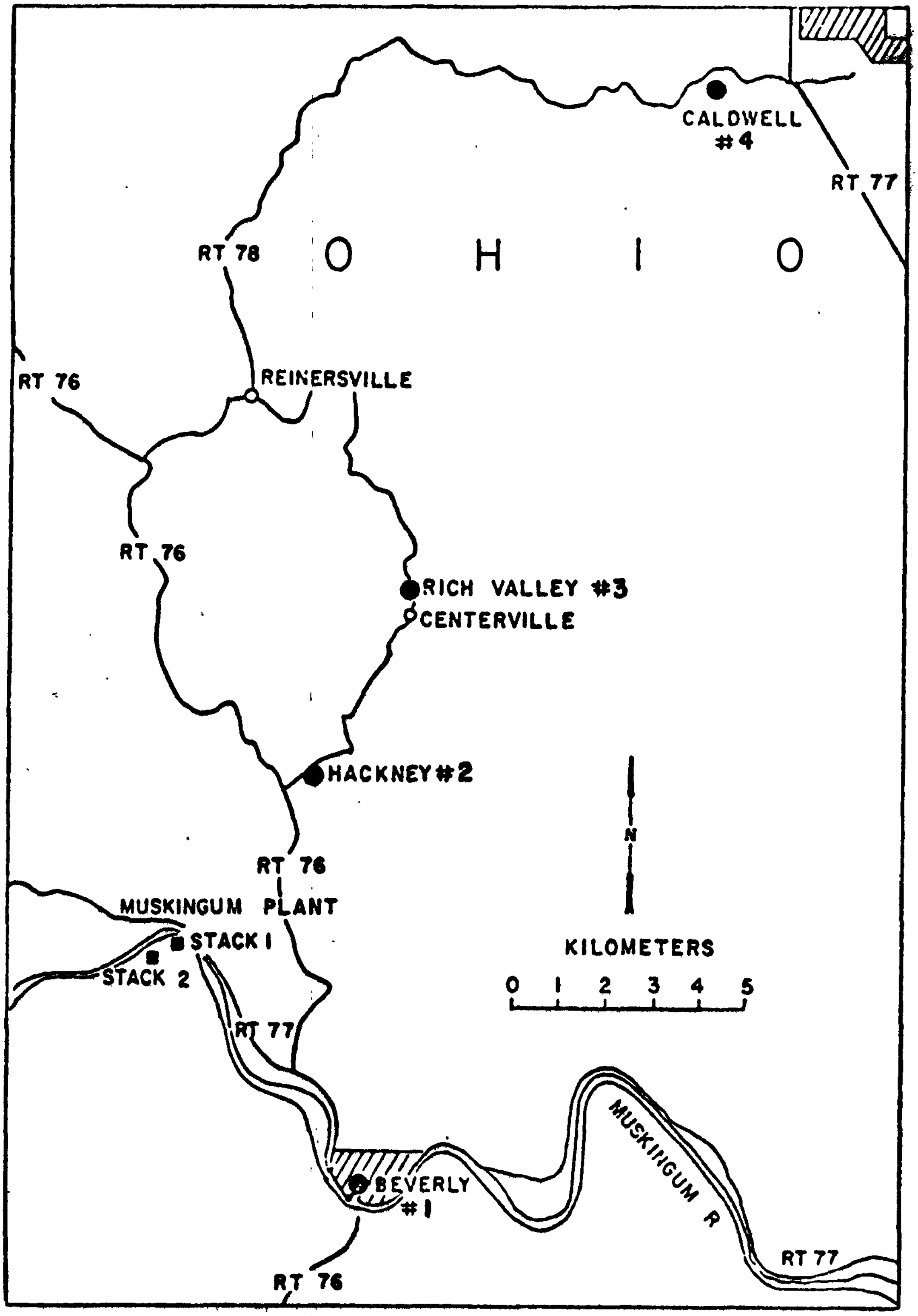

Figure 3. Sketch of the Muskingum Plant area showing locations of four automatic SO_2 monitoring stations

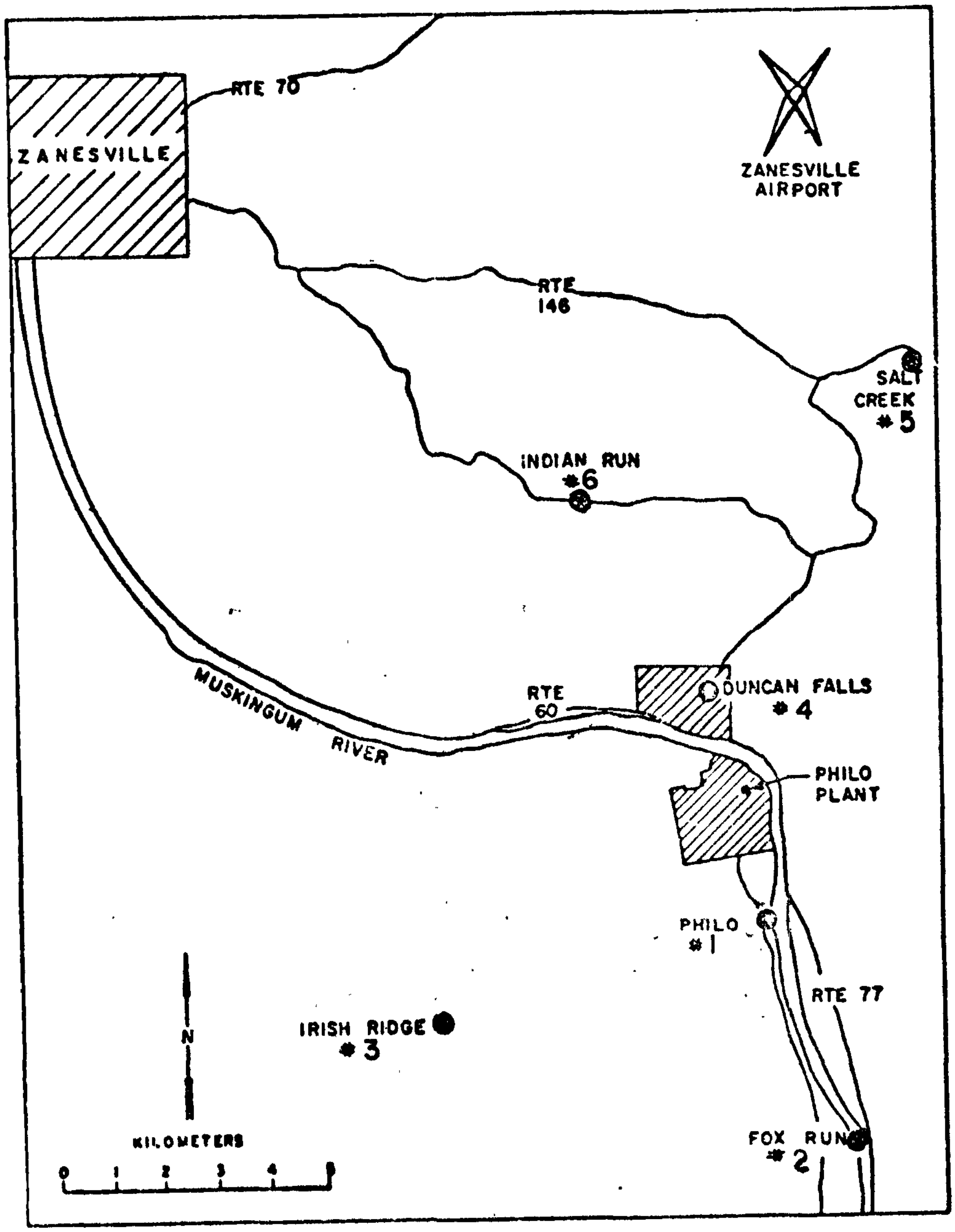

Figure 4. Sketch of the Philo Plant area showing locations of six automatic SO_2 monitoring stations

Table 2. SULFUR DIOXIDE MONITOR STATIONS

Plant	Station No.	Station Name	Distance (km)	Bearing (degrees)	Elevation above stack base (M)
Stuart	1	Boone	2.398	34.64	115
	2[a]	Brudysville	6.550	14.95	85
	3	Bentonville	13.350	27.60	121
	4[b]	Manchester	8.733	48.50	- 7
	5	Maysville	3.830	279.11	- 4
	6	Rectorville	8.411	155.84	115
	7[c]	Somo	5.011	220.07	115
	M	Wind instrument	-	-	40
	-	Top of stacks	-	-	244
Muskingum	1	Beverly	5.275	140.35	64
	2	Hackney	4.284	39.52	82
	3	Rich Valley	8.264	35.35	101
	4	Caldwell	19.628	34.93	128
	M	Beverly	5.275	140.35	97
	M	Hackney	4.284	39.52	104
	-	Top of stacks	-	-	251
Philo	1	Philo	1.710	174.	3
	2	Fox Run	4.839	166.	2
	3	Irish Ridge	4.981	235.	99
	4	Duncan Falls	1.319	343.	12
	5	Salt Creek	5.955	25.	26
	6	Indian Run	4.214	334.	63
	M	Irish Ridge (L)	-	-	104
	M	Irish Ridge (U)	-	-	140
	M	Duncan Falls	-	-	14
	-	Top of stacks			81

[a]Station in operation for about the first quarter of the year only.

[b]Station in operation for about the last three quarters only.

[c]Station in operation for about the first two quarters only.

Note: M = Meteorological data station.

The monitor at Station 2 was moved to Station 4 on March 10, 1973, and the monitor at Station 7 was discontinued on June 17, 1973. Therefore no data is available at Station 2 for 9 months, Station 4 for 3 months, and Station 7 for 6 months. The instruments were all Leeds & Northrup Company, Catalog No. 7860-SW, Aeroscan Air Quality Monitors, purchased in 1968. The sample was obtained by passing ambient air taken from 5 feet above ground level, through an absorption column along with an absorption solution. The sample analysis method was by electrolytic conductivity. Data was taken continuously and listed every hour. Electrical calibration tests were performed weekly for zero and half scale operation. Overall calibration tests were made every six months at 0.2 ppm using the permeation tube method whose accuracy is traceable to the U.S. Bureau of Standards. There were some additional hours of missing data due to loss of electrical power; periods of calibration and maintenance; and system failures caused by presence of foreign material in the sample flow, pump failure, loss of ink supply, failure of the conductivity cell, etc.

The manufacturer's performance accuracy specifications are as follows. In a typical ambient atmosphere which includes the normal interfering gasses, this instrument has:

- Zero drift = 2 percent of full scale per week
- Sensitivity drift < 1 percent of full scale per week
- Reproducibility < 1 percent of full scale
- Sensitivity = 0.01 ppm
- Recorder error < 0.5 percent of full scale
- Range = approximately 0 - 1 ppm

Overview of Muskingum Plant Monitoring Program

There are four sulfur dioxide monitoring stations which comprise the monitoring network. These are shown on the map in Figure 3 and their elevations, distances, and bearings from the plant are listed in Table 2.

The monitoring station was established in 1969 to monitor the ambient changes when the new stacks were installed. Data were available from all stations for January 1 to November 21, 1973. During the entire year of 1973, Station 1 missed 57 days and the other three stations missed approximately 41 days. The monitors were the same type used at the Stuart Plant, with the same calibration procedure, except that they were automatically zeroed once a day.

Overview of Philo Plant Monitoring Program

There were six automatic SO_2 monitoring stations which comprised the monitoring system in 1974. These are shown on the map in Figure 4 and their elevations, distances and bearings from the plant are listed in Table 2. Data was recorded for all of 1974 except the following:

Station Outages

Station 1	First 91 days of year	
Station 4	First 91 days of year	
Station 6	Second 91 days of year	April-July

The monitoring system maintenance and data acquisition were performed by Environmental Research and Technology in Lexington, Massachusetts.

The instruments were calibrated every 6 months in Lexington and zeroed every night by computer. These monitors were made by Malloy and have the following specifications:

Malloy SO_2 Sensor Specifications

Range	0-1 ppm
Sensitivity	0.005 ppm
Noise	$\pm$ 0.5 percent FS
Response lag	< 15 seconds
Rise time to 90 percent	< 30 seconds

Fall time to 90 percent	$<$ 30 seconds
Precision	$\pm$ 1 percent FS
Accuracy	$\pm$ 1 percent FS
Zero drift	$\pm$ 0.01 ppm/day
	$\pm$ 0.02 ppm/3 days
Span drift	$\pm$ 0.01 ppm/day
	$\pm$ 0.02 ppm/3 days
Linearity	$\pm$ 1 percent FS

Fuel Analysis

The following fuel analysis procedures were employed for all three plants. Each barge of coal from a specific vendor was sampled during the unloading process. Analysis was performed on all samples. In the process of determining the caloric value of the coal by bomb calorimeter, the bomb washings were titrated using tetra-hydroxyquionone to determine the acid content which indicates the sulfur level. This is known as the THQ colorimetric method and is a typical loaboratory procedure practiced by the Dayton Power and Light Company, the Ohio Power Company and the American Electric Power System. It has been shown to be in excellent agreement with the standard ASTM method. Average monthly sulfur content of coal for all of 1973 was tabulated in the FPC-67 report.

On-Site Meteorological Measurements

The only type of on-site meteorological data employed in this modeling study was the wind direction, which was used to identify upwind stations for hourly estimates of SO_2 background concentrations. Meteorological input data for the Single Source Model was obtained from the nearest surface and upper air weather stations. The on-site meteorological instrumentation at the J. M. Stuart Plant was a Bendix-Friez wind speed and direction device, mounted 40 meters above the ground on the coal stacking tower. Hourly atmospheric stability estimates were determined according to a "Gustiness Classification" method. These stabilities were not used, however, in this particular modeling study. There were two wind monitoring stations consisting of Bendix-Friez Aerovane wind speed and direction devices at the Muskingum Plant. One station was located 33 meters above ground at Beverly, and the other at the Hackney SO_2 monitoring station, where the wind monitors were located 22 meters above ground. The data from Hackney was used in this study, as it was higher and common to more stations, but Beverly data was used when the Hackney system was not recording. There were three meteorological stations at Philo:

1. Irish Ridge Upper - elevation 140 meters above plant base, (50 meters above ground). This station monitored wind speed and direction, and temperature difference from the lower station.
2. Irish Ridge Lower - elevation 104 meters above plant base, (11 meters above ground). This monitor measured wind speed and direction, and temperature.
3. Duncan Falls - elevation 14 meters above plant base, (6 meters above ground). Only wind speed and direction were recorded here.

The instrumentation system components included:

- Climet WD-012-10 Vane and WS-011-1 Anemometer
- Climet 015-2 and 3 Thermister
- Bendix T20-510072-6 3 blade Impeller

The system was maintained by ERT. The first 100 days of meteorological data were not recorded for 1974. The primary station for wind direction measurements was Irish Ridge Upper. If this station was not operating, wind direction data was taken from Irish Ridge Lower or Duncan Falls.

SECTION II

DATA BASE PREPARATION

DATA INPUT TO MODEL

Meteorological Data

Hourly surface observations from airport log sheets were keypunched onto cards. The airports were:

Plant	Surface observations airport	Year	Mixing heights Airport
J. M. Stuart	Cincinnati, Ohio	1973	Dayton
Muskingum	Huntington, W. Va.	1973	Huntington
Philo	Columbus, W. Va.	1974	Dayton

The surface observations included:

- station
- date and time
- ceiling height
- ambient temperature
- wind direction
- wind speed
- percent cloud cover

Daily mixing heights from radiosonde observations were supplied on cards. A few missing observations were filled in as 500 meters for minimum mixing heights and 1000 meters for maximum mixing heights.

Figure 1 shows the locations of the airports and the plants.

PLANT PARAMETERS

The stack parameters are listed in Table 1 for the three plants. The percent sulfur from the fuel analysis is:

Month	Stuart % S	Muskingum % S	Philo % S
January	1.8	4.9	3.9
February	1.6	4.8	4.8
March	1.8	4.8	4.7
April	1.7	4.5	4.4
May	1.8	4.7	3.3
June	1.6	5.0	3.2
July	1.5	4.7	2.6
August	1.5	4.7	3.2
September	1.5	4.3	3.2
October	1.5	4.6	2.4
November	1.8	4.5	2.6
December	2.1	4.4	3.7

These monthly average percent sulfur values were applied to hourly fuel consumption rates to obtain hourly SO_2 emissions.

J. M. Stuart Plant

An average annual plant capacity factor of 71.8 percent was found by averaging the factors given for the three boilers in FPC-67 Schedule B line 20. This capacity was used to find the average stack exit velocity and temperature, by interpolating between the 50 percent and 75 percent load figures given in FPC-67.

Fuel consumption was keypunched from copies of the hourly fuel consumption log computer printouts for each of the three boilers. The copies which were supplied were sometimes illegible and often had data missing due to computer equipment failure. If an hourly consumption figure was illegible but the individual loader components of this consumption were readable, they were added to find the consumption. If the component loadings were also missing or illegible, the readable hourly consumptions were subtracted from the daily consumptions, and the remainder was used to find the missing average consumptions. If the daily consumption was missing in addition an interpolation between the previous and next readable consumption figure was used. There were a few instances, however, where a good "guess" had to be used. It is felt that any errors thus encountered have an insignificant effect on the model output, but questionable cases were logged for future reference.

Muskingum Plant

The average stack exit temperature and velocity for the Munskingum Plant were supplied by the Ohio Power Company. Hourly values for generated megawatts were keypunched for each unit from computer log sheets. These values were then multiplied by an average yearly conversion factor of pounds of coal per net generated megawatt hour to find the hourly coal consumption figure. The conversion factors were:

Muskingum	Unit 1	0.95 lb/KWH
	Unit 2	0.94 lb/KWH
	Unit 3	0.92 lb/KWH
	Unit 4	0.93 lb/KWH
	Unit 5	0.88 lb/KWH

The generation data was checked by computer program for data inconsistencies and also checked against a tape of hourly gross generation data supplied by the Smith-Singer Company. Several errors were discovered in the generation log sheets and the Smith-Singer tape, and have been logged for future reference.

Philo Plant

The Philo Plant parameters were supplied by the Ohio Power Company and are listed in Table 1. Fuel consumption was calculated from 1974 hourly gross generated megawatt data purchased on tape from Environmental Research and Technology. Ohio Power supplied conversion factors for 1973 hourly net generation data so new factors had to be calculated for 1974 gross generation data.

	1973	1974
Philo Unit 4	1.23 lb/KWH*	1.376 lb/KWH+
Unit 5	1.26 lb/KWH*	1.344 lb/KWH+
Unit 6	1.11 lb/KWH*	0.983 lb/KWH+

RECEPTOR PARAMETERS

The J. M. Stuart receptor locations were measured from a USGS topographical map supplied by the Dayton Power and Light Company. The Muskingum and Philo receptor locations were supplied by the Ohio Power Company. The spatial parameters for these receptors are listed in Table 2.

MEASURED AMBIENT SO_2 CONCENTRATIONS

J. M. Stuart Plant

Ambient concentrations were keypunched from supplied copies of the monitoring station network computer printouts. All the data was readable,

*1973 conversion factors for net generation data.

+1974 conversion factors for gross generation data.

and missing data was entered as "999." Wind data was also included on these printouts. Again, missing data was entered as "999" and wind direction during calms as "888."

<u>Muskingum and Philo Plants</u>

Ambient concentrations were supplied on tape from the Smith-Singer Company for the Muskingum Plant, and purchased on tape from Environmental Research and Technology for the Philo Plant.

SECTION III

DATA REDUCTION METHODS

QUALITY CONTROL IN DATA MANAGEMENT

When keypunching and handling large volumes of data, Quality Control is very important. The data supplied in written form was keypunched with the date and time preceding the measured values. The keypunched cards were verified by re-keying them on a verifying machine or by reading both the original and punched numbers. A computer program then checked for missing hours, cards out of chronological order, input data outside limits, and extreme changes between consecutive data values. The cards were stored on tape with each record prefixed by a plant code to prevent the unlikely mixup of plant tapes. All programs which modify the data have all checking routines to assure that they read the correct data, and the output from each program was spotchecked by manual calculations. Previous experience with similar programs and processing have also contributed to the overall Quality Control.

DATA FLOW AND MODIFICATION

J. M. Stuart Plant

Due to the similarity in stack parameters, the hourly fuel consumption of all three boilers was added together to yield a total hourly consumption. The monthly sulfur content was then multiplied by this con... ...n and a conversion coefficient to yield the hourly sulfur dioxide emission rate from the plant. These data, along with the Cincinnati meteorological data, were used in the Single Source Model to predict hourly SO_2 concentrations. Local SO_2 concentration measurements and on site wind direction data was used to estimate hourly background concentrations. The background was assumed to be the average of those concentrations from stations outside of a 90^o sector centered about the wind flow vector, as measured by the plant wind vane. This average background concentration was subtracted from the concentration measurements for all stations for that hour. Any negative concentration values resulting from the background subtraction were set equal to zero. In the case of missing data or calms, the last recorded wind direction was assumed to persist until a station reported a concentration over 0.1 ppm, in which case the wind was assumed to blow towards that station until a wind direction was recorded or another station reported a concentration over 0.1 ppm. The resultant concentration measurements, corrected for background were then processed by a cumulative frequency program and plotted by computer.

Muskingum Plant

The source data available for the Muskingum Plant existed in a format different from that used for Stuart, in that, instead of hourly coal tonnage figures, only hourly generation figures could be obtained. These hourly load values were then converted to a fuel consumption rate for each boiler by means of a set of conversion constants supplied to us by the utility. Hourly SO_2 emission rates were then obtained from monthly percent sulfur values. Emission rates for boilers 1-4 were combined since they feed into a common stack. Boiler 5 was treated as a separate source. The model application and background subtraction procedures were identical to those used for the Stuart Plant.

Philo Plant

Since all three stacks had different parameters, they were treated as three separate sources. The hourly generated megawatt data was converted to an SO_2 emission rate by the following procedure. A program was written to total the megawatts per year per unit. The tons coal per year per unit figure was divided by the total megawatts per year to find an average conversion coefficient of pounds coal per gross kilowatt. The SO_2 emission rate was this coefficient multiplied by the hourly megawatts and the monthly percent sulfur in the coal.

The plant wind direction data for background subtraction was chosen in the following way. The wind direction was taken from Irish Ridge Upper since it was the highest station. If that data was not recorded it was taken from Irish Ridge Lower and if that data was not recorded it was taken from Duncan Falls. If that data was not recorded it was filled in as '999.' Since the first 100 days were missing they were all listed as '999,' so that the alternate background subtraction technique, described during our discussion of the Stuart Plant data reduction, was employed.

SECTION IV

MODEL VALIDATION PROCEDURE

MODEL DESCRIPTION

The diffusion model used in this validation study was a gaussian type model developed by EPA Division of Meteorology. The code (known as CRSTER) was written to calculate maximum daily concentration of SO_2 for a year, meteorological conditions which can lead to these maxima, and hourly and daily concentrations for an array of receptor locations. These concentrations are written on tape for the 252 receptor positions situated at each of 36 directions from the source and seven different distance ranges (as was the case for the J. M. Stuart Plant). The model can handle from 1 to 19 sources but treats all of them as if they were at the same physical location.

Meteorological input to the model consists of hourly surface observations of wind speed (knots), wind direction sector (1-36), temperature (^{o}F), total cloud cover (tenths), and twice daily mixing depths (meters). The format for most of these data is that used by the National Climatic Center for WBAN-144 hourly surface observations. These data are input into a preprocessor program which in turn writes a tape containing hourly values of stability index, mixing height, temperature, windspeed, flow vector (wind direction plus 180^{o}), and randomized flow vector. The randomized flow vector is equal to the flow vector minus 4 degrees plus a random number between 0 and 9 degrees. The preprocessor output tape is then read by the Single Source Model which performs the actual concentration calculations.

The preprocessor program generates hourly mixing depths from the twice daily mixing depth measurements according to the interpolation scheme for rural areas given in the Single Source Model in the Interim User's Guide.[4] Hourly stabilities are determined according to the system given by Turner[1] employing Pasquill's classification scheme with the addition of a stability class 7 (i.e., G) for which the assumption is made that the plume does not reach the ground. Wind speeds u_o measured at instrument height h_o (7 meters is common for weather stations) are adjusted by means of a stability dependent power law ($u = u_o (h/h_o)^P$) to correspond to values one would expect at the stack height h. Plume rise is calculated on an hourly basis using the method of Briggs.[5] If the plume rise calculation indicates that the plume axis will rise above the mixing layer, then a zero concentration contribution is specified. If the final height plume is below the top of the mixing layer, the presence of the top of the layer is accounted for by the introduction of image plumes[1] to satisfy the zero flux conditions at ground level and at the top of the mixing layer.

Source input to the Single Source Model may possess several degrees of temporal resolution. In the seasonal version of the model an annual average SO_2 source strength is specified along with monthly variation factors. In addition to the seasonal factors, the diurnal version of the model employs hourly emission variation factors for each month of the year. A modification made to the model used in our validation study allowed actual hourly source strengths to be utilized. A second modification made to the model allowed actual receptor elevations to be accounted for.

VALIDATION RESULTS

The model results were plotted by computer with the actual measured concentrations and background subtracted measured concentrations for 1, 3, and 24-hour concentrations. The plots are shown for:

Stuart Plant in Figures 5 through 28
Muskingum Plant in Figures 29 through 43
Philo Plant in Figures 44 through 64.

The ninety-fifth percentile, ninety-ninth percentile, second highest, and highest concentrations were calculated and listed for:

Stuart Plant in Tables 3 through 5
Muskingum Plant in Tables 6 through 8
Philo Plant in Tables 9 through 11.

Average 24-hour concentrations were included in the frequency distributions only if data for each hour was available. In the calculation of running three hour average concentrations, those hours with no concentration measurement were not included in the average, so that for each hour an average was computed unless data for that hour and the two preceding hours was missing.

Stuart Plant Validation Results

The most striking feature of the comparison between frequency distributions of measured and calculated SO_2 concentrations is the rather poor agreement for low concentrations. This discrepancy is due primarily to errors associated with the background subtraction technique which does not provide for spatial variation in hourly background concentration. For the high concentration end of the frequency distribution, the model came much closer to predicting the actual 1-hour concentrations than the 3-hour and 24-hour concentrations. It overpredicted for three stations, underpredicted for three stations, came very close at one station, and came very close to predicting the combined data from all stations. Over- or underpredicting does not seem to be correlated with station elevation or direction, though there is some correlation with distance as seen in Table 13. Overpredicted stations are over 5 km from the plant and

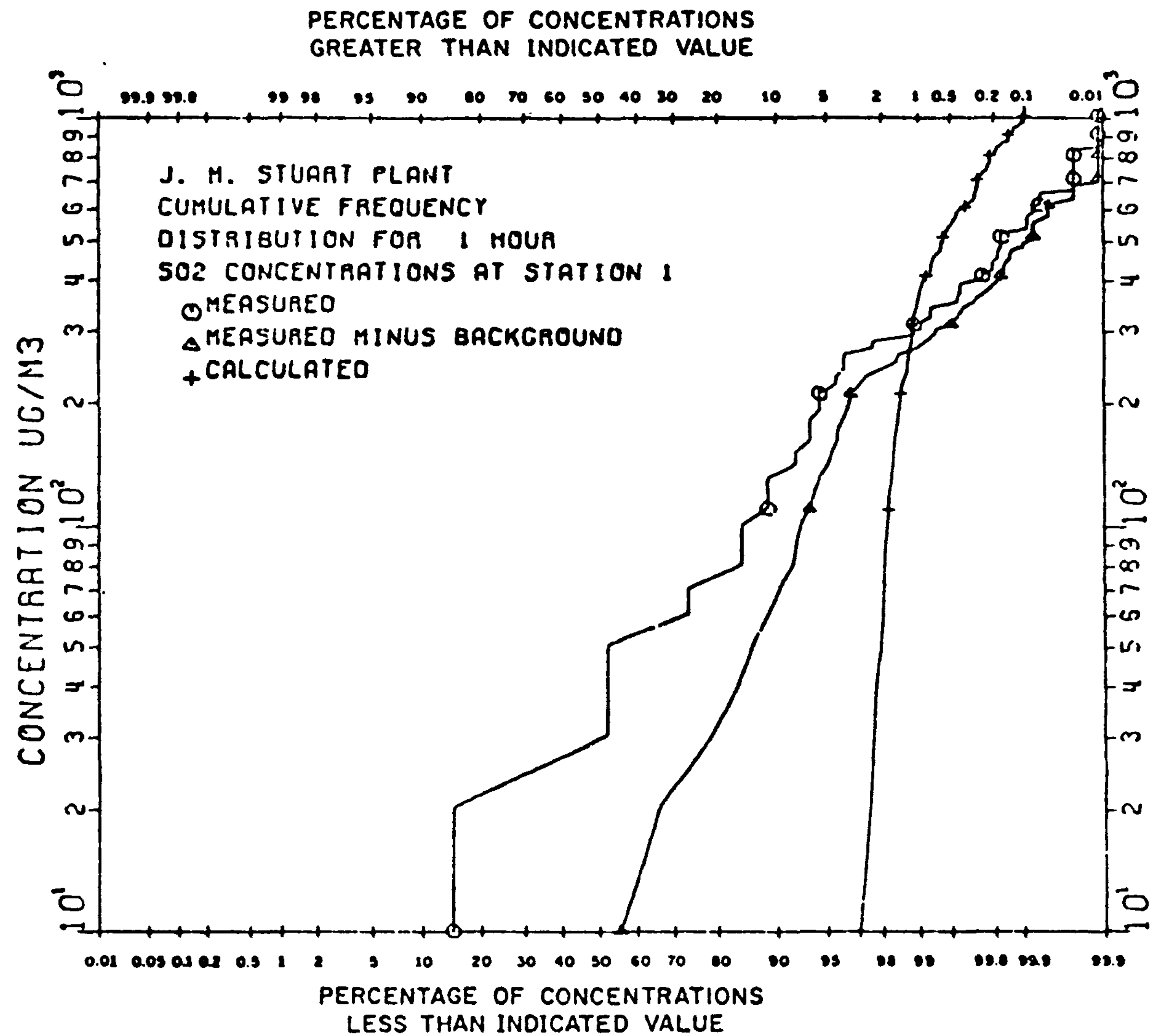

Figure 5. J. M. Stuart plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 1. Number of measured concentrations = 8173; number of calculated concentrations = 8760

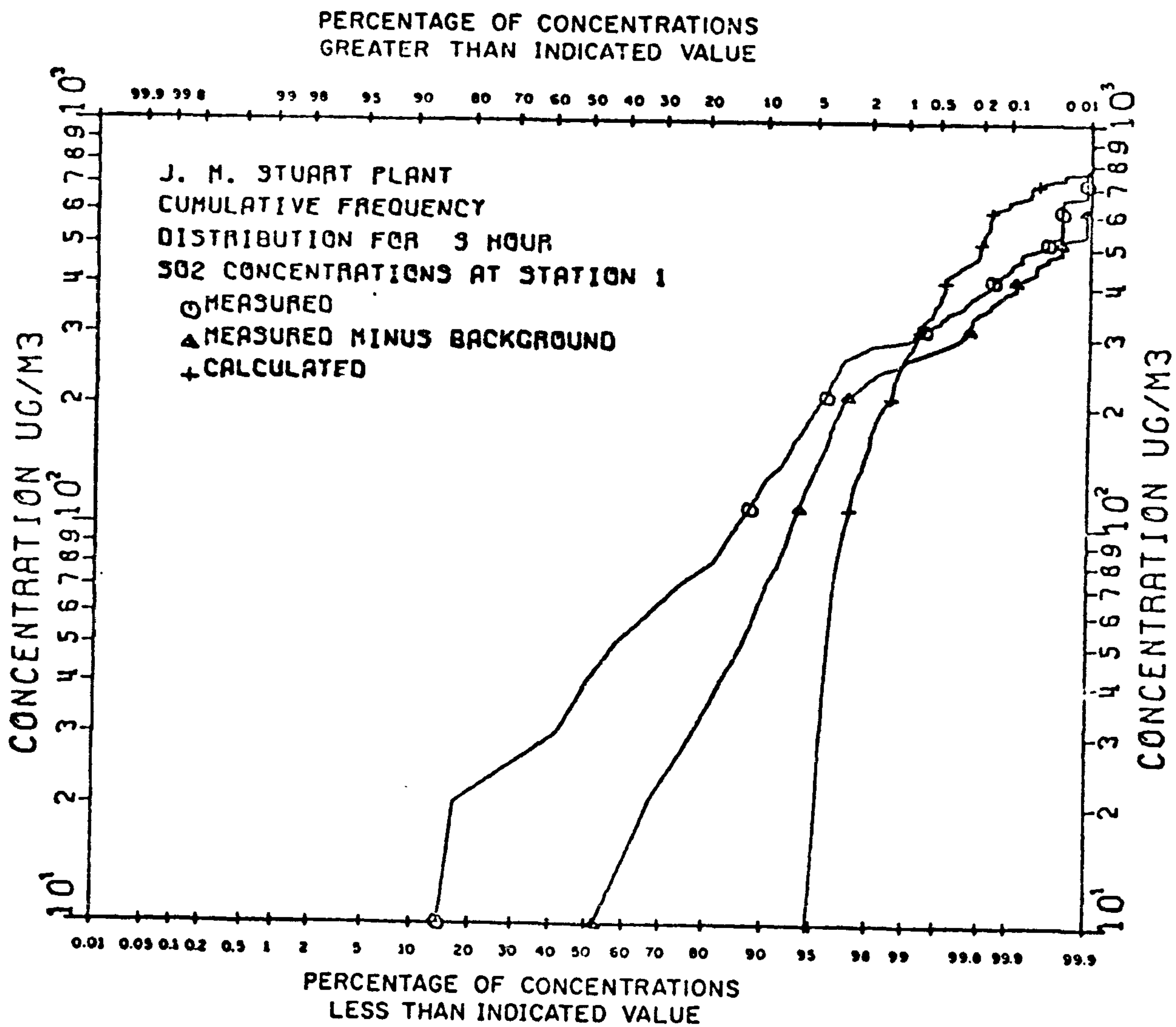

Figure 6. J. M. Stuart plant cumulative frequency distribution for 3-hour SO_2 concentrations at station 1. Number of measured concentrations = 8300; number of calculated concentrations = 8760

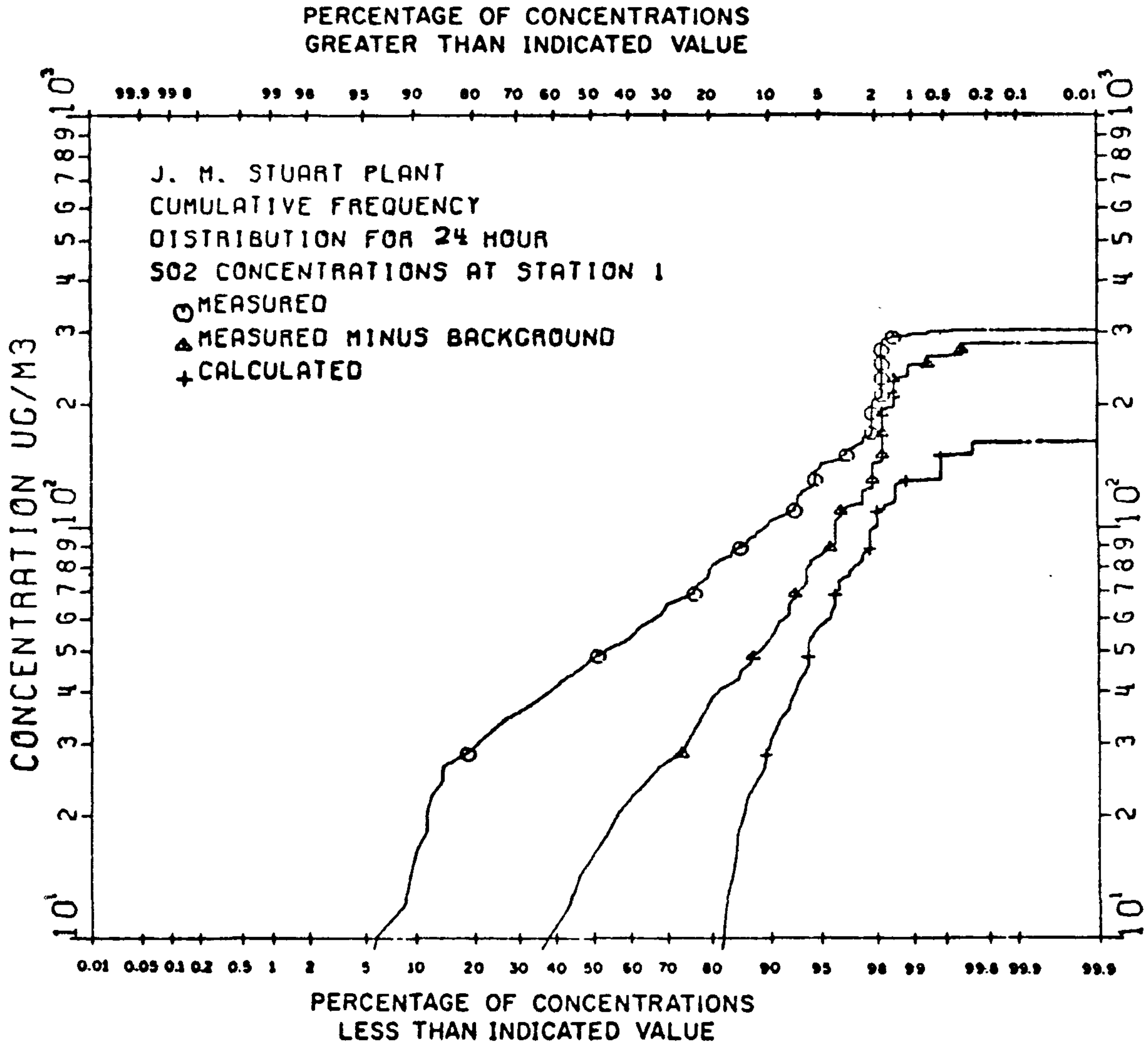

Figure 7. J. M. Stuart plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 1. Number of measured concentrations = 288; number of calculated concentrations = 365

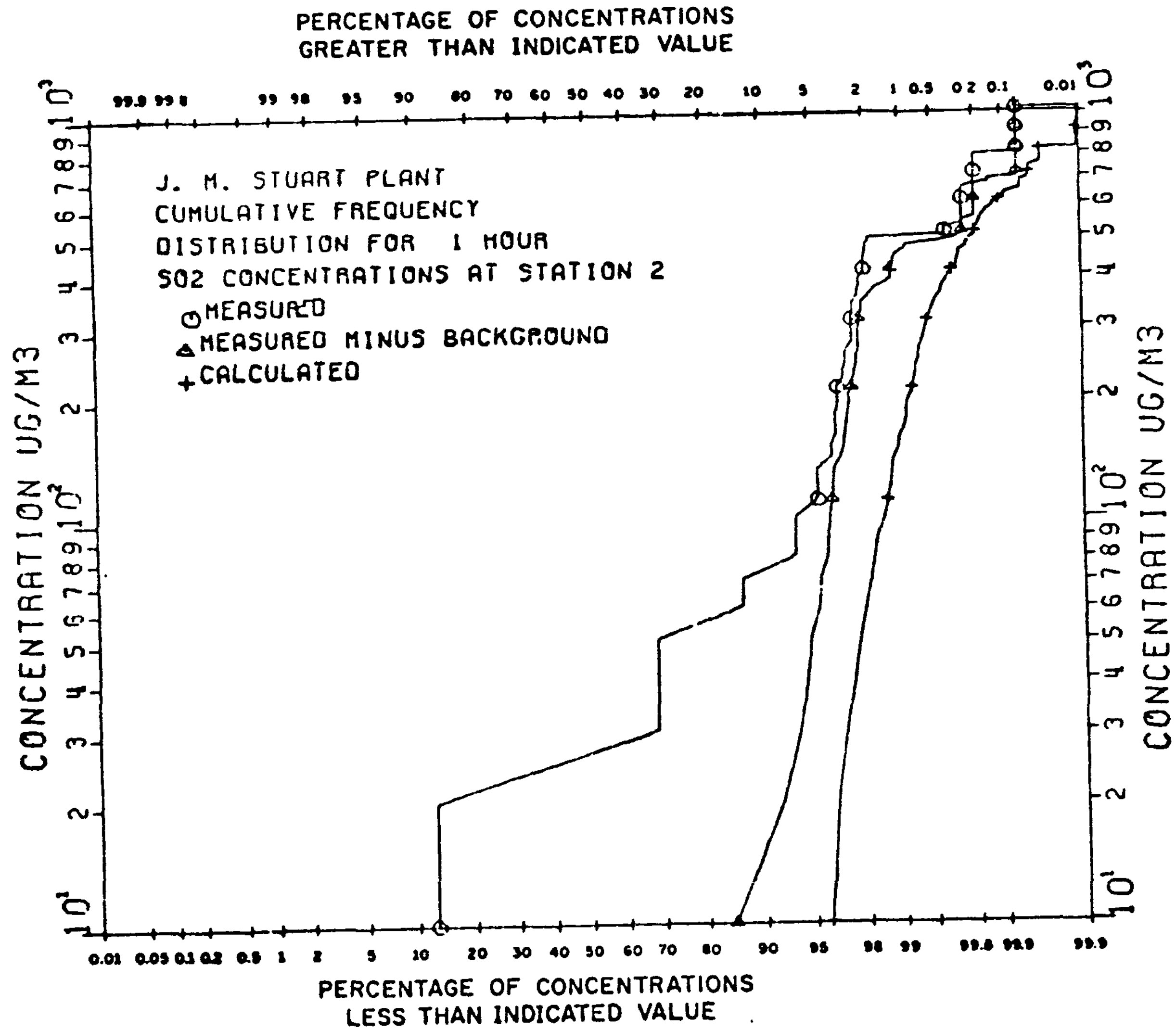

Figure 8. J. M. Stuart plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 2. Number of measured concentrations = 1628; number of calculated concentrations = 8760

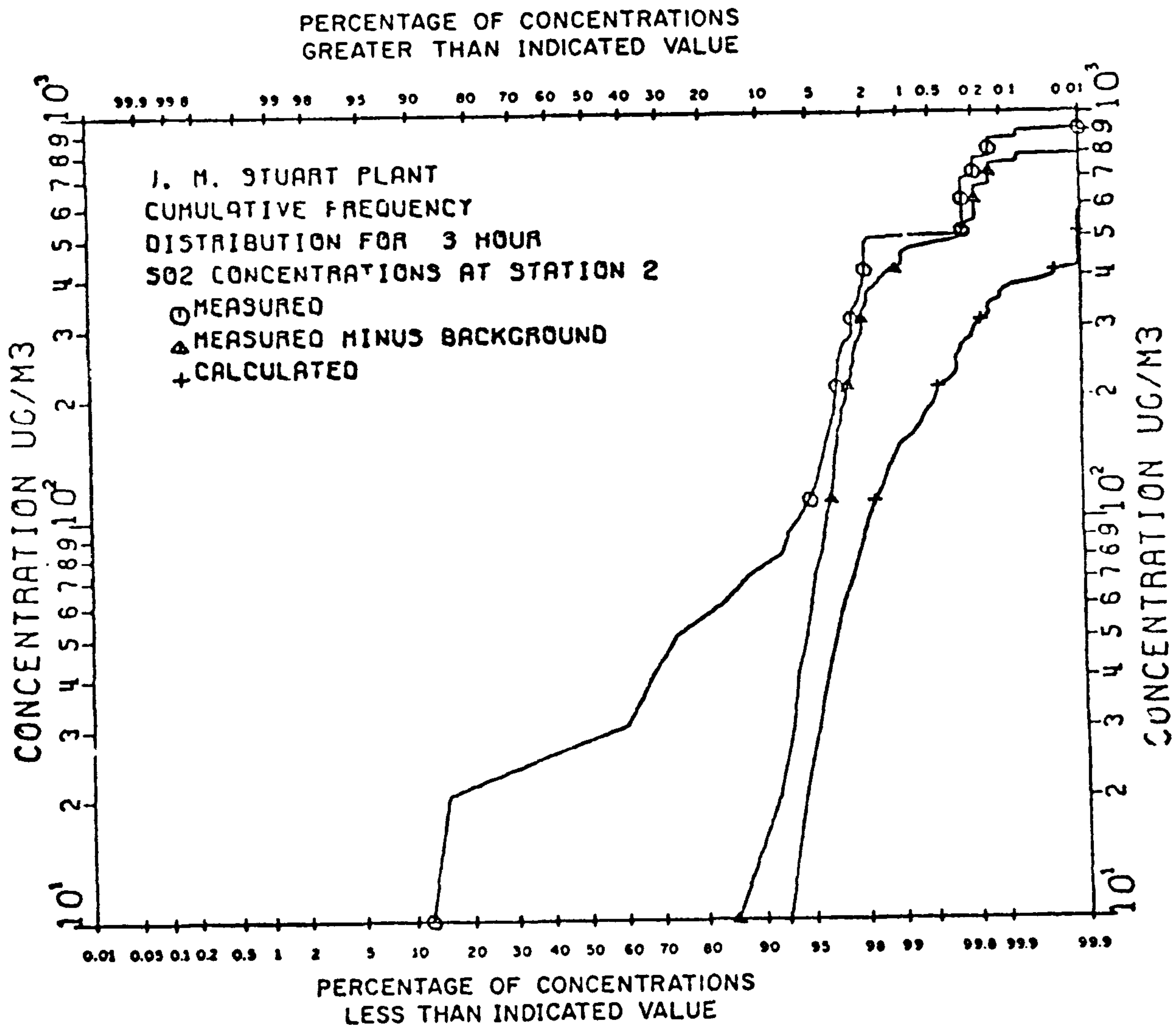

Figure 9. J. M. Stuart plant cumulative frequency distribution for 3-hour SO_2 concentrations at station 2. Number of measured concentrations = 1650; number of calculated concentrations = 8760

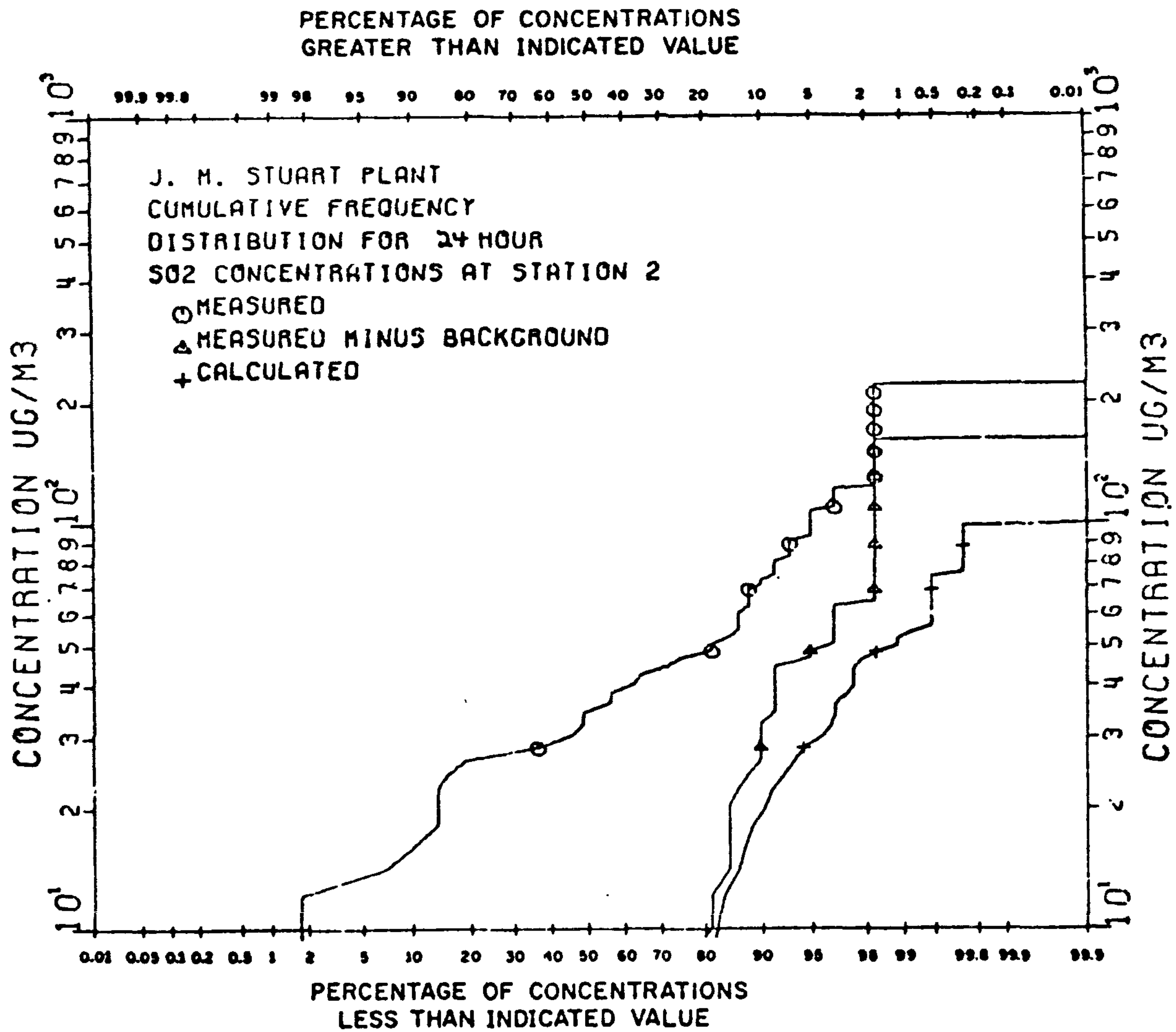

Figure 10. J. M. Stuart plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 2. Number of measured concentrations = 60; number of calculated concentrations = 365

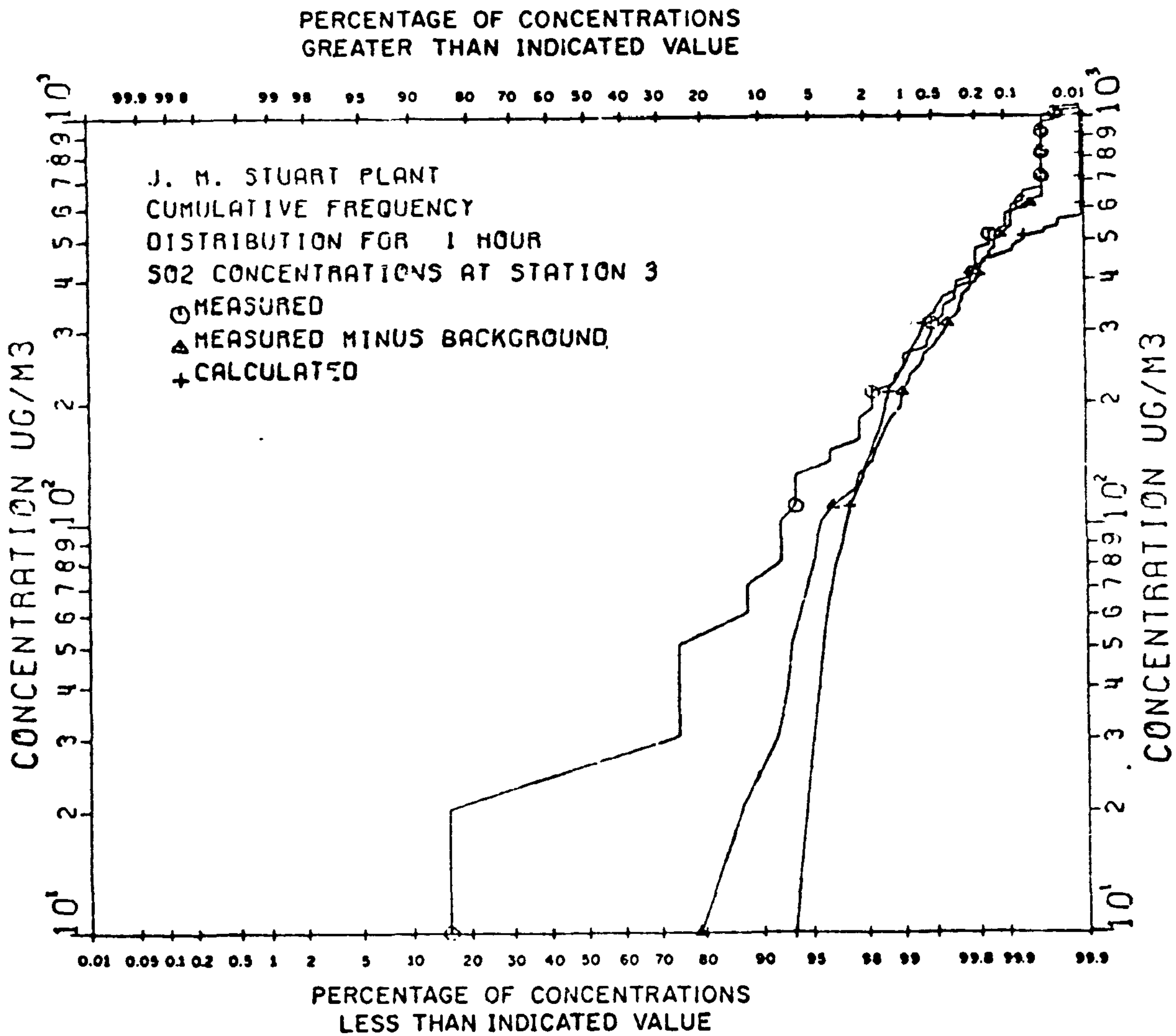

Figure 11. J. M. Stuart plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 3. Number of measured concentrations = 8444; number of calculated concentrations = 8760

