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IMPACT OF ENERGY SHORTAGE ON AMBIENT SULFUR DIOXIDE AND PARTICULATE LEVELS IN METROPOLITAN BOSTON AQCR

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Waste Management
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by

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I. INTRODUCTION

A. PROBLEM BACKGROUND

Demand for energy in the United States has increased at an average annual rate of 4.3 percent in recent years while per capita demand has grown at a corresponding rate of 3.5 percent [1]. Both rates are significantly higher than long-term historical averages. The bulk of this increased demand for energy has been met by increased use of liquid fossil fuels. Consumption of oil increased each year since 1970 at an average annual rate of more than a million barrels per day (mbd) to over 17 mbd by end of 1973.* During this same period, oil production by domestic sources and traditional foreign suppliers (Canada and Venezuela) decreased, forcing an increased reliance on oil imports from the Middle East. The American Petroleum Institute reports that foreign oil imports accounted for 36.9 percent of the oil consumed in the United States in 1974. This increased dependency on foreign suppliers placed the United States in an extremely vulnerable position in October 1973 when the politically motivated Middle East oil embargo began. The embargo drastically restricted oil imports into the country throughout the winter of 1973-1974 leading to severe supply problems in many sections of the country during the critical winter heating period. In addition, the embargo caused the price of imported oil to more than triple in a year's time. This situation has come to be known as the "energy crisis" or the "energy shortage" of 1973-1974.

Prior to the oil embargo, as part of State Implementation Plans to attain national ambient air quality standards for sulfur dioxide (SO_2) and total suspended particulates (TSP), several states adopted regulations limiting the sulfur and ash content of fuels burned in their jurisdictions. During the winter of 1973-1974, the Environmental Protection Agency (EPA) granted several temporary variances on these regulations due to restricted

* Total petroleum demand fell 3.3 percent in 1974 from 1973 levels.

supplies of low sulfur oils. In some cases, fuel utilization facilities were permitted to convert from oil to coal usage to avoid complete curtailment of their activities. Such changes were expected to cause increased emissions of SO_2 and particulates, while, by contrast, concomitant conservation efforts were expected to decrease fuel consumption and, therefore, emission of these pollutants. Thus, the impact on ambient SO_2 and TSP levels, of the fuel changes necessitated by the energy shortage, is not readily apparent. Observed variations in meteorological conditions between the winter of 1972-1973 (no shortage) and the winter of 1973-1974 (shortage) further complicates resolution of the question of the impact on ambient air quality of the energy shortage.

B. PROGRAM OBJECTIVE

The purpose of this project was to evaluate the impact of the 1973-1974 energy shortage on ambient air quality on a case study basis for a major urban area, Metropolitan Boston. Three principal tasks were undertaken to achieve this objective: an air quality analysis, a regulatory and emissions analysis, and a diffusion modeling analysis.

The objective of the air quality analysis was to identify, quantify and interpret trends or changes in trends in measured SO_2 and TSP levels during the period January 1970 through March 1974. The principal focus of the analysis was to statistically test the relation between trends in regional air quality levels, and SIP regulations and variances granted because of the energy shortage. Other factors simultaneously influencing the measurements, such as meteorological conditions, were also evaluated.

• The objective of the regulatory and emissions analysis was to develop quarterly emissions and fuel use inventories for SO_2 and particulates in the Metropolitan Boston Air Quality Control Region (AQCR) for the period January 1973 to June 1974 to support the subsequent modeling analysis task. These data were developed to reflect gross changes in fuel use between the base case (1972) and the periods of interest related to growth, conservation measures, meteorological factors such as degree-days, and variances granted and implemented on the Massachusetts SIP regulations.

The objective of the diffusion modeling task was to obtain a clearer understanding of the impact and potential impact of the energy shortage on air quality levels throughout the AQCR by isolating the relative effects of factors such as meteorology, growth and conservation, and variances on ambient SO_2 and TSP concentrations. The results were used to corroborate the findings of the analogous statistical decomposition of measured air quality data undertaken in the air quality analysis.

C. SUMMARY OF RESULTS AND CONCLUSIONS

A combination of statistical analysis of ambient monitoring data and simulation analysis based on diffusion modeling was used to examine the effects of the energy shortage on sulfur dioxide (SO_2) and total suspended particulate (TSP) levels throughout the Metropolitan Boston AQCR. Changes in the emission of these pollutants associated with the energy shortage during the first quarter of 1974 arose principally from fuel conservation efforts, variances from existing sulfur in fuel regulations, and conversion of the Salem Harbor power plant to coal-firing from oil-firing. The findings of the study relative to these and other factors are as follows.

1. The modeling analysis indicated that the energy shortage was responsible for average concentration levels lower than those projected to occur if historical fuel use trends had continued during the winter of 1973-1974. This result is a consequence of conservation measures' being more pronounced than the opposing effect from implementation of variances. Modeling analysis indicates that, in the absence of the energy shortage, SO_2 concentrations would have risen an average of approximately 3 percent across the AQCR between the first quarter of 1973 and the first quarter of 1974, due to the combined effect of growth and changes in meteorology. The analysis further indicates that the decrease observed across the AQCR in SO_2 concentrations was approximately 12 percent, reflecting a net decrease of 15 percent due to the energy-shortage-related parameters. Fuel conservation contributes approximately 18 percent to the decrease, while variances contribute to an increase of 3 percent.

2. A major factor in the balance of energy shortage effects is that the actual implementation of variances by combustion facilities in the AQCR represents realization of only a small fraction of the potential for consumption of higher sulfur fuel oil. This result was determined from a survey conducted during the study of fuel distributors in the Region. Simulation modeling indicated that if the variances had been fully implemented, SO_2 levels would have deteriorated significantly across the AQCR in spite of conservation effects.* The analysis indicated a potential 52 percent average increase in average SO_2 concentrations across the AQCR associated with full implementation of the variances. The combined effect of full variance implementation, meteorology, and growth and conservation would have led to a net increase of 37 percent across the AQCR. Further, this potential increase would have been highly variable across the region, ranging from a net decrease of 6 percent southwest of Boston to a net increase of 57 percent along coastal exposures. The impact of full variance implementation is primarily due to a projected larger source contribution from power plants and distillate area source users. Their combined contribution would have been more than 90 percent of the total increase in SO_2 levels due to variances.

3. The modeling analysis indicates that TSP concentrations in the AQCR were largely unaffected by the energy shortage. Full implementation of variances would not have significantly affected this finding.

4. The statistical analysis of air quality monitoring data between the first quarter of 1973 and 1974 also indicates that the influence of meteorology on TSP and SO_2 levels involved two opposing effects: the tendency for the change in wind-stability patterns between these years to decrease concentrations, and the effect of degree-days to increase concentrations. SO_2 concentrations in the AQCR which are strongly related to space heating requirements (degree-days) showed a net balance between these factors. TSP concentrations, however, are affected considerably less by

* Assuming no additional conservation efforts concommitant with full variance implementation.

changes in degree-days and without this "balancing" factor showed a net decrease due to changes in wind-stability patterns. Urban core TSP concentrations are more strongly influenced by space heating requirements, due to the predominance of dwelling units and commercial establishments, and thus showed a stronger balance between these factors.

5. The statistical analysis of air quality data also revealed that SO_2 concentrations in the AQCR did not significantly increase during the energy shortage period in spite of the partial implementation of the variances granted on the State Implementation Plan to burn higher sulfur fuel in several cases. In fact, in most cases, the trend of lower SO_2 concentrations observed prior to the energy shortage continued. Note, however, that the emissions and regulatory analysis and the diffusion modeling study showed that only a limited number of the granted variances were fully implemented throughout the AQCR. These analyses further indicate that if full implementation had occurred, significantly higher SO_2 levels would have been observed across the region.

6. Spatial variations of SO_2 levels across the region were shown by the modeling analysis to be primarily a consequence of changes in <u>wind directional</u> frequencies between 1973 and 1974. The 1974 first-quarter wind rose indicates a greater frequency of northeasterly flow than occurred in 1974. This resulted in coastal stations observing lower SO_2 concentrations during 1973 due to the lack of emission sources to the northeast of Boston. Receptors to the southwest of Boston observed higher than normal transport of emissions from the city during that year. Consequently, with the return of the normal strong northwesterly flow in the winter of 1974, the total effect of changes in meteorology was to increase SO_2 levels at coastal stations an average of 15 percent, which significantly differs from the 1 percent average increase observed for the AQCR. A decrease in SO_2 concentrations of 32 percent in the area southwest of Boston, two-thirds of which is attributable to meteorology, was also observed in 1974.

7. The modeling analysis also indicates that, in the absence of the energy shortage, TSP levels would have <u>decreased</u> an average of approximately 18 percent across the AQCR between the first quarter of 1973 and the

first quarter of 1974, due to the combined effect of growth and changes in meteorology. The analysis further indicates that the actual decrease across the AQCR in TSP concentrations was approximately 20 percent, reflecting a combined 2 percent decrease due to the energy-shortage-related parameters of conservation (-3 percent) and actual variances implemented (+1 percent). As indicated above, full variance implementation would not have significantly affected these findings.

The modeling analysis also indicates that the only variance granted which significantly affected particulate emission rates among fuel combustion sources in the Metropolitan Boston AQCR was the allowance for burning coal in three units of New England Power Company's Salem Harbor power plant. The coastal location and emission characteristics of this source, coupled with the dominant northwesterly wind flow in the winter quarter of 1974, resulted in predicted inland concentrations approximately only 2 percent higher than the hypothetical no-variance case, even though the facility's particulate emissions increased by a factor of more than 9.

8. Other findings of this program include the indication that major SIP fuel use regulations effective July 1, 1970, and October 1, 1971 (see Table 2-1), are associated with statistically significant decreases in regional SO_2 and TSP levels. This is explained by the fact that both of these regulations were responsible for conversion of many large fuel utilization facilities to fuels with lower sulfur and ash contents.

II. AIR QUALITY ANALYSIS

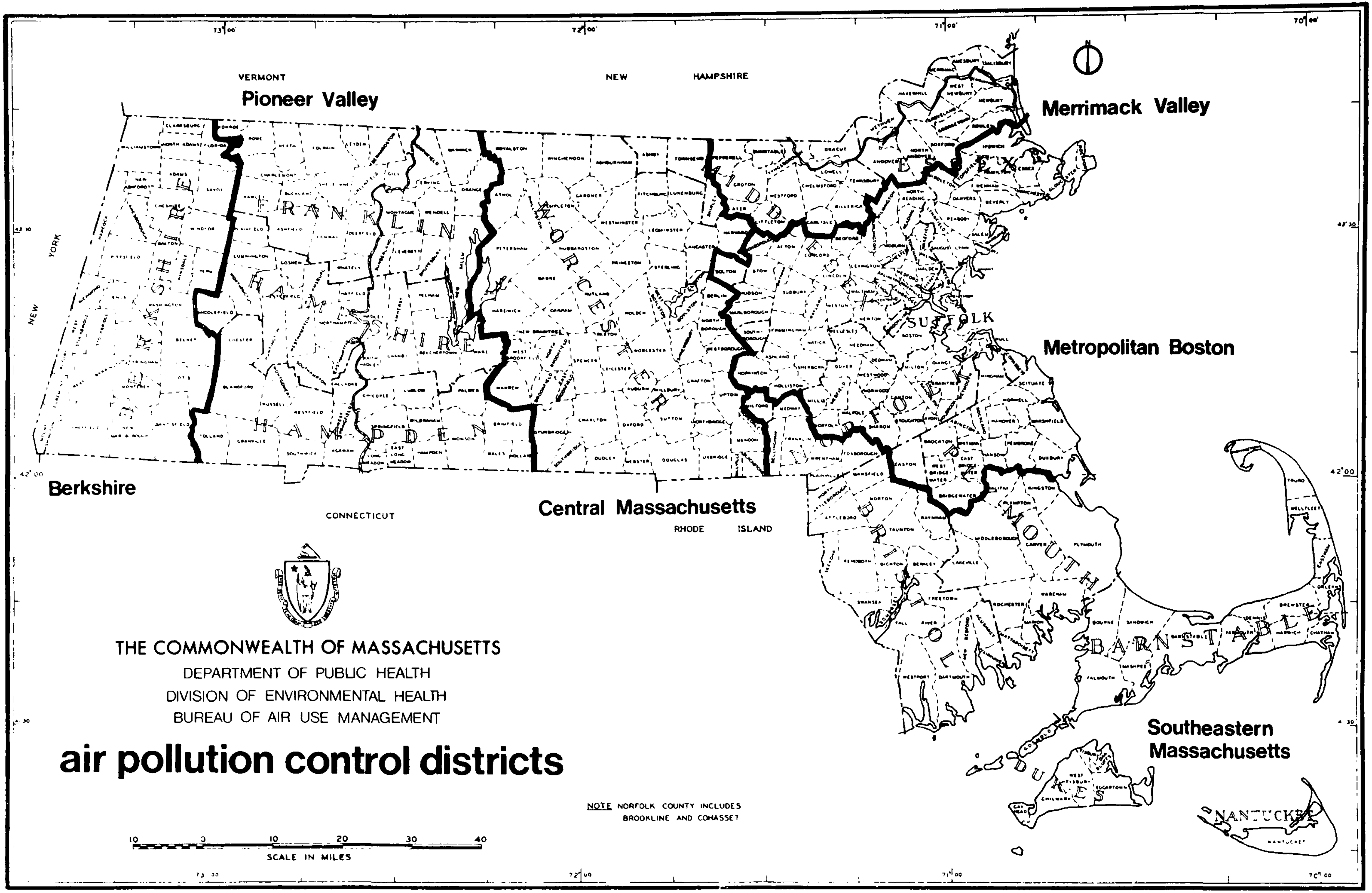
A. BACKGROUND

1. Regulatory

Effective July 1, 1970, the Commonwealth of Massachusetts Department of Public Health divided Massachusetts into six Air Pollution Control Districts (APCDs) as shown in Figure 2-1. The Metropolitan Boston APCD (MBAPCD) was formed from 102 cities and towns comprising 1,400 square miles and having a population of approximately three million people [2]. Also effective on July 1, 1970, was a ban on all open burning in the MBAPCD and a limit on the ash content of any fossil fuel burned in the MBAPCD to nine percent by dry weight. On October 1, 1970 and on October 1, 1971, several regulations promulgated by the State Bureau of Air Quality Control (BAQC) limiting the sulfur content of fuels burned in the MBAPCD became effective. Table 2-1 summarizes these regulations.

On March 9, 1971, the Administrator of the U.S. Environmental Protection Agency (EPA) designated six Air Quality Control Regions (AQCRs) in Massachusetts. These six AQCRs are shown in Figure 2-2. Note that three of these AQCRs are interstate and contain portions of adjacent New England states while the others correspond exactly to APCDs. The Metropolitan Boston Intrastate AQCR (MBAQCR) coincides with the Commonwealth's MBAPCD.

On May 31, 1972, pursuant to Section 110 of the Federal Clean Air Act, the EPA Administrator approved a plan implementing the National Ambient Air Quality Standards for the Commonwealth of Massachusetts [3]. This State Implementation Plan (SIP) contained regulations for the control of air pollution adopted to become effective June 1, 1972, under the provisions of Section 142D, Chapter 111, General Laws of the Commonwealth. All state regulations that were already in effect prior to June 1, 1972 pertaining to control of air pollution were consolidated into the SIP regulations. Regulations limiting the sulfur and ash content of fuels burned in the MBAQCR were consolidated into SIP Regulation 5 with a few additions (see Table 2-1). A complete summary of the SIP regulations is shown in Table 2-2.



VERMONT
NEW HAMPSHIRE
NEW YORK
CONNECTICUT
RHODE ISLAND
Pioneer Valley
Merrimack Valley
Metropolitan Boston
Berkshire
Central Massachusetts
Southeastern Massachusetts
BERKSHIRE
FRANKLIN
HAMPSHIRE
HAMPDEN
WORCESTER
MIDDLESEX
ESSEX
SUFFOLK
NORFOLK
PLYMOUTH
BRISTOL
BARNSTABLE
DUKES
NANTUCKET
THE COMMONWEALTH OF MASSACHUSETTS
DEPARTMENT OF PUBLIC HEALTH
DIVISION OF ENVIRONMENTAL HEALTH
BUREAU OF AIR USE MANAGEMENT
air pollution control districts
NOTE NORFOLK COUNTY INCLUDES BROOKLINE AND COHASSET
SCALE IN MILES

TABLE 2-1

A SUMMARY OF REGULATIONS ADOPTED TO CONTROL THE SULFUR AND ASH CONTENT OF FUELS BURNED IN THE METROPOLITAN BOSTON AIR QUALITY CONTROL REGION*

Effective Date of Adoption	Regulations in Effect in Metropolitan Boston AQCR
July 1, 1970	Ban on all open burning
	Ash content of fossil fuels limited to 9% by dry weight
October 1, 1970	Residual oil sulfur content limited to 2.2% and to 1.0% in core**
	Distillate oil sulfur content limited to 0.3%
	Coal sulfur content limited to 1.5% and to 0.75% in core**
October 1, 1971	Residual oil sulfur content limited to 1.0% and to 0.5% in core**
	Coal sulfur content limited to 0.7% and to 0.37% in core**
June 1, 1972	Ban on residual oil use at facilities with rated boiler capacities of 3 million Btu/hour or less
	Ban on solid fuel use at hand-fired facilities with rated boiler capacities in excess of 150 thousand Btu/hour

* Coincident with the Metropolitan Boston Air Pollution Control District.

** The 13 core cities and towns are: Arlington, Belmont, Boston, Brookline, Cambridge, Chelsea, Everett, Malden, Medford, Newton, Somerville, Waltham, and Watertown.

Figure 2-2

Air Quality Control Regions in Massachusetts

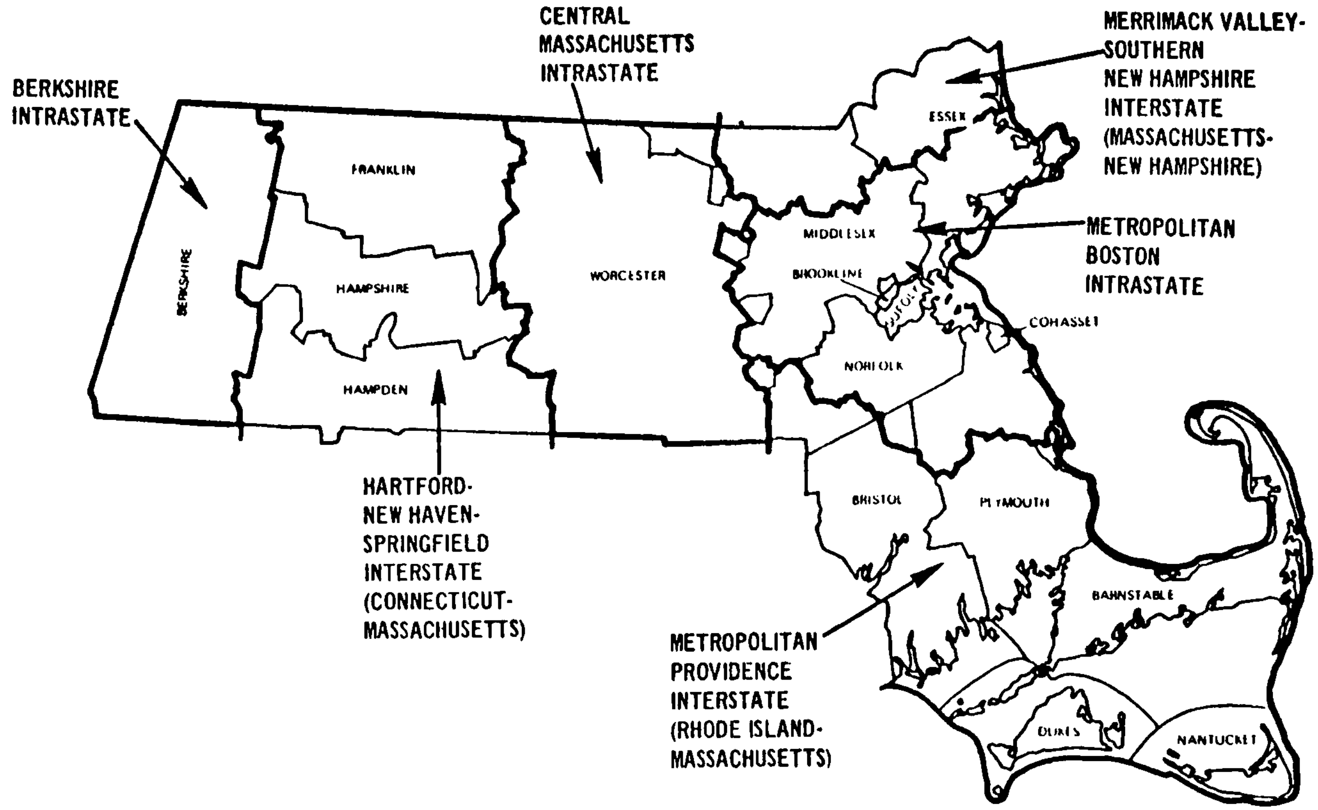


TABLE 2-2

SUMMARY OF REGULATIONS FOR THE CONTROL OF AIR POLLUTION IN MASSACHUSETTS [4]

(Regulations effective June 1, 1972 with amendments effective September 1, 1972)

Regulation Number	Topic
1	General prohibition of air pollution
2	Plant approval and emission limitations (Note: Sections 2.1 and 2.5 amended September 1, 1972)
2.1	New and modified facilities; Department approval needed for the plans, specifications, standard operating procedure and maintenance procedures.
2.2	Role of Department in the evaluation of plans is defined.
2.3	Field of application for Regulation 2 includes fossil fuel utilization facilities within capacities greater than 3 million Btu per hour, manufacturing facilities of all types and dry cleaning establishments.
2.4	Department may request and review plans on <u>any</u> facility which has a likelihood of causing air pollution.
2.5	Emissions limits specified. Three categories: (1) existing sources, critical areas of concern (i.e., urban areas); (2) existing sources, other areas; and (3) new sources. Particulates: detailed specifications, all types of facilities. NO_2: total emission weight and stack gas concentration limits. SO_2: same as NO_2. Organic material: requirement for vapor traps.
3	Nuclear energy facilities
4	Fossil fuel utilization facilities (Note: amended September 1, 1972)
4.1	Plans approved required for facilities with capacities greater than 3 million Btu per hour (already required by Regulation 2).

TABLE 2-2
(CONTINUED)

Regulation Number	Topic
4.2	Smoke density indicators required by April 1, 1973 on all facilities with capacities greater than 10 million Btu per hour (Note: devices must be approved by the Department).
4.3	All facilities (i.e., existing facilities as well as new facilities) with capacities greater than 10 million Btu per hour must have standard operating procedures approved by the Department by July 1, 1973.
4.4,4.5	Illegal to remove or circumvent the operation of control devices.
5	Fuel regulations
5.1	Sulfur content of fuels
5.1.1	Residual oil: Boston core* area: 0.5% S maximum
5.1.2	Remainder of state: 1.0% S maximum
5.1.3	Distillate oil (throughout the state): 0.3% S maximum. Fuel users may submit alternative plans for review by the Department. Fuel suppliers must register with the Department.
5.2.1	No facility with capacity less than 3 million Btu per hour may use residual oil.
5.2.2	After July 1, 1973, in core* areas, no facility with capacity less than 6 million Btu per hour may use residual oil.**
5.3	No solid fuel use permitted in hand-fired facilities with capacities larger than 150,000 Btu per hour.

* See Table 1 for definition of core area.

** This regulation was never implemented by the BAQC due to a procedural error in which it was omitted from public hearings on the proposed regulations. The BAQC does not currently plan to implement 5.2.2 in the future since SO_2 and TSP standards have been achieved in the core.

TABLE 2-2
(CONTINUED)

Regulation Number	Topic
5.4	Ash content of fuels not in excess of 9%. Fuel shippers must provide evidence.
5.5	Fuel additives controlled.
5.6	Fuel suppliers must make analyses and maintain records.
6	Visible emissions (Note: amended September 1, 1972). Smoke emissions not greater than #1, except for 6 minutes per hour (then limited to #2). Incinerator emissions never greater than #1.
7	Open burning prohibited (specific exceptions permitted).
8	Incinerators. Sale of new incinerators and operation of all incinerators must be approved by the Department.
9	Dust and odor control (Note: amended September 1, 1972). General prohibition, and specific prohibitions for transportation, construction and demolition.
10	Noise control
11	Transportation media
12	Registration, recordkeeping and reporting. All sources with energy capacities in excess of 3 million Btu per hour shall register with the Department annually, and shall report standard data. All other manufacturing sources having emissions above stated levels shall also register annually. The Department will acknowledge the registration in writing.
13	Stack testing. Required of all facilities designated by the Department (present designation: all facilities with capacity in excess of 100 million Btu per hour). The operator of the facility must provide access to stack, etc.
14	Monitoring devices. The Department may require the use of emission monitoring devices.
15	Asbestos (added by amendment, September 1, 1972). Spray application of asbestos fibers is prohibited.

TABLE 2-2
(CONTINUED)

Regulation Number	Topic
50	Variances. (Variances can be granted for periods up to one year, and must be approved both by EPA and by the Department. Four items must be covered in the request for a variance: (1) undue hardship; (2) public good; (3) evidence that standards will be met; (4) evidence that no significant deterioration of air quality will result.)
51	Hearings. Rules for hearings relative to orders and approvals.
52	Enforcement provisions. Designates building officials, health, police and fire departments as having authority in specific cases.

During the summer of 1973, the major oil companies issued warnings and predictions in relation to shortages of petroleum products. The events that followed, which came to be known as "the energy crisis", set in motion the machinery for granting special variances on the Massachusetts SIP air pollution control regulations.

On August 13, 1973, the Governor of the Commonwealth of Massachusetts asked the Secretary of the Executive Office of Consumer Affairs (EOCA) to conduct a survey and analysis of the heating oil situation confronting the Commonwealth for the coming winter [4]. Starting in the summer and throughout the fall, oil companies (the majors and also Massachusetts independents) provided forecasts of distillate oil shortages to the State Bureau of Air Quality Control (BAQC). Oil retailers, suppliers, and consumers (including industries, utilities, municipalities, and public authorities) informed State officials and legislators, the BAQC, and the Governor's Energy Task Force (headed by the Secretary of the EOCA) of their lack of firm contracts for conforming distillate fuel, i.e., having a sulfur content less than or equal to 0.3%. Based on their assessment of a potential oil shortage, the BAQC held public hearings on September 19, 1973, concerning a proposed relaxation of SIP regulatory controls on the sulfur content of distillate oil from 0.3% to 0.5% on a statewide basis. On November 2, 1973, the Massachusetts Department of Public Health Council voted to approve the relaxation of distillate oil sulfur content regulations as proposed by the BAQC. On December 11, 1973 [5], the EPA Administrator approved a change in Massachusetts Regulation 5.1.3 which relaxed the sulfur content of distillate oil burned statewide from 0.3% to 0.5% for the period November 15, 1973 to May 15, 1974.

In addition to distillate fuel, there were also shortages of low sulfur <u>residual</u> oil. To deal with this situation, the BAQC granted variances to sources burning residual oil on a case-by-case basis using three strategies:

- SIP Regulation 5.1.2(d) for large sources
- Additional special variances for large sources
- Special variances for small sources

Regulation 5.1.2(d) allowed statewide use of 2.2% sulfur residual oil by facilities with a rated boiler capacity at or above 250 million Btu per hour until May 15, 1974, if certain conditions were met. These conditions and the full text of 5.1.2(d) are listed in Table 2-3. This modification to the SIP regulations was approved by the EPA Administrator on January 30, 1974 [6]. On May 16, 1974, EPA published in the Federal Register [7] the approval for 23 specific sources in Massachusetts to use 2.2% residual oil. The subset of those sources in the MBAQCR granted this special variance under SIP Regulation 5.1.2(d) is shown in Table 2-4, along with the effective dates of the variances. Several other special variances not covered by Regulation 5.1.2(d) were granted for large sources in the MBAQCR by the Massachusetts BAQC and are summarized in Table 2-5.

For sources with a rated boiler capacity of less than 250 million Btu per hour, application for a special variance to burn nonconforming residual oil had to be received from both the source and the fuel supplier along with documentation of real need for the variance [10]. Most major fuel suppliers refused to be the principal involved in variance requests. Instead, they applied intense pressure on their customers to apply to the BAQC for variances. In all, 601 small-source variances were granted in the MBAQCR through 12 fuel distributors. These data are summarized in Table 2-6 by supplier. Of the major distributors, only one independent distributor voluntarily cooperated with the BAQC in redistribution plans to insure priority allocation of the lowest sulfur fuel available to the Boston core area.

An analysis of the actual quantities of nonconforming fuel burned in the Metropolitan Boston AQCR under variances granted on fuel use regulations is presented in Section III.

2. Measured Data

a. Air Quality

Monthly summaries of air quality measurements in the Metropolitan Boston AQCR for SO_2 and TSP between January 1970 and June 1974

TABLE 2-3

Emergency Regulation Adopted by Massachusetts Department of Public Health on November 2, 1973 (Sulfur in fuel)

5.1.2(d) In the Commonwealth of Massachusetts it will be permissible for fossil fuel facilities with an input capacity, as rated by the Department, at or in excess of 250 million B.t.u./hour to burn residual fuel oil with a sulfur content up to 2.2% (1.22 pounds per million B.t.u. heat release potential) during the period beginning November 15, 1973 and ending May 15, 1974 providing:

a. such facility conforms with guidelines developed by the Division of Environmental Health,

b. such facility acquires approval in writing from the Department to operate, and

c. the Division of Environmental Health will conduct a monthly review of fuel supplies and Air Quality Conditions and make appropriate recommendations for amendments to the Public Health Council.

All such fossil fuel facilities located in the Berkshire Air Pollution Control District, the Pioneer Valley Air Pollution Control District, the Central Massachusetts Air Pollution Control District, the Southeastern Massachusetts Air Pollution Control District, the Merrimack Valley Air Pollution Control District, and the Metropolitan Boston Air Pollution Control District except those cities and towns specified in Regulation 5.1.1, * burning a residual fuel oil with a sulfur content up to 2.2% must have available for conversion within 6 hours of notice from the Department a three (3) day supply of 1.0% sulfur content fuel. Notice for such conversion will be given by the Department in the event of predictions of adverse meteorological conditions.

In the cities and towns specified in Regulation 5.1.1 of the Metropolitan Boston Air Pollution Control District fossil fuel facilities rated with a capacity at or in excess of 250 million B.t.u./hour burning a residual fuel oil with a sulfur content up to 2.2% must have available for conversion within 6 hours of notice from the Department a three (3) day supply of 0.5% sulfur content fuel. Notice for such conversion will be given by the Department in the event of predictions of adverse meteorological conditions.

* Arlington, Belmont, Boston, Brookline, Cambridge, Chelsea, Everett, Malden, Medford, Newton, Somerville, Waltham and Watertown.

TABLE 2-4

FUEL UTILIZATION SOURCES IN THE METROPOLITAN BOSTON AQCR
WITH A RATED BOILER CAPACITY EQUAL TO OR EXCEEDING 250 MILLION BTU/HOUR
GRANTED A SPECIAL VARIANCE TO BURN 2.2% SULFUR RESIDUAL OIL
UNDER SIP REGULATION 5.1.2(d) [7]

Source	Location	Eff. Date
Boston Edison Co.	Weymouth	Nov. 20, 1973
Brandeis University	Waltham	Nov. 30, 1973
Cambridge Electric	Cambridge	Nov. 21, 1973
Mass. Bay Transportation Authority	Boston	Nov. 20, 1973
Mass. Institute of Technology	Cambridge	Nov. 21, 1973
Revere Sugar Refinery	Charlestown	Nov. 21, 1973
A.C. Lawrence Leather Co.	Peabody	Dec. 19, 1973
Eastman Gelatine Corp.	Peabody	Nov. 20, 1973
U.S.M. Corp.*	Beverly	Nov. 20, 1973
General Electric Lynn River Works*	Lynn	Nov. 20, 1973

TABLE 2-5

ADDITIONAL SPECIAL VARIANCES GRANTED LARGE SOURCES
IN THE METROPOLITAN BOSTON AQCR

Source	Variance	Effective Dates	EPA Approval
New England Power Co.*			
Salem Harbor Station, Salem			
All Units	2.6% Sulfur Residual Oil	Jan. 1, 1974-May 15, 1974	[7]
Units 1, 2, 3	2.5% Sulfur & 15% Ash Coal	Jan. 23, 1974-May 15, 1974	[8]
Boston Housing Authority			
13 Housing Facilities in Boston	1.0% Sulfur Residual Oil	Nov. 15, 1973-May 15, 1974	[9]
Boston Edison Co.			
New Boston & L St. Stations, Boston	2.6% Sulfur Residual Oil	Jan. 22, 1974-May 15, 1974	**
Edgar Station, Weymouth			
Mystic Station, Everett			

* NEPCO's Brayton Point Station in Somerset, Mass., was also granted variances but is located in the Metropolitan Providence Interstate AQCR.

** EPA approval not published in the Federal Register.

TABLE 2-6

FUEL UTILIZATION SOURCES IN THE METROPOLITAN BOSTON AQCR
WITH A RATED BOILER CAPACITY OF LESS THAN 250 MILLION BTU/HOUR
GRANTED A SPECIAL VARIANCE TO BURN NONCONFORMING RESIDUAL OIL

	No. of Sources Affected in MBAQCR			
Fuel Distributor	In Core*	Outside Core	Content Allowed	Effective Date**
C.K. Smith & Co., Inc.	3	29	2.4%	Jan. 10, 1974
Gibbs Oil Co.	120	--	1.0%	Dec. 7, 1973
Glendale Mortion Petroleum Corp.	33	--	1.0%	Dec. 28, 1973
(supplied by Union Petroleum)	--	2	2.0%	Dec. 28, 1973
H.N. Hartwell & Son, Inc.	--	2	2.2%	Dec. 11, 1973
Mass. Oil & Fuel Co., Inc.	6	--	1.0%	Dec. 13, 1973
Metropolitan Petroleum Co.	1	--	1.0%	Dec. 11, 1973
Northeast Petroleum Corp.	15	--	1.0%	Nov. 30, 1973
Oil Service of New England	1	--	1.0%	Dec. 26, 1973
Old Colony Oil Heat, Inc.	224	--	1.0%	Nov. 30, 1973
	--	1	2.2%	Nov. 30, 1973
Pen-Tex Oil Co.	17	--	1.0%	Dec. 11, 1973
	--	4	2.0%	Dec. 28, 1973
Union Petroleum Corp.	40	--	1.0%	Dec. 13, 1973
	--	90	2.0%	Dec. 12, 1973
White Fuel Co.	7	--	1.0%	Nov. 30, 1973
	--	6	2.2%	Nov. 30, 1973

* Refer to Table 2-1 for a list of the 13 core cities and towns.

were obtained through the EPA air quality data handling system, SAROAD,* and from the BAQC. All data were edited to facilitate completion of a suitable data base for analysis.

The data base contained several substantive data gaps, thereby providing an inadequate analysis base at several monitoring sites. To insure a meaningful analysis, a data subset, consisting of data from air quality monitoring sites for which there were sufficient measurements taken, was compiled by excluding any site that had more than two consecutive months of missing data. One exception to this guideline was made for SO_2 measurements collected at Kenmore Square in the City of Boston. Here a single three-month stretch of missing data from March through May 1971 was not used to invalidate the site, as this is the prime benchmark site used in the development of the State Implementation Plan designed to insure the attainment of ambient air quality standards in Metropolitan Boston by 1977 [11]. The final results of the selection process are shown in Table 2-7 and indicate that SO_2 data from 13 sites and TSP data from 7 sites are sufficient for data analysis from January 1971 to June 1974. For the more extended period beginning in January 1970, only 3 sites have sufficient SO_2 data, and one site sufficient TSP data. Fortunately, however, the Kenmore Square site is included in both of these sets. The geographical locations of the selected air quality monitoring sites are shown in Figure 2-3. It should be noted that several of the monthly average concentrations are based on as few as three daily measurements.

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* Storage and Retrieval of Aerometric Data. These published data, maintained in the National Aerometric Data Bank by EPA, formed the basis for the air quality data analysis.

TABLE 2-7

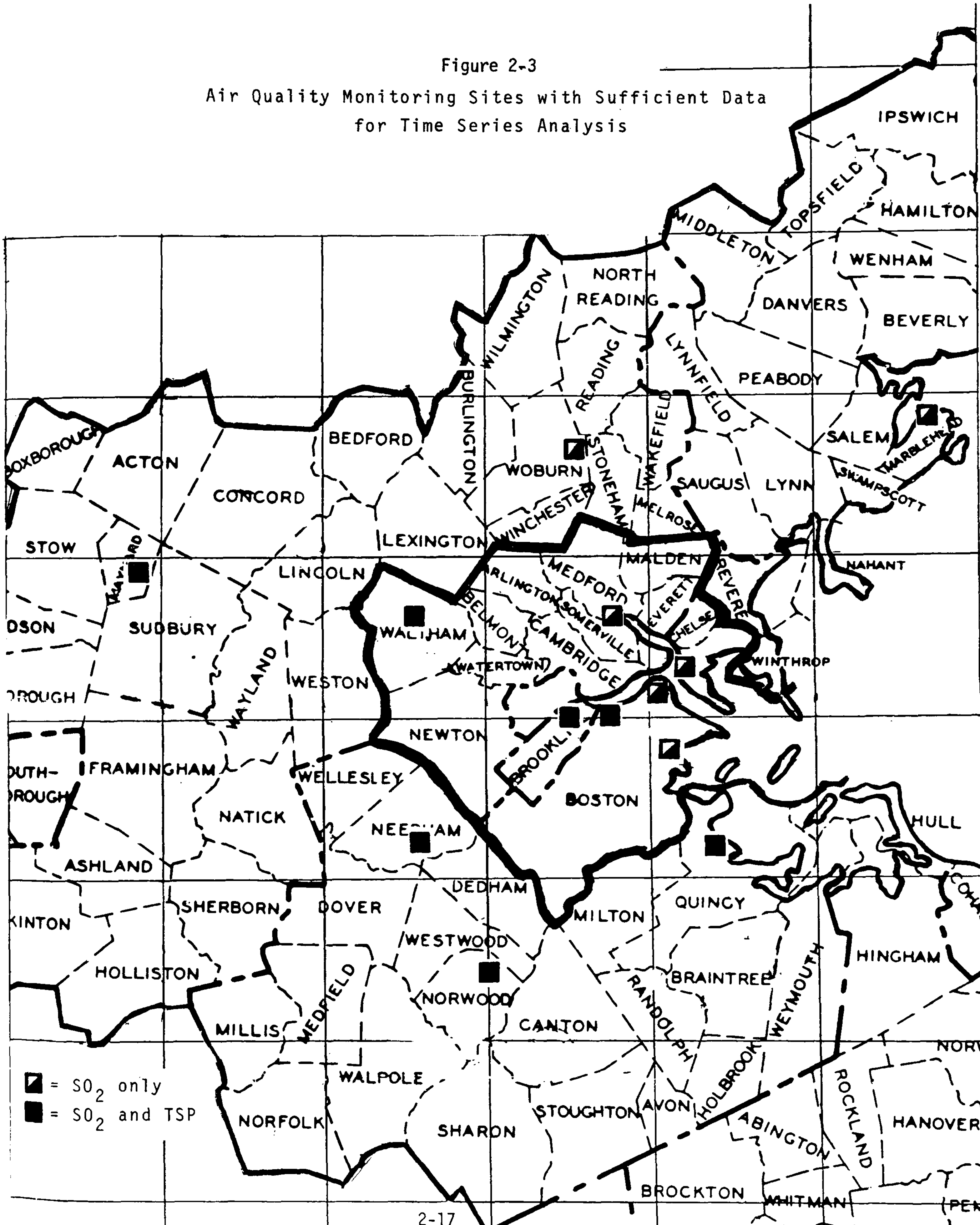
METROPOLITAN BOSTON AIR QUALITY MONITORING SITES
RECORDING SUFFICIENT DATA FOR TIME SERIES ANALYSIS
IN THE INDICATED TIME PERIODS

SAROAD* Site Code	Site Location	Site Description	Series Name	Time Span of Data 1970-74	Time Span of Data 1971-74	Urban Core Sites
SO_2						
0240001(F01)	Government Center, Boston	Center City-Commercial	SO2A	✓	✓	✓
0240002(F01)	Kenmore Square, Boston	Center City-Commercial	SO2B	✓	✓	✓
0240012	South Bay, Boston	Suburban-Industrial	SO2C		✓	✓
0240013	Central Square, East Boston	Center City-Commercial	SO2D	✓	✓	✓
0340001	Greenough St., Brookline	Center City-Residential	SO2E		✓	
1160001	Village St., Marblehead	Center City-Commercial	SO2F		✓	
1200001	US Army Site, Maynard	Rural-Agricultural	SO2G		✓	
1220002	Main St., Medford	Center City-Commercial	SO2H		✓	
1480002	Dedham Ave., Needham	Center City-Residential	SO2I		✓	
1700001	Nahatan St., Norwood	Center City-Residential	SO2J		✓	
1880001	Hancock St., Quincy	Center City-Commercial	SO2K		✓	
2340003	Beaver St., Waltham	Rural Agricultural	SO2L		✓	
2620002	Montvale Ave., Woburn	Center City-Commercial	SO2M		✓	
TSP						
0240002(F01)	Kenmore Square, Boston	Center City-Commercial	TSP1	✓	✓	✓
0340001	Greenough St., Brookline	Center City-Residential	TSP2		✓	
1200001	US Army Site, Maynard	Rural-Agricultural	TSP3		✓	
1480002	Dedham Ave., Needham	Center City-Residential	TSP4		✓	
1700001	Nahatan St., Norwood	Center City-Residential	TSP5		✓	
1880001	Hancock St., Quincy	Center City-Commercial	TSP6		✓	
2340003	Beaver St., Waltham	Rural-Agricultural	TSP7		✓	

*Storage and Retrieval of Aerometric Data

Figure 2-3

Air Quality Monitoring Sites with Sufficient Data for Time Series Analysis



For the selected sites, small gaps of one or two consecutive missing data points in the time series of the monthly average pollutant concentrations were initially filled using a simple linear interpolation scheme between adjacent months. After preliminary data analysis by the ratio to moving average technique, a number of the inserted values were found to contribute to unusually large irregularities in the analyzed trends. Using a standard procedure, these were replaced by more reasonable values suggested by the analysis that incorporated measurements from similar time periods in different years. The replacement values were obtained by removing the irregular component from the data time series using the ratio to moving average technique described in Section II.B.2. With these changes, the data base of SO_2 and TSP ambient air quality measurements, for use in the data analyses, was complete.

A continued review of the individual data points used in the computation of the discrete time series of monthly SO_2 and TSP averages led to selection of three representative series for SO_2 and TSP each (see Table 2-8). These six series were used to help sort out and highlight significant cause-effect relationships in the measured air quality data.

b. Meteorological

Monthly degree-day and wind-speed data were obtained for Boston for the period January 1970 through August 1974 from Local Climatological Data (LCD) summaries. These data are based on measurements taken at Boston's Logan International Airport and were used in the data and statistical inference analyses.

B. DATA ANALYSIS

1. Objectives and Scope

The objective of the data analysis task was to isolate, identify, and quantify trends in ambient SO_2 and TSP concentrations in the Metropolitan Boston AQCR for the period January 1970 through June 1974.

TABLE 2-8

REPRESENTATIVE METROPOLITAN BOSTON AIR QUALITY MONITORING SITES
CHOSEN FOR DATA ANALYSIS

SAROAD*	Site		Series	Time Span
Site Code	Location	Description	Name	of Data
SO_2				
0240002(F01)	Kenmore Square, Boston	Center City-Commercial	SO2B	January 1970-May 1974
1700001	Nahatan St., Norwood	Center City-Residential	SO2J	January 1971-June 1974
2340003	Beaver St., Waltham	Rural-Agricultural	SO2L	March 1971-June 1974
TSP				
0240002(F01)	Kenmore Square, Boston	Center City-Commercial	TSP1	January 1970-June 1974
1700001	Nahatan St., Norwood	Center City-Residential	TSP5	January 1971-June 1974
2340003	Beaver St., Waltham	Rural-Agricultural	TSP7	March 1971-June 1974

*Storage And Retrieval of Aerometric Data

2. Methodology

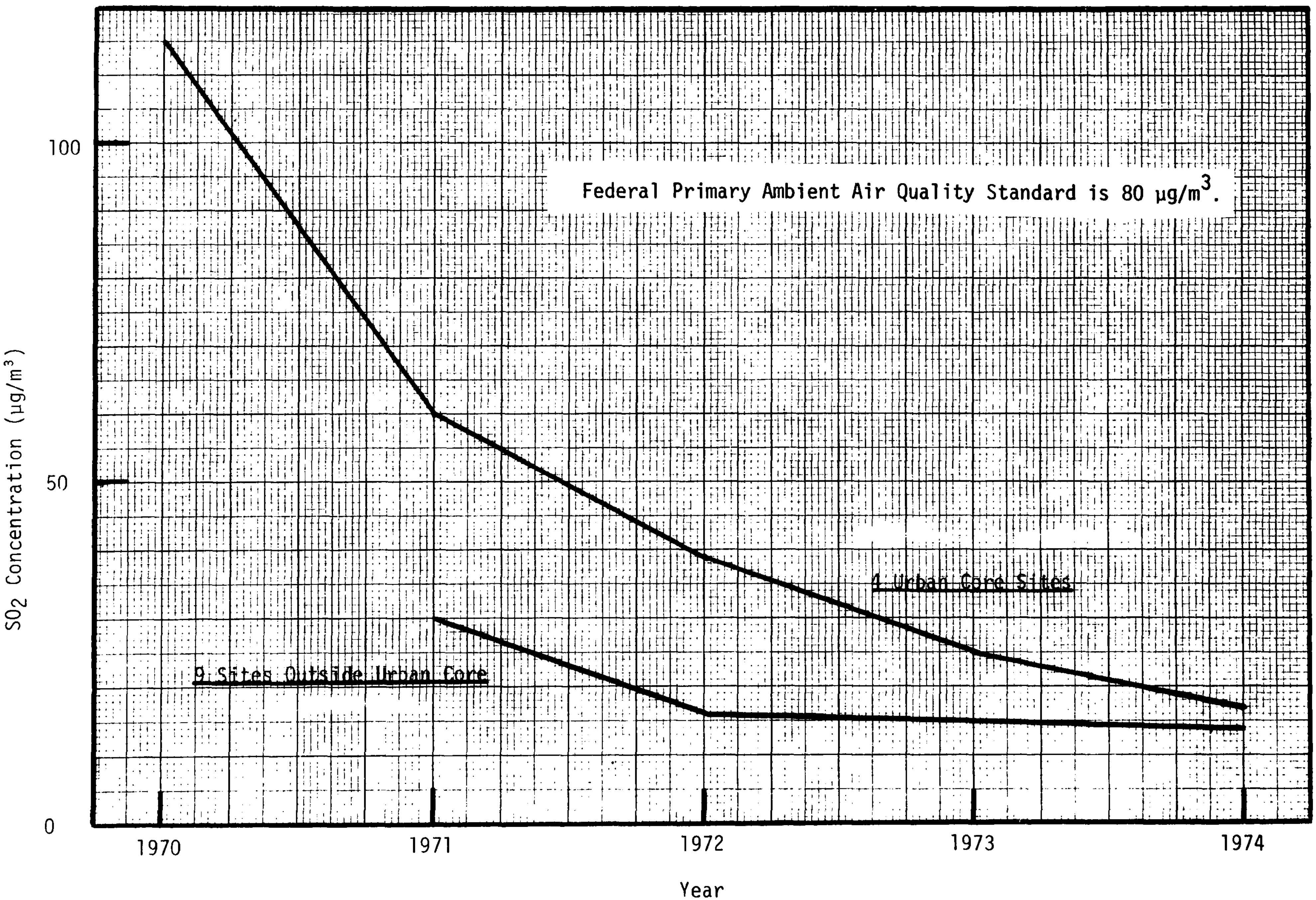
The data analysis was exploratory in that it examined the air quality data for trends (or changes in trends) without use of the knowledge of when fuel use regulations and variances (granted because of the energy shortage) occurred. In addition, the data were analyzed to extract, model and quantify persistent periodic behavior related to temporal factors such as seasonal climatology.

Air monitoring data, for ambient concentrations of SO_2 (13 sites) and TSP (7 sites) in the AQCR, was judged sufficient for data analysis. Time series of monthly pollutant concentrations measured at these sites were decomposed into three components or movements using a ratio to moving average technique [12]. These movements are: a trend-cycle component composed of both long- and short-term trends in the data, a seasonal component that quantifies the persistent periodic behavior in the series that can be related to temporal factors, and an irregular component that quantifies the non-periodic and unpredictable part of the series. This analysis was performed using both an additive and multiplicative model of the series components. Triple exponential smoothing techniques were used to confirm the trend-cycle component derived in the ratio to moving average analysis.