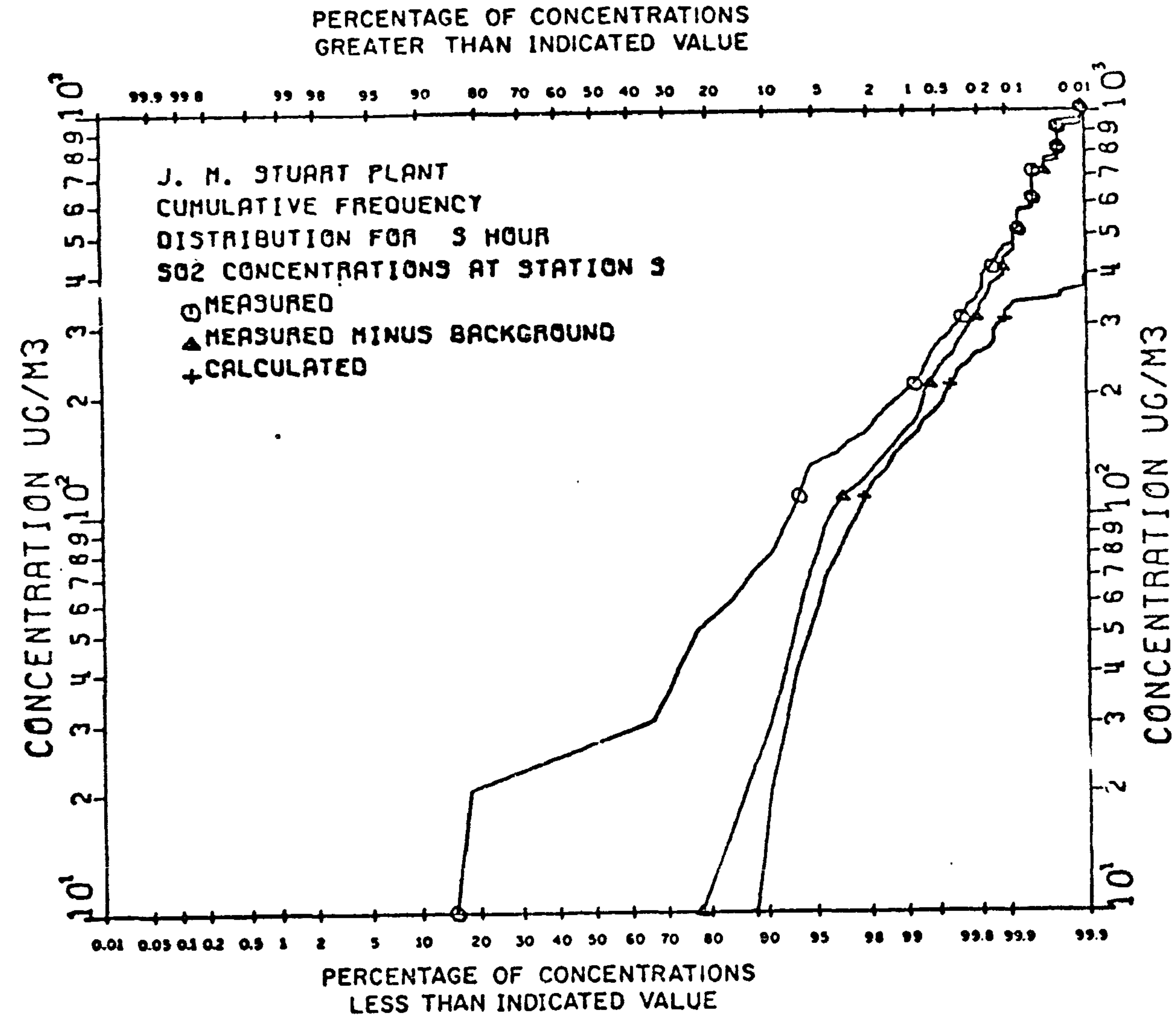

Figure 12. J. M. Stuart plant cumulative frequency distribution for 3-hour SO_2 concentrations at station 3. Number of measured concentrations = 8561; number ofcalculated concentrations = 8760

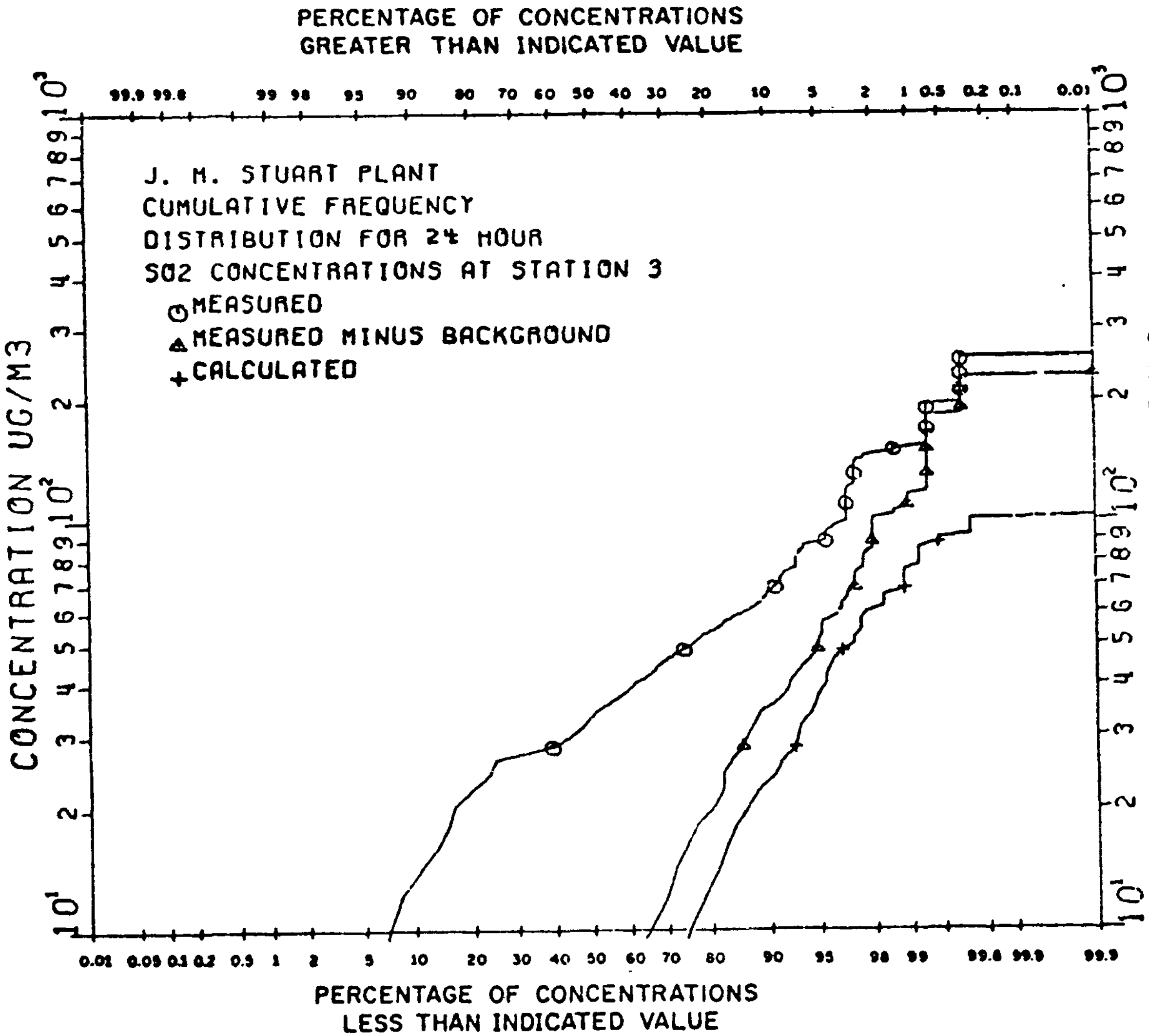

Figure 13. J. M. Stuart plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 3. Number of measured concentrations = 300; number of calculated concentrations = 365

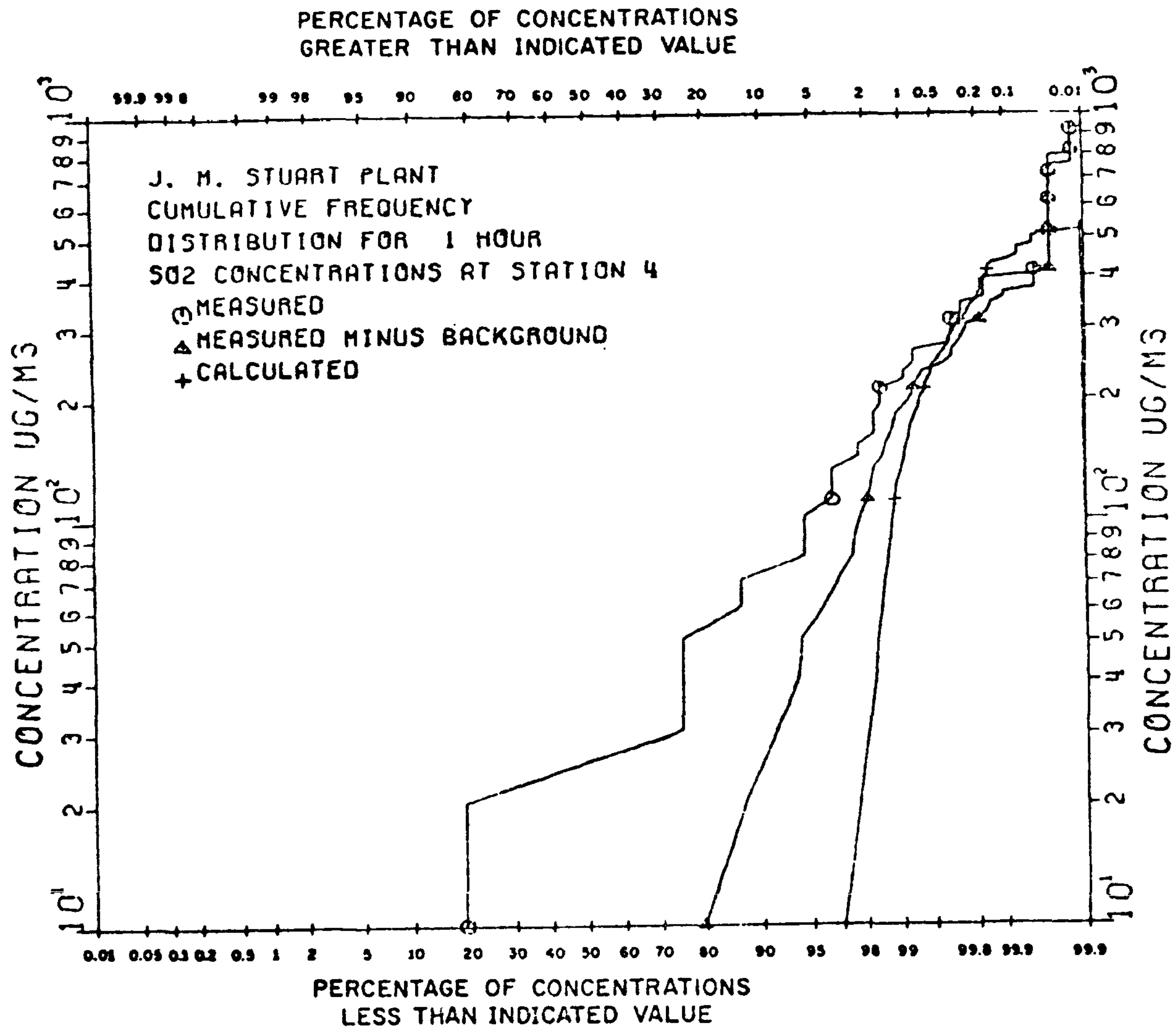

Figure 14. J. M. Stuart plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 4. Number of measured concentrations = 6929; number of calculated concentrations = 8760

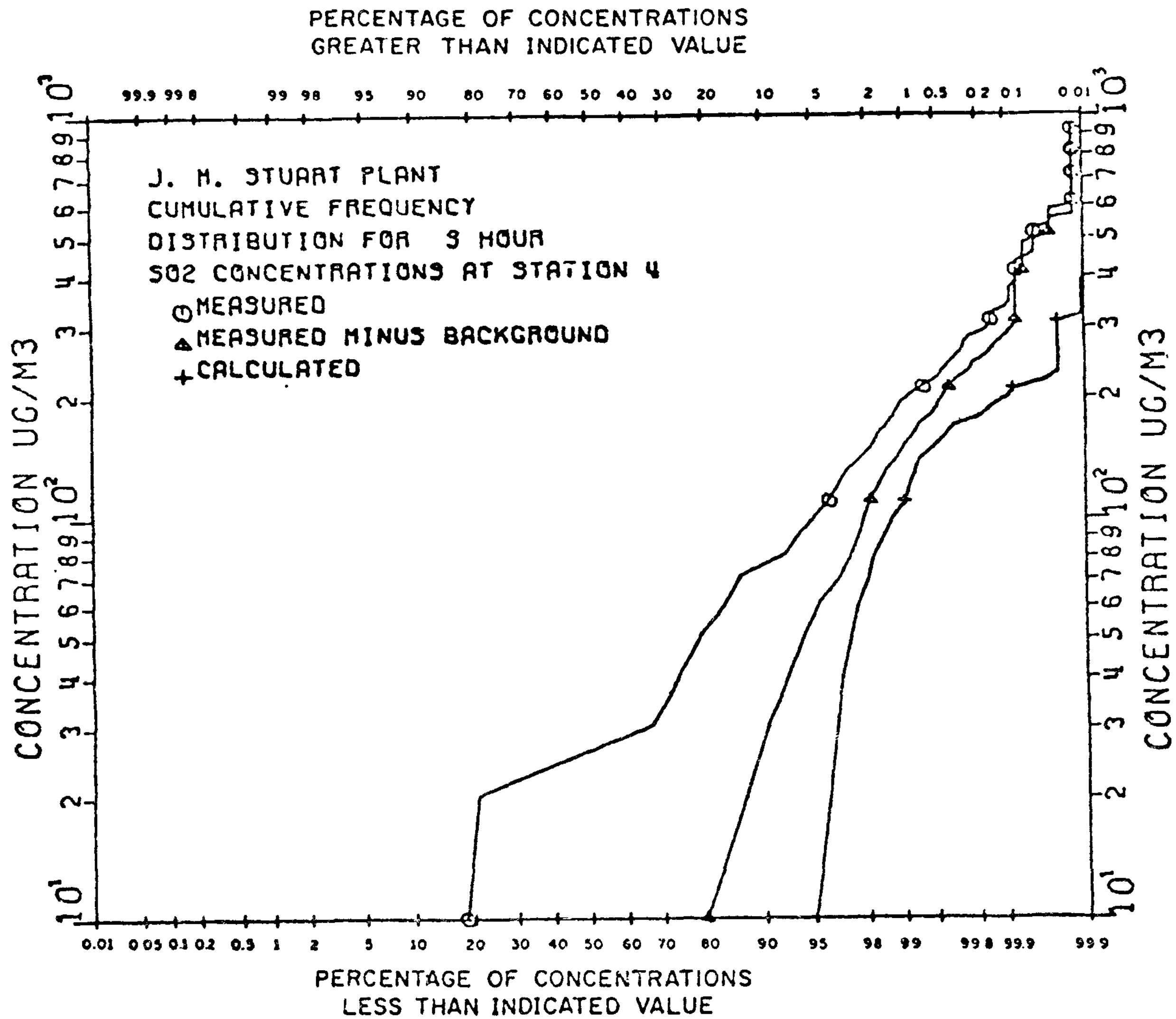

Figure 15. J. M. Stuart plant cumulative frequency distribution for 3-hour SO_2 concentrations at station 4. Number of measured concentrations = 6935; number of calculated conce..trations = 8760

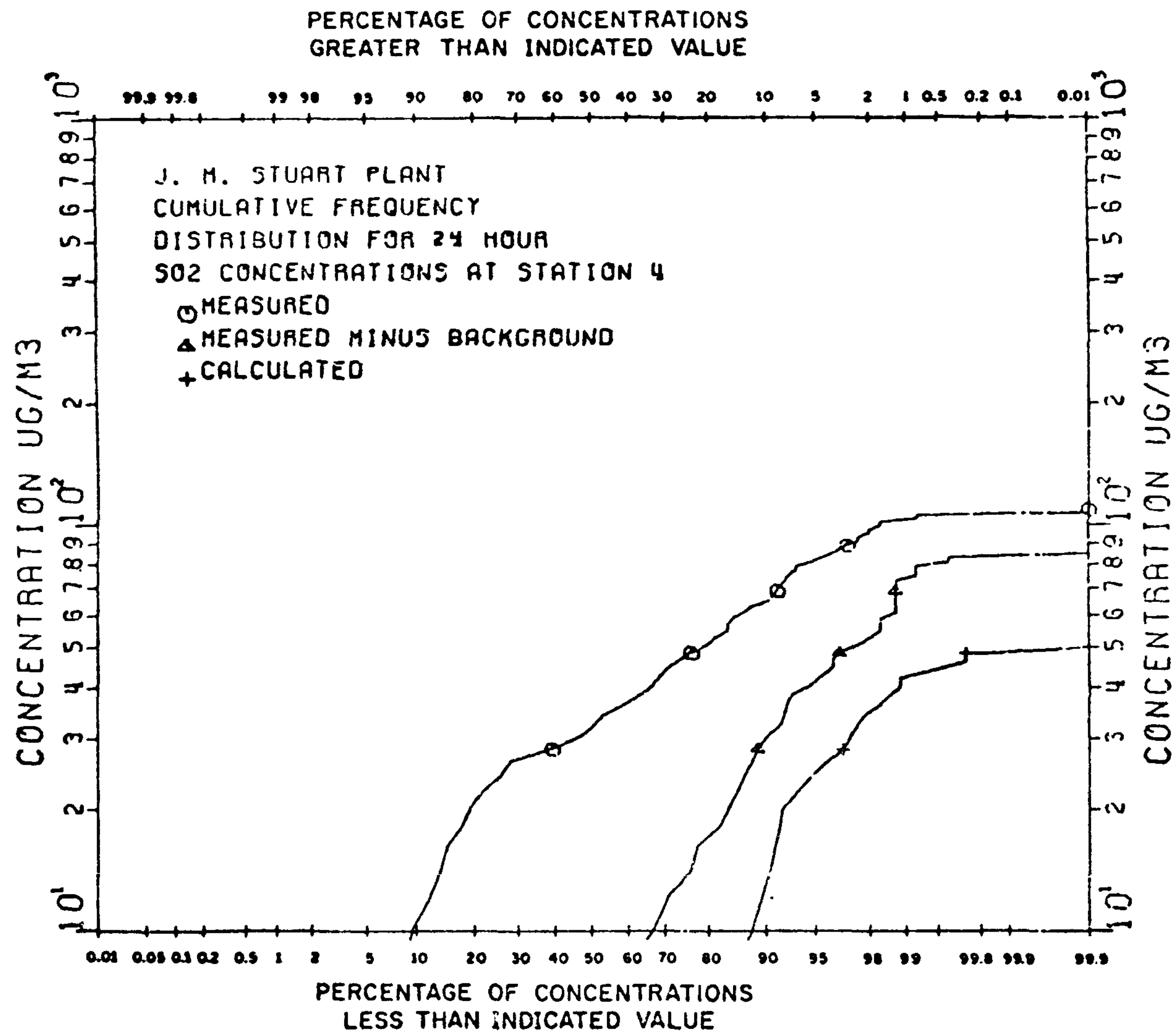

Figure 16. J. M. Stuart plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 4. Number of measured concentrations = 250; number of calculated concentrations = 365

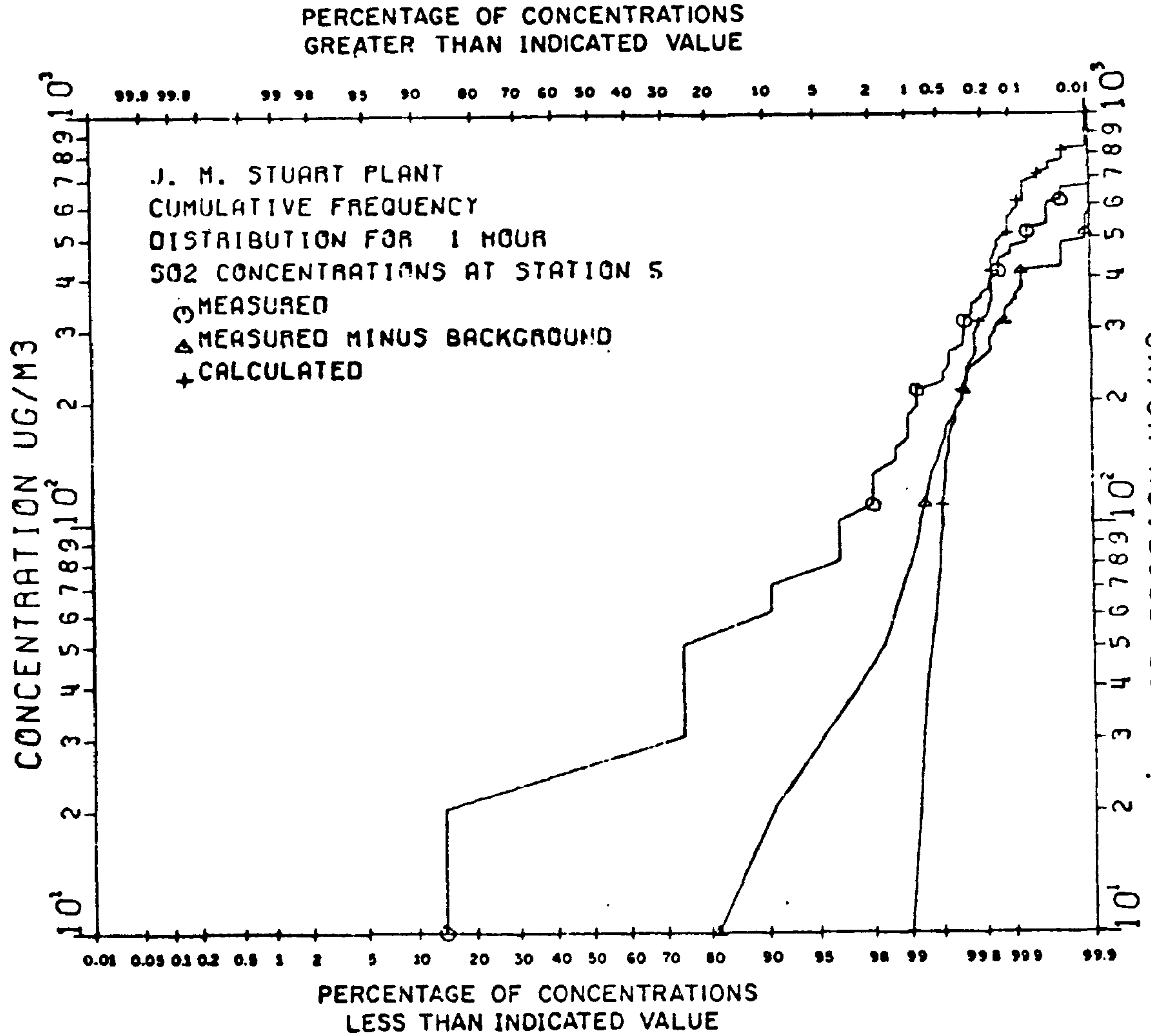

Figure 17. J. M. Stuart plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 5. Number of measured concentrations = 8289; number of calculated concentrations = 8760

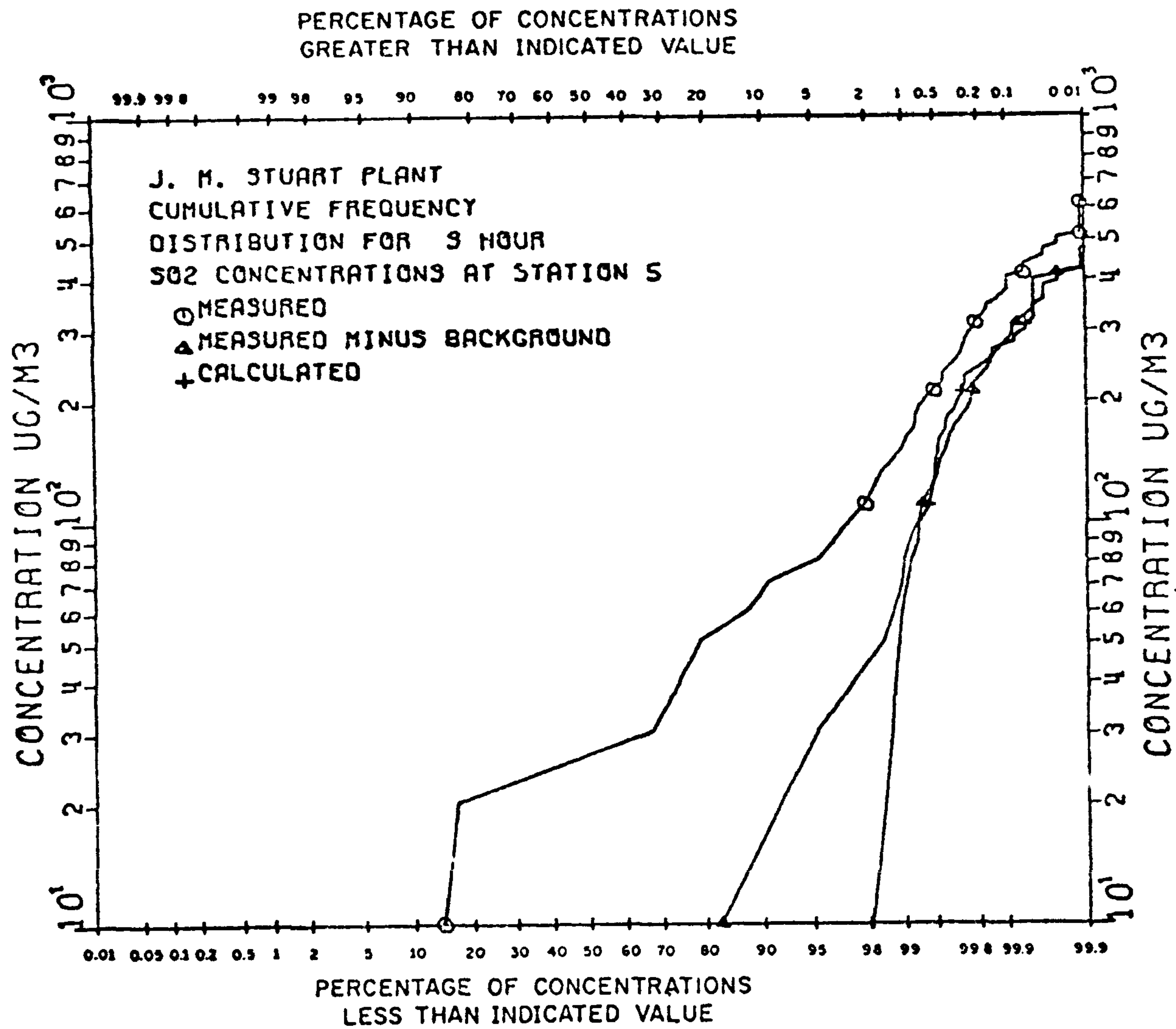

Figure 18. J. M. Stuart plant cumulative frequency distribution for 3-hour SO_2 concentrations at station 5. Number of measured concentrations = 8403; number of calculated concentrations = 8760

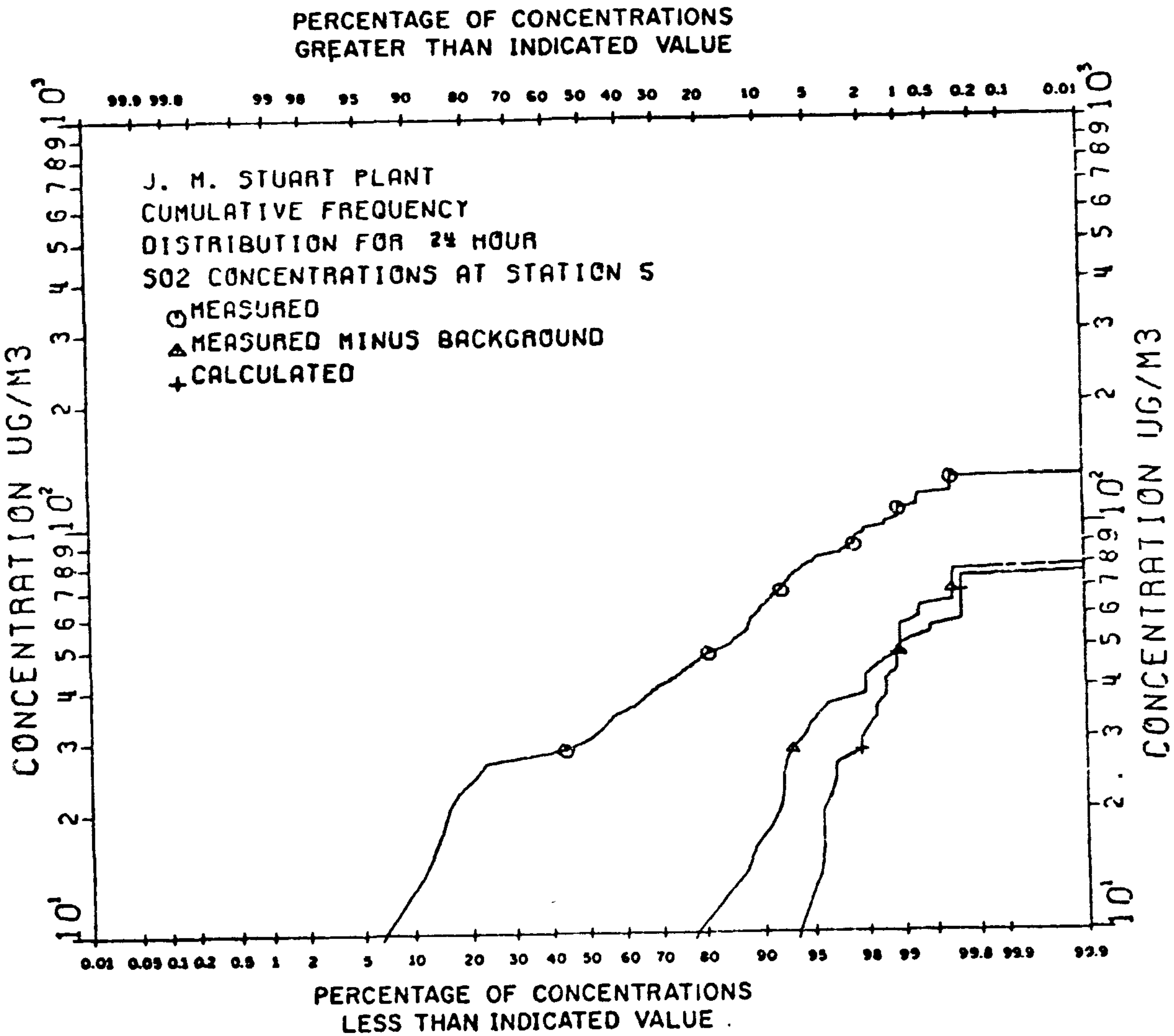

Figure 19. J. M. Stuart plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 5. Number of measured concentrations = 295; number of calculated concentrations = 365

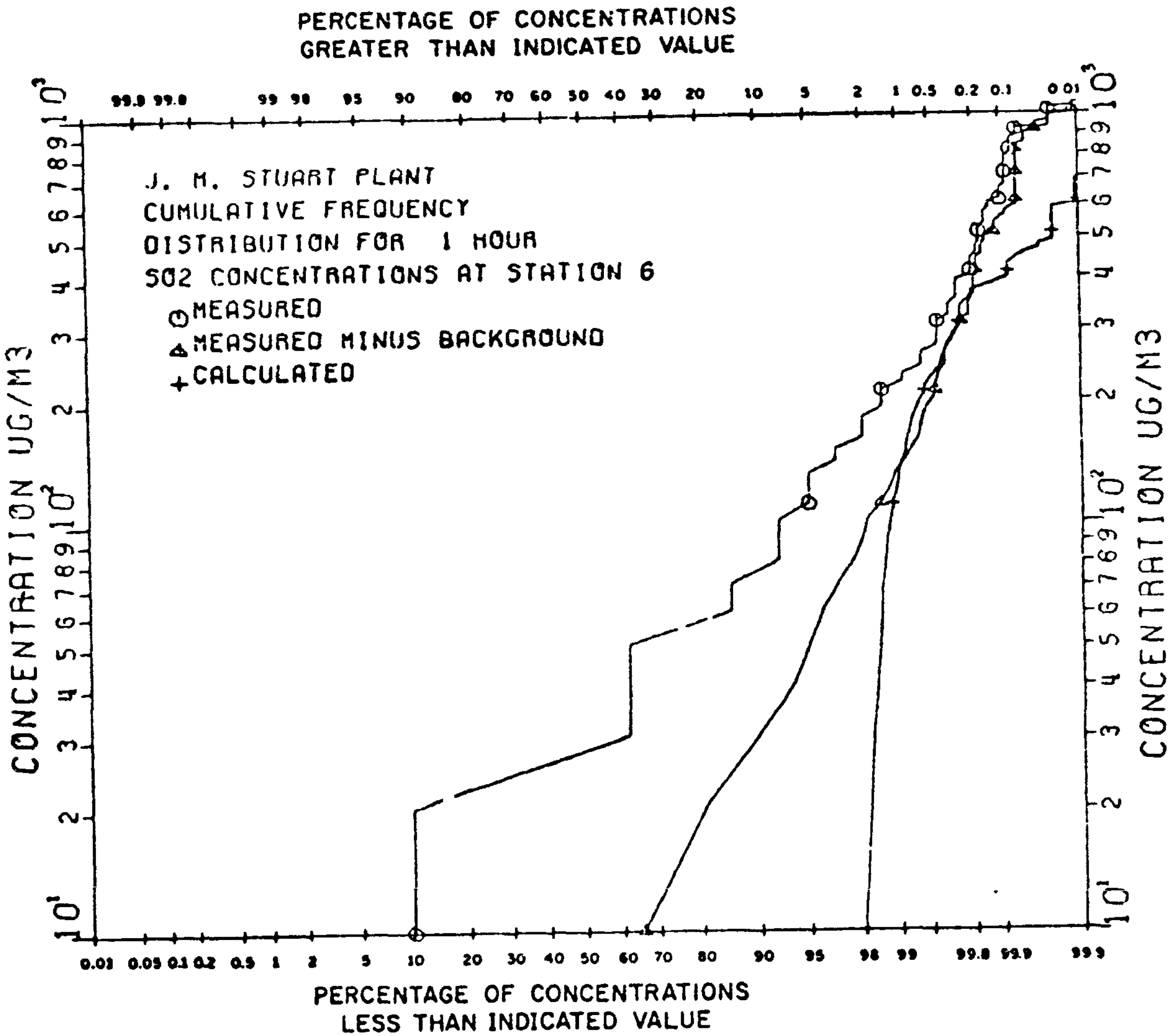

Figure 20. J. M. Stuart plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 6. Number of measured concentrations = 8334; number of calculated concentrations = 8760

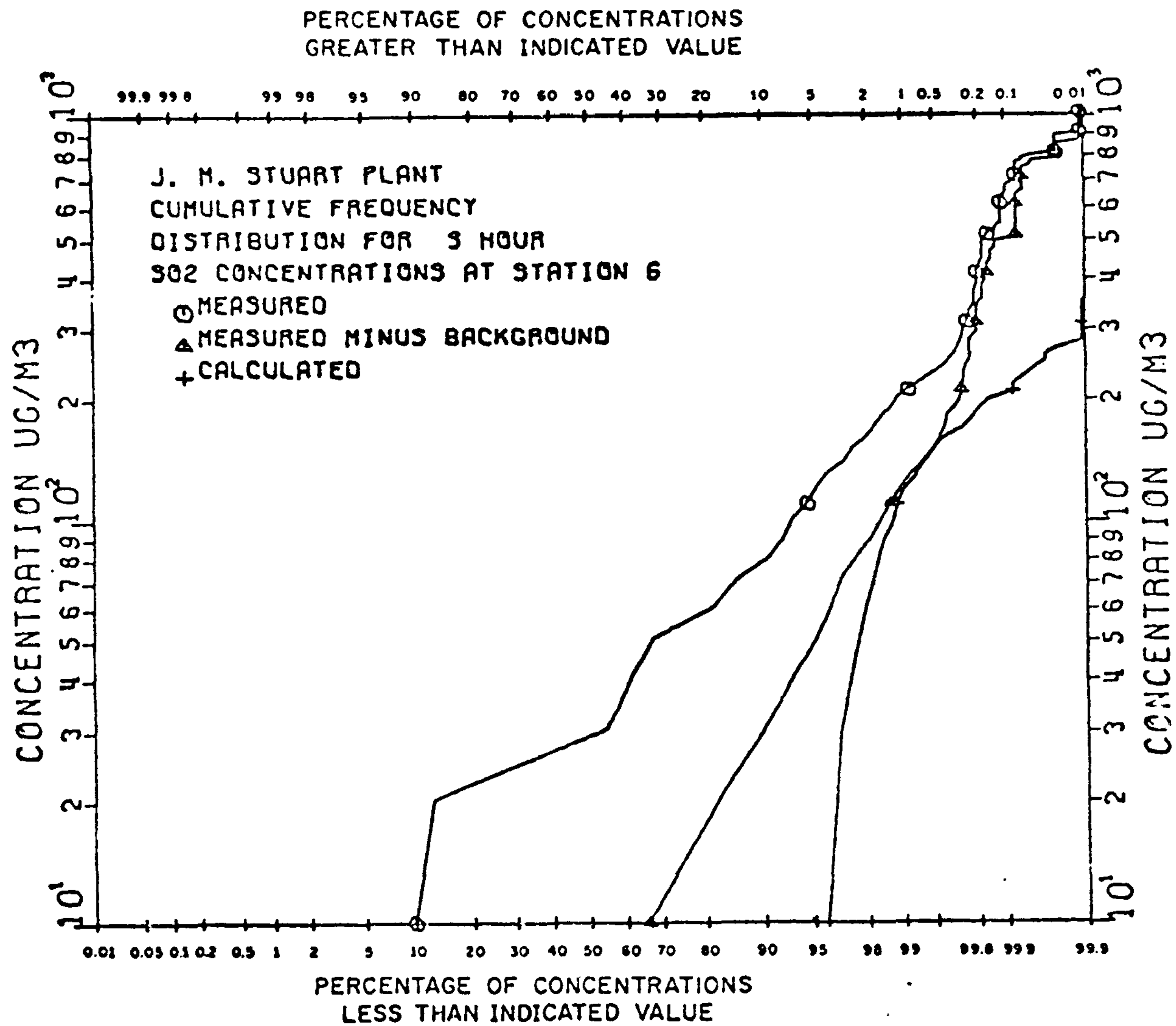

Figure 21. J. M. Stuart plant cumulative frequency distribution for 3-hour SO_2 concentrations at station 6. Number of measured concentrations = 8403; number of calculated concentrations = 8760

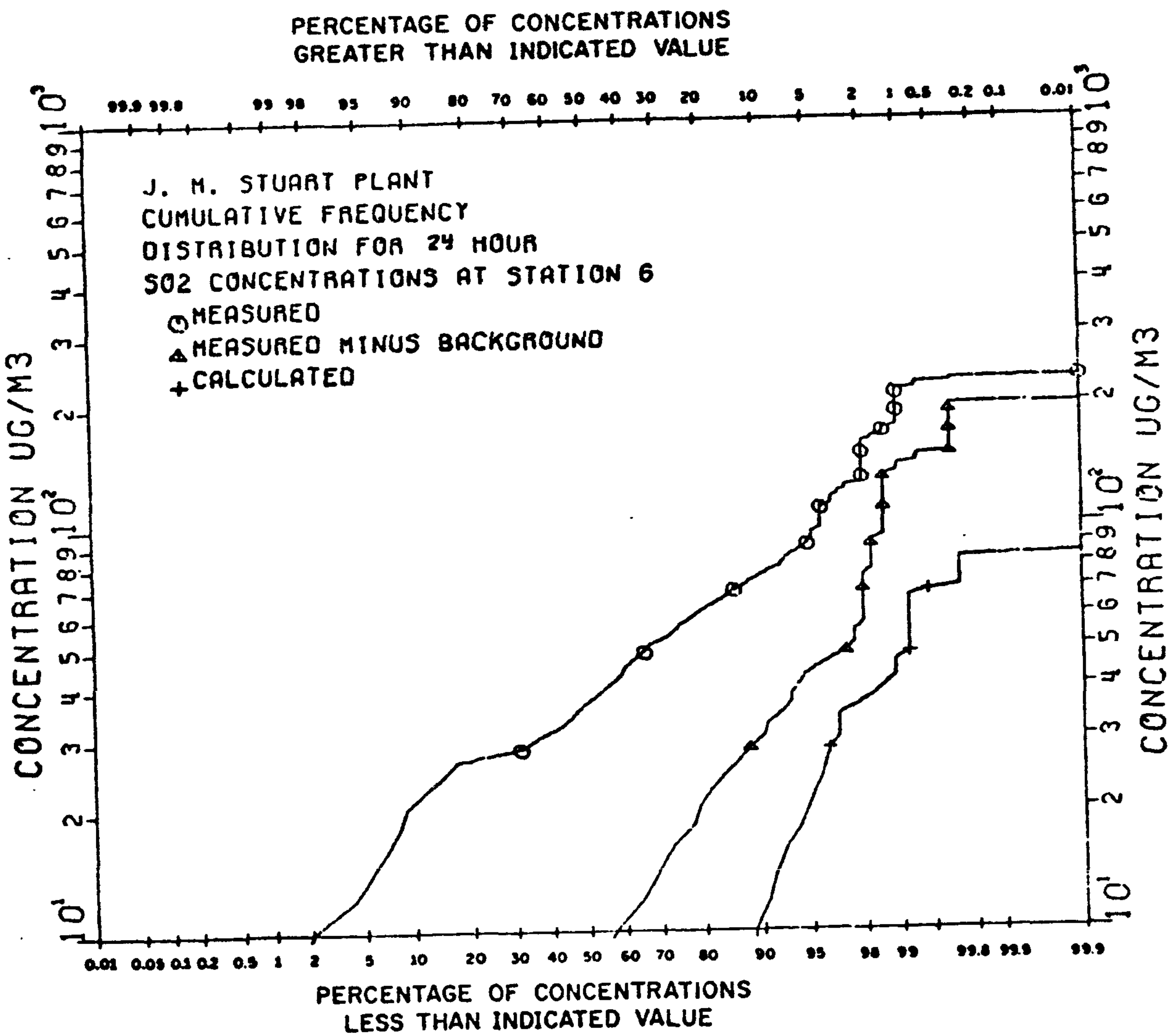

Figure 22. J. M. Stuart plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 6. Number of measured concentrations = 300; number of calculated concentrations = 365

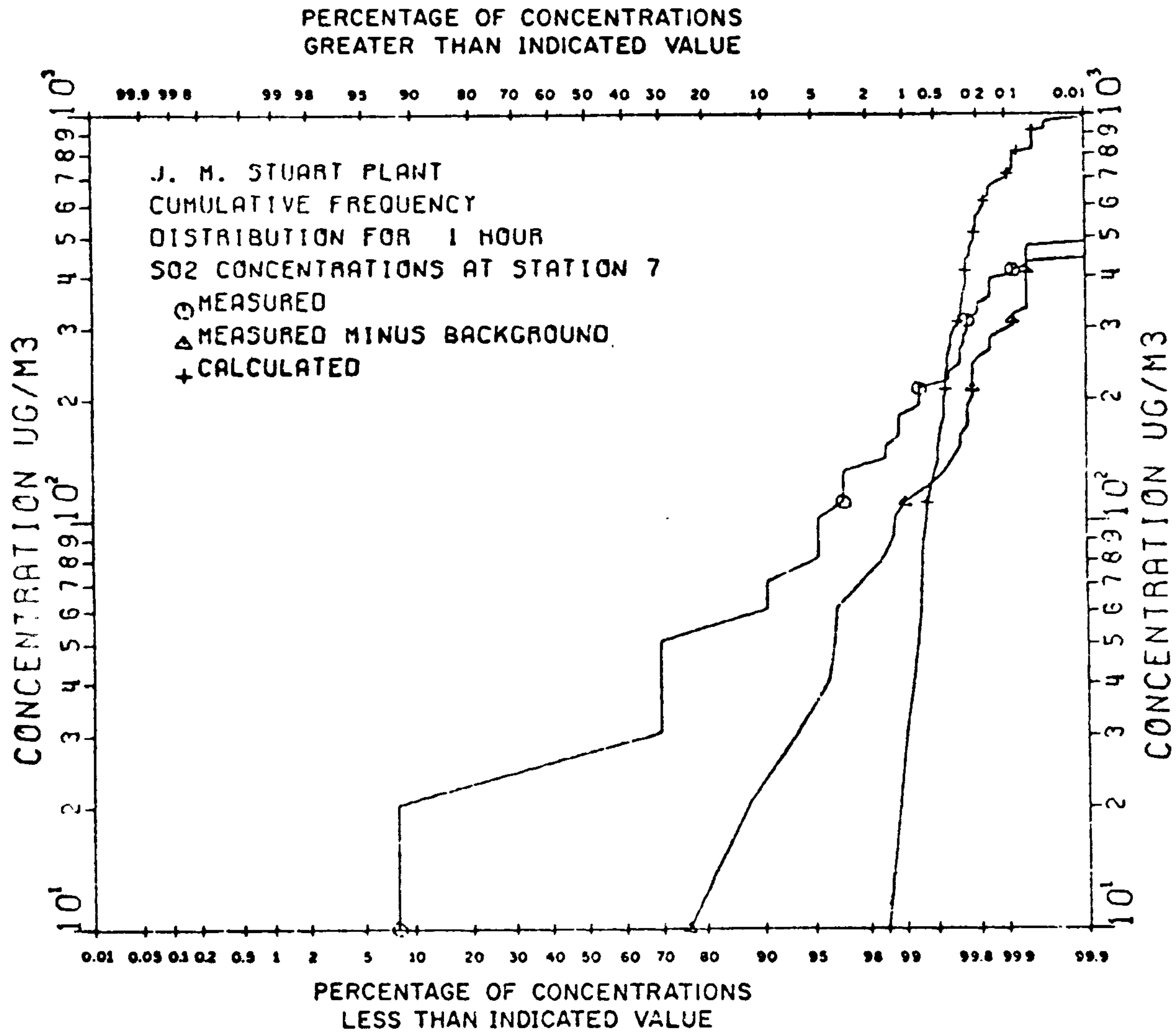

Figure 23. J. M. Stuart plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 7. Number of measured concentrations = 3715; number of calculated concentrations = 8760

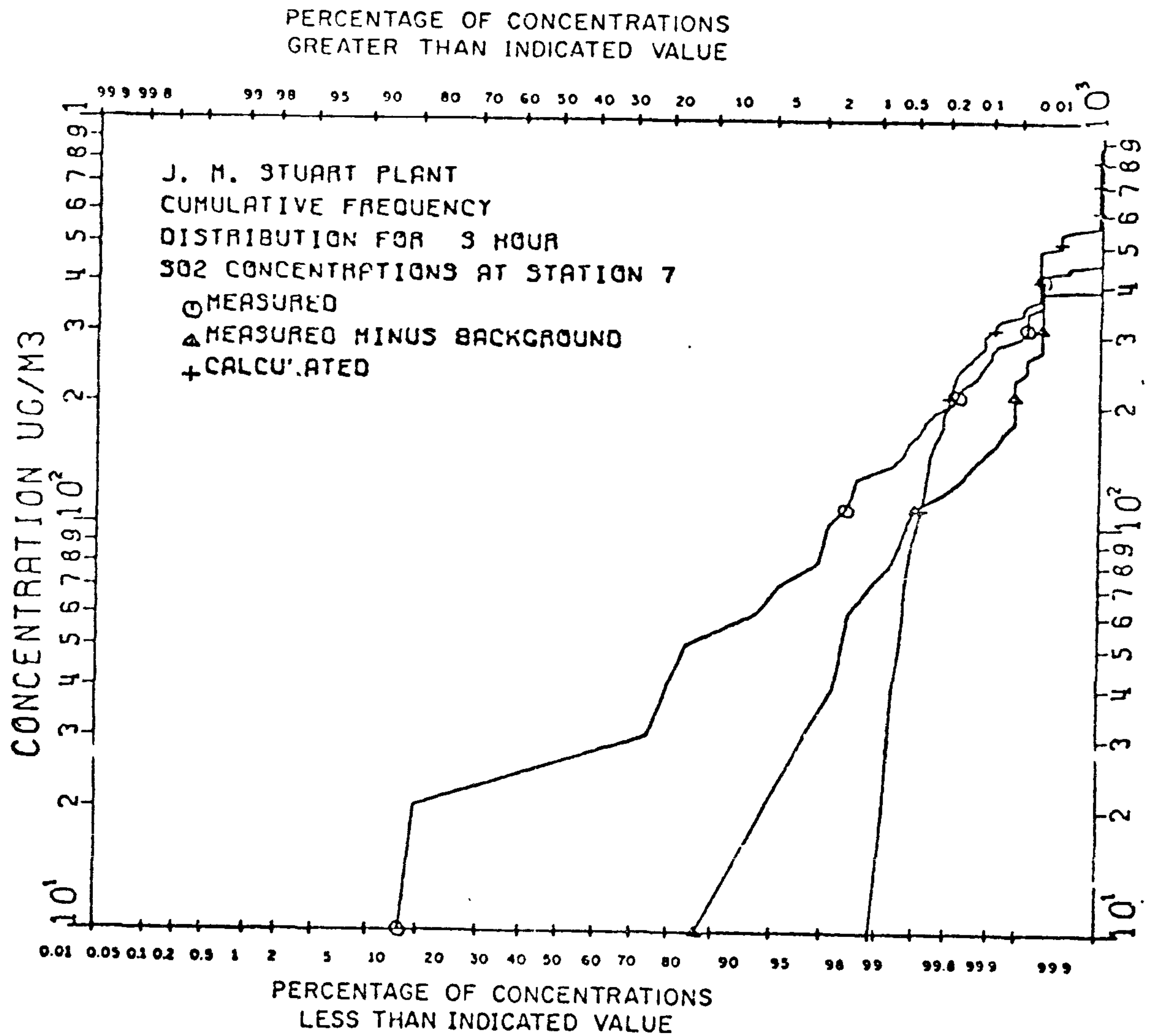

Figure 24. J. M. Stuart plant cumulative frequency distribution for 3-hour SO_2 concentrations at station 7. Number of measured concentrations = 3779; number ofcalculated concentrations = 8760

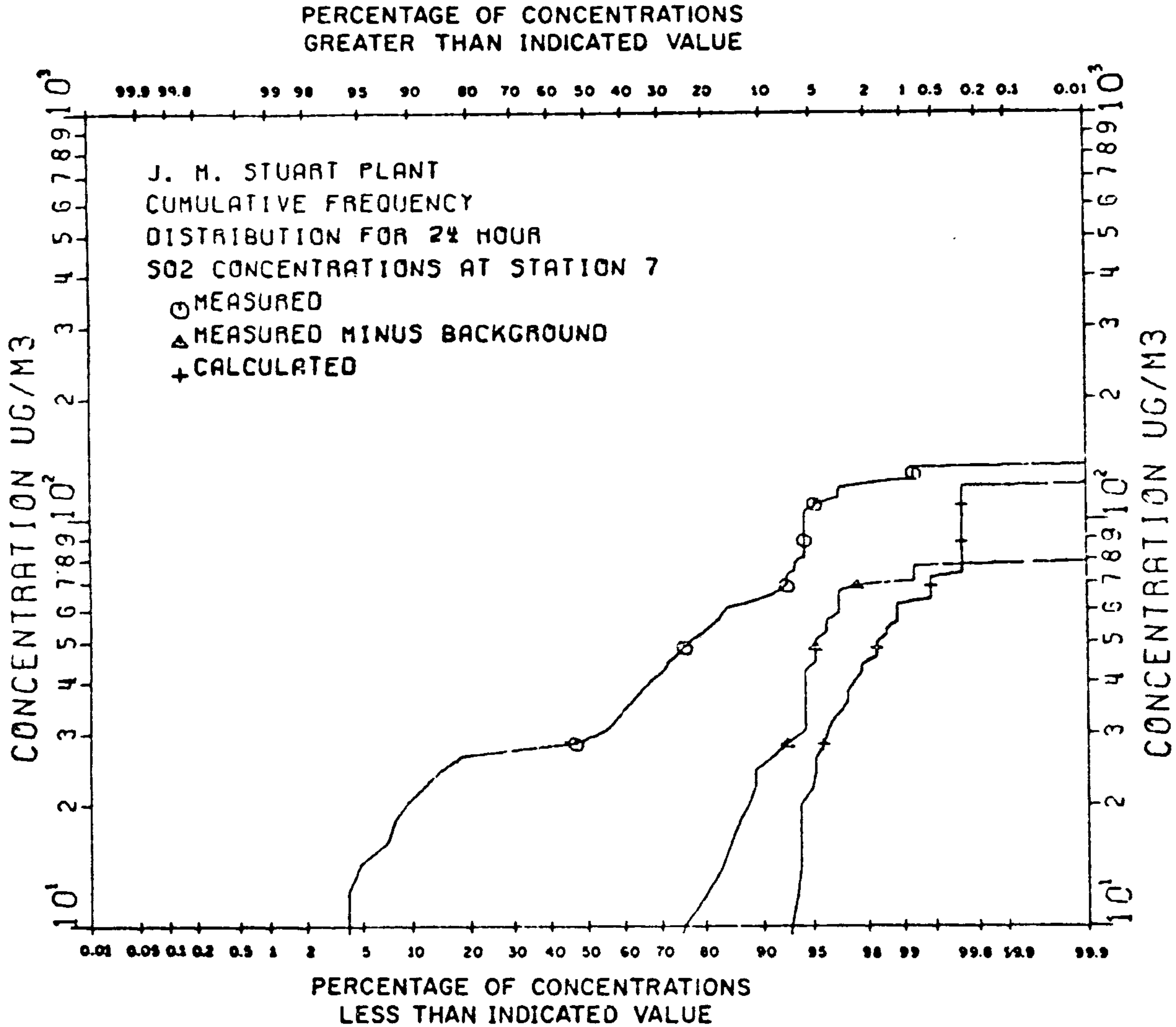

Figure 25. J. M. Stuart plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 7. Number of measured concentrations = 130; number of calculated concentrations = 365

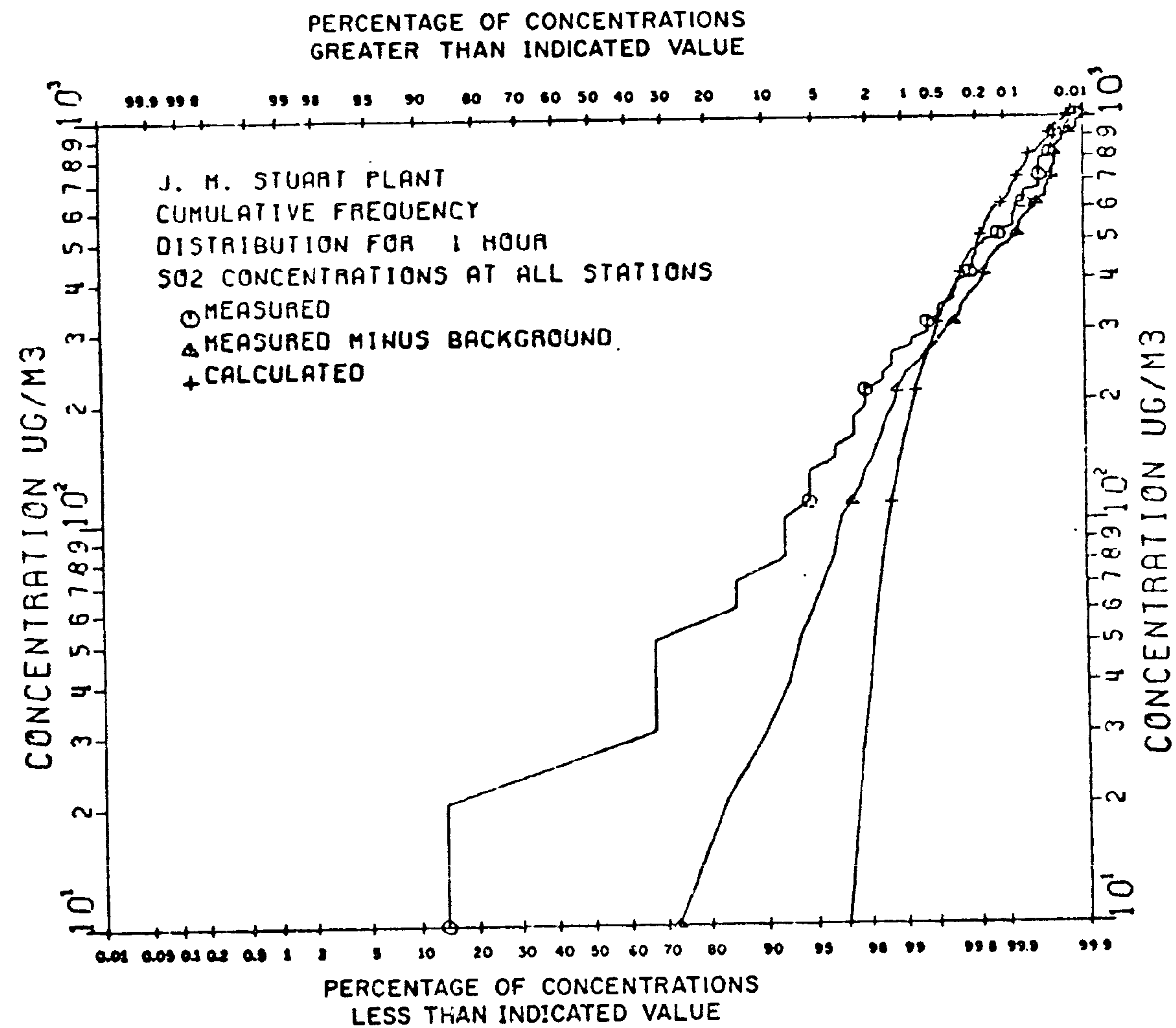

Figure 26. J. M. Stuart plant cumulative frequency distribution for 1-hour SO_2 concentrations at all stations. Number of measured concentrations = 45,512; number of calculated concentrations = 61,320

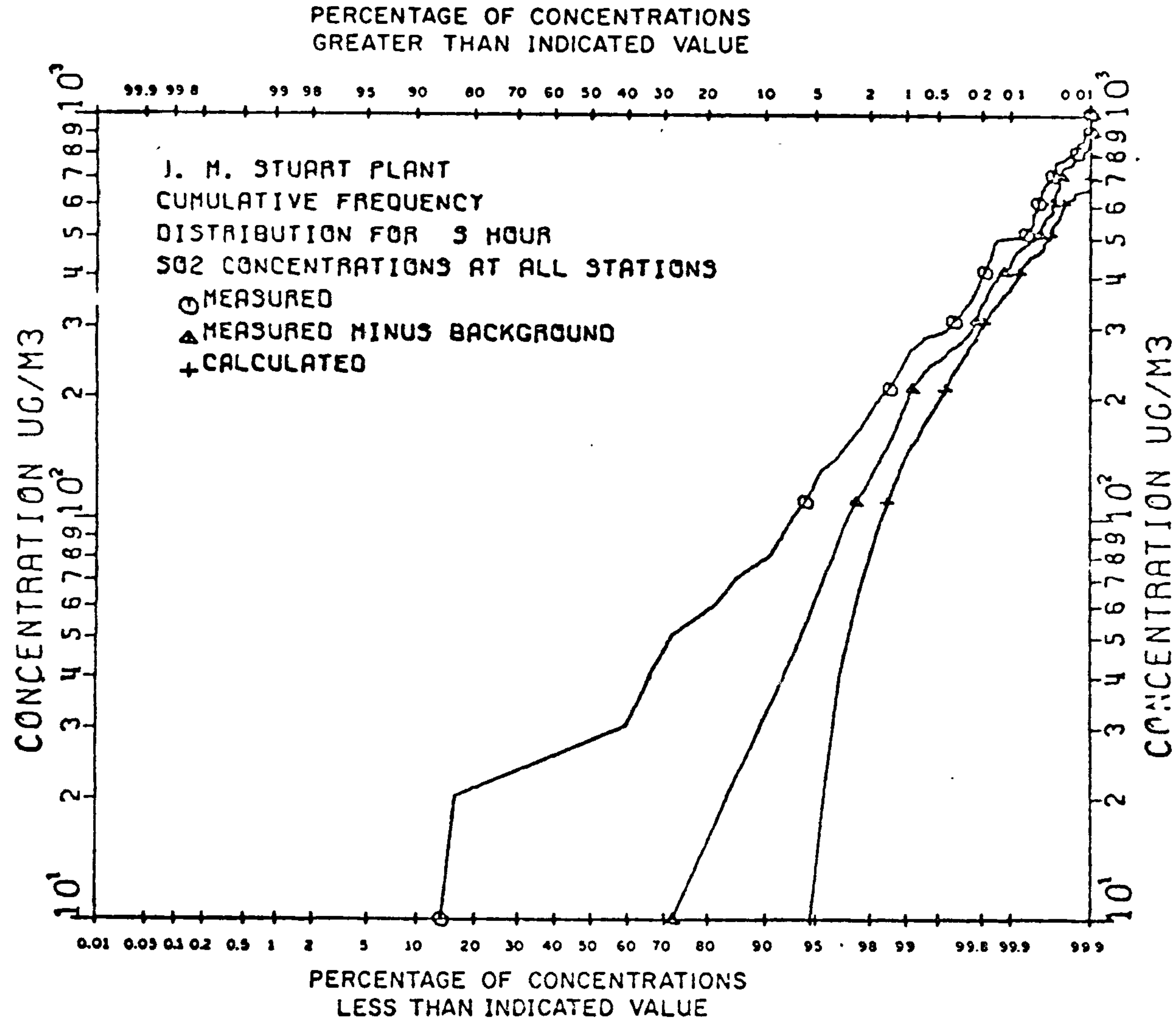

Figure 27. J. M. Stuart plant cumulative frequency distribution for 3-hour SO_2 concentrations at all stations. Number of measured concentrations = 46,065; number of calculated concentrations = 61,320

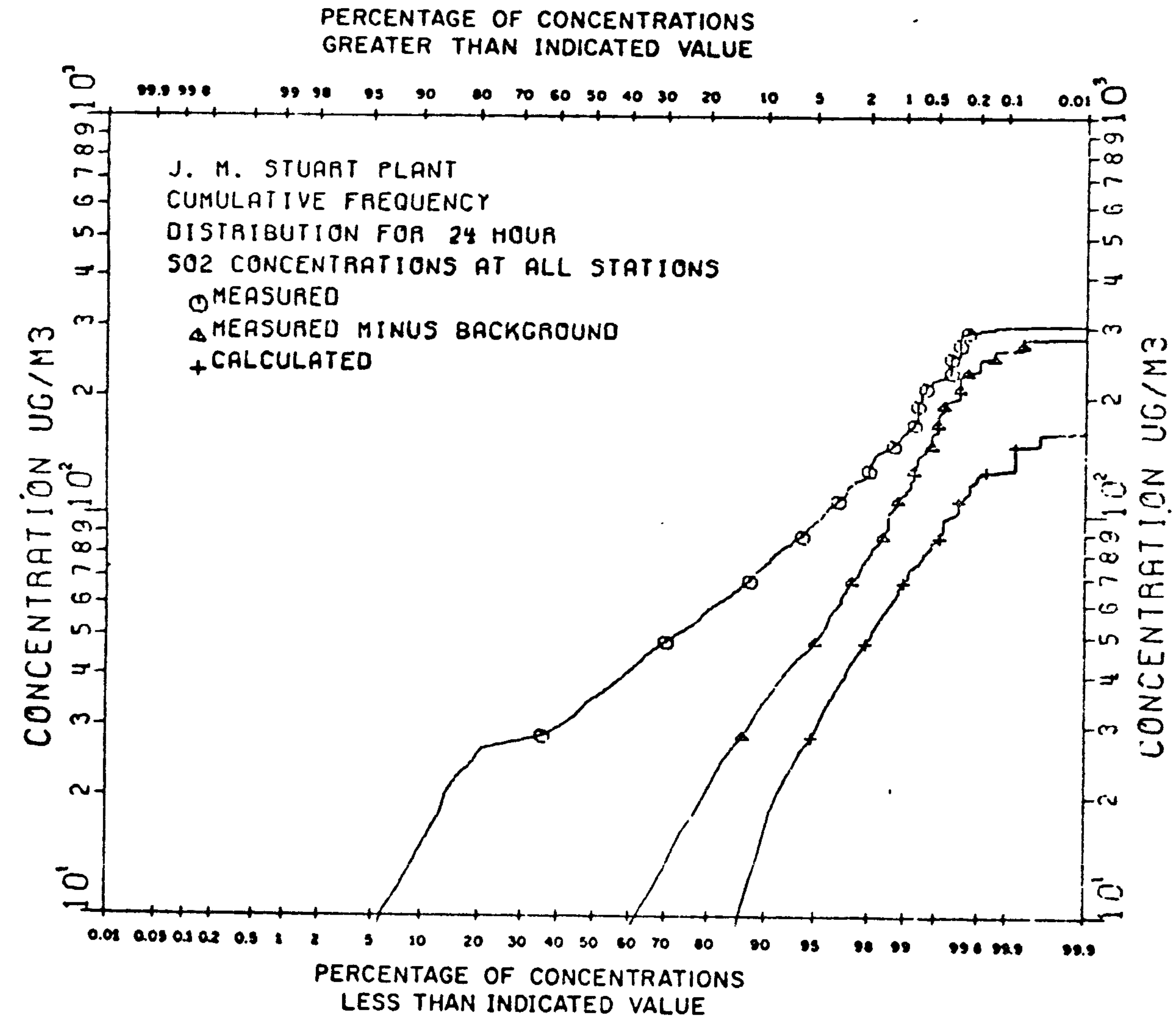

Figure 28. J. M. Stuart plant cumulative frequency distribution for 24-hour SO_2 concentrations at all stations. Number of measured concentrations = 1623; number of calculated concentrations = 2555

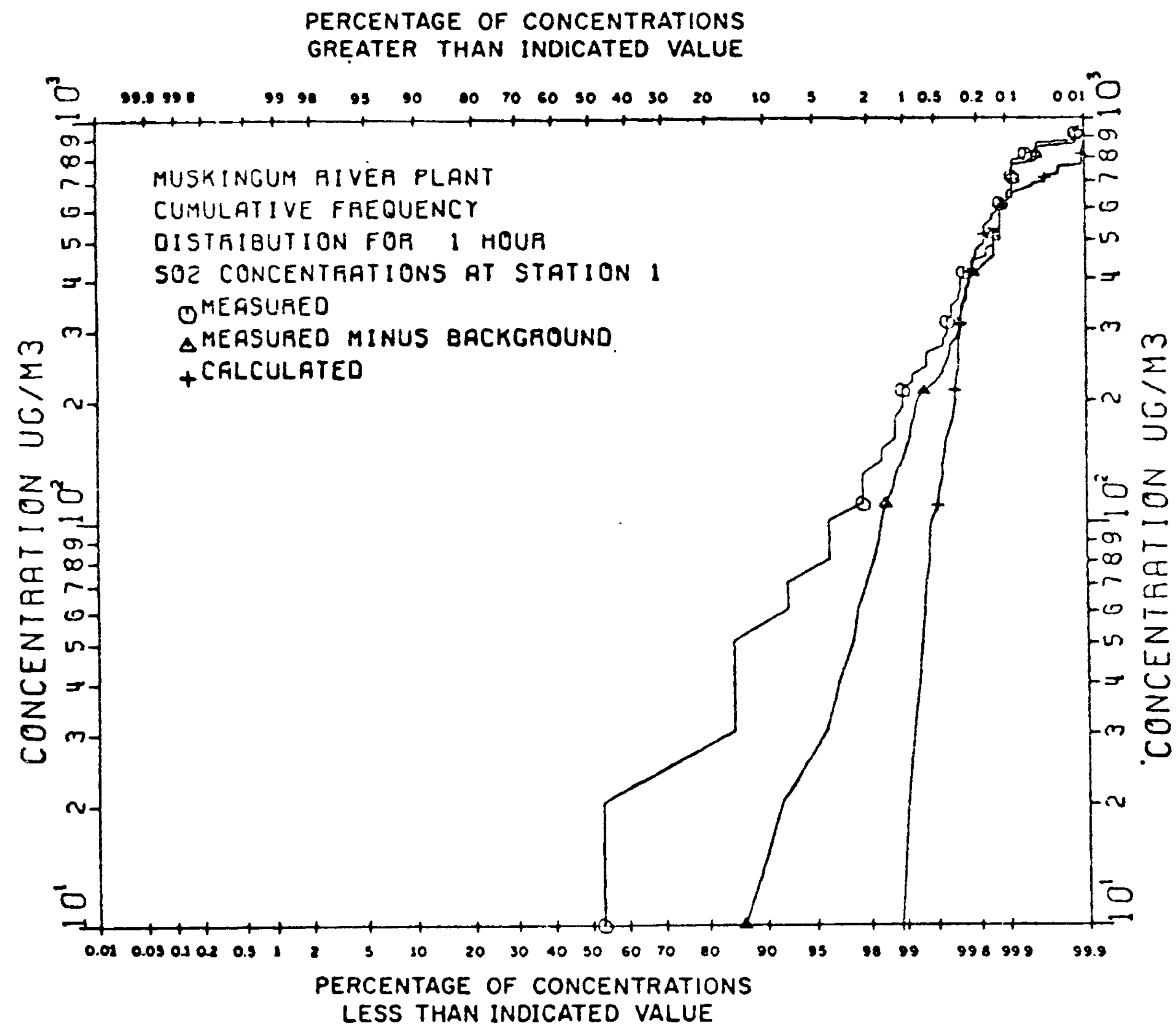

Figure 29. Muskingum River plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 1. Number of measured concentrations = 7356; number of calculated concentrations = 8760

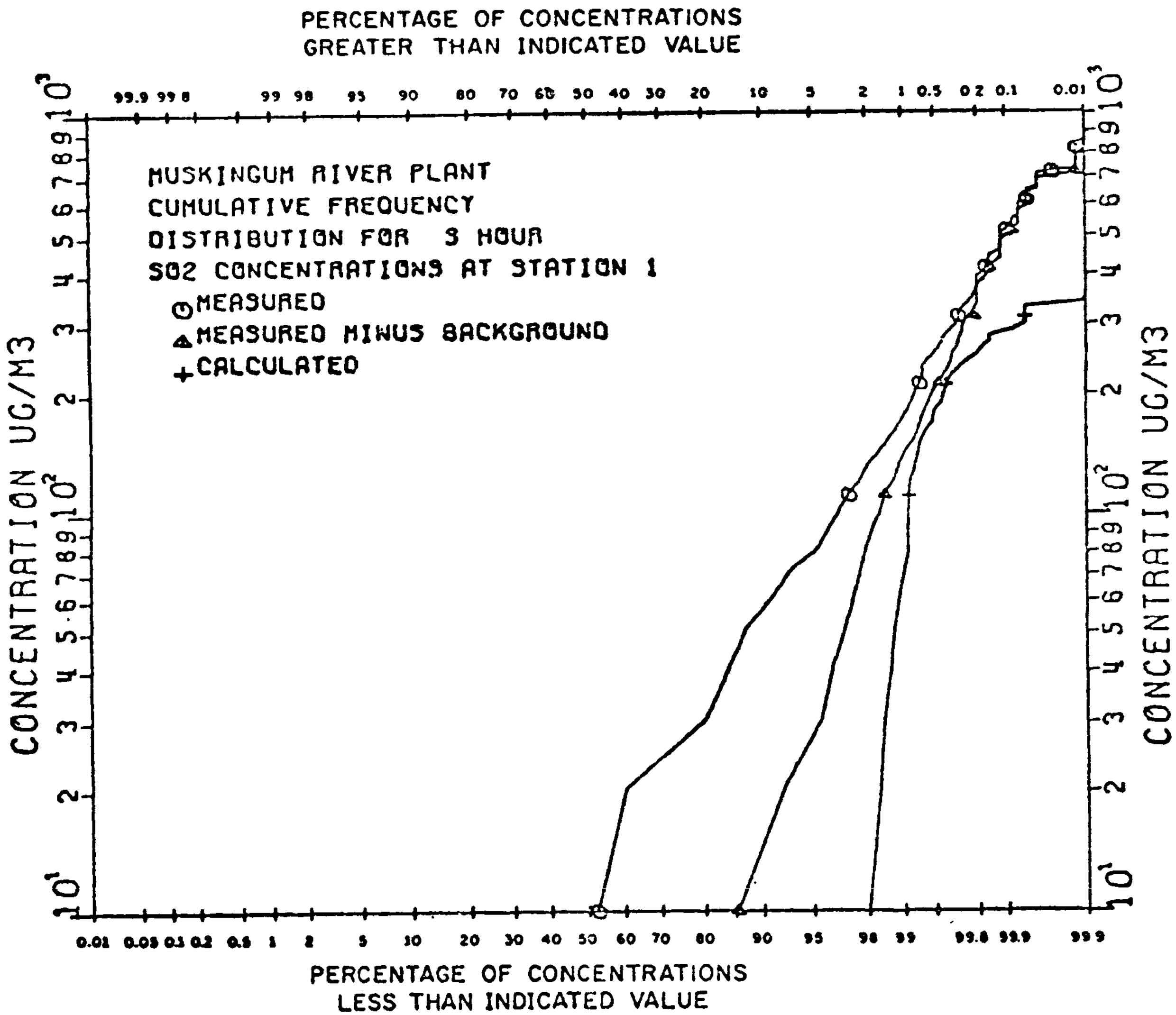

Figure 30. Muskingum River plant cumulative frequency distribution for 3-hour SO_2 concentrations at station 1. Number of measured values = 7396; number of calculated values = 8760

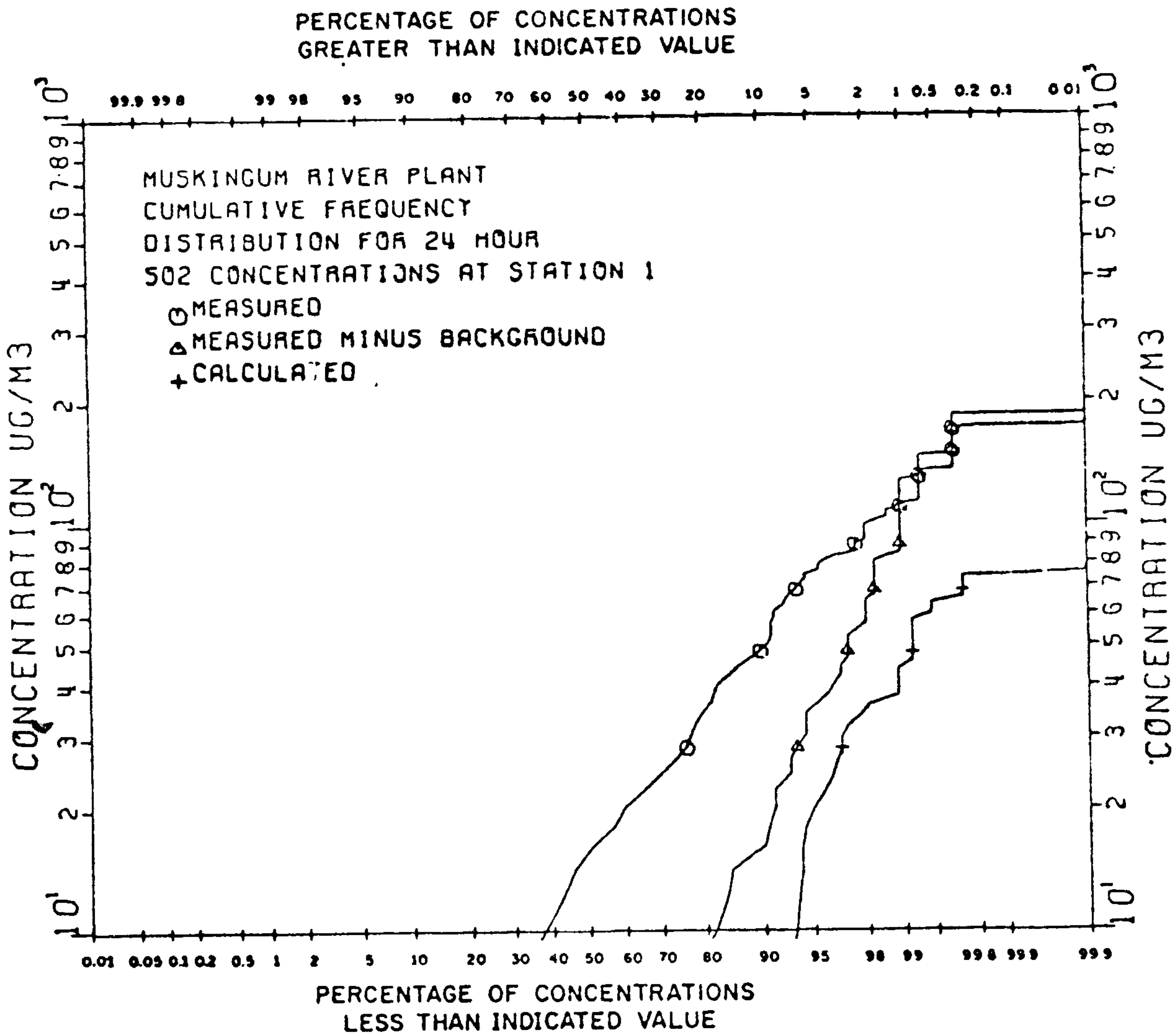

Figure 31. Muskingum River plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 1. Number of measured values = 297; number of calculated values = 365

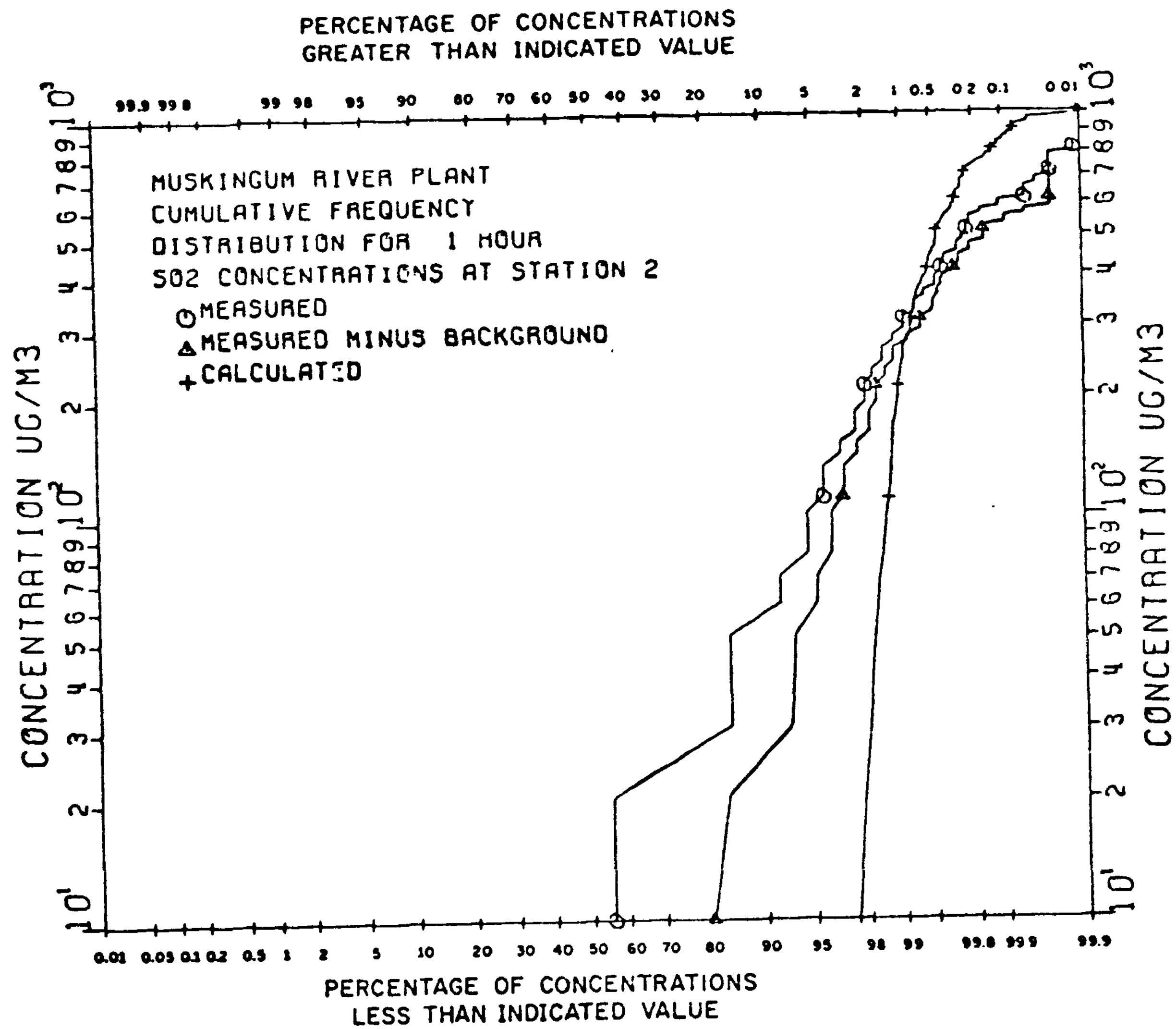

Figure 32. Muskingum River plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 2. Number of measured values = 7732; number of calculated values = 8760

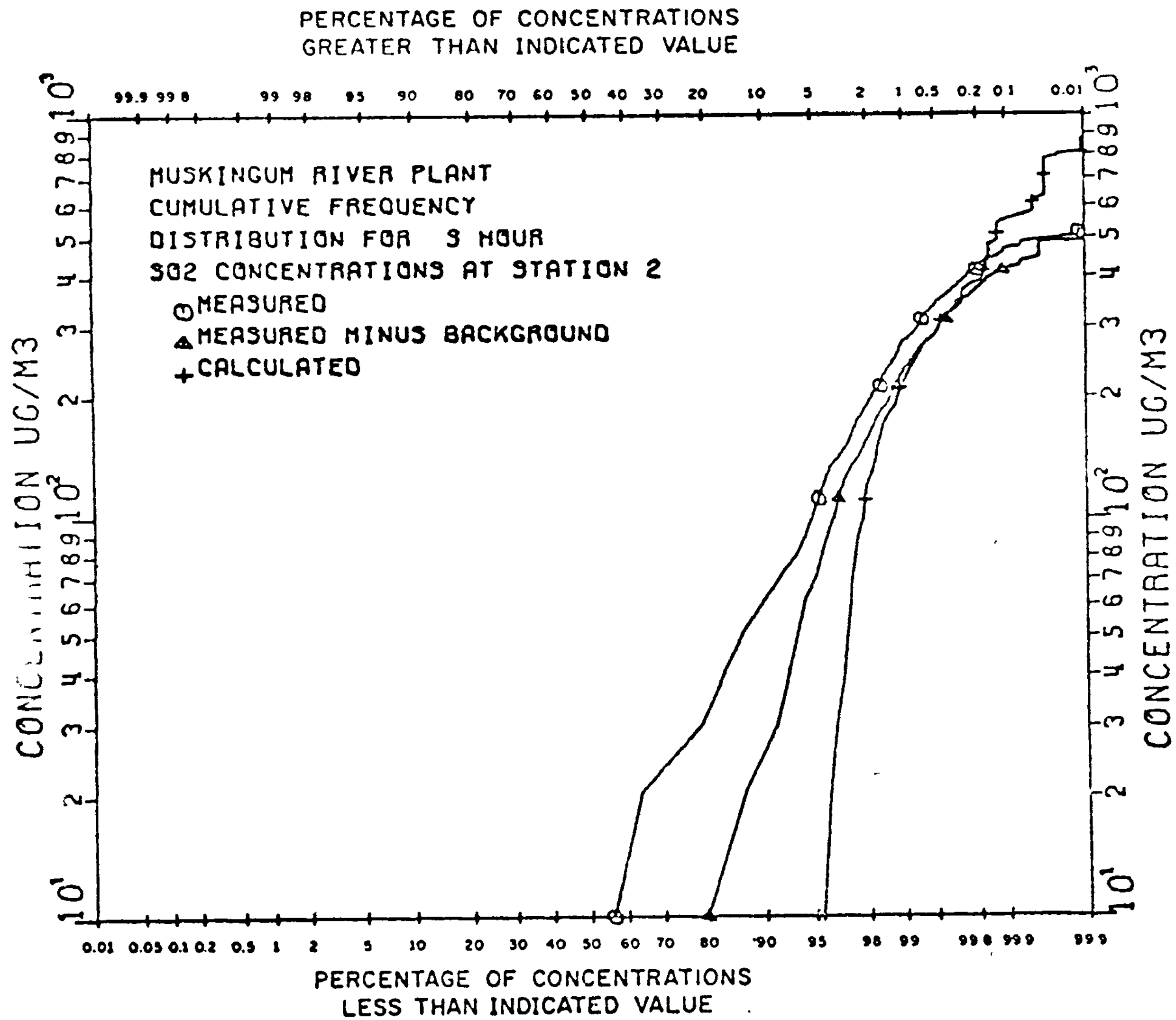

Figure 33. Muskingum River plant cumulative frequency distribution for 3-hour SO_2 concentrations at station 2. Number of measured concentrations = 7740; number of calculated concentrations = 8760

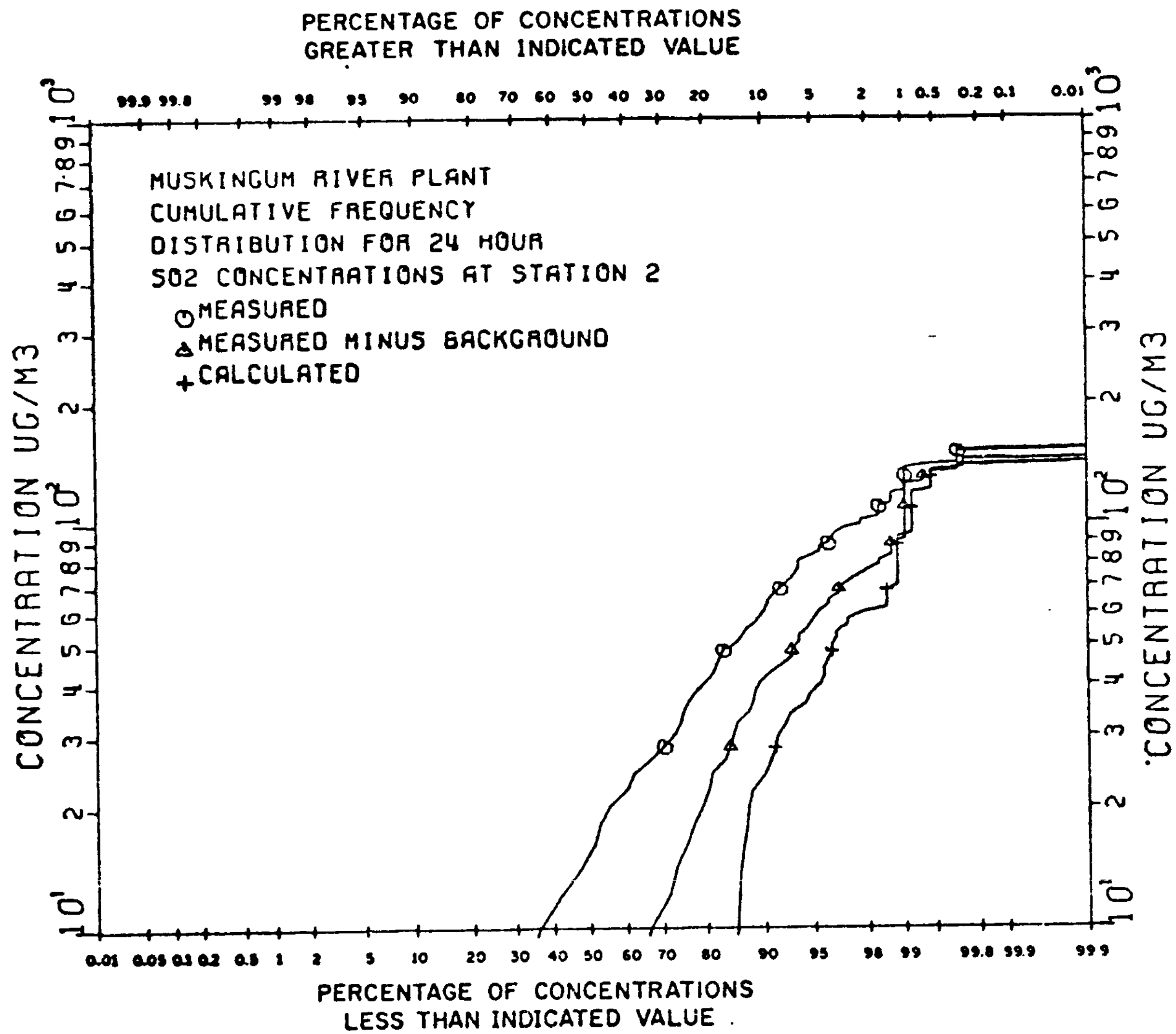

Figure 34. Muskingum River plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 2. Number of measured concentrations = 319; number of calculated concentrations = 365

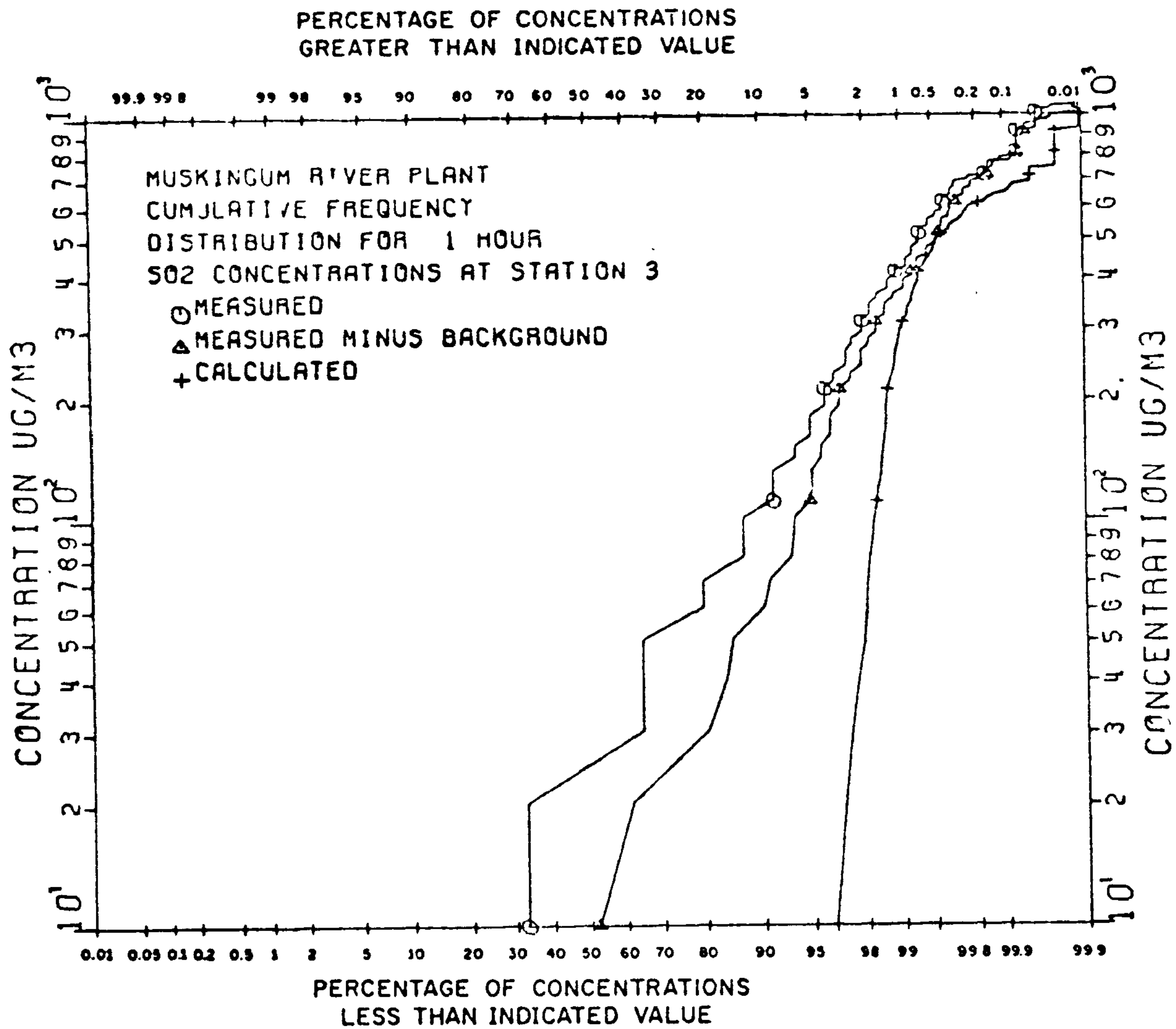

Figure 35. Muskingum River plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 3. Number of measured concentrations = 7765; number of calculated concentrations = 8760

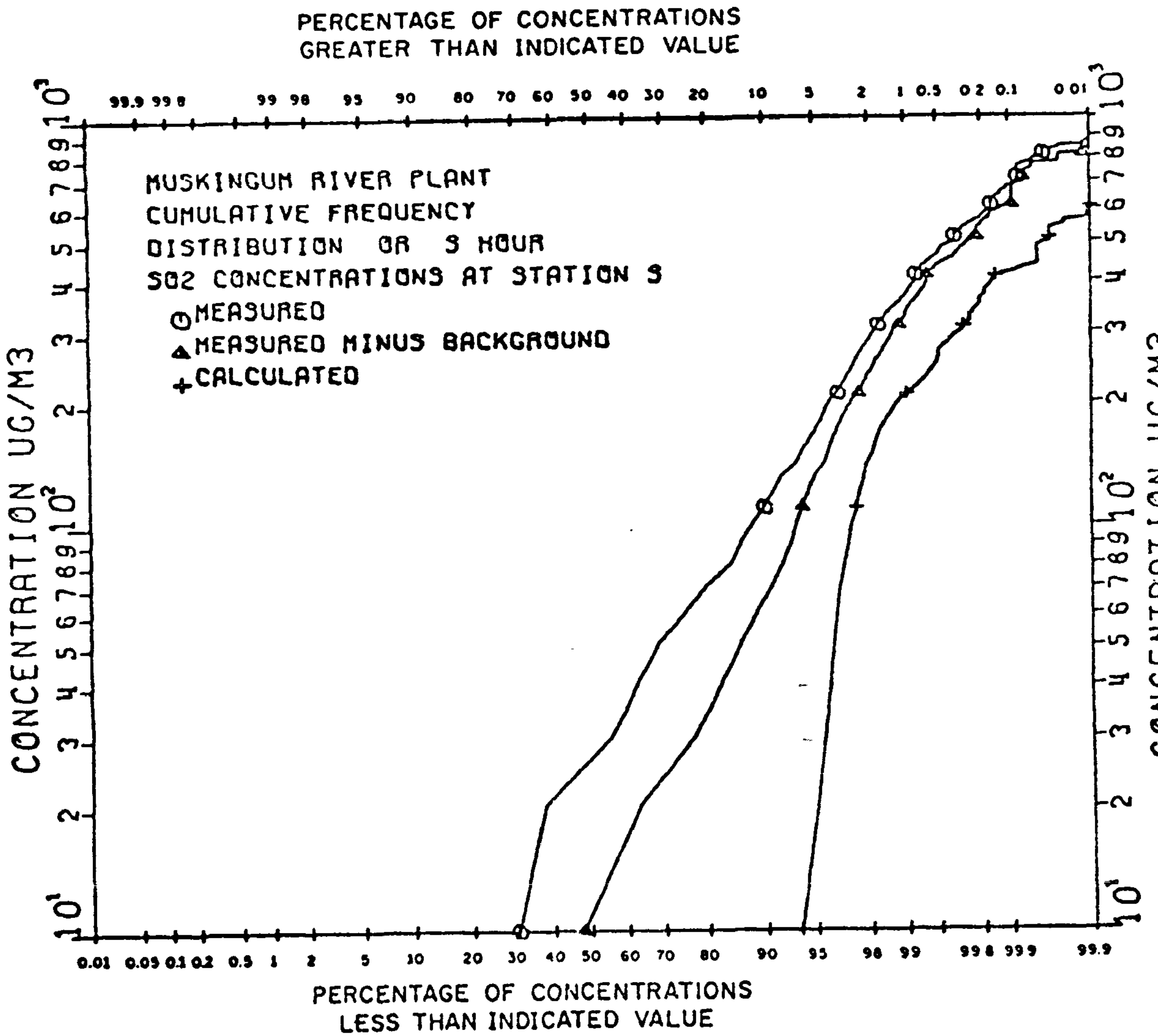

Figure 36. Muskingum River plant cumulative frequency distribution for 3-hour SO_2 concentrations at station 3. Number of measured concentrations = 7772; number of calculated concentrations = 8760

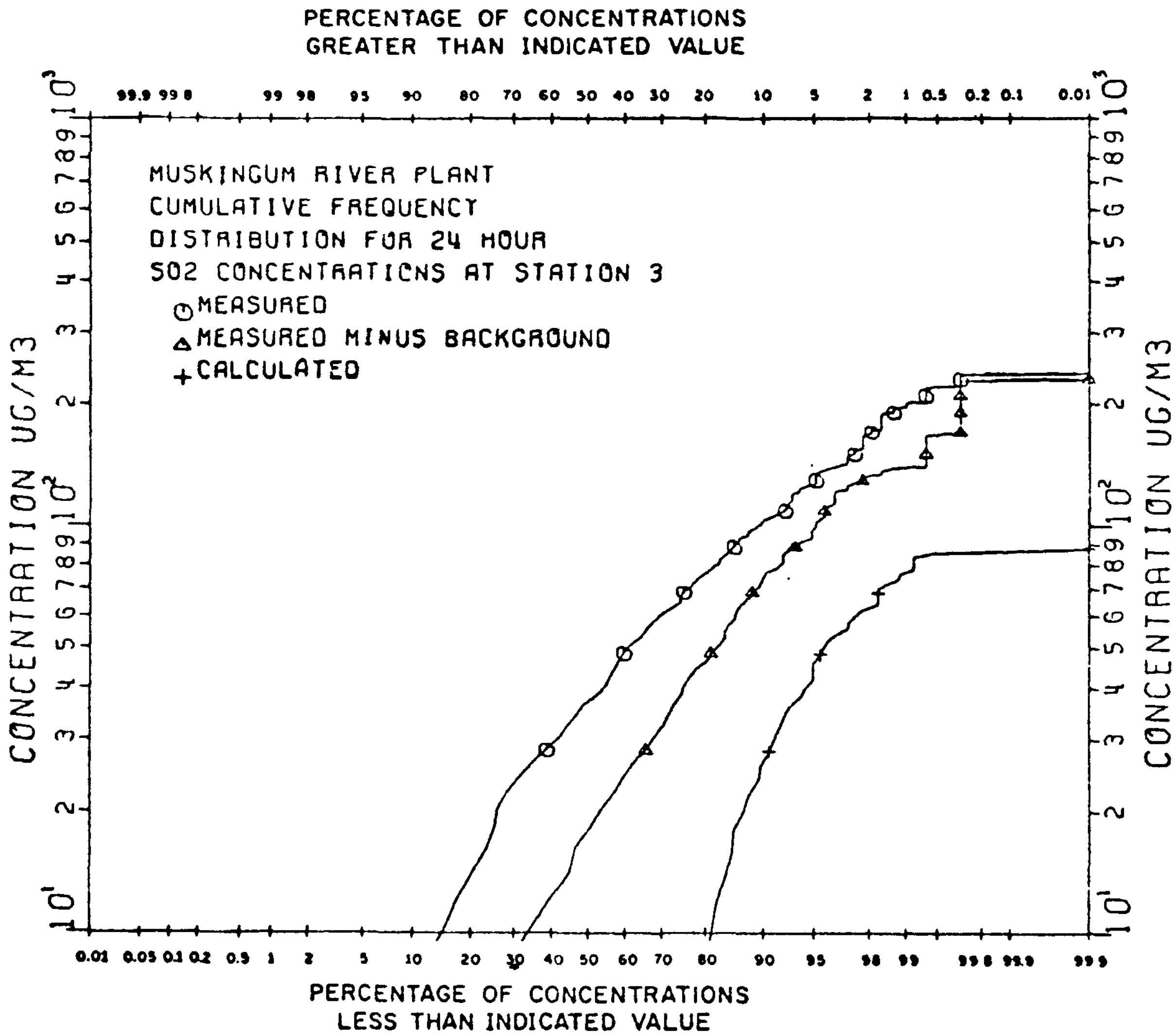

Figure 37. Muskingum River plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 3. Number of measured concentrations = 320; number of calculated concentrations = 365