3. Results

Although the series components derived using additive and multiplicative models were comparable in each case, the additive model produced the smaller irregular component when applied to measured SO_2 data, i.e., it was able to explain more of the series behavior in the trend-cycle and seasonal components. By contrast, the multiplicative model was found most appropriate for the measured TSP data. Trend-cycle components for the data series revealed that, in general, regional SO_2 levels fell consistently during the entire time period of analysis, with the steepest decline occurring prior to 1972 (see Figure 2-4). Ambient TSP levels also exhibited a general downward trend similar to that of SO_2 levels, but not

Figure 2-4
Composite Annual SO_2 Trend-Cycle Components
in Metropolitan Boston AQCR



as pronounced or consistent (see Figure 2-5). Figures 2-4 and 2-5 show, respectively, composite annual average SO_2 and TSP trend-cycle components from the multiplicative model in the Metropolitan Boston AQCR with data from sites inside/outside the urban core area of Boston graphed separately. Site descriptions are shown in Table 2-7. The procedure followed to produce Figures 2-4 and 2-5 involved application of the ratio to moving average technique to the monthly average SO_2 and TSP measurements taken in Metropolitan Boston. The multiplicative form of the series components was used, and seasonal and non-periodic elements of the data time series were filtered out to obtain the trend-cycle component. Because the seasonal and irregular components are temporal functions with a mean value of 1.0 in the multiplicative model, the magnitude of the trend-cycle component is directly comparable to that of the original time series. The monthly trend-cycle components were then averaged to obtain annual values, and composite components were formed by averaging together annual values from different geographical locations.

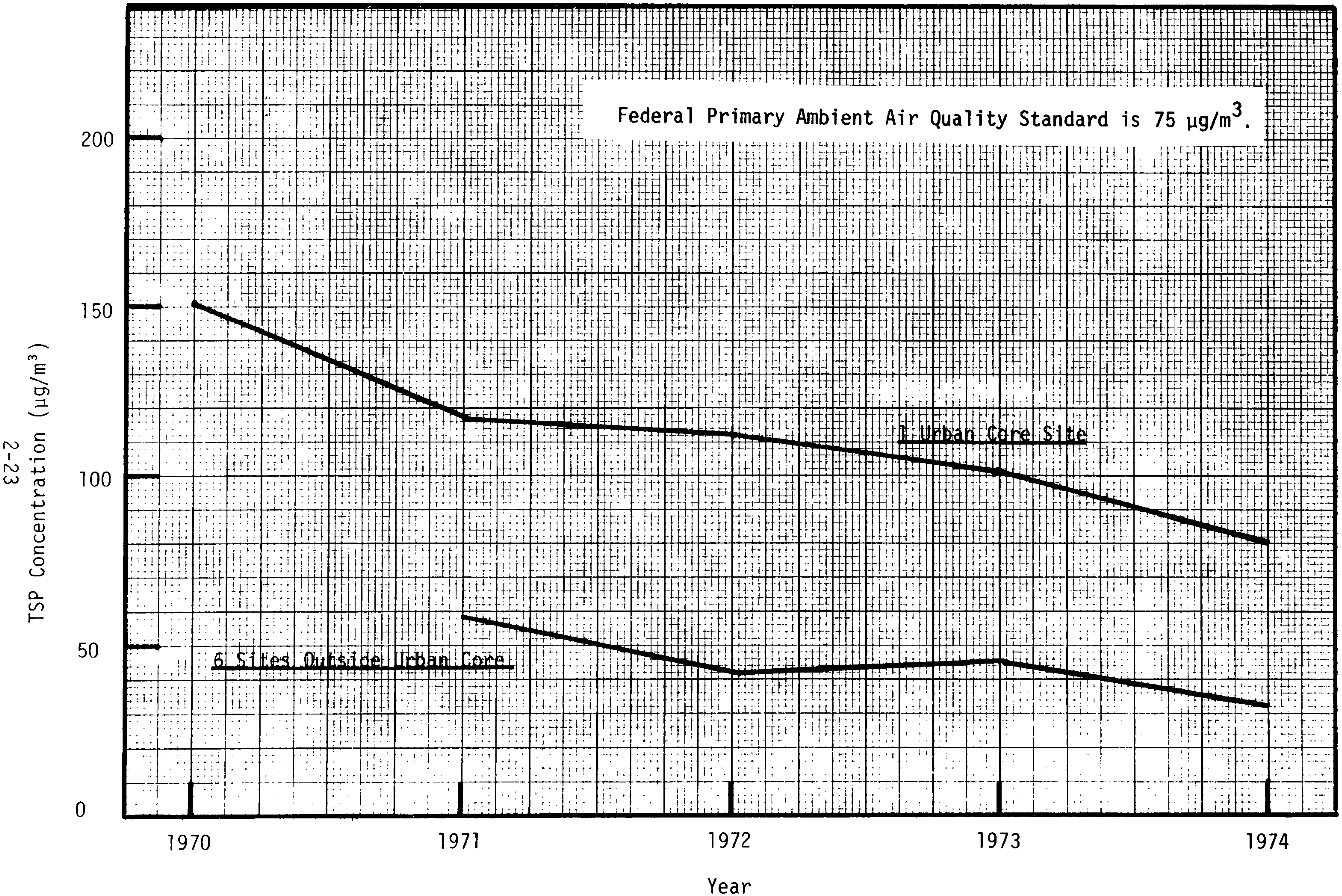
A separate examination of annual Boston heating degree-day statistics (a measure of local fuel burning activities) for the years 1970 through 1974 showed that a long-term trend in meteorological conditions over the time period of analysis towards lower annual degree-day totals (i.e., warmer winters) did not exist. Consequently, the observed long-term changes in ambient SO_2 and TSP levels cannot be attributed to corresponding changes in this meteorological parameter.

Statistically consistent seasonal variations in pollutant concentrations were found in the majority of the data series. Ambient TSP concentrations at urban sites displayed seasonal patterns characterized by high winter values and relatively low summer values. By contrast, seasonal patterns of non-urban sites were typified by high summer peaks and low winter values. These results parallel the findings of an earlier study [13] of nationwide TSP levels. Ambient SO_2 concentrations were, in general, characterized by high winter values and lower summer values at all sites.

Statistically significant interdependence was found between heating degree days and wind speed for Boston, reflecting the climatological

Figure 2-5

Composite Annual TSP Trend-Cycle Components
in Metropolitan Boston AQCR



relationship between these parameters. Similar interdependence was found between these meteorological variables and the data series' seasonal components. The implication of this finding is that the meteorological variables, degree-days and mean wind speed, can be used as a measure of the seasonality in ambient SO_2 and TSP levels. A more detailed summary of the methodology and results is given in Appendix A (Section VI.A).

C. STATISTICAL INFERENCE

1. Objectives and Scope

The objective of the statistical inference task was to interpret trends (or changes in trends) in ambient SO_2 and TSP concentrations in the Metropolitan Boston AQCR for the period January 1970 through June 1974. The principal focus of the analysis was to test statistically the relation between trends in regional air quality levels and the implementation of the SIP fuel use regulations and special variances granted because of the energy shortage.

2. Methodology

The statistical analysis was confirmatory in that it verified the existence of trends in the data coincident with the implementation of fuel use regulations and variances, and it interpreted these trends using information concerning the regulations and variances. These trends were consistent with those identified in the data analysis task. Nonregulatory factors simultaneously influencing the measurements, such as meteorological conditions (e.g., heating degree-days and mean wind speed) were also evaluated. The intercorrelation structure of the principal variables thought to affect air quality levels with the pollutant concentration series was quantified, and a ranking of the variables in their ability to explain the meaured levels of pollutants was produced.

The first step in the statistical analysis involved a procedure employing the forecast potential of triple exponential smoothing. The technique used to test the effect of regulations and variances on ambient air quality levels was to compare statistically the actual measured values after the implementation date of a regulation or variance with those predicted by the exponential smoothing model. These latter values were computed under the assumption of no changes in air quality trends. The analysis was applied to the seasonally-adjusted form (i.e., seasonal component removed) of the time series of monthly pollutant concentrations in an attempt to isolate the effects of only regulations and variances. The results from this analysis provided the basis for the general multiple linear regression analysis, which utilized both stepwise and complete regression techniques. The utility of the multiple regressions was that they permitted identification of which of a large number of independent varaibles were most significant in explaining the variations in measured air quality levels. The independent variables selected for the regression analysis represented meteorological conditions, seasonal variations, regulatory impositions, and special variances granted. The dependent variable in the regression analysis consisted of either the measured ambient SO_2 and TSP levels or the natural logarithms of these quantities.

3. Results

The results of the statistical analyses indicate that major SIP fuel use regulations effective July 1, 1970, and October 1, 1971 (see Table 2-1), are associated with statistically significant decreases in regional SO_2 and TSP levels. This is explained by the fact that both of these regulations were responsible for the conversion of many large fuel utilization facilities to fuels with lower sulfur and ash contents. The first set of regulations, limiting the ash content of fossil fuels burned in the AQCR, caused conversions principally from coal to oil and gas. Note that although this set of regulations did not limit the sulfur content of fuels, the net results of these fuel conversions was usage of fuels with a lower ash and sulfur content.

Additional results show that no statistically significant rise in regional SO_2 and TSP concentrations occurred coincident with variances granted, because of the energy shortage, during the winter of 1973-1974. In fact, the results of the complete regressions indicate statistically significant decreases in these pollutant levels occurred regionally commencing in December 1973. The implication of this finding is that some other mechanism, most probably fuel conservation efforts by consumers, overrode the effects of any increase in SO_2 and TSP emissions due to the combustion of nonconforming fuel.

The following table indicates the variables and events which, in the stepwise regression, made the greatest total contribution toward explaining variations in regional SO_2 and TSP levels between 1970 and 1974. These quantities are listed in the order of their ability to explain these variations.

SO_2 (Entire Region)	TSP (Urban Core)	TSP (Non-Urban)
Heating degree-days	Heating degree-days	(Mean wind speed)$^{-1}$
Oct. 1, 1971, regulations	July 1, 1970, regulations	Oct. 1, 1971, regulations

In those cases where heating degree-days and the reciprocal of mean wind speed were significant in the multiple linear regression, they were found to be directly proportional to measured pollutant concentrations. Degree-days are a measure of local fuel burning activities and emissions; mean wind speed is a measure of the dilution capability of the atmosphere. These proportionality results are consistent with the relationships normally assumed between pollutant concentrations, emissions, and wind speed in most air quality models.

The conclusions based on the above results are: (1) fuel burning emissions dominate SO_2 concentrations throughout the Metropolitan Boston AQCR; (2) TSP concentrations in the urban core also are dominated by fuel burning sources; but (3) TSP levels at non-urban sites are dominated by emission sources other than fuel burning facilities, most probably local particulate sources, road dust, and pollen. These results confirm the classical seasonal patterns and the urban/non-urban split found in the measured SO_2 and TSP data in the data analysis task. A more detailed summary of methodology and results is given in Appendix A (Section VI.A).

III. REGULATORY AND EMISSIONS ANALYSIS

A. OBJECTIVES AND SCOPE

In order to accurately predict the ambient air quality of a region through the application of atmospheric diffusion models, it is essential that an accurate inventory of fuel use and emissions within that region be available. This inventory must be representative of the time period of interest and include estimates of the emission rate and physical characteristics of each emission source. The objective of this analysis was to create accurate quarterly inventories of fuel use and emissions in the Metropolitan Boston AQCR for the period of January 1973 to June 1974.

The scope involved in preparing these inventories included updating and projecting a 1972 annual inventory to 1973 and 1974 to account for:

(1) the effects of heating degree-days on fuel use
(2) the impact of changes in State Implementation Plan (SIP) regulations on fuel use and emissions
(3) changes in fuel uses induced by population growth, migration, and economic conditions

and partitioning of these inventories into the quarterly intervals of interest. The effects of the energy shortage on fuel use and emissions in each quarter were represented by estimating the degree to which variance on SIP regulations (granted as a result of the energy shortage) were implemented and by estimating gross changes in fuel use patterns due to energy conservation. These quarterly inventories were then used as input to a diffusion model to predict air quality in the region. Five quarterly fuel use and emission inventories were prepared for this simulation:

(1) 1973 first quarter emissions reflecting 1973 heating requirements
(2) A hypothetical emissions inventory reflecting 1973 first quarter emissions adjusted for 1974 heating requirements
(3) 1974 first quarter emissions reflecting 1974 heating requirements

(4) A hypothetical emissions inventory reflecting 1974 first quarter emissions modified to reflect no variances granted

(5) A hypothetical emissions inventory reflecting 1974 first quarter emissions modified to reflect full variance implementation

The scope involved the following steps:

(1) Acquisition of the 1972 fuel use inventory for the Metropolitan Boston AQCR from the Bureau of Air Quality Control of the Commonwealth of Massachusetts

(2) Review of the 1972 inventory for closures and new sources in 1973 and 1974

(3) Update of the inventory to 1973 and 1974 using annual degree-day data to estimate changes in space heating, fuel consumption, and growth factors (demographic indicators) obtained from the Massachusetts Department of Environmental Affairs to estimate changes in process fuel use

(4) Modification of the 1973 and 1974 inventories to reflect gross changes in fuel use patterns and the impact of variances granted on the State Implementation Plan as a consequence of the energy shortage. Data on the degree of implementation of the variance were collected by a survey of major fuel suppliers and users in Metropolitan Boston.

B. METHODOLOGY

This section describes the methodologies used to update an existing 1972 fuel use and emissions inventory to 1973 and the first half of 1974 and to incorporate the effects of the energy shortage into these updated inventories. This section includes a brief discussion of the inventory structure, a description of the base year inventory, and a summary of the assumptions and methods used to project and apportion the inventories. Appendix B includes a more detailed description of each of these steps.

1. General

All fuel consumption can be broadly categorized into use by stationary sources and by non-stationary (transportation) sources. This latter category comprises all modes of combustion-power transportation, including automobiles, busses, trucks, trains, vessels, and aircraft.

Stationary sources may also be classified into different user categories and type of use. The major categories of source types include domestic (residential), commercial, institutional, manufacturing, and steam-electric utilities. Most of these can be further classified as point sources, which represent individual establishments using large quantities of fuel, as distinguished from area sources, which represent, collectively, a large number of smaller sources distributed over the survey area. In addition, certain types of activity which also produce air pollutants, such as the marketing of gasoline, the use of solvents, on-site incineration, forest fires, and structure fires are included as area sources.

The methodology used in the analysis required that accurate data be available for all of these fuel use and emissions categories. Each category was then analyzed to determine what type of demographic indicator would best represent annual growth in this category and what portion of fuel use would have a seasonal component.

2. Base Case

The base case inventory used for this study was an inventory in National Emission Data System (NEDS) format reflecting total fuel use in the Metropolitan Boston AQCR for the calendar year 1972. The point source section of this inventory is based on information collected by the Massachusetts Bureau of Air Quality Control (BAQC) during the period 1970 through 1972. The area source section of the inventory was developed by Walden Research and the BAQC in support of an Air Quality Maintenance Plan for Massachusetts by disaggregation of statewide non-point source fuel to the APCDs by demographic indicators and to a grid system by land use factors [22].

The 1972 point source inventory contains approximately 400 sources. These data were reviewed on a source-by-source basis to insure that all SIP regulations in effect during 1972 were reflected in the inventory. No attempt was made to update fuel use rates to 1972 for source information received prior to that year (i.e., 1970-1971) unless the information conflicted with 1972 SIP regulations. This was done for three reasons: (1) all large emission sources had been previously updated by the BAQC with 1972 operating data; (2) prior to the energy shortage, the annual change in fuel use of a particular source was diminishingly small; and (3) the area source fuel use inventory was created by subtracting the fuel use of this point source inventory from the total fuel use in the AQCR apportioned from data reported by the Bureau of Mines [23].

The 1972 NEDS-based area source inventory is composed of about 1,700 grid squares ranging in size from one to 256 km^2, located throughout the AQCR. Each grid square contains an estimate of fuel use for 31 source classifications within the area represented by the grid. A number of the smaller grids (less than 64 km^2) located more than 15 km from the Boston central business district were combined to form larger grids, approximately 100 km^2 in area.

Emission factors used for this study are those assembled and published by the Environmental Protection Agency [24] with the exception of fuel combustion particulate emissions. The latter factors were derived from a study of the local mix of burner-boiler types throughout the AQCR [25]. Table 3-1 tabulates the emission factors used in preparing the inventory. Emission rates were computed by assuming the maximum emissions allowable by the SIP regulations for each source category, fuel type, and control device. Exceptions to this rule were several power plants for which the actual average 1972 sulfur content of the fuel was provided.

3. Projection and Apportionment Procedures

Projection of the base year inventory to 1973 and 1974 and apportionment of these projected inventories to quarters was accomplished by execution of the following tasks.

TABLE 3-1

EMISSION FACTORS
(mass of emissions/fuel unit burned)

	Sulfur Dioxide		Particulates	
	Metric+	English++	Metric+	English++
FUEL OIL				
Residual Oil				
Sources> $9x10^6$ j/sec*	19S**	157S	1.0	8
Sources< $9x10^6$ j/sec*	19S	157S	1.1	9
Distillate Oil	17S	140S	0.3	140
NATURAL GAS	9.6	0.6	128	8
COAL	19S	38S	6.5A***	13A

\+ Metric units: Mass - kg; fuel oils - m^3; coal - 10^3 kg; natural gas - 10^8 m^3

++ English units: Mass - lb; fuel oils - 10^3 gal; coal - ton; natural gas - 10^6 ft^3

* $8.8x10^6$ j/sec = $30x10^6$ Btu/hr

** Percent sulfur by weight

*** Percent ash by weight

(a) Addition of new point sources not included in the base inventory and deletion of point sources closed during the period of interest

(b) Adjustment of process fuel use to reflect economic growth

(c) Adjustment of all space heating fuel use to reflect annual degree-day differences

(d) Adjustment of area source space heating fuel use to reflect population growth

(e) Adjustment of the emissions inventory by fuel type and establishment to reflect the degrees of implementation of variances granted by EPA to the facility

(f) Adjustment of the fuel use inventory by fuel type and source category to reflect energy conservation

(g) Verification of 1973 fuel use projections by fuel type and source category by comparison of these estimates with apportioned published regional totals [23]

(h) Apportionment of the projected inventories to quarters by allocating space heating fuel use to quarters based on the quarterly variation of degree-days within the year of interest and by allocating process fuel used to quarters based on uniform fuel use throughout the year.

A detailed summary of each of these steps is presented in Appendix B-1.

C. RESULTS

1. Fuel Use Trends

a. Trend Components

Based on historical indicators, the expected growth in fuel use in the Metropolitan Boston area had been quite small during the 1970's [23]. Between 1970 and 1973, there was no net change in residual oil use in Massachusetts; distillate oil use increased only one percent annually. This situation resulted from two factors:

(a) The tendency towards no growth in regional population restricted any new growth in the residential and commercial sectors [26]

(b) The high cost of labor and materials in this area has forced many manufacturing firms out of New England. Thus, total process emissions and industrial fuel use were expected to remain constant or even decline in the 1970's.

These conditions are reflected in the demographic growth factors* obtained from the Commonwealth of Massachusetts [26] which indicated that average annual increases in manufacturing employment would be about 0.6%, non-manufacturing employment about 2.4%, and population about 0.6%, between 1970 and 1975 within the Metropolitan Boston SMSA. The change in population by city and town indicated that populations in the core area (Boston and the 12 surrounding cities and towns) would decrease by 0.3% and that the outlying areas would increase at a rate of 1.4% annually.

With the onset of the energy shortage, a significant change in fuel use patterns occurred. The scarcity and high cost of all fuels resulted in considerable conservation efforts by both private and public sectors of the economy. The 1974 consumption of distillate oil, which is used primarily for space heating, was reduced by 15% from 1973 levels after accounting for differences in meteorological heating requirements, while smaller users of residual oil showed savings of 12% (see discussion in Appendix B-2). The electric utilities, which consume approximately 78% of the residual oil burned in the region, showed a decline in fuel use for all purposes of about four percent.

The Metropolitan Boston area consumes a considerable amount of fuel for space heating. Thus, the total heating requirements for a given year strongly influences total fuel demand. As shown below, the base year, 1972, was approximately five percent colder than the 30-year climatological average for the region (as measured by degree-days), whereas 1973 was nine percent warmer than average, and 1974 was approximately equal to the 1972 average.

DEGREE-DAY DATA
Logan International Airport

Year	Degree-Days Annual	First Quarter
1972	5914	2889
1973	5144	2670
1974	5898	2832
30-Yr Mean	5621	2913

*See Table B-1 in Appendix B.

Walden

b. Analysis of Component Effects

The combined effects of growth and conservation on fuel use indicate that a small increase in the annual rate of fuel use occurred during the first three quarters of 1973. With the advent of the energy shortage in the fourth quarter of 1973, major conservation efforts began and by the first quarter of 1974, completely overshadowed any increases in fuel use due to economic growth.

The effect of meteorology* on fuel use was to decrease fuel use in 1973, especially residential and commercial distillate which are used primarily for space heating. Empirical data indicate that space heating fuel use is not linearly proportional to degree-days [27]. Therefore, this fuel use will decrease by less than the 13% differential in degree-days between 1972 and 1973. Fuel use in 1974 would have changed little from the 1972 total, if only meteorology was used as an indicator.

Appendix B documents the methods used to determine and incorporate the effects of growth, conservation, and meteorology. Table 3-2 presents total fuel use by fuel type and source category for the three years of interest.

2. Regulatory and Variance Analysis

The Bureau of Air Quality Control (BAQC) of the Commonwealth of Massachusetts has adopted a number of regulations affecting fuel burning and process emission sources designed to control SO_2 and particulate emissions. Table 2-1 presents a summary of the regulations relevant to this study. Other than a regulation requiring extremely small users of residual oil to convert to distillate oil, no significant regulations were enacted during the period of this analysis.

Variances in these regulations were granted in order to allow for greater leeway in the quality of fuels burned in anticipation of a significant shortage of conforming fuel.

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*Degree-days.

TABLE 3-2

ANNUAL FUEL USE IN METROPOLITAN BOSTON

	Bureau of Mines*		Inventory**		
	1972	1973	1972	1973	1974
Distillate ($10^2 m^3$)					
Residential	25,797	24,554	25,797	24,476	21,777
Commercial-Institutional	14,095	13,374	14,278	13,895	11,966
Industrial	7,918	8,501	7,966	7,978	6,983
	47,810	46,429	48,042	46,349	40,726
Residual ($10^2 m^3$)					
Electric Generating	37,325	36,088	37,612	35,967	33,963
Industrial	15,761	16,187	15,691	15,604	13,689
Commercial-Institutional	21,269	20,647	21,514	20,811	18,045
	74,355	72,922	74,527	72,382	65,697
Natural Gas ($10^6 m^3$)					
Industrial	458	428	457	459	400
Commercial-Institutional	510	545	535	518	448
Residential	1,358	1,323	1,356	1,286	1,145
	2,326	2,296	2,348	2,263	1,993

*Actual totals apportioned to MBAQCR from state total.

**Sum of inventory entries.

Note: Coal used by external combustion sources in 1972 was limited to one source (Boston Engine Terminal) which used 1.32×10^8 kg of bituminous coal. This source converted to residual oil in 1973. Coal use in 1974 resulted from variances granted to the Salem Harbor Plant. This plant burned 15.7 kg/sec bituminous coal during the period when the variance was in force.

Note: $10^2 \text{ m}^3 = 2.64 \times 10^4$ gal; $10^6 \text{ m}^3 = 35.3 \times 10^6 \text{ ft}^3$

Variances granted in the Metropolitan Boston AQCR as a consequence of the energy shortage were of four types:

(a) A blanket relaxation of the sulfur in fuel limitation in distillate fuel from 0.3% to 0.5%

(b) 300-400 individual variances relaxing residual fuel limiations from 0.5% and 1.0% to up to 2.2%

(c) Conversion of Units 1-3 at the Salem Harbor Power Plant from oil to coal

(d) Operation of some sources $\geq$ 250 MBtu/hr heat input allowing combustion of residual fuel oil with up to a 2.6% sulfur content.

A study of the actual implementation of these variances has indicated that, for the most part, they were only implemented to a limited extent. This resulted from the shortage of <u>all</u> grades of oil. The variance granted which was most nearly fully implemented was the allowance for three units of the Salem Harbor Power Plant to burn coal. This source burned 15.7 kg/sec of coal containing 15.6% ash and 0.77% sulfur during the entire period of the variance.* The variance allowed for 15.6% ash and 2.5% sulfur coal.

The use of nonconforming fuels increased SO_2 emissions in the AQCR from distillate users by only 2 percent, based on the assumption that all conforming fuel used during the period was equal to the SIP regulatory limit. <u>Average</u> residual oil sulfur content from large power plants did not exceed the SIP regulations, although small residual users in the core area of the AQCR which were granted variances used oil with an average sulfur content 13 percent above the regulatory limit. Table 3-3 presents a summary of the actual and allowable sulfur content for residual oil users granted variances.

Particulate emissions were generally not affected by the variances granted; the particulate emission rate for the various fuel types varies very little with increasing sulfur content. However, the variance allowing the Salem Harbor Power Plant to burn coal increased average particulate emissions from this plant 900 percent during the first quarter of 1974.

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* January 23, 1974, to May 15, 1974

Table 3-4 summarizes annual emissions of SO_2 and particulates in the Metropolitan Boston AQCR. Detailed information on variance implementation is contained in Appendix B-3.

TABLE 3-3

IMPLEMENTATION OF VARIANCES GRANTED TO

SOURCES BURNING RESIDUAL OIL

Source	SIC Code	1972 Fuel Use: meters^3	1972 Fuel Use: 10^3 gals.	% Sulfur in Fuel: no variance	% Sulfur in Fuel: actual imple.	% Sulfur in Fuel: full variance
Boston Edison	4911					
Edgar		373,150	98,600	0.94	0.95	2.2*
Mystic		746,200	197,160	0.49	0.49	2.6**
New Boston and L Street		1,320,400	348,900	0.44	0.48	2.6**
New England Power Co.	4911					
Salem Harbor Plant						
Units 1, 2 and 3		524,800	138,660	0.65	coal+	2.6**
Unit 4		314,260	83,040	0.65	0.75	2.6**
Cambridge Electric	4911					
Blackstone		98,820	26,100	0.50	0.56	2.2
and Kendall		62,200	16,440	0.41	0.56	2.2
MBTA	4931	283,000	74,780	0.50	0.56	2.2
M.I.T.	8221	16,482	4,355	0.50	0.56	2.2
Revere Sugar	2062	45,480	12,000	0.50	0.56	2.2
A. C. Lawrence	3111	29,020	7,668	1.00	1.00	2.2
Eastman Gelatine	2891	52,260	14,337	1.00	1.00	2.2
USM Corporation	3999	1,786	472	1.00	1.00	2.2
General Electric	3562					
Lynn River Works		116,410	30,760	1.00	1.00	2.2
Brandeis University	8221	12,410	3,280	0.50	0.56	2.2
Lipton Pet Foods	2010	2,089	552	1.00	1.00	2.0
	2042	3,346	884	1.00	1.00	2.0

* Until January 22, 1974, and 2.6% from then until May 15, 1974. Average full variance sulfur content: 2.5%

** Not approved until January 22, 1974. Average full variance sulfur content: 2.1%

+ Not approved until January 22, 1974. Average coal sulfur content: 0.77%

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TABLE 3-3 (cont.)

IMPLEMENTATION OF VARIANCES GRANTED TO SOURCES BURNING RESIDUAL OIL

Source	SIC Code	1972 Fuel Use meters^3	1972 Fuel Use 10^3 gals.	% Sulfur in Fuel No variance	% Sulfur in Fuel actual imple.	% Sulfur in Fuel full variance
Middlesex County Hospital	8062	1,896	501	0.50	0.56	2.40*
New England Confectionary	2071	4,129	1,091	0.50	0.56	1.00
U.S. Gypsum Company	3274	3,410	901	0.50	0.56	1.00
William Carter Co.	2341	749	198	1.00	1.00	2.20
M.M. Mades Company	2013	787	208	0.50	0.56	1.00
Columbia Packing	2013	2,301	608	0.50	0.56	1.00
American Biltrite Rubber Company	3069	7,350	1,942	0.50	0.56	1.00
Container Corporation of America (Medford)	2691	1,972	521	0.50	0.56	1.00
Tufts University	8221	6,032	1,594	0.50	0.56	1.00
William Underwood Co.	2013	1,124	297	0.50	0.56	1.00
Draper Brothers	2231	2,422	640	1.00	1.0	2.20
Amstar Corporation	2062	18,896	4,993	0.50	0.56	1.00
Converse Rubber Co.	3021	5,313	1,404	0.50	0.56	1.00
General Electric	3722	4,552	1,203	0.50	0.56	1.00
First National Stores	5411	5,423	1,433	0.50	0.56	1.00

* Not effective until January 10, 1974.

TABLE 3-3(cont.)

IMPLEMENTATION OF VARIANCES GRANTED TO

SQURCES BURNING RESIDUAL OIL

Source	SIC Code	1972 Fuel Use		% Sulfur in Fuel		
		$Meters^3$	10^3 gals.	No variance	Actual imple.	Full variance
Avco Research Labs.	7391	2,566	678	0.50	0.56	1.00
Felton and Sons	2085	1,177	311	0.50	0.56	1.00
Solvent Chemical Co.	2818	787	208	0.50	0.56	1.00
National Laundry	7210	1,052	278	0.50	0.56	1.00
Whidden Memorial Hospital	8061	715	189	0.50	0.56	1.00
Northeastern University	8221	2,774	733	0.50	0.56	1.00
Cambridge Thermionic Corporation	3679	146	552	0.50	0.56	1.00

TABLE 3-4

ANNUAL SULFUR DIOXIDE AND PARTICULATE EMISSION RATES
IN METROPOLITAN BOSTON

(10^3 metric tons)

	Sulfur Dioxide			Particulates		
	1972	1973	1974**	1972	1973	1974**
External Combustion Boilers*						
Residual Oil						
Electrical Generation	43.7	41.4	36.0	3.7	3.6	3.4
Industrial	24.8	24.4	22.0	1.7	1.7	1.5
Commercial-Institutional	33.1	31.9	28.4	2.4	2.3	2.0
Distillate Oil						
Industrial	4.0	4.0	3.6	0.2	0.2	0.2
Commercial-Institutional	7.2	6.7	6.1	0.4	0.4	0.3
Residential	13.0	12.3	11.2	0.7	0.7	0.6
Coal	0.2	0.0	6.4+	1.0	0.0	4.0+
Process Emissions	1.3	1.3	0.1++	0.2	0.2	0.2
Incineration	1.3	1.2	1.2	9.1	8.7	8.6
Mobile	3.1	3.2	3.1	9.5	9.8	9.5
TOTALS	131.7	126.4	118.1	28.9	27.6	30.3

* Emissions from natural gas combustion is less than 0.05×10^3 MT for all categories.

** Includes effects of variances implemented.

++ A major bisulfite plant closed in 1973

\+ Emissions of Salem Harbor Plant for period January 23 to May 15. Emission rate reflects a 92 percent reduction due to the use of electrostatic precipitators.

Note: mt/yr = 0.003 tons/day

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IV. MODELING ANALYSIS

A. OBJECTIVES AND SCOPE

The objective of the modeling analysis was to isolate and quantify the effect of meteorology, growth and conservation, and source class variances on sulfur dioxide (SO_2) and particulate levels in the Metropolitan Boston AQCR during the period of the energy shortage in order to obtain a clearer understanding of the impact and potential impact of that shortage on ambient air quality. The scope of this analysis included prediction of ground-level concentration of SO_2 and particulates during the first quarter (January - March) of 1972, 1973, and 1974 at monitoring sites throughout the AQCR, reconciliation of the predicted concentrations with the observed data, calibration of the model to reflect the reconciliation, and extension of the modeling analysis to a series of actual and hypothetical conditions to permit isolation of the effect of the parameters of interest on air quality during the winter of 1973-1974.

B. METHODOLOGY

This section describes the methodology used to perform the diffusion analysis and the procedures used to disaggregate the change in air quality between the first quarter of 1973 and 1974 into the components of interest. Included is a brief description of the diffusion model, a summary of the validation/calibration process, and a description of the simulation cases which were studied. Appendix C provides a comprehensive description of these analysis elements.

1. Model Characteristics

The diffusion model used to simulate the various cases was the Air Quality Display Model (AQDM) [28] in the form of a segment of the Air Quality Implementation Planning Program (IPP) [29]. This computer program is a formalization of a simulation model originally developed by Martin and Tikvart [30] and has received wide application in the evaluation of regional air quality.

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The AQDM is designed to provide seasonal or annual predictions of ambient concentration levels. The average concentration at a receptor point from a given source is determined by solving the diffusion equation for specified combinations of meteorological conditions, and weighting these by the frequency of occurrence of these conditions. A total of 480 combinations are considered based on 16 wind direction azimuths, six wind speed classes, and five stability categories. The total concentration at the receptor point is given by the summation of contributions from all other emission sources in the study area.

This model has been modified from its original form to include the Briggs plume rise estimates and to produce a source contribution file to facilitate case evaluation. Appendix C-1 presents more detailed information of the model, the assumptions involved in executing the simulations, and on the simulation scaling procedure.

2. Reconciliation of Measured Air Quality Concentrations with Model Predictions

Using the emission inventories developed in the Regulatory and Emissions Analysis (Chapter III) which estimate actual conditions for the first quarters of 1972, 1973 and 1974, predictions of average concentrations of sulfur dioxide and particulates were made for monitoring stations operated by the Massachusetts Department of Public Health within the Metropolitan Boston AQCR. These predictions were then compared with the measured data at these sites during the same time period to permit calibration of the diffusion model.

a. Sulfur Dioxide

To provide consistency with the results of the air quality data analysis (Chapter II) and to eliminate potential inconsistencies due to instrumental differences, only monitoring sites using the West-Gaeke bubbler sampling technique were used in the validation process. The data from these monitoring stations were carefully screened to assure that a representative quarterly average was obtained* (see Appendix C-2). This process resulted in seven sites for validation in 1972, four in 1973, and eight in 1974. Various regression techniques were studied in order to develop a single statistically significant calibration which could be applied to the entire AQCR. The technique selected was a forced zero-intercept linear regression. This technique was used because the natural background for SO_2 is essentially zero.

b. Particulates

A validation procedure similar to that described for SO_2 was performed at stations measuring total suspended particulates (TSP) using high-volume samplers within the Metropolitan Boston AQCR. There were only three monitoring sites with adequate data for validation in each year.

The small number of validation points considerably limits the ability to develop a statistically significant calibration procedure in any one year. Therefore, the calibration was developed using data for all years combined. The slope-intercept method of calibration was used for TSP to allow for the natural TSP background.

3. Description of Simulations

Five simulations were undertaken to isolate the relative effects of three parameters on air quality: meteorology, SIP variances, and growth and conservation. These simulations were:

(1) 1973 first quarter emissions inventory data with 1973 dispersion data

(2) A hypothetical inventory reflecting 1973 first quarter emissions inventory patterns modified for 1974 degree-days, with 1974 dispersion data

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* A quarterly average was considered adequate for validation if there were at least three observations made within each of the three months. This limited number of observations is used because most non-continuous monitoring is performed only once every six days, resulting in a maximum of four or five observations per month.

(3) 1974 first quarter emissions inventory data with 1974 dispersion data

(4) A hypothetical emissions inventory reflecting 1974 first quarter emissions inventory data, modified to simulate no variances granted, with 1974 dispersion data

(5) A hypothetical emissions inventory reflecting 1974 first quarter emissions inventory data, modified to simulate full implementation of variances granted, with 1974 dispersion data.

These simulations were performed by selecting various combinations of the parameters of interest. Comparison of the results between any two simulations isolates the effect of the parameter not common to each. Table 4-1 presents the parameters incorporated in each simulation. The various choices of parameters are as follows.

a. Fuel Use Patterns - Conservation and Growth

This parameter allows a choice of 1973 fuel use patterns which include no conservation efforts of 1974 fuel use patterns reflecting only the change in fuel use between 1973 and 1974 that would result from growth and conservation efforts.

b. Meteorology

This category allows a change in fuel use dependent only upon difference in space heating requirements (as measured by degree-days) between 1973 and 1974. Also, a choice of atmospheric dispersion characteristics representative of 1973 or 1974 is allowed. These effects were not specifically separated in this study.

c. SIP Variance

Three conditions are allowed in this category: no variance implementation, estimated actual variance implementation, and full variance implementation.

Simulations 1 and 3 represent the actual conditions which occurred during 1973 and 1974, respectively. The remaining inventories are hypothetical, i.e., they never actually occurred.

TABLE 4-1
SIMULATION COMPONENTS

	Simulation 1	2	3	4	5
Fuel Use Patterns*					
Conservation & Growth			✓	✓	✓
Meteorology**					
1973	✓				
1974		✓	✓	✓	✓
SIP Variance					
None	✓	✓		✓	
Actual			✓		
Full					✓

* Assumes 1973 to be the base inventory.

** Includes both degree-day and dispersion data.

The differences among these simulations can be compared to isolate the effects of interest. Meteorological effects are the only difference between simulations 1 and 2; thus, the difference between concentrations predicted by these simulations isolates the effects of meteorology between 1973 and 1974. The only difference between simulations 3 and 4 is the extent to which variances were actually implemented, thus isolating that effect. Similarly, simulations 2 and 4 isolate the effects of growth and conservation and simulations 4 and 5 the effects of full variance implementation.

The Metropolitan Boston AQCR contains a considerable variety of geographical areas; coastal, urban, suburban, and rural. The spatial variation in the effects within each simulation can also be studied by comparing receptors grouped by the various geographical types.

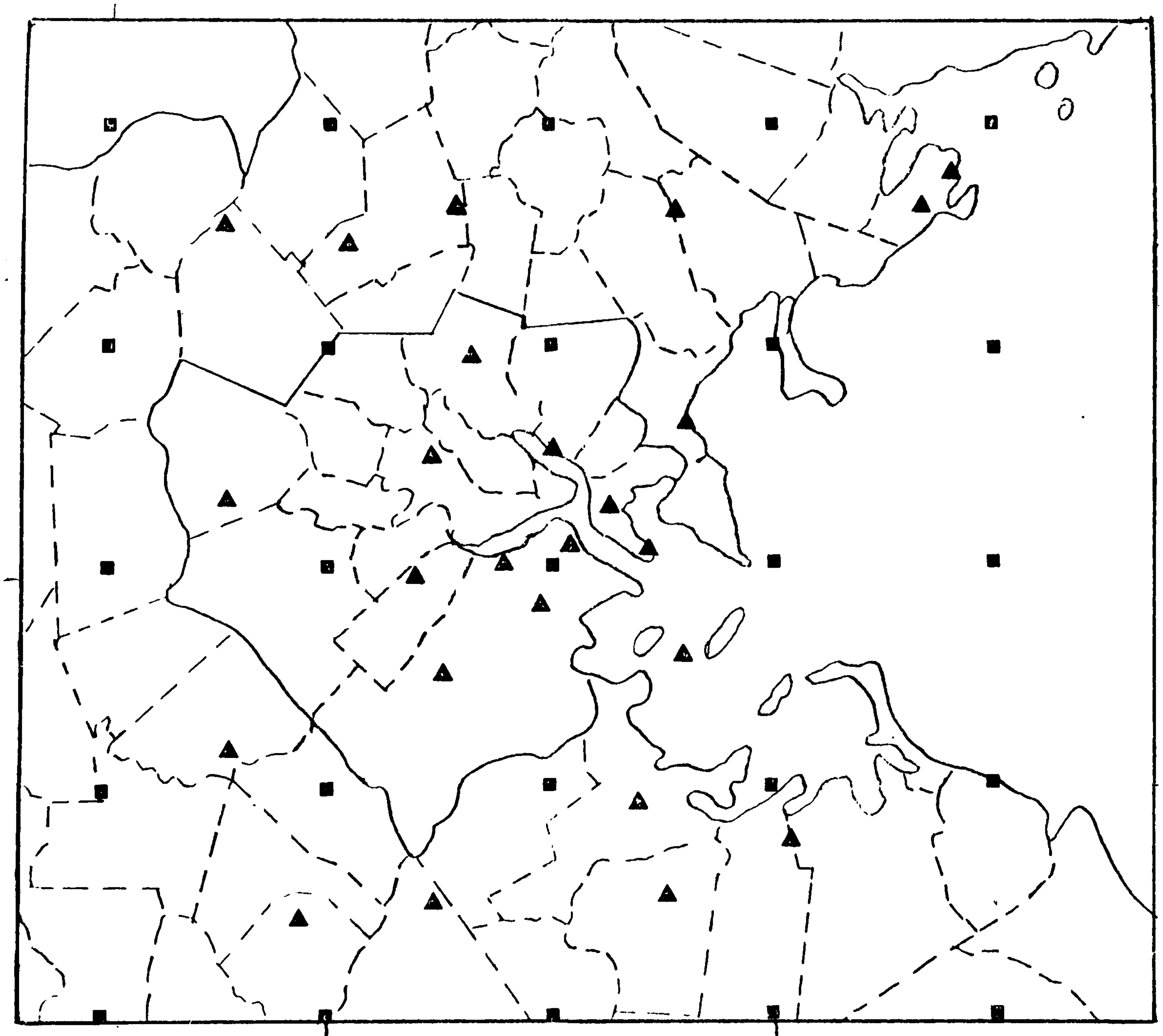
Sulfur dioxide and total suspended particulate concentrations were, therefore, predicted at 50 receptor points for each simulation case throughout the Metropolitan Boston AQCR. The base grid used was a square comprised of 25 prediction points spaced at 10 kilometer intervals on a side. The remaining receptors were located at the coordinates of the Commonwealth's SO_2 and TSP monitoring stations in the AQCR, and at other special interest sites. Figure 4-1 shows the receptor locations.

C. RESULTS

1. Calibration

a. Sulfur Dioxide

As noted previously, the calibration procedure used to model SO_2 ambient concentration was a linear regression forcing the intercept of the regression to zero. The following summarizes the results of this analysis for the first quarter of 1972 and 1973.



■ = Base Grid Receptors ▲ = Additional Receptors

Figure 4-1. Receptor Locations.

Time Period	Correlation Coefficient	Line
1972	0.75	Y=0.86X
1973	0.48	Y=0.83X

The extreme scatter of the measured data in 1974 resulted in no correlation with predictions.

The 1972 correlation coefficient indicated that the regression line is a statistically significant fit. The 1973 regression is not statistically significant; however, the line of prediction for these data is statistically identical with that of 1972. The inability to validate the 1974 measured data appears to be the result of non-representative samples and not errors in the modeling analysis. When plotted, however, the 1974 data also appear to be well represented by the 1972 line of prediction. Therefore, the 1972 line of prediction was used to calibrate all simulations. Figure C-1 in Appendix C-2 presents a complete plot (1972-1974) of this validation. Appendix C-2 also presents the data used in this validation and discusses the calibration attained by using the best-fit slope-intercept form of validation, which, by definition, gives a better fit for the data.

b. Particulates

A regression using the slope-intercept technique was performed with the particulate data. However, due to the limited number of receptors, a year-by-year calibration was not attempted.

The regression analysis indicates that the line of best fit is Y = 1.07 X + 20. The correlation coefficient for this line is 0.73, which is statistically significant at the 95% level. Appendix C-2 presents the data used in this validation.

2. Modeling Results

a. Air Quality Predictions

SO_2

Modeling of the five cases resulted in average first quarter air quality predictions for the Metropolitan Boston area. Figures 4-2 through 4-6 present the predictions of SO_2 concentrations for each of these respective cases. All data on these figures reflect application of the calibration technique described in the preceding subsection.

The maximum concentration observed in the AQCR for each case occurs in the central business district of Boston. Concentrations at this point vary little (less than 10 percent) for each of the first four cases. Concentrations resulting from the hypothetical full variance case (Simulation 5), however, were considerably greater than the concentration predicted in 1973. The only significant change in isopleth patterns among the cases is the tendency for isopleths to extend to the southwest of Boston during 1973 and to the southeast of Boston for the cases which simulate 1974 meteorology.

TSP

The principal sources of particulate emissions in the Metropolitan Boston AQCR were not significantly affected by the energy shortage, as was noted in Section III. The TSP isopleths for the five cases, Figures 4-7 through 4-11 respectively, verify this observation. These data indicate that there was no significant change in TSP levels at any receptors predicted by Simulations 1, 2, and 4. Simulations 3 and 5, the 1974 actual implementation and hypothetical full variance cases, show slightly increased concentrations in the vicinity of the Salem Harbor Power Plant, which was burning coal during the first quarter of 1974. Note that the actual implementation at Salem Harbor was identical with full variance implementation for particulate matter.

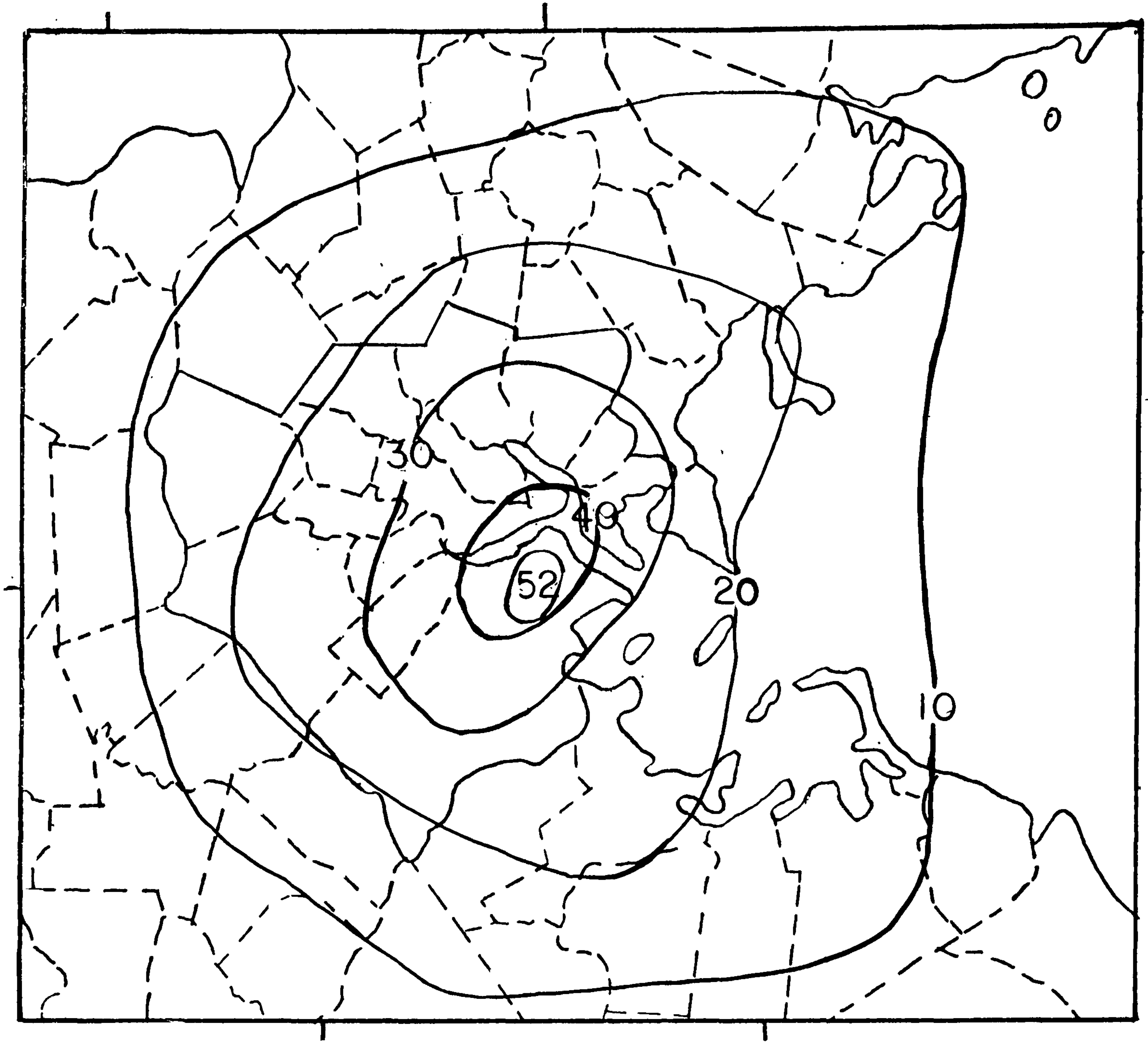


Figure 4-2. Sulfur Dioxide Concentrations (μg/m³) 1973 First Quarter - *Simulation 1*

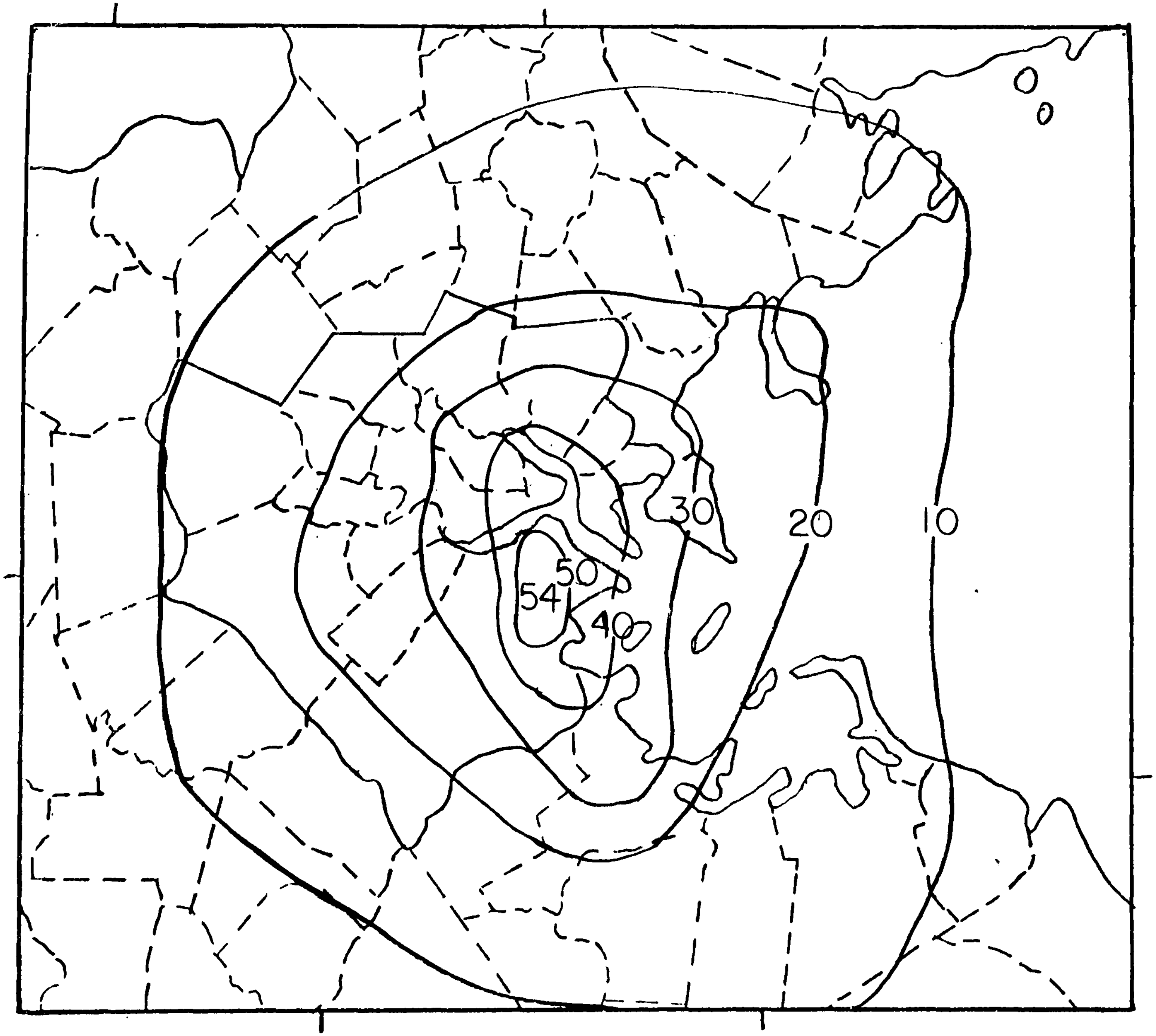


Figure 4-3. Sulfur Dioxide Concentrations ($\mu g/m^3$) 1974 First Quarter Meteorology and 1973 Fuel Use Patterns - Simulation 2

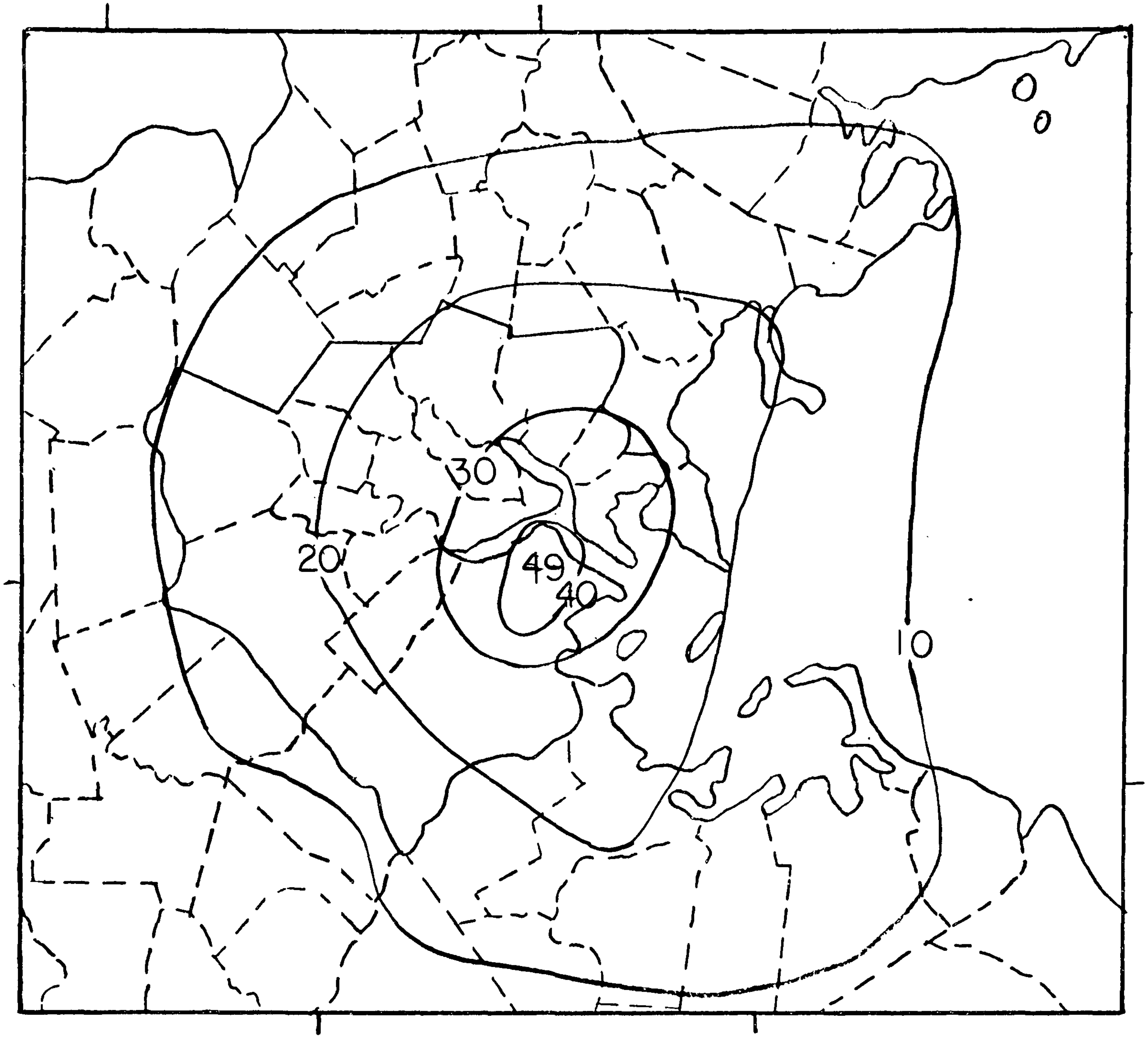


Figure 4-4. Sulfur Dioxide Concentrations (μg/m³) 1974 First Quarter Actual Variance Implementation - Simulation 3

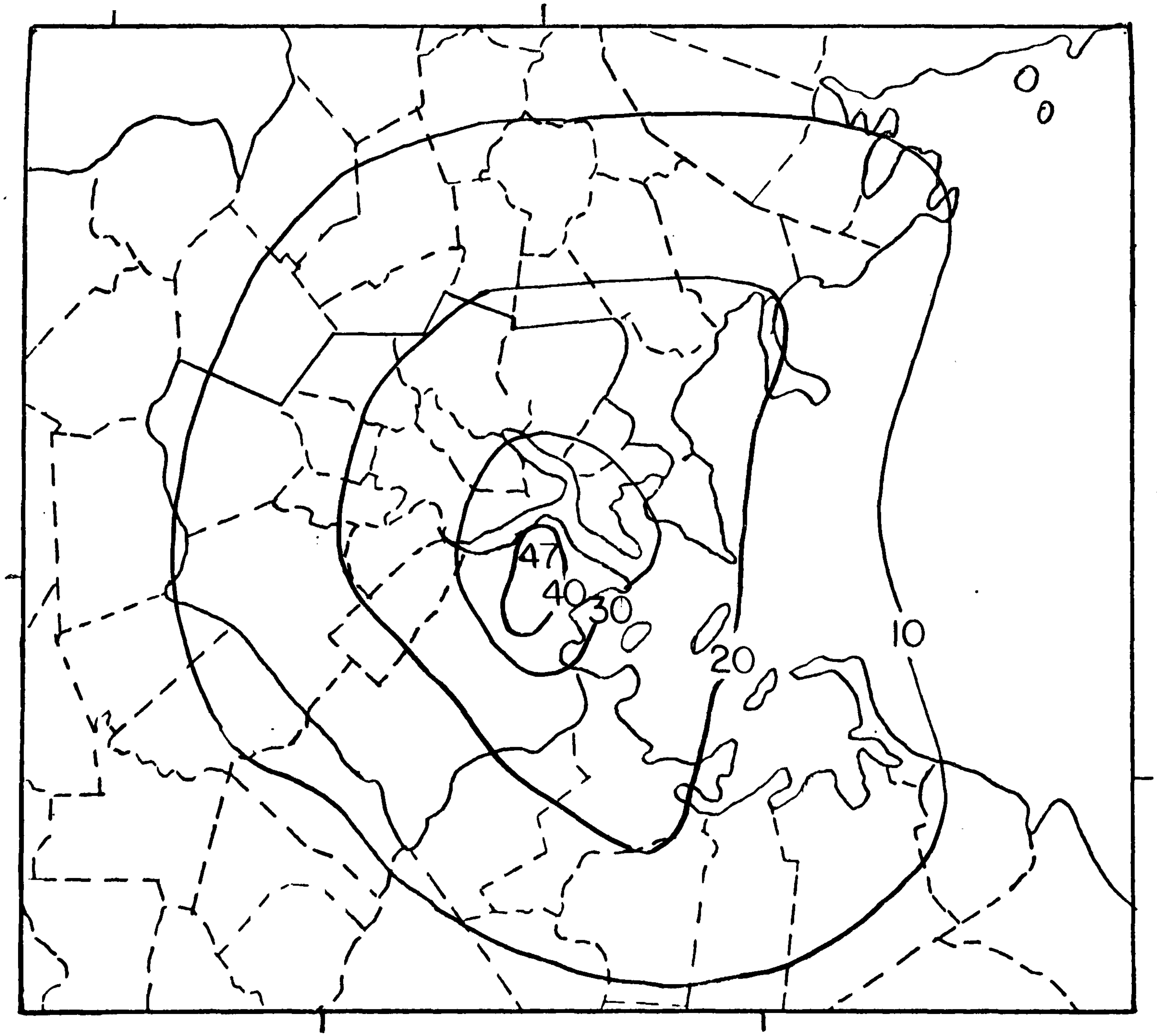


Figure 4-5. Sulfur Dioxide Concentrations (μg/m^3) 1974 First Quarter No Variance Implementation - Simulation 4

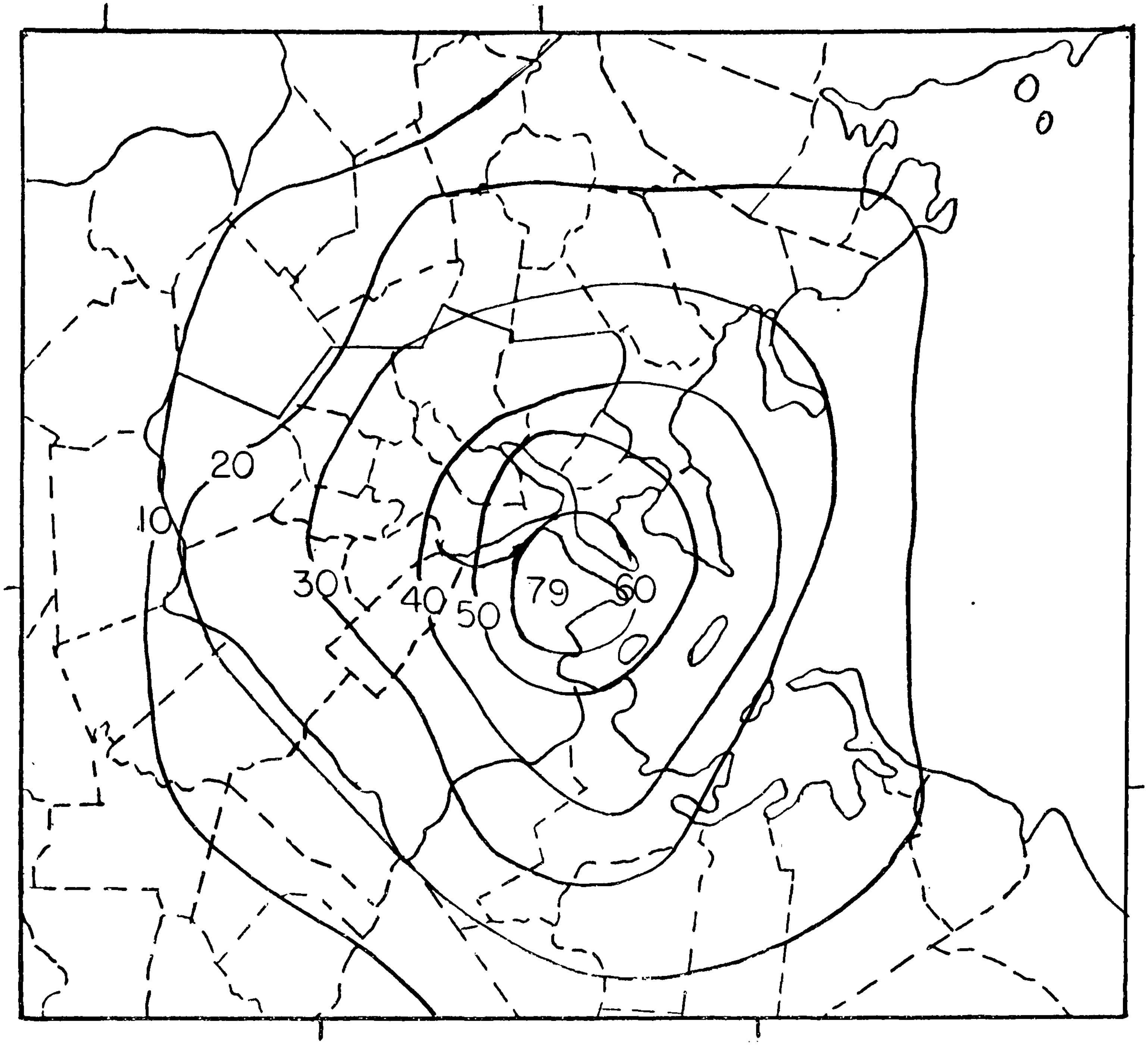


Figure 4-6. Sulfur Dioxide Concentrations (μg/m³) 1974 First Quarter Full Variance Implementation - Simulation 5

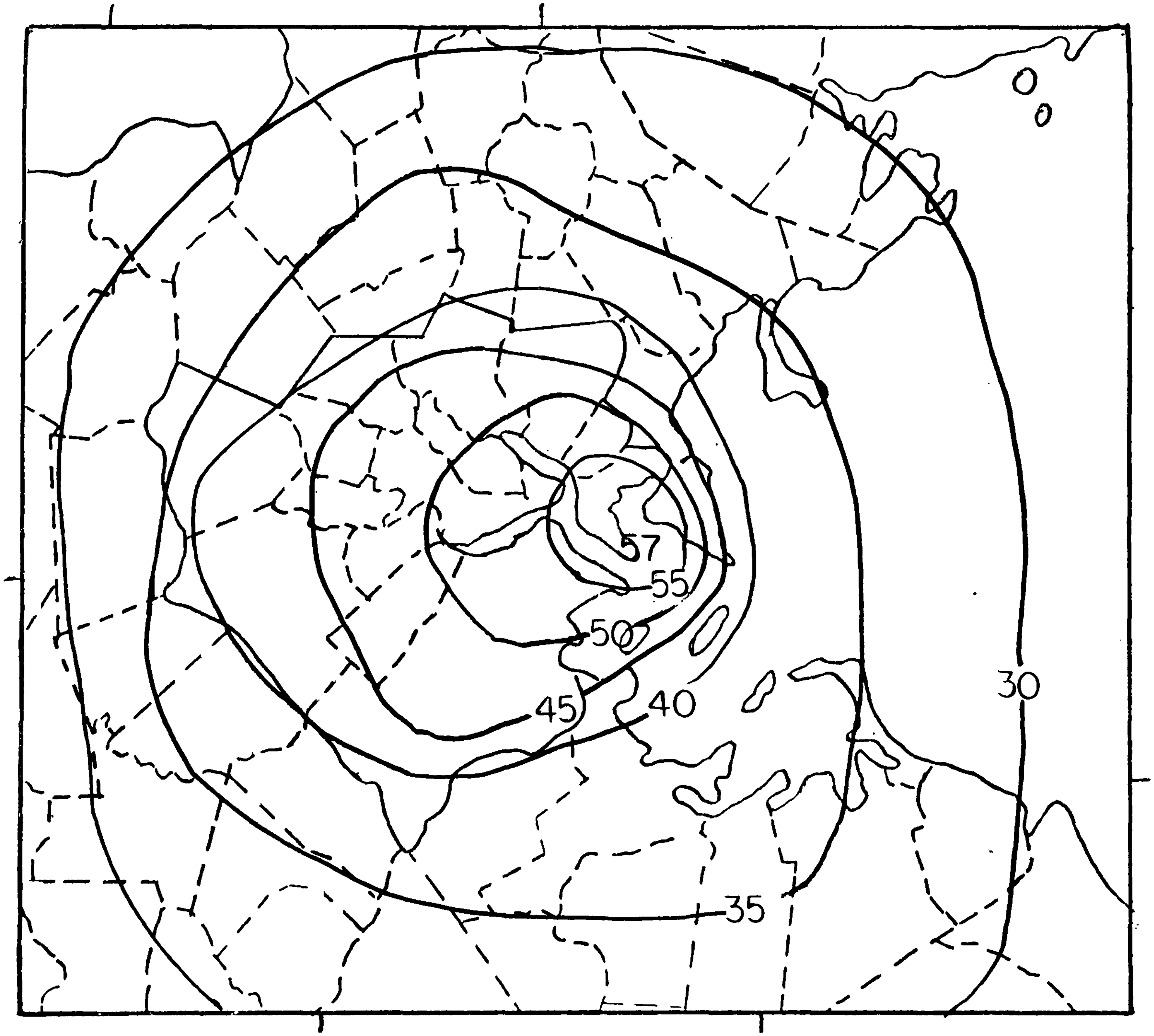


Figure 4-7. TSP Concentrations (μg/m³) 1973 First Quarter - Simulation 1

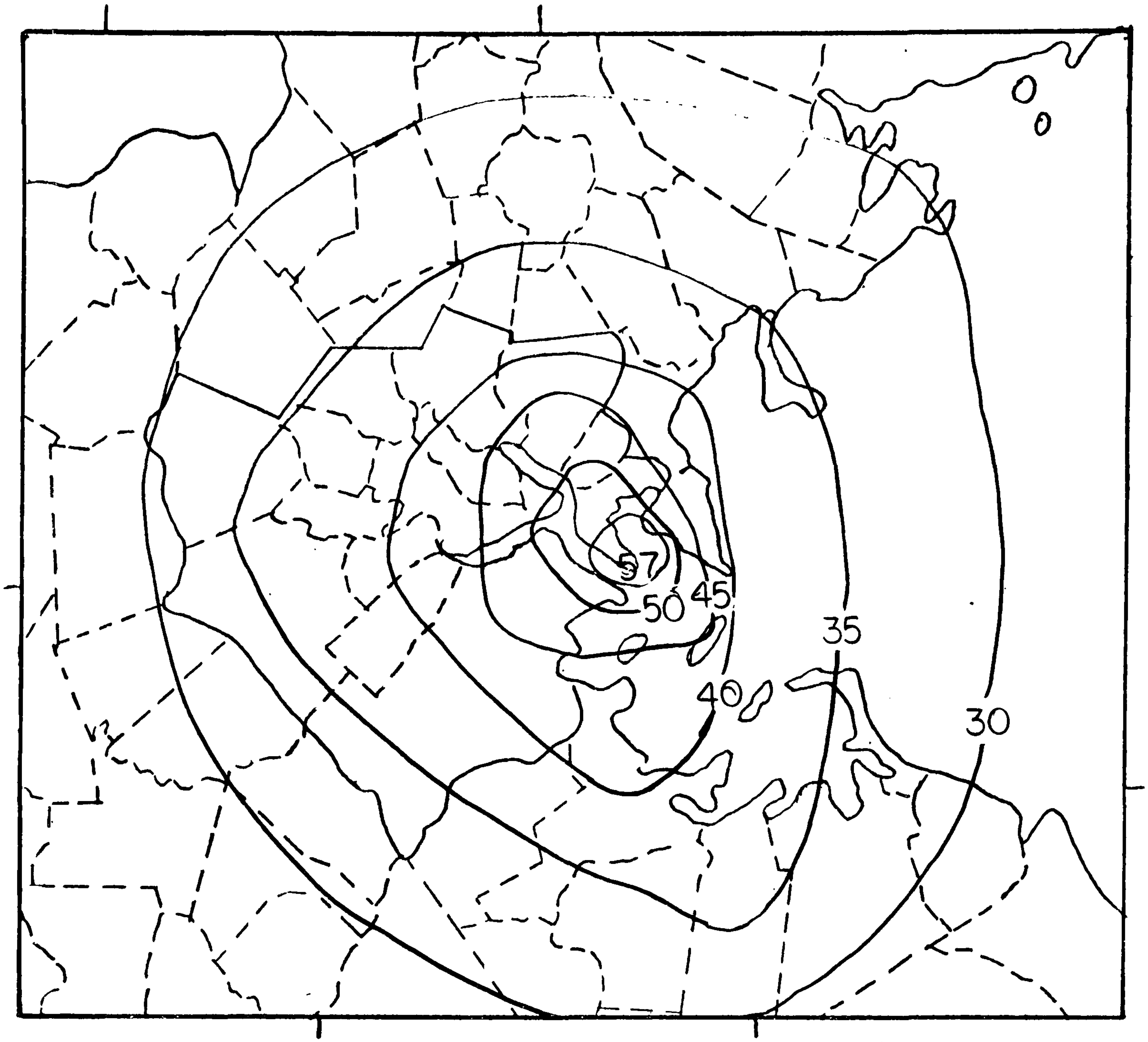


Figure 4-8. TSP Concentrations ($\mu g/m^3$) 1974 First Quarter Meteorology and 1973 Fuel Use Patterns - Simulation 2

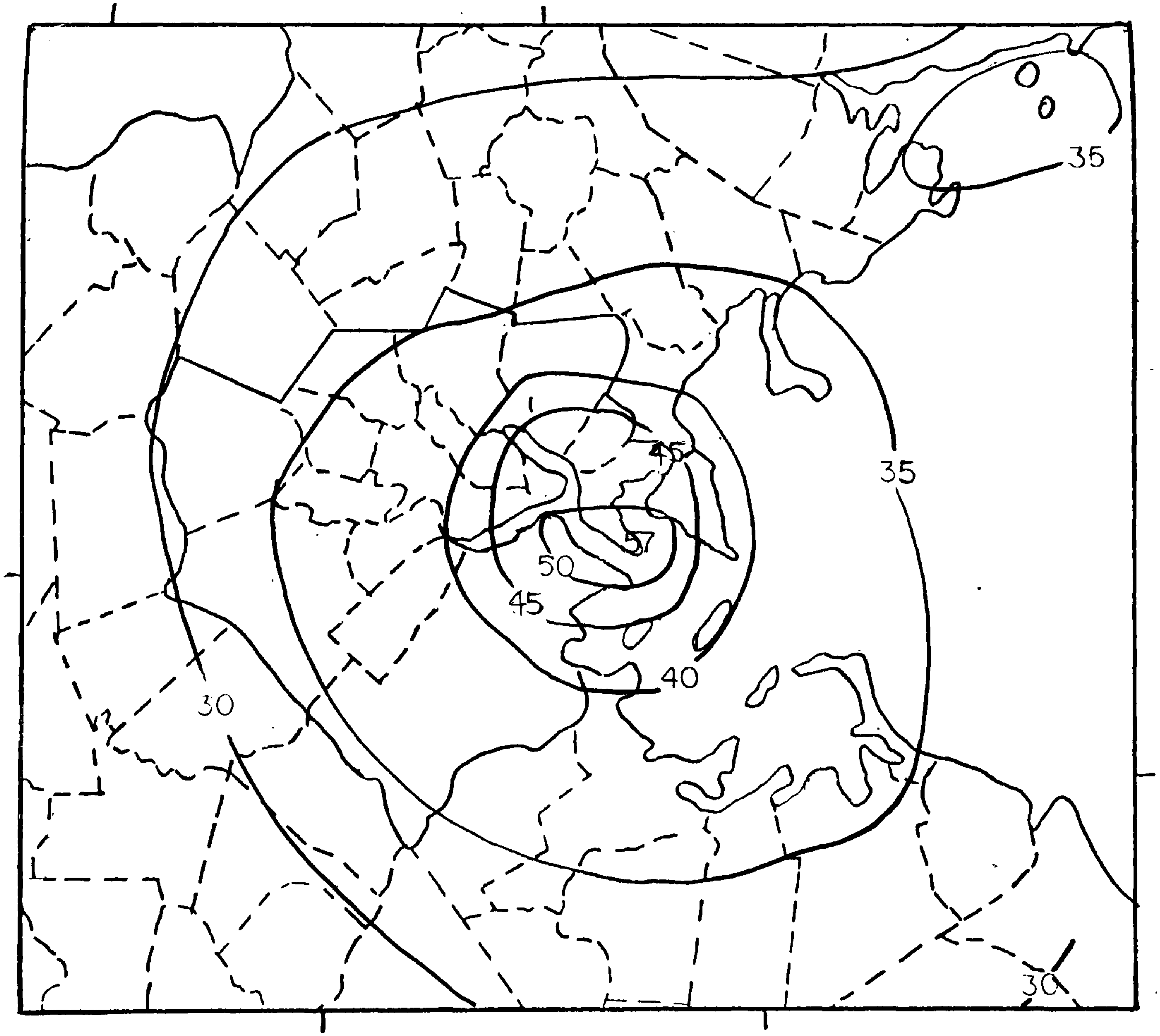


Figure 4-9. TSP Concentrations (μg/m³) 1974 First Quarter Actual Variance Implementation - Simulation 3

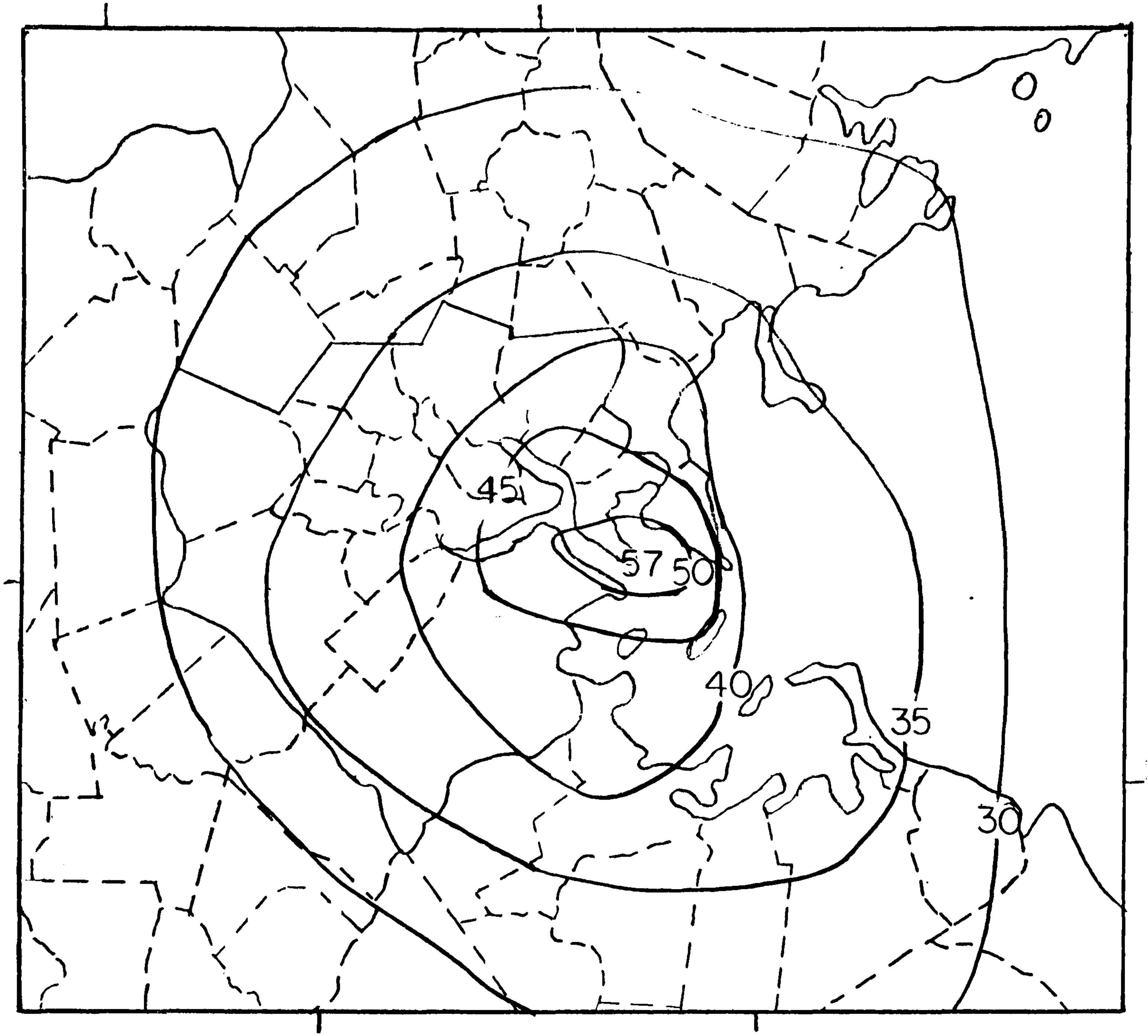


Figure 4-10. TSP Concentrations (μg/m³) 1974 First Quarter No Variance Implementation - Simulation 4

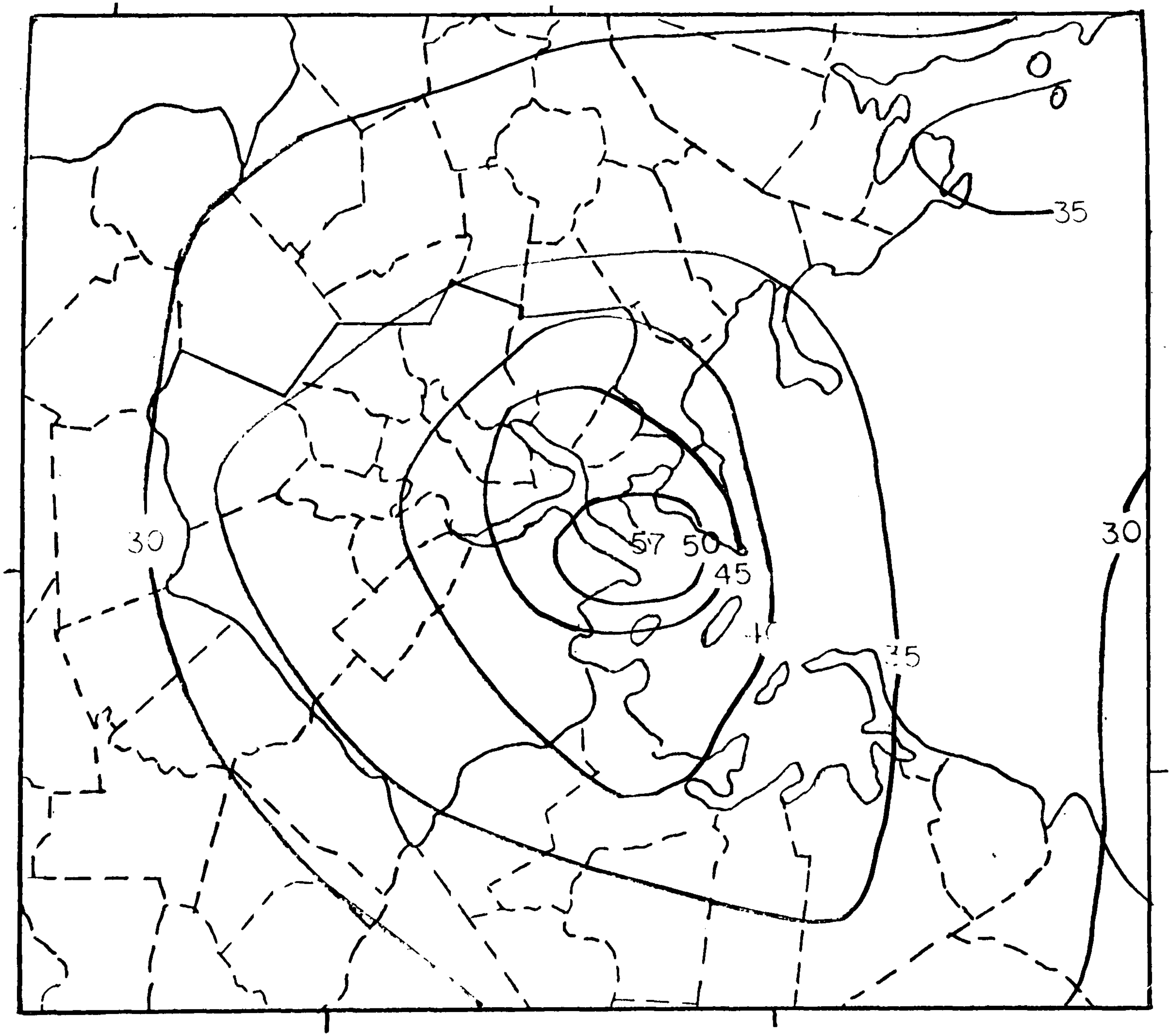


Figure 4-11. TSP Concentrations (μg/m³) 1974 First Quarter Full Variance Implementation - Simulation 5

b. Isolation of Effects

Modeling of the five cases permitted isolation of the relative effects of meteorology, variance implementation (actual and hypothetical "worst case"), and the combined effects of growth and conservation on ambient air quality in the AQCR during the energy shortage.

(1) Sulfur Dioxide

Table 4-2 presents the average percentage change in sulfur dioxide concentrations between the first quarter of 1973 and the first quarter of 1974 based on model predictions for the base grid (simulations (1) and (3) described in Section IV.B.3). The base grid is 25 receptors equally spaced throughout the AQCR which are assumed to represent average change.

TABLE 4-2

	SO_2 Net Change 1973-1974	Component		
		Weather	Growth and Conservation	Variances Implemented
Mean Percent Change	-12.0	1.3	-16.0	2.7
Standard Deviation	15.8	17.5	3.5	2.2

Also included in this table is a dissection of the total change into the three components of interest: meteorology, growth and conservation, and variances implemented. These results indicate that the most significant influence on SO_2 levels in this period was the growth and conservation parameter.*

* Note that "growth" rate was less than 2% for all inventory categories between 1973 and 1974.

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SO_2 ambient concentration levels improved (i.e., decreased) by 16 percent as a consequence of growth and conservation, while meteorology and "variances implemented" tended to degrade air quality very slightly. Table 4-2 also presents the standard deviation of the model predictions. These statistics indicate that the observed effects of conservation and growth, and of "variances implemented" vary little throughout the region. However, the effects of weather vary markedly; primarily due to differences in wind directional frequencies between 1973 and 1974.

Table 4-3 presents the average percentage changes in SO_2 concentrations that can be attributed to the causal components, as derived from the simulations for the base grid and various geographically similar groups of receptors. Table 4-3 also presents an indication of what would have resulted from full implementation of all variances. These estimates indicate that, in general, SO_2 concentrations would have increased 37 percent over the "no variance" situtation.

The variable effects of meteorology, especially due to changes in wind direction frequency, are evident from Table 4-3. The differences have been analyzed based on Figure 4-12 which presents the first quarter wind roses for 1972, 1973 and 1974, based on observations made at Boston's Logan Airport. The 1973 wind rose indicated a greater frequency of occurrence of wind flows from the northeast than occurred in 1974. This resulted in coastal stations observing lower SO_2 concentrations during 1973 due to the lack of emission sources to the northeast of Boston. Also, receptors to the southwest of Boston observed higher than normal transport of emissions from the city during that year. Consequently, with the return of the more normal dominant northwesterly flow in the winter of 1974, coastal station SO_2 levels increased an average of 15%, which significantly differs from the 12 percent average decrease observed for the AQCR. A decrease in SO_2 concentrations of 32 percent in the area southwest of Boston, two-thirds of which is attributable to meteorology (i.e., dispersion and degree-days), was also observed in 1974.

TABLE 4-3

PERCENT CHANGE IN SULFUR DIOXIDE CONCENTRATIONS
AS PREDICTED BY MODEL
FIRST QUARTER 1973 TO FIRST QUARTER 1974
BASE RECEPTOR GRID

Receptor Grouping	Net Change 1973 - 1974	Components			Full Variance Implementation
		Weather	Growth and Conservation	Variances Implemented	
Base	-12.0	1.3	-16.0	2.7	52.3
Urban Locations	-13.1	0.4	-17.2	3.6	51.3
Coastal Locations	0.8*	15.3*	-19.4	4.8*	71.9
Southwest Boston	-32.0*	-21.1*	-12.4	1.5	28.1*

* Significantly different from base case.

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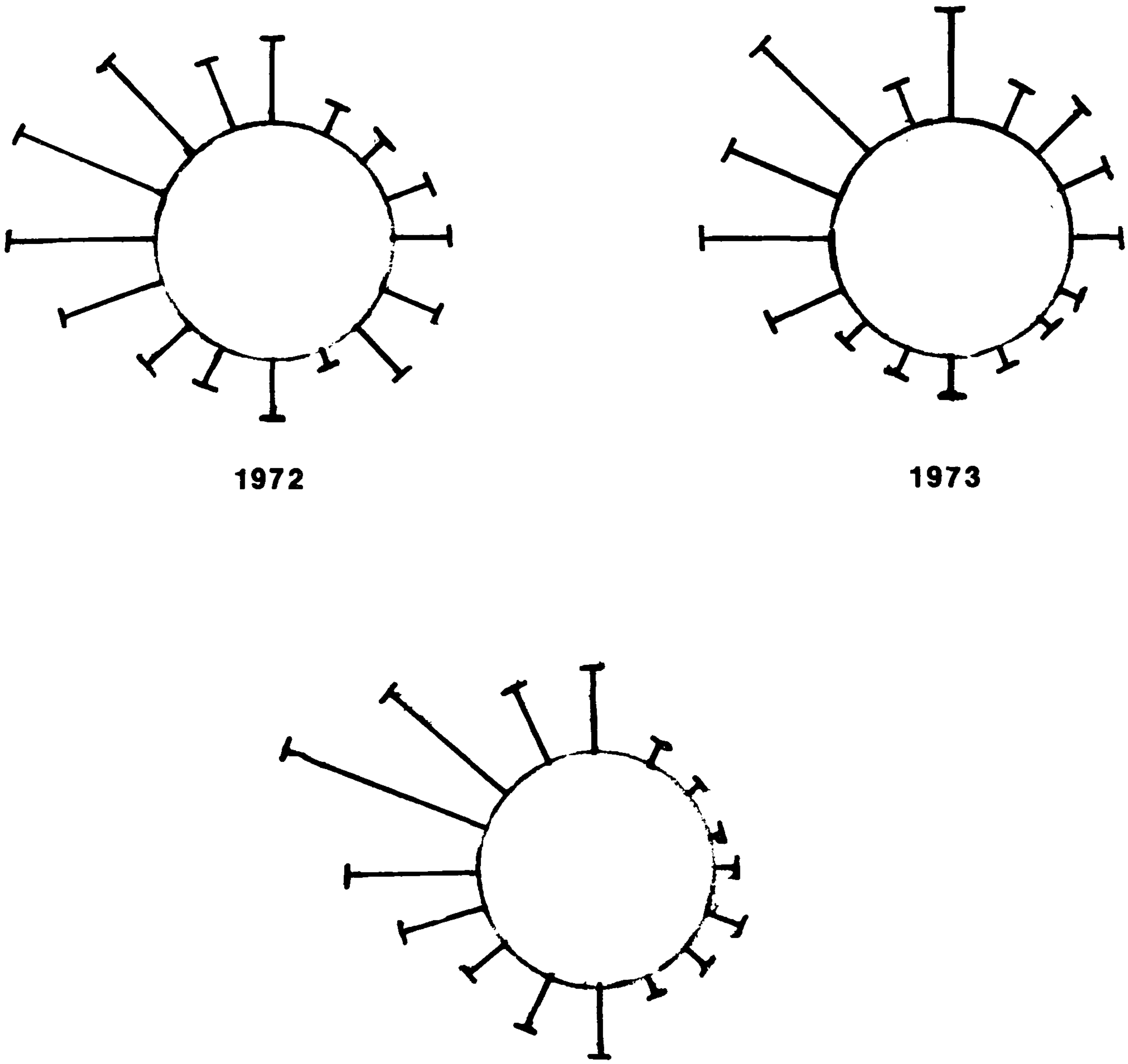

Scale

one inch = 12.5%

Figure 4-12. First Quarter Wind Roses
Logan International Airport

As noted, the average increase in concentration due to the actual variance component was 2.7 percent, and the increase in concentration due to the hypothetical full variance component was 52 percent. Table 4-4 presents the relative contribution of three source categories (power plants, large* residual oil users other than power plants, small residual oil users and all distillate users) to the increase in SO_2 concentrations observed during actual variance implementation and hypothetical full variance implementation case above the no variance case. Data are presented for four individual receptors positioned to represent spatial variation and for two receptors positioned to indicate the effect in the vicinity of two large power plants which were granted variances.

These data indicate that distillate oil and small residual oil users contributed about 75 percent of the increase in concentration due to actual variance implementation; power plants contributed about 15 percent. With full variance implementation, the small users would contribute about 60 percent and power plants 30 percent.

(2) Total Suspended Particulates

The principal sources of particulates in the Metropolitan Boston region are incinerators, mobile sources and combustion sources. Neither incinerators nor mobile sources were significantly affected by conservation efforts during the energy shortage, nor are their emission rates a function of heating requirements.** The only variance granted which significantly affected particulate emission rates among fuel combustion sources in the Metropolitan Boston AQCR was the allowance for burning coal in three units of New England Power Company's Salem Harbor power plant.

Table 4-5 presents the average percentage change in TSP concentrations between the first quarter of 1973 and the first quarter of 1974 based on model predictions for the base grid (Simulations (1) and (3) described in Section IV.B.3).

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* $\geq$ 20 million gallons/year.

** i.e., they do not vary significantly with heating degree-days.

TABLE 4-4

COMPONENTS OF CHANGE IN SO_2 CONCENTRATIONS
RESULTING FROM VARIANCES BY SOURCE CATEGORY

	Actual Implementation				Hypothetical Full Variance Implementation			
	Net Change (Percent)	(Component % of Net Change) PP+	LR*	SR+D**	Net Change (Percent)	(Component % of Net Change) PP+	LR*	SR+D**
Region of AQCR								
West	2.0	14.3	3.6	82.1	40.8	32.2	2.2	65.6
Central Business District	4.5	14.8	8.5	76.7	62.1	37.3	7.7	55.0
North	1.7	29.2	0.0	70.8	44.3	29.3	3.7	67.0
Coastal	4.4	18.7	8.7	72.6	97.2	58.3	10.7	31.0
Point Source Dominated								
3 km ESE of Edgar Plant	1.8	25.0	2.5	72.5	73.1	55.0	2.1	42.9
3 km ESE of Salem Harbor Plant	9.7	88.3	0.8	10.9	74.0	45.7	3.8	50.5

+ Power plants

* Large residual oil users other than power plants

** Small residual oil users and all distillate oil

TABLE 4-5

	TSP Net Change 1973-1974	Component		
		Weather	Growth and Conservation	Variances Implemented
Mean Percent Change	-20.0	-20.3	-0.5	0.9
Standard Deviation	20.5	19.4	1.3	1.5

Also included in this table is a dissection of the total change into the three components of interest: meteorology, growth and conservation, and variances implemented. These results indicate that the average net change in TSP concentrations was a 20 percent decrease between the first quarter of 1973 and the first quarter of 1974. This change results almost entirely from a 20 percent decrease in concentration due to differences in meteorology. Growth and conservation and variances granted had a negligible impact on changes in TSP concentrations during this period.

Table 4-6 compares these relative components with those of two selected geographical areas - downtown Boston and the Salem Harbor plant area. These data indicate that meteorological factors do not influence the TSP concentrations in urban areas as strongly as they do for the base grid system. Furthermore, comparison with similar data for SO_2 indicates a very small net change due to the weather component for this pollutant. A qualitative analysis of these changes between 1973 and 1974 indicates that the effects of weather were a composite of two opposing effects: the tendency of the change in wind-stability patterns was to decrease concentrations, and the effect of degree-days was to increase concentrations. SO_2 concentrations, which are strongly tied to space heating requirements, showed a balance between these factors. TSP concentrations, however, are affected considerably less by change in degree-days and without this balancing factor showed a significant drop in the total weather component. Urban TSP concentrations are more strongly influenced by space heating requirements due to the concentration of dwelling and commercial establishments and thus are more nearly balanced by these two components.

TABLE 4-6

PERCENT CHANGE IN TSP CONCENTRATIONS

1st QUARTER 1973 TO 1st QUARTER 1974

BASE RECEPTOR GRID

Receptor Grouping	Net Change 1973-1974	Components			
		Weather	Growth and Conservation	Variances Imple.	Full Variance Implementation
Base	-21.0	-20.3	-0.6	0.9	0.9
Urban Locations	-11.6	-10.5*	-1.1	0.0	0.0
Salem Harbor Area	14.6*	8.7*	3.9*	1.9	1.9

* Significantly different from base case.

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Meteorological effects in the vicinity of the Salem Harbor plant produced an increase in TSP concentrations similar to the increase in SO_2 observed at coastal stations. The variance to allow coal burning at this plant had little effect on TSP concentrations due to the efficiency of its electrostatic precipitators and its coastal location.

Full variance implementation would not have significantly changed TSP concentrations.

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VI. APPENDICES

A. AIR QUALITY ANALYSIS

1. Data Analysis

a. X-11 Ratio to Moving Average Analysis

(1) Methodology

Air monitoring data, for ambient concentrations of SO_2 (13 sites) and TSP (7 sites) in the Metropolitan Boston AQCR, was judged sufficient for time series analysis (see Table A-1). Time series of monthly pollutant concentrations measured at these sites were decomposed into three components or movements using a ratio to moving average technique. These movements are: a trend-cycle component T which is comprised of both long-term and short-term trends, a seasonal component S that quantifies the persistent periodic behavior in the series that can be related to the temporal changes from one month to another, and an irregular component I which quantifies the nonperiodic and unpredictable part of the series. The X-11 Variant of the Census Method II Seasonal Adjustment Program [12] was used to perform this analysis. This program is based on a complex ratio to moving average technique. Note that an a priori concept of what the "trend" of the data should be was not assumed in this analysis. Rather, the trend-cycle component was defined by the analytical procedure.

The analysis was performed on the original air quality data using both a multiplicative (T*S*I) and an additive (T+S+I) model of the series components in order to assess the most appropriate model in each case. The decision criteria used in this assessment was to determine which model produced the smallest irregular component in each case. To measure the magnitude of the irregular component, the final irregular series standard derivation expressed as a percentage of the original series mean value was calculated.