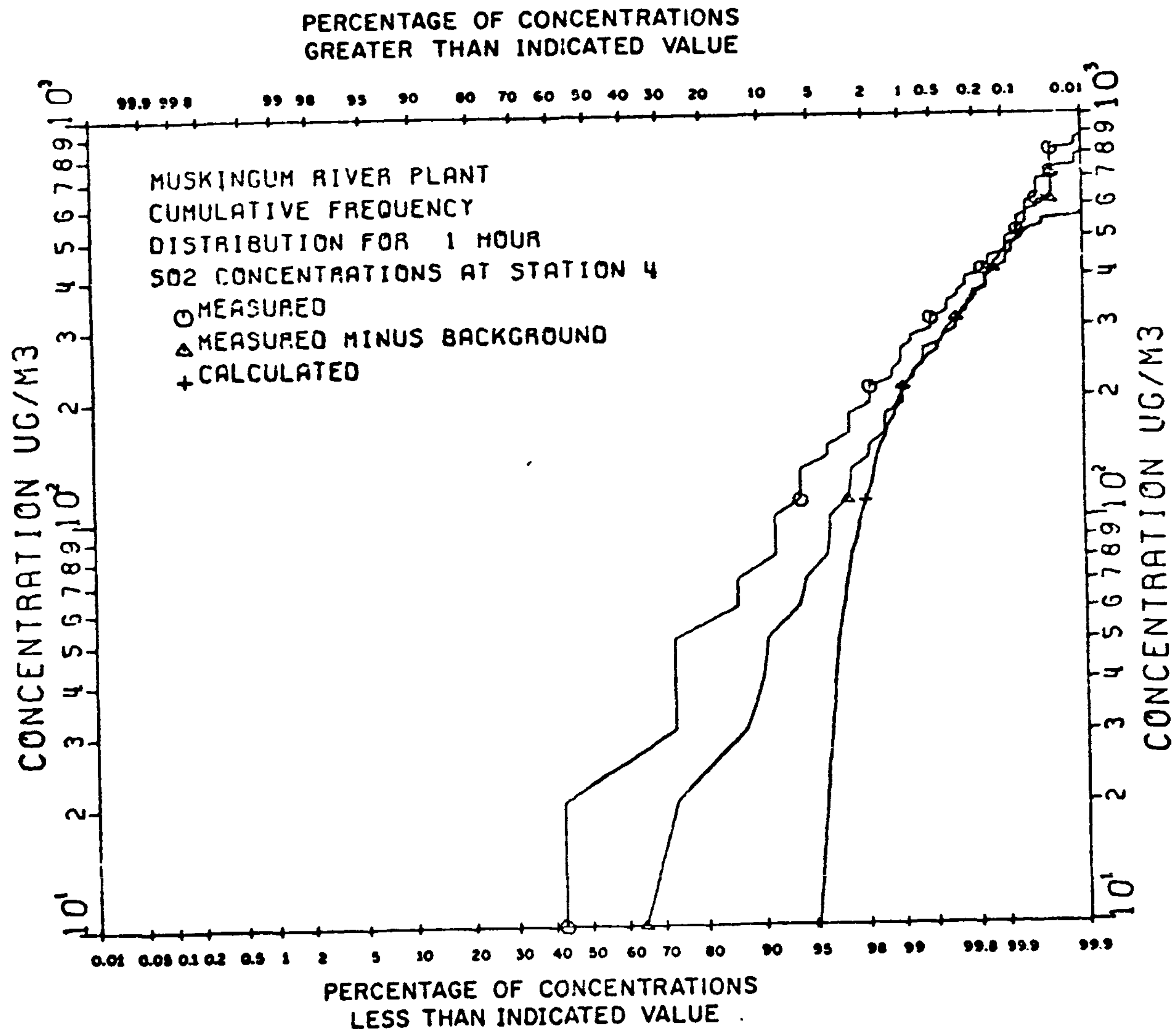

Figure 38. Muskingum River plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 4. Number of measured concentrations = 7769; number of calculated concentrations = 8760

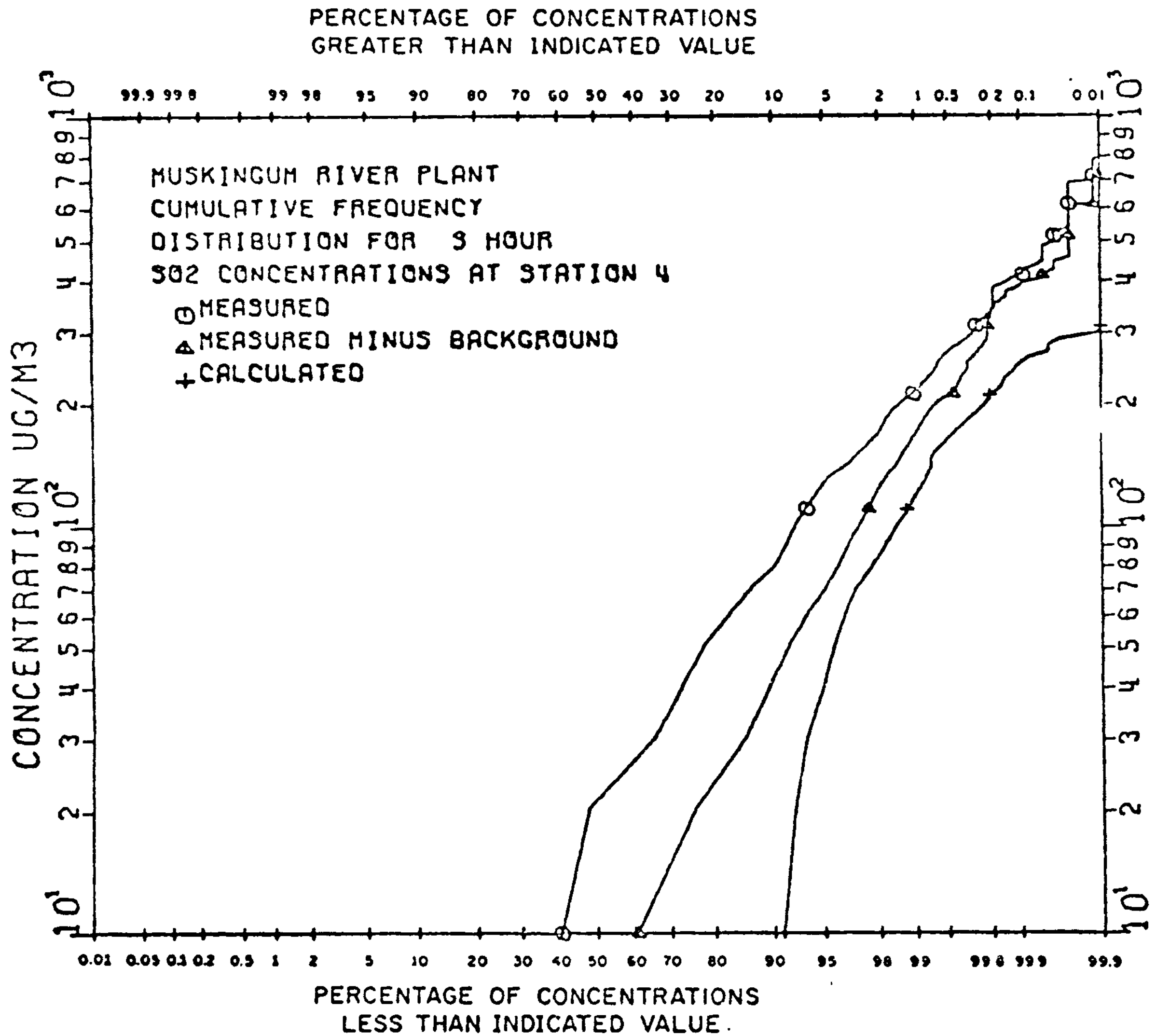

Figure 39. Muskingum River plant cumulative frequency distribution for 3-hour SO_2 concentrations at station 4. Number of measured concentrations = 7775; number of calculated concentrations = 8760

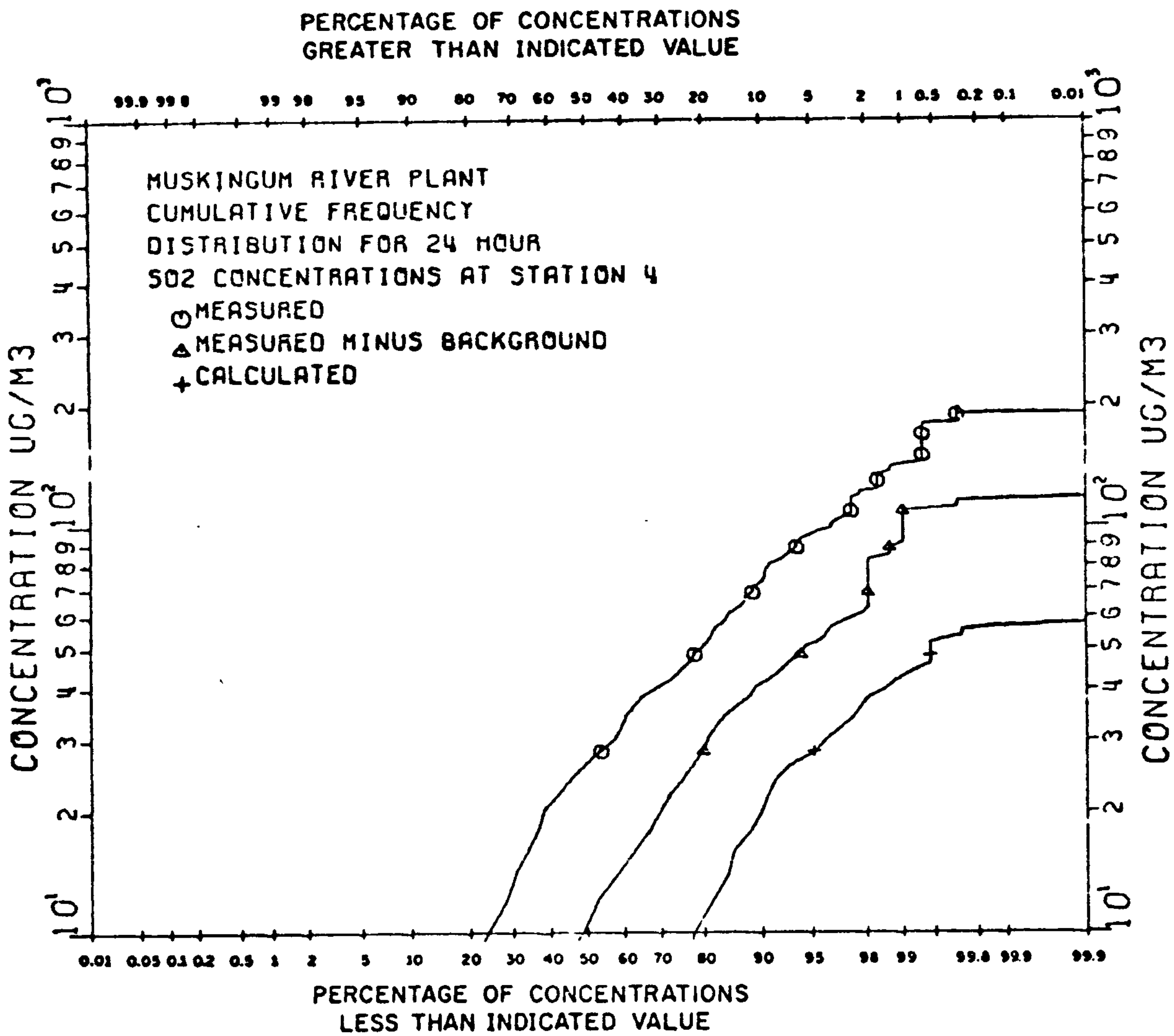

Figure 40. Muskingum River plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 4. Number of measured concentrations = 320; number of calculated concentrations = 365

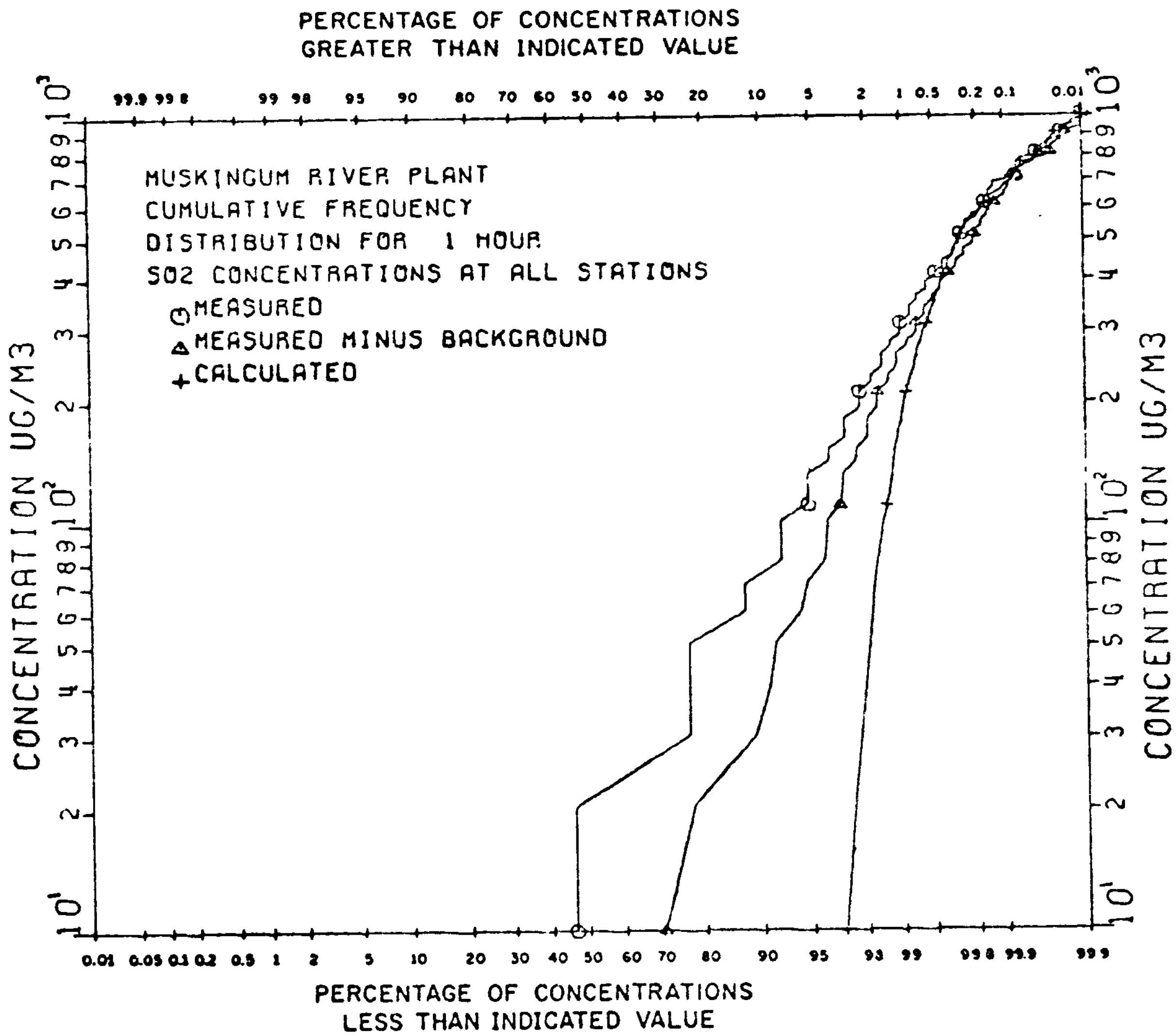

Figure 41. Muskingum River plant cumulative frequency distribution for 1-hour SO_2 concentrations at all stations. Number of measured concentrations = 30,622; number of calculated concentrations = 61,320

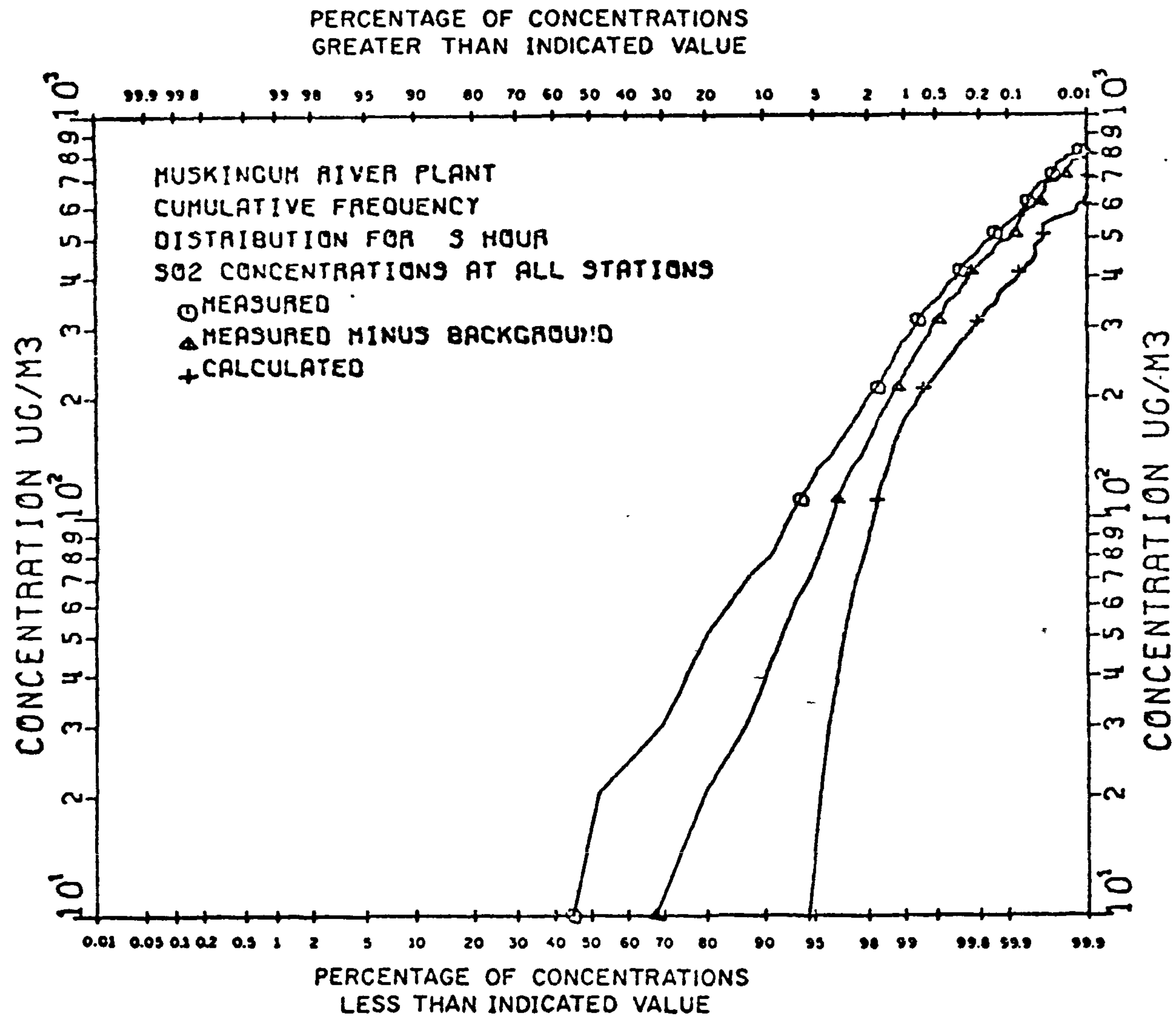

Figure 42. Muskingum River plant cumulative frequency distribution for 3-hour SO_2 concentrations at all stations. Number of measured concentrations = 30683; number of calculated concentrations = 35040

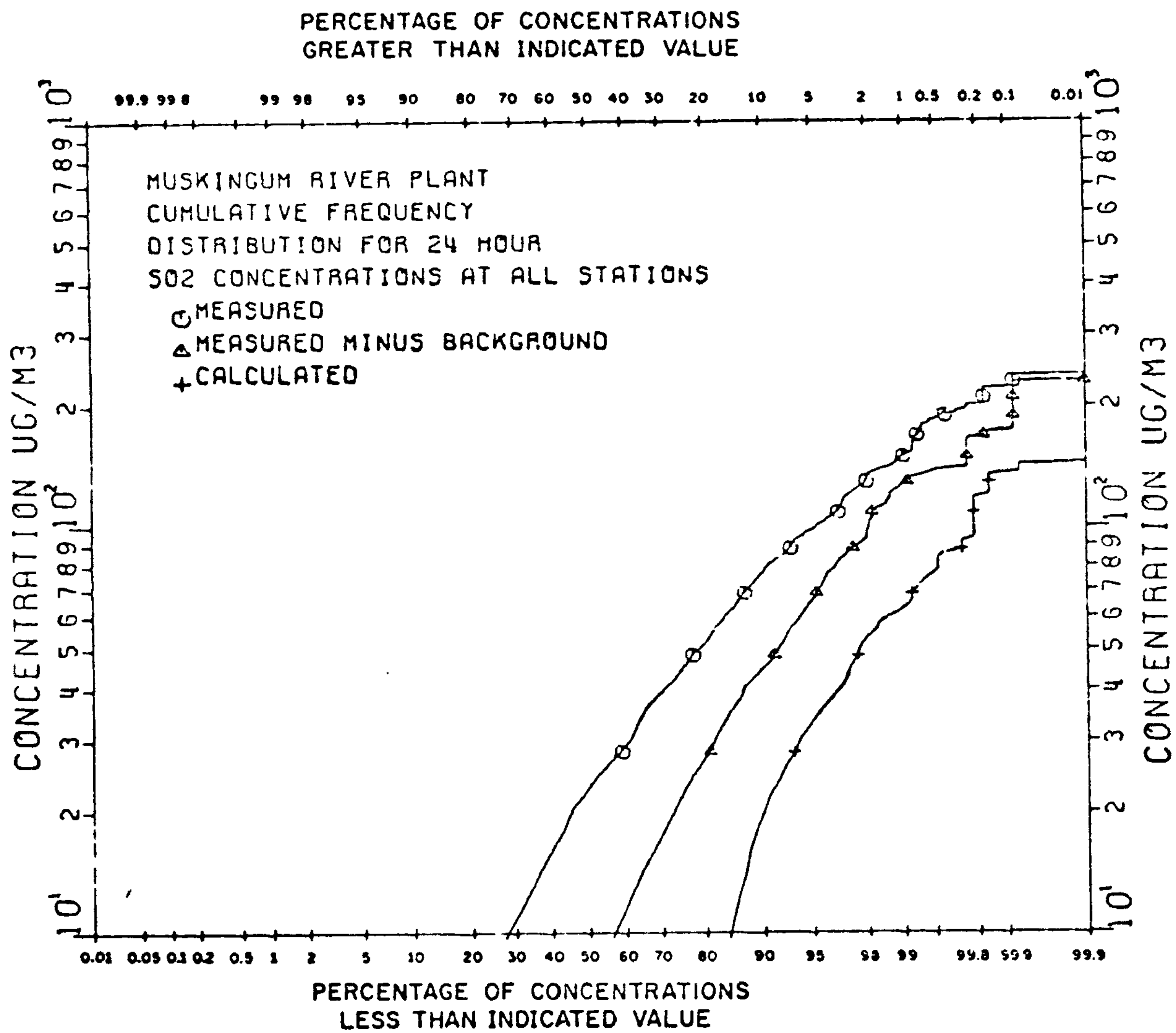

Figure 43. Muskingum River plant cumulative frequency distribution for 24-hour SO_2 concentrations at all stations. Number of measured concentrations = 1256; number of calculated concentrations = 1460

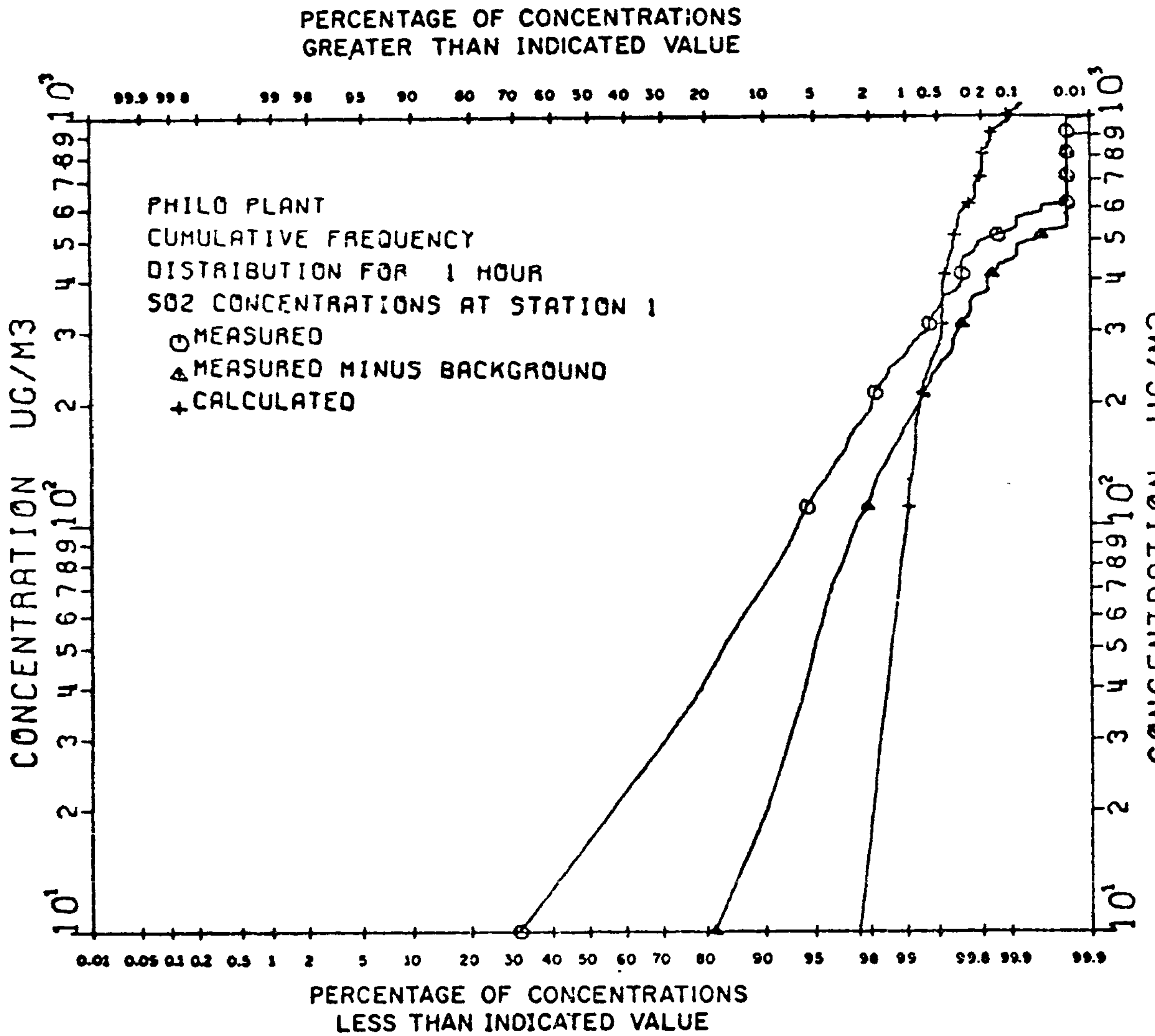

Figure 44. Philo plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 1. Number of measured concentrations = 4905; number of calculated concentrations = 8760

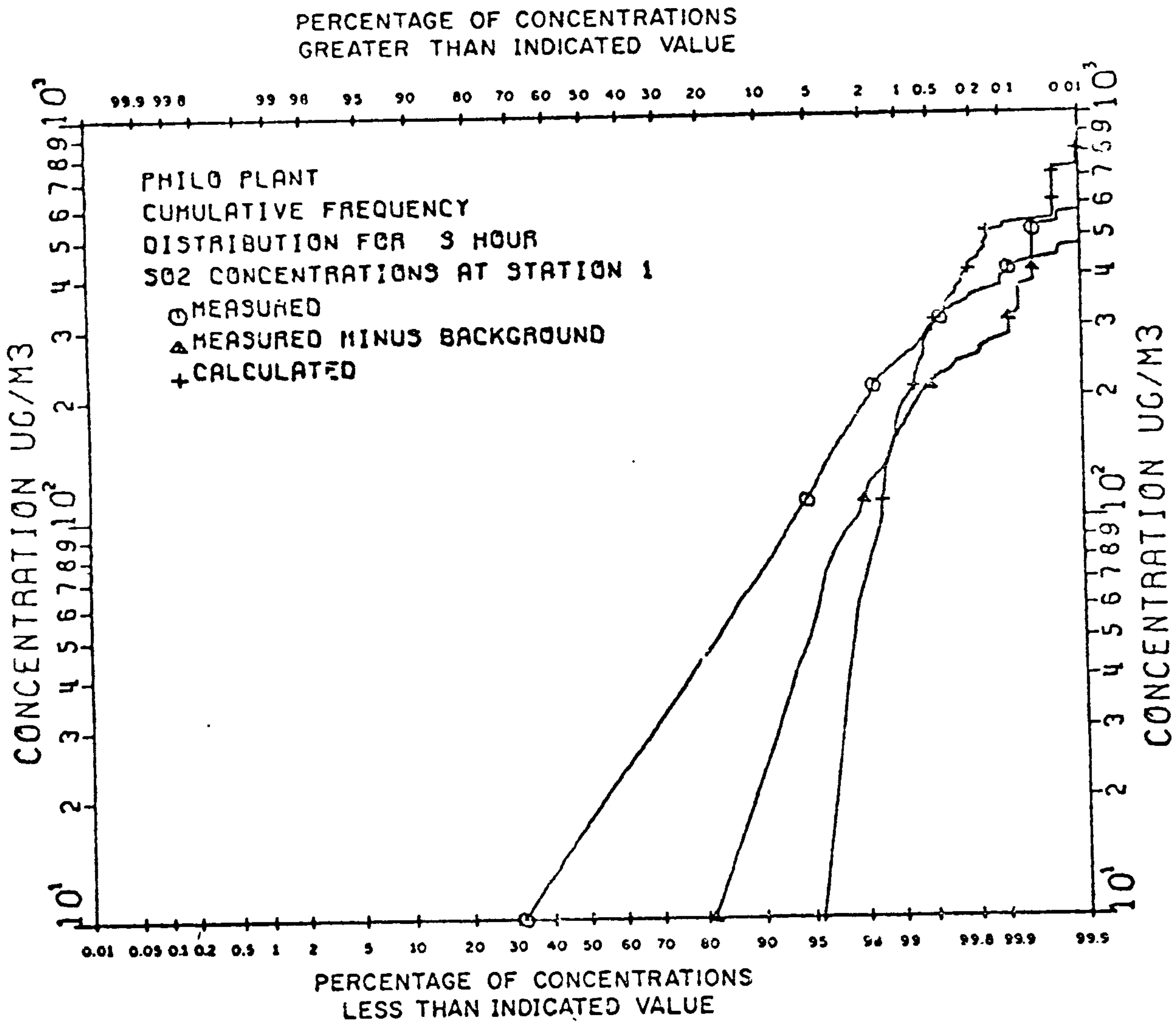

Figure 45. Philo plant cumulative frequency distribution for 3-hour SO_2 concentrations at station 1. Number of measured concentrations = 4974; number of calculated concentrations = 8760

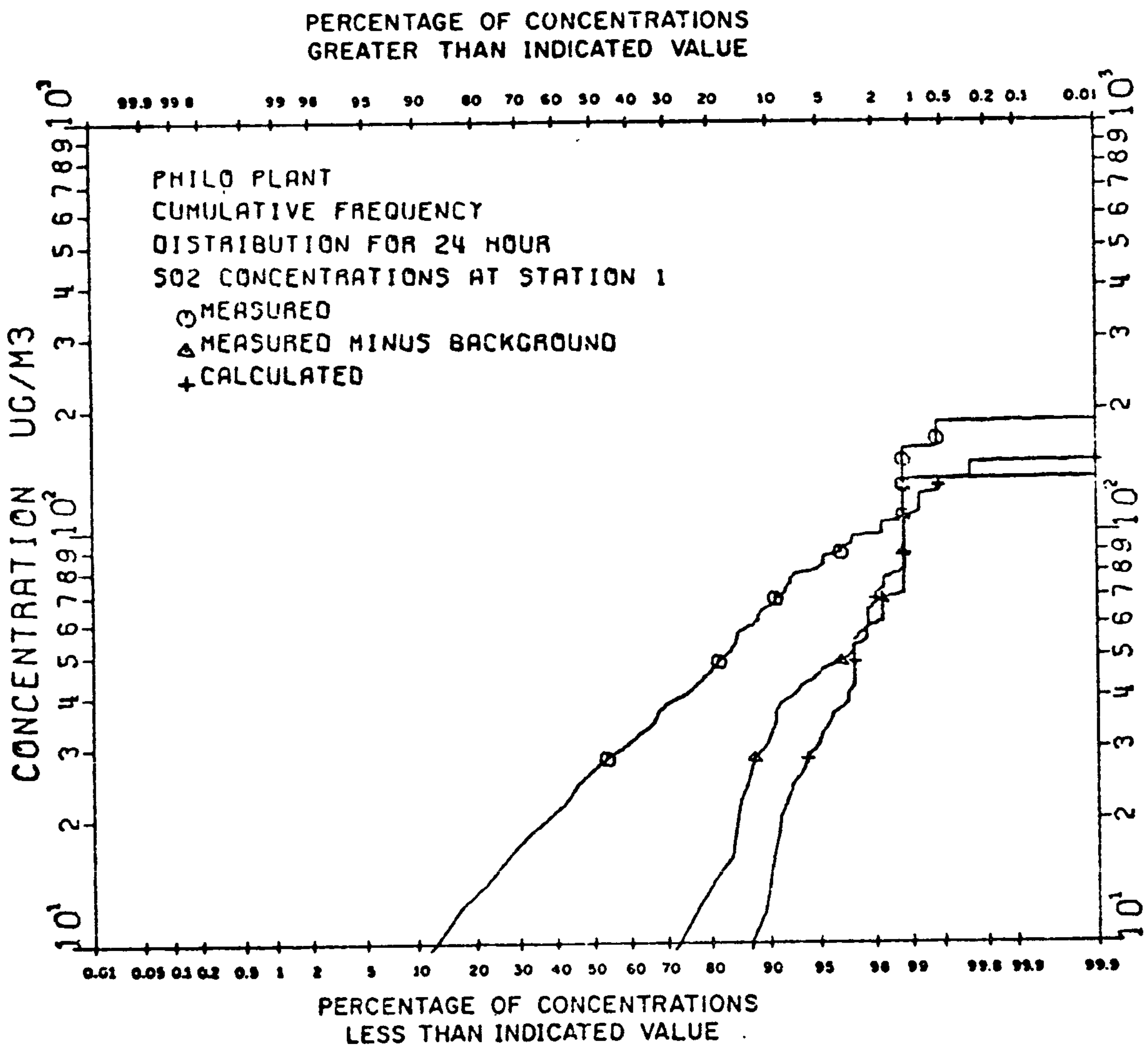

Figure 46. Philo plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 1. Number of measured concentrations = 178; number of calculated concentrations = 365

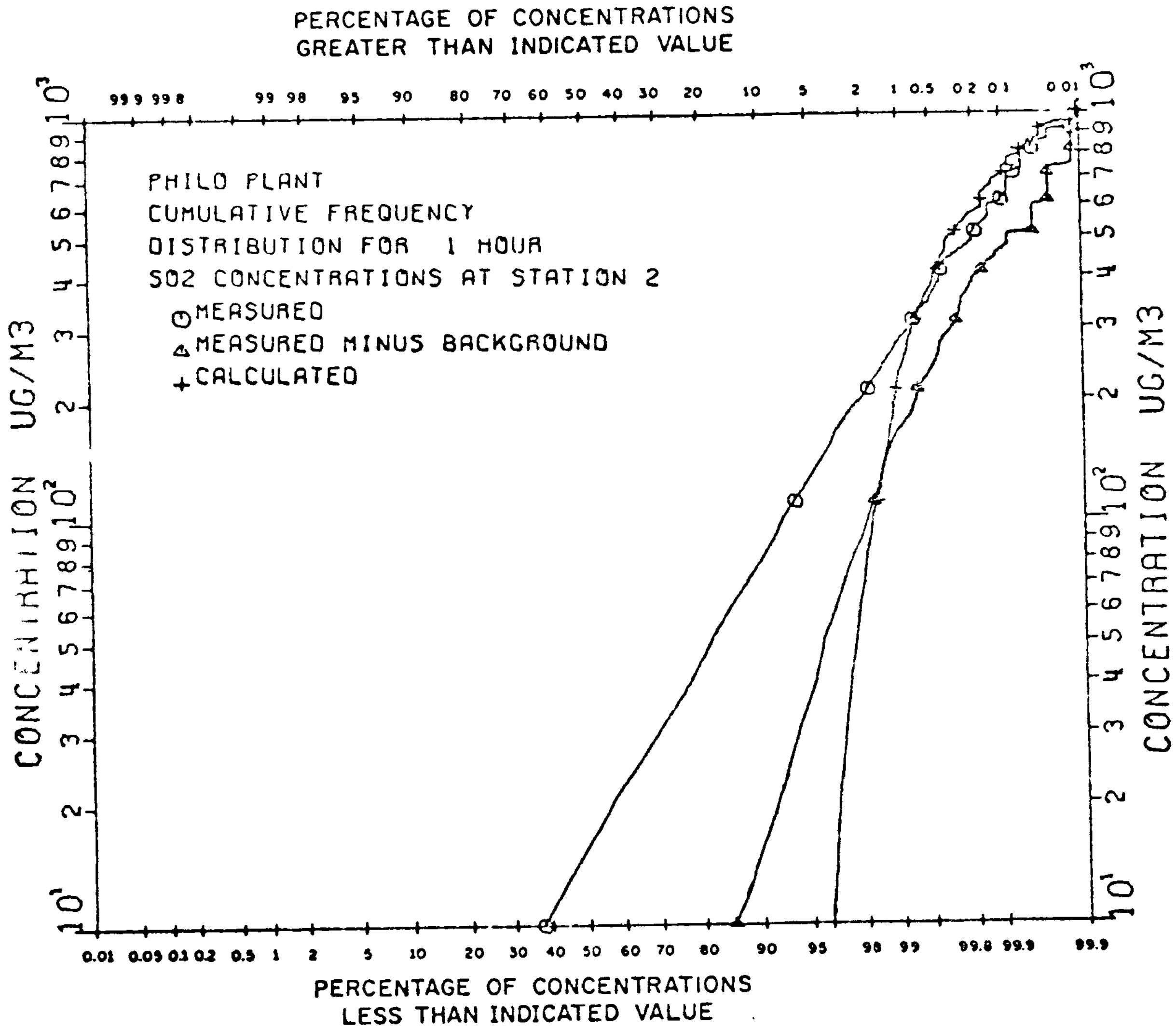

Figure 47. Philo plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 2. Number of measured concentrations = 7365; number of calculated concentrations = 8760

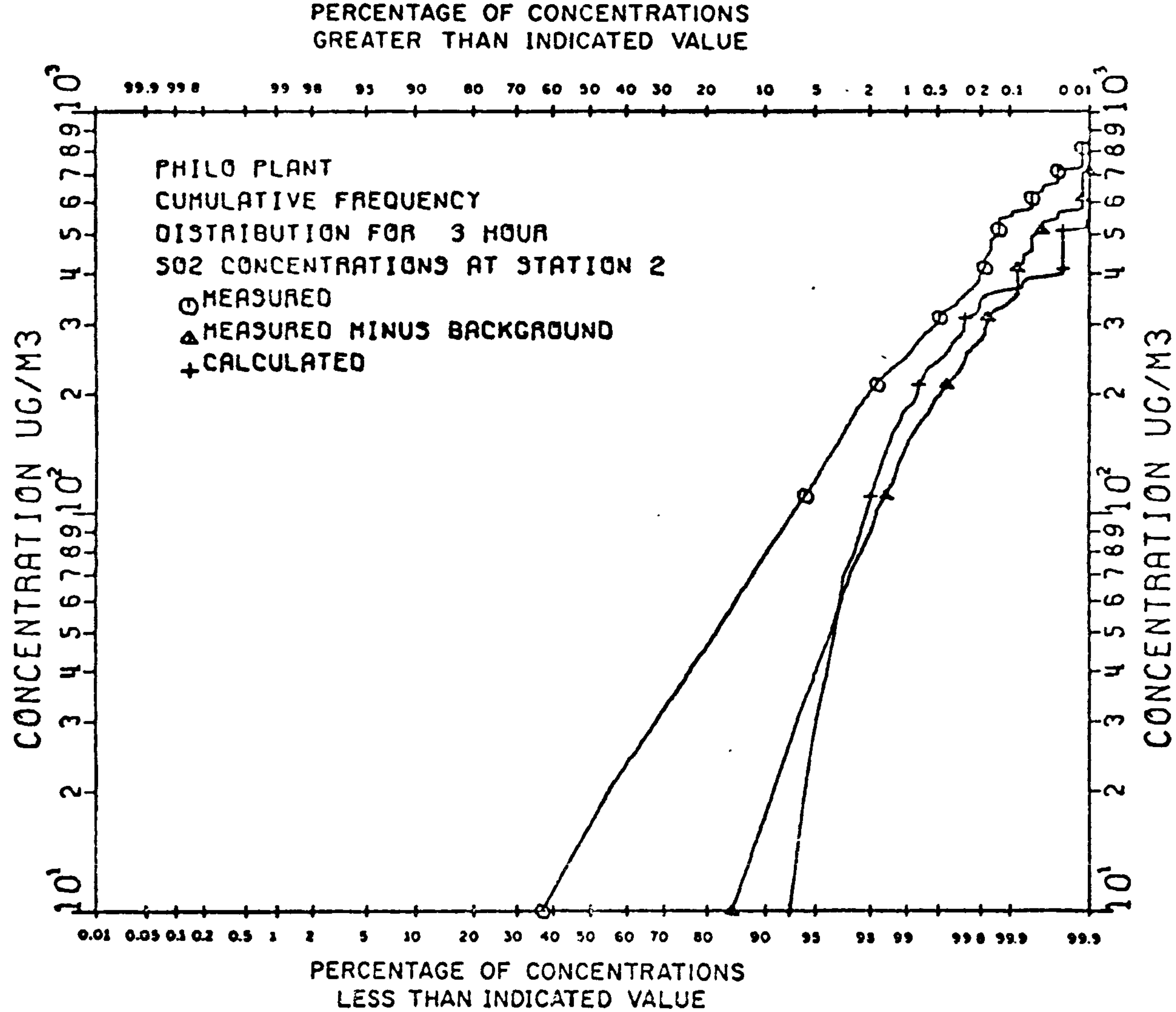

Figure 48. Philo plant cumulative frequency distribution for 3-hour SO_2 concentrations at station 2. Number of measured concentrations = 7584; number of calculated concentrations = 8760

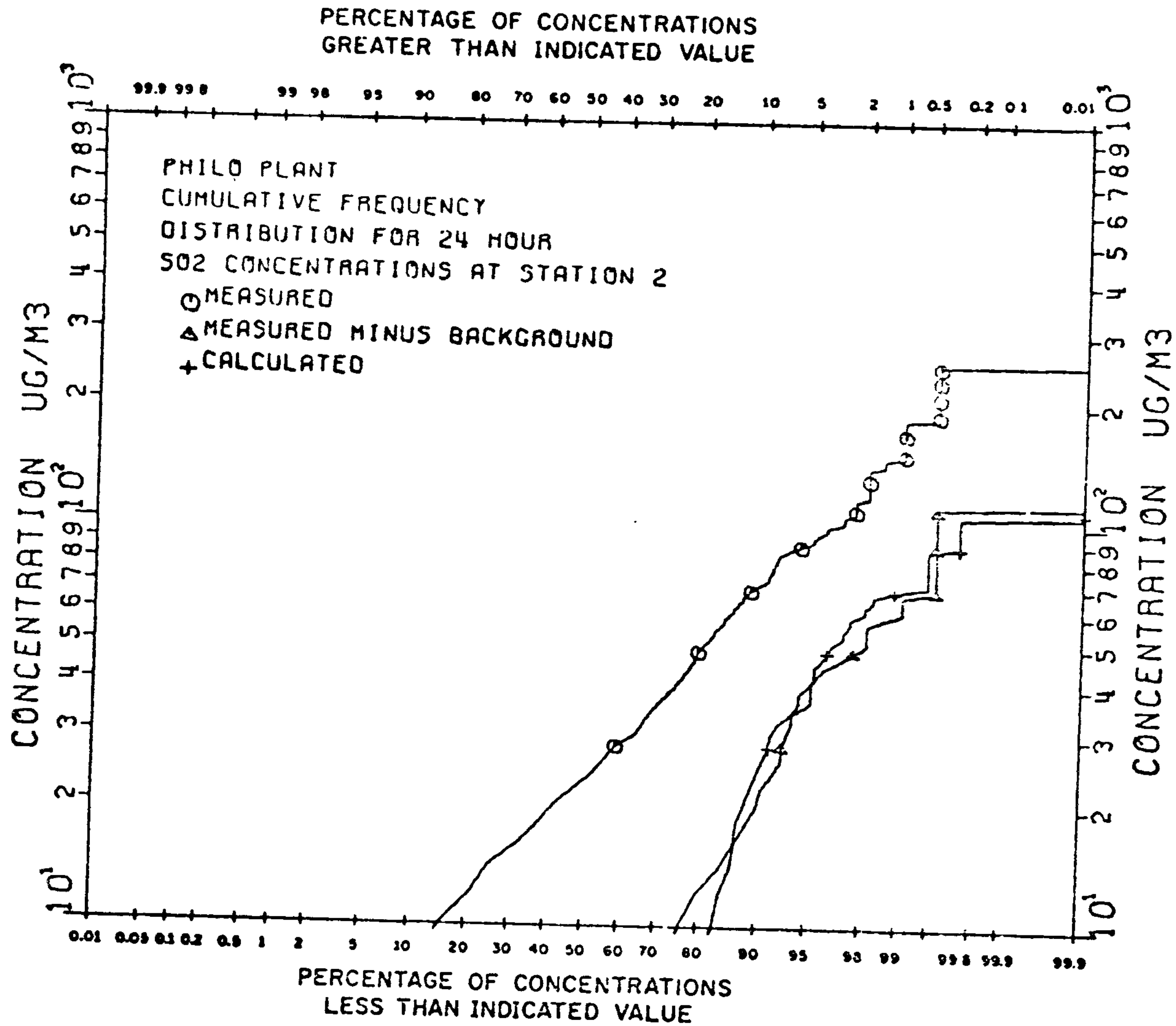

Figure 49. Philo plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 2. Number of measured concentrations = 216; number of calculated concentrations = 365

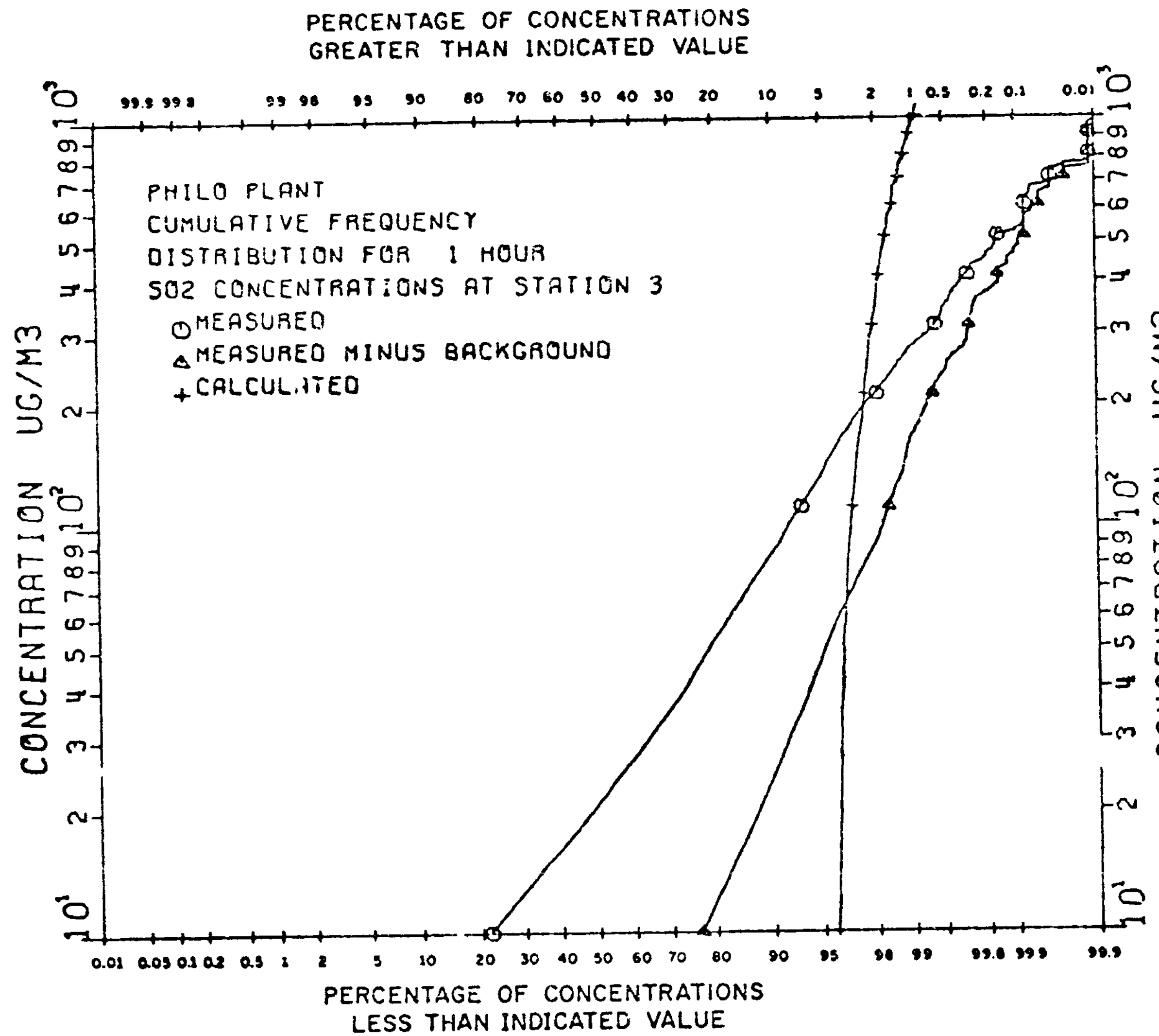

Figure 50. Philo plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 3. Number of measured concentrations = 7954; number of calculated concentrations = 8760

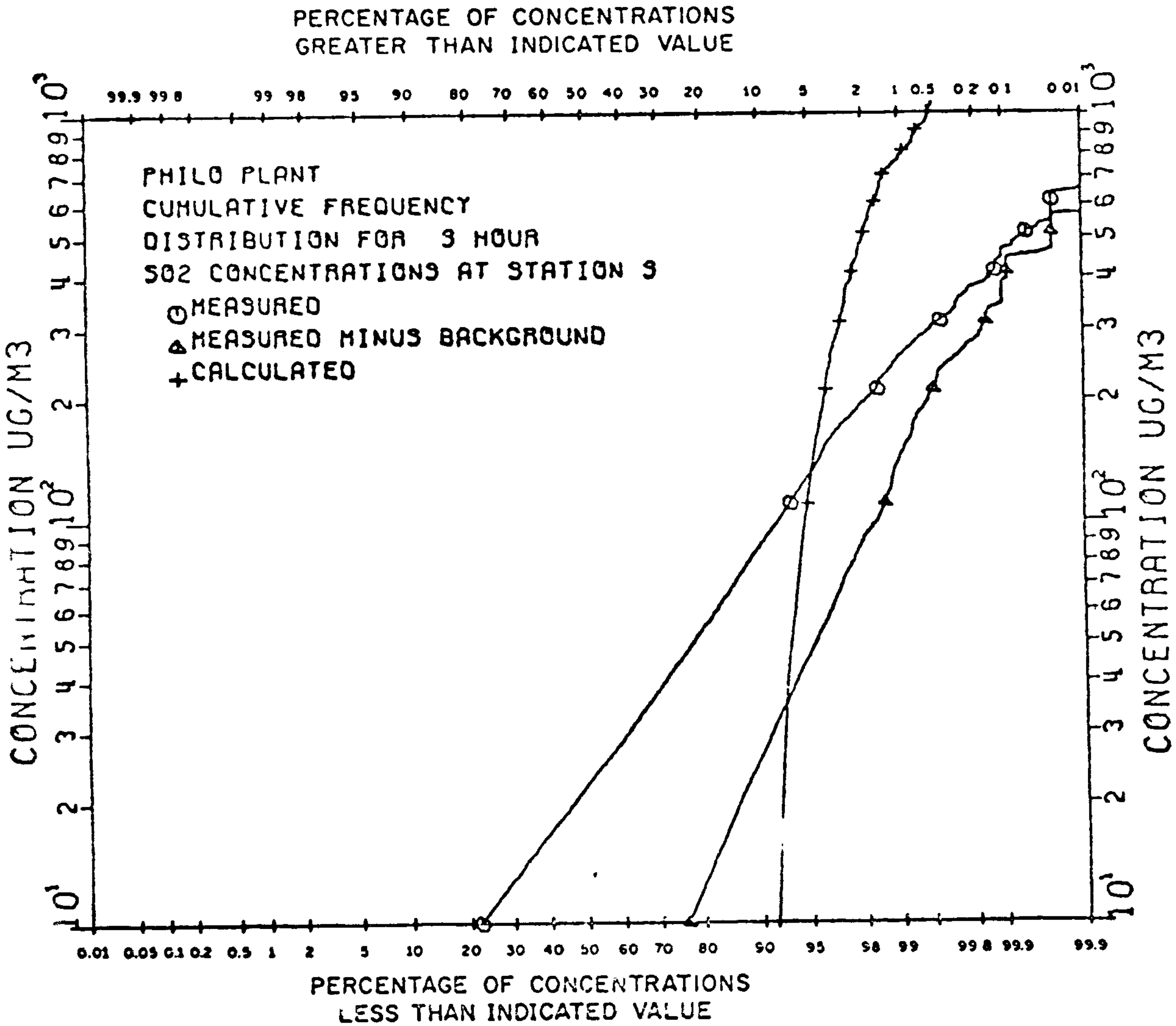

Figure 51. Philo plant cumulative frequency distribution for 3-hour SO_2 concentrations at station 3. Number of measured concentrations = 8053; number of calculated concentrations = 8760

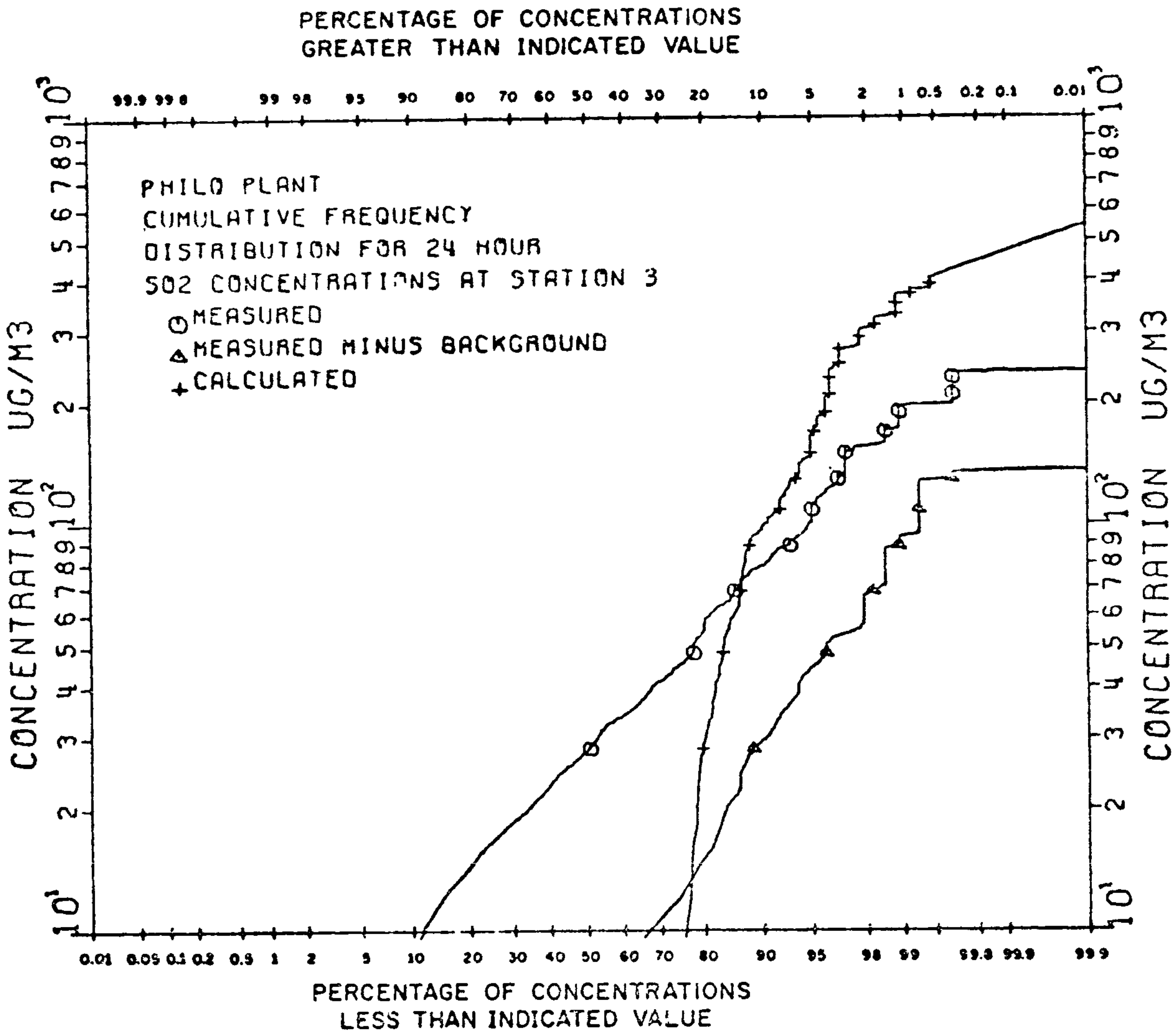

Figure 52. Philo plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 3. Number of measured concentrations = 289; number of calculated concentrations = 365

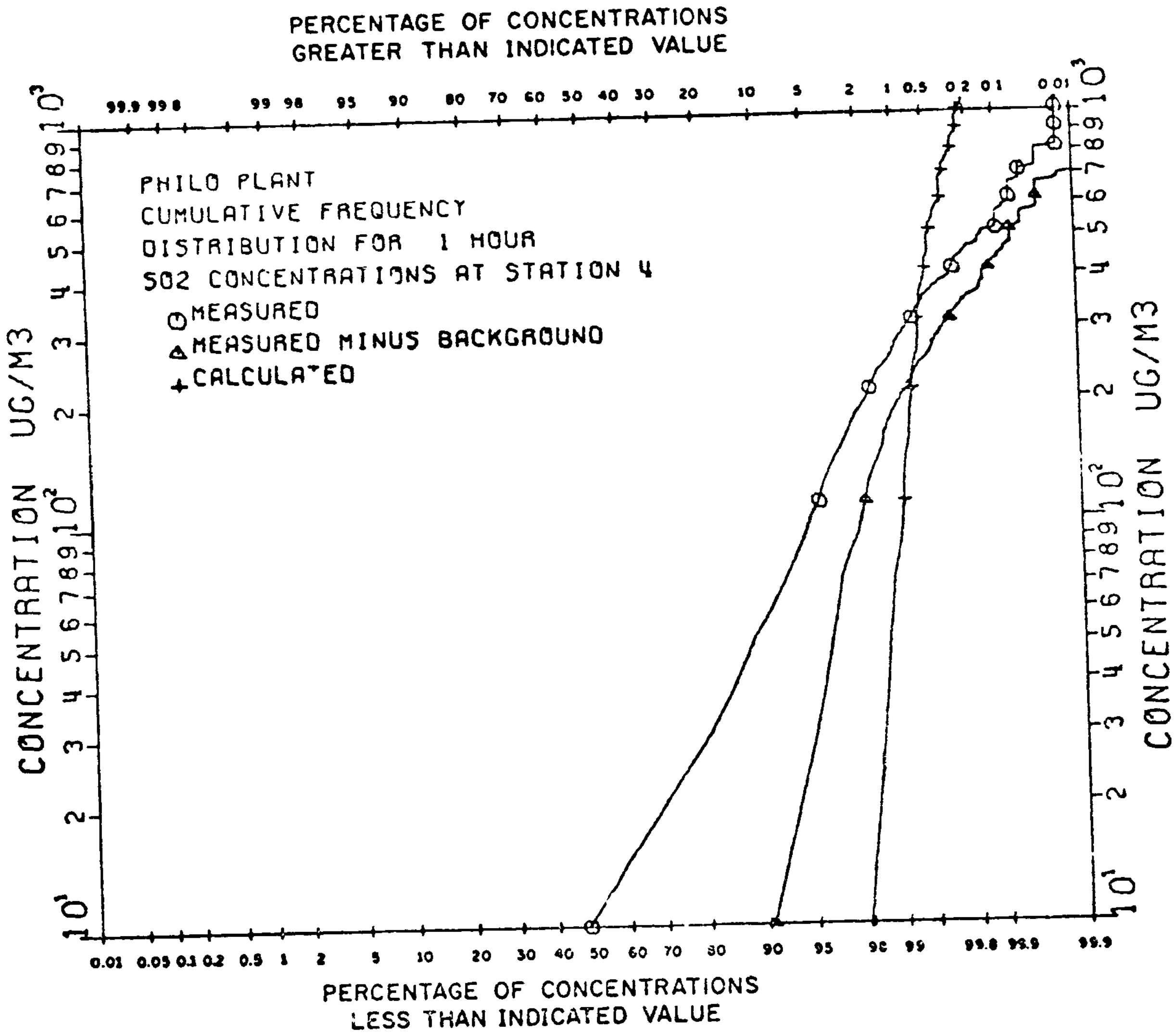

Figure 53. Philo plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 4. Number of measured concentrations = 6156; number of calculated concentrations = 8760

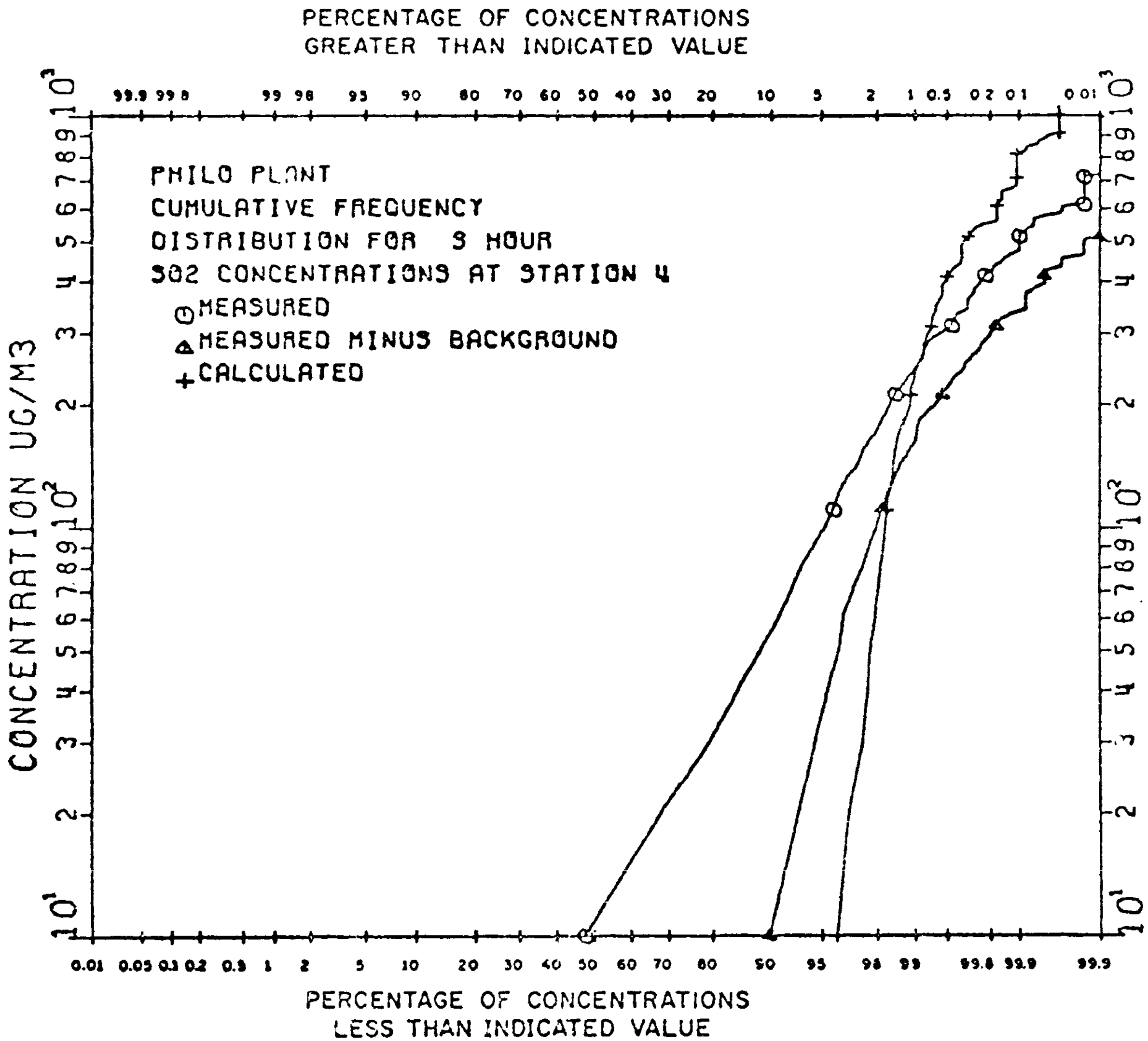

Figure 54. Philo plant cumulative frequency distribution for 3-hour SO_2 concentrations at station 4. Number of measured concentrations = 6210; number of calculated concentrations = 8760

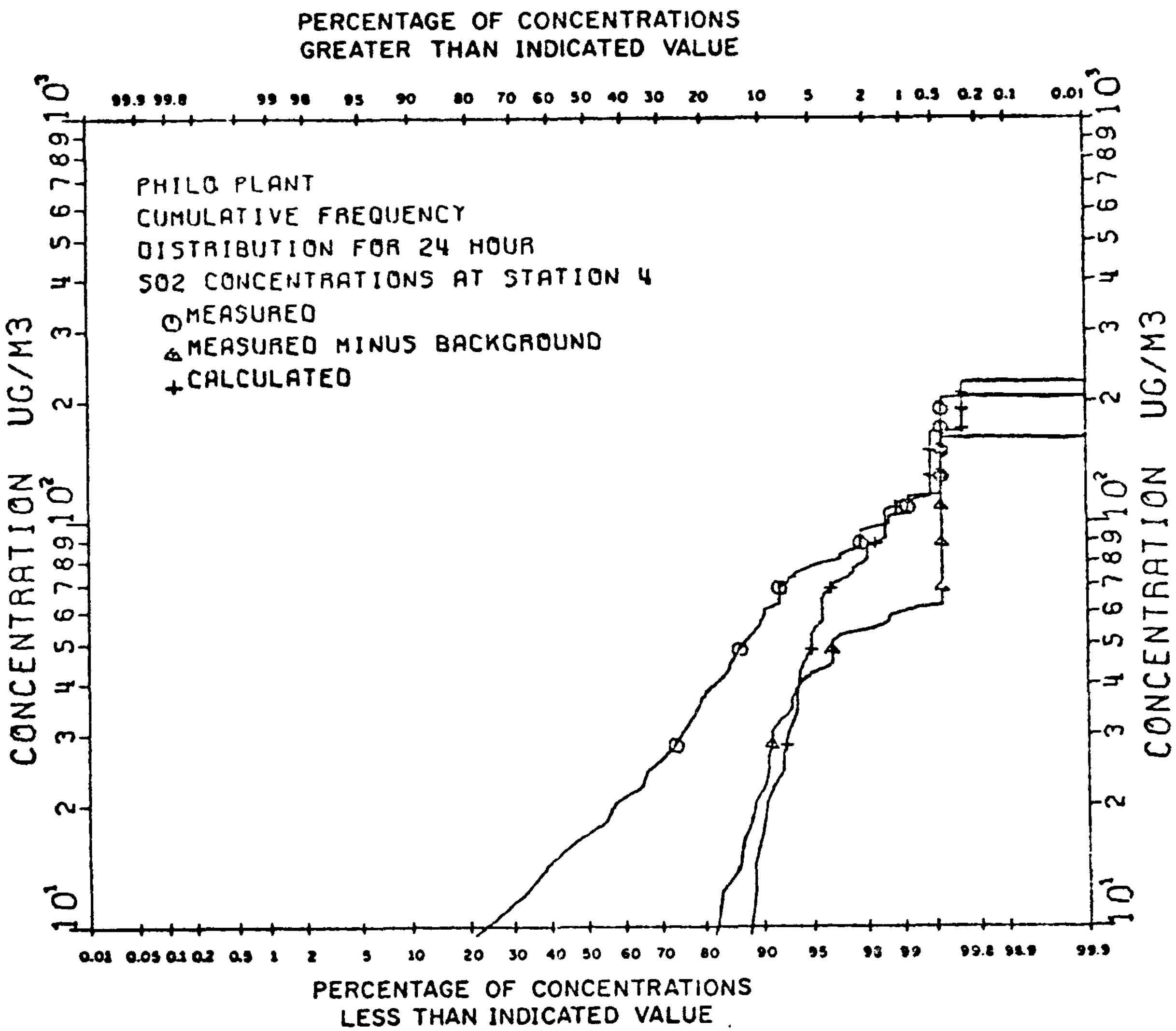

Figure 55. Philo plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 4. Number of measured concentrations = 231; number of calculated concentrations = 365

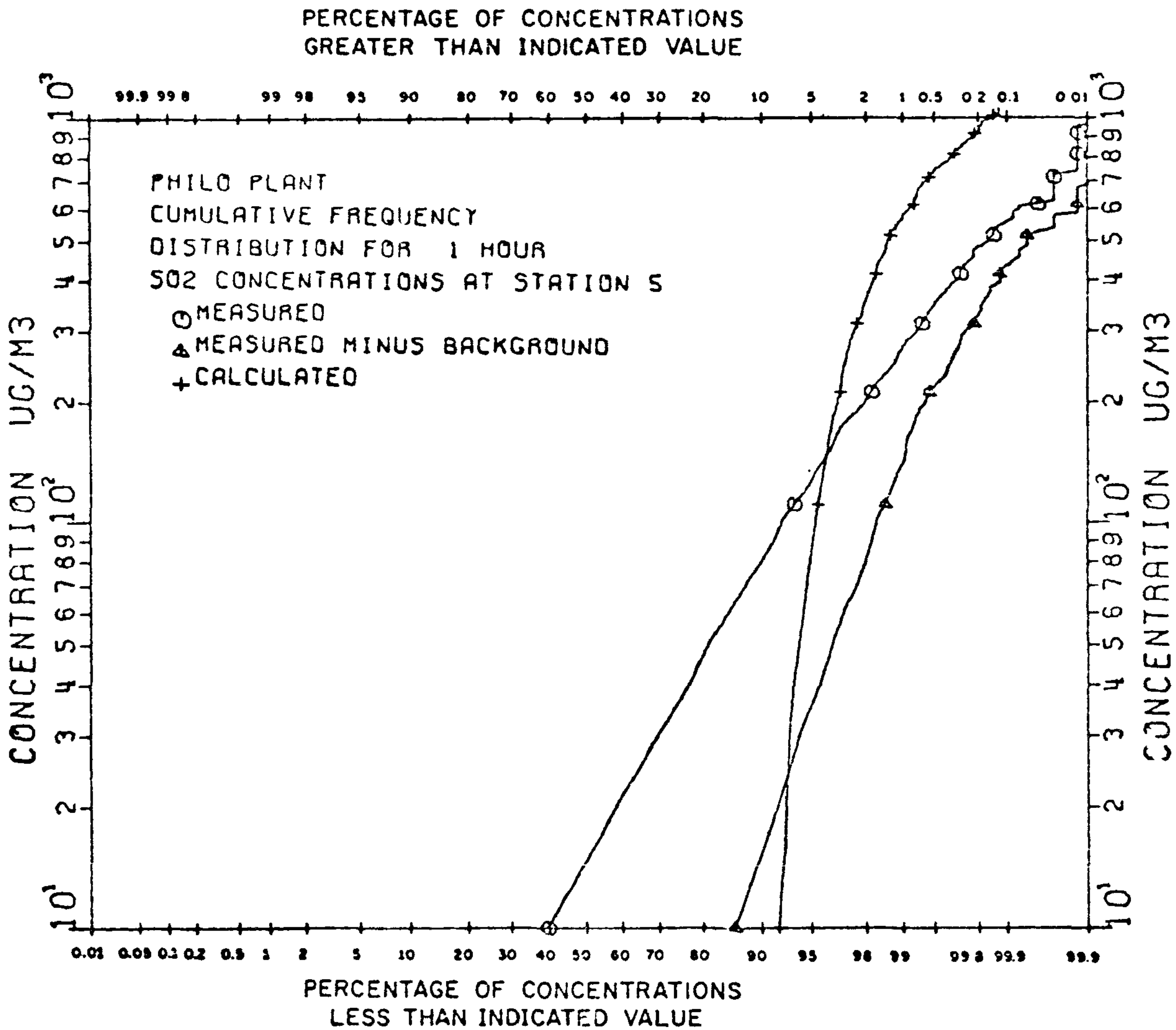

Figure 56. Philo plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 5. Number of measured concentrations = 7209; number of calculated concentrations = 8760

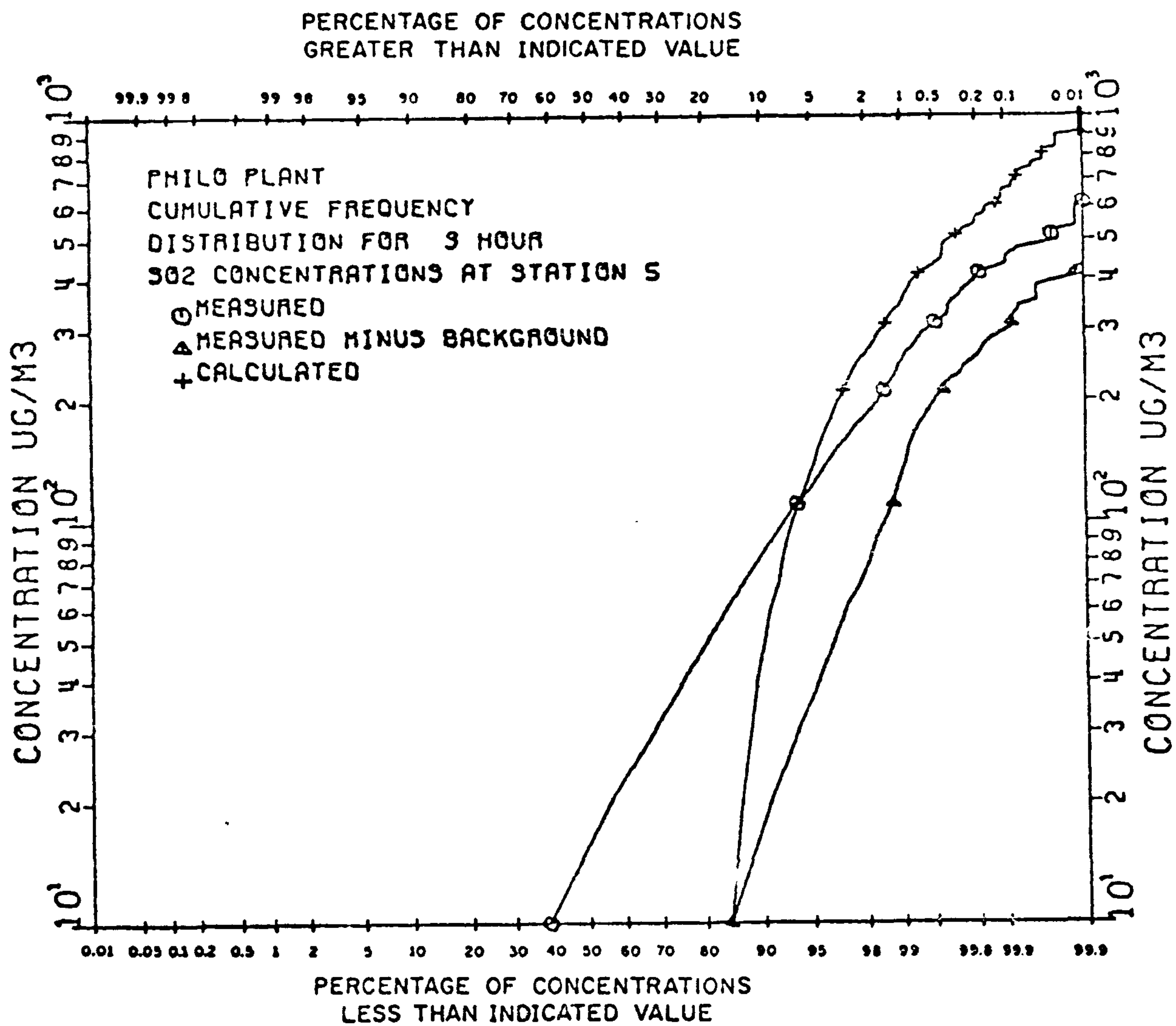

Figure 57. Philo plant cumulative frequency distribution for 3-hour SO_2 concentrations at station 5. Number of measured concentrations = 7452; number of calculated concentrations = 8760

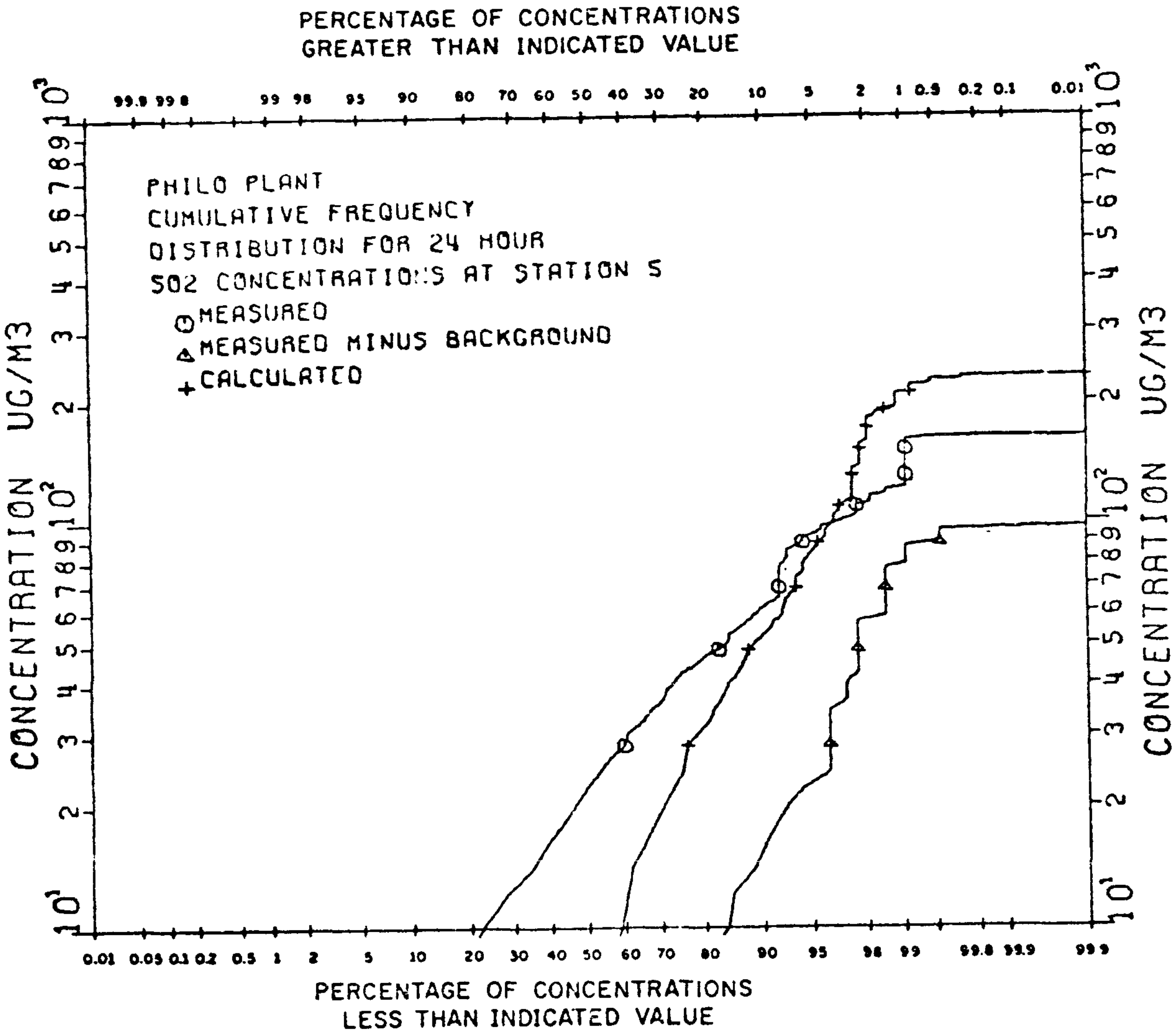

Figure 58. Philo plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 5. Number of measured concentrations = 219; number of calculated concentrations = 365

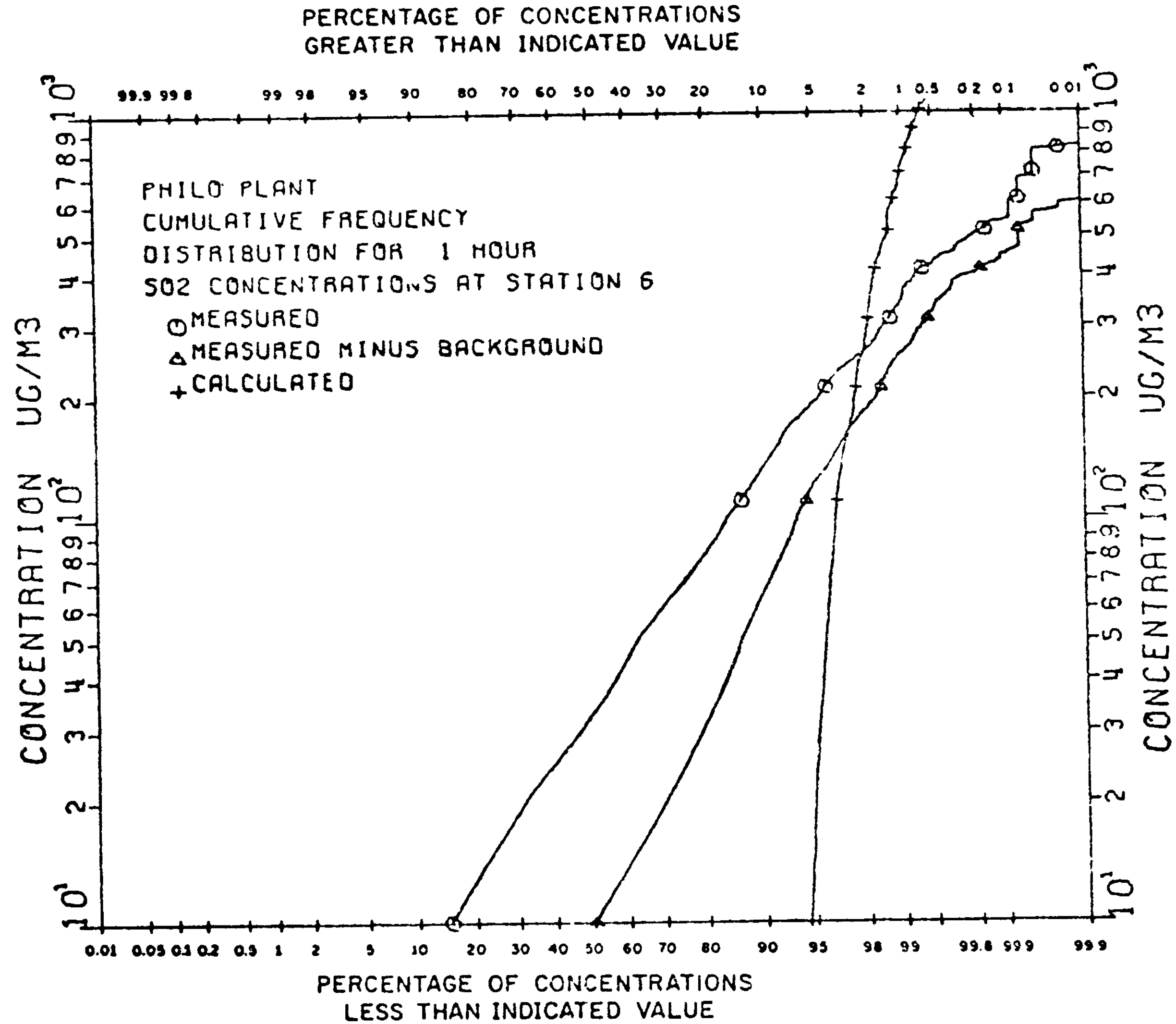

Figure 59. Philo plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 6. Number of measured concentrations = 4882; number of ca.culated concentrations = 8760

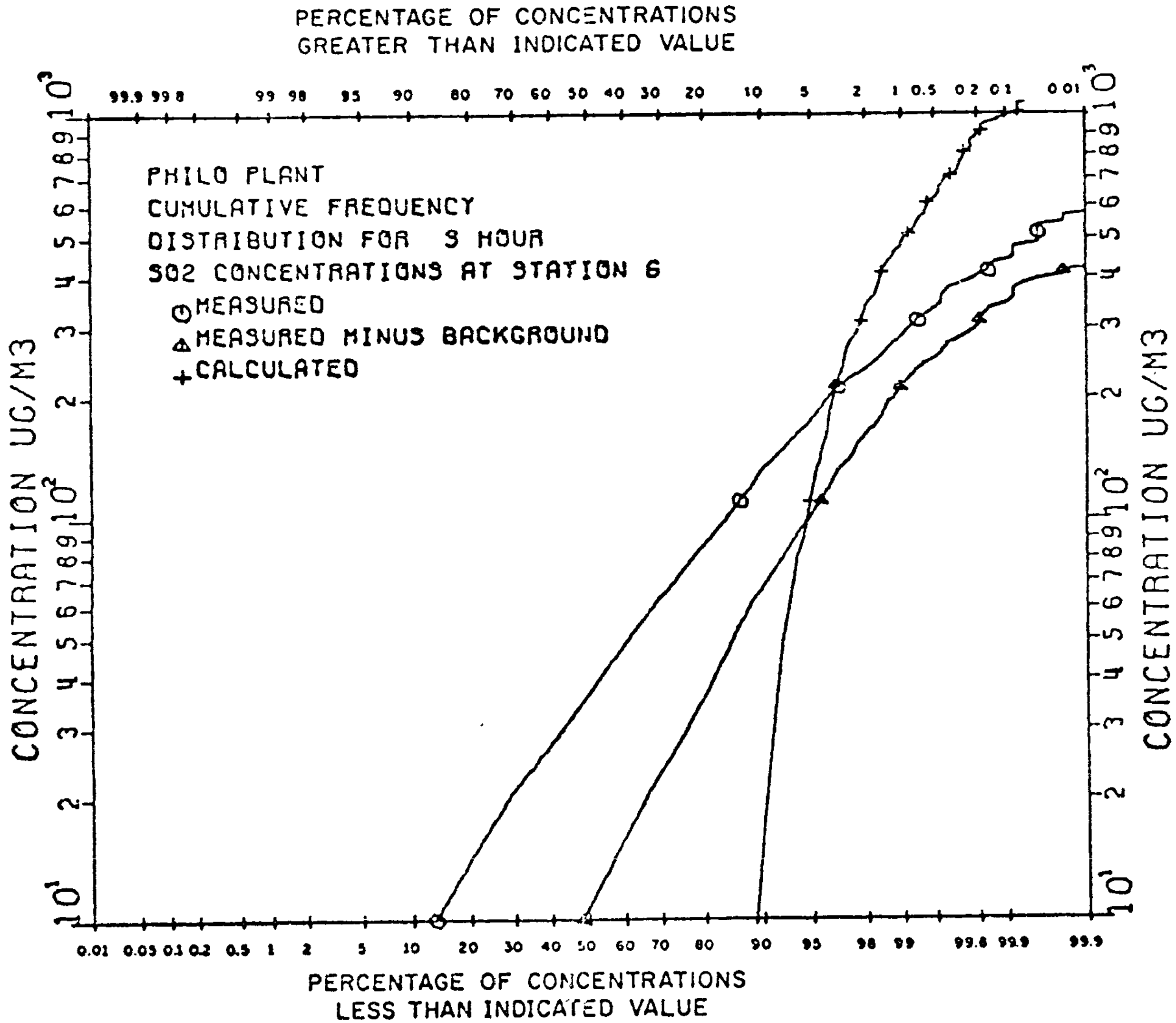

Figure 60. Philo plant cumulative frequency distribution for 3-hour SO_2 concentrations at station 6. Number of measured concentrations = 5012; number of calculated concentrations = 8760

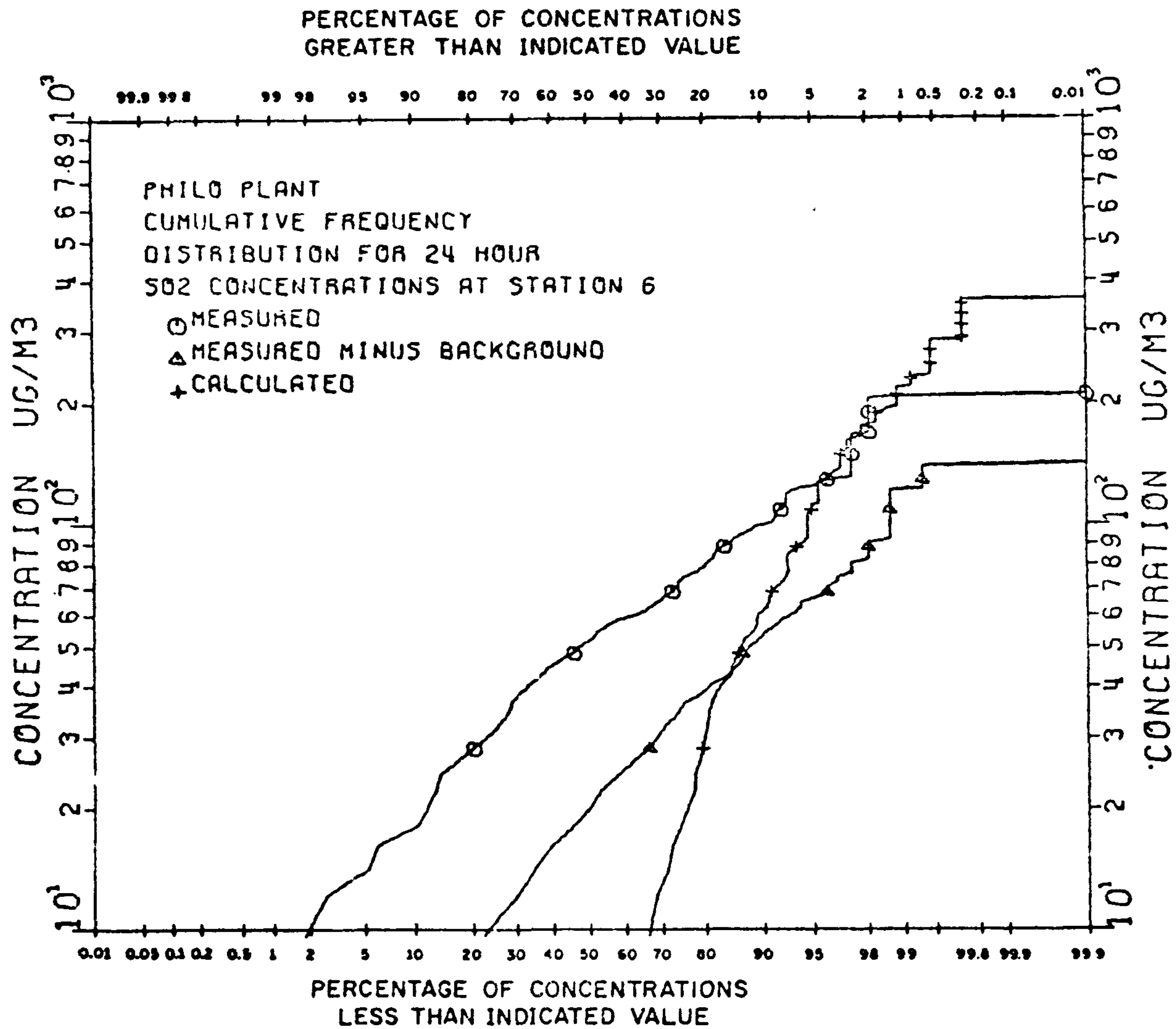

Figure 61. Philo plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 6. Number of measured concentrations = 157; number of calculated concentrations = 365

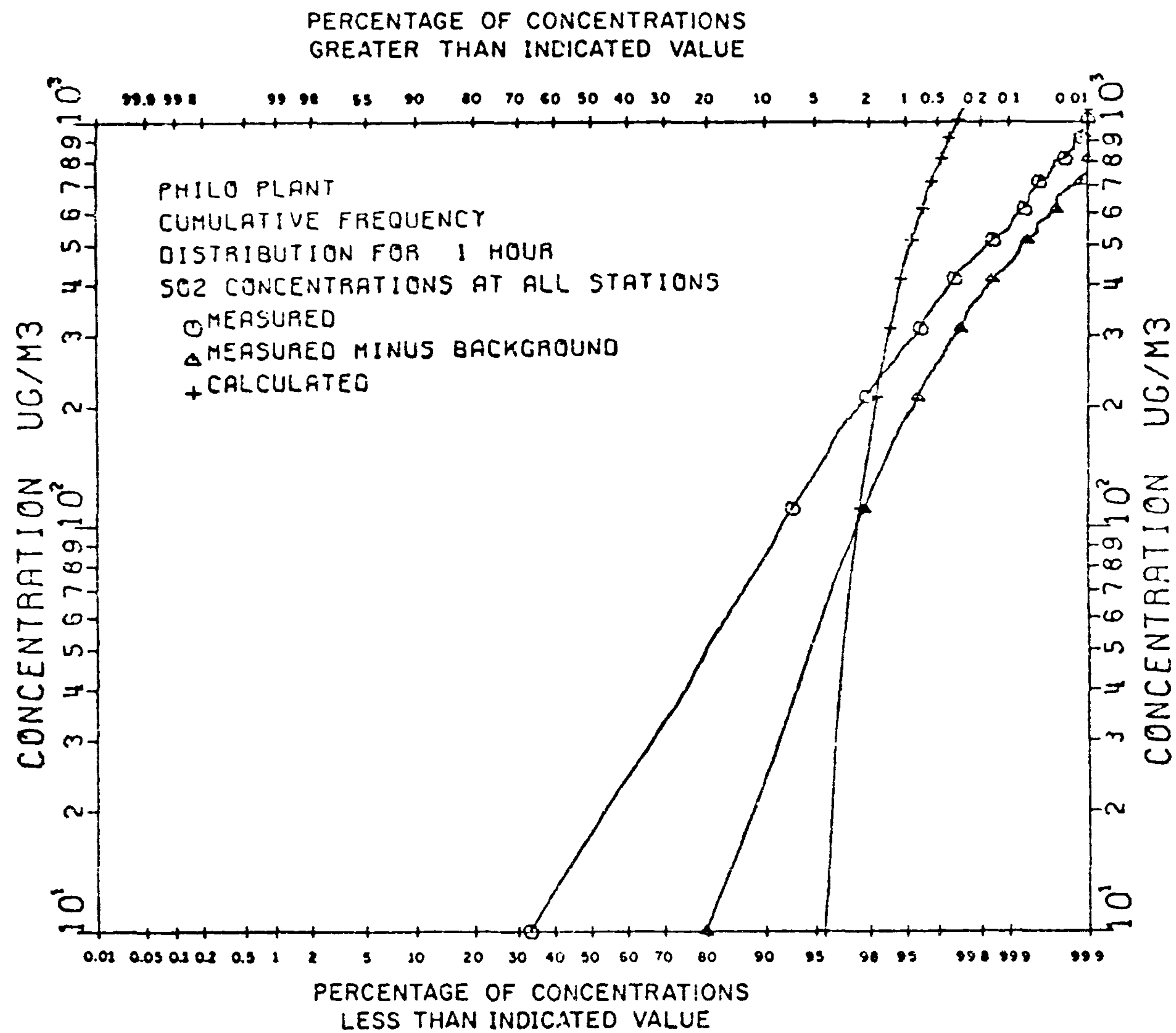

Figure 62. Philo plant cumulative frequency distribution for 1-hour SO_2 concentrations at all stations. Number of measured concentrations = 38471; number of calculated concentrations = 52560

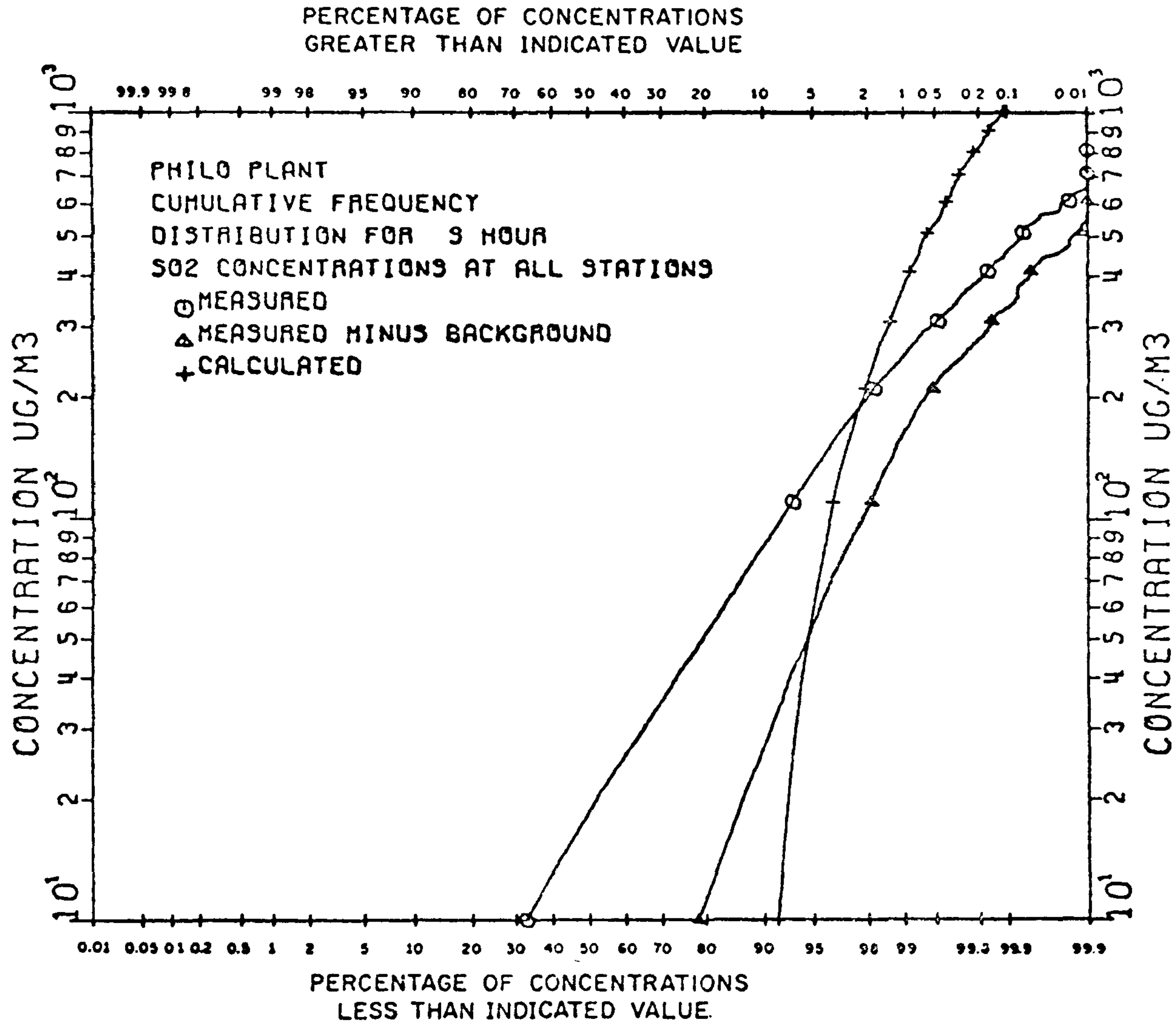

Figure 63. Philo plant cumulative frequency distribution for 3-hour SO_2 concentrations at all stations. Number of measured concentrations = 39,285; number of calculated concentrations = 52,560

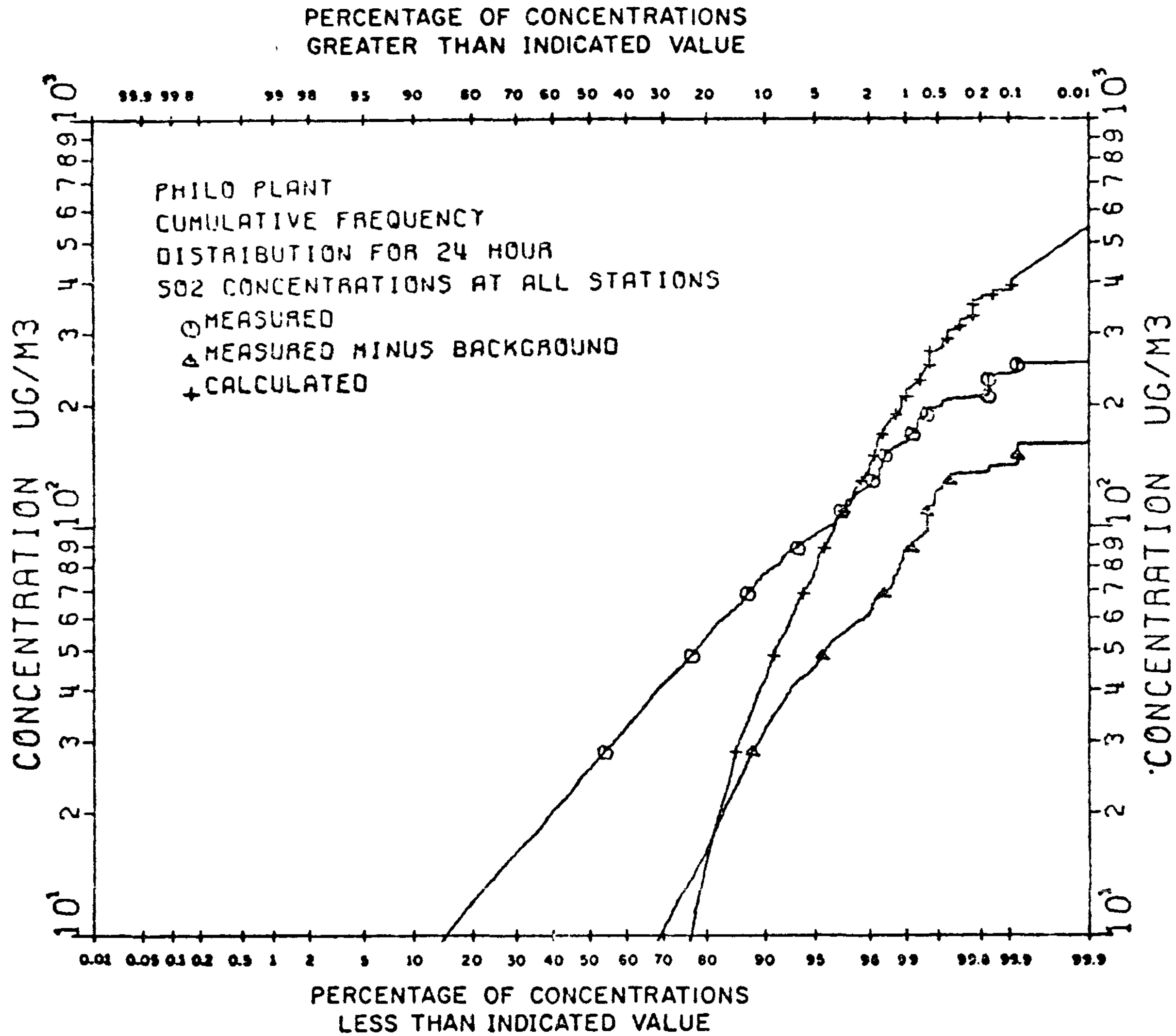

Figure 64. Philo plant cumulative frequency distribution for 24-hour SO_2 concentrations at all stations. Number of measured concentrations = 1290; number of calculated concentrations = 2190

Table 3. J. M. STUART PLANT 1-HOUR CONCENTRATION DISTRIBUTION STATISTICS FOR MEASUREMENTS AND MODEL VALIDATION RUN ($\mu g/m^3$)

Station	Ninety-fifth percentile[a]		Ninety-ninth percentile[a]		Second highest		Highest	
	M[b]	P[c]	M	P	M	P	M	P
1	140	< 10	270	400	685	1372	857	1393
2	80	< 10	445	180	685	814	1014	948
3	74	26	200	240	1022	565	1153	1022
4	53	< 10	180	130	750	515	883	541
5	28	< 10	80	< 10	495	823	565	1219
6	48	< 10	135	120	980	595	1053	693
7	33	< 10	102	30	325	976	435	1000
All	59	< 10	220	151	1022[d]	1372[d]	1153	1393

[a]Percentile values given in terms of cumulative percent of concentrations less than given values.