TABLE A-1

METROPOLITAN BOSTON AIR QUALITY MONITORING SITES RECORDING SUFFICIENT DATA FOR TIME SERIES ANALYSIS IN THE INDICATED TIME PERIODS

SAROAD* Site Code	Site Location	Site Description	Series Name	Time Span of Data 1970-74	Time Span of Data 1971-74	Urban Core Sites
SO_2						
0240001(F01)	Government Center, Boston	Center City-Commercial	SO2A	✓	✓	✓
0240002(F01)	Kenmore Square, Boston	Center City-Commercial	SO2B	✓	✓	✓
0240012	South Bay, Boston	Suburban-Industrial	SO2C		✓	✓
0240013	Central Square, East Boston	Center City-Commercial	SO2D	✓	✓	✓
0340001	Greenough St., Brookline	Center City-Residential	SO2E		✓	
1160001	Village St., Marblehead	Center City-Commercial	SO2F		✓	
1200001	US Army Site, Maynard	Rural-Agricultural	SO2G		✓	
1220002	Main St., Medford	Center City-Commercial	SO2H		✓	
1480002	Dedham Ave., Needham	Center City-Residential	SO2I		✓	
1700001	Nahatan St., Norwood	Center City-Residential	SO2J		✓	
1880001	Hancock St., Quincy	Center City-Commercial	SO2K		✓	
2340003	Beaver St., Waltham	Rural Agricultural	SO2L		✓	
2620002	Montvale Ave., Woburn	Center City-Commercial	SO2M		✓	
TSP						
0240002(F01)	Kenmore Square, Boston	Center City-Commercial	TSP1	✓	✓	✓
0340001	Greenough St., Brookline	Center City-Residential	TSP2		✓	
1200001	US Army Site, Maynard	Rural-Agricultural	TSP3		✓	
1480002	Dedham Ave., Needham	Center City-Residential	TSP4		✓	
1700001	Nahatan St., Norwood	Center City-Residential	TSP5		✓	
1880001	Hancock St., Quincy	Center City-Commercial	TSP6		✓	
2340003	Beaver St., Waltham	Rural-Agricultural	TSP7		✓	

*Storage and Retrieval of Aerometric Data

The X-11 program produced three potential trend indicators — the final seasonally adjusted series (T*I or T+I), the months for cyclical dominance series (MCD), and the final trend-cycle series (T). These are labeled (1), (2), and (3), respectively, in Figure A-1 which compares the characteristics of these three trend indicators for a typical economic time series [14]. Referring to Figure A-1, it is important to note that the fluctuations in series (1) are dominated by the irregular component, whereas those in series (3) are dominated by the trend component. In (3) a longer time span is used in computing the moving average than in (2) or (1) and as the time span increases, the trend component grows more important relative to the irregular and eventually dominates it. The crossover point is called the "months for cyclical dominance", and the span associated with this point is used to derive the MCD curve (2). Obviously, the smoothest of the three trend indicators, the final trend series (3) is excellent for historical purposes. By contrast, the seasonally adjusted series is the best of the series for analyzing very recent trends in data because of its sensitivity to short span fluctuations in the data.

(2) Time Series Component Graphs

Significant changes were made to the printed output from the Census Bureau X-11 ratio to moving average analysis program to provide a complete set of graphs for all series components of interest. As an example, series component graphs from the multiplicative model for the six representative data series (see Table A-2 and section II.A.2.a) are shown in Figures A-2 through A-19. An index to the content of these graphs is listed in Table A-3. All concentrations shown are in $\mu g/m^3$. Note that although graphs are shown for only the results from the multiplicative model for the six series, the X-11 ratio to moving average analysis was undertaken using both the additive and multiplicative models applied to all twenty original series (see Table A-1).

Figure A-1. A Comparison of the Characteristics of the Trend Series Indicators for a Typical Economic Time Series [14].

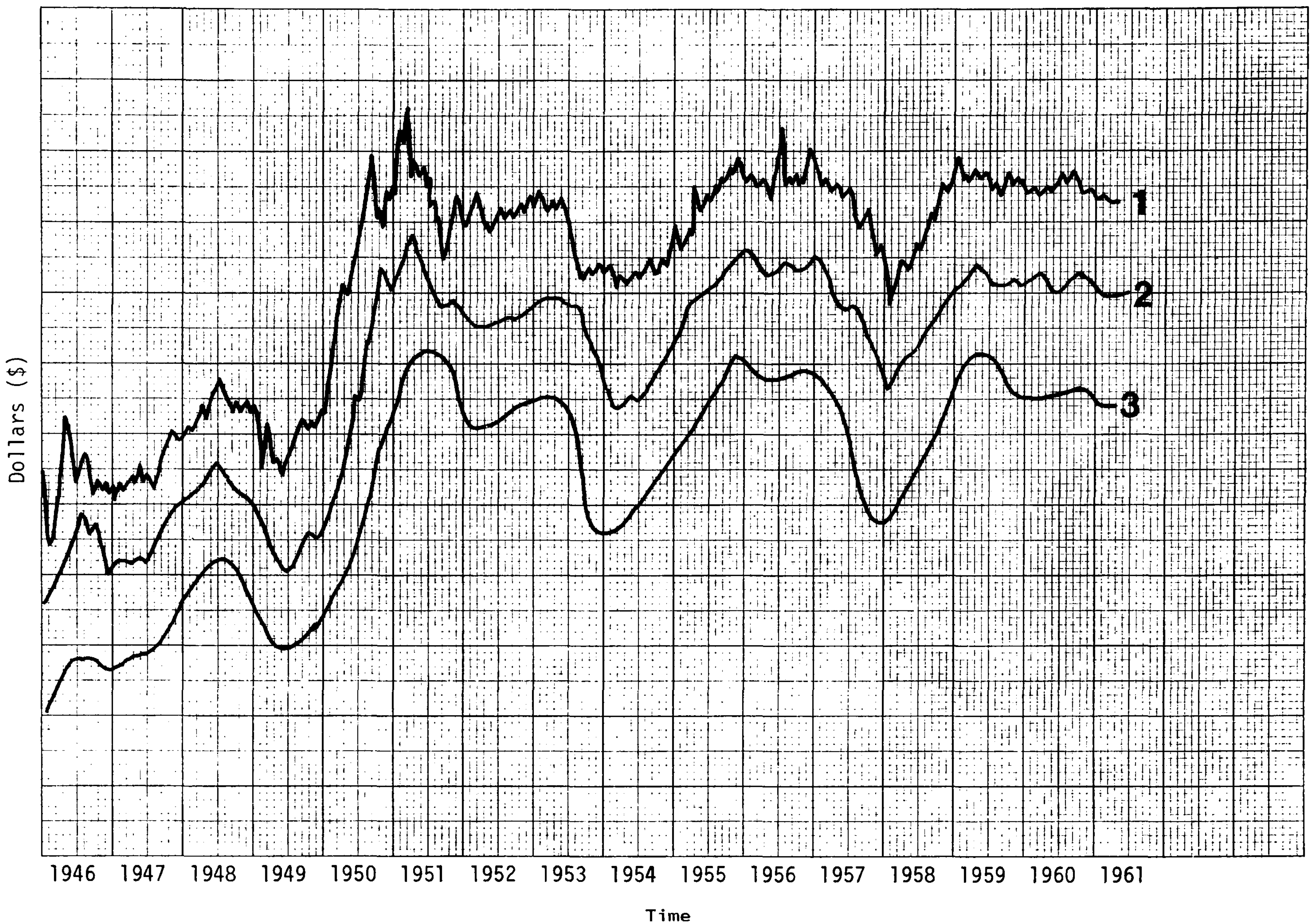


TABLE A-2

REPRESENTATIVE METROPOLITAN BOSTON AIR QUALITY MONITORING SITES CHOSEN FOR DATA ANALYSIS

SAROAD* Site Code	Site Location	Site Description	Series Name	Time Span of Data
SO_2				
0240002(F01)	Kenmore Square, Boston	Center City-Commercial	SO2B	January 1970-May 1974
1700001	Nahatan St., Norwood	Center City-Residential	SO2J	January 1971-June 1974
2340003	Beaver St., Waltham	Rural-Agricultural	SO2L	March 1971-June 1974
TSP				
0240002(F01)	Kenmore Square, Boston	Center City-Commercial	TSP1	January 1970-June 1974
1700001	Nahatan St., Norwood	Center City-Residential	TSP5	January 1971-June 1974
2340003	Beaver St., Waltham	Rural-Agricultural	TSP7	March 1971-June 1974

*Storage And Retrieval of Aerometric Data

Figure A-2

SO2 AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
KENMORE SQUARE, BOSTON SITE
SERIES SO2B

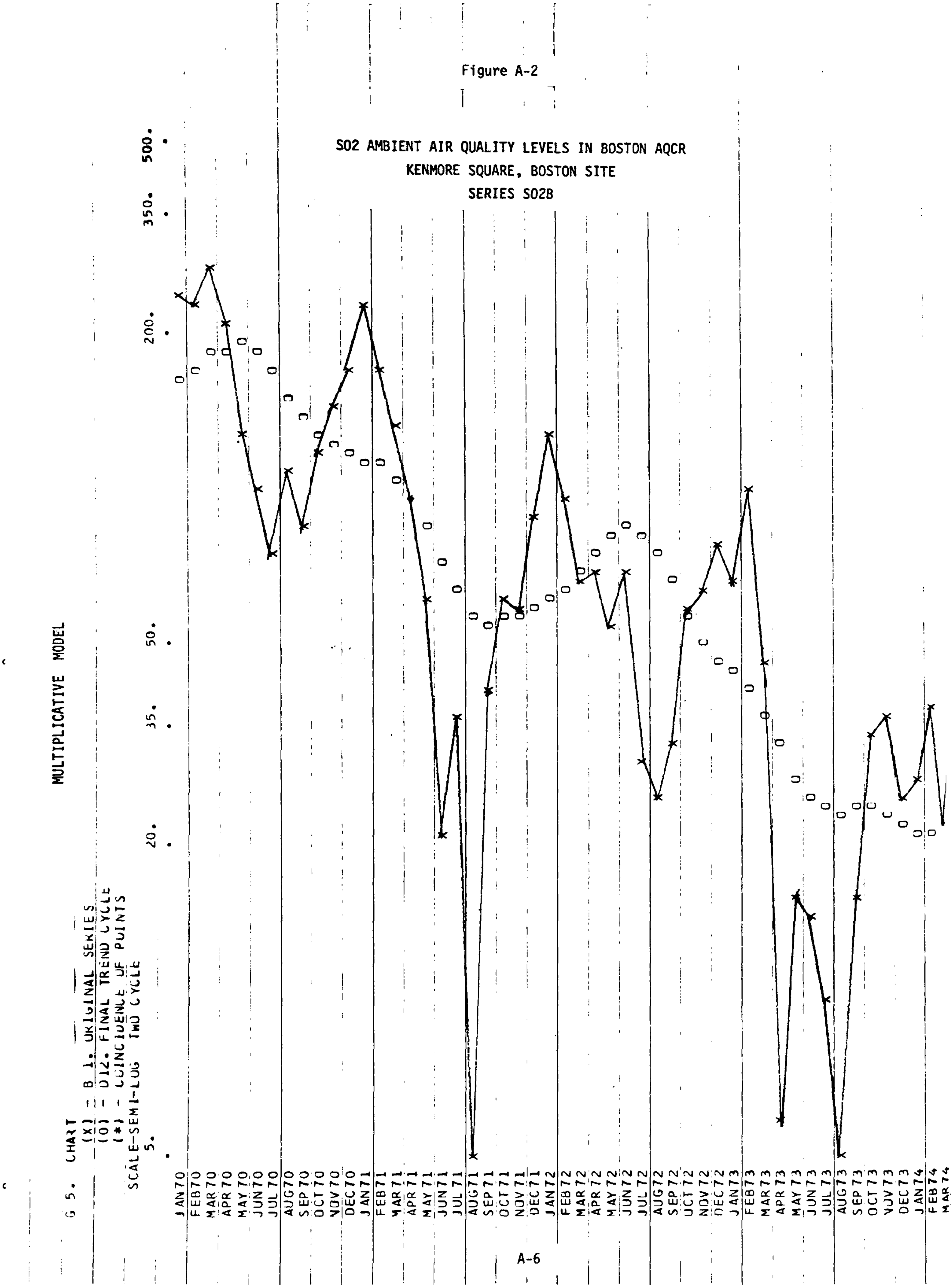


Figure A-3

SO2 AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
NAHATAN STREET, NORWOOD SITE
SERIES SO2J

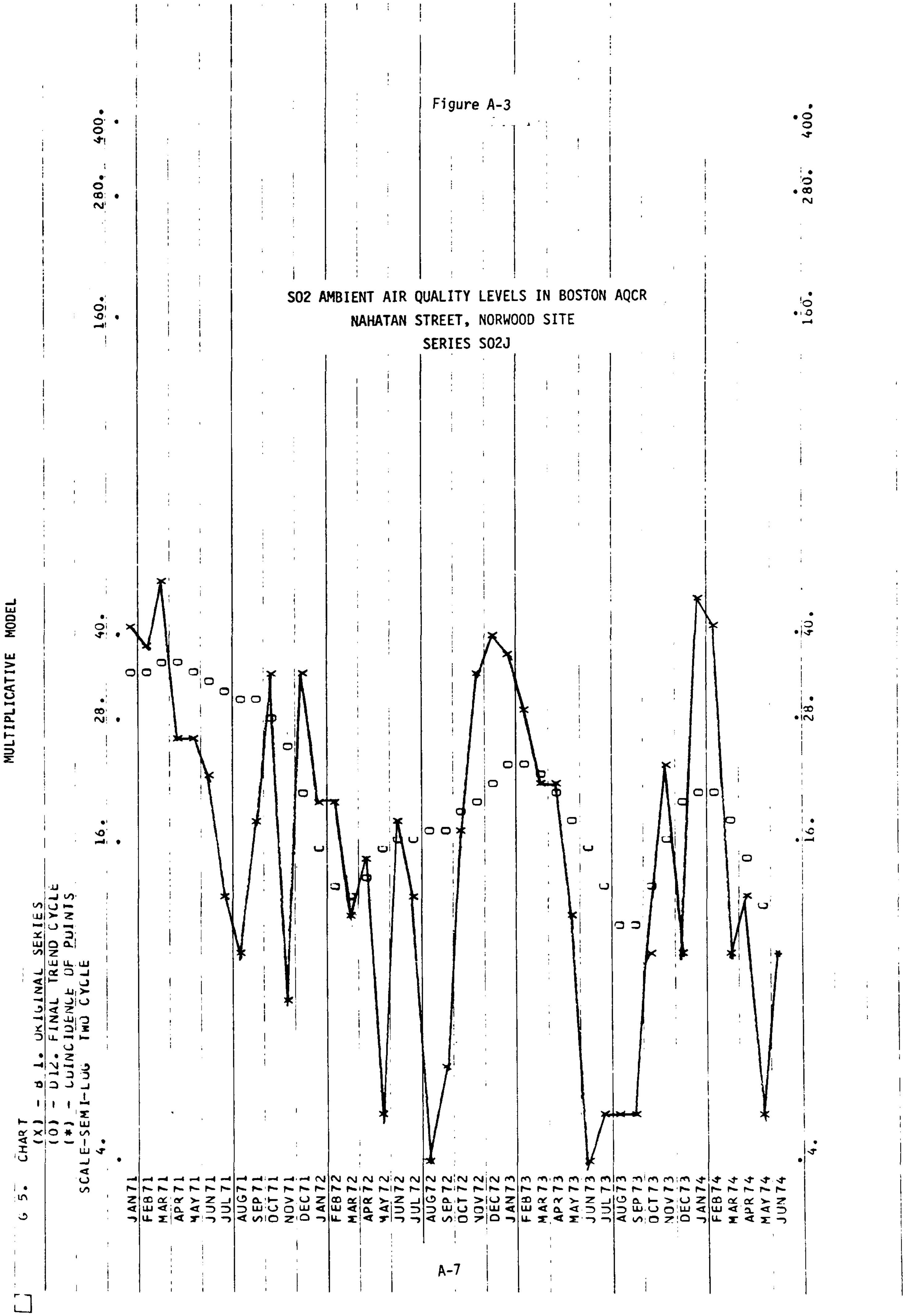


Figure A-4

SO2 AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
BEAVER STREET, WALTHAM SITE
SERIES SO2L

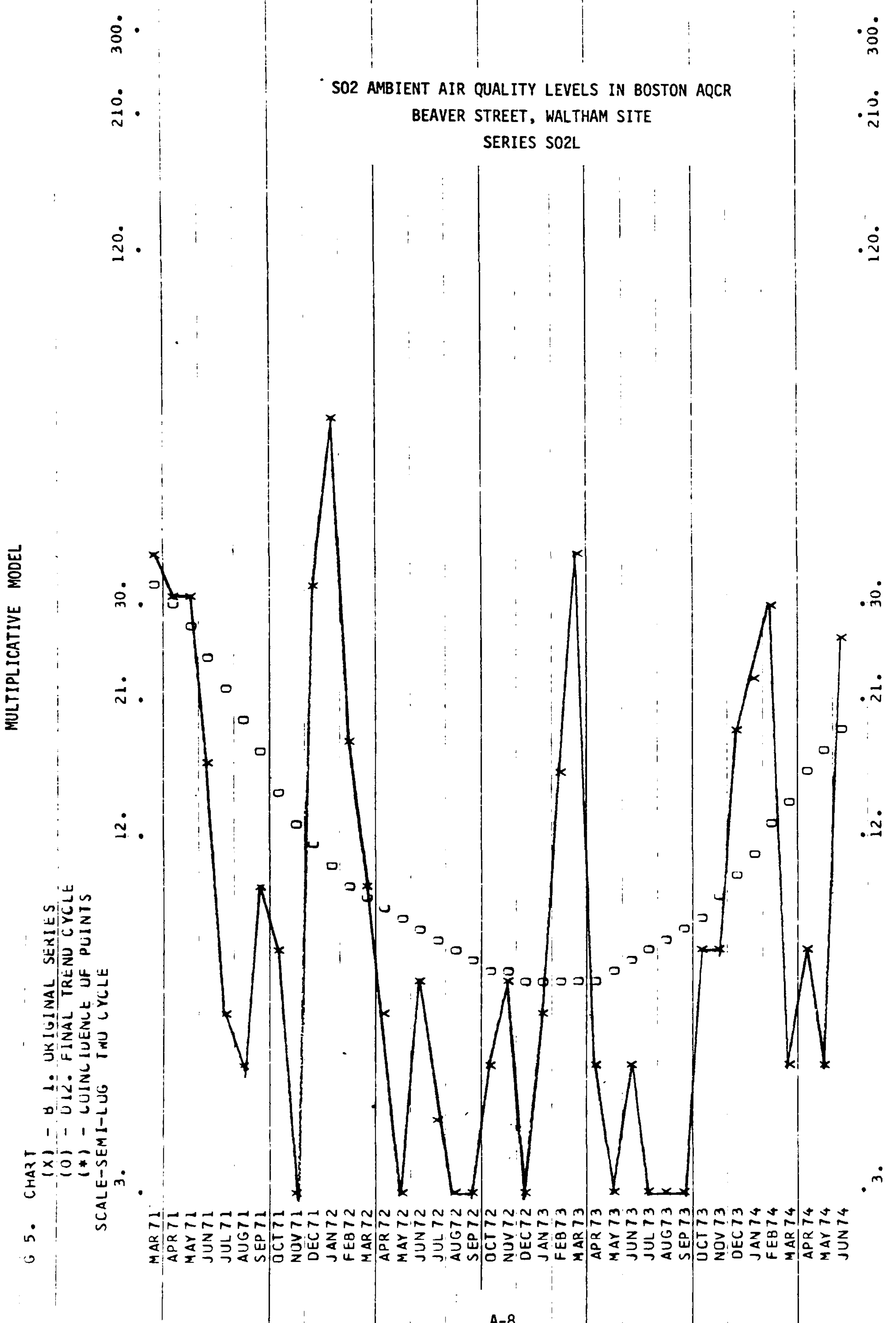
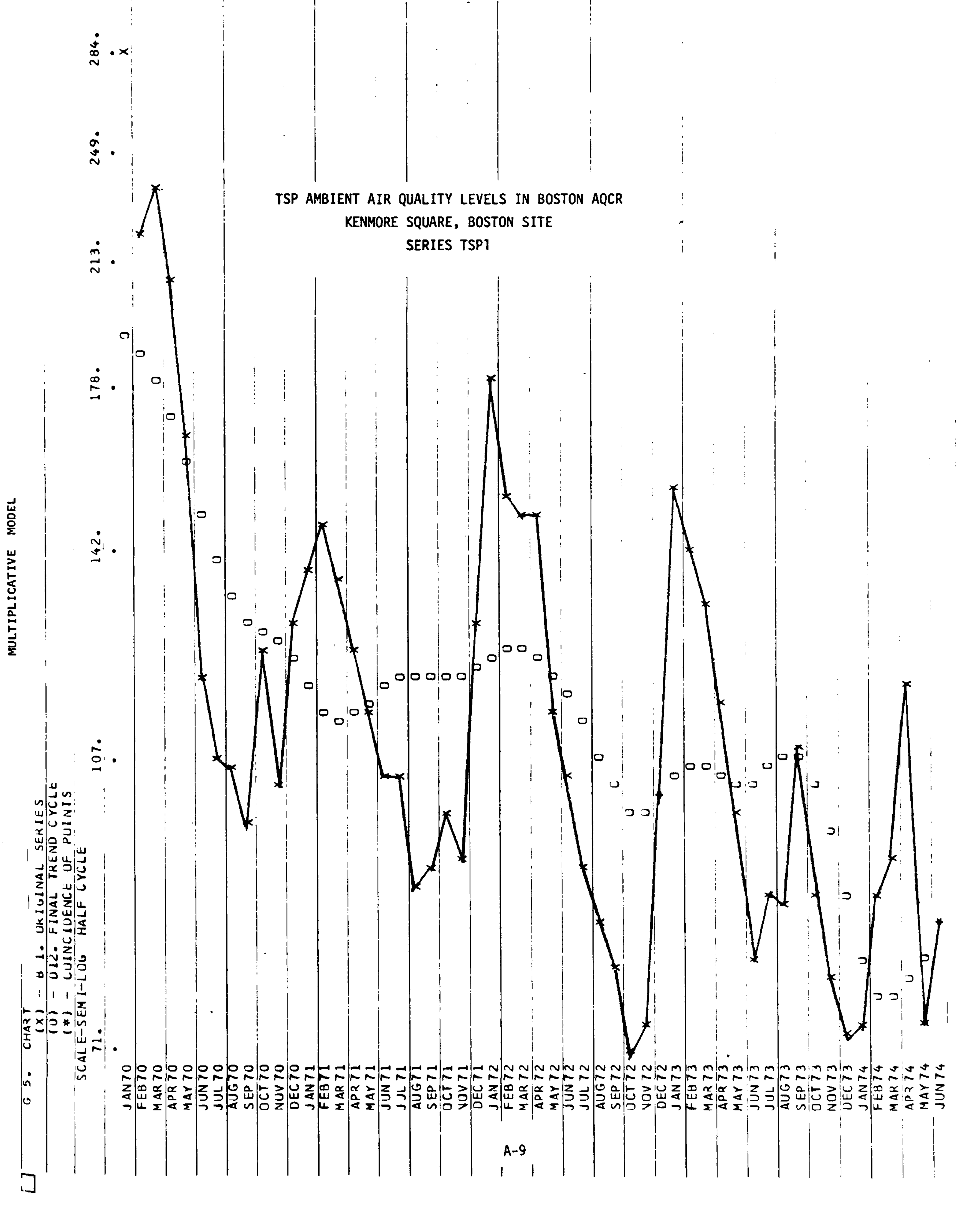


Figure A-5

TSP AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
KENMORE SQUARE, BOSTON SITE
SERIES TSP1



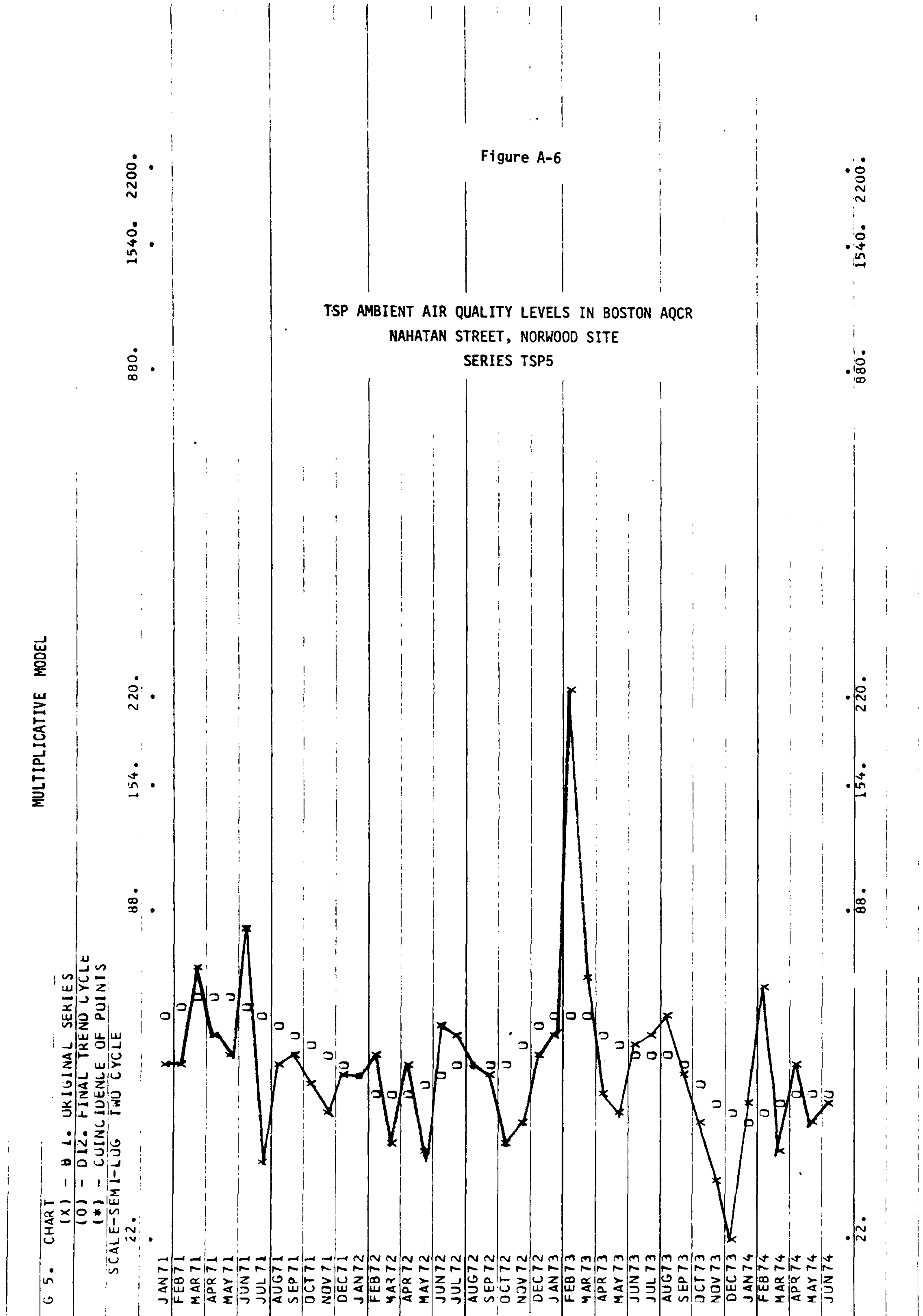


Figure A-6

TSP AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
NAHATAN STREET, NORWOOD SITE
SERIES TSP5

Figure A-7

TSP AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
BEAVER STREET, WALTHAM SITE
SERIES TSP7

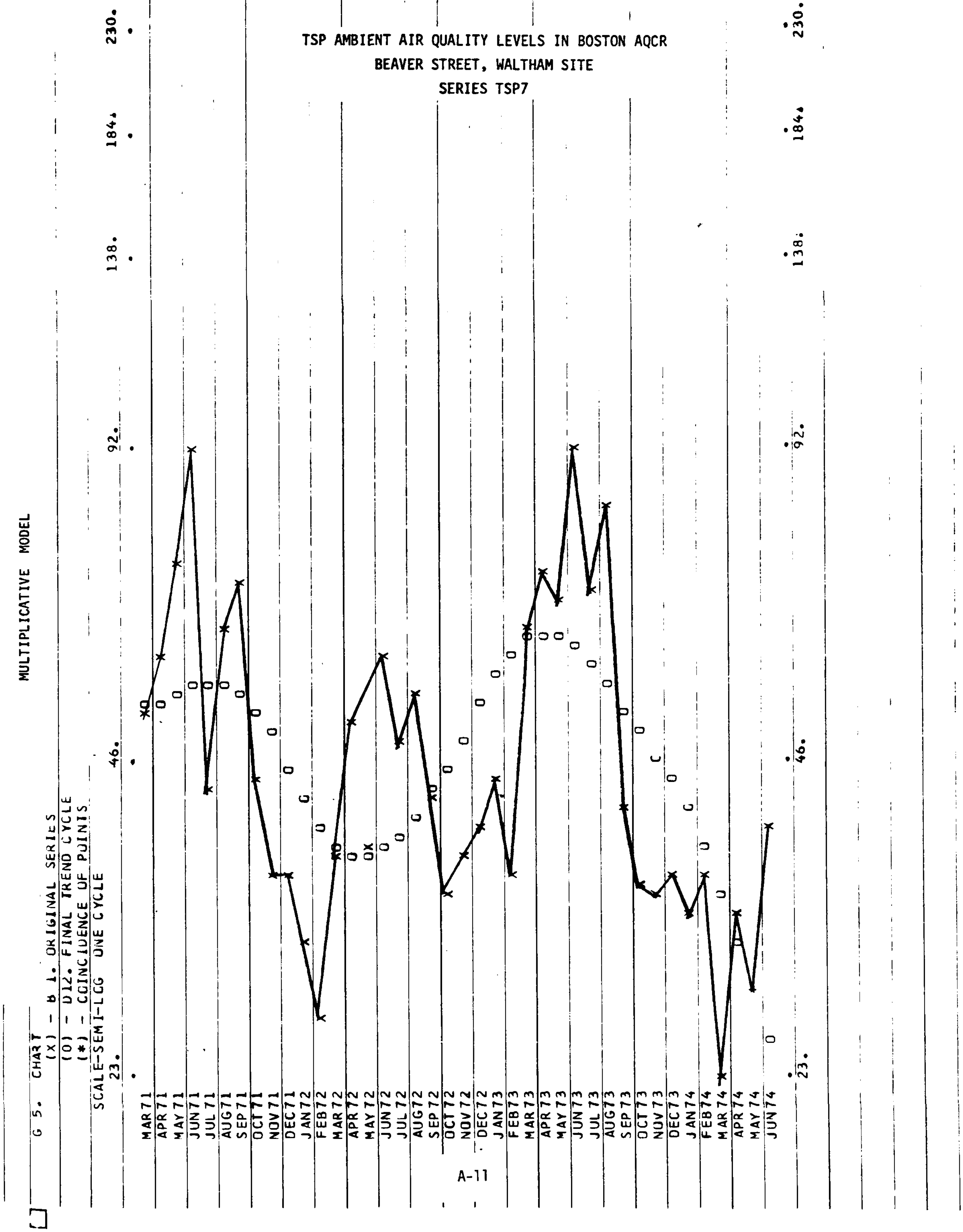


Figure A-8

SO2 AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
KENMORE SQUARE, BOSTON SITE
SERIES SO2B

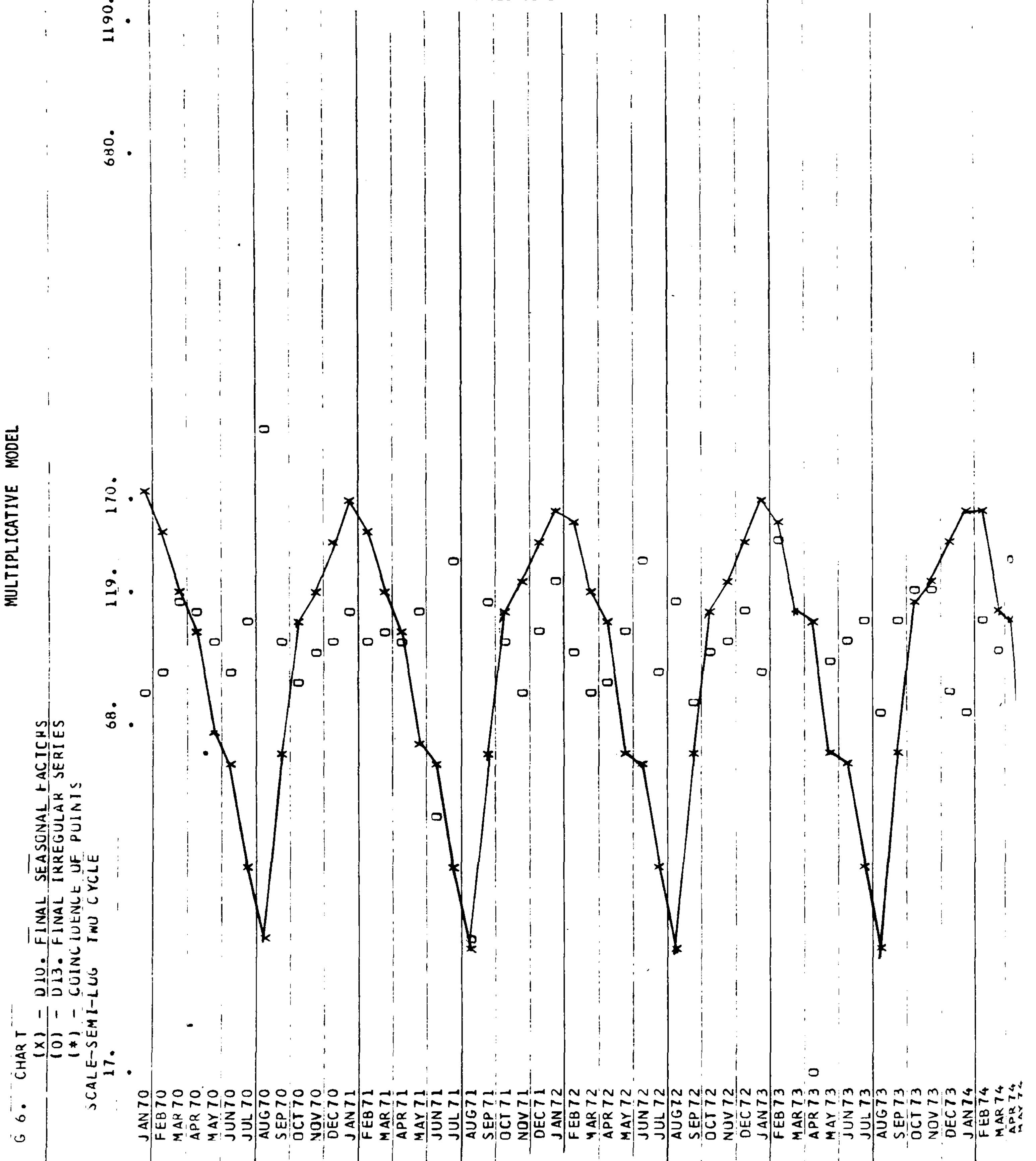


Figure A-9

SO2 AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
NAHATAN STREET, NORWOOD SITE
SERIES SO2J

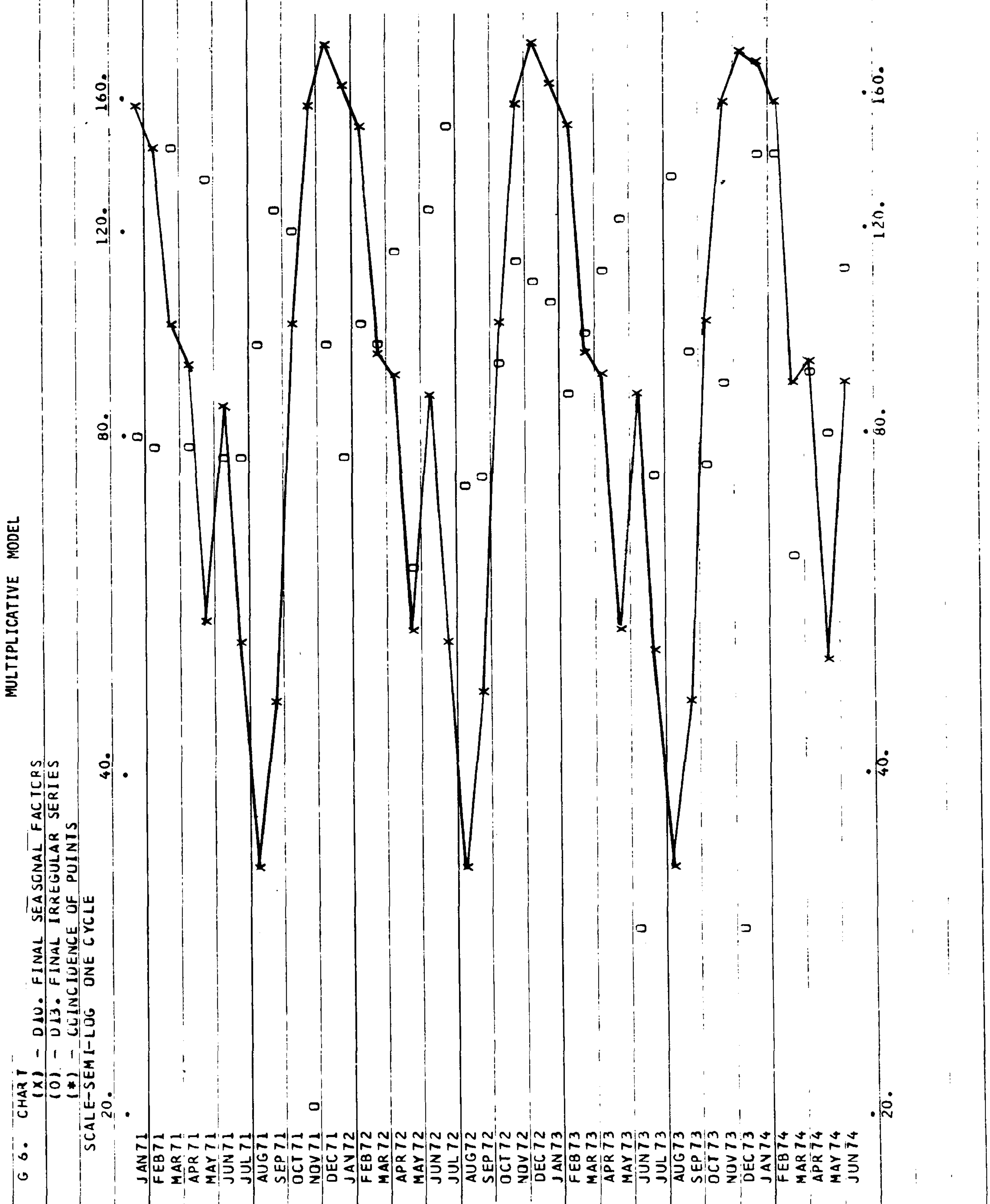


Figure A-10

SO2 AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
BEAVER STREET, WALTHAM SITE
SERIES SO2L

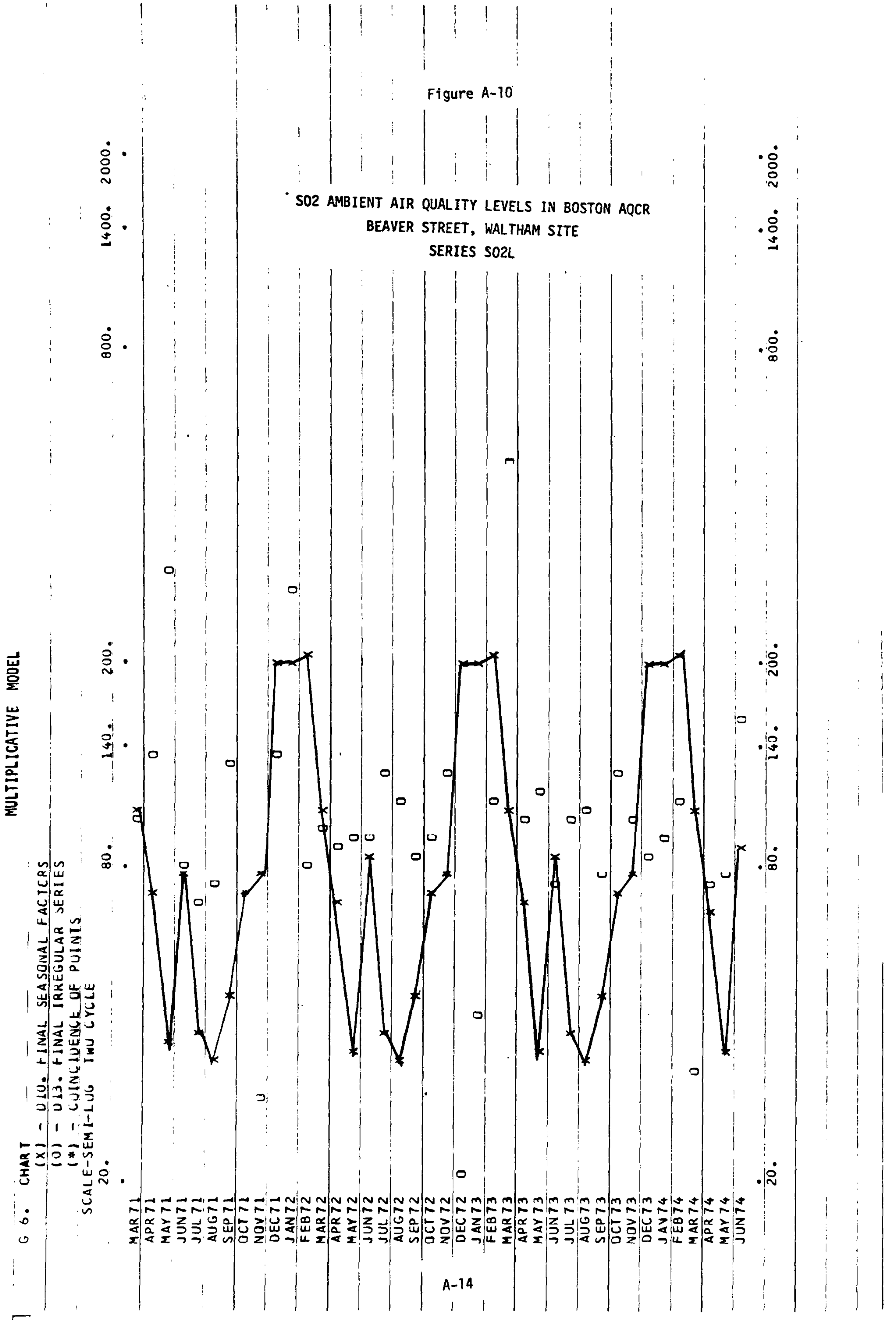


Figure A-11

TSP AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
KENMORE SQUARE, BOSTON SITE
SERIES TSP1

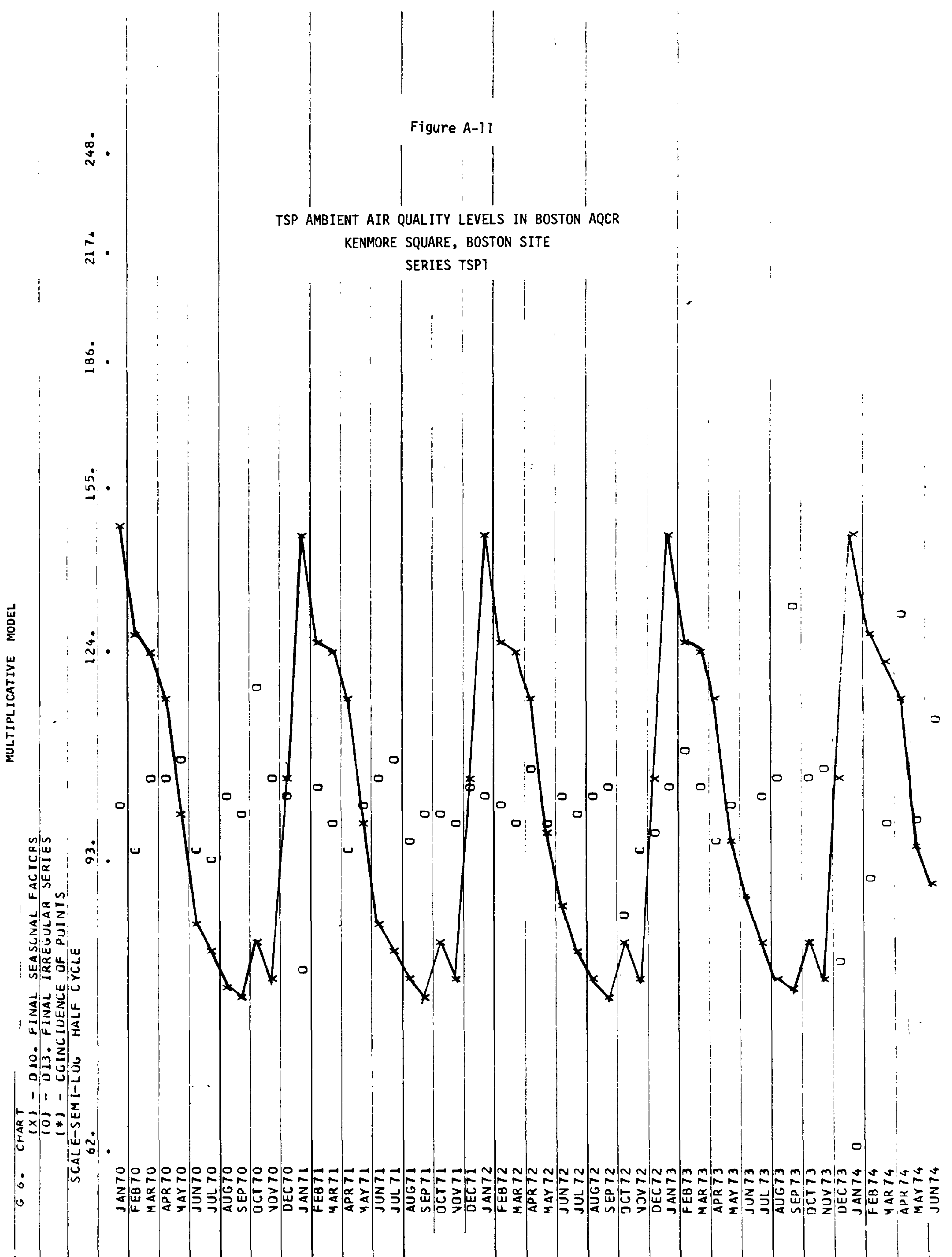


Figure A-12

TSP AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
NAHATAN STREET, NORWOOD SITE
SERIES TSP5

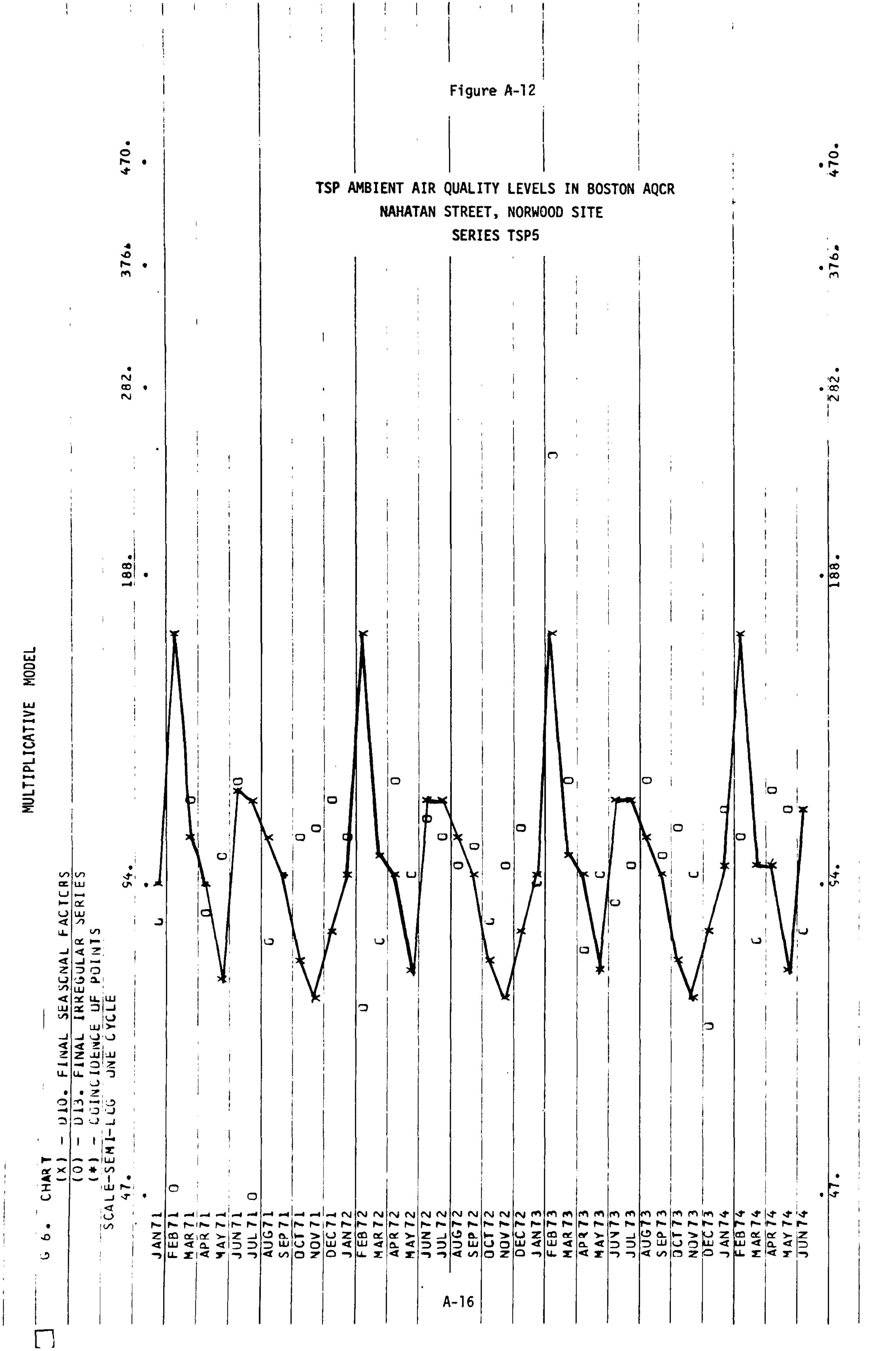


Figure A-13

TSP AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
BEAVER STREET, WALTHAM SITE
SERIES TSP7

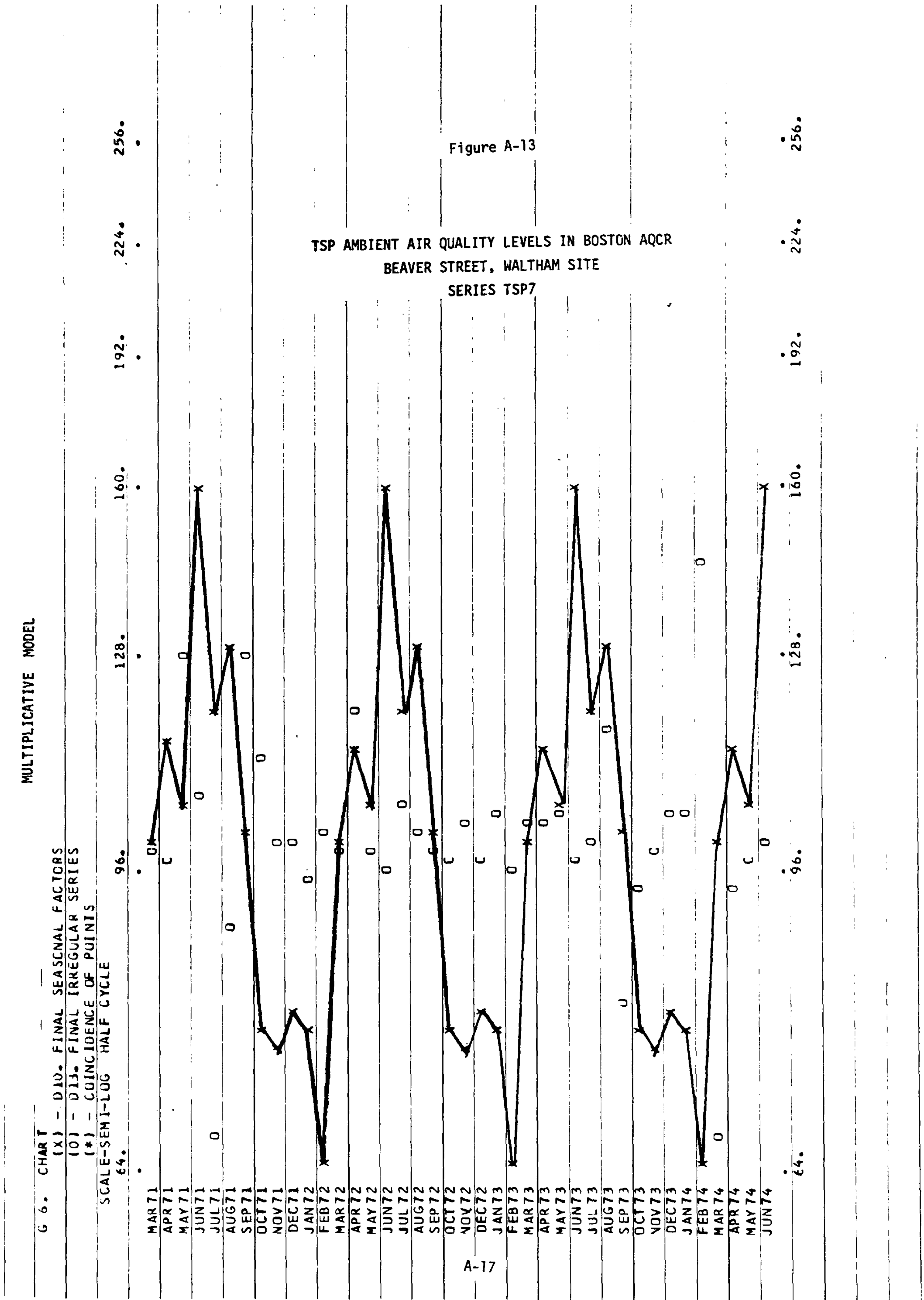
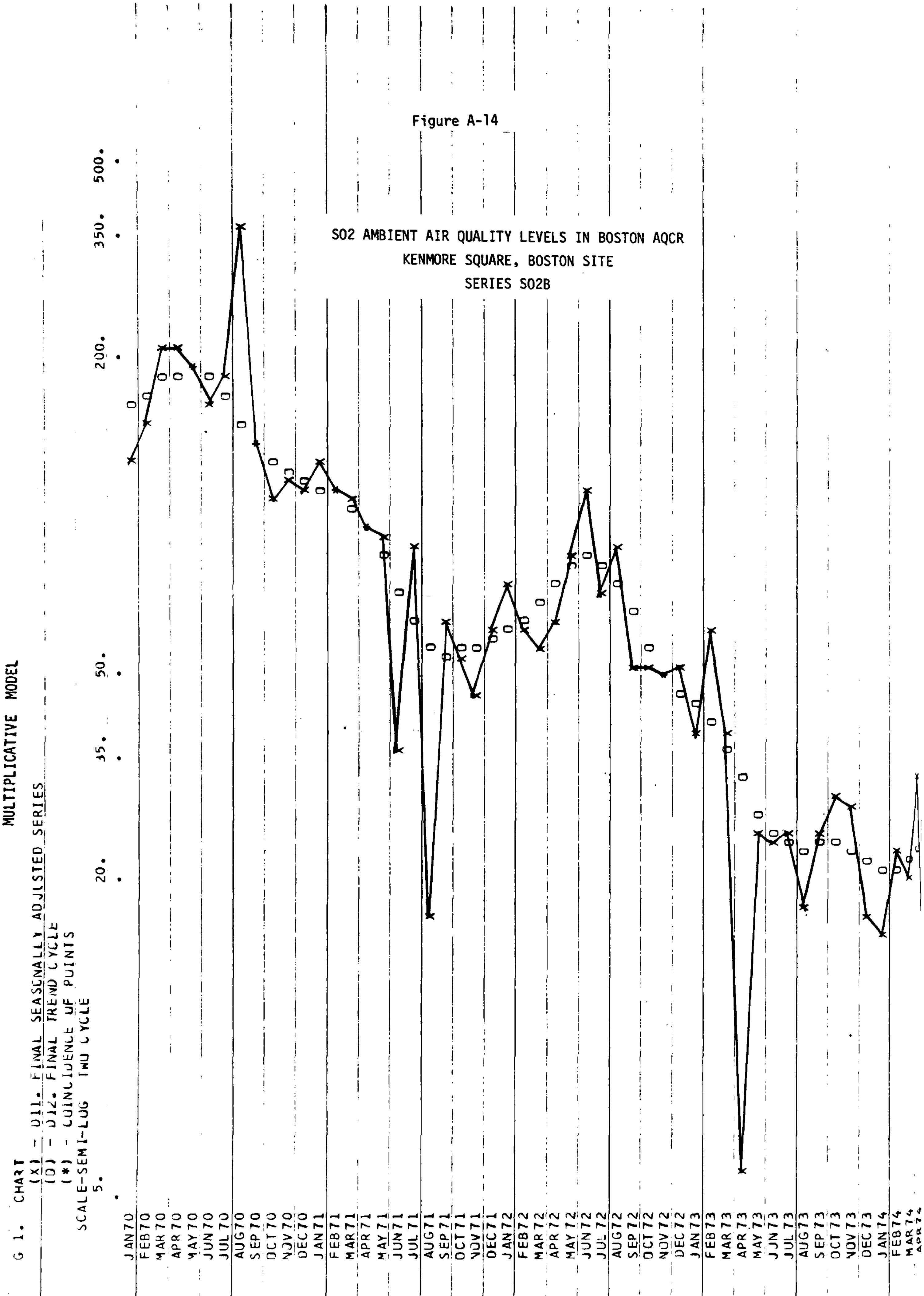


Figure A-14

SO2 AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
KENMORE SQUARE, BOSTON SITE
SERIES SO2B



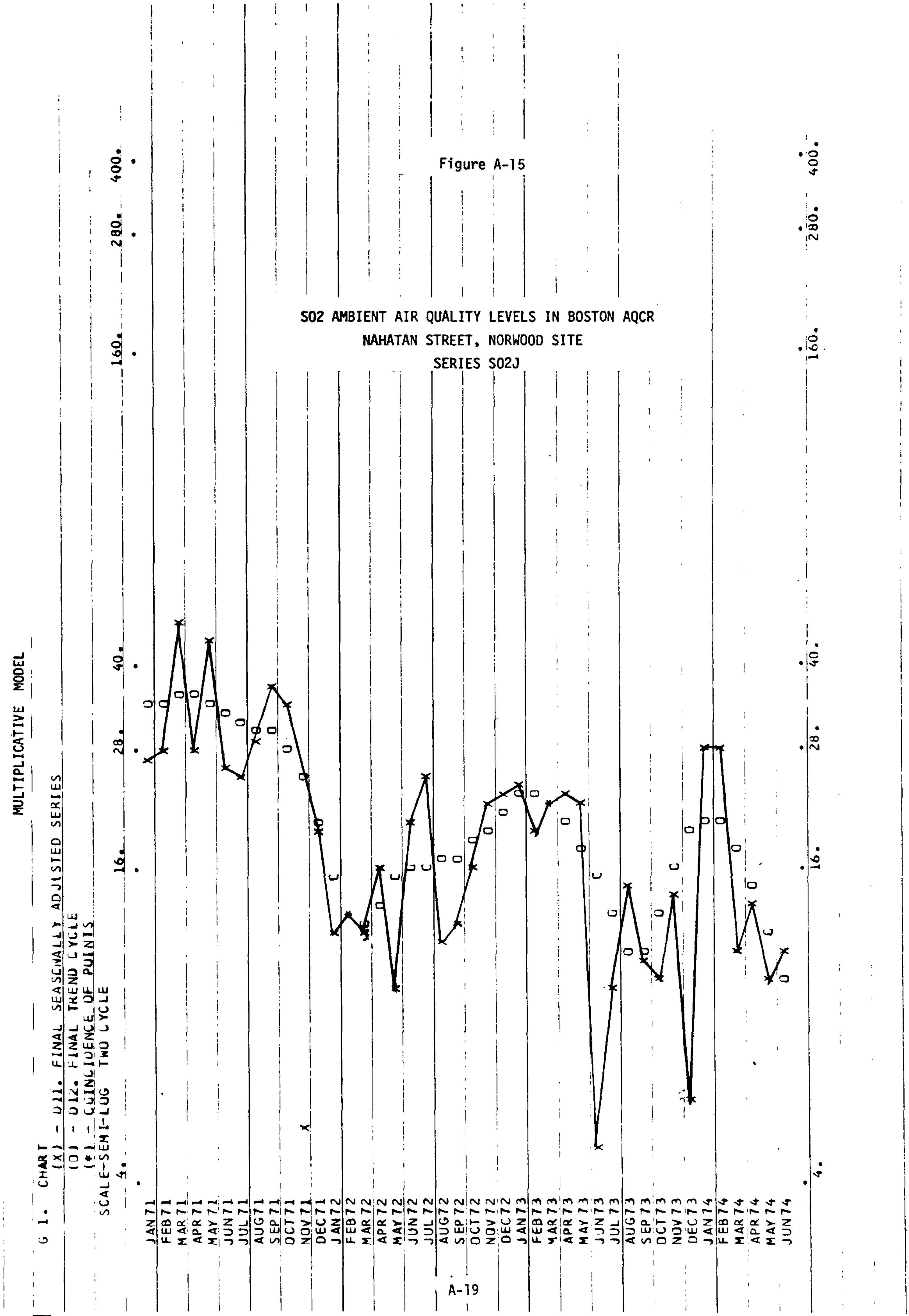


Figure A-15

SO2 AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR

NAHATAN STREET, NORWOOD SITE

SERIES SO2J

Figure A-16

SO2 AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
BEAVER STREET, WALTHAM SITE
SERIES SO2L

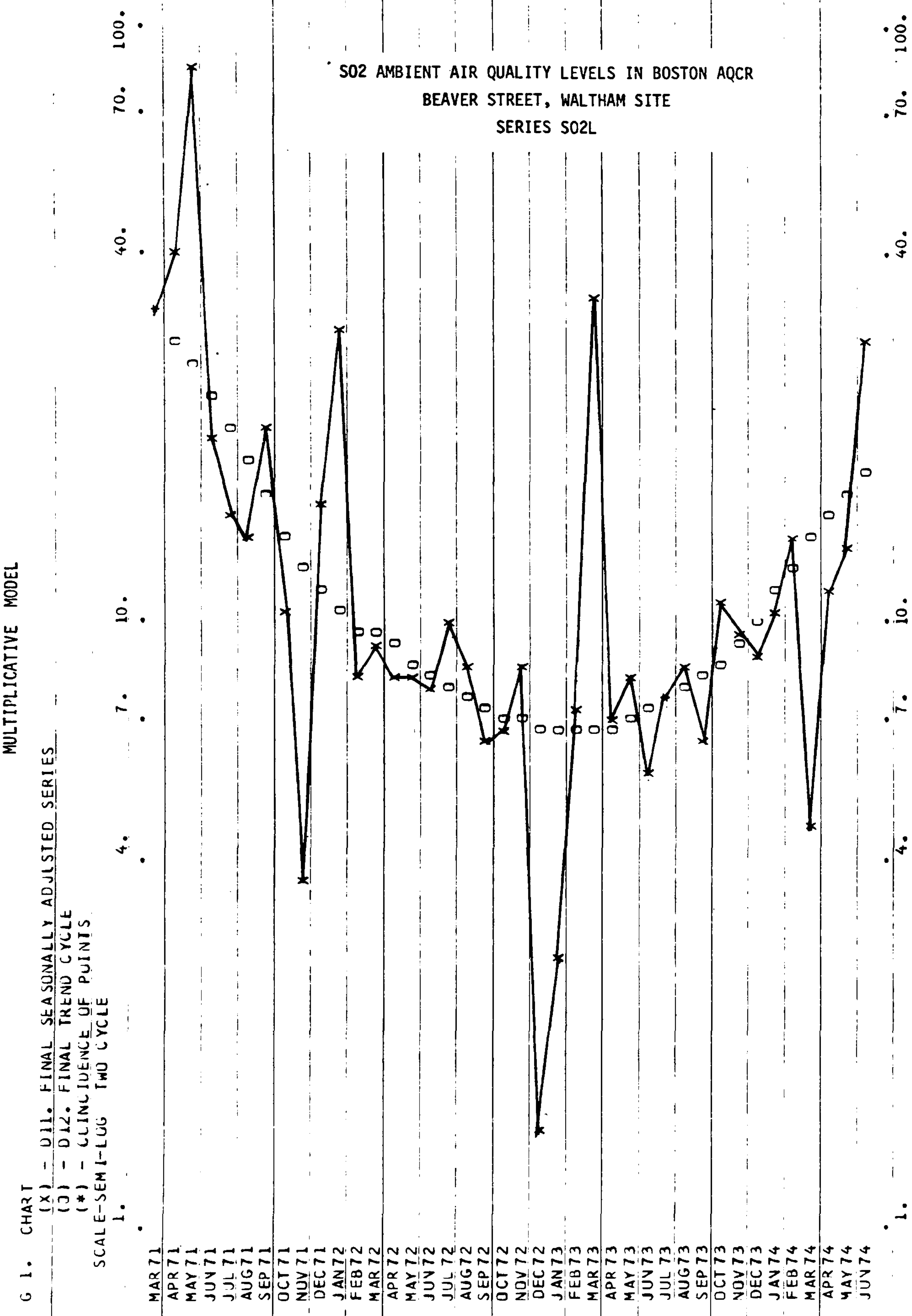


Figure A-17

TSP AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
KENMORE SQUARE, BOSTON SITE
SERIES TSP1

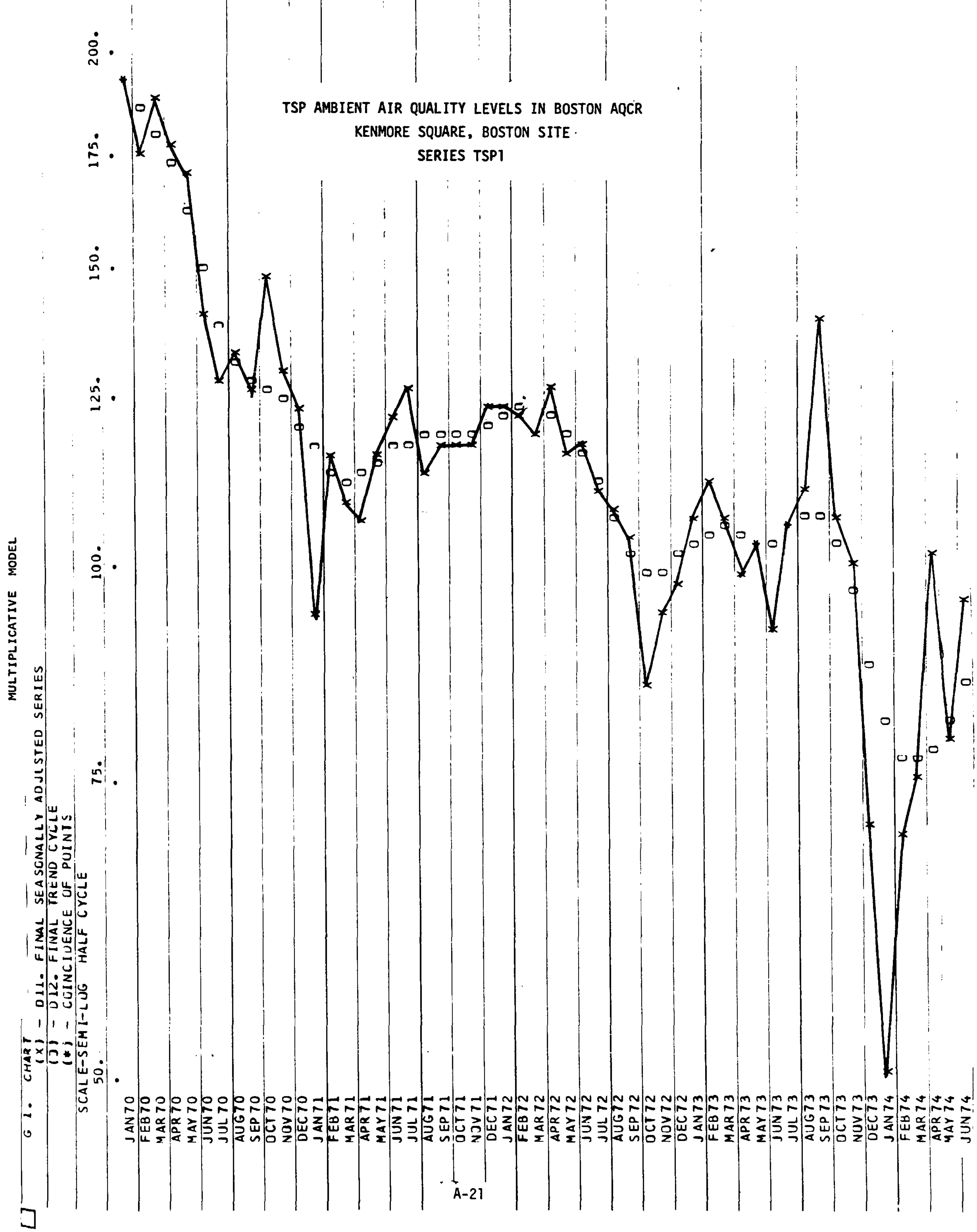


Figure A-18

TSP AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
NAHATAN STREET, NORWOOD SITE
SERIES TSP5

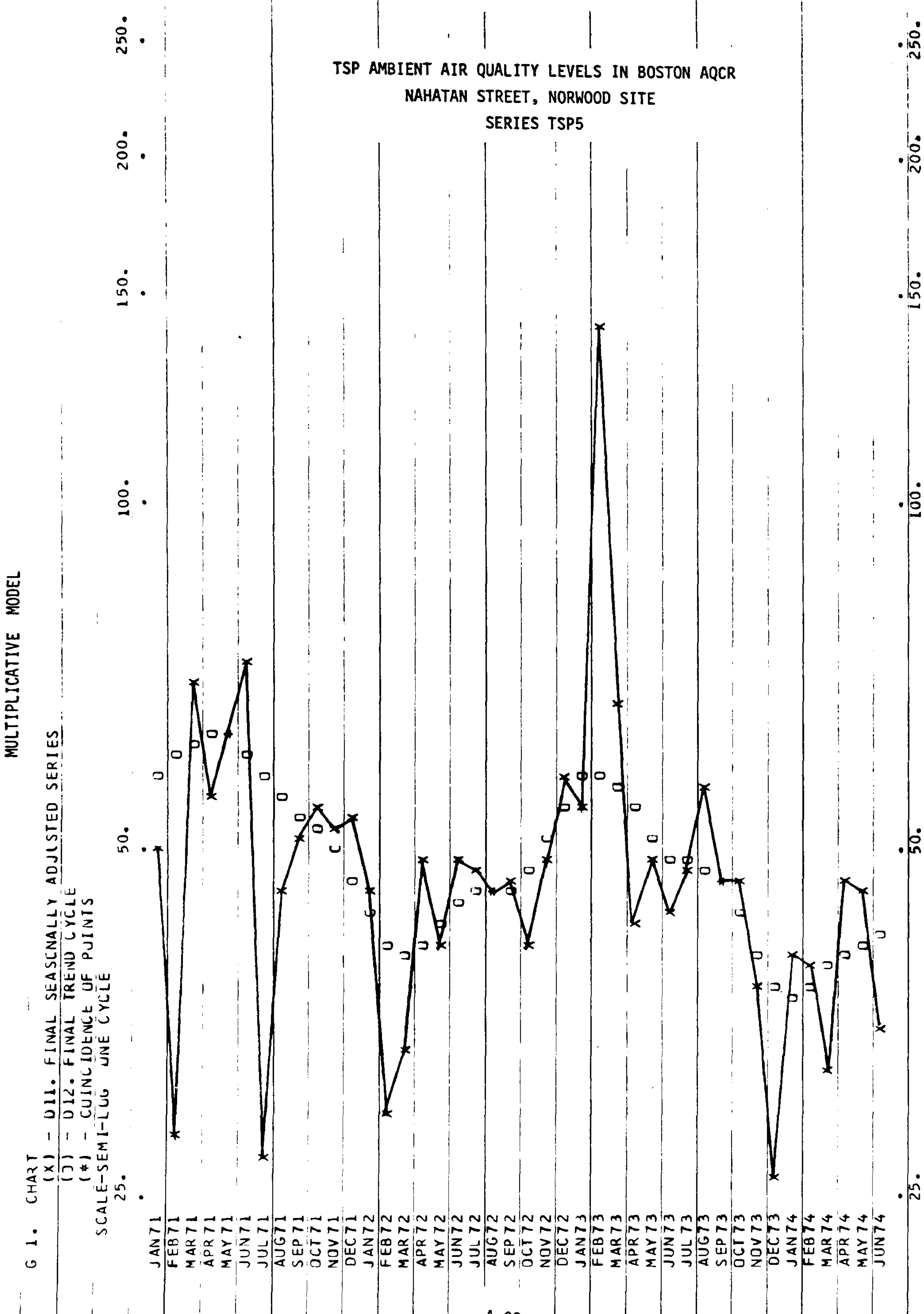


Figure A-19

TSP AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
BEAVER STREET, WALTHAM SITE
SERIES TSP7

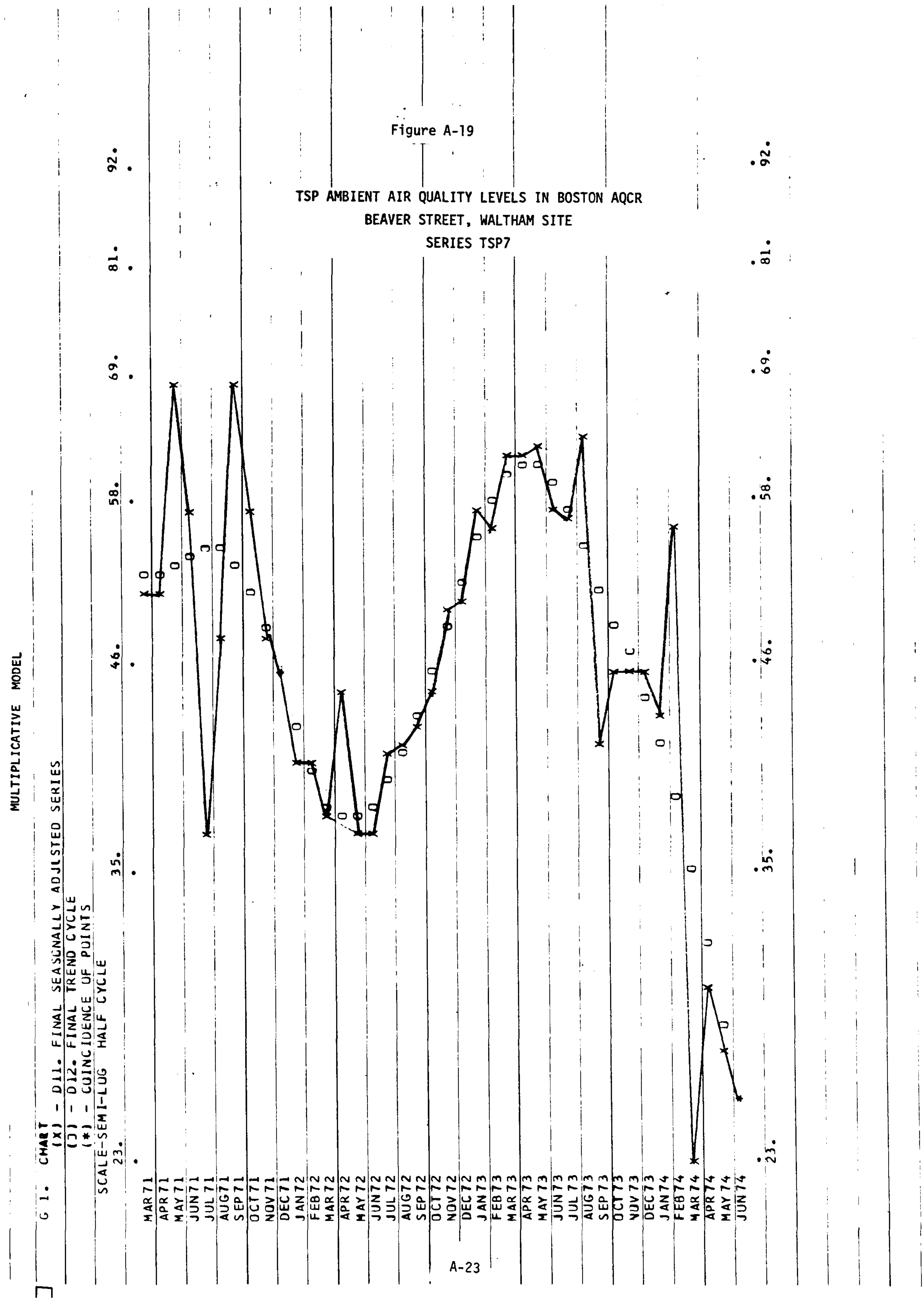


TABLE A-3

INDEX TO SERIES COMPONENT GRAPHS PRODUCED BY THE X-11 RATIO TO MOVING AVERAGE ANALYSIS (MULTIPLICATIVE MODEL) FOR SIX REPRESENTATIVE TIME SERIES

Series Components Graphed	Figure Number
Original Series (O) & Trend-Cycle Component (T)	A-2 - A-7
Seasonal Component (S) & Irregular Component (I)	A-8 - A-13
Seasonally-Adjusted Series (T*I) & Trend-Cycle Component (T)	A-14 - A-19

(3) Results

The first task in evaluating the results of the X-11 analysis was to determine which model produced the smallest irregular component in each case. To measure the magnitude of the irregular component, the final irregular series standard deviation as a percentage of the original series mean value was calculated. The results, shown in Table A-4, reveal an additive model to be most appropriate to the SO_2 data 69% of the time (9 of 13 cases), while the TSP data were modeled best by a multiplicative model 86% of the time (6 of 7 cases). It is interesting to note that the SO_2 data are arithmetic monthly averages of daily measurements, while the TSP data are geometric monthly averages. The difference between the two data reduction procedures is due to the manner in which Federal and Massachusetts Ambient Air Quality Standards have been specified. Although one model performs slightly better than the other in each instance, the trend-cycle and seasonal component results are comparable in each case. Therefore, in analyses to follow, the additive and multiplicative forms were used interchangeably. In some instances, it will be seen that only the multiplicative model is used. Since the seasonal and irregular components are temporal functions with a mean value of 1.0, the magnitude of the multiplicative trend-cycle component is directly comparable to that of the original time series.

Next, the X-11 program results were evaluated to determine whether any of the data were not amenable to statistical trend analysis. In this regard, the X-11 program applied an analysis-of-variance F-test for stable seasonality to determine whether a true seasonal component was present in the data series. The results of this test distributed by model configuration are shown in Table A-5. One cause of lack of stable seasonality in measured data can be that monthly averages are based on too few measurements. For the analyzed data, the individual data points that were used in the computation of the monthly averages were scanned to ascertain if any time series should be eliminated from further analysis due to an inadequate amount of measurements or due to dominance by the irregular component. The results indicate that none of the data series are based on too few measurements or dominated by an irregular component to the extent that they are totally unreliable. However, it should be noted that, at most monitoring sites, only a small number of daily measurements were available for use in computing the monthly average. Except

TABLE A-4

FINAL IRREGULAR SERIES COMPONENT STANDARD DEVIATION AS A PERCENTAGE OF THE ORIGINAL SERIES MEAN VALUE

Series Name	Model Multiplicative M	Model Additive A	Recommended Model
SO2A	64.0	43.9	A
B	30.8	23.1	A
C	40.8	40.2	A
D	43.5	50.3	M
E	50.1	70.4	M
F	83.0	51.9	A
G	141.2	53.0	A
H	62.8	43.9	A
I	69.4	49.2	A
J	30.2	41.9	M
K	62.5	44.9	A
L	84.8	73.3	A
M	51.6	87.7	M
TSP1	10.1	9.9	A
2	42.3	70.5	M
3	21.6	29.3	M
4	15.1	15.3	M
5	27.9	46.4	M
6	15.0	16.4	M
7	13.6	14.1	M

TABLE A-5

TIME SERIES FOR WHICH STABLE SEASONALITY WAS PRESENT
AT THE 1% SIGNIFICANCE LEVEL
USING THE INDICATED MODEL CONFIGURATION

Series Name	Model: Multiplicative M	Model: Additive A
SO2A	✓	✓
B	✓	✓
C	✓	✓
D	✓	
E	✓	
F		
G		
H		
I	✓	✓
J	✓	✓
K	✓	✓
L		
M		
TSP1	✓	✓
2		
3	✓	✓
4	✓	✓
5		
6	✓	✓
7	✓	✓

Walden

at the Kenmore Square site, the number of daily measurements per month ranged from 3 to 8 in 1970 - 1974. By contrast, an average of 19 measurements formed the basis for Kenmore Square monthly concentrations. Because of this larger data base, the time series data from Kenmore Square contains a smaller irregular component than that from other sites (see Table A-4).

Evaluation of the long-term trend in a sequence of air quality parameters, such as annual average concentrations is important in order to assess the effects of relevant causal factors. Tables A-6 and A-7 show, respectively, the annual averages of ambient SO_2 and TSP concentrations measured at the monitoring stations in the AQCR from which data was available. The averages are also given for the series trend-cycle components derived using a multiplicative model of the X-11 ratio to moving average technique. Figures 2-4 and 2-5 show composite annual average SO_2 and TSP trend-cycle components from the multiplicative model in the AQCR; data from sites in the innermost core area of Boston are graphed separately. Trend-cycle components for the data series revealed that, in general, regional SO_2 levels fell consistently during the entire time period of analysis, with the steepest decline occurring prior to 1972 (see Figure 2-4). Ambient TSP levels also exhibited a general downward trend similar to that of SO_2 levels, but not as pronounced or consistent (see Figure 2-5).

The hypothesis that long-term changes in ambient SO_2 and TSP levels are caused principally by changes in annual meteorological conditions, and not by fuel use regulations or other factors, implies a strong positive correlation should be found between annual average concentrations and total heating season degree-days. The annual degree-day totals as measured at Boston's Logan International Airport are shown below:

Year	Total Degree-Days
1970	5,852
1971	5,738
1972	5,912
1973	5,139

TABLE A-6

ANNUAL AVERAGE SO_2 CONCENTRATIONS MEASURED IN THE METROPOLITAN BOSTON AQCR ($\mu g/m^3$)

Data Series	Original Series					Trend-Cycle Component**				
	1970	1971	1972	1973	1974*	1970	1971	1972	1973	1974*
$SO_2A^†$	86	50	24	29	23	108	53	17	29	22
$SO_2B^†$	167	89	68	32	26	170	82	71	29	23
$SO_2C^†$	95	51	34	26	16	101	51	32	27	13
$SO_2D^†$	90	61	34	14	12	82	54	36	14	9
SO_2E	--	47	23	23	15	--	45	25	19	15
SO_2F	--	22	16	13	13	--	20	15	11	15
SO_2G	--	11	8	7	5	--	14	6	7	5
SO_2H	--	42	21	18	22	--	40	23	20	18
SO_2I	--	19	10	10	12	--	23	9	9	9
SO_2J	--	27	17	15	22	--	32	17	17	16
SO_2K	--	36	36	26	23	--	38	28	30	18
SO_2L	--	19	11	10	17	--	22	9	8	15
SO_2M	--	23	13	12	18	--	30	12	12	16

* Does not contain data beyond June 1974.

** From a multiplicative ratio to moving average model.

† Urban core site.

TABLE A-7

ANNUAL AVERAGE TSP CONCENTRATIONS MEASURED IN THE METROPOLITAN BOSTON AQCR (μg/m³)

Data Series	Original Series					Trend-Cycle Component**				
	1970	1971	1972	1973	1974*	1970	1971	1972	1973	1974*
TSP1 †	158	114	113	104	89	151	117	112	102	80
TSP2	--	87	47	46	36	--	90	46	46	36
TSP3	--	33	24	36	22	--	33	25	31	21
TSP4	--	49	39	38	31	--	48	39	37	28
TSP5	--	50	44	61	43	--	57	46	49	40
TSP6	--	66	54	49	48	--	66	55	50	46
TSP7	--	56	41	55	32	--	52	42	55	33

* Does not contain data beyond June 1974.

** From a multiplicative ratio to moving average model.

† Urban core site.

Practically no correlation exists between annual SO_2 and TSP levels and degree-day totals. A prediction based solely on degree-day data would forecast the peak annual concentrations of SO_2 and TSP to occur in 1972, a fact which is not borne out by the measured data. Consequently, the observed long-term changes in ambient SO_2 and TSP levels cannot be attributed to corresponding changes in this meteorological parameter.

b. Exponential Smoothing — Confirmation of X-11 Trend Components

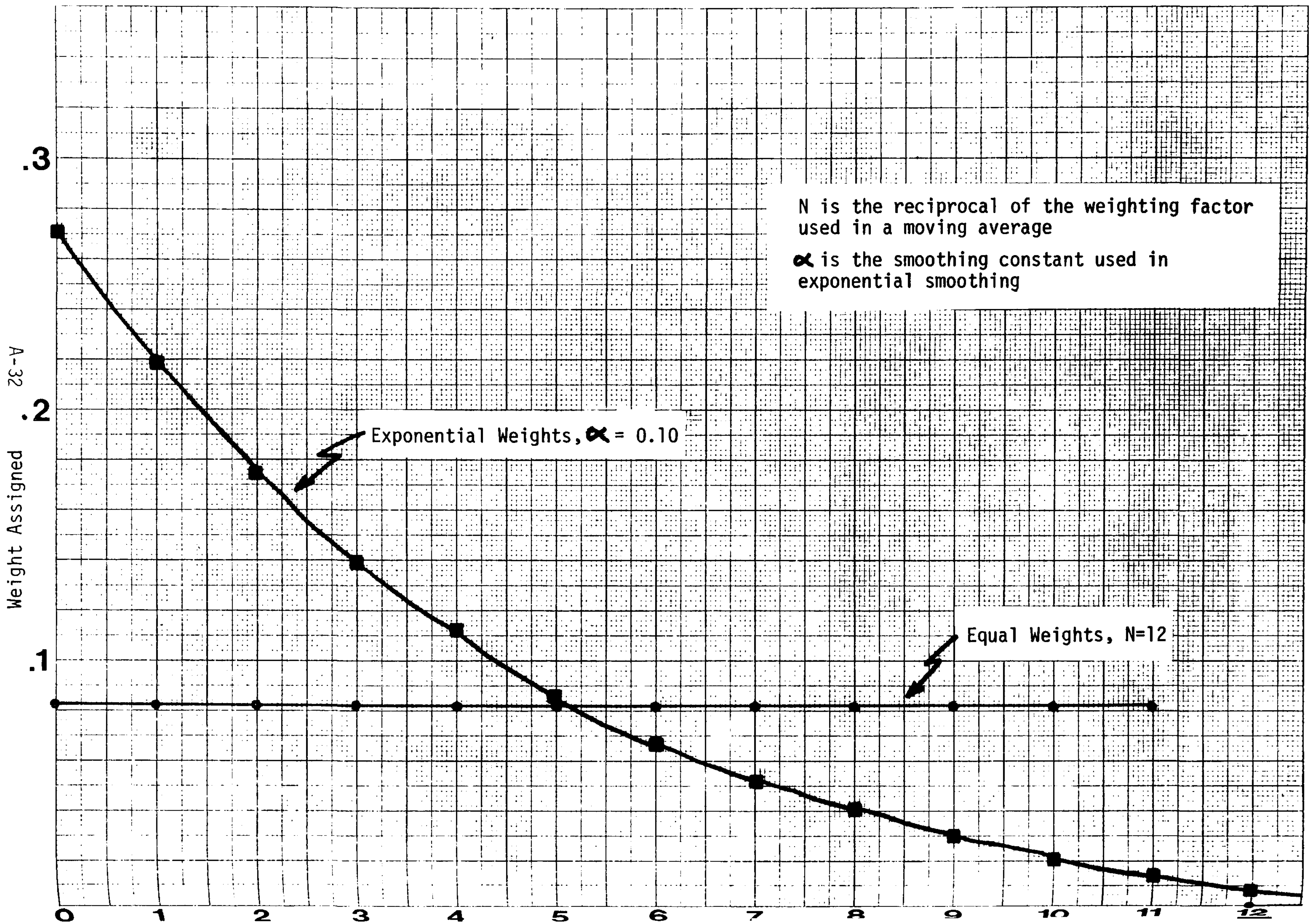
(1) Methodology

The results of the ratio to moving average analysis were exploratory, allowing identification of trends and changes in trends in the measured data. The next step in the data analysis was to confirm the results of the moving average analysis in identifying and quantifying trends. The technique selected to supply this confirmation was triple exponential smoothing [15]. The smoothing technique was applied to the seasonally adjusted series. Alternatively, the original series could have been used, but then a separate exponential smoothing step just to remove seasonality would have been necessary.

Exponential smoothing is an analytical technique for estimating trends by weighting all previous observations. By this technique, weighting factors decrease exponentially, being largest for observations in the most recent past. Exponential smoothing produces an average time series in which past observations are geometrically discounted according to age. By contrast, an N-month moving average weights the N most recent observations each 1/N, and all earlier observations have weight zero. These two basic smoothing techniques are compared in Figure A-20 which shows the weights used to obtain a 12-month moving average time series (equal) and a triple exponentially smoothed time series (exponential). Note the two examples shown do not necessarily produce equivalent results. The exponential smoothing weights shown in Figure A-20 were derived using a smoothing constant of 0.10.

FIGURE A-20

Two Ways of Weighting Data in Smoothing Discrete Time Series



Selection of a suitable smoothing constant is an important part of any trend analysis employing exponential smoothing as this parameter controls the response sensitivity of the process. The smoothing constant is defined in the range 0.0 to 1.0. The lower the value of the smoothing constant, the higher the degree of data smoothing obtained. The rate of response (i.e., sensitivity) to a changing trend improves with a higher smoothing constant, but this virtue is mitigated by a decreasing ability to smooth out random fluctuations. These two properties must be balanced against one another in choosing an appropriate smoothing constant. In the current application, the value that was found to produce adequate smoothing of the data and sufficient response sensitivity by visual inspection varied between 0.10 and 0.25, depending on the degree of irregularity of the data. It should be noted that though exponential smoothing is analytically a more sensitive technique than moving averages, a slight lag in the smoothed data is always produced as a result of smoothing out random data fluctuations.

Triple exponential smoothing makes the assumption that the process represented by the discrete time series (X), in this case ambient SO_2 and TSP levels, can be modeled in time (t) using a quadratic function:

$$X(t) = a + bt + ct^2$$

The values of the model coefficients a, b, and c change stepwise throughout the smoothing analysis and thus provide a predictive model based on the most complete information at any given time step in the analysis. This predictive ability was used in the statistical inference analysis to permit testing of statistically significant changes in trends (i.e., corresponding to changes in fuel regulations or implementation of variances). Since exponential smoothing is a continuous process, it requires specification of a set of initial model coefficients. There are several established formulas for estimating initial values of a, b and c. None of these starting techniques produced acceptable results in that the smoothed series did not begin to follow the general directions of the raw data until 10 or 20 time steps (months) into the analysis. The cause of these failures was the large initial drop in pollutant levels in many of the series. Therefore, a unique technique was devised whereby each time series was smoothed in reverse initially, using one of the established starting techniques to determine a set of final model coefficients. These coefficients were then used to forecast the series forward using negative values of the time parameter, t. Alternatively, if the sign of b is reversed, the coefficients provide acceptable initial values for the exponential smoothing analysis.

The X-11 program used in the time series component decomposition process produced three potential candidate series for the exponential smoothing: the final seasonally adjusted series, the months for cyclical dominance series, and the final trend series. Each of these series are discussed in more detail in Section VI.A.1.a.(1). The final seasonally adjusted series was judged the best series to use in confirming the ratio to moving average trend analysis results through exponential smoothing. The seasonally adjusted series is the original series with only the seasonal component removed, whereas the other two series have had portions of the irregular component removed as well. Since the seasonally adjusted series contains the full irregular component, it provided the best basis for a comparison of the trend lines produced by the exponential smoothing and ratio to moving average analyses. As previously mentioned, the original series could have been used, but then a separate exponential smoothing step just to remove seasonality would have been necessary.

The exact form of the quadratic exponential smoothing function depended on whether the seasonally adjusted series to be smoothed was derived in the X-11 program using an additive (T + I) or multiplicative (T * I) model. In the current application, the following functional forms were assumed:

$$X = (T + I) = a + bt + ct^2 + E \qquad \text{(Additive)}$$

$$X = (T * I) = E * \exp\ (a + bt + ct^2) \qquad \text{(Multiplicative)}$$

where E is the error term.

(2) Results

Graphs of the triple exponentially smoothed seasonally adjusted series and the final trend series for each of the six representative time series (see Table A-2) are shown in Figures A-21 through A-26 (additive model) and in Figures A-27 through A-32 (multiplicative model). Although the results of the exponential smoothing analysis are shown for only the six representative time series, this confirmatory analysis was undertaken on all twenty original series (see Table A-1). On the basis of visual inspection, the exponential smoothing and X-11 ratio to moving average analyses produced comparable trend lines in all cases. These results justified use of exponential smoothing techniques to test for statistically significant changes in air quality trends. This analysis was undertaken and is described in Section VI.A.2.a.