[b]Measured concentrations with subtracted background.

[c]Predicted concentrations.

[d]Highest concentration not exceeded more than once per year by any given station.

Table 4. J. M. STUART PLANT 3-HOUR CONCENTRATION DISTRIBUTION STATISTICS FOR MEASUREMENTS AND MODEL VALIDATION ($\mu g/m^3$)

Station	Ninety-fifth percentile[a]		Ninety-ninth percentile[a]		Second highest		Highest	
	M[b]	P[c]	M	P	M	P	M	P
1	130	11	270	260	471	762	611	763
2	55	15	420	330	483	415	788	575
3	80	50	160	140	567	355	1048	395
4	58	10	150	110	448	315	883	395
5	30	< 10	83	53	419	415	470	455
6	50	< 10	130	107	772	275	981	355
7	36	< 10	120	100	235	505	389	875
All	65	13	190	150	772[d]	762[d]	1048	875

[a]Percentile values given in terms of cumulative percent of concentrations less than given values.

[b]Measured concentrations with subtracted background.

[c]Predicted concentrations.

[d]Highest concentration not exceeded more than once per year by any given station.

Table 5. J. M. STUART PLANT, 24-HOUR CONCENTRATION DISTRIBUTION STATISTICS FOR MEASUREMENTS AND MODEL VALIDATION RUN ($\mu g/m^3$)

Station	Ninety-fifth percentile[a]		Ninety-ninth percentile[a]		Second highest		Highest	
	M[b]	P[c]	M	P	M	P	M	P
1	83	55	245	128	25[illegible]	149	277	161
2	46	28	160	52	63	75	159	98
3	50	36	110	75	181	91	225	102
4	40	24	63	41	79	45	83	49
5	31	5	52	50	63	57	77	75
6	42	21	135	46	147	69	195	83
7	45	23	69	60	69	73	77	120
All	47	21	115	63	259[d]	149[d]	277	161

[a]Percentile values given in terms of cumulative percent of concentrations less than given values.

[b]Measured concentrations with subtracted background.

[c]Predicted concentrations.

[d]Highest concentration not exceeded more than once per year by any given station.

Table 6. MUSKINGUM PLANT, 1-HOUR CONCENTRATION DISTRIBUTION STATISTICS FOR MEASUREMENTS AND MODEL VALIDATION RUN ($\mu g/m^3$)

Station	Ninety-fifth percentile[a]		Ninety-ninth percentile[a]		Second highest		Highest	
	M[b]	P[c]	M	P	M	P	M	P
1	27	< 10	150	160	857	[illegible]	925	1083
2	57	< 10	270	150	786	1304	786	1310
3	130	< 10	350	210	996	873	1179	933
4	72	< 10	200	160	735	465	786	645
All	72	< 10	250	180	996[d]	1304[d]	1179	1310

[a]Percentile values given in terms of cumulative percent of concentrations less than given values.

[b]Measured concentrations with subtracted backgr[illegible]

[c]Predicted concentrations.

[d]Highest concentr[illegible] not [illegible] more than once per year by any given station.

Table 7. MUSKINGUM PLANT, 3-HOUR CONCENTRATION DISTRIBUTION STATISTICS FOR MEASUREMENTS AND MODEL VALIDATION RUN ($\mu g/m^3$)

Station	Ninety-Fifth percentile[a]		Ninety-Ninth percentile[a]		Second highest		Highest	
	M[b]	P[c]	M	P	M	P	M	P
1	28	< 10	130	180	696	555	823	645
2	70	< 10	225	150	489	615	489	625
3	130	12	325	150	803[d]	465	838	495
4	71	22	170	100	410	265	707	285
All	73	12	225	140	803[d]	625[d]	838	645

[a]Percentile values given in terms of cumulative percent of concentrations less than given values.

[b]Measured concentrations with subtracted background.

[c]Predicted concentrations.

[d]Highest concentration not exceeded more than once per year by any given station.

Table 8. MUSKINGUM PLANT, 24-HOUR CONCENTRATION DISTRIBUTION STATISTICS FOR MEASUREMENTS AND MODEL VALIDATION RUN ($\mu g/m^3$)

Station	Ninety-fifth percentile[a]		Ninety-ninth percentile[a]		Second highest		Highest	
	M[b]	P[c]	M	P	M	P	M	P
1	32	32	100	69	133	81	170	97
2	55	32	100	80	131	82	137	91
3	98	31	130	58	165	73	227	74
4	52	24	95	41	109	45	115	47
All	66	28	120	66	170[d]	91[d]	227	97

[a]Percentile values given in terms of cumulative percent of concentrations less than given values.

[b]Measured concentrations with subtracted background.

[c]Predicted concentrations.

[d]Highest concentration not exceeded more than once per year by any given station.

Table 9. PHILO PLANT, L-HOUR CONCENTRATION DISTRIBUTION STATISTICS FOR MEASUREMENTS AND MODEL VALIDATION RUN ($\mu g/m^3$)

Station	Ninety-fifth percentile[a]		Ninety-ninth percentile[a]		Second highest		Highest	
	M[b]	P[c]	M	P	M	P	M	P
1	50	< 10	170	98	525	1295	893	1639
2	37	< 10	163	222	735	945	891	1059
3	47	< 10	163	920	745	4049	917	4593
4	27	< 10	190	88	665	1945	695	1981
5	35	80	134	555	575	1279	675	1344
6	118	20	253	650	565	2369	595	2482
All	53	< 10	183	443	745[d]	4049[d]	917	4593

[a]Percentile values given in terms of cumulative percent of concentrations less than given values.

[b]Measured concentrations with subtracted background.

[c]Predicted concentrations.

[d]Highest concentration not exceeded more than once per year by any given station.

Table 10. PHILO PLANT, 3-HOUR CONCENTRATION DISTRIBUTION STATISTICS FOR MEASUREMENTS AND MODEL VALIDATION RUN ($\mu g/m^3$)

Station	Ninety-Fifth percentile[a]		Ninety-Ninth percentile[a]		Second highest		Highest	
	M[b]	P[c]	M	P	M	P	M	P
1	51	< 10	160	179	312	735	466	818
2	39	28	180	182	490[d]	515	708	545
3	44	111	140	765	451	2572	567	2572
4	34	< 10	160	225	377	1264	509	1361
5	35	130	130	343	399	900	422	1078
6	100	110	220	475	381	1175	414	1664
All	53	57	160	370	490[d]	2572[d]	708	2572

[a]Percentile values given in terms of cumulative percent of concentrations less than given values.

[b]Measured concentrations with subtracted background.

[c]Predicted concentrations.

[d]Highest concentration not exceeded more than once per year by any given station.

Table 11. PHILO PLANT, 24-HOUR CONCENTRATION DISTRIBUTION STATISTICS FOR MEASUREMENTS AND MODEL VALIDATION RUN ($\mu g/m^3$)

Station	Ninety-fifth percentile[a]		Ninety-first percentile[a]		Second highest		Highest	
	M[b]	P[c]	M	P	M	P	M	P
1	45	29	134	139	132	133	133	147
2	35	39	60	69	67	86	110	104
3	44	143	92	368	127	471	132	541
4	41	47	60	111	62	165	158	220
5	23	81	78	207	87	222	94	226
6	65	107	121	217	121	282	138	356
All	45	73	116	207	132[d]	471[d]	158	541

[a] Percentile values given in terms of cumulative percent of concentrations less than given values.

[b] Measured concentrations with subtracted background.

[c] Predicted concentration.

[d] Highest concentration not exceeded more than once per year by any given station.

Table 12. RATIOS OF MEASURED MINUS BACKGROUND TO PREDICTED 1-HOUR CONCENTRATIONS

Plant	Station	Highest	Second highest	Ninety-ninth percentile
Canal[6]	1	1.55	1.72	16.8
	2	3.45	3.18	72.0
	3	1.44	1.00	9.0
	4	1.33	1.35	31.0
Stuart	1	0.62	0.50	0.68
	2	1.07	0.84	2.47
	3	1.13	1.80	0.83
	4	1.63	1.46	1.38
	5	0.46	0.60	8.0
	6	1.52	1.65	1.13
	7	0.44	0.33	3.4
Muskingum	1	1.08	1.12	7.5
	2	0.77	0.80	1.29
	3	1.00	1.08	1.17
	4	1.39	1.40	1.00
Philo	1	0.54	0.41	1.73
	2	0.84	0.78	0.73
	3	0.20	0.18	0.18
	4	0.35	0.34	2.16
	5	0.50	0.45	0.24
	6	0.24	0.24	0.39

underpredicted stations are under 5 km away, but the model came closest to predicting the farthest stations from the plant - No. 3, at 13 km. The 24-hour concentrations were generally underpredicted by the model, except for Station 7 which it overpredicted and Station 5 which it predicted very closely. The predicted and calculated running three-hour averages are in reasonably good agreement for the upper end of the distribution. Four stations were underpredicted and three were overpredicted.

Muskingum Plant Validation Results

The highest predicted 1-hour concentrations closely agreed with the measured concentrations for the Muskingum Plant. Stations 1 and 4 were underpredicted. Station 2 was overpredicted and Station 3 was very closely predicted, as was the combination of all stations. Station 2 showed close agreement between measured and predicted values for the 3-hour and 24-hour concentrations, but all other stations were underpredicted. As can be seen from Table 13, there appears to be a correlation between the ratio of the second highest measured to predicted 1-hour concentration and the plant-receptor distance, but due to the small number of stations no statistical significance could be attached to this result.

Philo Plant Validation Results

Predicted 1-hour, 3-hour, and 24-hour concentrations were found to exceed the corresponding measured values at each of the six measurement stations. Only at station 2 were the model predictions reasonably close to the measured values. At stations 3 and 6 this overprediction may be directly traced to the fact that the receptor is located at an elevation close to that of the top of the stacks. Since the model accounts for the effect of terrain by reducing the stack height by the difference between receptor and stack base elevation, concentrations will be overestimated for these two stations unless a further correction is made to account for the effect of terrain upon the plume itself. This overprediction for small source-receptor elevation differences is responsible for the 0.74 correlation

Table 13. CORRELATIONS

Correlation of ratio of second highest measured to predicted 1-hour concentration versus distance

Plant	Correlation coefficient estimate	95% confidence interval	Significance
Canal[6]	0.16	-0.947 to 0.972	none
Stuart	0.89	0.415 to 0.984	significant to 1%
Muskingum	0.88	-0.526 to 0.997	none
Philo	0.15	-0.753 to 0.857	none
All	0.25	-0.204 to 0.615	none

Correlation of ratio of second highest measured to predicted 1-hour concentration versus elevation of top of stack above receptor

Plant	Correlation coefficient estimate	95% confidence interval	Significance
Canal[6]	0.82	-0.66 to 0.996	none
Stuart	-0.30	-0.859 to 0.585	none
Muskingum	-0.65	-0.992 to 0.829	none
Philo	0.74	-0.179 to 0.969	none
All	0.14	-0.310 to 0.539	none

coefficient given in Table 13. Although at the other stations the over-prediction problem is not as extreme, the method of stack height reduction employed in the model is at least partially responsible for the poor agreement.

Summary of Modeling Results

Based upon our model validation studies for these three Ohio power plants we can make the following observations:

- Much better agreement is obtained between measured and calculated concentration frequency distributions for the higher concentrations. The poor agreement at lower concentrations is due largely to uncertainties associated with the determination of background concentrations.

- The best agreement between measured and predicted concentrations was obtained for 1-hour and 3-hour concentrations with geometric means of measured to predicted second highest concentrations of 0.93 and 1.17 respectively. The 24-hour concentrations were generally underpredicted with a geometric mean of measured to predicted concentration of 1.59. In the determination of these ratios, data from the Philo Plant was excluded due to the effect of low stacks and rugged terrain which may have affected the accuracy of the model.

- The model has a tendency to underpredict concentrations at larger distances (Table 13). The correlation between source-receptor distance and measured to predicted second highest concentration was, however, found to be statistically significant only for the Stuart Plant.

- The treatment of terrain effects used by the model was found to be inapplicable for those receptor locations with elevation near stack height.

- The model validation results for these three plants were quite different than those obtained from the initial validation study[6] conducted at the Canal Plant in Massachusetts. Concentrations from this seacoast facility were considerably underpredicted for all stations and averaging times.

SECTION V

ANALYSIS OF CONCENTRATION RATIO DISTRIBUTIONS

ANALYSIS OF PRESENT STUDY

The peak 1-hour to average 3-hour ratio must be between 1 and 3. Likewise the peak 1-hour to average 24-hour ratio has a range of 1 to 24. Since the cumulative distributions are bounded by a maximum and minimum value it is difficult to describe them in terms of standard types of distributions such as normal or log-normal. The distributions are closer to being log-normal than normal, as can be seen when they are graphed on the log-normal probability paper in Figure 65, for the J. M. Stuart Plant, and the normal probability paper in Figure 66. Distributions for the Muskingum and Philo Plants are shown in Figures 67 through 70. Another complication arises from the fact that the original concentration values were recorded to the nearest 0.01 ppm. This leads to the ratio distributions being discrete in nature. The most obvious example of this can be seen from the peak 1-hour to average 3-hour normal plot in Figure 66. There is a large jump in the curve as the ratio approaches 1.5. This is due to the large number of combinations of three discrete consecutive 1-hour concentrations which can cause a ratio of 1.5. If the three concentrations are x_1, x_2, x_3 and x_1 is the concentration for the peak hour, then if $x_2 + x_3 = x_1$ the ratio will be 1.5. Examples of this would be (0.01, 0.01, 0), (0.01, 0, 0.01), (0, 0.01, 0.01), (0.02, 0.02, 0) etc.

The statistics associated with these ratio distributions are given in Table 14. In addition to the ratio distribution statistics for the three Ohio power plants, we have also listed the results for the Canal Plant study[6] and those obtained by the Tennessee Valley Authority (TVA)[2] in the

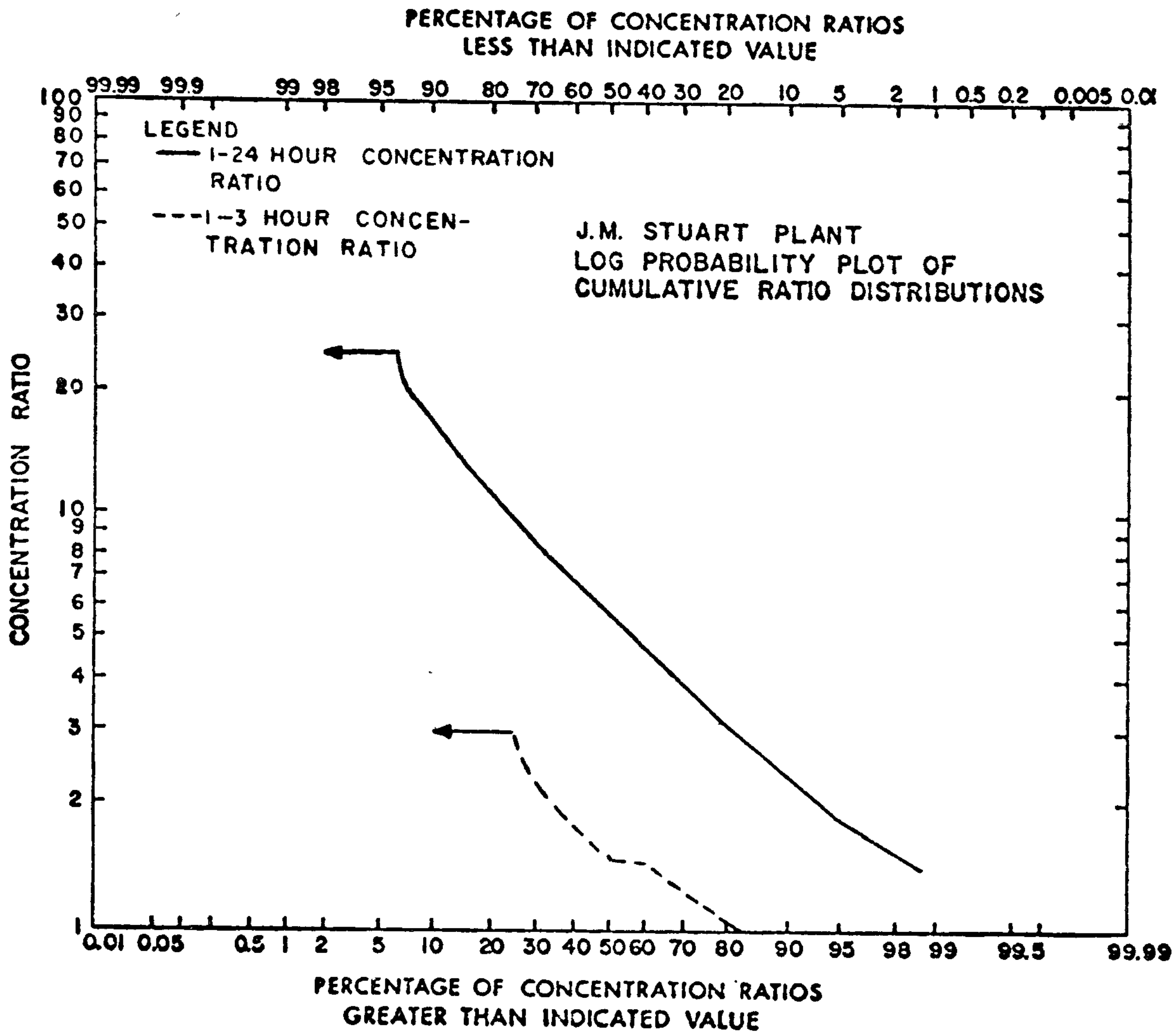

Figure 65. J. M. Stuart Plant log probability plot of cumulative ratio distributions

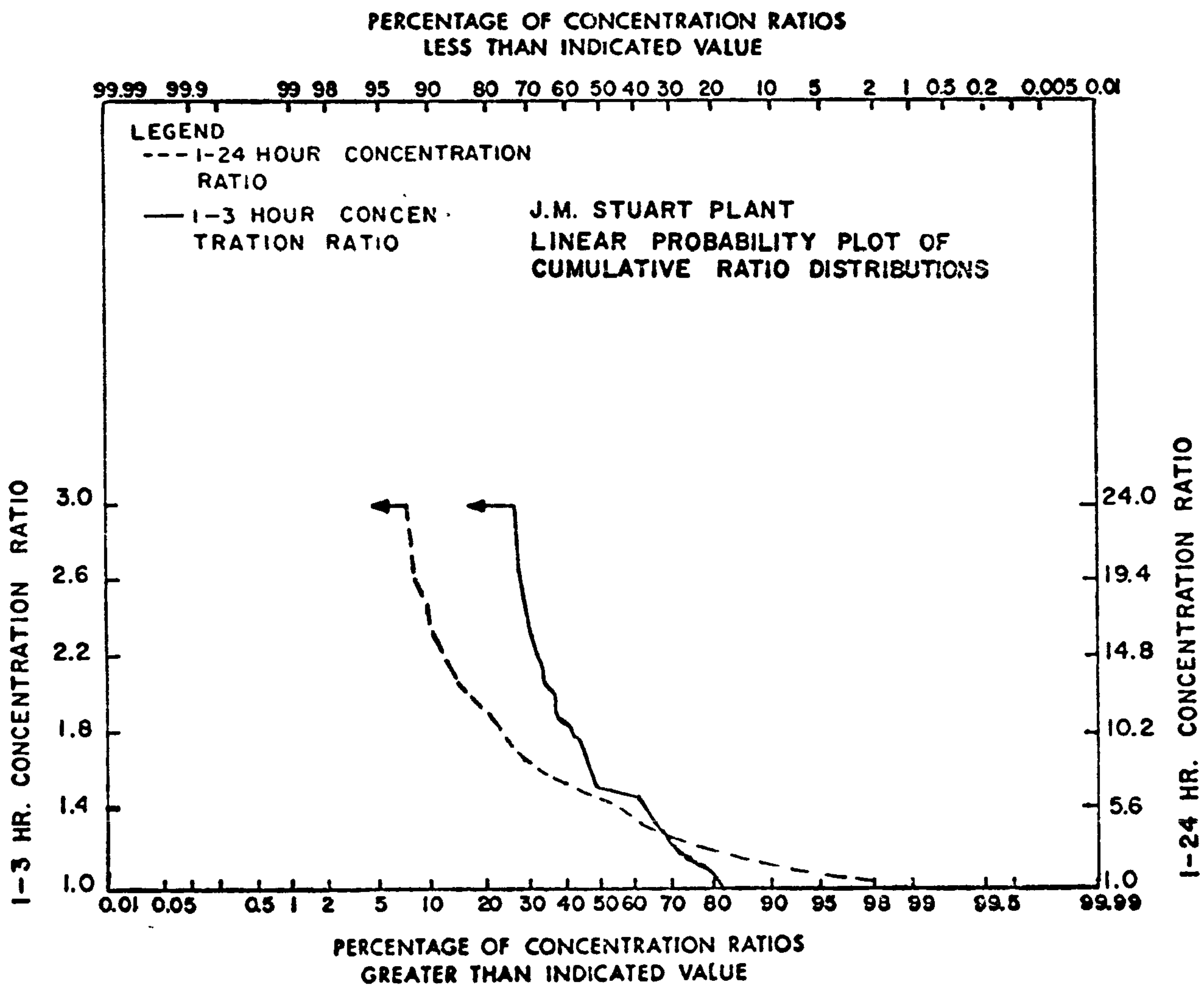

Figure 66. J. M. Stuart Plant linear probability plot of cumulative ratio distributions

Table 14. STATISTICS FOR RATIO DISTRIBUTION

Ratios	Arithmetic mean	Arithmetic standard deviation	50%[a]	95%[a]	99%[a]	Correlation[b]	95% Confidence interval
J. M. STUART PLANT							
1-3 hour[c]	1.86	0.76	1.55	1.00	1.00	-0.0584	-0.07148 to -0.04530
1-24 hour[d]	7.71	5.94	5.95	1.93	1.40	0.00155	-0.05081 to +0.05390
MUSKINGUM PLANT							
1-3 hour	1.99	0.76	1.74	1.00	1.00	-0.079	-0.0949 to -0.0631
1-24 hour	9.23	6.79	6.65	2.38	1.77	-0.151	-0.2083 to -0.0927
PHILO PLANT							
1-3 hour	2.00	0.72	1.77	1.04	1.01	-0.36	-0.3720 to -0.3479
1-24 hour	8.77	5.77	6.98	2.47	1.92	-0.40	-0.4474 to -0.3503
CANAL PLANT[6]							
1-3 hour	1.81	0.70	1.50	1.02	1.02	-0.017	-0.0283 to -0.0057
1-24 hour	7.84	6.31	5.37	1.69	1.23	-0.008	-0.0573 to -0.0414
PARADISE PLANT[2]							
1-3 hour	1.80	-	1.63	0.99	-	-	-
1-24 hour	15.9	-	12.4	4.00	-	-	-

[a]Percentile values given in terms of cumulative percent of ratios greater than given values.

[b]Correlation between ratio and peak 1-hour concentration.

[c]Peak 1-hour to average 3-hour ratio for measured minus background SO_2 concentration.

[d]Peak 1-hour to average 24-hour ratio for measured minus background SO_2 concentration.

vicinity of the Paradise Power Plant with data taken over a 2-1/2 year period from January 1968 through June 1970. The ratio statistics do not vary significantly except for the Paradise Plant where the peak 1-hour to average 24-hour ratios are greater by a factor of 2. The 1-3 hour ratio means ranged from 1.80 at Paradise to 2.00 at Philo, and the standard deviation associated with these ratio distributions ranged from 0.70 at Canal to 0.76 at Stuart and Muskingum. With the exception of the Paradise Plant the 1-24 hour ratio means ranged from 7.71 at Stuart to 9.23 at Muskingum, and the standard deviations ranged from 5.77 at Philo to 6.74 at Muskingum.

The discrepancy between the 1-24 hour ratio distribution statistics for Paradise and the other power plants could be due to the fact that at the peak concentrations reported for the Paradise network were actually 5-minute averages which had to be converted to the 1-hour averaging time according to the method outlined in Table 5.1 of Turner's[1] Workbook. The fact that concentrations less than 0.10 ppm were excluded from the analysis of the Paradise data could also be responsible for this difference.

Suggestions for Future Study

Since the primary application of these concentration ratio distributions would be the estimation of average 24-hour concentrations associated with highest or second highest peak 1-hour concentrations, it would be instructive to carry out the preceding time-concentration analysis for those peak 1-hour concentrations above a given cutoff value. This procedure would avoid the problem of the distributions being weighted toward those low concentrations near the threshold of the sampler. Another approach which would prove useful in the extension of 1-hour concentrations to longer averaging times would be the analysis of the behavior of ratio distribution statistics for different meteorological conditions. A study of this type performed during the Canal Plant study[6] found a significant increase in 1-3 hour ratios for the lower stability classes (A,B).

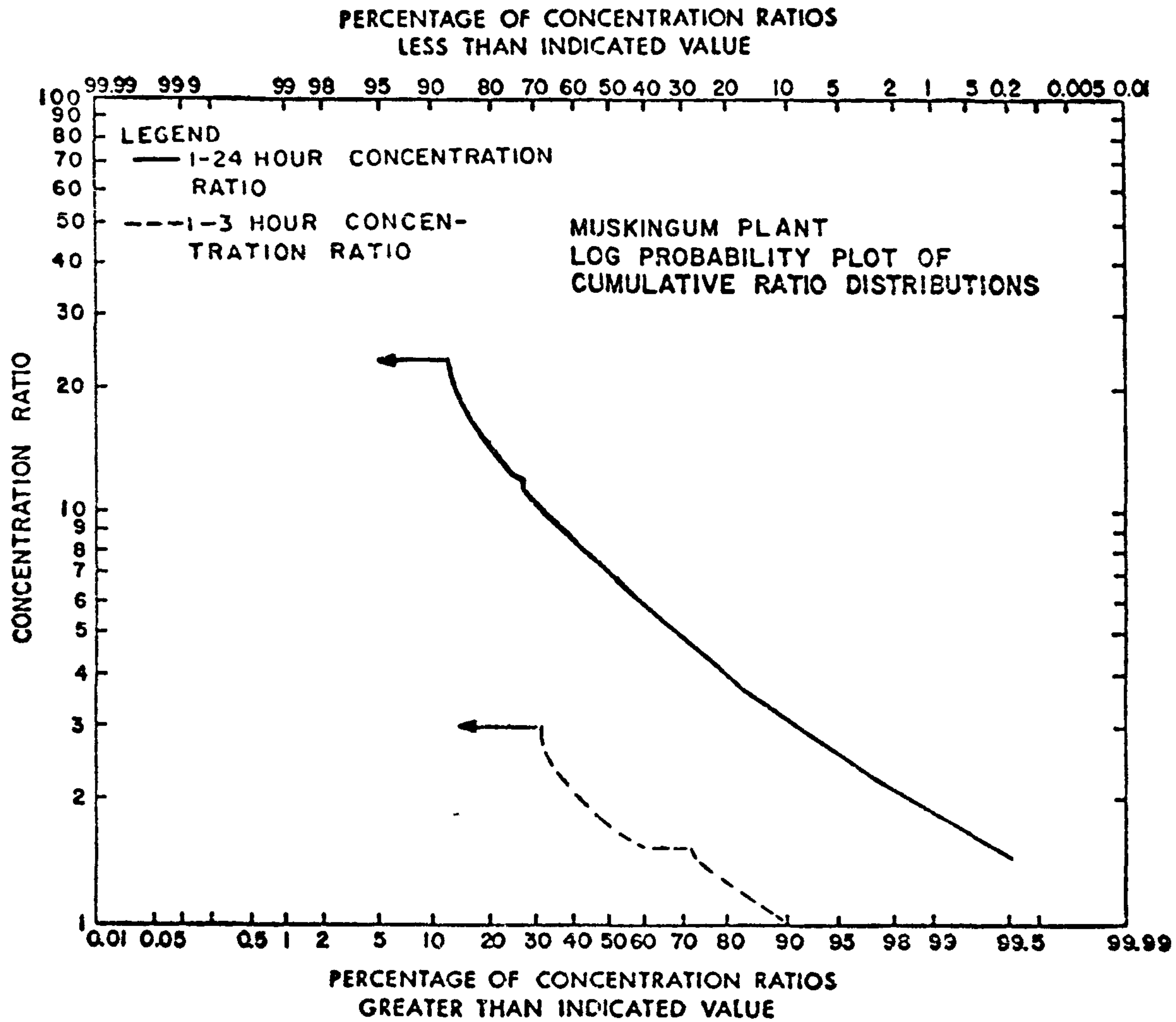

Figure 67. Muskingum Plant log probability plot of cumulative ratio distributions. Number of 1-3 hour ratios = 15,059; number of 1-24 hour rations = 1100

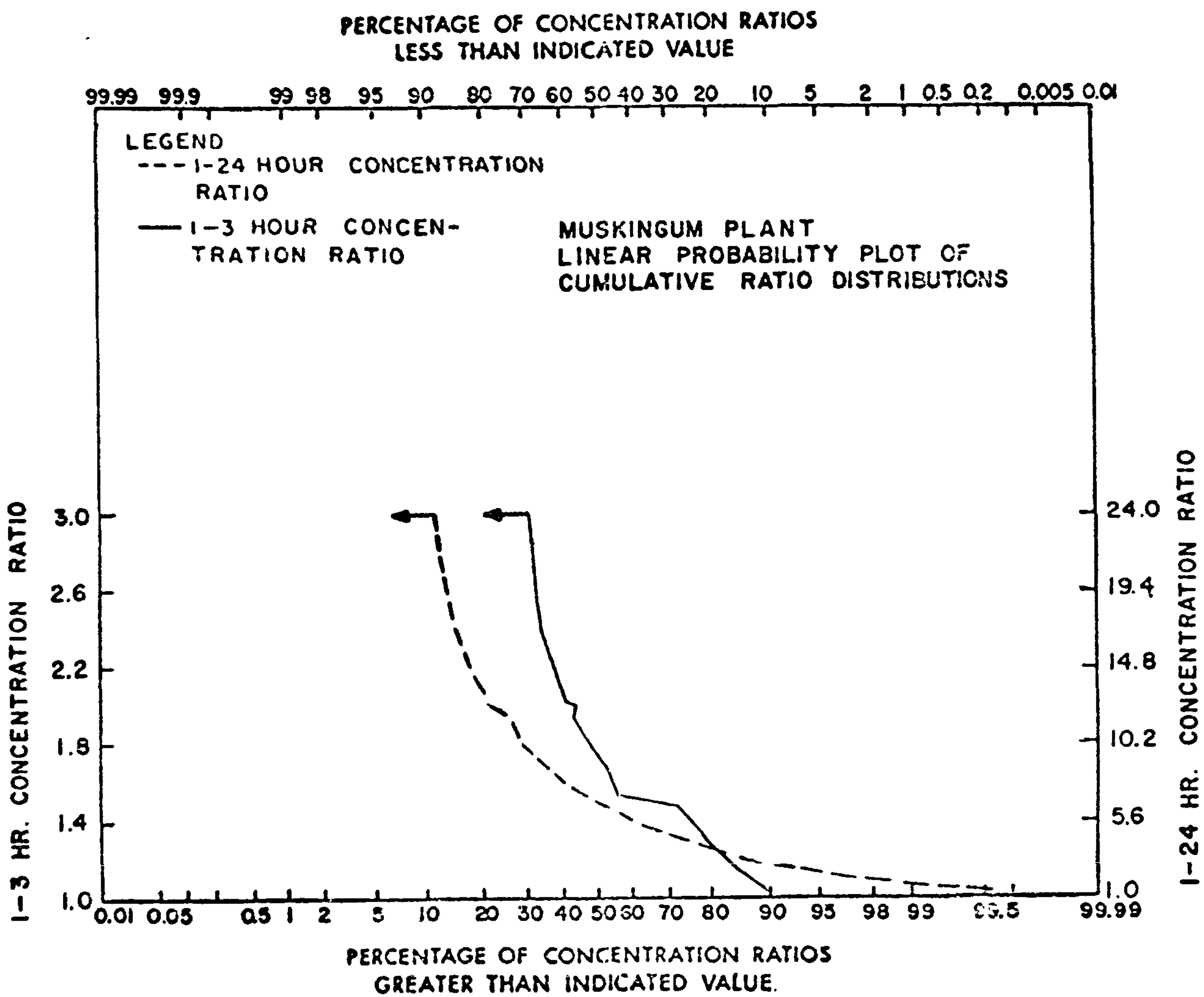

Figure 68. Muskingum Plant linear probability plot of cumulative ratio distributions. Number of 1-3 hour ratios = 15,059; number of 1-24 hour ratios = 1100

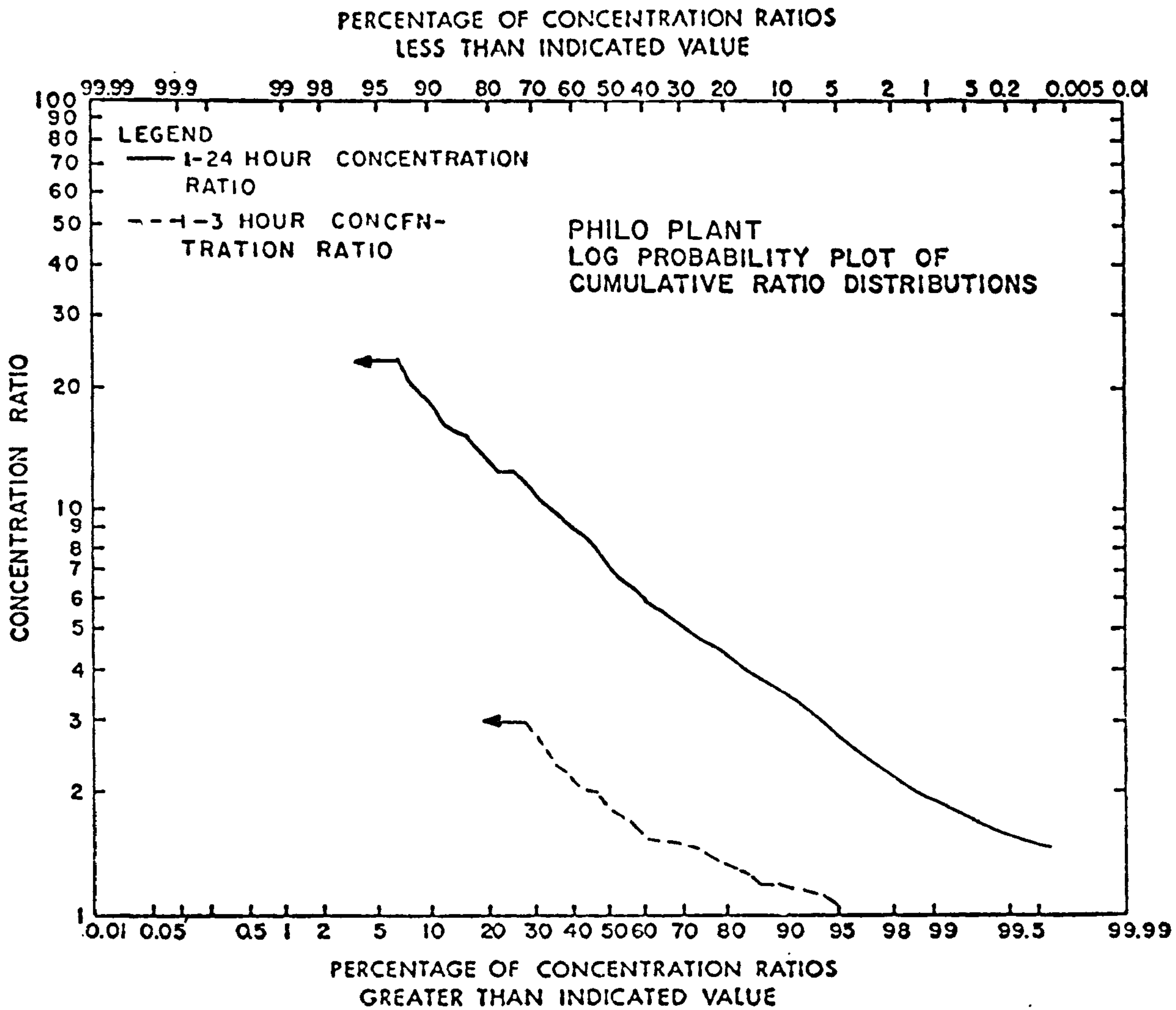

Figure 69. Philo Plant log probability plot of cumulative ratio distributions. Number of 1-3 hour ratios = 20,142; number of 1-24 hour ratios = 1,152

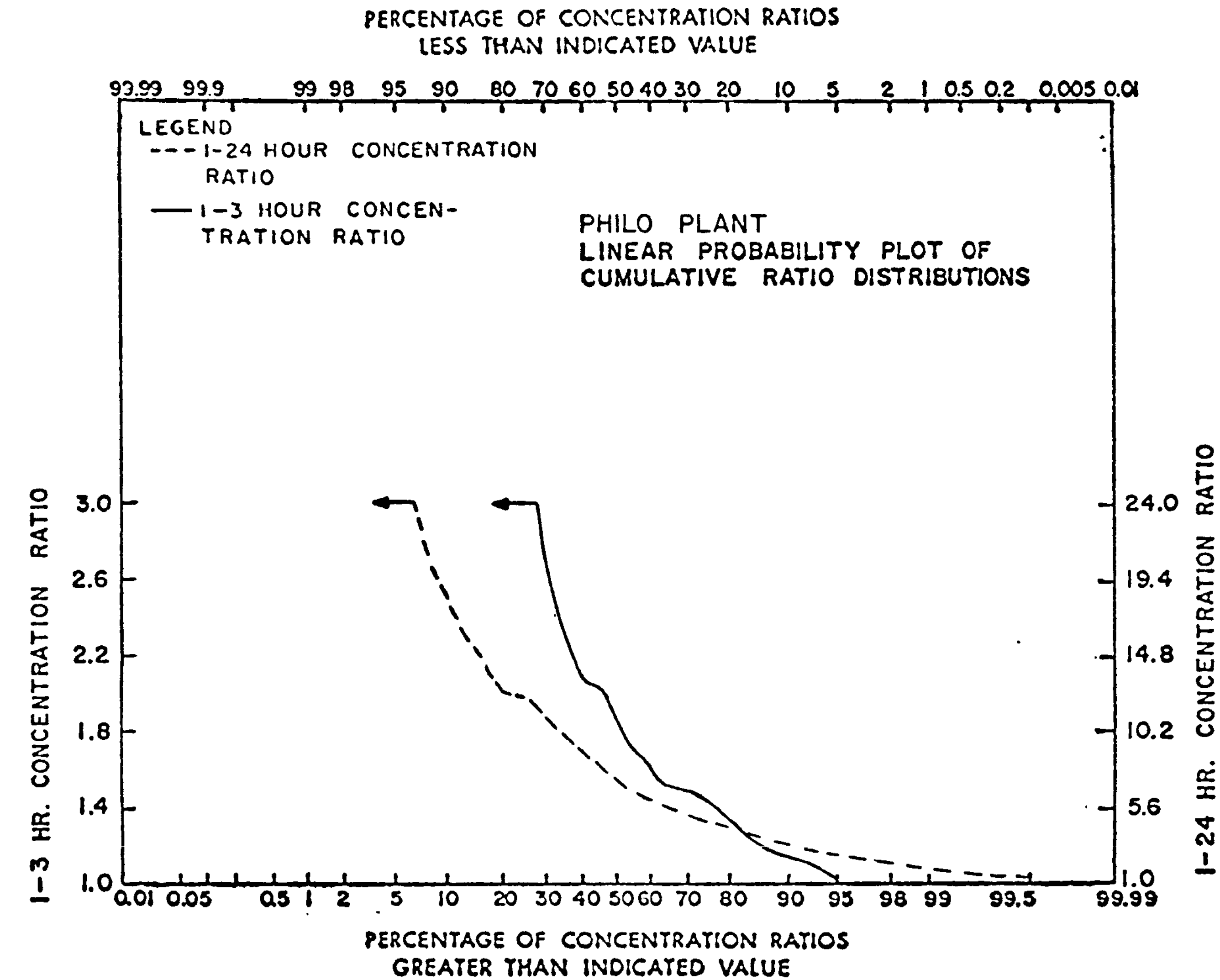

Figure 70. Philo Plant linear probability plot of cumulative ratio distributions. Number of 1-3 hour ratios = 20,142; number of 1-24 hour ratios = 1,152

SECTION VI

FURTHER ANALYSIS OF MODEL VALIDATION PROCEDURES

A comparison of the frequency distributions of the model calculations and the observed 1-hour concentrations shows that the model predicts the upper percentile fairly well, but significantly underpredicts most of the remainder of the distribution. A similar effect occurs in the frequency distributions of the 24-hour concentrations. Part of the underprediction may be due to sampler errors since many of the lower concentrations are measured near the threshold of the sensing device. Also, much of the low concentration end of the distribution does not represent pollution from the plant at all, but rather differences between the estimated background and the actual background at the sampler. For example, if three samplers upwind of the plant recorded concentrations 10, 20 and 45 $\mu g/m^3$, the "background" would be considered the average of the upwind stations, in this case 25 $\mu g/m^3$. This "background" is subtracted from each concentration recorded at that hour, so that, in this case, we have two negative concentrations, and one positive value of 20 $\mu g/m^3$. Corresponding model predictions would, quite correctly, be zero. When the background is added to the predicted concentrations, the predicted and measured concentrations appear to be in better agreement for the lower concentrations as shown in Figures 71 through 86 for the J. M. Stuart Plant receptor locations. This apparent improvement in model predictions at low concentrations is largely a cosmetic effect, however, since for the most part we are comparing background concentrations with themselves.

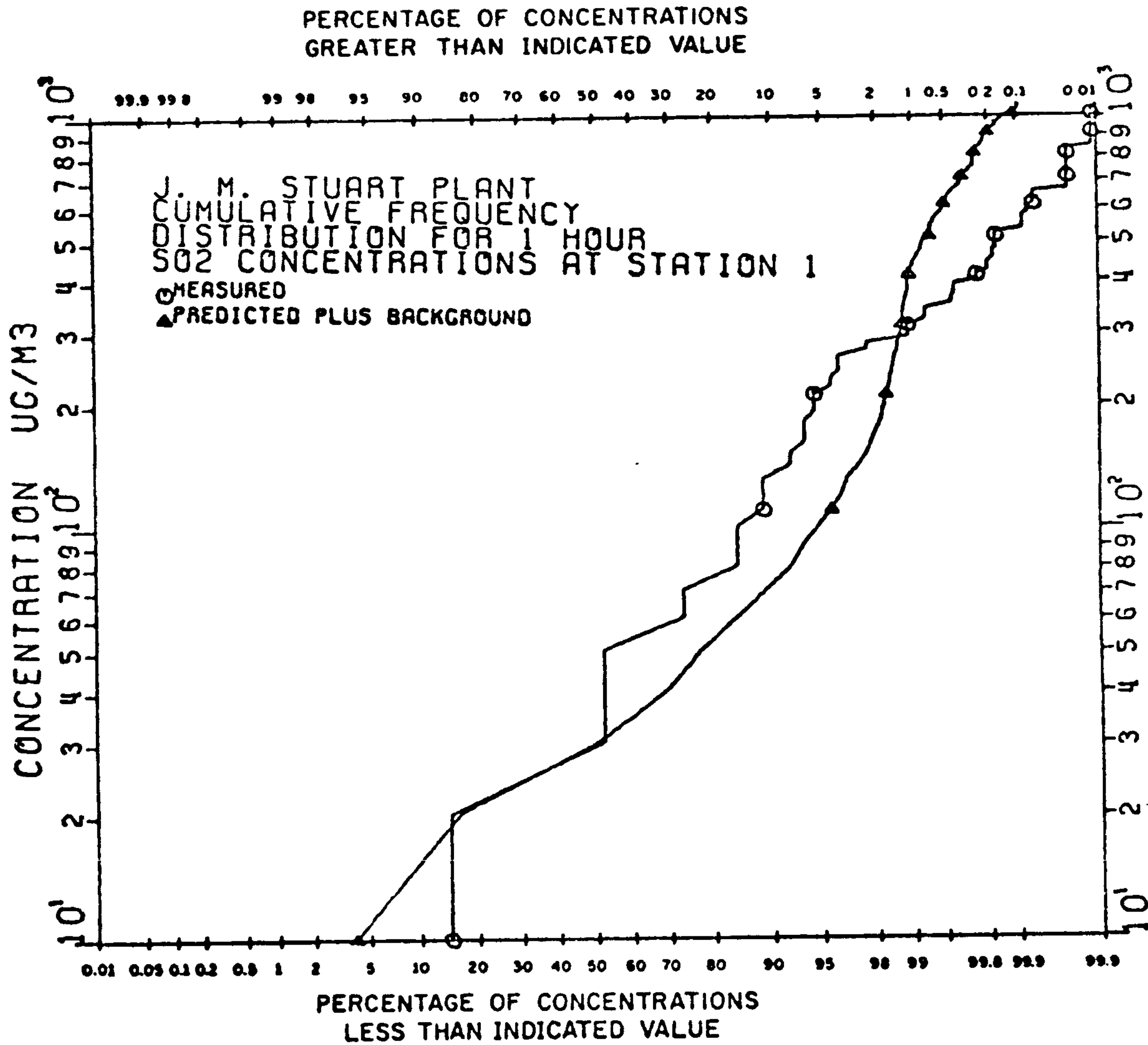

Figure 71. J. M. Stuart Plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 1

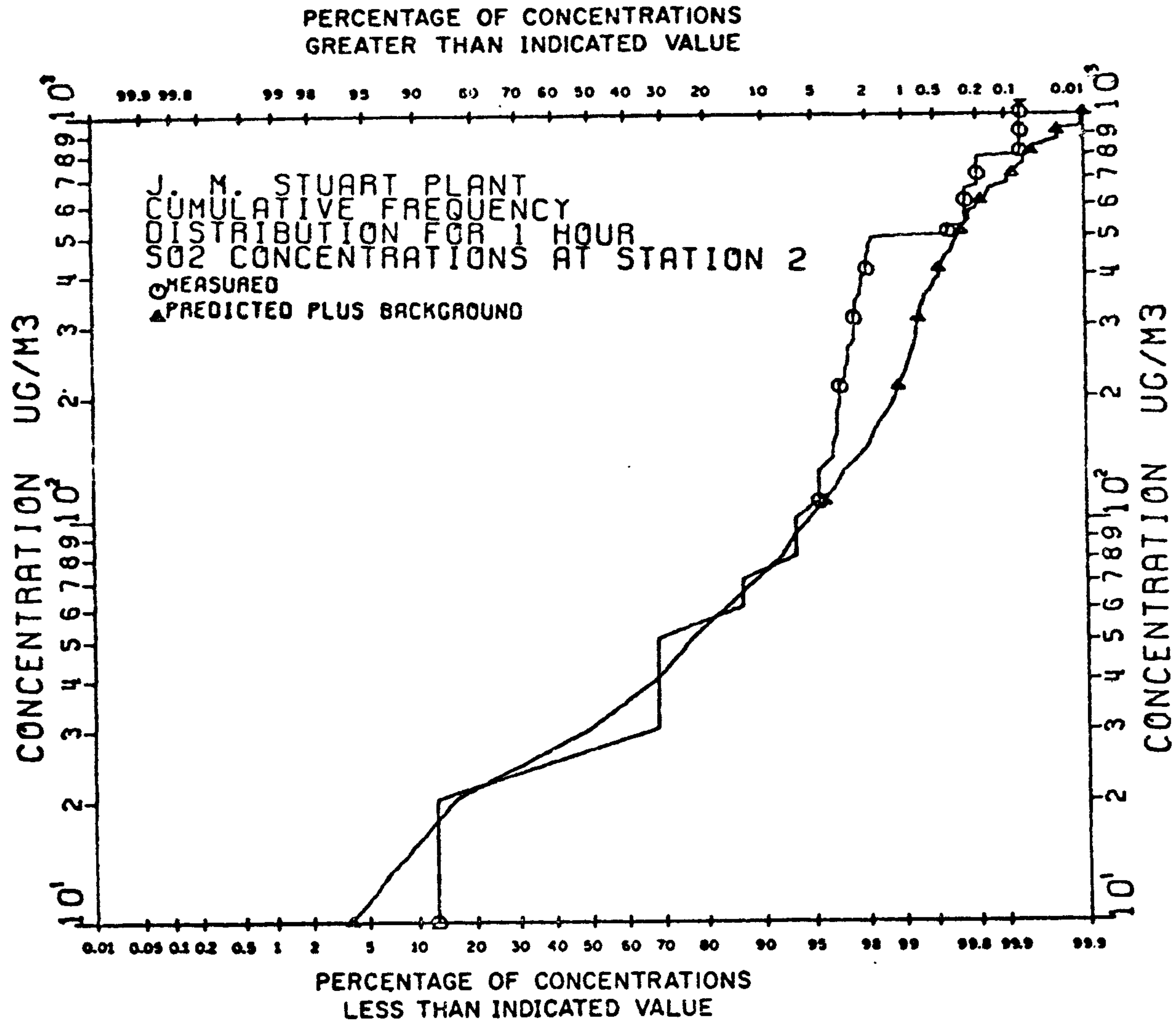

Figure 72. J. M. Stuart Plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 2

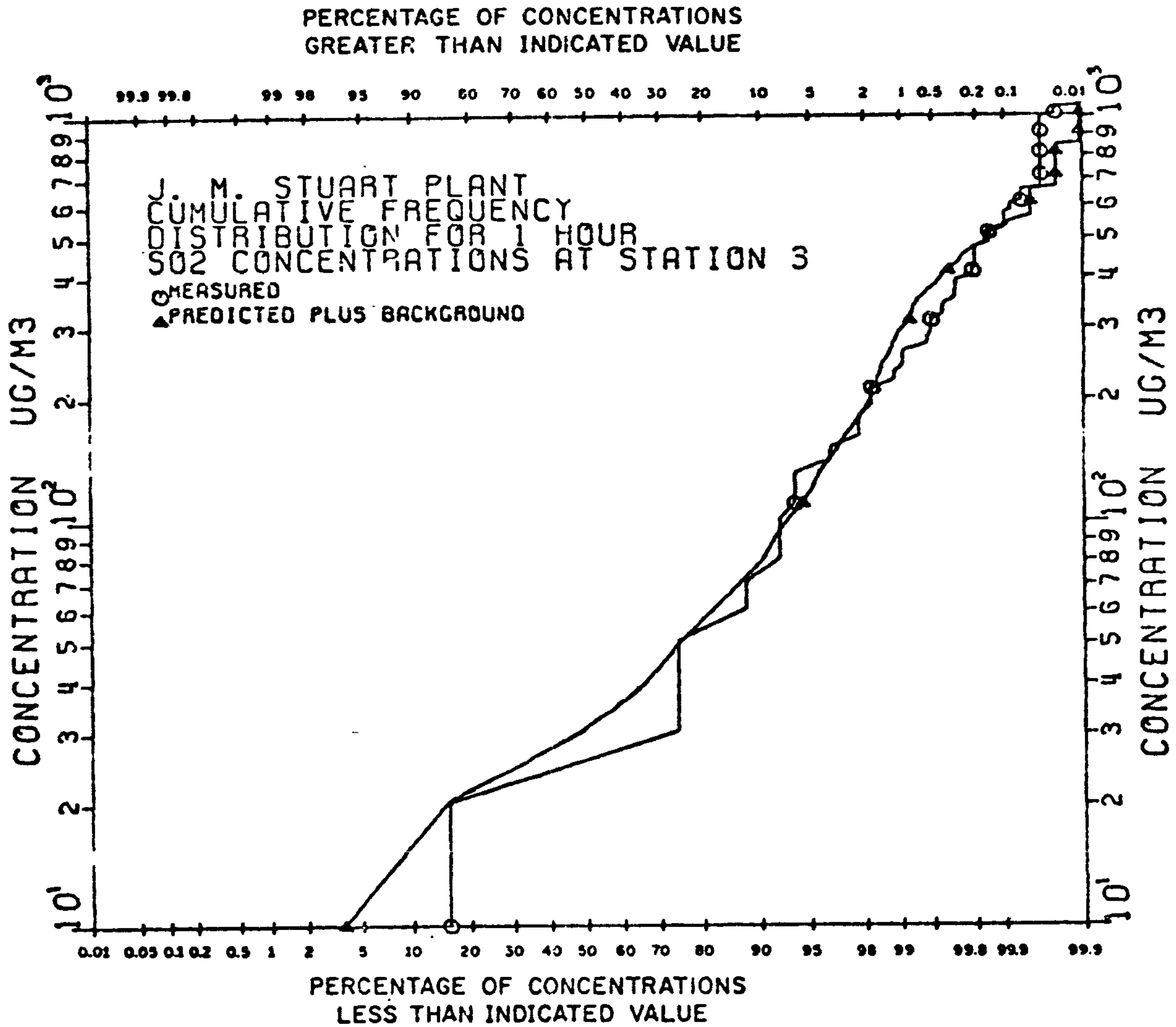

Figure 73. J. M. Stuart Plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 3