Since exponential smoothing is a more sensitive analytical technique than the moving averages procedure, it is expected that in cases where the irregular component dominated the analysis, the exponentially smoothed series would exaggerate trend component minima and maxima. Table A-8 gives a listing of the relative irregular component magnitudes for the series shown in Figures A-21 through A-32. Such distortions did occur in the data in Figures A-22, A-23, and A-25 for the additive model, corresponding to the series for which the irregular component standard deviation as a percentage of the original series mean value exceeded 40%. In Figures A-27 and A-32, such distortions are not readily comparable, due to the non-linearities of the semi-logarithmic scale of the graphs. As stated in Section VI.A.1.a.(3), the monthly averages were sometimes based on just a few observations. In these instances, the original series possess large fluctuations, and it is hard to detect trends in the data. The distortions observed in Figures A-22, A-23, and A-25 are probably due to this sample size problem.

c. Seasonal Patterns in Ambient Particulate Levels

In exploring the observed trends in the data, comparisons were made with the TSP data and results of an earlier study [13] of nationwide TSP levels. That study analyzed ten years of data (1957-1966) from the National Air Surveillance Network (NASN), also using a ratio to

Figure A-21

SO2 AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR

KENMORE SQUARE, BOSTON SITE

SERIES SO2B

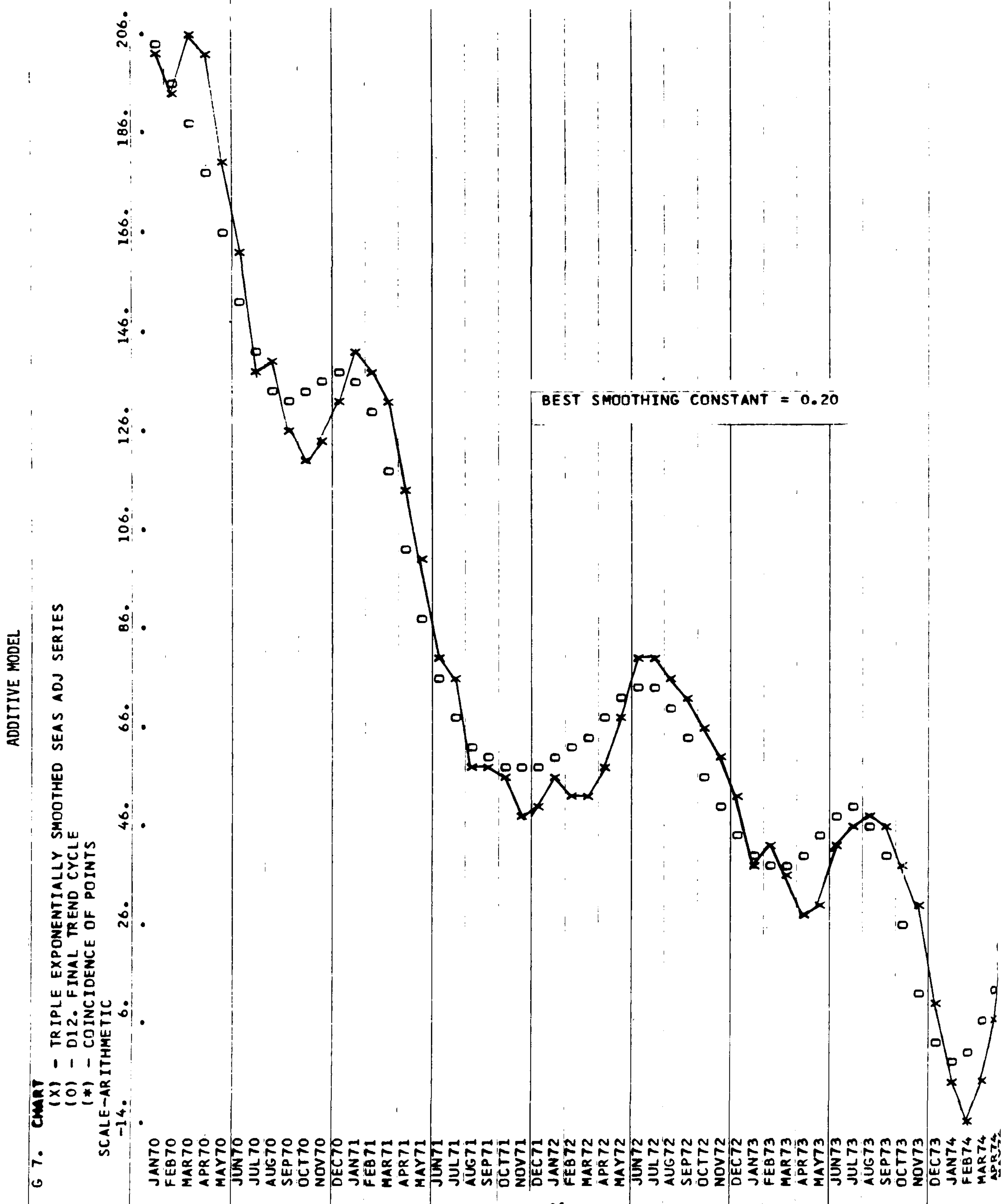


Figure A-22

SO2 AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
NAHATAN STREET, NORWOOD SITE
SERIES SO2J

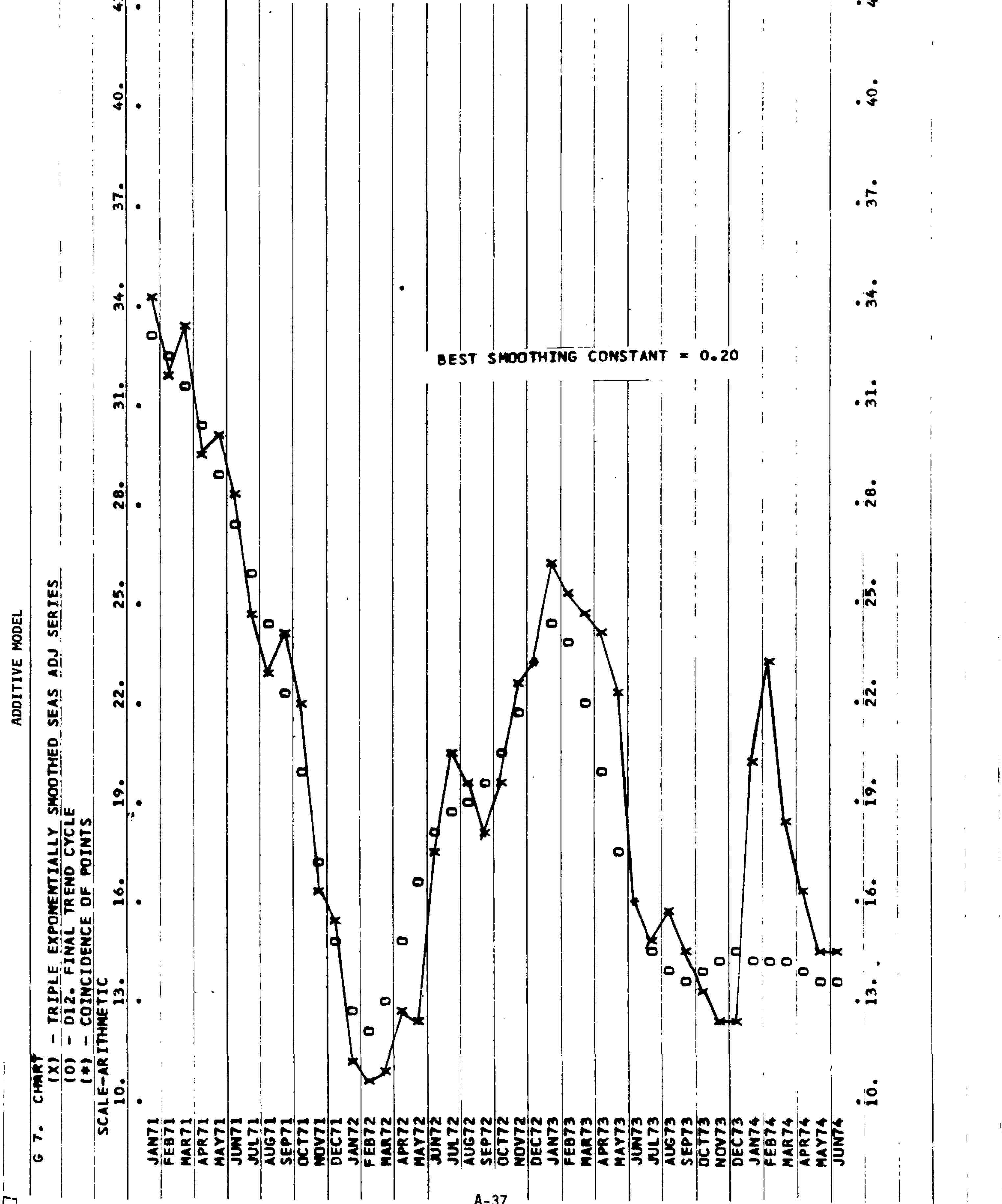


Figure A-23

SO2 AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
BEAVER STREET, WALTHAM SITE
SERIES SO2L

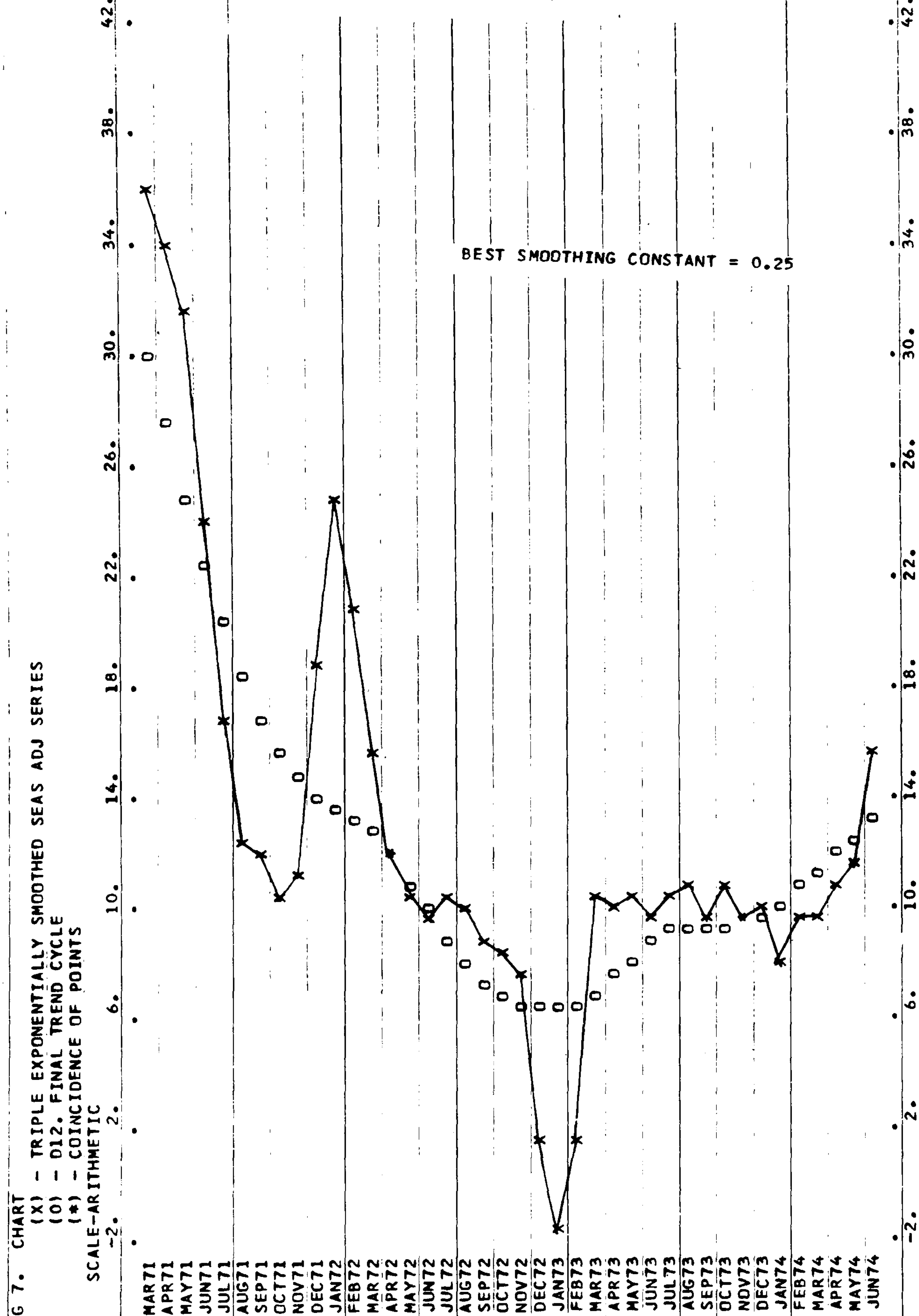


Figure A-24

TSP AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
KENMORE SQUARE, BOSTON SITE
SERIES TSP1

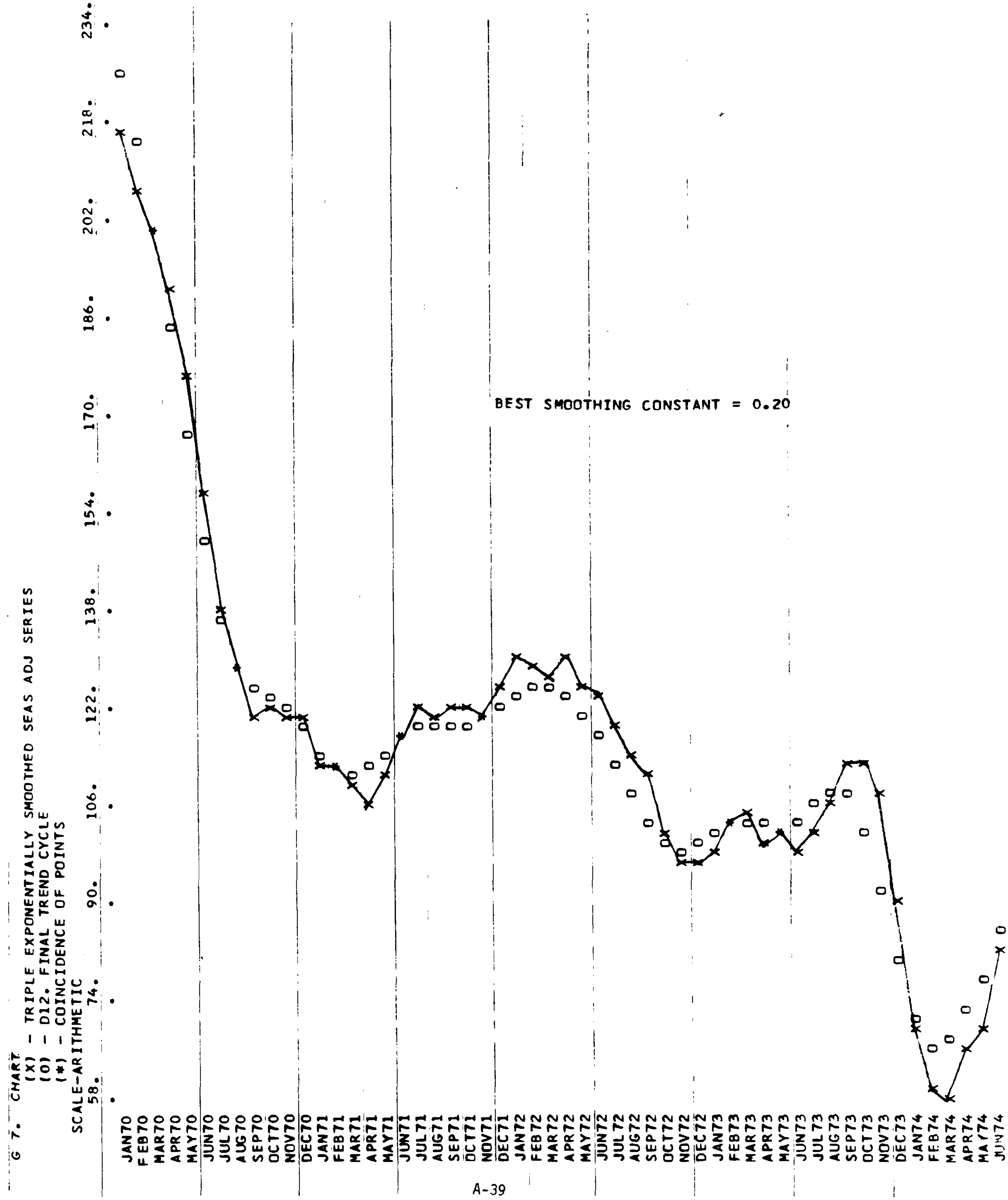


Figure A-25

TSP AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR

NAHATAN STREET, NORWOOD SITE

SERIES TSP5

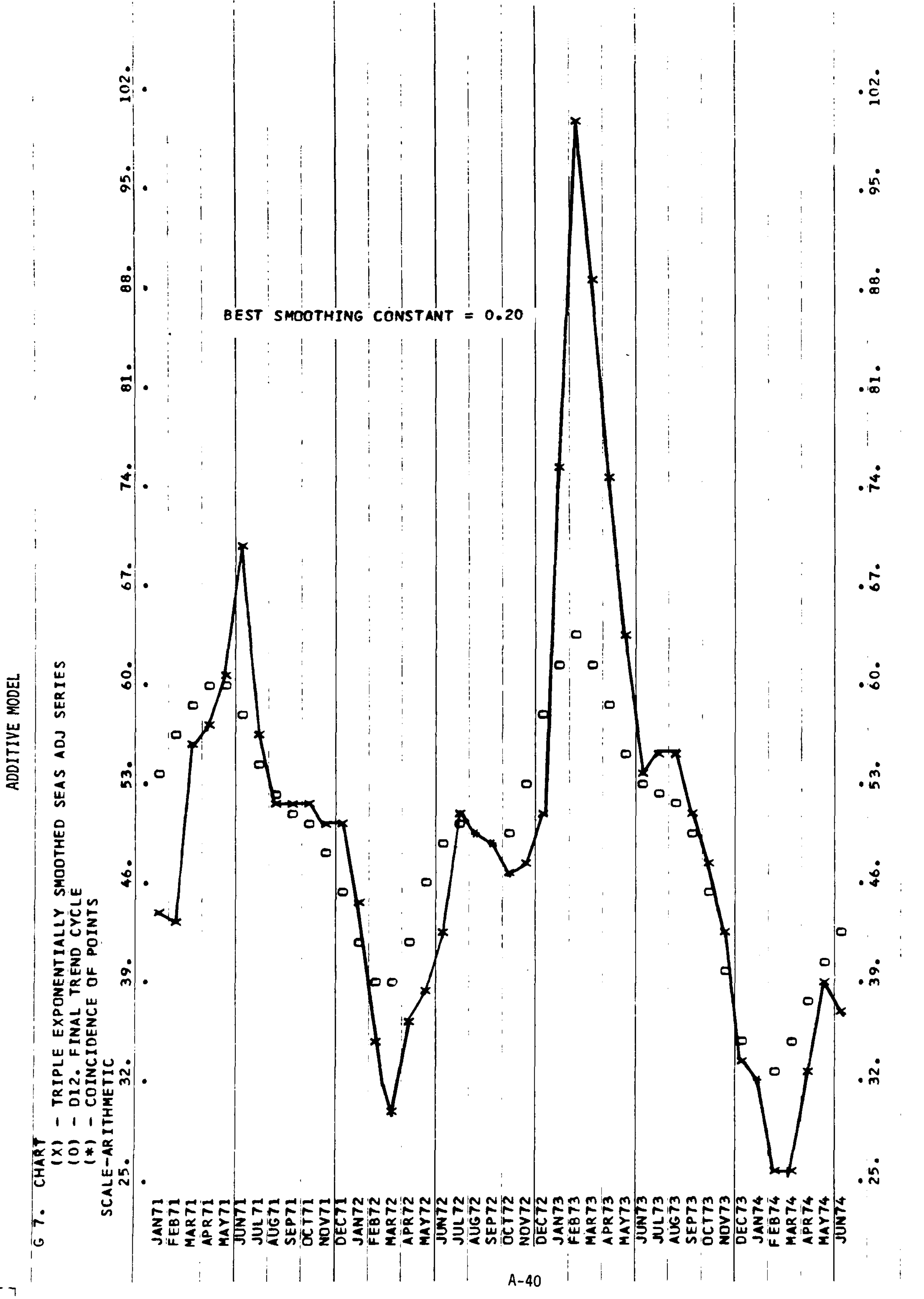


Figure A-26

TSP AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR

BEAVER STREET, WALTHAM SITE

SERIES TSP7

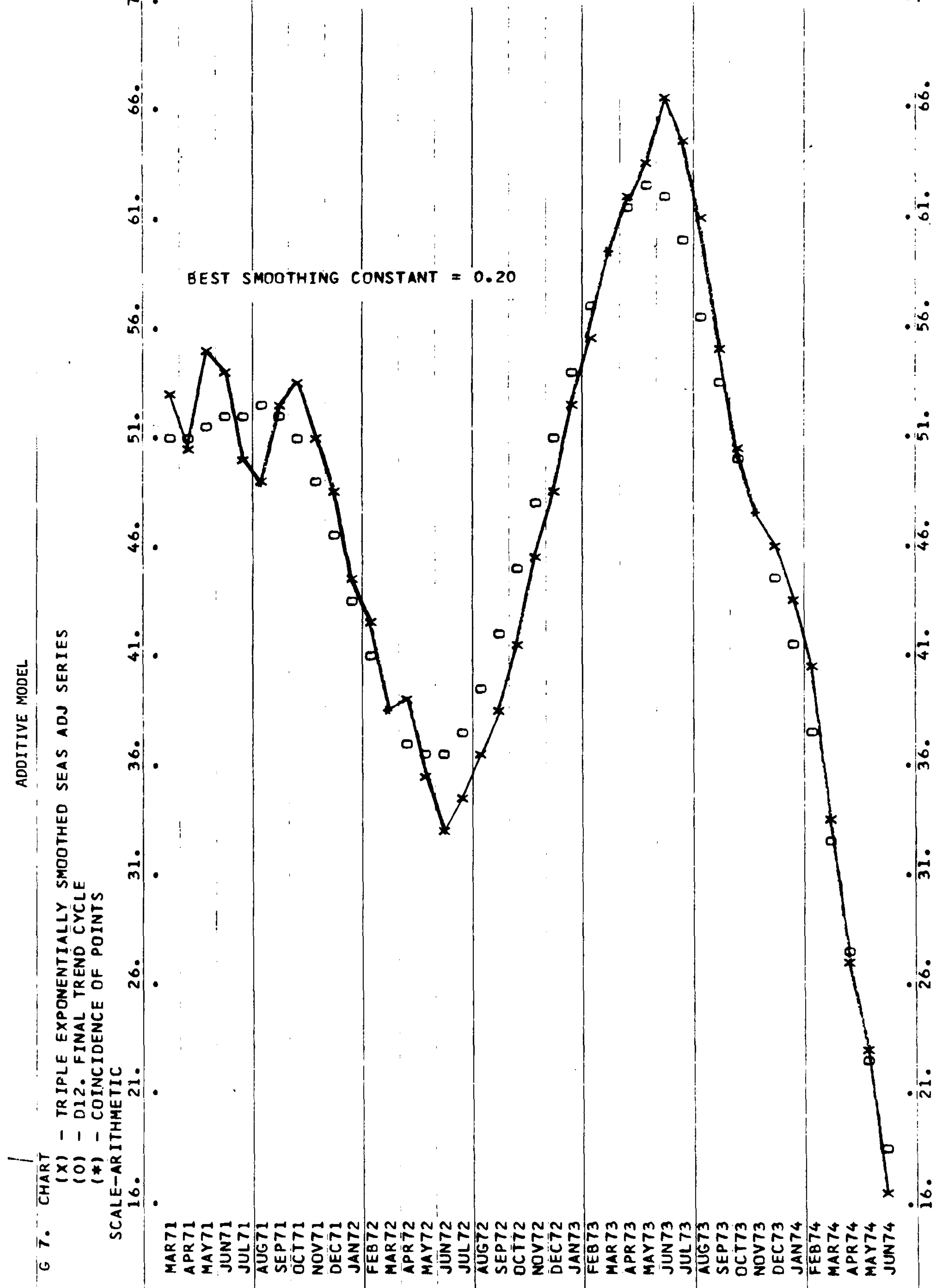


Figure A-27

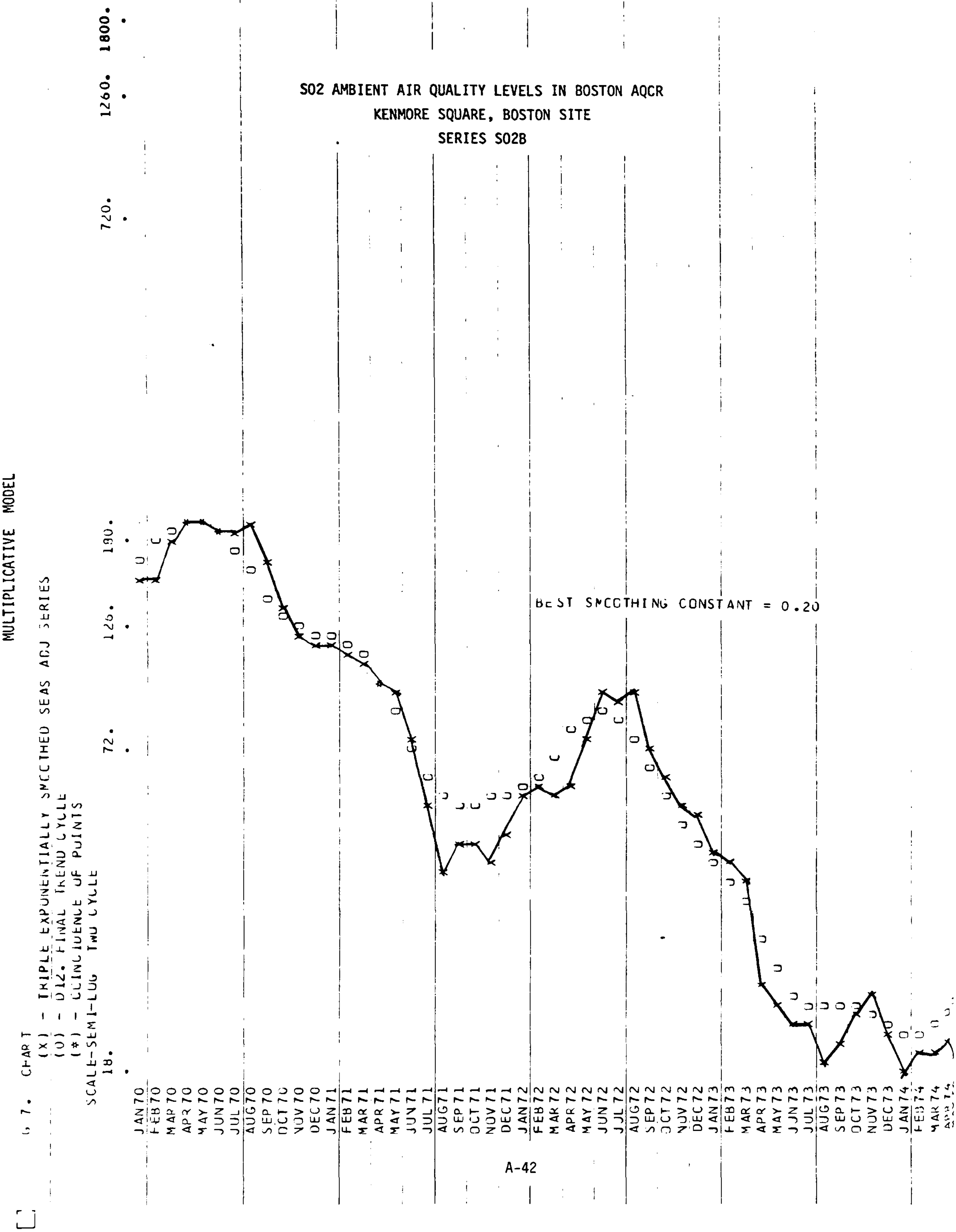
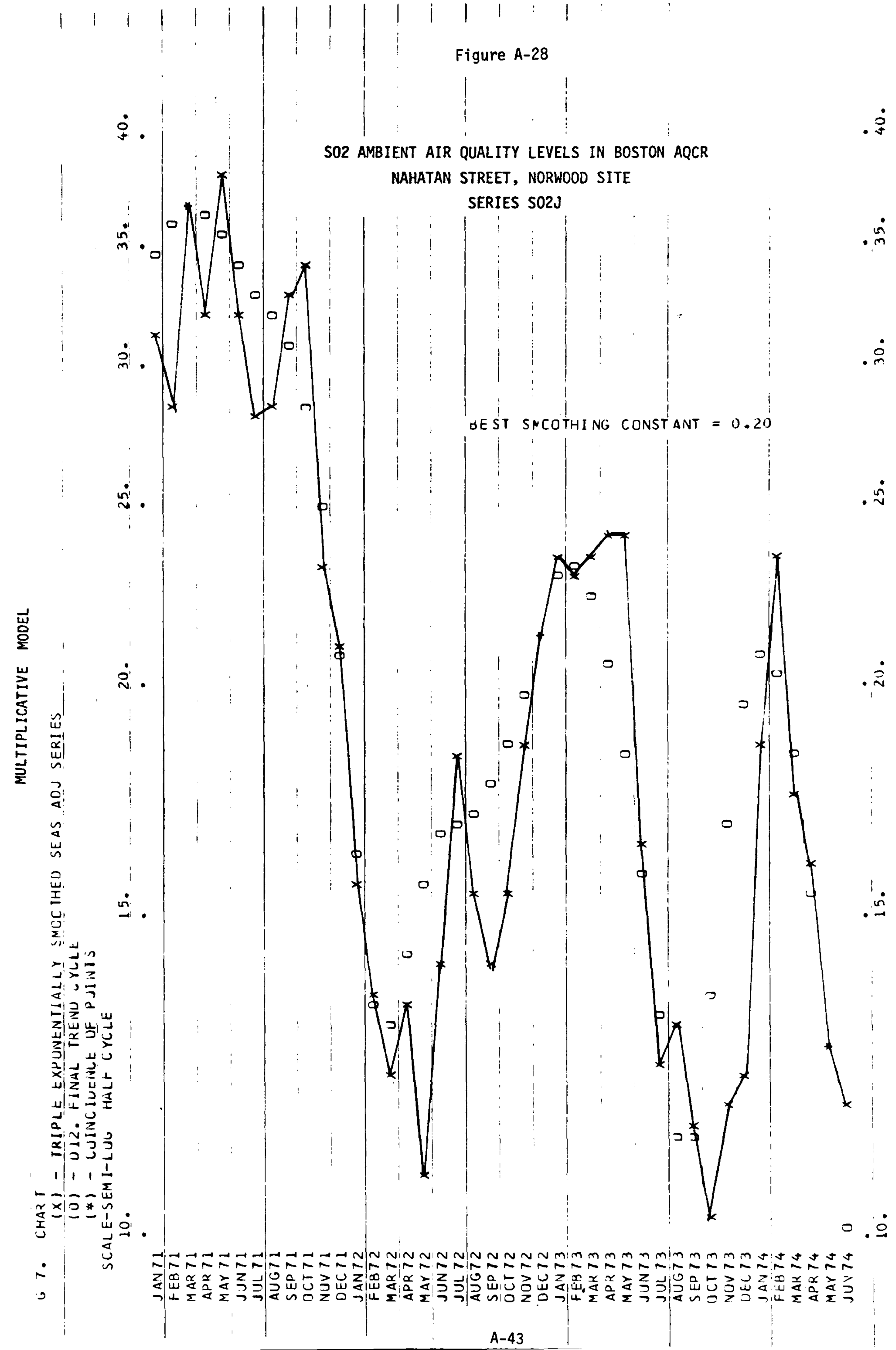

SO2 AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
KENMORE SQUARE, BOSTON SITE
SERIES SO2B
MULTIPLICATIVE MODEL
CHART
(X) - TRIPLE EXPONENTIALLY SMOOTHED SEAS ADJ SERIES
(O) - D12. FINAL TREND CYCLE
(*) - COINCIDENCE OF POINTS
SCALE-SEMI-LOG TWO CYCLE
18.
72.
126.
180.
720.
1260.
1800.
BEST SMOOTHING CONSTANT = 0.20
JAN70
FEB70
MAR70
APR70
MAY70
JUN70
JUL70
AUG70
SEP70
OCT70
NOV70
DEC70
JAN71
FEB71
MAR71
APR71
MAY71
JUN71
JUL71
AUG71
SEP71
OCT71
NOV71
DEC71
JAN72
FEB72
MAR72
APR72
MAY72
JUN72
JUL72
AUG72
SEP72
OCT72
NOV72
DEC72
JAN73
FEB73
MAR73
APR73
MAY73
JUN73
JUL73
AUG73
SEP73
OCT73
NOV73
DEC73
JAN74
FEB74
MAR74

Figure A-28



SO2 AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
NAHATAN STREET, NORWOOD SITE
SERIES SO2J
BEST SMOOTHING CONSTANT = 0.20
MULTIPLICATIVE MODEL
CHART 7.
(X) - TRIPLE EXPONENTIALLY SMOOTHED SEAS ADJ SERIES
(0) - D12. FINAL TREND CYCLE
(*) - COINCIDENCE OF POINTS
SCALE-SEMI-LOG HALF CYCLE
10.
15.
20.
25.
30.
35.
40.
JAN71
FEB71
MAR71
APR71
MAY71
JUN71
JUL71
AUG71
SEP71
OCT71
NOV71
DEC71
JAN72
FEB72
MAR72
APR72
MAY72
JUN72
JUL72
AUG72
SEP72
OCT72
NOV72
DEC72
JAN73
FEB73
MAR73
APR73
MAY73
JUN73
JUL73
AUG73
SEP73
OCT73
NOV73
DEC73
JAN74
FEB74
MAR74
APR74
MAY74
JUN74

Figure A-29

SO2 AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
BEAVER STREET, WALTHAM SITE
SERIES SO2L

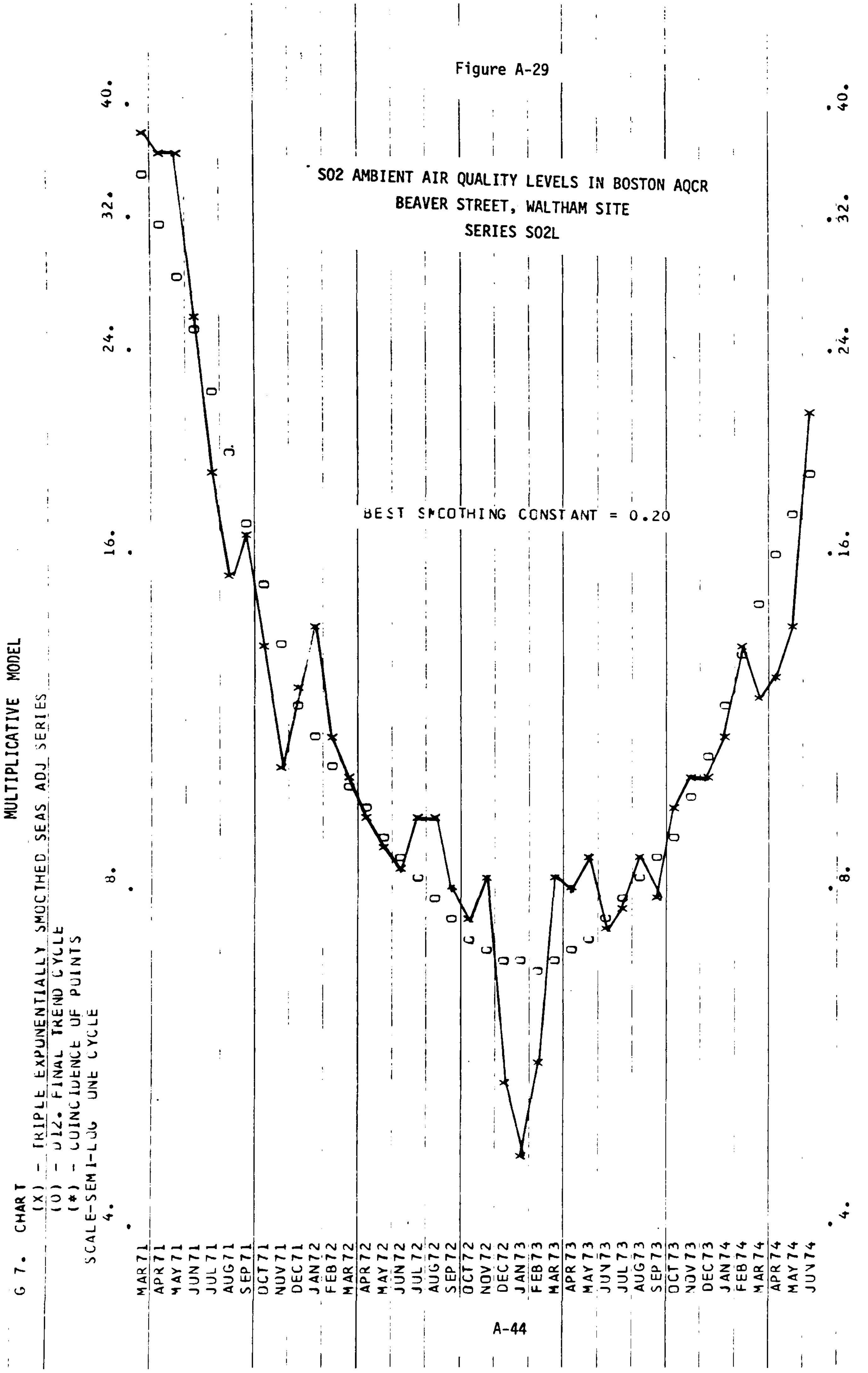


Figure A-30

TSP AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR

KENMORE SQUARE, BOSTON SITE

SERIES TSP1

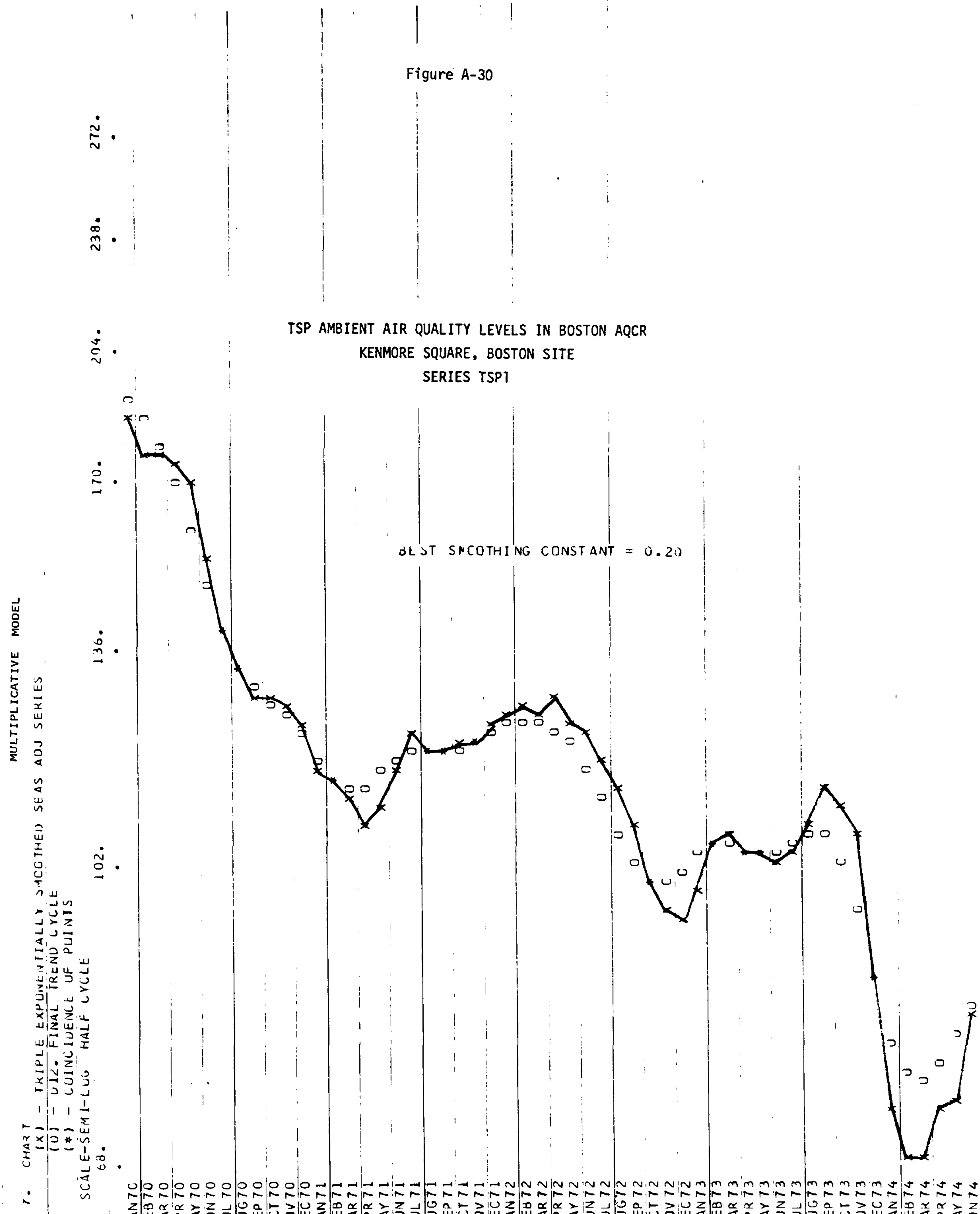


Figure A-31

TSP AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
NAHATAN STREET, NORWOOD SITE
SERIES TSP5

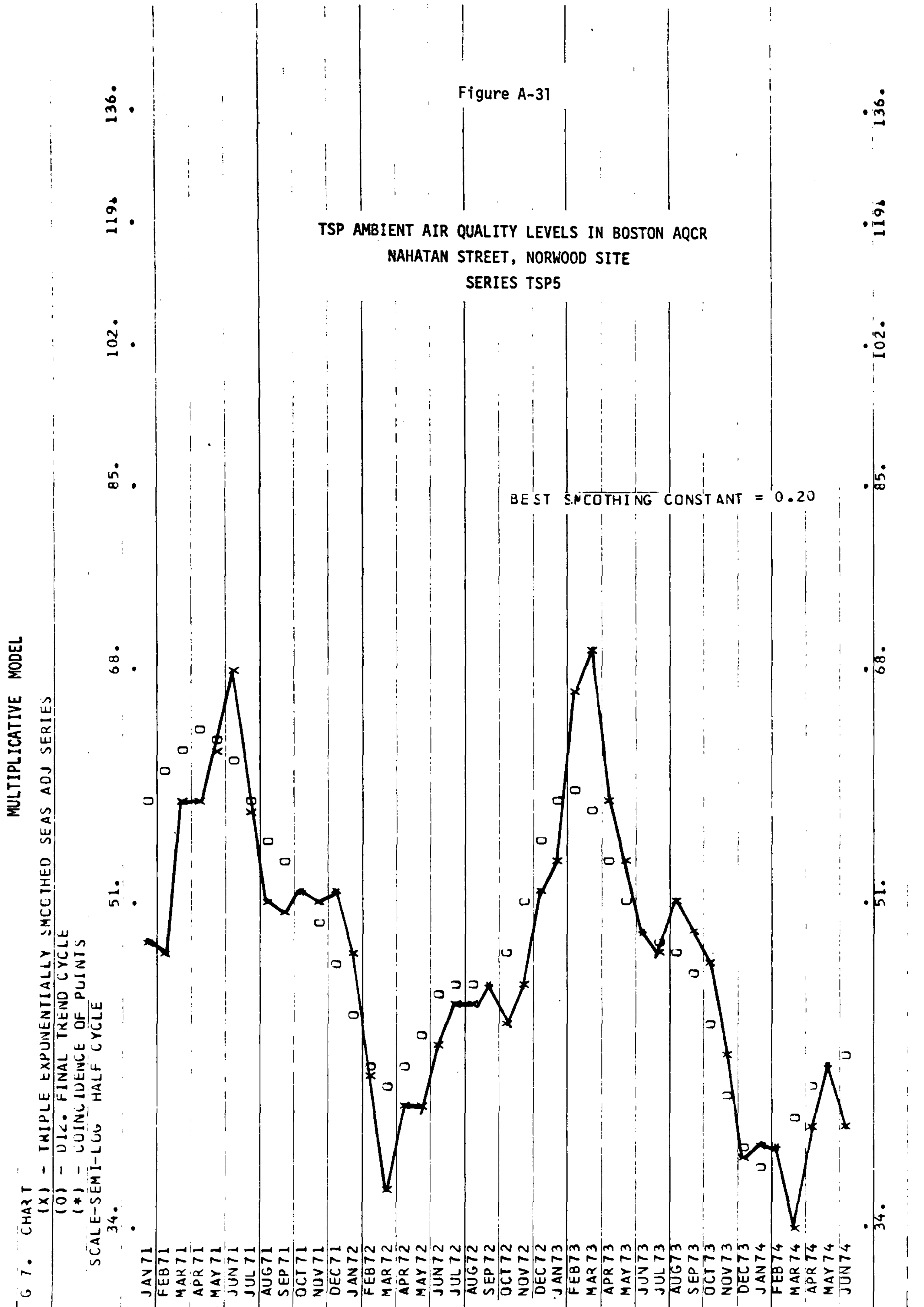


Figure A-32

TSP AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR

BEAVER STREET, WALTHAM SITE

SERIES TSP7

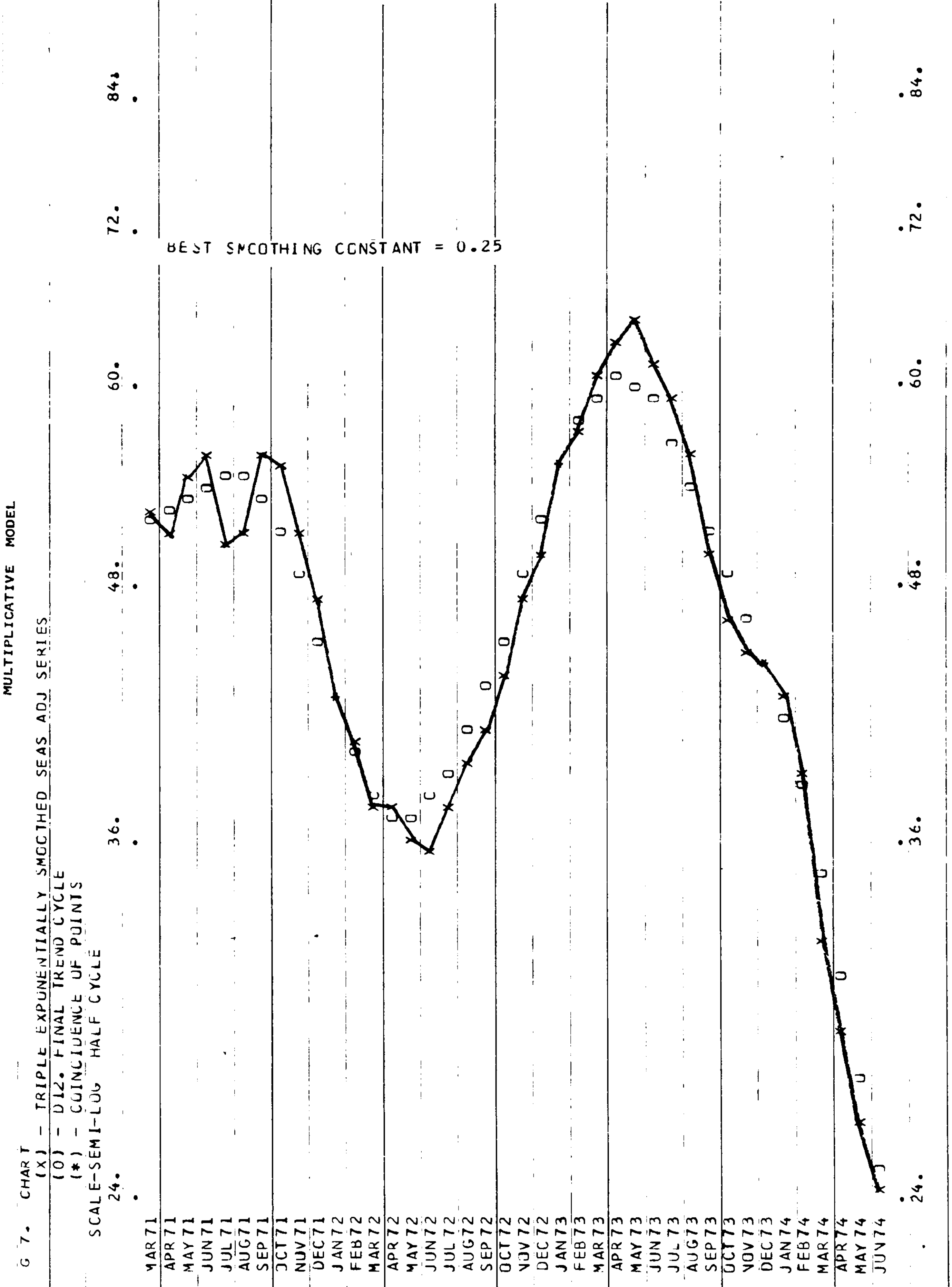


TABLE A-8

FINAL IRREGULAR SERIES COMPONENT STANDARD DEVIATION AS A PERCENTAGE OF THE ORIGINAL SERIES MEAN VALUE

Series Name	Irregular Component (Percentage)	Figure Number of Triple Exponentially Smoothed Series
Additive Model		
SO2B	23.1	A-21
SO2J	41.9	A-22
SO2L	73.3	A-23
TSP1	9.9	A-24
TSP5	46.4	A-25
TSP7	14.1	A-26
Multiplicative Model		
SO2B	30.8	A-27
SO2J	30.2	A-28
SO2L	84.8	A-29
TSP1	10.1	A-30
TSP5	27.9	A-31
TSP7	13.6	A-32

moving average technique. The NASN data revealed that ambient TSP concentrations at urban sites demonstrated seasonal patterns generally characterized by high winter values and relatively lower summer values. By contrast, seasonal patterns of non-urban sites were typified by high summer peaks and low winter values.

The first column of Table A-9 gives a preliminary breakdown by SAROAD* site description of data used in the current study. These categories are based on two descriptors [16]. The first descriptor defines a sampling site as being either in a Center City, Suburban or Rural area. For the second site descriptor it was necessary to estimate the dominating influence within a 1-mile radius of the sampling site. For Center City of Suburban, the following categories were possible:

(1) Industrial: implies product-oriented establishments such as manufacturing concerns, utilities, mining, and graineries.

(2) Commercial: implies service-oriented establishments. A unique traffic pattern into and out of the area would be expected. Retail establishments, shopping centers, gas stations, laundramats, etc., comprise this category.

(3) Residential: because many other areas are also used residentially, this category is selected only in the absence of a dominating industrial or commercial influence.

For rural sampling sites, two other categories were used:

(4) Near Urban: category for samplers placed in a rural area, yet close enough to a major urban center to be materially affected by the urban area.

(5) Agricultural: category encompassing orchards, crop raising, cattle and sheep grazing, etc.

---

* Storage and Retrieval of Aerometric Data.

Table A-9

A Comparison of Actual Site Description and That Implied by the Characteristics of the Seasonal Component of TSP Time Series Data Collected in the Metropolitan Boston Region

Series Name	Consolidated SAROAD Site Description	Site Description Implied by Seasonal Component Characteristics Using Definitions from an NASN Study [13]
TSP1	Urban	Urban
TSP2	Suburban	Nonurban
TSP3	Nonurban	Nonurban
TSP4	Suburban	Nonurban
TSP5	Suburban	Urban
TSP6	Urban	Urban
TSP7	Nonurban	Nonurban

It was desirable to consolidate these site descriptions into urban and non-urban categories for purposes of comparison with the NASN results. The technique used to accomplish this was to label Center City-Commercial sites as urban, Rural-Agricultural sites as non-urban, and all other sites (e.g., Center City-Residential) as suburban.

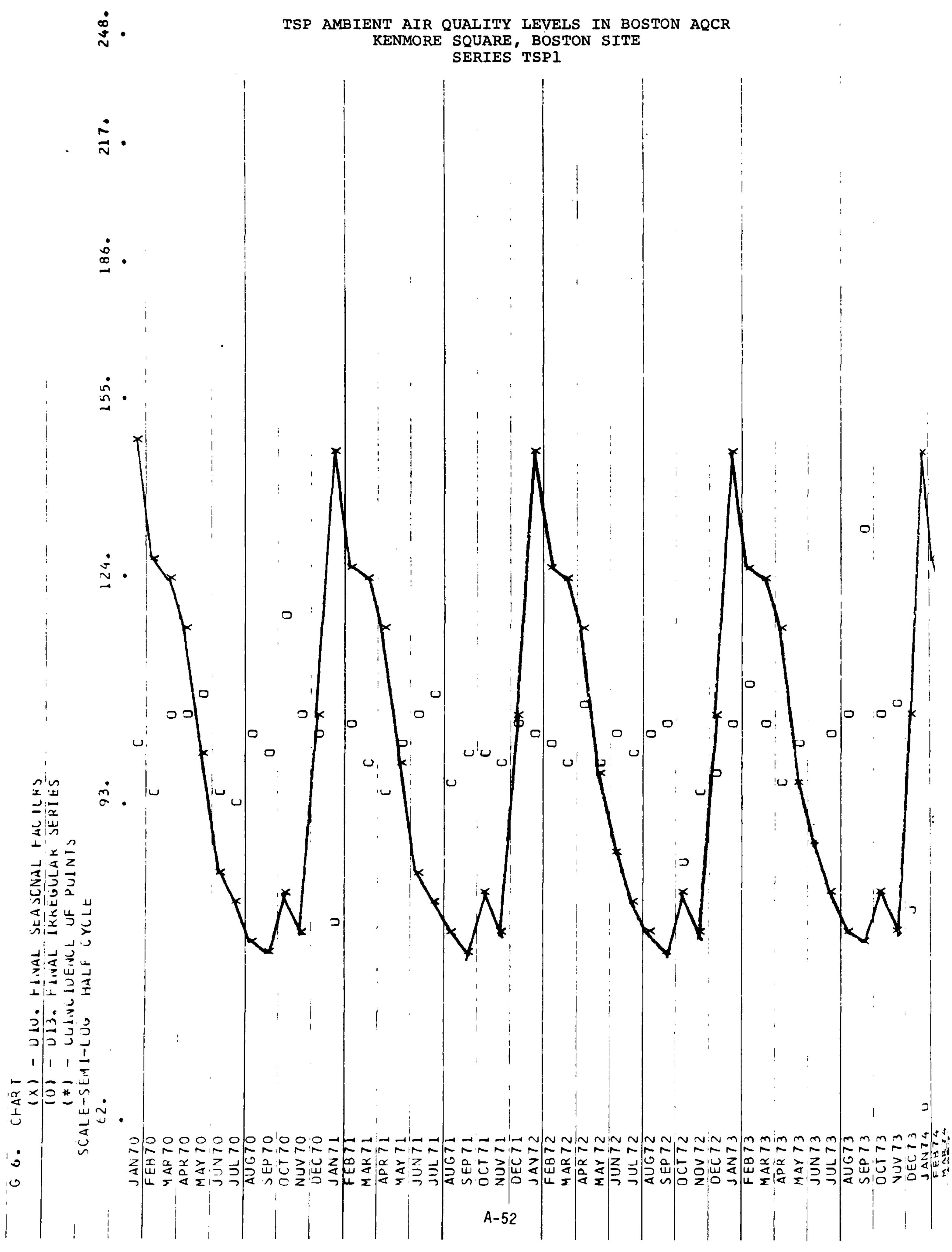
Figures A-33 through A-39 show the seasonal components (S) of time series TSP1 through TSP7 using a multiplicative ratio to moving average model. By comparing the time of year of the seasonal component's peak with the NASN definitions, the second column in Table A-9 was constructed. Note that series TSP2 through TSP6 (Figures A-34 through A-38) are characterized by double peaks, one in summer and one in winter. In these cases, the site description listed as implied by the seasonal component characteristics is the one that predominated. Based on the above results, it is concluded that the observed seasonal patterns in TSP levels confirm those found in the NASN study [13] of nationwide TSP levels.

d. Analysis of the Correlation Between the Seasonal Component Produced by the X-11 Analysis and Meteorological Variables

In order to ascertain whether significant interdependence existed between measured heating degree-day or mean wind speed data and the periodic components derived in the X-11 ratio to moving average analysis of measured air quality data, linear regressions between these variables were performed for the six representative time series (Table A-2). The results are shown in Table A-10. It can be seen from the correlation coefficients that significant interdependence does exist in all series, except TSP5. The implication of this finding is that the meteorological variables, degree-days and mean wind speed can be used as a measure of the seasonality in ambient SO_2 and TSP levels.

Other important characteristics worth noting from Table A-10 are that all the SO_2 series have a seasonal component positively correlated with degree-days, i.e., both SO_2 levels and degree-days exhibited a periodicity with maxima in the winter and minima in the summer.

FIGURE A-33


MULTIPLICATIVE MODEL
TSP AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
KENMORE SQUARE, BOSTON SITE
SERIES TSP1
G 6. CHART
(X) - D10. FINAL SEASONAL FACTORS
(O) - D13. FINAL IRREGULAR SERIES
(*) - COINCIDENCE OF POINTS
SCALE-SEMI-LOG HALF CYCLE
62.
93.
124.
155.
186.
217.
248.
JAN70
FEB70
MAR70
APR70
MAY70
JUN70
JUL70
AUG70
SEP70
OCT70
NOV70
DEC70
JAN71
FEB71
MAR71
APR71
MAY71
JUN71
JUL71
AUG71
SEP71
OCT71
NOV71
DEC71
JAN72
FEB72
MAR72
APR72
MAY72
JUN72
JUL72
AUG72
SEP72
OCT72
NOV72
DEC72
JAN73
FEB73
MAR73
APR73
MAY73
JUN73
JUL73
AUG73
SEP73
OCT73
NOV73
DEC73
JAN74
FEB74

MULTIPLICATIVE MODEL

FIGURE A-34

TSP AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
GREENOUGH STREET, BROOKLINE SITE
SERIES TSP2

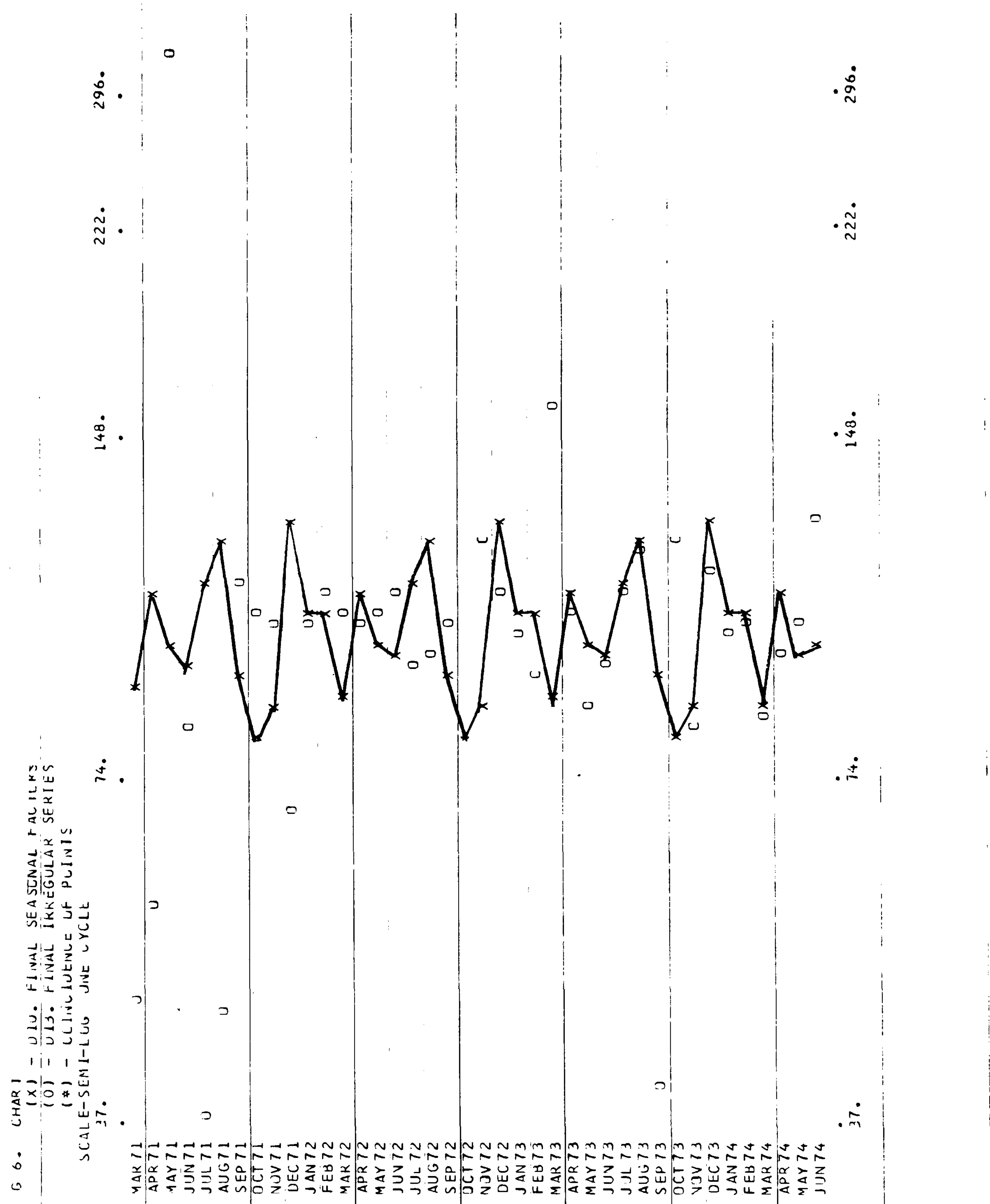


FIGURE A-35

TSP AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
U.S. ARMY SITE, MAYNARD
SERIES TSP3

MULTIPLICATIVE MODEL

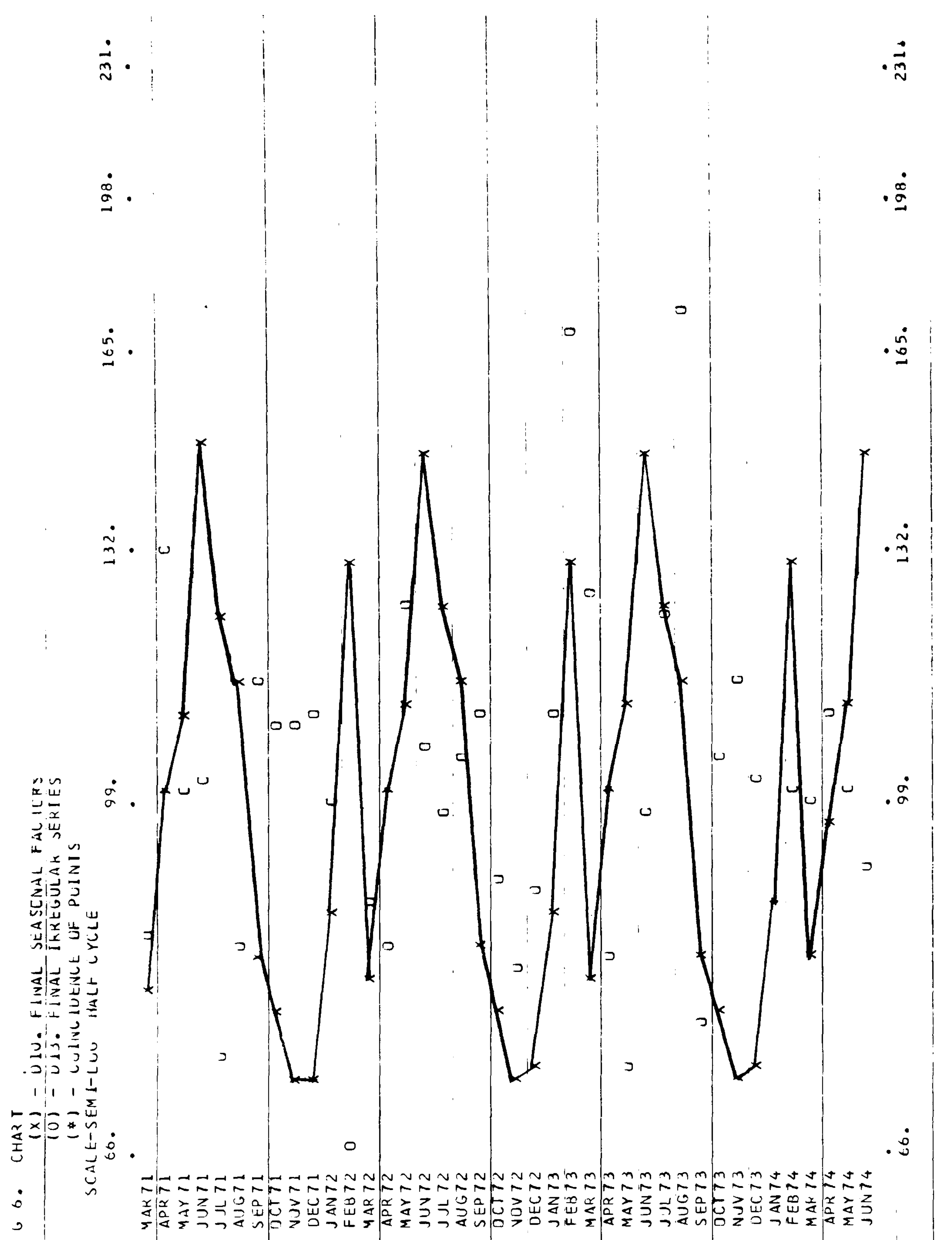


FIGURE A-36

TSP AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
DEDHAM AVENUE, NEEDHAM SITE
SERIES TSP4

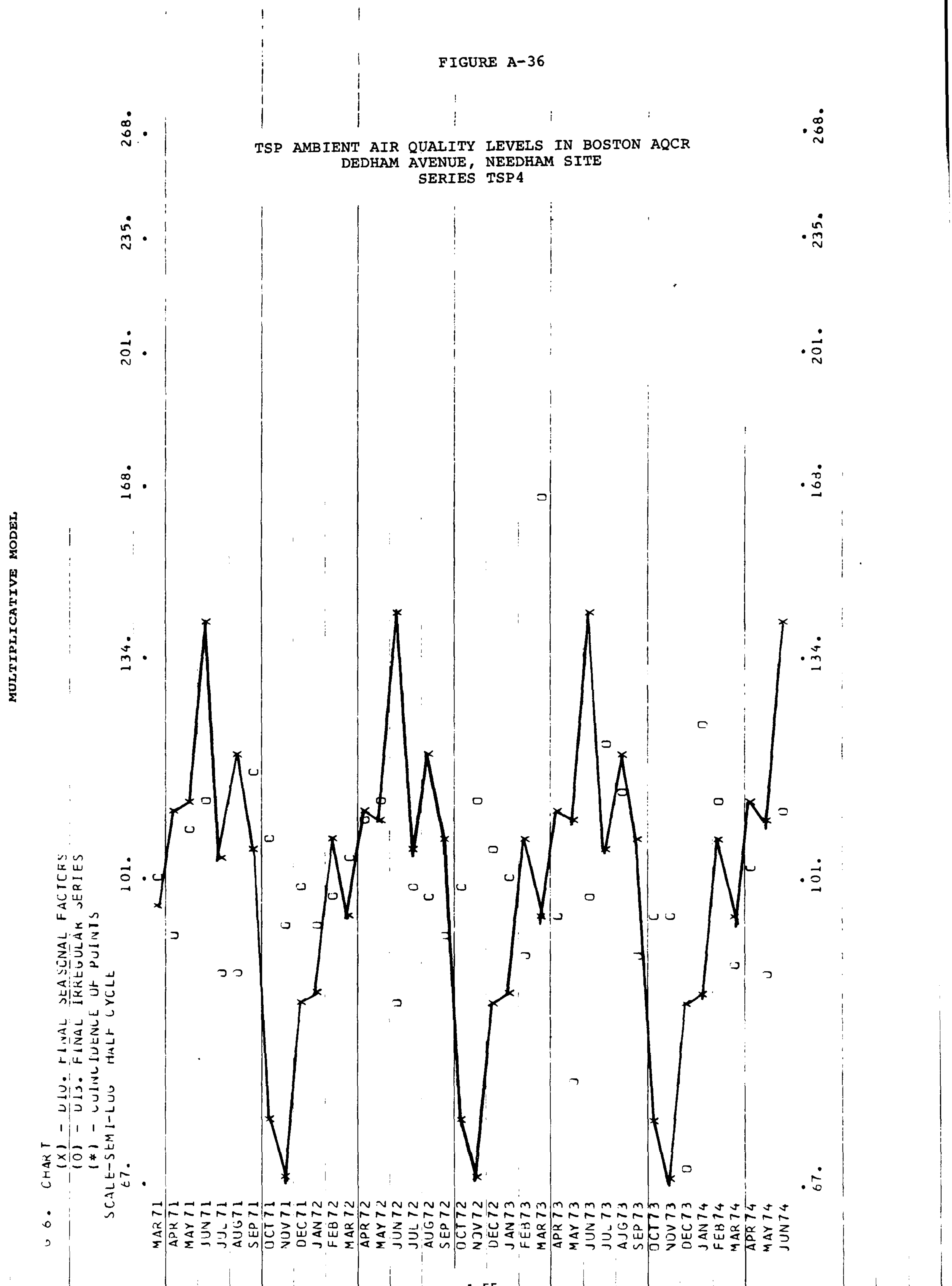


FIGURE A-37

TSP AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
NAHATAN STREET, NORWOOD SITE
SERIES TSP5

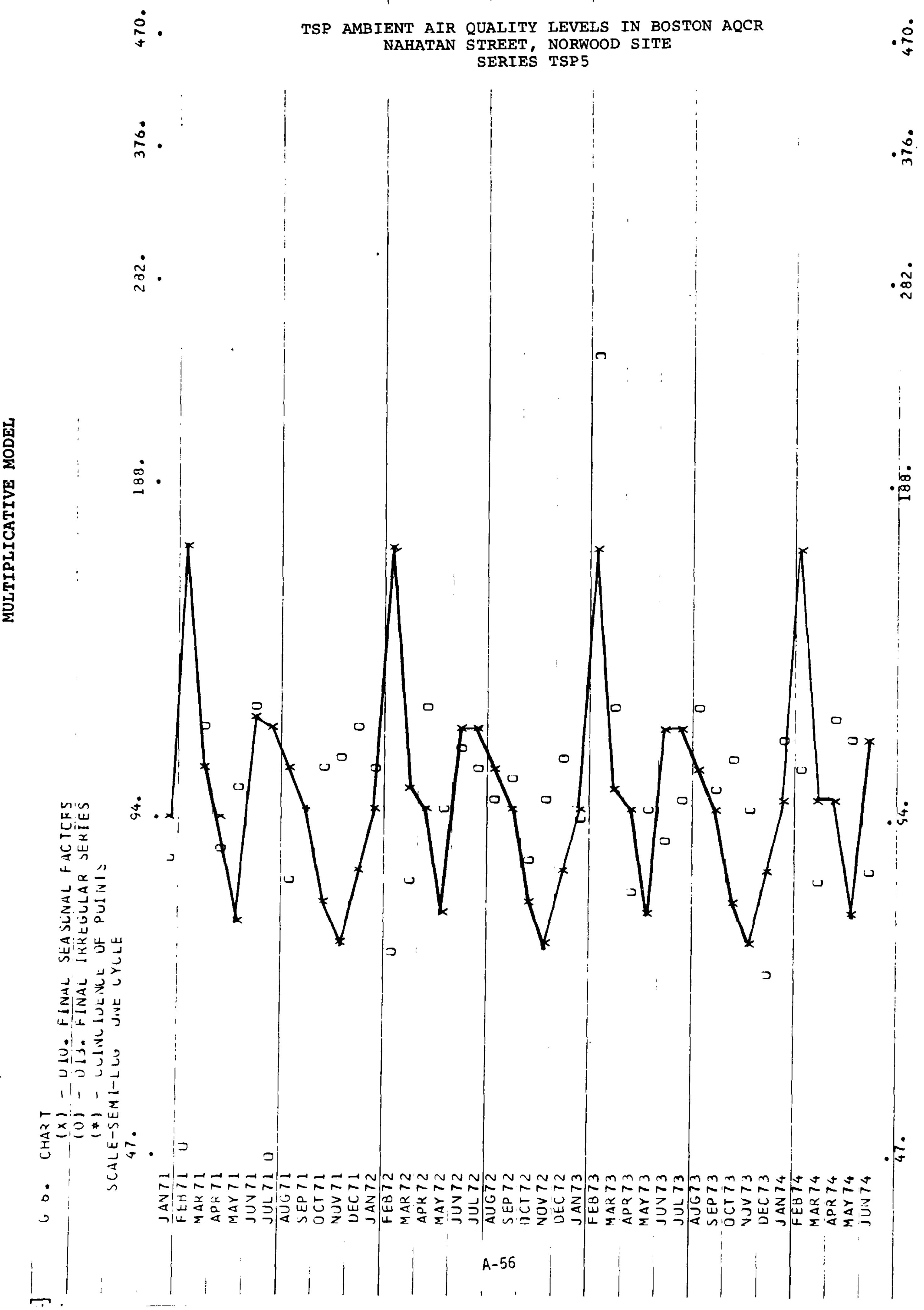
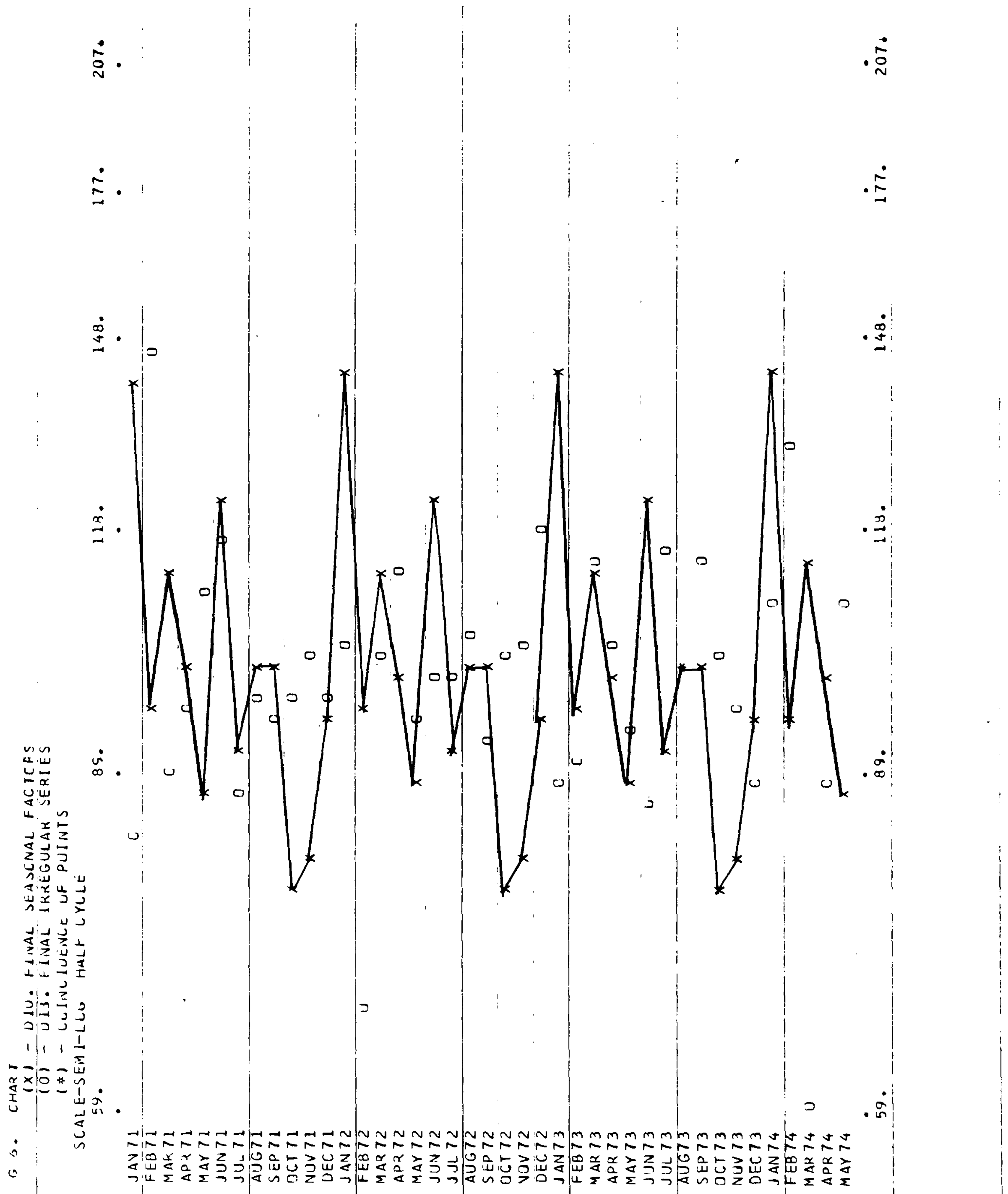


FIGURE A-38

TSP AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
HANCOCK STREET, QUINCY SITE
SERIES TSP6



MULTIPLICATIVE MODEL

TSP AMBIENT AIR QUALITY LEVELS IN BOSTON AQCR
BEAVER STREET, WALTHAM SITE
SERIES TSP7

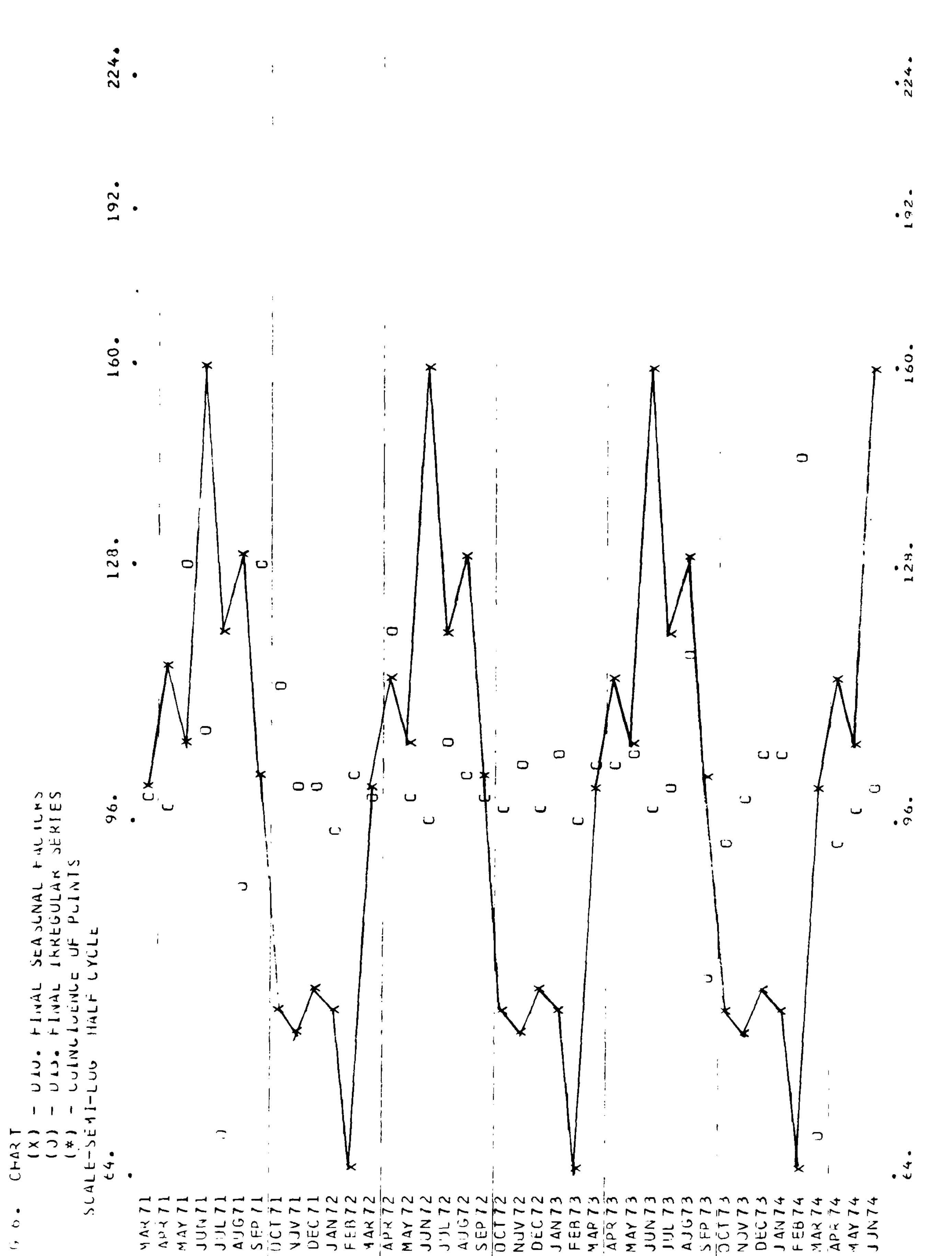


TABLE A-10

LINEAR REGRESSIONS BETWEEN THE SEASONAL COMPONENT OF MEASURED AMBIENT SO_2 AND TSP LEVELS DERIVED IN THE X-11 RATIO TO MOVING AVERAGE ANALYSIS AND METEOROLOGICAL VARIABLES

	Heating Degree Days			Mean Wind Speed*		
Data Series	R**	Slope	Intercept	R**	Slope	Intercept
X-11 Multiplicative Model						
SO2B	0.95	0.11	48	-0.71	-1940	275
SO2J	0.84	0.10	52	-0.61	-1530	238
SO2L	0.84	0.15	32	-0.54	-1910	271
TSP1	0.83	0.050	79	-0.56	-734	167
TSP5	0.20	0.012	95	-0.07	-88	109
TSP7	-0.71	-0.051	125	0.56	827	27
X-11 Additive Model						
SO2B	0.96	0.081	-38	-0.74	-1450	131
SO2J	0.85	0.020	-10	-0.62	-310	28
SO2L	0.86	0.017	-8	-0.56	-232	21
TSP1	0.83	0.054	-24	-0.56	-862	79
TSP5	0.43	0.016	-8	-0.30	-253	23
TSP7	-0.75	-0.026	12	0.59	416	-37

* Evaluated as the reciprocal of mean wind speed in the regressions.

** Correlation coefficient: an absolute value of 0.31 or larger corresponds to a level of significance at most equal to the 5% level, i.e., there is at least a 95% chance that the correlation is significant.

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The TSP data, however, show two seasonal patterns. The TSP1 series (Kenmore Square, Boston) exhibited a positive correlation with degree-days which is characteristic of seasonal patterns observed at urban sites in a study of nationwide TSP levels [13]. By contrast, the seasonal component at the TSP7 series (Beaver Street, Waltham) exhibited the converse behavior, i.e., with maxima in the summer months and minima in the winter. This pattern is characteristic of TSP levels measured at rural sites in the same nationwide study. These results are comparable with those given in Section VI.A.1.c. Further analysis of these interdependence relationships is given in Section VI.A.2.b.(3).

2. Statistical Inference

a. Exponential Smoothing — Statistical Trend Analysis

(1) Methodology

Since 1970, the Commonwealth of Massachusetts Bureau of Air Quality Control (BAQC) has promulgated several regulations limiting the sulfur and ash content of fuels burned in the Metropolitan Boston AQCR (MBAQCR). These are summarized in Table A-11. During the winter of 1973-74, when shortages of conforming fuel appeared imminent, many variances were granted on these regulations by the BAQC to large fuel users in the MBAQCR during the period of December 1, 1973 to May 15, 1974. A procedure employing the forecast potential of triple exponential smoothing was devised to permit testing of the statistical significance of changes in trends of measured air quality data corresponding to the onset of fuel use regulations and variances.

The technique used to test the effect of regulations and variances on ambient air quality levels was to compare the actual seasonally adjusted values after the implementation date of a regulation or variance with those values predicted by a triple exponential smoothing model. These latter values were computed under the assumption of no changes in air quality trends and this hypothesis was tested against the observed series.

TABLE A-11

A SUMMARY OF REGULATIONS ADOPTED TO CONTROL THE SULFUR AND ASH CONTENT OF FUELS BURNED IN THE METROPOLITAN BOSTON AIR QUALITY CONTROL REGION

Effective Date of Adoption	Regulations in Effect in Metropolitan Boston AQCR
July 1, 1970	Ban on all open burning
	Ash content of fossil fuels limited to 9% by dry weight
October 1, 1970	Residual oil sulfur content limited to 2.2% and to 1.0% in core*
	Distillate oil sulfur content limited to 0.3%
	Coal sulfur content limited to 1.5% and to 0.75% in core*
October 1, 1971	Residual oil sulfur content limited to 1.0% and to 0.5% in core*
	Coal sulfur content limited to 0.7% and to 0.37% in core*
June 1, 1972	Ban on residual oil use at facilities with rated boiler capacities of 3 million Btu/hour or less
	Ban on solid fuel use at hand-fired facilities with rated boiler capacities in excess of 150 thousand Btu/hour

*The 13 core cities and towns are: Arlington, Belmont, Boston, Brookline, Cambridge, Chelsea, Everett, Malden, Medford, Newton, Somerville, Waltham, and Watertown

Statistical tests of significance were applied to the residuals (actual minus predicted values) obtained from the above procedure [17, 18]. Conclusions were then drawn as to whether a statistically significant change in the trends of measured air quality data occurred coincident with the onset of regulations and variances.

The predictive ability of the exponential smoothing model depends on the value of a smoothing constant which controls the response sensivity of the process. Values which enable a high degree of data smoothing tend to produce the best long-range forecasts. In order to ensure the model predicted the trend of the air quality data, the values of the smoothing constant used in the current application were those employed in the trend analysis confirmation. On the basis of visual inspection, the predictive ability of the model under these circumstances was judged adequate for no more than a period of ten months (or ten time steps).

The analysis of testing for statistically significant changes in trends of measured air quality data after a certain time, t, was undertaken using the seasonally adjusted form (i.e., seasonal component removed) of the six representative time series listed in Table A-2. The original series were not used, since it was felt that seasonality in the data would confuse statistical test results. The form of the exponential smoothing model used, i.e., multiplicative or additive, depended on whether the seasonally adjusted series was derived using a multiplicative of additive X-11 technique. Thus, the actual values were from the seasonally adjusted form of the original series:

$$\text{Actual} = T + I \quad \text{or} \quad T * I$$

The predicted values were from a seasonally adjusted series predicted by the exponential smoothing model assuming no change in the trend, T', after time t:

$$\text{Predicted} = T' + I \quad \text{or} \quad T' * I$$

The residuals used in the statistical tests were the Actual minus the Predicted values. An example showing how the Actual and Predicted series compared is shown in Figure A-40 for the TSP1 series (additive model) and for t = December 1, 1973.

It should be noted that the seasonally adjusted series produced by the ratio to moving average technique may have still contained some seasonal effects, although tests for residual seasonality were not performed,

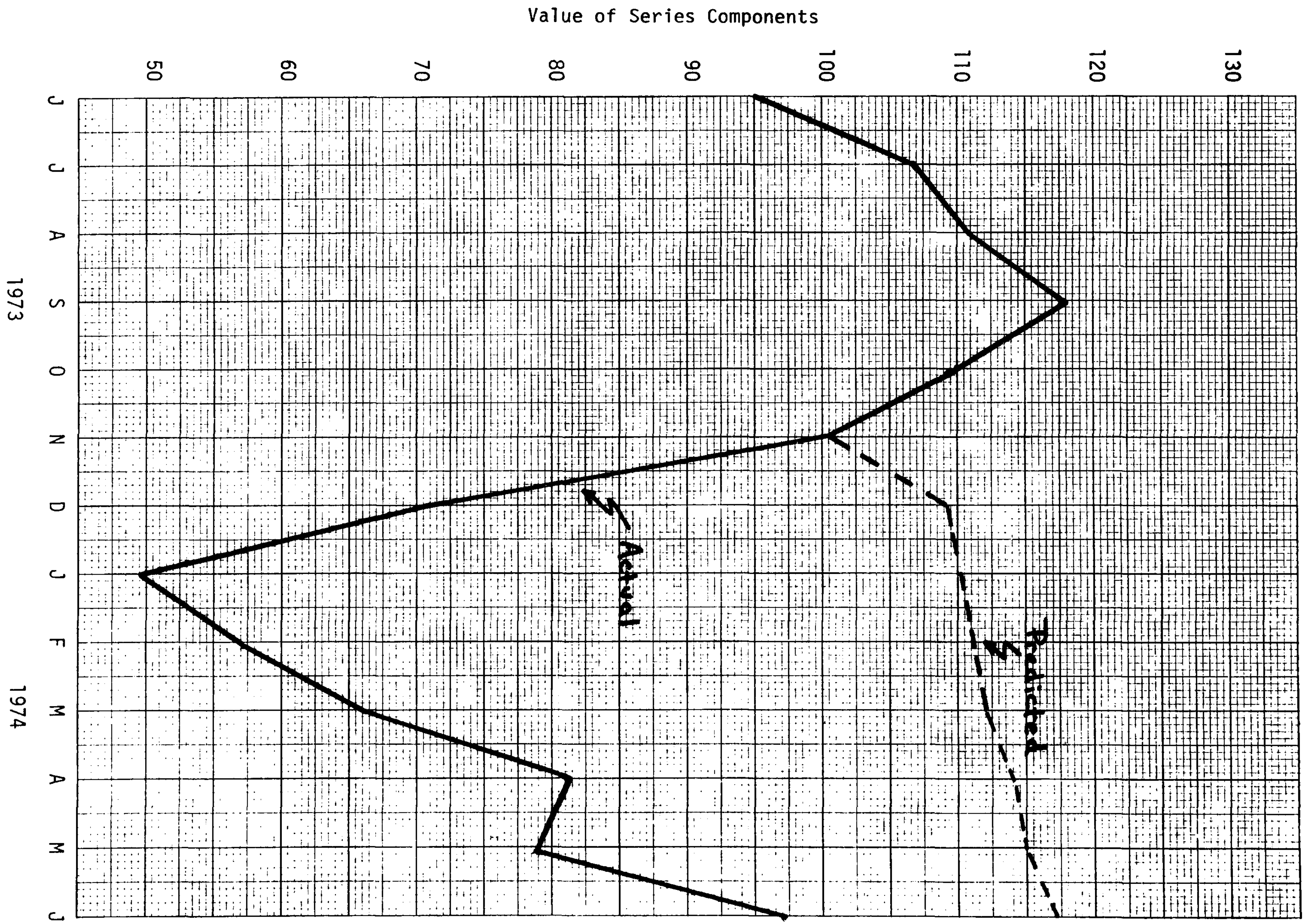

Figure A-40. Comparison of Actual and Predicted Seasonally Adjusted TSP1 Series after December 1, 1973 due to the inconclusive results of the statistical tests. Residual seasonality, in the data that were analyzed, may have caused apparent changes in air quality trends where none actually existed. Therefore, particular care was taken in interpreting the results of this analysis. The stepwise multiple linear regression provided a more objective analysis of the effect of regulations and variances on ambient air quality levels and was used to expand on the following results.

(2) Results

Nonparametric statistical tests of significance, the Sign test and Runs test [18], were applied to the residuals obtained from the previously described procedure. Each time series listed in Table A-2 yielded residuals (corresponding to the ten-month predictive ability of the model) for each of the four effective dates of regulations listed in Table A-11 and for the mean effective date of variances granted of December 1, 1973, using both the additive and multiplicative exponential smoothing models. The null hypothesis assumed in the Sign test was that the residuals had a probability destribution with mean zero. The null hypothesis was rejected when the numbers of positive and negative signs differed significantly from equality. The Runs test, in turn, was used to test whether the positive and negative signs of the residuals were distributed randomly in time or whether they were grouped in runs. A five percent level of significance was used in both tests. The results are shown in Table A-12 for the Sign test and in Table A-13 for the Runs test. Table A-12 shows the percentage of negative signs in each series of residuals and the corresponding percentage ranges indicative of significant changes in the trend of measured air quality data. In Table A-13, a + sign indicates a significant upward change, and a - sign indicates a significant downward change in the trend of the measured air quality data coincident with the effective dates of fuel use regulations or variances.

From Tables A-12 and A-13, it can be seen that the results of the Sign and Runs tests are comparable. In general, the direction of trend changes for each regulation or variance date is mixed; i.e., there are indications of both upward and downward changes depending on the data series analyzed. The only definitive results are that a significant decrease in TSP levels is noted coincident with the October 1, 1971, regulations (see Table A-11). A downward trend change for TSP and SO_2 levels on July 1, 1970, is noted, but unfortunately, these results are based on data from only one monitoring station - Kenmore

TABLE A-12

SIGN TEST: PERCENTAGE OF NEGATIVE SIGNS IN RESIDUALS BETWEEN MEASURED AND PREDICTED AIR QUALITY LEVELS FOR THE TIME PERIOD FOLLOWING THE ONSET OF FUEL USE REGULATIONS AND VARIANCES

Data Series	Regulations* Jul. 1970	Oct. 1970	Oct. 1971	Jun. 1972	Variance** Dec. 1973
Multiplicative Model					
S02B	80	100	0	90	100
S02J	No Data		90	0	0
S02L	No Data		80	80	83
TSP1	100	0	100	100	100
TSP5	No Data		20	0	33
TSP7	No Data		100	0	83
Average	90	50	65	45	67
Additive Model					
S02B	20	0	0	90	67
S02J	No Data		90	0	0
S02L	No Data		0	100	100
TSP1	40	0	100	100	100
TSP5	No Data		30	0	33
TSP7	No Data		90	10	67
Average	30	0	52	50	61
Trend Changes***					
Downward if ≥	90	90	90	90	100
Upward if ≤	10	10	10	10	0

* Based on a 10-month time period.

** Based on only a 6-month time period due to unavailability of data.

*** Percentage range indicative of significant changes in the trend of measured air quality data at the 5% significance level.

TABLE A-13

RUNS TEST: SIGNIFICANT CHANGES IN THE TREND OF MEASURED AIR QUALITY DATA COINCIDENT WITH THE ONSET OF FUEL USE REGULATIONS AND VARIANCES*

Data Series	Regulations Jul. 1970	Regulations Oct. 1970	Regulations Oct. 1971	Regulations Jun. 1972	Variance Dec. 1973
Multiplicative Model					
S02B	-	-	+	-	-
S02J	No Data		-	+	+
S02L	No Data				
TSP1	-	+	-	-	-
TSP5	No Data			+	
TSP7	No Data		-	+	
Additive Model					
S02B		+	+	-	
S02J	No Data		-	+	+
S02L	No Data		+	-	
TSP1		+	-	-	-
TSP5	No Data			+	
TSP7	No Data		-	+	

* At 5% significance level, + denotes upward change in trend and - denotes downward change in trend, while a blank denotes no change in trend.

Square, Boston. Occasional differences between the additive and multiplicative results are due to the varying abilities of these two models in simulating time series behavior.

Similarities in the patterns of the signs of the residuals at different monitoring sites, produced by the above procedure, were compared in order to judge if the measured series from several site locations qualitatively exhibited similar behavior coincident with the onset of regulations or variances. The appropriate statistical test of significance employed was the two-way analysis of variance [18], with a 5% significance level. The results of the Sign test analysis, shown in Table A-12, were used in these comparisons.

For each regulation or variance date, the column of percentages from Table A-12 was arranged in a three by four matrix representing the three representative monitoring sites (see Table A-2) and the four seasonally adjusted series analyzed from each site (viz., a multiplicative and additive model of series components for both SO_2 and TSP). The two-way analysis of variance technique was then applied to these data to obtain estimates of the variance in the data due to different monitoring sites and the residual variance, a measure of the variance independent of that due to different sites or different data series. The null hypothesis used was that the percentage of negative signs in the data did not differ significantly from site to site, i.e., similarity. The null hypothesis was rejected when an F-ratio of the variance due to different sites and the residual variance indicated significant differences. This analysis could not be applied to the July and October 1970 regulation dates due to the lack of data from more than one monitoring site.

The null hypothesis was rejected (i.e., lack of similarity) for every regulation and variance date except October 1971. These results indicate that data from the three different monitoring sites exhibit qualitatively similar behavior coincident with the onset of the October 1, 1971, fuel use regulations.

b. Multiple Linear Regression Analysis

(1) Methodology

The utility of stepwise multiple regression was that it permitted the identification of which of a large number of independent variables were most significant in explaining the variations in measured air quality levels. The chosen variables are presented in the order of their significance as predictors of the dependent variable and the multiple correlation coefficient provides an indication of the overall fit of the model. The regression also provided an empirical functional relationship between the dependent variable (ambient air quality levels) and the various independent variables for use in future analyses.

The limitations that may be encountered in the application of this technique include the definition of variables, i.e, functional relations, and the testing of the statistical significance of the derived regression equation. A standard assumption used in testing the fit of a regression model to a given set of data is that the independent variables be chosen at random from the set defined for the model. The stepwise multiple regression procedure did not select predictors at random, but instead chose them in the order of their significance in explaining the variability in the data. For this reason, the standard F-test for significance had to be modified prior to its application to the stepwise regression results.

In order to illustrate how multiple regression analysis was applied to the current problem, let the dependent variable, Y, represent ambient SO_2 or TSP levels, and the independent variables X_1, X_2, ... X_K represent various periodic, meteorological, and regulatory predictors. Assume that there are n sets of random observations of the Y and X_i variables. Multiple regression analysis attempted to fit this data to an equation of the form:

$$Y = a_0 + a_1X_1 + a_2X_2 + \dots + a_KX_K$$

where a_0, a_1, ... a_K are constant coefficients to be determined by the regression analysis so as to provide a best fit to the data in the least squares sense. The common measure of the fit of the model to the data was provided by the multiple correlation coefficient, R. R^2 is the amount of variance of the dependent variable, Y, explained by the assumed regression model.

In the present study, a stepwise procedure was followed in order to select the most significant variables from the total set of those defined. The procedure consisted of adding one variable at each step and computing the multiple correlation coefficient and the residual sum of squares. At each step of the procedure, the variable selected from the list of unused variables was the one that, when added to the equation of the previous step, provided the greatest reduction in the residual sum of squares. That is, the variable that provided the most additional information about the dependent variable Y. Thus, at some step in the procedure, a variable that was highly correlated with Y may not have been chosen in favor of one that had a lower correlation with Y. This occurred if the highly correlated variable simply duplicated information provided by a previously chosen variable. This masking of significant variables (discussed in Section VI.A.2.B.(3)) occurred between time and regulatory variables, and between seasonal and meteorological variables in the current analysis.

In order to test that the variance in the data explained by the regression model was not merely a random occurrence, it was necessary to determine the statistical significance of the fit provided by the model. For this purpose, an F-ratio test was used at each step of the multiple regression procedure to determine whether the reduction in the residual sum of squares due to the added variable was statistically significant [19]. The critical F value used was 3.0, i.e., an independent variable was added into the regression if its F-ratio equalled or exceeded 3.0. This critical value corresponds approximately to a ten percent level of significance, i.e., there is at most a ten percent chance of accepting a variable as significant in the regression when it actually is not.

An important underlying assumption in application of the F-test is that the added variable whose significance is being tested has been randomly chosen for the total group defined. In the case of the stepwise regression analysis, however, this choice was not random. In fact, at each step the most significant of the remaining variables was selected, and therefore, the F-test was likely to overestimate the significance of the added variable. The use of a critical F value of 3.0 may correspond to an actual level of significance higher than ten percent in any one given multiple regression. However, the regression analysis was performed on not one, but twenty data series representing thirteen different monitoring sites in Metropolitan Boston (see Table A-1), and the obtained results from all of these regressions were combined in order to make general statements regarding the effects of fuel use regulations and variances on ambient air quality levels. The combined or overall level of significance was, therefore, smaller than any one individual level of significance [20]. For example, if one has K independent tests, each significant at level P_i, i = 1, ... , K, then the overall level of significance is found by use of the chi square distribution where $-2\sum_{i=1}^{K} \ln P_i$ has a chi square distribution with 2K degrees of freedom. Using this expression, it can be shown that if we have two tests, each significant at the ten percent level, the overall significance is smaller at approximately five percent. Thus, when combining the results of many tests, each using a critical value of 3.0, it can be said with certainty that the overall level of significance is equal to or lower than five percent.

The independent variables selected for the regression analysis represented meteorological conditions, seasonal variations, regulatory impositions and time. Four dummy variables [19] quantifying the effects of the four significant regulatory dates listed in Table A-11 were chosen along with a dummy variable for the mean effective date of special variances granted of December 1, 1973. These variables were defined as 0 before the associated effective date and 1 otherwise. Twelve dummy variables quantifying the effect of seasonal variations were used in the regression analysis. Each monthly variable was defined as 1 on its associated month and 0 otherwise. Additional independent variables were monthly heating degree-days and the reciprocal of monthly average wind speed, both measured at Boston's Logan International Airport, and time variables, t, t^2, and t^3, associated with the number of months (t) since the beginning of the measured SO_2 or TSP data time series.

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The dependent variable in the regression analysis consisted of either the measured ambient SO_2 and TSP levels or the natural logarithms of these quantities. The results obtained by analyzing the data and the logarithms of the data were so similar that only those associated with analysis on the original data are presented in this report. The regression analysis was applied separately to each of the twenty available time series shown in Table A-1.

(2) Zero Order Correlations

The zero order (i.e., simple) correlations between the dependent variables and various independent variables are shown in Tables A-14 and A-15, respectively, for the SO_2 and TSP data. The sign of the correlation coefficients indicates whether these variables are positively or negatively correlated. An absolute value of 0.31 or larger for these simple correlation coefficients corresponds to the five percent significance level, i.e., there is at least a 95 percent chance that a correlation is significant. The cut-off value of 0.31 is conservative in that it is based on the smallest sample size of all the time series analyzed.

From Tables A-14 and A-15, it can be seen that the regulation and variance variables are consistently negatively correlated with ambient SO_2 and TSP levels. Statistical significance is attained most often for the regulations effective in July and October 1970 and October 1971. The correct interpretation of these negative correlations is that the average SO_2 and TSP levels after an effective date of a regulation or variance are statistically significantly lower than the average levels before this date. The large quantity of significant negative correlations indicates we are justified in further analysis of the relationship between changes in the SO_2 and TSP levels and the specific regulations and variances.