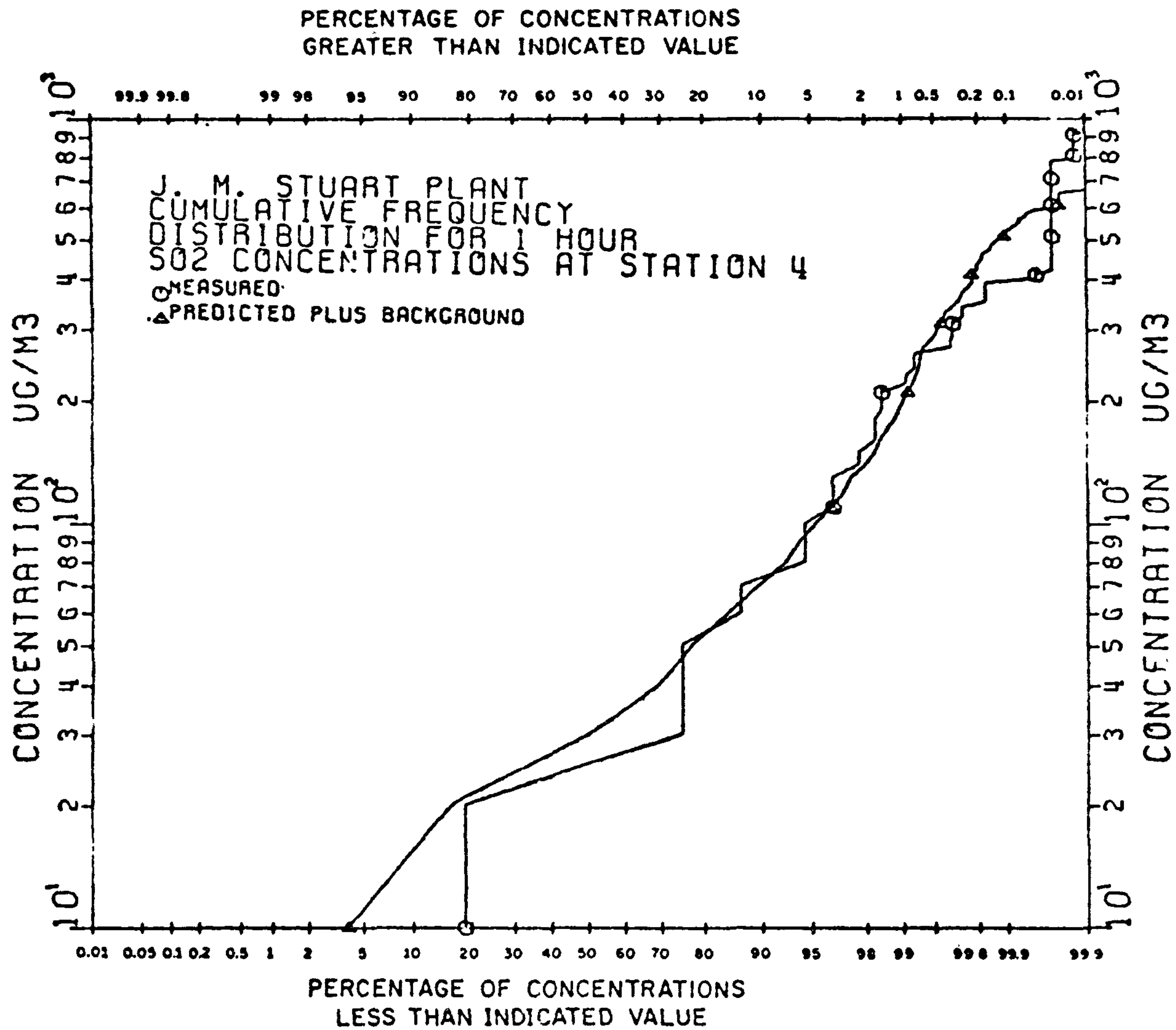

Figure 74. J. M. Stuart Plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 4

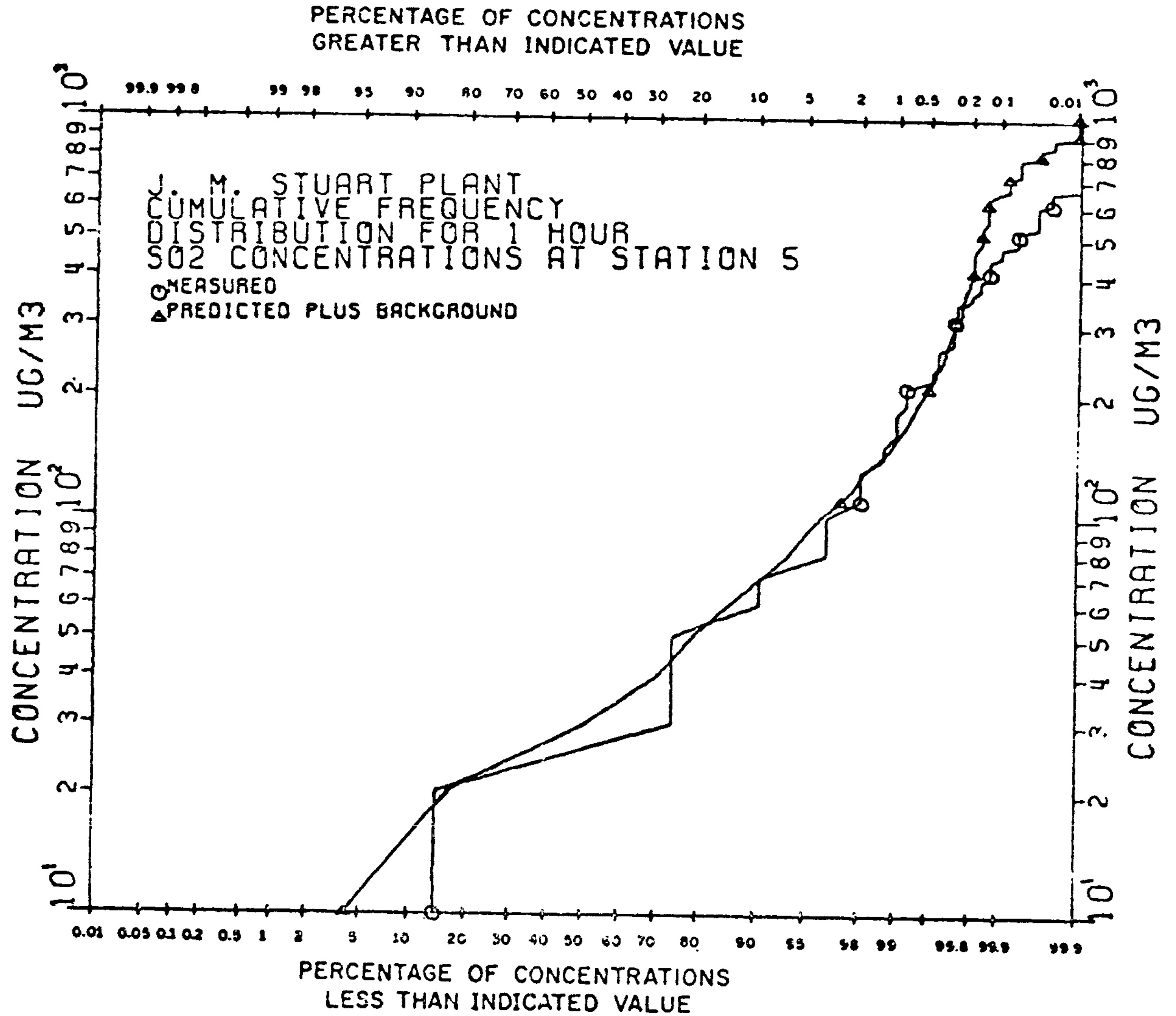

Figure 75. J. M. Stuart Plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 5

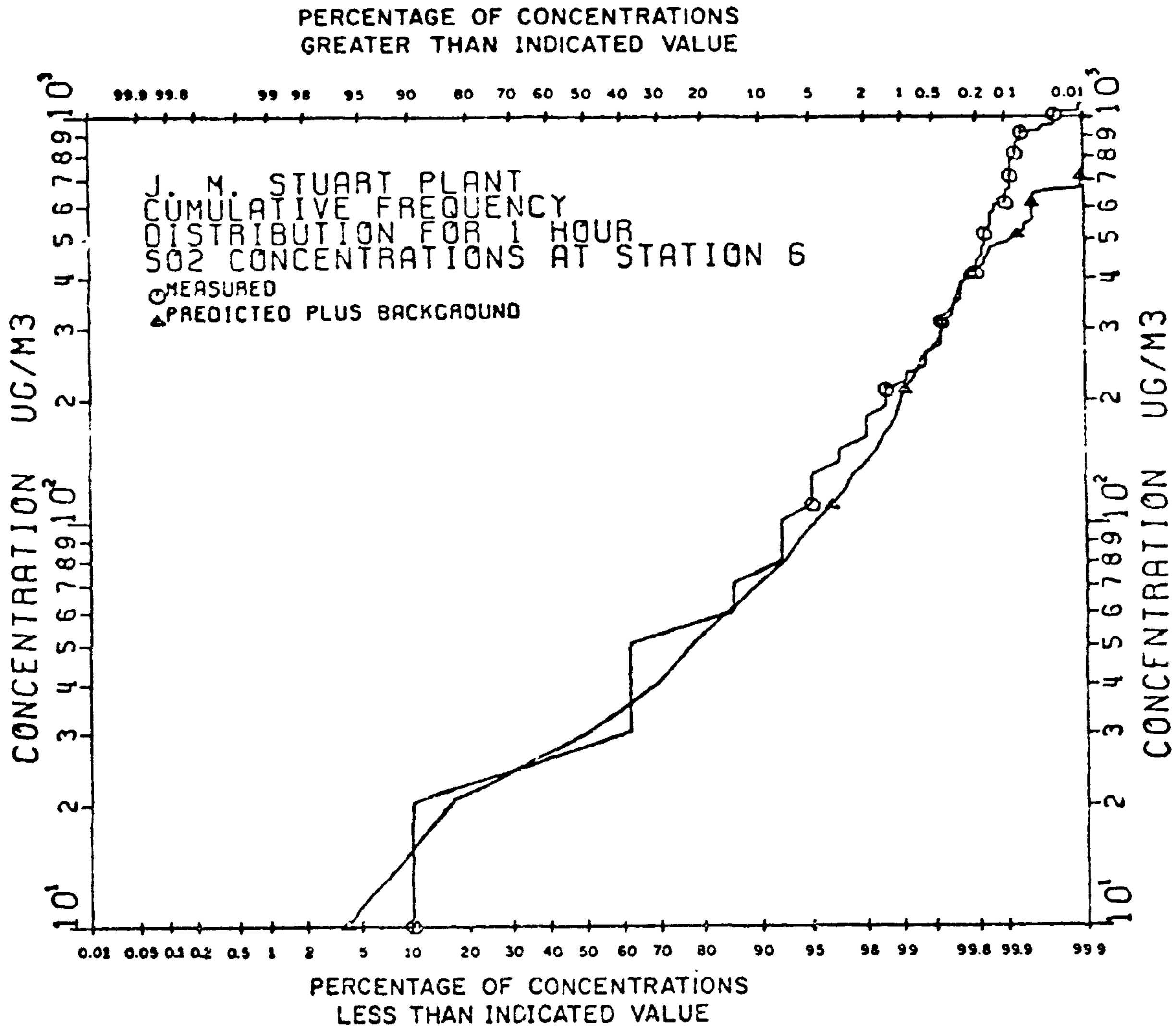

Figure 76. J. M. Stuart Plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 6

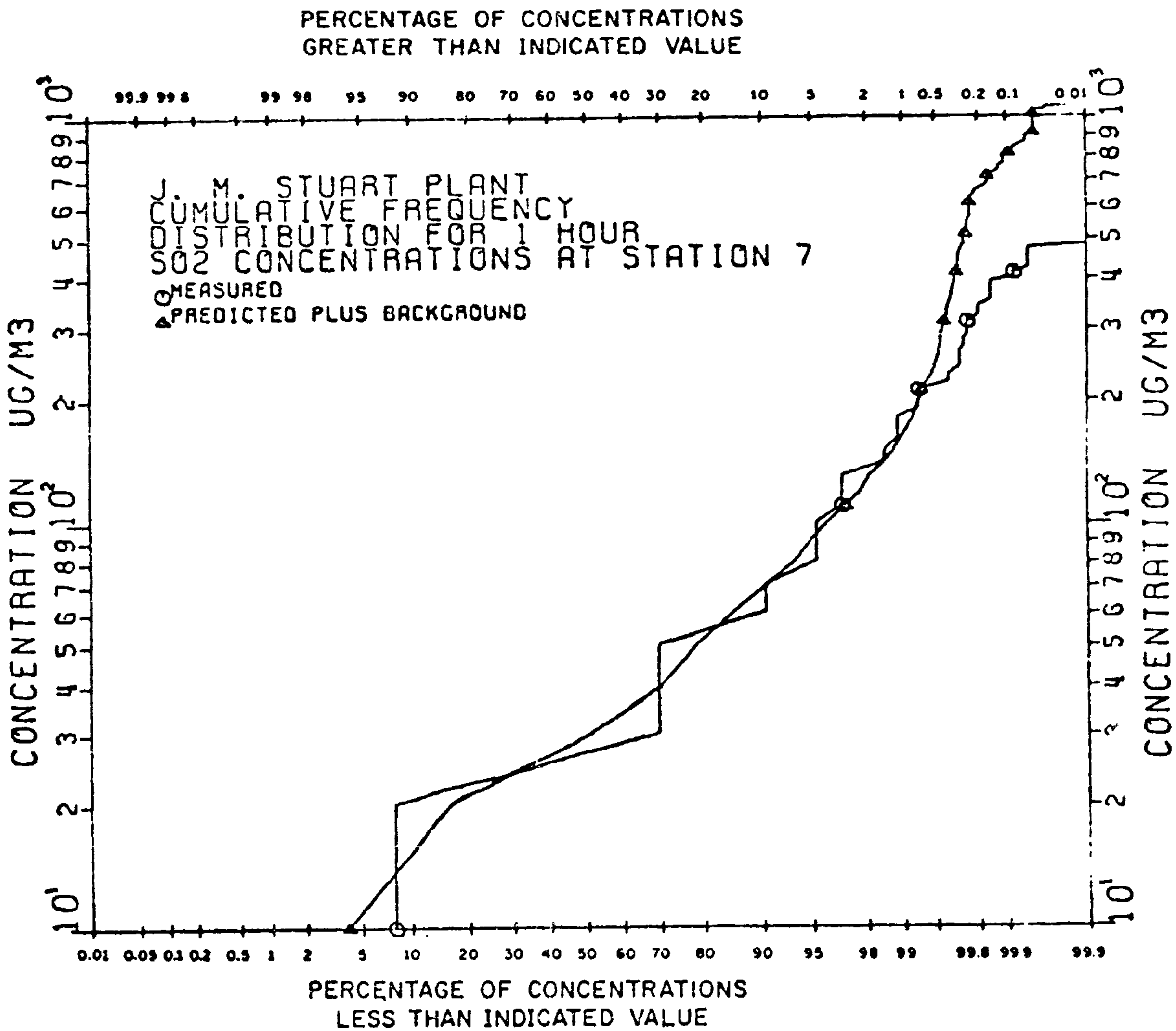

Figure 77. J. M. Stuart Plant cumulative frequency distribution for 1-hour SO_2 concentrations at station 7

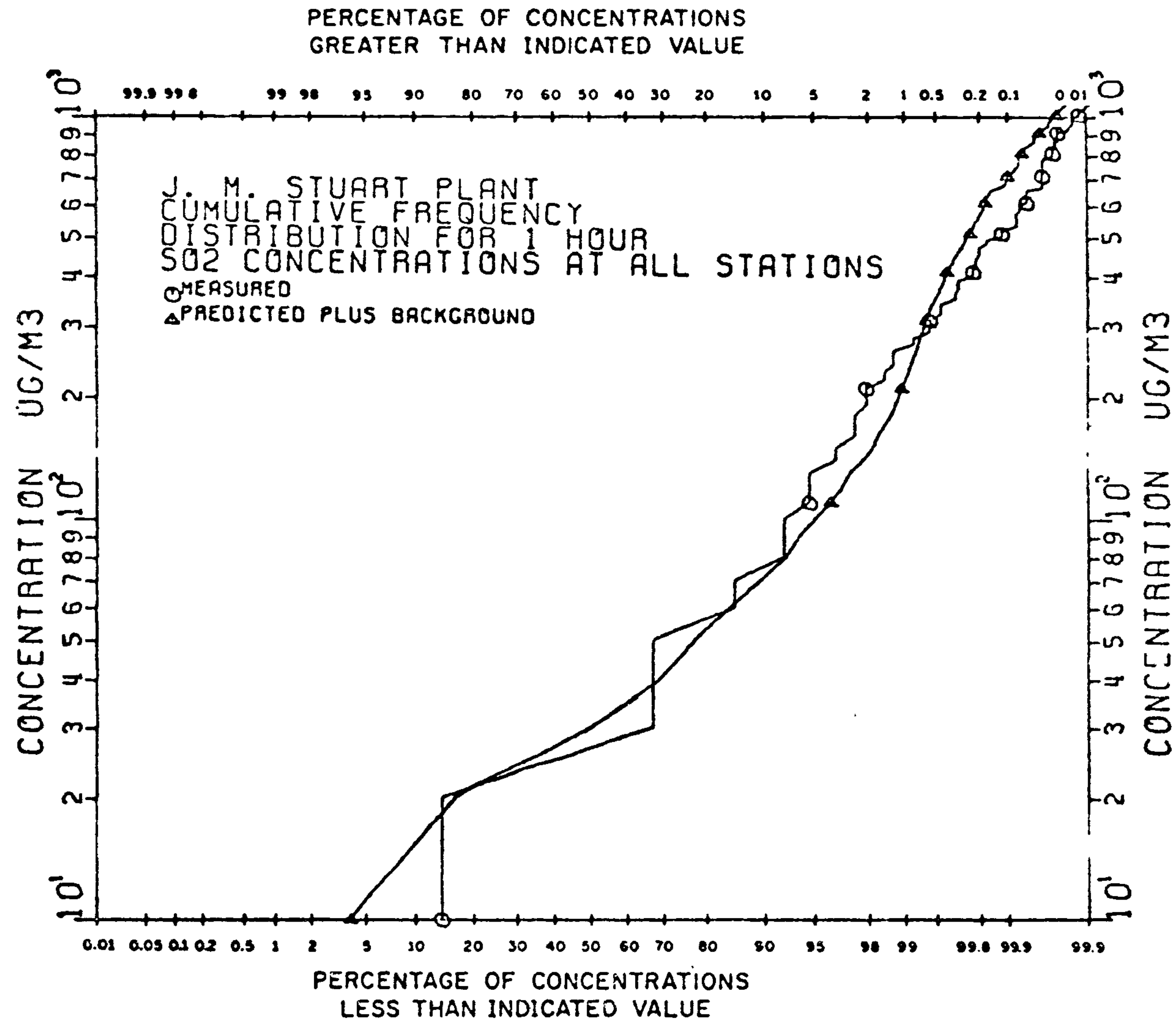

Figure 78. J. M. Stuart Plant cumulative frequency distribution for 1-hour SO_2 concentrations at all stations

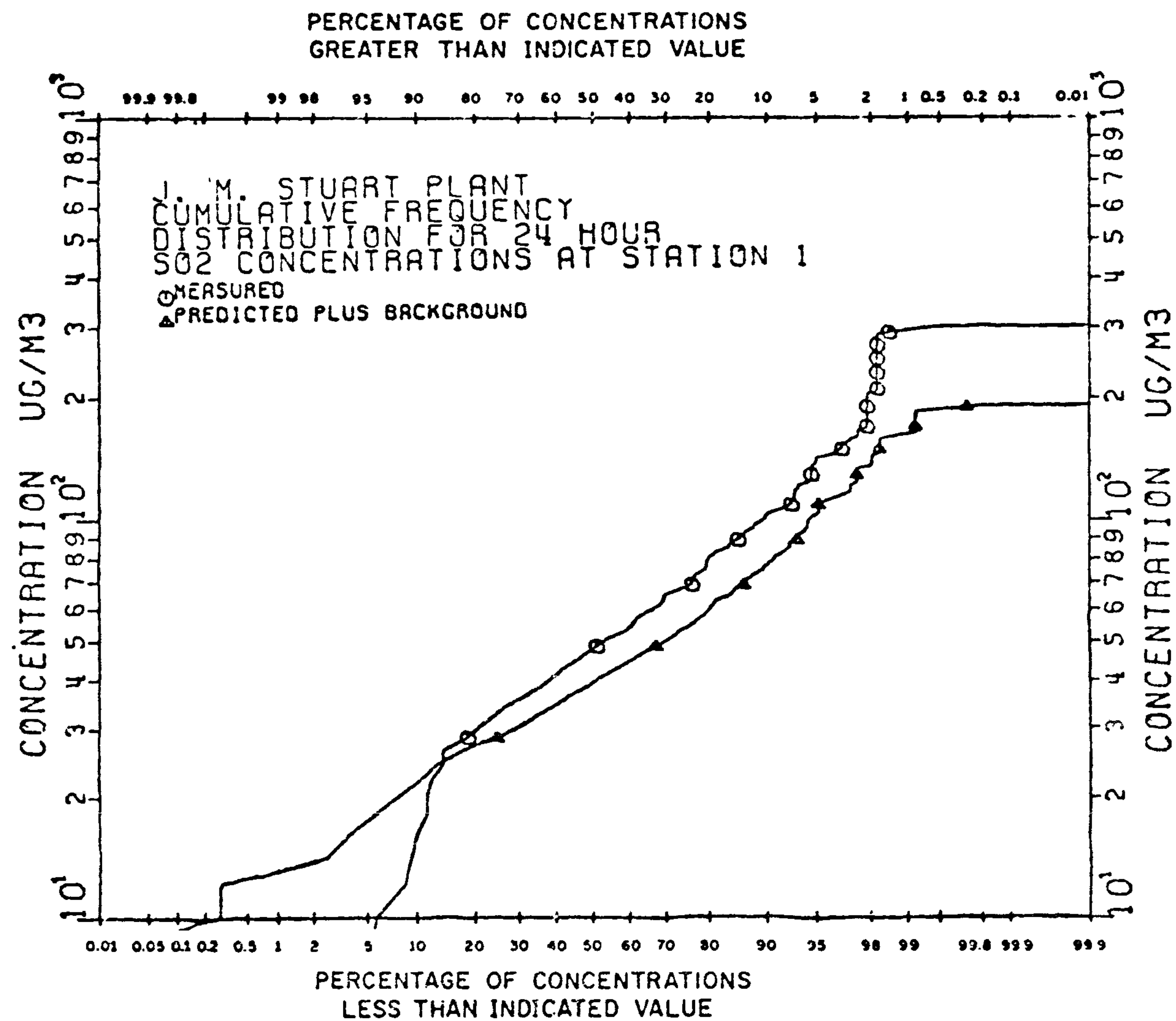

Figure 79. J. M. Stuart Plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 1

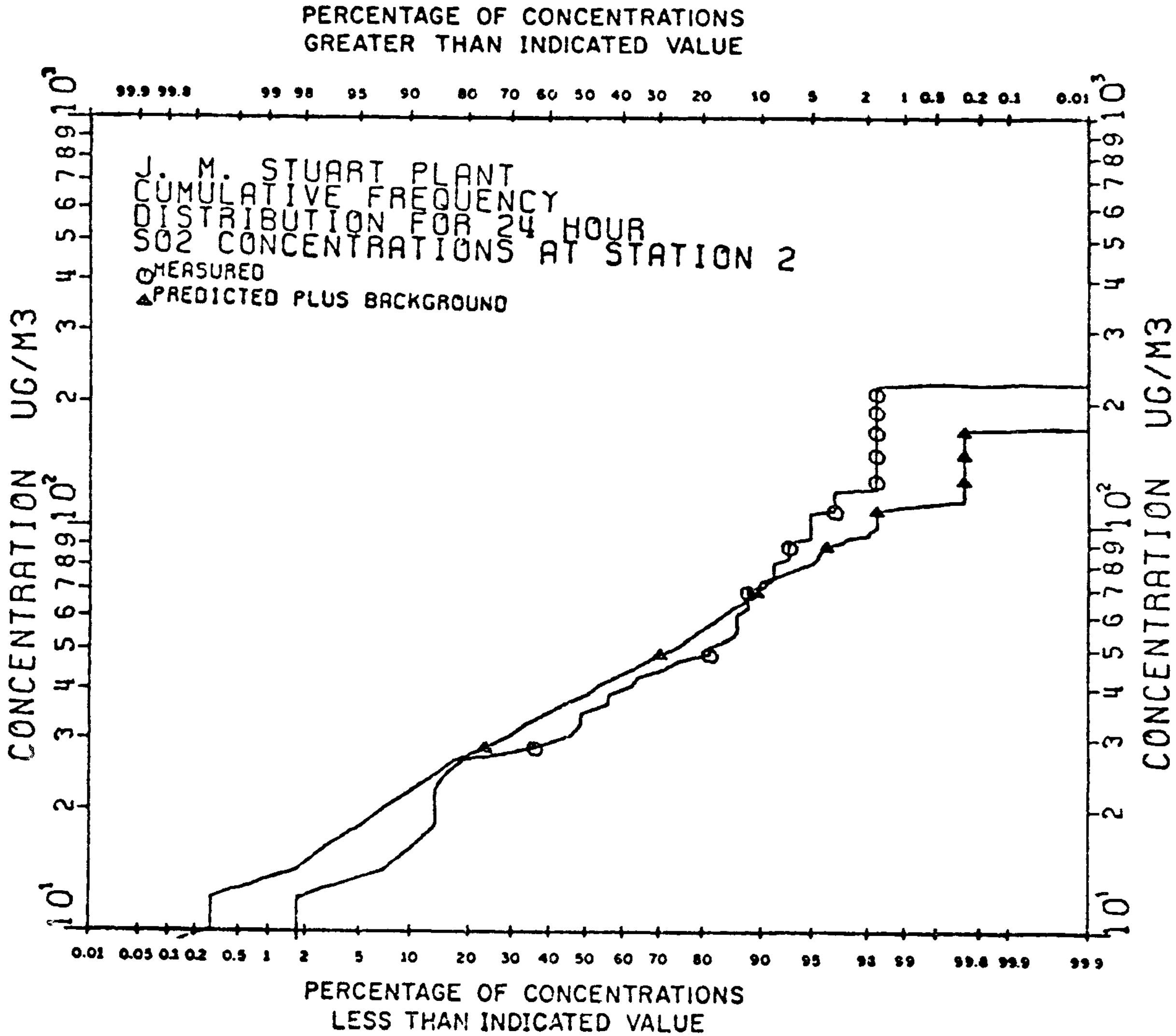

Figure 80. J. M. Stuart Plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 2

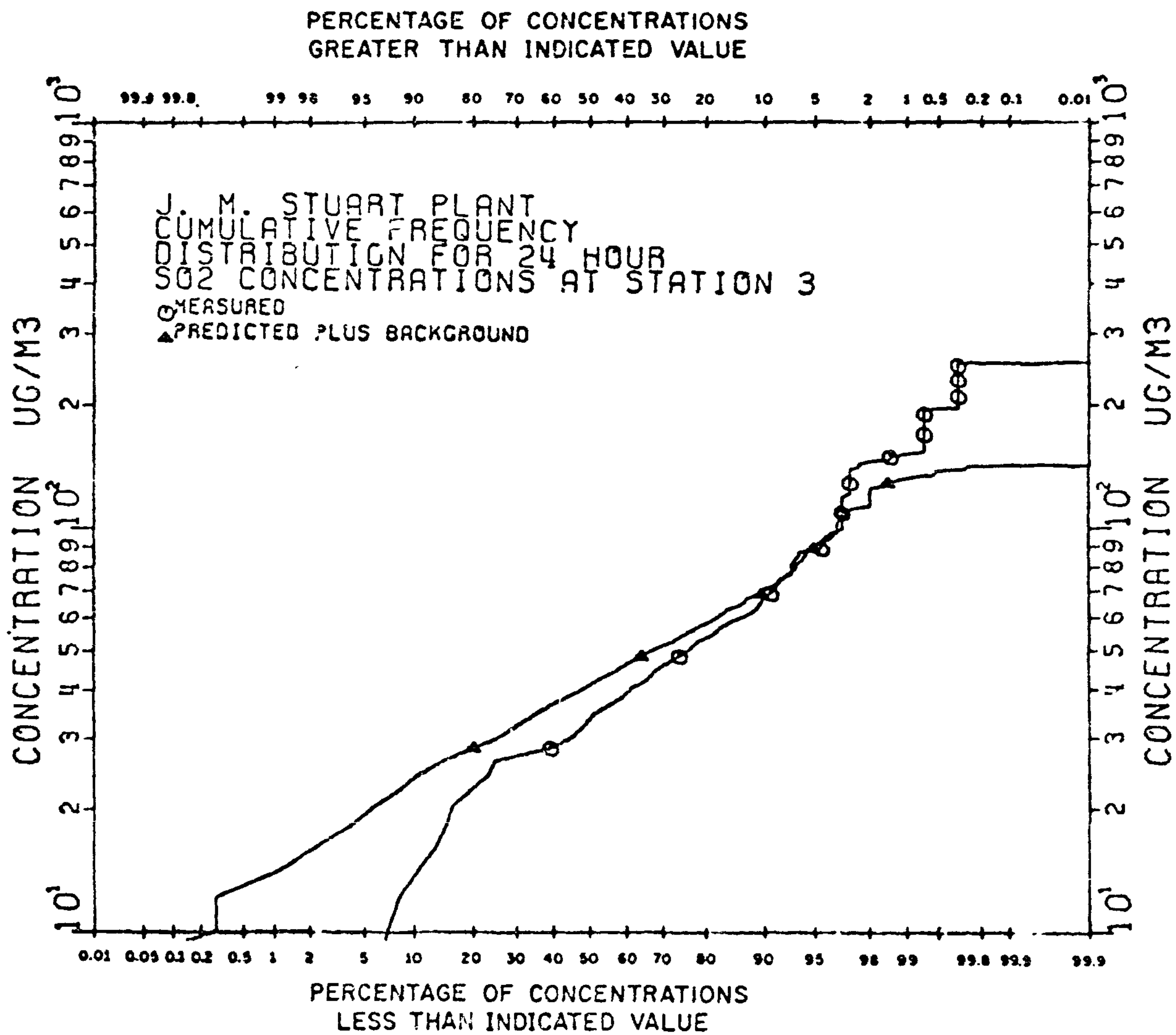

Figure 81. J. M. Stuart Plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 3

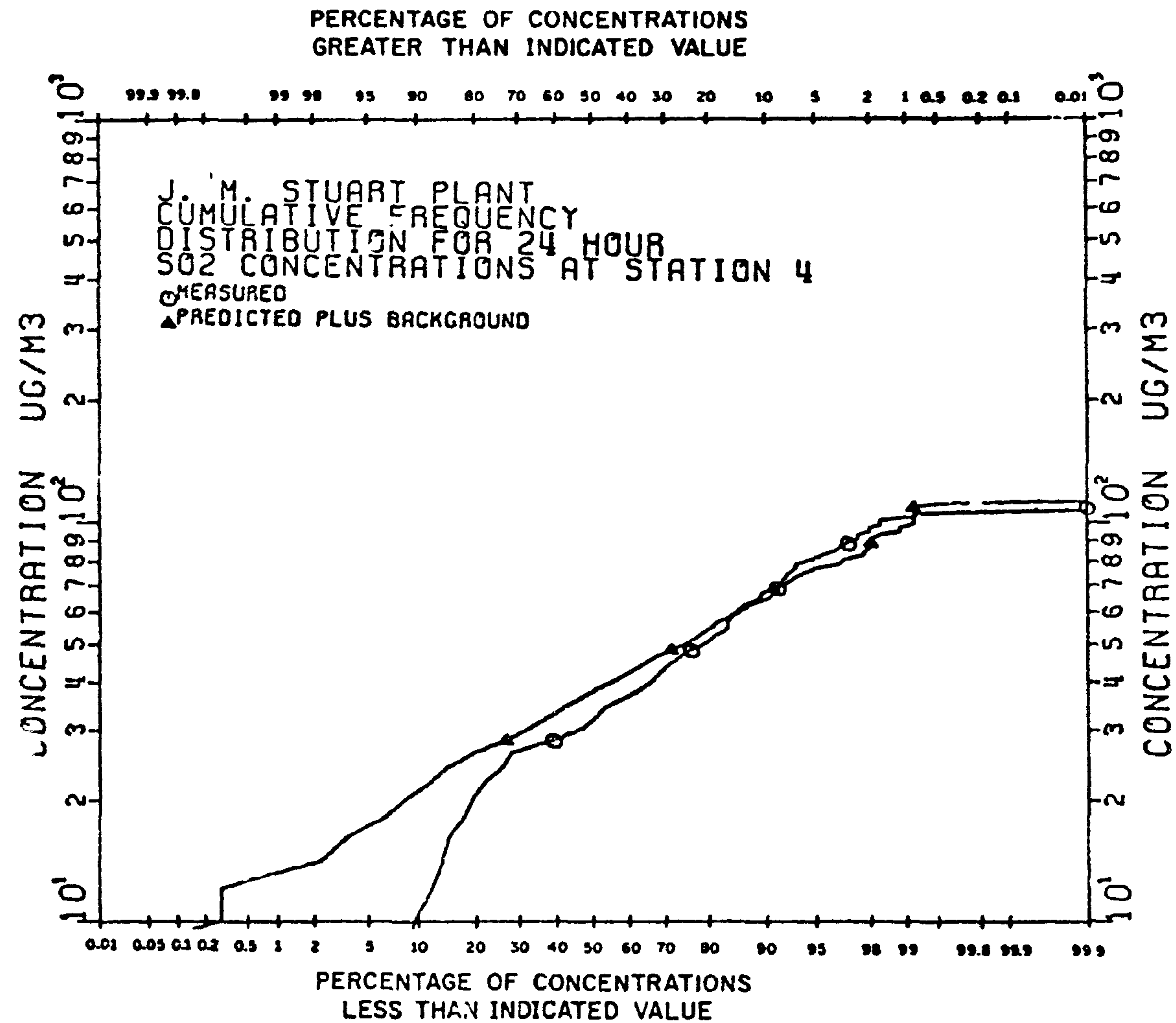

Figure 82. J. M. Stuart Plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 4

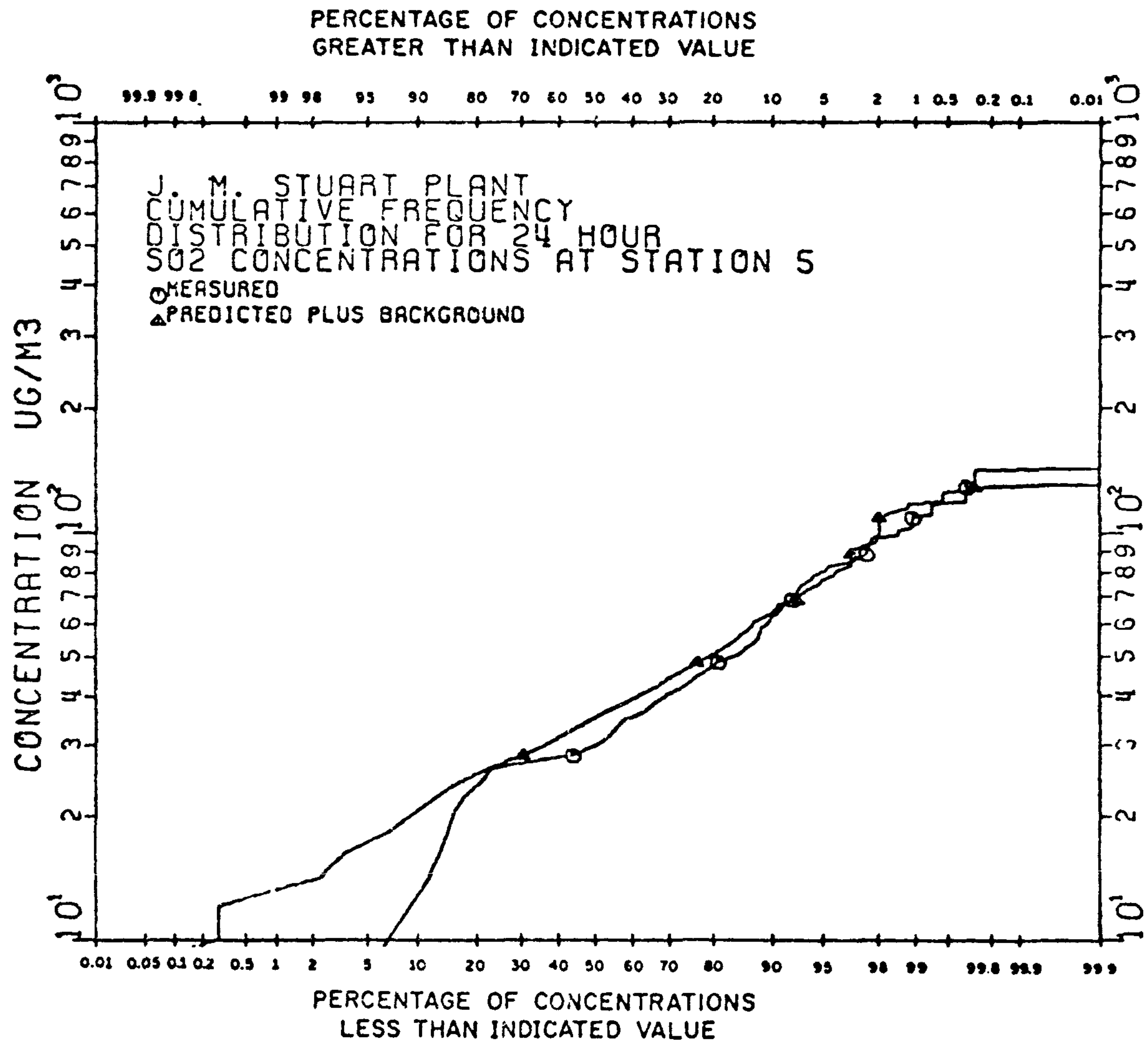

Figure 83. J. M. Stuart Plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 5

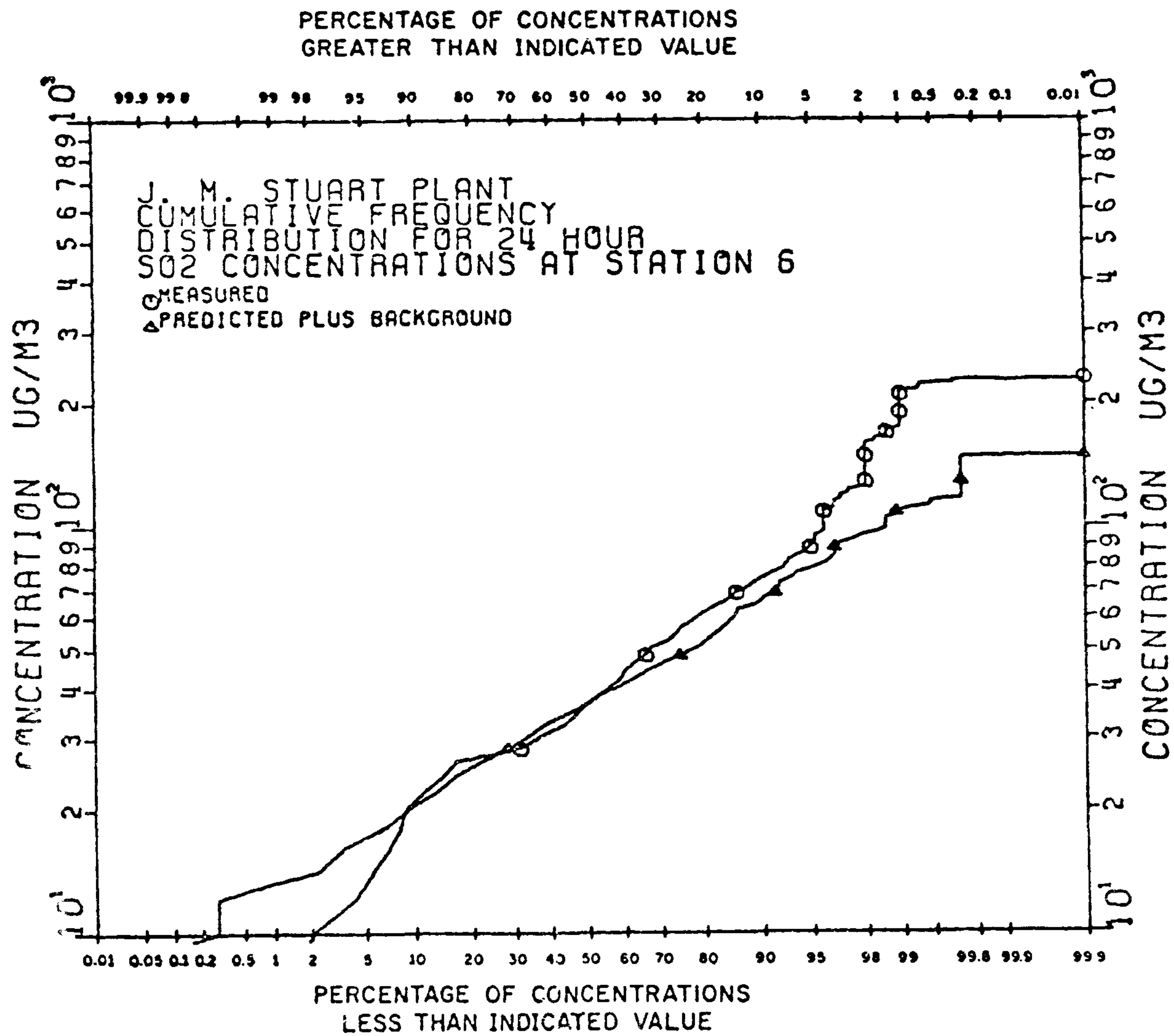

Figure 84. J. M. Stuart Plant cumulative frequency distribu.ion for 24-hour SO_2 concentrations at station 6

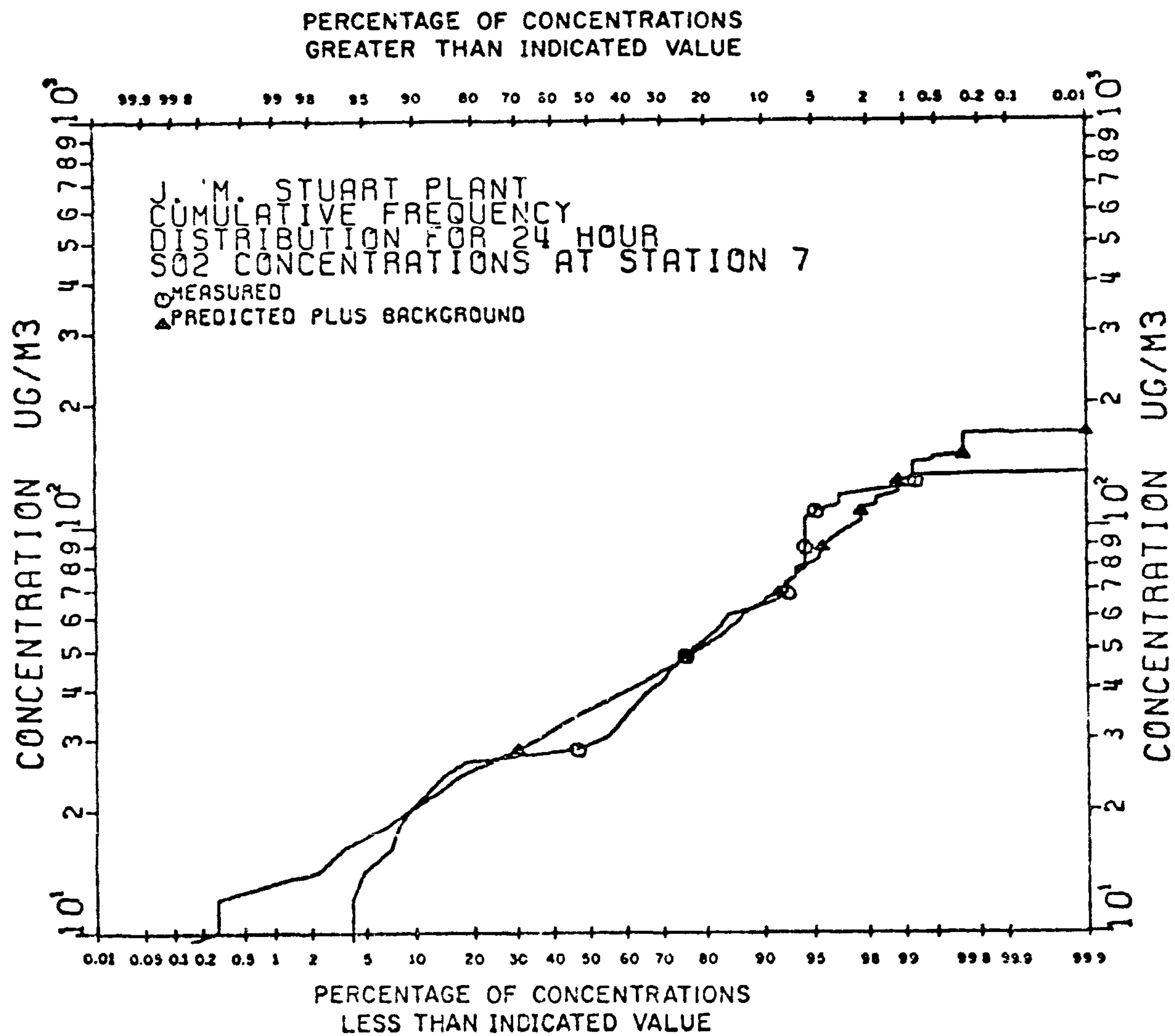

Figure 85. J. M. Stuart Plant cumulative frequency distribution for 24-hour SO_2 concentrations at station 7

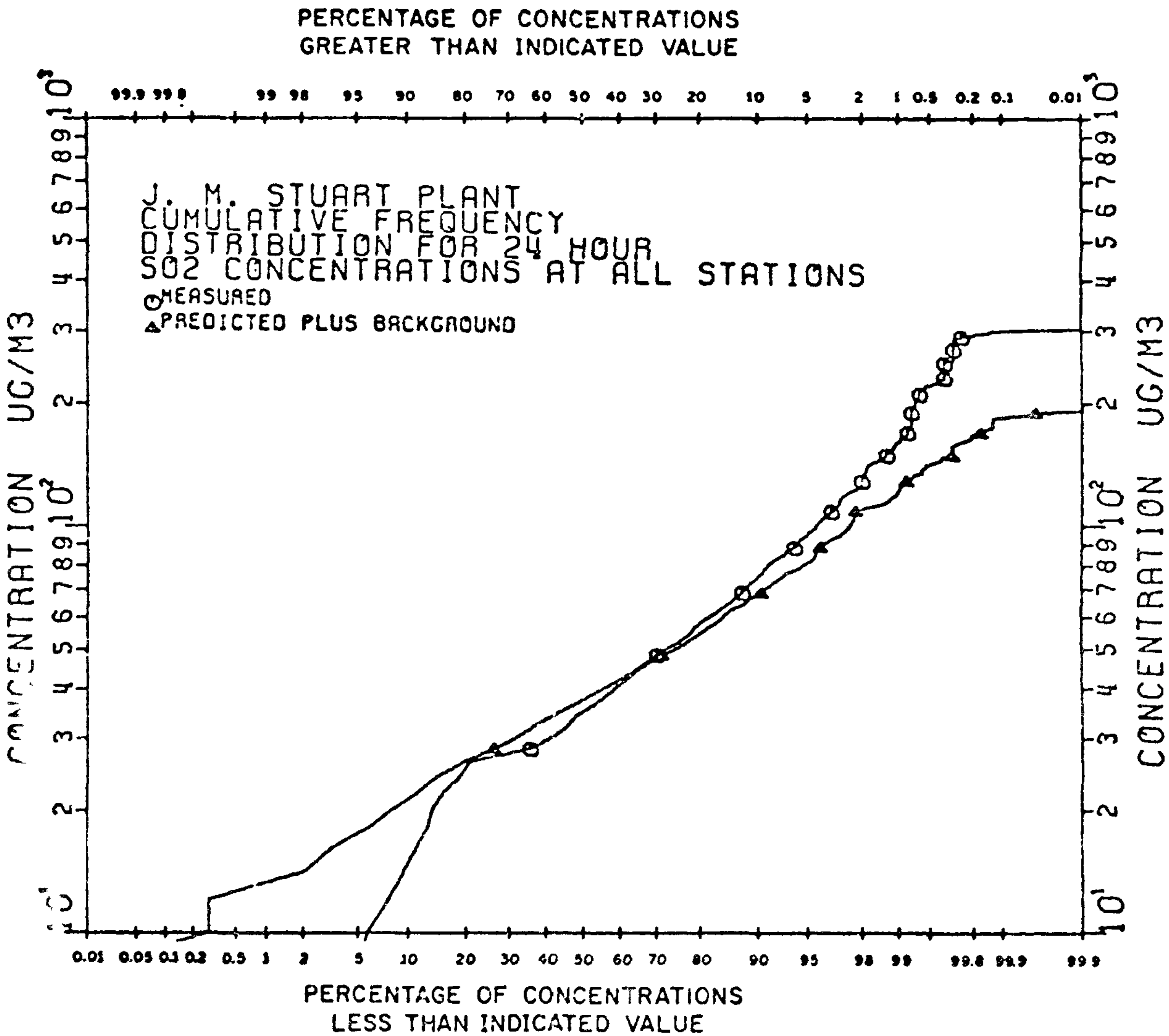

Figure 86. J. M. Stuart Plant cumulative frequency distribution for 24-hour SO_2 concentrations at all stations

The method of determining background concentrations from plant wind direction data was examined more closely since the local wind sensors were seldom at the same height or location as the stacks. The plots in Figure 87 of the background concentration at the three plants indicate some rather high levels. The high background concentrations apparently occur when there is only a single upwind station reporting a high concentration, either due to a high local emission or a discrepancy between the actual transport wind direction and the reported wind direction. The highest background recording at Stuart - 650 $\mu g/m^3$ - occurred on May 23, 1973 at 1400 hours, due to the following recording.

Station	Concentration	Bearing of station from plant
1	0.01 ppm	35°
4	0.01 ppm	49°
5	0.25 ppm	279°
2,3,6,7	no report	

The wind was recorded as blowing from 247° and toward 67° which caused stations 1 and 4 to be considered within the 90° sector of the plumes centerline. Stations 1 and 4 were considered downwind of the plant and not used for background subtraction, while station 5 was considered upwind and a background of 0.25 ppm or 650 $\mu g/m^3$ was obtained. The plots in Figure 88 were made of the concentrations when the stations were upwind of the plant, to determine if local sources were contributing to any particular station. All seven stations show the same trend, although station 6 seems to have the highest upwind concentrations. There is no simple explanation for this because station 6 is one of the more remote stations (Figure 2) although there may be local sources not apparent on the USGS map. Since there were many cases of high upwind concentrations, it was decided to try a simple background calculation technique which was independent of wind direction. The procedure adopted was to find

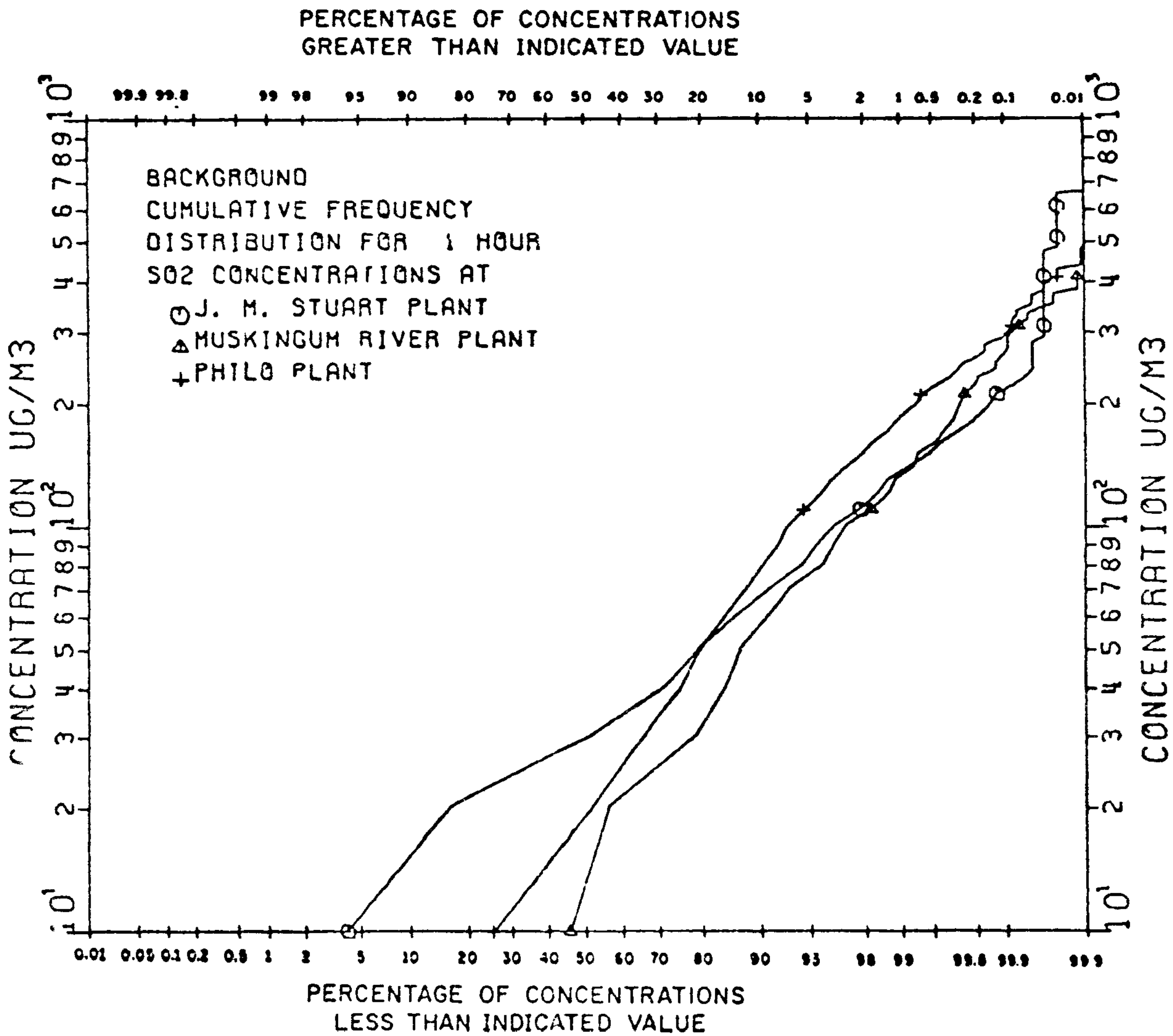

Figure 87. Background cumulative frequency distribution for 1-hour SO_2 concentrations at J. M. Stuart Plant, Muskingum River Plant and Philo Plant

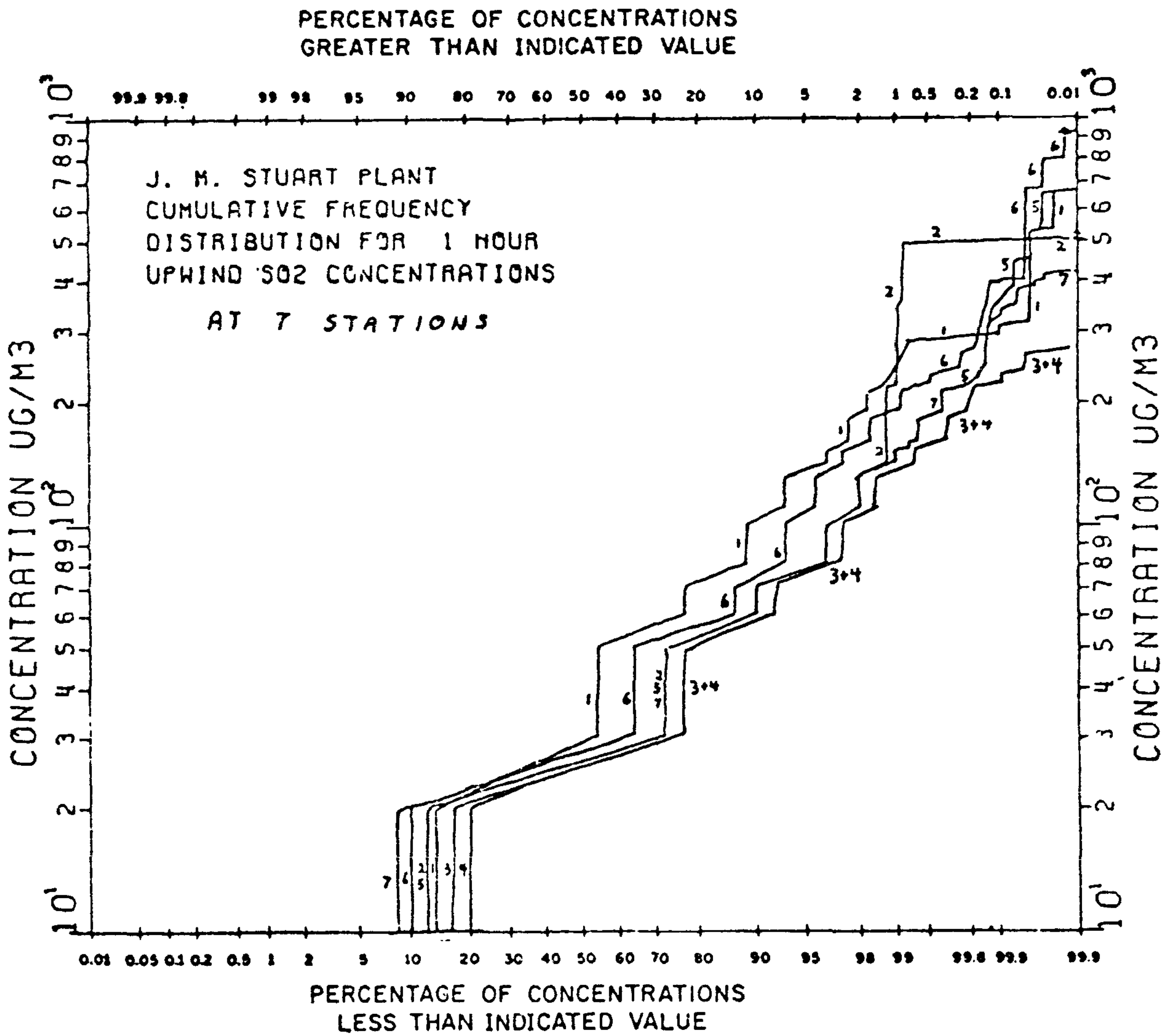

Figure 88. J. M. Stuart Plant cumulative frequency distribution for 1-hour upwind SO_2 concentrations at 7 stations

the mean and standard deviation of concentrations for all monitoring stations every hour. A station whose concentration was above the mean plus one standard deviation was disregarded for that hour, and the background was taken to be the mean of the remaining stations. The new background computed from this technique is shown with the old background in Figure 89. The new background has the same slope as the old, but does not have the same high concentration values.

New measured minus background curves are shown in Figures 90 to 96 for the 1-hour case, and in Figure 97 for the 1-hour "all station" case. These results indicate that the two background subtraction methods yield similar results except for the highest values. As seen from Table 15, the second technique shows better agreement with the highest predicted values. Since the alternate technique yields a smoother background cumulative frequency distribution (Figure 98), is slightly closer to the predicted values, and requires no plant wind data, it may be the better of the two methods, and deserves future study.

SUGGESTIONS FOR FUTURE STUDY

There are several possible ways to improve the agreement between measured and predicted concentrations.

- The model hourly output should only include those hours during which a monitoring station was operating. The predicted concentration plots shown are plots of all hours for the year, while the plots of the measured values have some missing hours. For instance, at the J. M. Stuart Plant, Station 2 operated only from January to March, Station 4 operated only from March to December, and Station 7 operated only from January to July. Comparing predicted hours only to those actually measured may yield closer agreement.

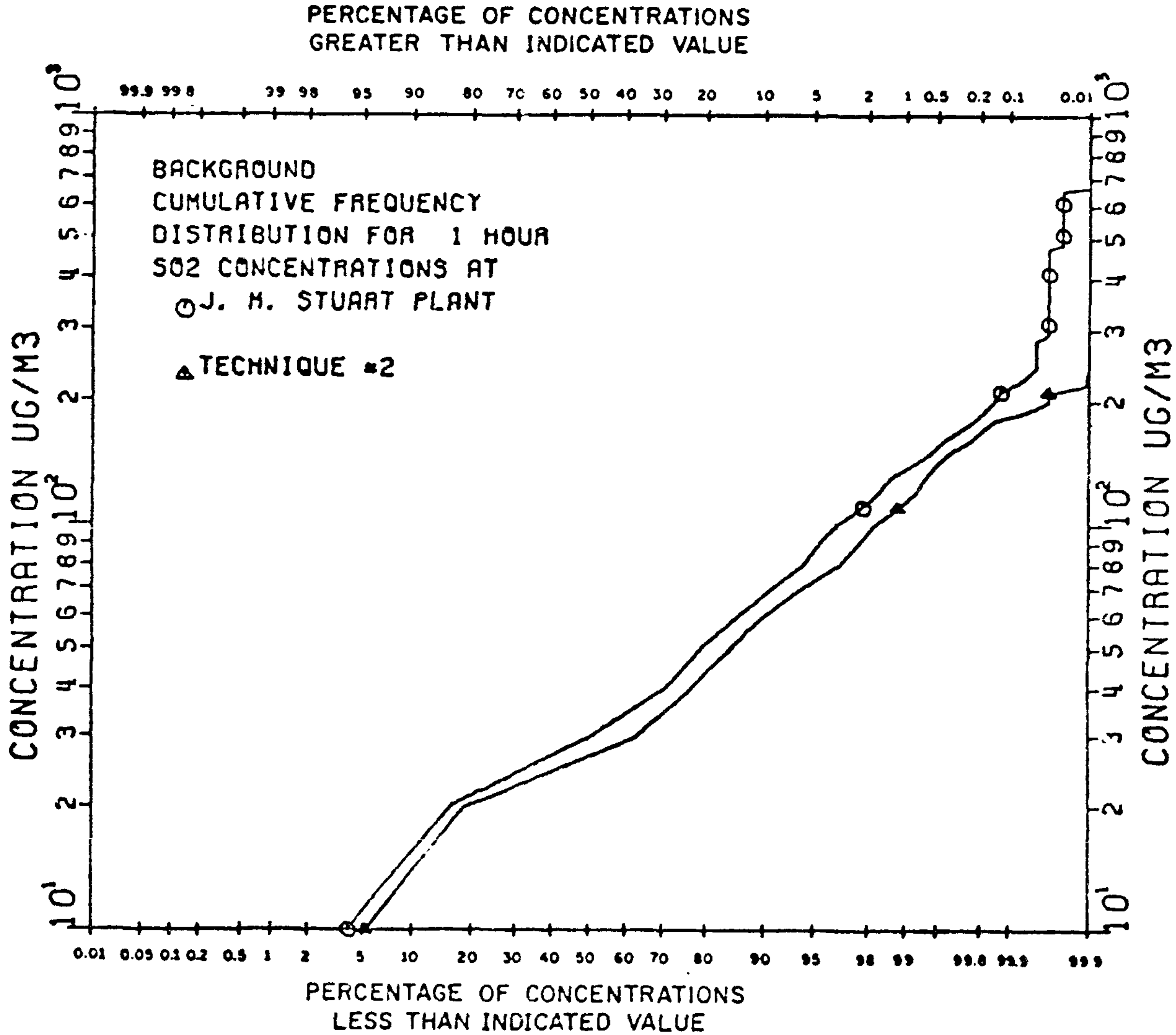

Figure 89. Background cumulative frequency distribution for 1-hour SO_2 concentrations at J. M. Stua ι Plant

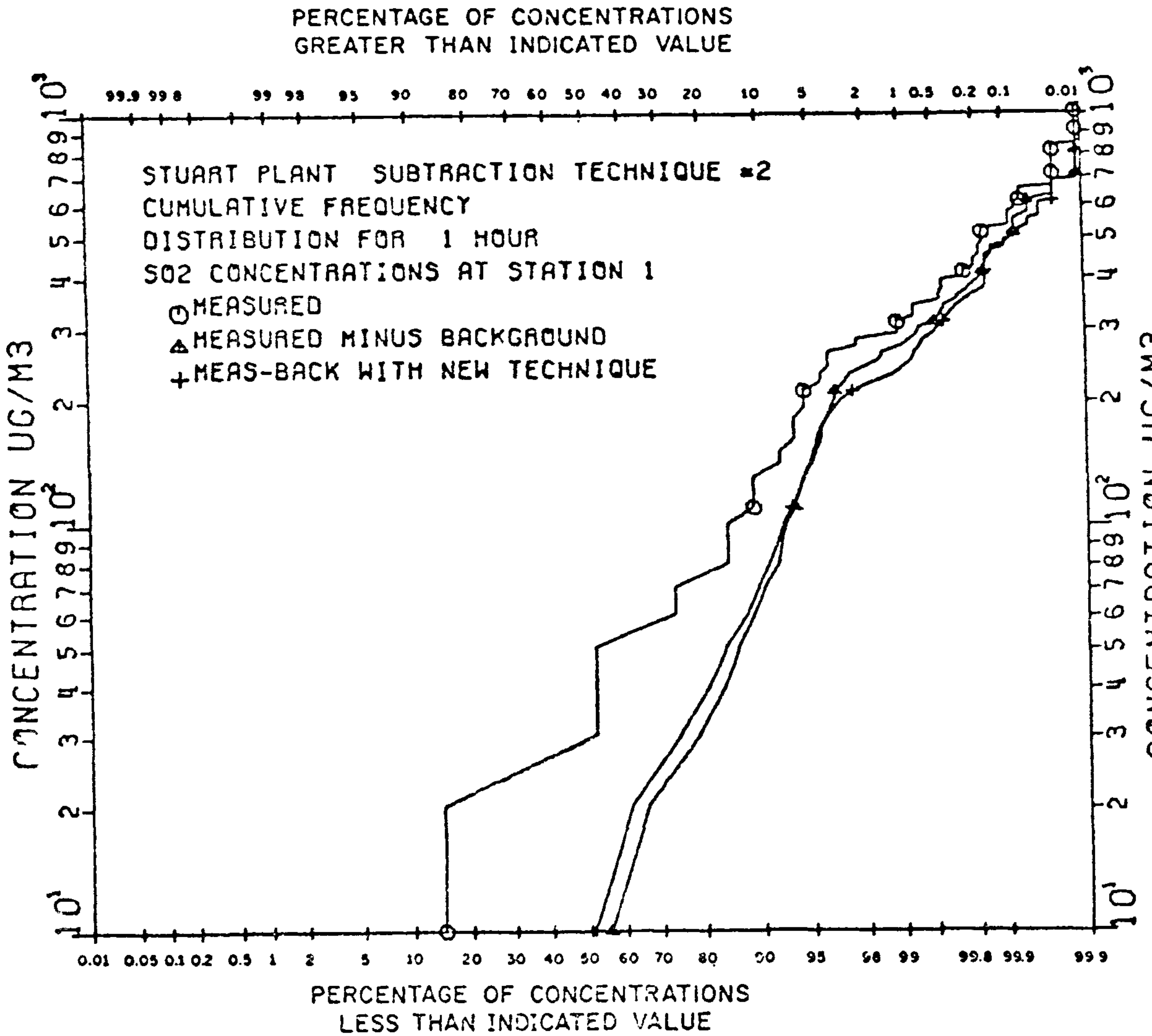

Figure 90. Stuart Plant subtraction technique #2 cumulative frequency distribution for 1-hour SO_2 concentrations at station 1

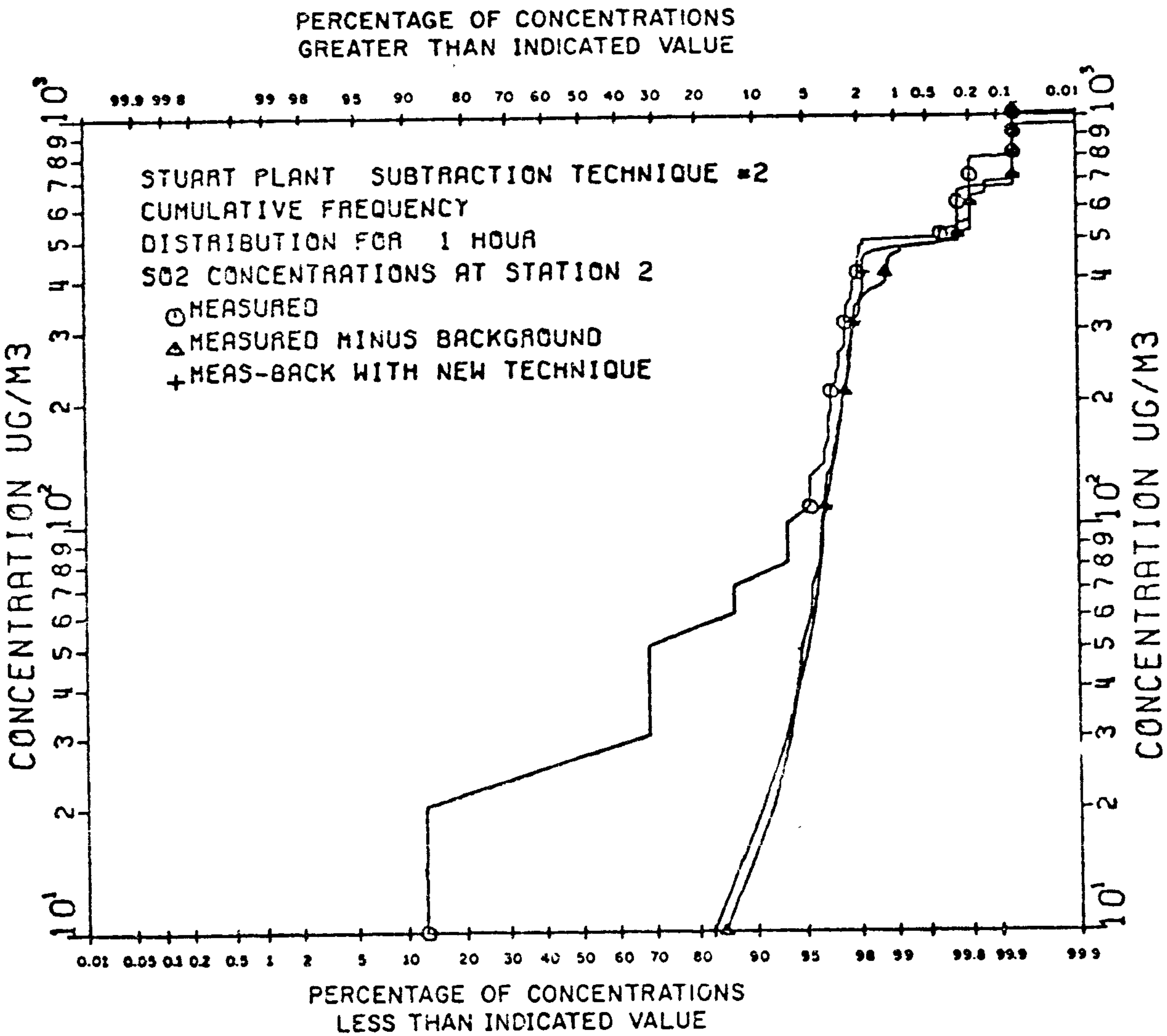

Figure 91. Stuart Plant subtraction technique #2 cumulative frequency distribution for 1-hour SO_2 concentrations at station 2

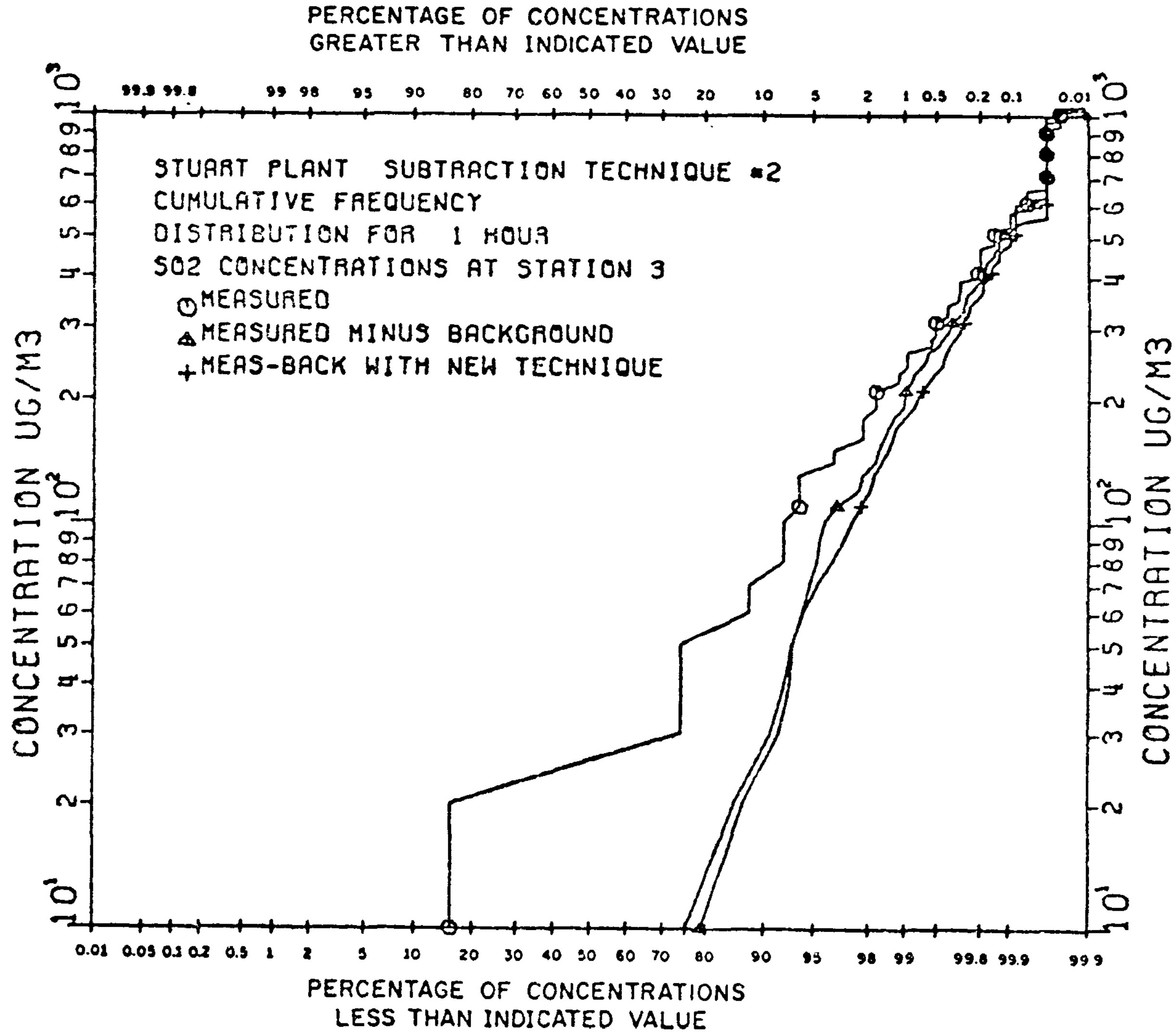

Figure 92. Stuart Plant subtraction technique #2 cumulative frequency distribution for 1-hour SO_2 concentrations at station 3

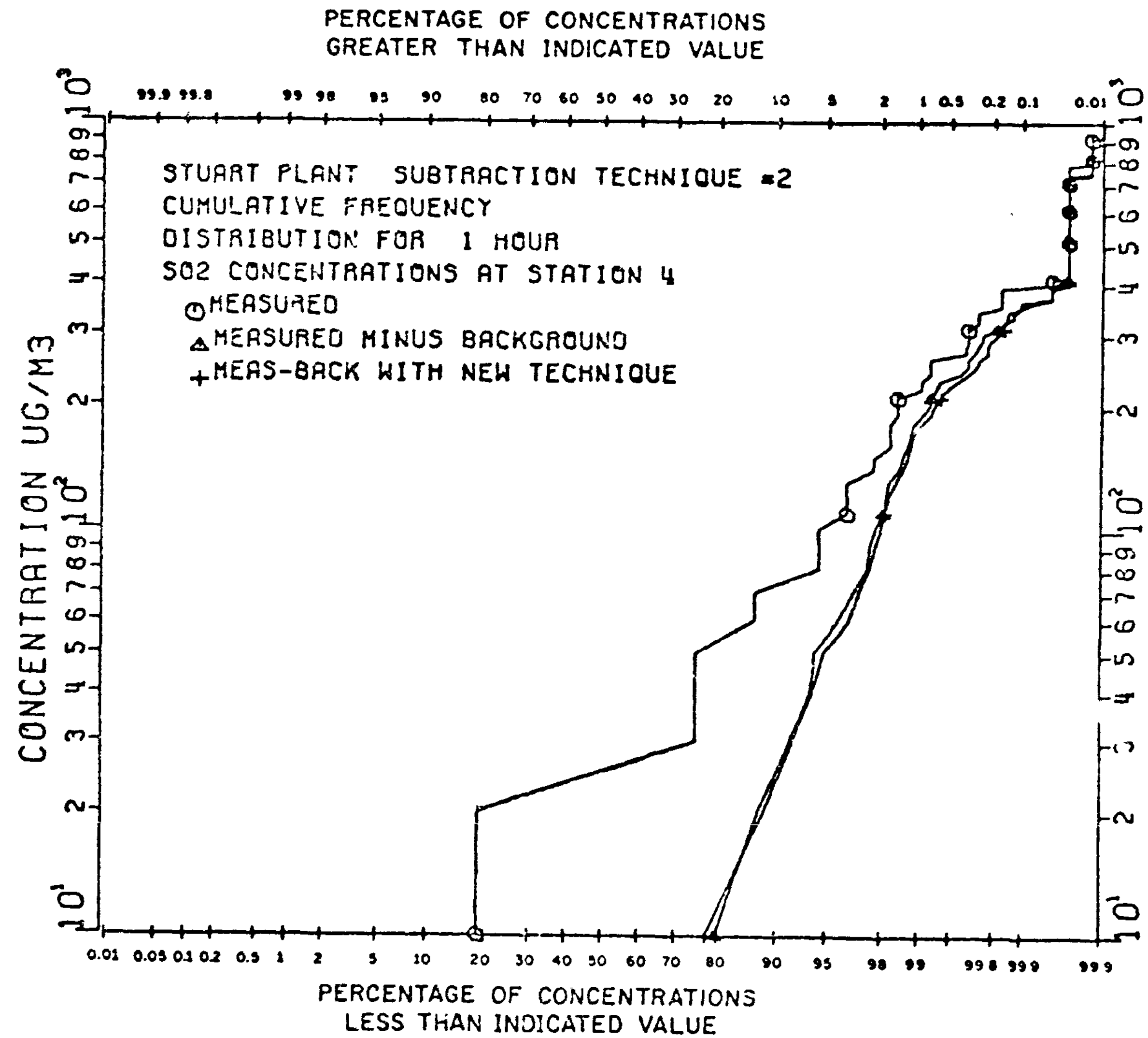

Figure 93. Stuart Plant subtraction technique #2 cumulative frequency distribution for 1-hour SO_2 concentrations at station 4

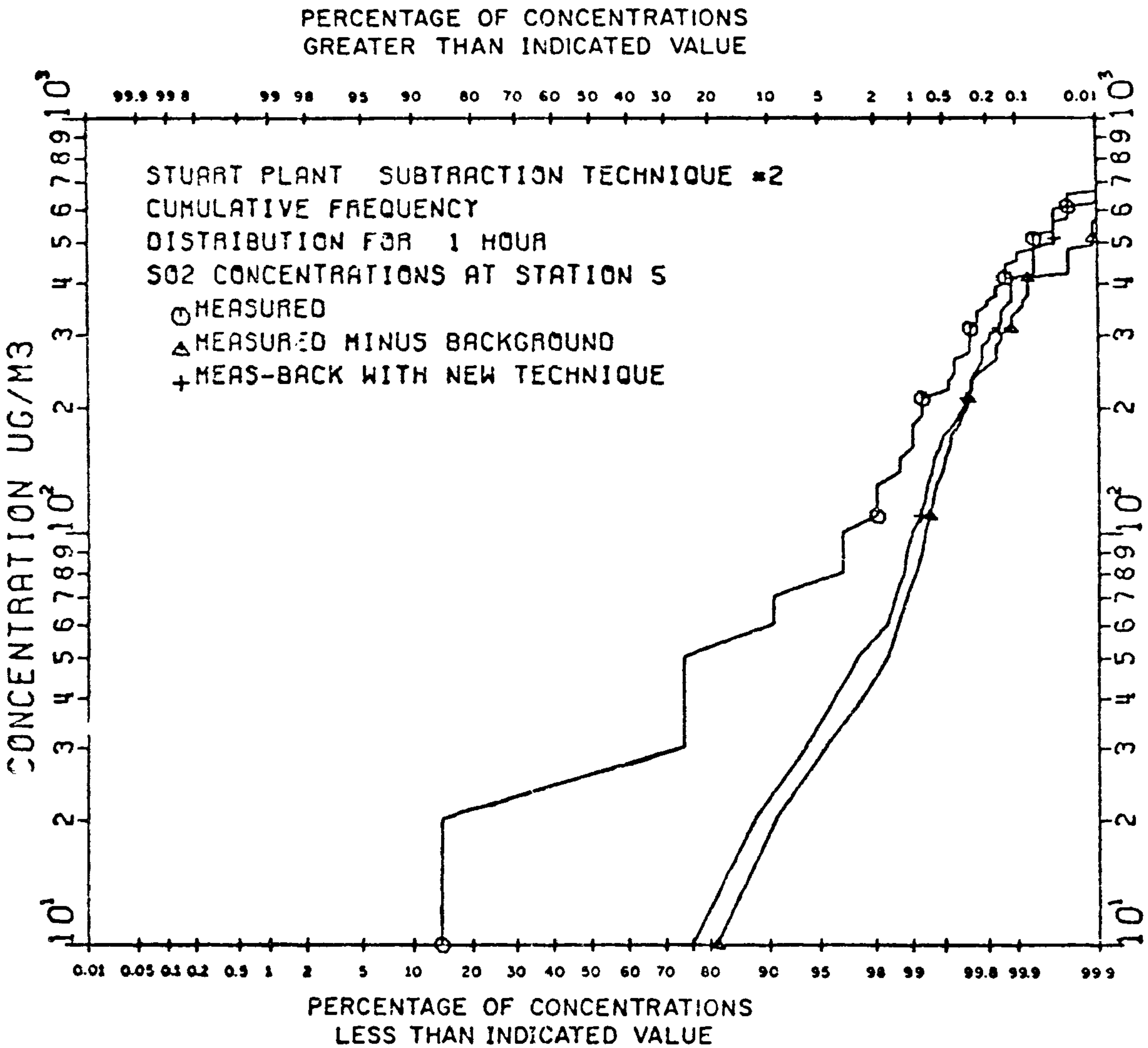

Figure 94. Stuart Plant subtraction technique #2 cumulative frequency distribution for 1-hour SO_2 concentrations at station 5

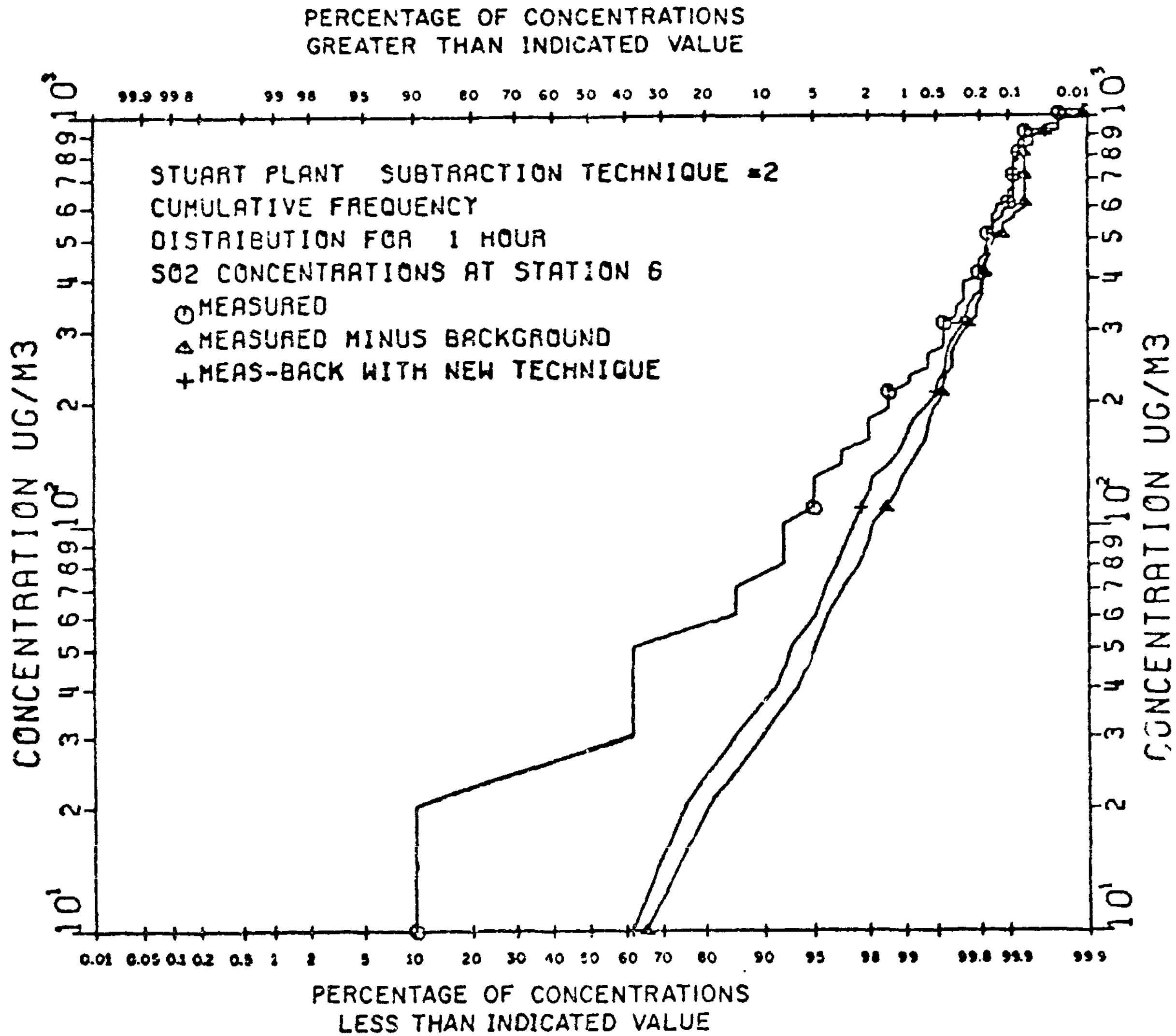

Figure 95. Stuart Plant subtraction technique #2 cumulative frequency distribution for 1-hour SO_2 concentrations at station 6

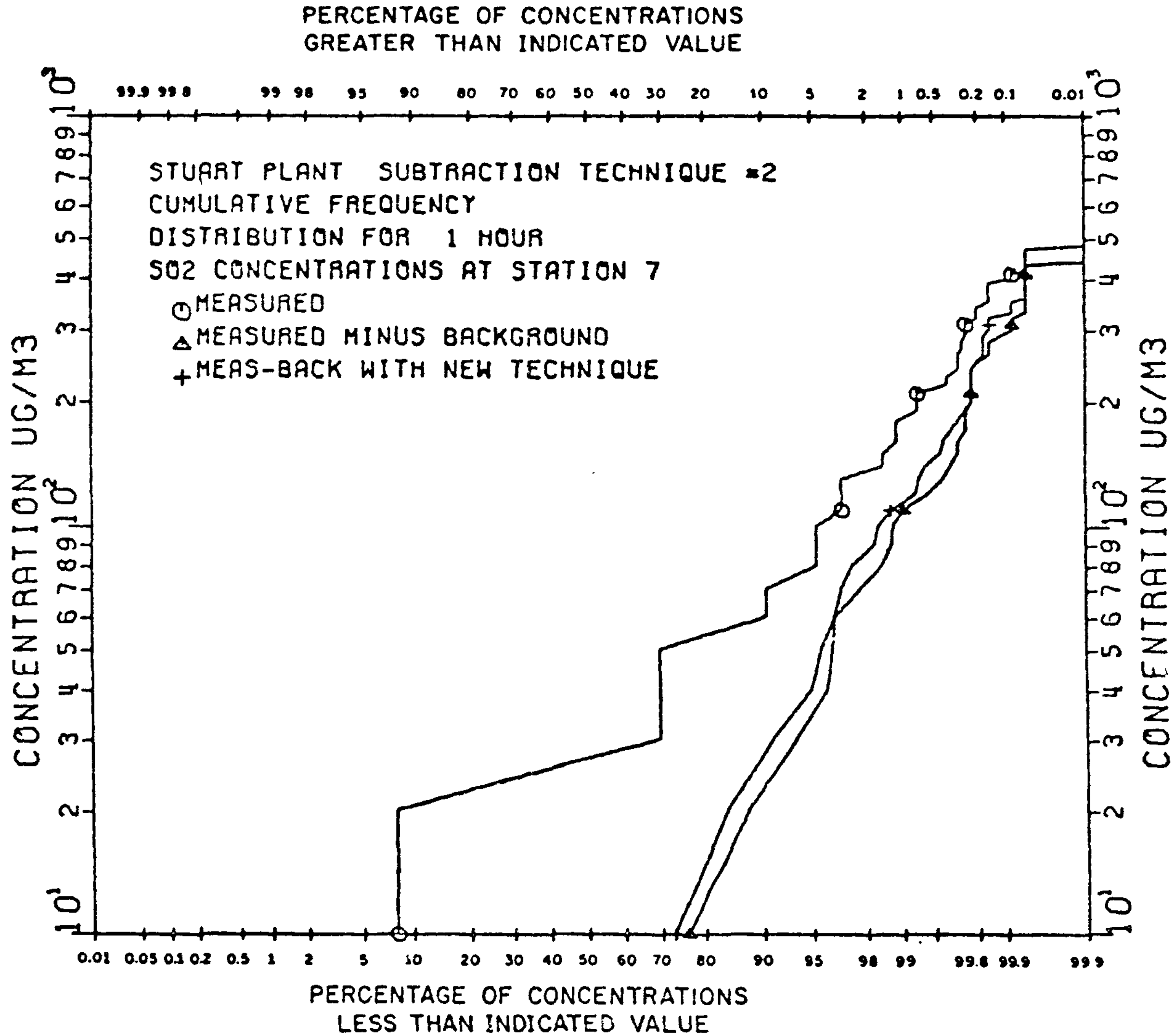

Figure 96. Stuart Plant subtraction technique #2 cumulative frequency distribution for 1-hour SO_2 concentrations at station 7

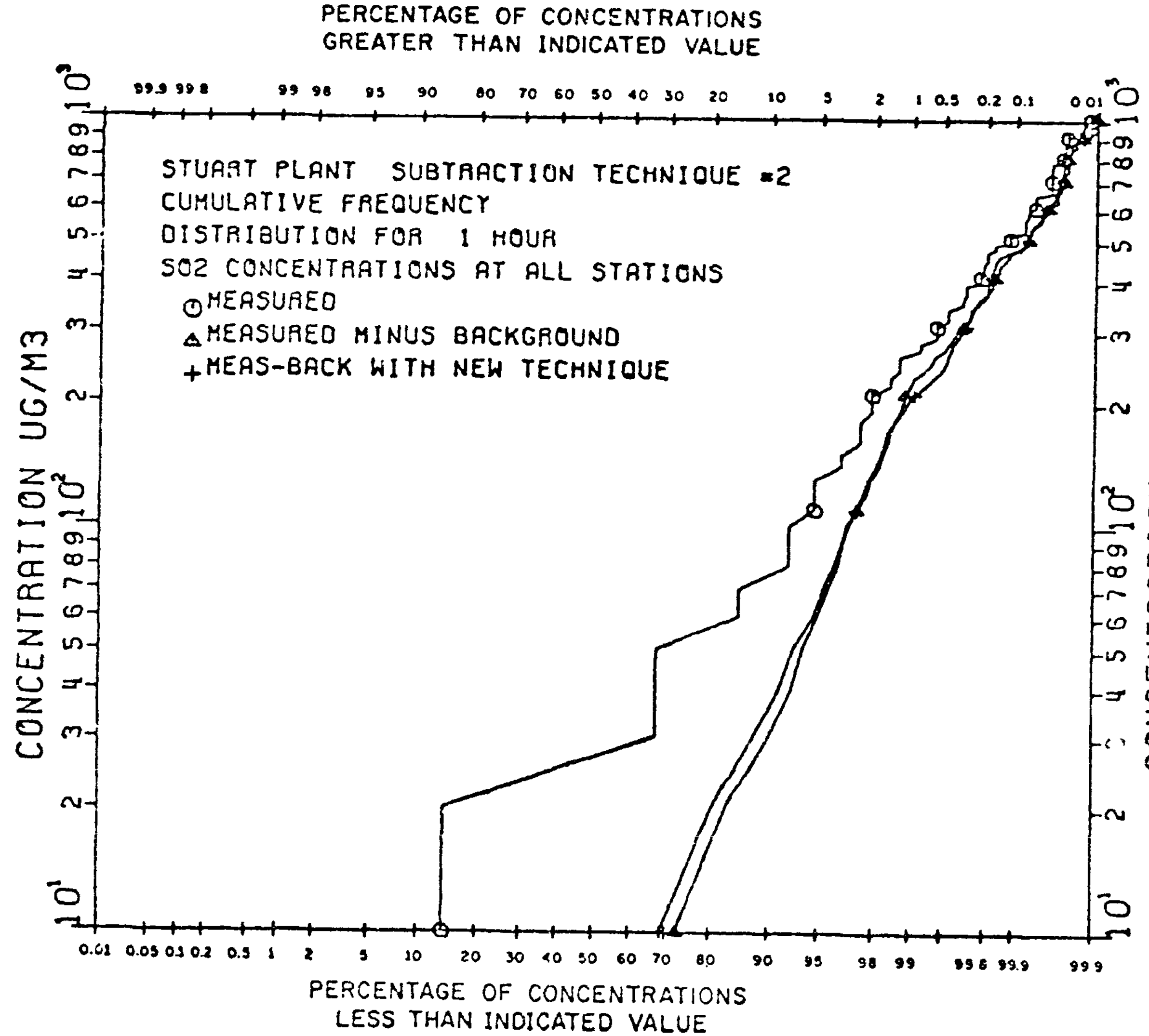

Figure 97. Stuart Plant subtraction technique #2 cumulative frequency distribution for 1-hour SO_2 concentrations at all stations

Table 15. J. M. STUART, CONCENTRATIONS DISTRIBUTION STATISTICS FOR MEASURED MINUS BACKGROUND AND PREDICTED CONCENTRATIONS USING OLD AND NEW BACKGROUND SUBTRACTION TECHNIQUES ($\mu g/m^3$)

Station	Second highest			Highest		
	Measured[a]	Measured[b]	Predicted[c]	Measured[a]	Measured[b]	Predicted[c]
1-Hour						
1	685	685	1372	857	886	1393
2	685	665	814	1014	943	948
3	1022	1009	565	1153	1132	1022
4	750	735	515	883	817	541
5	495	615	823	565	625	1219
6	980	980	595	1053	1053	693
7	325	433	976	435	438	1000
All	1022[d]	1009[d]	1372[d]	1153	1132	1393
24-Hour						
1	259	225	149	277	235	161
2	63	57	75	159	161	98
3	181	150	91	225	210	102
4	79	69	45	83	84	49
5	63	75	57	77	80	75
6	147	188	69	195	197	83
7	69	85	73	77	88	120
All	259[d]	225[d]	149[d]	277	235	161

[a]Measured concentrations with subtracted background using old wind dependent technique.

[b]Measured concentrations with subtracted background using new wind independent technique.

[c]Predicted concentrations.

[d]Highest concentration not exceeded more than once per year by any given station.

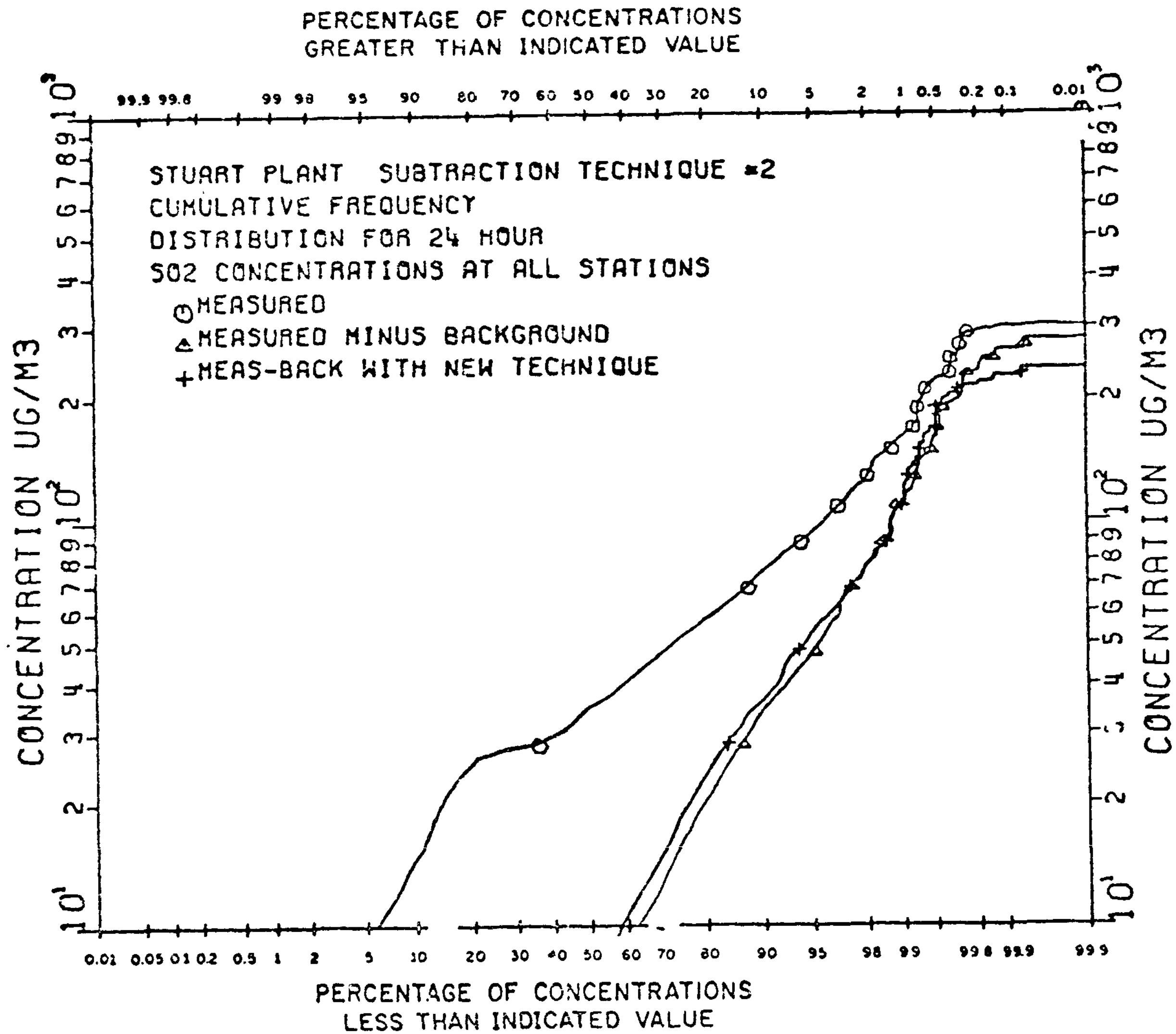

Figure 98. Stuart Plant subtraction technique #2 cumulative frequency distribution for 24-hour SO_2 concentrations at all stations

- The model used wind data from airports which are fairly distant. Running the model with wind data taken from the plant wind instrumentation may yield better correlation, although the plant wind instruments only measured wind characteristics of the lower valley, and not those at plume height or at the monitoring stations.

- Wind direction may vary with altitude, so the wind direction at the top of the stacks and at plume height may be different than the measured wind direction. Varying the measured airport wind by a constant angular displacement may yield better agreement between measured and calculated values, but still would not account for the variation of wind direction with height which results in a greater horizontal plume spread than that predicted by the model.

- The method of background subtraction by determining plume direction from plant wind data may not be the best, since the plant wind data is more characteristic of the lower valley. An alternate method would be to choose the lowest concentration among the monitoring stations as the background concentration for the hour in question.

- Buoyancy flux for each stack was assumed to be constant while this parameter actually varies as a function of the generation load for each boiler. This effect could be included in the model if the buyoancy flux were made proportional to the firing rate.

- The model was not designed to handle receptors level with the top of the stack, so that it overpredicted the high concentrations at the Philo sampling locations. Assuming that the problem occurs in the model and not in the receptors, the model could be altered to handle cases of low plume rise and narrow spread. First, an initial dispersion such as a virtual source image could be added to compensate for multiple stacks being treated as a single stack, or a single stack with multiple wind directions could be used. Secondly, the method of determining stability class could be modified. The highest predicted value at Philo occurred when a class 4 stability hour followed a class 7 hour. To avoid rapid fluctuation of stability, the program changed the class 4 to a class 6 which has the narrowest plume spread. Whether this hour was a class 4 as measured, or a class 6 as predicted is hard to say, but perhaps allowing a class 5 in this instance may have been closer to actual average conditions. Thirdly, the modified model used for this study allowed the receptor elevation to be subtracted from the plume height, but did not allow the plume to rise as the terrain did. Allowing some rise for neutral and unstable cases may prove worthwhile. Fourthly, the wind during stable conditions usually fluctuates, and the plume rise and spread coefficients for stable classes should be looked at more closely to ascertain whether or not they actually hold for an hour.

- The Single Source Model should be modified to provide for the incorporation of other techniques for the determination of horizontal and vertical dispersion coefficients. Dispersion calculation methods which could be tested with the data from this study include those due to F. B. Smith,[7] Smith-Singer,[8] and G. A. Briggs.[9]

SECTION VII

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16. ABSTRACT

This report presents an analysis of the EPA Single Source Model using SO_2 concentration and meteorological data collected in the vicinity of three Ohio Power Plants: J. M. Stuart, Muskingum River, and Philo. The model predicts the upper percentile of the frequency distribution of 1-hour and 3-hour concentrations reasonably well. Concentrations over the remainder of the distribution are significantly underpredicted, due in part to the errors in the determination of background concentrations. The second highest 24-hour concentrations tend to be underpredicted by the model except at the Philo plant, where the model is less likely to account properly for terrain influences. Also investigated during this study were the frequency distributions of peak 1-hour to average 3-hour and peak 1-hour to average 24-hour concentration ratios. Statistics of these distributions were found to vary little from one plant to the next.

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