TABLE A-14

CORRELATION COEFFICIENTS** BETWEEN AMBIENT SO_2 LEVELS AND VARIOUS OTHER VARIABLES AT SEVERAL MONITORING SITES IN METROPOLITAN BOSTON

	Data Series												
Variable	SO_2A	SO_2B	SO_2C	SO_2D	SO_2E	SO_2F	SO_2G	SO_2H	SO_2I	SO_2J	SO_2K	SO_2L	SO_2M
Reciprocal of Mean Wind Speed	-.406	-.430	-.379	-.344	-.399	-.263	-.276	-.295	-.402	-.559	-.448	-.299	-.358
Degree Days	.485	.535	.424	.360	.461	.163	.248	.347	.469	.679	.607	.455	.341
Regulations:													
July 1, 1970	-.538	-.637	*	-.492	*	*	*	*	*	*	*	*	*
Oct. 1, 1970	-.485	-.561	*	-.438	*	*	*	*	*	*	*	*	*
Oct. 1, 1971	-.508	-.601	-.509	-.557	-.390	-.268	-.433	-.358	-.232	-.291	-.053	-.220	-.278
June 1, 1972	-.412	-.589	-.443	-.590	-.342	-.358	-.185	-.426	-.260	-.200	-.065	-.325	-.175
Variance:													
Dec. 1, 1973	-.179	-.286	-.261	-.284	-.135	.023	-.183	-.063	.009	.047	-.148	.051	.103
Time (t)	-.566	-.748	-.607	-.711	-.423	-.338	-.373	-.474	-.306	-.299	-.206	-.220	-.196

* No data available

** An absolute value of 0.31 or larger for these simple correlation coefficients corresponds to the five percent significance level.

TABLE A-15

CORRELATION COEFFICIENTS** BETWEEN AMBIENT TSP LEVELS AND VARIOUS OTHER VARIABLES AT SEVERAL MONITORING SITES IN METROPOLITAN BOSTON

Variable	TSP 1	TSP 2	TSP 3	TSP 4	TSP 5	TSP 6	TSP 7
			Data Series				
Reciprocal of Mean Wind Speed	-.291	-.072	.293	.483	-.056	-.080	.656
Degree Days	.500	-.069	-.190	-.359	.154	.226	-.555
<u>Regulations</u>:							
July 1, 1970	-.716	*	*	*	*	*	*
Oct. 1, 1970	-.550	*	*	*	*	*	*
Oct. 1, 1971	-.403	-.448	-.301	-.587	-.044	-.572	-.428
June 1, 1972	-.497	-.298	-.044	-.484	.074	-.445	-.079
<u>Variance</u>:							
Dec. 1, 1973	-.262	-.142	-.258	-.431	-.134	-.224	-.399
Time (t)	-.593	-.355	-.166	-.550	-.052	-.567	-.272

* No data available

** An absolute value of 0.31 or larger for these simple correlation coefficients corresponds to the five percent significance level.

(3) Partial Correlation Structure

The results in Table A-14 show that degree-days are significantly positively correlated with SO_2 levels at most monitoring stations. That is, both quantities vary seasonally, with winter maxima and summer minima. From the meteorological observations, a strong correlation (-0.743) was found between heating degree-days and the reciprocal of mean wind speed for Boston, reflecting the climatological relationship between these quantities. The implication of this interdependence is that partial correlations of SO_2 levels with the reciprocal of wind speed, removing the linear relationship with degree-days, are all close to zero. In other words, the previously discussed masking situation is occurring where, if degree-days are already present in the regression, they dominate the correlations, and the addition of wind speed as a variable adds little or no information about the SO_2 levels. Thus, the apparent negative correlation between SO_2 levels and the reciprocal of wind speed in Table A-14 is due principally to the strong correlation climatologically between wind speed and degree-days.

Table A-15 shows that the same situation is observed for the TSP1 (Kenmore Square, Boston) series. Of the remaining TSP series, only TSP4 (Dedham Avenue, Needham) and TSP7 (Beaver Street, Waltham) have significant correlations with both wind speed and degree-days. At these sites, where wind speed is the more important of the two variables, the correlation of the reciprocal with TSP levels is positive, i.e., both quantities vary seasonally with maxima in the summer and minima in the winter months. The partial correlations of TSP levels with degree-days at these two sites, removing the linear relationship with wind speed, are all close to zero, emphasizing the dominant effect of wind speed on TSP levels.

In order to investigate the possibility that statistically significant downward changes in SO_2 and TSP levels coincident with the effective dates of fuel use regulations and variances are due principally to changes in meteorological conditions, the partial correlations of SO_2 or TSP levels with the regulatory and variance variables were computed, removing the linear relationship with either degree-days or the reciprocal of wind speed. The analysis was conducted for the six representative time series (see Table A-2), and the results are shown in Table A-16. It can be seen that all the correlations are still negative, and the majority are still statistically significant. Note that some correlations which were

TABLE A-16

PARTIAL CORRELATION COEFFICIENTS** OF AMBIENT SO_2 OR TSP LEVELS
WITH REGULATORY OR VARIANCE VARIABLES
AT THREE REPRESENTATIVE MONITORING SITES
(Removing the Linear Relationship with either Degree-Days or Wind Speed)

Variable	Reciprocal of Wind Speed Removed						Degree-Days Removed					
	SO_2B	SO_2J	SO_2L	TSP 1	TSP 5	TSP 7	SO_2B	SO_2J	SO_2L	TSP 1	TSP 5	TSP 7
<u>Regulations</u>:												
July 1, 1970	-.70	*	*	-.74	*	*	-.69	*	*	-.76	*	*
Oct. 1, 1970	-.62	*	*	-.57	*	*	-.72	*	*	-.68	*	*
Oct. 1, 1971	-.61	-.29	-.24	-.39	-.04	-.55	-.74	-.44	-.38	-.48	-.05	-.36
June 1, 1972	-.59	-.16	-.33	-.48	-.08	-.15	-.64	-.14	-.34	-.51	-.10	-.13
<u>Variance</u>:												
Dec. 1, 1973	-.46	-.15	-.06	-.37	-.16	-.25	-.48	-.17	-.10	-.43	-.18	-.29

* No data available

** An absolute value of 0.32 larger for these correlation coefficients corresponds to the five percent significance level. The value increases because of a loss of one degree of freedom in the partial correlation coefficients.

significant are no longer (e.g., TSP7 and the variance), while others which were not significant before now are (e.g., SO_2B and the variance). In general, the pattern of correlations in Table A-16 is the same as that shown in Tables A-14 and A-15. Thus, it appears that statistically significant decreases in average SO_2 and TSP levels are associated with the effective dates of regulations and variances even after meteorological conditions have been taken into account.

(4) Stepwise Multiple Linear Regression

Stepwise multiple linear regression analysis was applied to the 13 SO_2 and seven TSP time series (see Table A-1). All previously listed independent variables were used except those involving time which would mask the effects of other independent variables. Tables A-17 and A-18 show, respectively, those variables which, when added to the regression in stepwise fashion, were significant in explaining the variance of the measured SO_2 and TSP time series at the 10 percent significance level. To aid in ranking the importance of individual independent variables in the final regression, the beta weights and t-statistics of the final regression are included in Tables A-17 and A-18, along with the multiple correlation coefficients, R. The final regression is the regression that includes all the variables that the stepwise procedure accepted as significant for inclusion. In general, the larger the beta weight (in absolute value), the greater the total contribution the independent variable makes to the final regression. The sign of the beta weight indicates whether the associated independent variable is negatively or positively correlated with the dependent variable, given that linear relationships with all other independent variables of the final regression have been removed. The t-statistic tests the hypothesis that the corresponding independent variable makes a significant added contribution to the final regression given that the contributions of all other independent variables of the final regression have been taken into account. A value of the t-statistic greater than or equal to 2 in absolute value indicates significance at the five percent level. The results of the beta weight and t-statistics would be the same if the independent variables in

TABLE A-17

STEPWISE MULTIPLE LINEAR REGRESSION ANALYSIS OF MEASURED SO_2 LEVELS

Step Number	Added Variable		R	Final Beta Weight	Final t Statistics
	Government Center, Boston (SO_2A)				
1	Regulation:	July 1970	.538	-.353	-4.059
2	Degree Days		.718	.376	3.653
3	Regulation:	October 1971	.804	-.355	-3.981
4	Seasonal:	February	.820	.235	2.562
5	Variance:	December 1973	.835	-.169	-2.016
6	Seasonal:	January	.847	.172	1.848
	Kenmore Square, Boston (SO_2B)				
1	Regulation:	July 1970	.637	-.236	-2.448
2	Degree Days		.788	.589	9.717
3	Regulation:	October 1971	.888	-.350	-4.984
4	Variance:	December 1973	.916	-.245	-4.058
5	Regulation:	October 1970	.922	-.185	-1.789
	South Bay, Boston (SO_2C)				
1	Regulation:	October 1971	.509	-.519	-5.694
2	Degree Days		.699	.622	6.634
3	Seasonal:	October	.768	.290	3.241
4	Variance:	December 1973	.799	-.226	-2.403
5	Seasonal:	March	.822	-.199	-2.180
	Central Square, East Boston (SO_2D)				
1	Regulation:	June 1972	.590	-.200	-1.385
2	Regulation:	July 1970	.676	-.289	-2.892
3	Degree Days		.751	.415	4.268
4	Regulation:	October 1971	.769	-.280	-1.948
5	Variance:	December 1973	.787	-.187	-1.819

TABLE A-17 (continued)

STEPWISE MULTIPLE LINEAR REGRESSION ANALYSIS
OF MEASURED SO_2 LEVELS

Step Number	Added Variable		R	Final Beta Weight	Final t Statistics
	Greenough Street, Brookline (SO_2E)				
1	Degree Days		.461	.482	3.830
2	Regulation:	October 1971	.619	-.414	-3.291
	Village Street, Marblehead (SO_2F)				
1	Regulation:	October 1971	.434	-.374	-2.545
2	Regulation:	June 1972	.511	-.277	-1.889
	U.S. Army Site, Maynard (SO_2G)				
1	Regulation:	October 1971	.433	-.523	-3.744
2	Degree Days		.565	.375	2.679
	Main Street, Medford (SO_2H)				
1	Regulation:	June 1972	.426	-.383	-2.756
2	Degree Days		.513	.290	2.092
	Dedham Avenue, Needham (SO_2I)				
1	Degree Days		.469	.421	3.018
2	Regulation:	October 1971	.588	-.378	-2.945
3	Seasonal:	February	.665	.340	2.488
	Nahatan Street, Norwood (SO_2J)				
1	Degree Days		.679	.695	6.589
2	Regulation:	October 1971	.753	-.326	-3.089
	Hancock Street, Quincy (SO_2K)				
1	Degree Days		.607	.655	5.449
2	Variance:	December 1973	.679	-.282	-2.345
3	Seasonal:	November	.711	.213	1.813

TABLE A-17 (continued)

STEPWISE MULTIPLE LINEAR REGRESSION ANALYSIS
OF MEASURED SO_2 LEVELS

Step Number	Added Variable	R	Final Beta Weight	Final t Statistics
	Beaver Street, Waltham (SO_2L)			
1	Degree Days	.455	.540	3.868
2	Regulation: October 1971	.568	-.360	-2.513
	Montvale Avenue, Woburn (SO_2M)			
1	Seasonal: March	.375	.312	2.220
2	Reciprocal of Wind Speed	.472	-.270	-1.914
3	Regulation: October 1971	.530	-.242	-1.753

TABLE A-18

STEPWISE MULTIPLE LINEAR REGRESSION ANALYSIS
OF MEASURED TSP LEVELS

Step Number	Added Variable		R	Final Beta Weight	Final t Statistic
	Kenmore Square, Boston (TSP 1)				
1	Regulation:	July 1970	.716	-.517	-8.920
2	Degree Days		.828	.548	9.125
3	Variance:	December 1973	.873	-.267	-4.357
4	Seasonal:	November	.901	-.233	-4.218
5	Seasonal:	December	.916	-.163	-2.830
6	Regulation:	June 1972	.926	-.153	-2.480
7	Seasonal:	April	.932	.108	1.984
	Greenough Street, Brookline (TSP 2)				
1	Regulation:	October 1971	.448	-.422	-3.200
2	Seasonal:	May	.599	.398	3.012
	U.S. Army Site, Maynard (TSP 3)				
1	Regulation:	October 1971	.301	-.617	-4.069
2	Seasonal:	February	.431	.446	3.547
3	Reciprocal of Wind Speed		.586	.318	2.390
4	Regulation:	June 1972	.648	.484	3.058
5	Seasonal:	September	.686	-.258	-2.113
6	Variance:	December 1973	.729	-.285	-2.083
	Dedham Avenue, Needham (TSP 4)				
1	Regulation:	October 1971	.587	-.505	-5.826
2	Reciprocal of Wind Speed		.754	.680	6.848
3	Regulation:	July 1973*	.793	-.239	-2.869
4	Seasonal:	July	.822	-.286	-3.129
5	Seasonal:	October	.848	-.196	-2.401
6	Seasonal:	November	.873	-.164	-1.967
7	Seasonal:	February	.886	.192	2.211
8	Seasonal:	March	.898	.155	1.838

TABLE A-18 (continued)

STEPWISE MULTIPLE LINEAR REGRESSION ANALYSIS
OF MEASURED TSP LEVELS

Step Number	Added Variable		R	Final Beta Weight	Final t Statistic
	Nahatan Street, Norwood (TSP 5)				
1	Seasonal:	February	.507	.506	3.715
	Hancock Street, Quincy (TSP 6)				
1	Regulation:	October 1971	.572	-.540	-5.055
2	Seasonal:	January	.711	.448	4.186
3	Seasonal:	June	.762	.274	2.554
	Beaver Street, Waltham (TSP 7)				
1	Reciprocal of Wind Speed		.656	.974	8.800
2	Regulation:	October 1971	.775	-.665	-7.266
3	Seasonal:	July	.837	-.336	-4.304
4	Regulation:	June 1972	.860	.435	4.612
5	Regulation:	July 1973 *	.894	-.268	-3.565
6	Seasonal:	April	.913	.218	3.281
7	Degree Days		.923	.272	2.500
8	Seasonal:	June	.933	.156	2.132

* A regulatory variable for July 1, 1973 was included as an independent variable in the original regression analysis before it was learned the regulations were in fact never implemented. As a point of interest, this variable was never chosen once in the stepwise regression analysis of SO_2 levels and only twice in the analysis of TSP levels. No statistically significant and consistent changes in TSP levels are associated with this date.

the regression were statistically independent, i.e., if zero-order correlation coefficients between them were nearly zero. This was not, however, the case as significant interdependence existed between seasonal and meteorological variables, and between time and regulatory variables.

To aid in extracting information from Tables A-17 and A-18, the regulations and variances which proved to be significant for each of the analyzed SO_2 and TSP time series (i.e., those chosen by the stepwise procedure), are indicated in Tables A-19 and A-20, respectively. Here, a + sign indicates significant increase and a - sign indicates a significant decrease in ambient SO_2 and TSP levels after the associated regulation or variance date.

Conclusions based on the stepwise regression analysis indicate that:

(a) The October 1971 Regulation (see Table A-11) was associated with a significant decrease in SO_2 and TSP levels in 80% of the data series.

(b) The July 1970 Regulation is also associated with a significant decrease in SO_2 and TSP levels, this time in 100% of the data series. However, this conclusion is based on data from only three monitoring stations for the SO_2 and one monitoring station for the TSP levels.

(c) No statistically significant rise in SO_2 and TSP concentrations occurred at any of the sites coincident with variances granted, because of the energy shortage, during the winter of 1973-1974. In fact, a statistically significant decrease in levels of these pollutants during this winter occurred in 35% of the data series, commencing in December 1973.

(5) Complete Multiple Linear Regression

In addition to the stepwise procedure, a complete multiple linear regression analysis was performed on all twenty data series. Here, all independent variables except time were included in the

TABLE A-19

STATISTICALLY SIGNIFICANT REGULATIONS AND VARIANCE
IN THE <u>STEPWISE</u> MULTIPLE LINEAR REGRESSION ANALYSIS
OF AMBIENT SO_2 LEVELS*

	Data Series Analyzed												
	SO_2A	SO_2B	SO_2C	SO_2D	SO_2E	SO_2F	SO_2G	SO_2H	SO_2I	SO_2J	SO_2K	SO_2L	SO_2M
Regulations													
July 1970	-	-	ND	-	ND	ND	ND	ND	ND	ND	ND	ND	ND
October 1970		-	ND		ND	ND	ND	ND	ND	ND	ND	ND	ND
October 1971	-	-	-	-	-	-	-		-	-		-	-
June 1972				-		-		-					
Variance													
December 1973	-	-	-	-							-		

ND denotes no data

* At 10% significance level,

+ denotes increase in measured levels

- denotes decrease in measured levels

a blank denotes no change in measured levels

TABLE A-20

STATISTICALLY SIGNIFICANT REGULATIONS AND VARIANCE IN THE STEPWISE MULTIPLE LINEAR REGRESSION ANALYSIS OF AMBIENT TSP LEVELS*

	Data Series Analyzed						
	TSP 1	TSP 2	TSP 3	TSP 4	TSP 5	TSP 6	TSP 7
Regulations							
July 1970	-	ND	ND	ND	ND	ND	ND
October 1970		ND	ND	ND	ND	ND	ND
October 1971		-	-	-		-	-
June 1972	-		+				+
Variance							
December 1973	-		-				

ND denotes no data

* At 10% significance level,
+ denotes increase in measured levels
- denotes decrease in measured levels
a blank denotes no change in measured levels

regression rather than just those with an F ratio above the critical value of 3.0. Tables A-21 and A-22 give the results of these regressions in the format used in Tables A-19 and A-20. Here, a regulation was noted as significant only if the corresponding t-statistic in the complete regression was significant. That is, if the added contribution of the regulatory variable, after all other independent variables have been taken into account, was significant at the five percent level. This was clearly a very stringent test. It can be seen from Tables A-21 and A-22 that only the October 1971 regulation was still strongly significant in both the SO_2 and TSP analyses after application of this new test. These analyses seem to be clearly demonstrating the effectiveness of that regulation. Note that the variance variable was not significant in the analysis of any of these series using this stringent test and so was not included in Tables A-21 and A-22.

Another interesting analysis was performed on the results of the complete regressions. The signs of the regression coefficients for the regulatory and variance variables (regardless of significance) were summarized from the complete regressions in Table A-23. The sign of a regression coefficient indicates the direction of change in the pollutant time series due to the independent variable involved. A negative sign indicates a drop in the series after the associated regulatory variance data and a positive sign represents a rise. A Sign test [25] (at the 5% level of significance) applied to the data in Table A-23, indicates statistically significant decreases in SO_2 and TSP levels occurred regionally after the October 1971 and December 1973 dates. This analysis takes the effects of all other variables into account before assessing the relationship with the regulatory or variance variable. These results are important in that they represent a combined analysis for all sites and the validity of the analysis does not depend on the usual regression analysis assumptions, e.g., no serial correlation (autocorrelation) in the time series data.

TABLE A-21

STATISTICALLY SIGNIFICANT REGULATIONS IN THE COMPLETE MULTIPLE LINEAR REGRESSION ANALYSIS OF AMBIENT SO_2 LEVELS*

	Data Series Analyzed												
Regulations	SO_2A	SO_2B	SO_2C	SO_2D	SO_2E	SO_2F	SO_2G	SO_2H	SO_2I	SO_2J	SO_2K	SO_2L	SO_2M
July 1970			ND		ND	ND	ND	ND	ND	ND	ND	ND	ND
October 1970			ND		ND	ND	ND	ND	ND	ND	ND	ND	ND
October 1971	-	-	-		-		-		-	-	-		-
June 1972							+				+		

* At 5% significance levels (t statistic for complete regression)

ND Denotes no data

\+ Denotes increase in measured levels

\- Denotes decrease in measured levels

a blank denotes no change in measured levels

TABLE A-22

STATISTICALLY SIGNIFICANT REGULATIONS IN THE COMPLETE MULTIPLE LINEAR REGRESSION ANALYSIS OF AMBIENT TSP LEVELS*

	Data Series Analyzed						
Regulations	TSP1	TSP2	TSP3	TSP4	TSP5	TSP6	TSP7
July 1970	-	ND	ND	ND	ND	ND	ND
October 1970		ND	ND	ND	ND	ND	ND
October 1971		-	-	-		-	-
June 1972	-		+				+

* At 5% significance level (t statistic for complete regression)

ND Denotes no data

\+ Denotes increase in measured levels

\- Denotes decrease in measured levels

a blank denotes no change in measured levels

TABLE A-23

SIGNS OF REGRESSION COEFFICIENT IN COMPLETE REGRESSION

Series Name	Regulatory and Variance Variables July 1970	Oct. 1970	Oct. 1971	June 1972	Dec. 1973
SO_2 A	-	-	-	+	-
B	-	-	-	-	-
C	ND	ND	-	+	-
D	-	-	-	-	+
E	ND	ND	-	+	-
F	ND	ND	-	-	+
G	ND	ND	-	+	-
H	ND	ND	-	-	+
I	ND	ND	-	+	-
J	ND	ND	-	+	-
K	ND	ND	-	+	-
L	ND	ND	-	-	-
M	ND	ND	-	+	-
TSP 1	-	-	+	-	-
2	ND	ND	-	+	-
3	ND	ND	-	+	-
4	ND	ND	-	-	-
5	ND	ND	-	+	-
6	ND	ND	-	-	-
7	ND	ND	-	+	-

ND denotes data not available

(6) The Independent Variable Time

One possible danger in the preceeding analysis was that the downward trends in ambient SO_2 and TSP levels that were significantly correlated with regulatory and variance information may have been already occurring, due to other causes, prior to the beginning of available data in 1970. This concern was addressed by redoing the stepwise multiple regression analysis with the time variables, t, t^2 and t^3, added into the pool of independent variables. This analysis was undertaken, and of the twenty regressions shown in Tables A-17 and A-18, only six changed. Tables A-24 and A-25 present the results of the new computations, presented in te same format used in Tables A-19 and A-20.

The important changes occurred in series SO_2A, SO_2B, SO_2C and SO_2D. The reasons these series showed significant correlation with the time variables was probably due to the fact that these series had the highest SO_2 levels prior to the first fuel use regulation in July 1970 and that each subsequent regulation reduced the series somewhat. In a deseasonalized (i.e., seasonal component removed) and error-free series, the combined effects of several succeeding regulations would produce a consistently decreasing trend that could appear to be due to an inverse relationship with increasing time. Supporting this hypothesis was the fact that the October 1971 regulation was no longer associated with a significant decrease in measured SO_2 levels in series SO_2A, SO_2B, SO_2C, and SO_2D in Table A-20 as it was in Table A-19 and A-21. That is, once time entered the stepwise regression as an in independent variable, it masked any correlations between regulatory or variance variables and measured air quality levels. Based on available data, it was therefore concluded that decreases in measured SO_2 and TSP levels concurrent with the effective dates of fuel use regulations were not due to a pre-existing downward trend in the data.

TABLE A-24

STATISTICALLY SIGNIFICANT REGULATIONS AND VARIANCE IN A STEPWISE MULTIPLE LINEAR REGRESSION ANALYSIS OF AMBIENT SO_2 LEVELS*
(TIME VARIABLES INCLUDED)

Regulations	Time Series Analyzed												
	SO_2A	SO_2B	SO_2C	SO_2D	SO_2E	SO_2F	SO_2G	SO_2H	SO_2I	SO_2J	SO_2K	SO_2L	SO_2M
July 1970		-	ND		ND	ND	ND	ND	ND	ND	ND	ND	ND
October 1970	+		ND	+	ND	ND	ND	ND	ND	ND	ND	ND	ND
October 1971				+	-	-	-		-	-		-	-
June 1972		+	+			-							
Variance													
December 1973	-										-		
Time Variables													
t	-	-	-	-				-					
t^2	+		+	+									
t^3	-			-									

* At 5% significance level
ND Denotes no data
\+ Denotes increase in measured levels
\- Denotes decrease in measured levels
a blank denotes no change in measured levels

TABLE A-25

STATISTICALLY SIGNIFICANT REGULATIONS AND VARIANCE IN A STEPWISE MULTIPLE LINEAR REGRESSION ANALYSIS OF AMBIENT TSP LEVELS*
(TIME VARIABLES INCLUDED)

Regulations	TSP1	TSP2	TSP3	TSP4	TSP5	TSP6	TSP7
			Time Series Analyzed				
July 1970	-	ND	ND	ND	ND	ND	ND
October 1970		ND	ND	ND	ND	ND	ND
October 1971		-	-	-		-	-
June 1972			+				+
Variance							
December 1973	-		-				
Time Variables							
t							
t^2							
t^3							

* At 5% significance level

ND Denotes no data

\+ Denotes increase in measured levels

\- Denotes decrease in measured levels

a blank denotes no change in measured levels

(7) Lagged Effects of Regulations and Variances

The regulatory and variance variables used in the preceeding regression analyses assumed that the implementation and subsequent effects of the corresponding regulation or variance took place simultaneously with its imposition. It may have been the case, however, that there was a lagged effect due to an implementation delay on the part of some sources. For example, a fuel use regulation limiting the sulfur content of certain fuels burned in the area that became law in October may not have shown itself in SO_2 levels until November (one-month lag) or even until December (two-month lag). It is further possible that there was a partial effect the first month, a further effect the second month and finally the full effect by three months. Regression analyses for these three situations were performed on the six representative series (see Table A-2). In no case was there a statistically significant gain over the methods originally employed for representing the regulatory and variance variables. Note however, it is entirely possible that the monthly data used in the statistical data analyses were too crude to detect any real lag effect.

(8) Test for Autocorrelation

An assumption made in applying statistical tests to the results of the stepwise regression analysis was that the residuals of the regression did not possess any autocorrelation, i.e., there was no unexplained serial correlation in the data. The validity of the statistical tests depended on this assumption. To ensure validity, the Runs test [18] was applied to the residuals from the stepwise regressions of the six representative series. Of these six only the SO_2B series (Kenmore Square) was found to possess significant autocorrelation, at the five percent significance level. This can be considered just a chance occurrence, i.e., in six series there is a good chance one will produce significance at the five percent level even if all six are uncorrelated. Another reason for finding significant autocorrelation in the Kenmore Square series could be that this series has a larger number of daily SO_2 measurements per month than any of the other series. One would expect values taken serially to exhibit serial correlation. Thus, the application of statistical tests to the results of the stepwise regressions was valid. Any further analysis of the data should entail an examination of the autocorrelation functions of the time series, possibly using the techniques of Box and Jenkins [21]. However, the time series may not be long enough for these types of statistical tests.

(9) Results

The results of the statistical regression analyses indicate that major SIP fuel use regulations effective July 1, 1970 and October 1, 1971 (see Table A-11) are associated with statistically significant decreases in regional SO_2 and TSP levels. This is explained by the fact that both of these regulations were responsible for the conversion of many large fuel utilization facilities to fuels with lower sulfur and ash contents. The first set of regulations, limiting the ash content of fossil fuels burned in the AQCR, caused conversions principally from coal to oil and gas. Note that although this set of regulations did <u>not</u> limit the sulfur content of fuels, the net result of these fuel conversions was usage of fuels with a lower ash <u>and</u> sulfur content. The October 1, 1971 regulations, severely restricting the sulfur content of residual oil burned in the AQCR, caused suppliers of residual oil to blend cleaner distillate oil into non-complying residual in order to produce fuel stocks of acceptable quality.

Additional results show that no statistically significant rise in regional SO_2 and TSP concentrations occurred coincident with variances granted, because of the energy shortage, during the winter of 1973-1974. In fact, the results of the complete regressions indicate statistically significant decreases in these pollutant levels occurred regionally commencing in December 1973. The implication of this finding is that some other mechanism, most probably fuel conservation efforts by consumers, overrode the effects of any increase in SO_2 and TSP emissions due to the combustion of nonconforming fuel.

The following table indicates the variables and events which, in the stepwise regression, made the greatest total contribution toward explaining variations in regional SO_2 and TSP levels between 1970 and 1974. These quantities are listed in the order of their ability to explain these variations.

SO_2 (Entire Region)	TSP (Urban Core)	TSP (Non-Urban)
Heating Degree-Days	Heating Degree-Days	(Mean Wind Speed)$^{-1}$
October 1, 1971, Regulations	July 1, 1970, Regulations	October 1, 1971, Regulations

In the cases where heating degree-days and the reciprocal of mean wind speed were the most significant variables in the multiple linear regression, they were found to be directly proportional to measured pollutant concentrations. Degree-days are a measure of local fuel burning activities and emissions; mean wind speed is a measure of the dilution capability of the atmosphere. These proportionality results are consistent with the relationships normally assumed between pollutant concentrations, emissions, and wind speed in most air quality models. Because of the strong negative correlation climatologically between the reciprocal of wind speed and degree-days, in cases where degree-days were found to be the most important variable (SO_2 and urban core TSP measurements), the correlation between pollutant concentrations and the reciprocal of wind speed was necessarily negative. Removing first the relationship between pollutant concentrations and degree-days, essentially zero correlation was found between the pollutant concentrations and the reciprocal of wind speed. This illustrates the type of illusory results that can be obtained when there is significant intercorrelation among variables.

The conclusions based on the above results are: (1) fuel burning emissions dominate SO_2 concentrations throughout the Metropolitan Boston AQCR; (2) TSP concentrations in the urban core are also dominated by fuel burning sources; but (3) TSP levels at non-urban sites are dominated by emission sources other than fuel burning facilities, most probably local particulate sources, road dust, and pollen. These results confirm the classical seasonal patterns and their urban/non-urban split found in the measured SO_2 and TSP data in the data analysis task.

c. Trends in Measured Air Quality Data during the Period of Variances

Results from the X-11 ratio to moving average data analysis were interpreted for trends during the period of variances. Two indicators of the trend of the measured air quality data, the Trend-Cycle (T) and the Months for Cyclical Dominance (MCD) components, are shown in Tables A-26 and A-27 for all data series for the time period during which variances were granted on fuel use regulations in the Metropolitan Boston

TABLE A-26

Monthly Average SO_2 Concentrations Measured During the Period December, 1973 to June, 1974 in the Metropolitan Boston Air Pollution Control District*

	Trend Cycle Series			MCD** Series		
Data Series	Dec. 1973	May 1974	June 1974	Dec. 1973	March 1974	April 1974
SO_2A	20.6	25.5	29.5	23.3	18.3	22.5
SO_2B	22.4	24.5	-	23.5	20.6	-
SO_2C	18.9	8.7	6.5	18.0	13.4	13.4
SO_2D	9.0	9.6	-	10.0	10.5	-
SO_2E	16.9	13.6	12.4	17.7	13.8	12.4
SO_2F	15.8	13.9	12.8	17.4	16.0	13.8
SO_2G	6.0	4.2	3.7	6.3	4.4	4.6
SO_2H	21.0	16.1	14.8	28.5	24.6	23.9
SO_2I	8.9	9.1	9.0	9.2	9.8	10.1
SO_2J	19.0	12.6	10.2	16.5	16.4	17.4
SO_2K	18.9	15.1	-	18.4	17.6	-
SO_2L	10.6	17.4	19.0	10.4	10.9	14.6
SO_2M	20.5	11.3	8.0	19.2	17.7	16.6

* In micrograms per cubic meter

** Months for cyclical dominance

TABLE A-27

Monthly Average TSP Concentrations Measured During the Period December, 1973 to June, 1974 in the Metropolitan Boston Air Pollution Control District*

Data Series	Trend Cycle Series			MCD** Series		
	Dec. 1973	May 1974	June 1974	Dec. 1973	March 1974	April 1974
TSP1	87.6	80.9	84.7	89.4	74.3	78.4
TSP2	41.0	36.8	38.1	38.6	36.4	36.6
TSP3	24.4	19.0	18.4	24.9	20.8	20.1
TSP4	32.4	25.3	24.2	32.5	28.1	28.7
TSP5	37.7	41.4	41.9	39.7	38.6	40.2
TSP6	48.0	44.1	——	51.2	44.6	——
TSP7	44.0	27.7	25.0	44.7	33.6	26.0

* In micrograms per cubic meter

** Months for cyclical dominance

AQCR, i.e., December 1973 through June 1974. These component series were produced using a multiplicative model in the X-11 ratio to moving average analysis. Note that due to the manner in which the MCD component series are computed, they end two months before the trend-cycle series.

A comparison of the December 1973 values with later values indicates quite clearly that the ambient levels of SO_2 and TSP did not rise in general during the period December 1973 to June 1974. On the contrary, significant decreases in ambient SO_2 and TSP levels were found to occur during this period using the Sign test at the 5 percent significance level applied to the MCD component data. As outlined in Section VI.A.1.a.(1), the MCD series is the most sensitive indicator output by the X-11 analysis for judging the behavior of short-term trends.

d. Trends in Measured Heating Degree-Day and Wind Speed Data

Previous analysis employing exponential smoothing and multiple linear regression techniques focused on the time periods associated with the effective dates of fuel use regulations and variances in order to observe any concurrent changes in the trend of measured air quality data. Additional time periods which warranted investigation were those during which heating degree-days and mean wind speed deviated significantly from climatological averages. Degree-days are a measure of local fuel burning activities and emissions; mean wind speed is a measure of the dilution capability of the atmosphere.

Monthly heating degree-days and mean wind speed measured at Boston's Logan International Airport are shown in Figures A-41 and A-42, respectively, as a ratio to the 30-year measured climatological averages. Gaps in the plot shown in Figure A-41 correspond to the summer season during which the ratio becomes meaningless due to diminishingly small or zero monthly degree-days totals. For this reason, extreme values which occurred in the late spring and early fall of several years, proximate to the summer season, had to be ignored. A significance level of 20% deviation from climatology was arbitrarily chosen and marked off on the graphs.

Figure A-40

Ratios of Monthly Heating Degree Days to 30-year Climatological Averages in Boston, Mass.

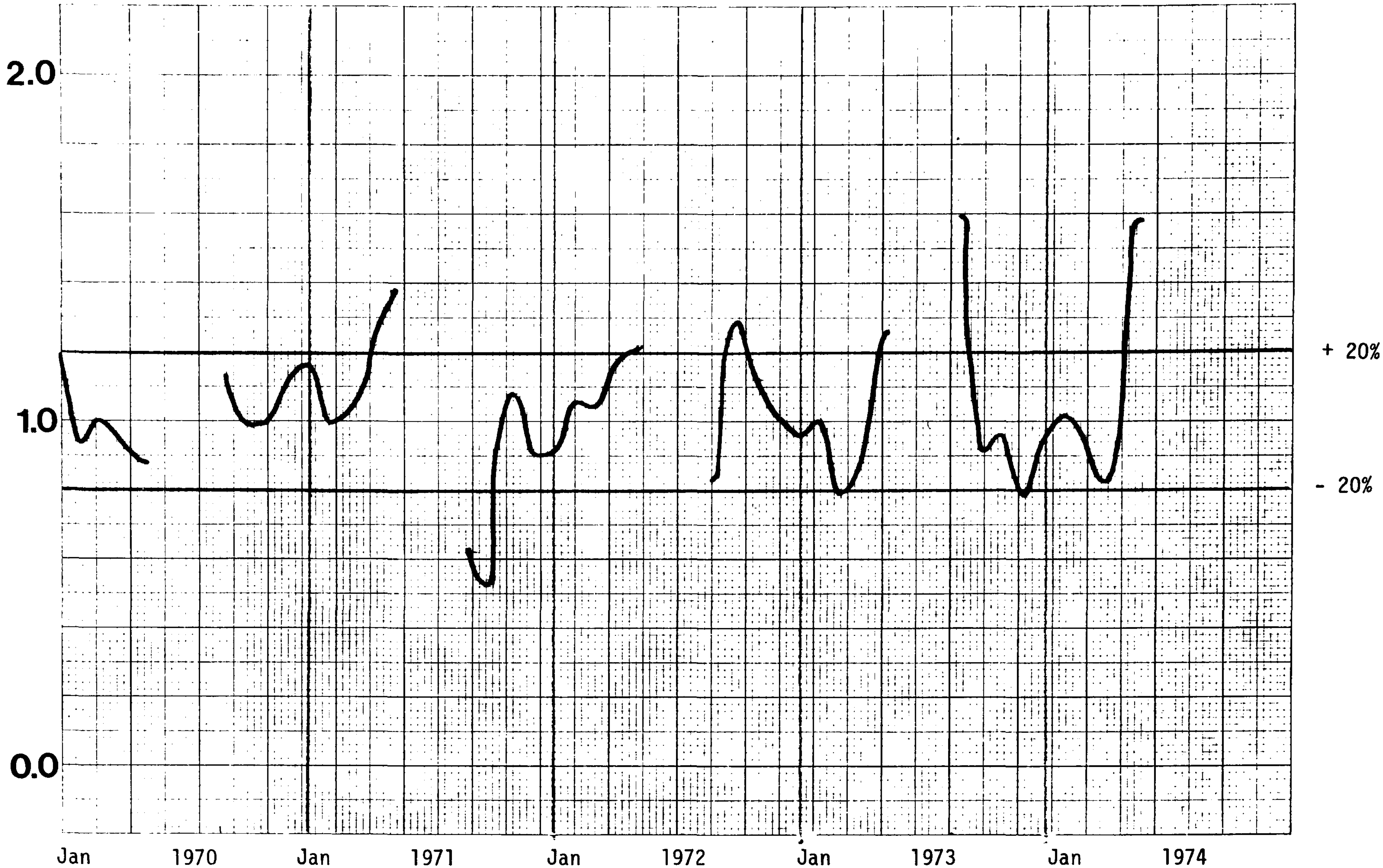
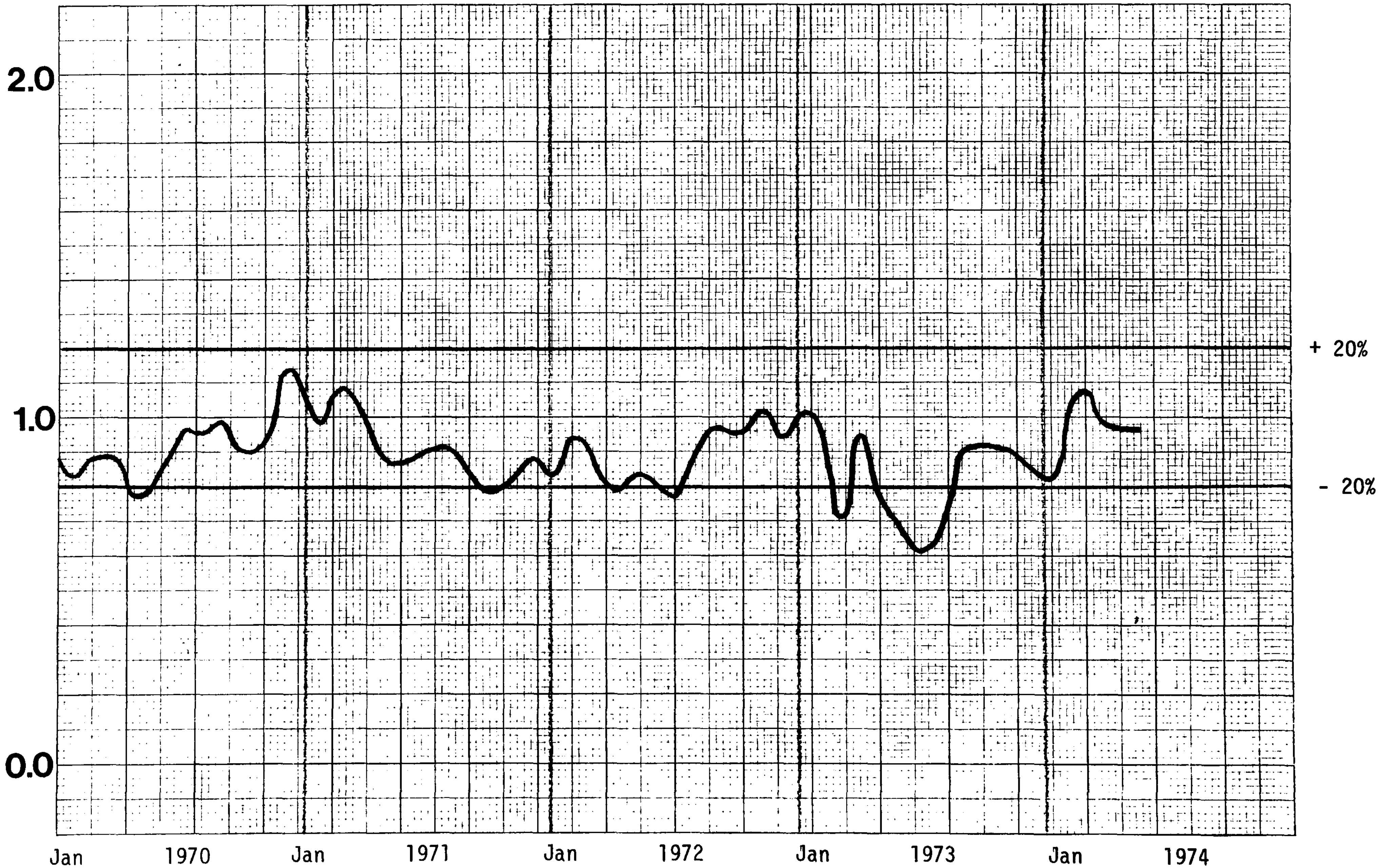


Figure A-41

Ratios of Monthly Mean Wind Speed to 30-year Climatological Averages in Boston, Mass.



It can be seen from Figure A-41 that the significant features are a marked increase in heating degree-day ratios from September 1971 to May 1972 and a decrease from October 1972 to March 1973. An examination of the trend-cycle component graphs for the six representative data series (Figures A-2 through A-7) showed that concurrent changes in the trend of measured air quality data occurred in the SO_2B (Kenmore Square, Boston) and TSP7 (Beaver Street, Waltham) series. During these two time periods, the trend-cycle component of the SO_2B series is positively correlated with heating degree-day totals. The trend-cycle component of the TSP7 series, however, is negatively correlated with heating degree-days in the same time periods, moving in the opposite directions. These results are in agreement with corresponding statistics derived in the multiple regression analysis and shown in Tables A-14 and A-15.

The graph of mean wind speed ratios (Figure A-42) exhibits only one significant feature, a marked decrease from April through October 1973 with a low point in July 1973. Concurrent rises in trend-cycle components during this period with peaks near July 1973 occurred in the SO_2B, TSP1 (Kenmore Square, Boston), and TSP7 series. These results compare favorably with the correlation structure for the entire TSP7 series from the regression in Table A-15. Here, the correlation of the reciprocal of wind speed with particulate levels is positive, as assumed in most air quality diffusion models. For the entire SO_2B and TSP1 series, however, the correlations with wind speed were found to be near zero in the regression analysis (see Section VI.A.2.b.(2)).

In general, therefore, an independent analysis of the time periods in the six representative series during which heating degree-days and mean wind speeds deviated significantly from climatological averages confirmed the results from the stepwise multiple linear regression analysis.

APPENDIX B

EMISSIONS AND REGULATORY ANALYSIS

B-1. PROJECTION AND APPORTIONMENT PROCEDURE

Projection of 1972 fuel use and emissions to the years 1973 and 1974 was accomplished (1) through the application of general indicators of economic and population change to the base year fuel use inventories to adjust industrial process fuel use, and (2) by applying estimates of degree-day differences between the base year and the year of interest to adjust space heating fuel use. This appendix summarizes the input data and tasks involved in performing these projections.

1. Point Source Update

Using information obtained from the Massachusetts Bureau of Air Quality (BAQC), a tabulation was made of all point sources which opened or closed between 1972 and 1974. This study indicated that no new point sources opened in 1973. A number of small existing sources which had previously been grouped within an area source were registered during 1973; however, these sources did not represent new fuel use and, thus, were not specifically introduced into the inventory.

Most significant of the point source closures between 1972 and 1974 was a bisulfite plant,located several kilometers from downtown Boston, which ceased operation in 1973. This plant had emitted SO_2 at an annual average rate of 0.037 kg/sec (1,286 tons/year) while in operation. Several small incinerators were also closed during this period as a consequence of the BAQC's particulate control efforts.

2. Growth Factor Development

Demographic indicators used to estimate changes in fuel use due to changes in population and the economy were obtained from various state agencies in the Commonwealth of Massachusetts. Specifically, population growth projections by city and town for the period 1970 to 1975 were received from the Department of Environmental Affairs. These factors were summarized by U.S.G.S. topographic quadrangle based on the relative land area of each city or town in the quadrangle. During summarization, some municipalities were assigned a zero weighting factor if it appeared that the population growth for that city would not be indicative of the quadrangle growth. This occurred if, for example, only a town's conservation land was in the quadrangle in question. Table B-1 summarizes these growth rates.

During the step associated with the application of these factors to the base year inventory for projection of residential fuel use, it was noted that differences in growth rates among quadrangles was very slight. Also, grouping core municipalities (Boston and the 12 surrounding communities) with neighboring suburbs tended to mask the trend of "urban flight". Therefore, it was decided to project residential fuel use only on a core-noncore basis, as also shown in Table B-1.

Industrial and commercial growth were estimated by projections made by the Department of Manpower Affairs of employment growth for the Metropolitan Boston SMSA. The annual growth rates derived from these data were 0.58% for industrial and 3.39% for commercial facilities, respectively.

3. Conservation Analysis

A survey of principal fuel users and distributors was conducted to determine a quantitative estimate of fuel savings which resulted from conservation efforts in the AQCR during the winter of 1973-74. The results of this survey are included as Appendix B-2.

4. Disaggregation of Seasonal Fuel Use

The NEDS point source file contains an estimate of the fraction of fuel each source uses for space heating. These data were used to disaggregate the fuel use of each point source into a space heating and a process use component. Estimates of the space heating use for each source category of the area source inventory were based on the average percent spaceheating requirement from a comparable point source category, or by procedures outlined in Reference 31. These procedures resulted in an estimate that 80 percent of residential and commercial-institutional fuel is used for space heating. Industrial fuel was assumed to be used entirely for process applications.

TABLE B-1

AVERAGE ANNUAL POPULATION GROWTH RATES
SUMMARIZED BY U.S.G.S. TOPOGRAPHIC QUADRANGLE
1970 – 1975

Quadrangle	Percent Population Change
Billerica	7.90
Blue Hills	1.38
Boston North	0.49
Boston South	-0.39
Brockton	1.98
Cohassett	2.05
Concord	2.62
Duxbury	4.30
Framingham	1.28
Franklin	7.55
Gloucester	0.97
Hanover	1.88
Holliston	2.16
Hull	-0.20
Ipswich	2.32
Lexington	1.13
Lynn	0.16
Mansfield	2.07
Marblehead North	1.79
Marblehead South	-0.02
Maynard	0.85
Medfield	3.67
Nantasket	-1.11
Natick	1.65
Newton	0.30
Norwood	1.73
Reading	1.60
Rockport	1.97
Salem	1.64
Scituate	3.89
Weymouth	0.81
Whitman	1.50
Wilmington	1.88
Wrentham	2.46

Average Core Area (13 Cities) Change -0.30%

Average Noncore Area Change 1.37%

5. Regional Meteorological Analysis

A study of the variation in heating requirements throughout the AQCR was performed. Table B-2 presents the ratio of annual degree-day totals to climatological mean degree-days for five meteorological stations located within or near the Metropolitan Boston AQCR. These data indicate that departures from climatological normals are not uniform through the area. However, these variations are not extreme, allowing for the assumption that degree-days totals recorded at Boston's Logan International Airport are representative of the AQCR.

Table B-3 presents a breakdown of the fraction of degree-days occurring in each quarter at Logan. These data were used to apportion fuel use to quarters.

6. Projection/Apportionment

Projection and apportionment of the point and area source inventory was performed by applying growth, conservation, and degree-day factors according to the relationship:

$$F_2 = 0.0025F_1 \sum_{i=1}^{4} (con_i)[(sh)(dd')(q_i) + (100 - sh)gf]$$

where:

F_2 = projected fuel usage (mass/year)

F_1 = base year fuel usage (mass/year)

sh = portion of fuel used for space heating (percent)

dd' = adjusted ratio of degree-days observed during the projected period to those observed during the base period

i = quarterly summation indicator

con_i = an estimate of the effect of fuel conservation by quarter

gf = the growth factor; an estimate in the change in activity of the source based on its SCC code

q_i = portion of annual degree-days occurring in each quarter

This procedure was used to simultaneously create a projected annual

TABLE B-2

COMPARISON OF ANNUAL DEGREE-DAY RATIOS*

FIVE STATIONS IN METROPOLITAN BOSTON

AIR POLLUTION CONTROL DISTRICT

Station	1969-1970**	1970-1971	1971-1972	1972-1973
Boston WSO (Logan International)	1.023	1.081	0.982	0.980
Worcester	1.059	1.053	0.989	0.988
Taunton	1.100	1.091	1.053	1.018
Chestnut Hill	1.130	1.214	1.111	msg
Framingham	1.110	1.112	1.039	0.998
Mean	1.084	1.110	1.035	0.996+

* Base period: 30-year climatology for each station

** Annual totals are based on year July through June

\+ Four-station average

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TABLE B-3

PROPORTION OF DEGREE-DAYS OCCURRING IN EACH QUARTER

BOSTON (LOGAN INTERNATIONAL AIRPORT)

1st Quarter (Jan., Feb., Mar.)	0.516
2nd Quarter (April, May, June)	0.134
3rd Quarter (July, Aug., Sept.)	0.012
4th Quarter (Oct., Nov., Dec.)	0.388

fuel use inventory plus inventories for each of quarterly periods of interest.

7. Verification of 1973 Projections

Verification of 1973 annual fuel use totals for the AQCR were performed by comparing projected fuel use totals by fuel type and source category to similar data estimated by the Bureau of Mines (23). These data were apportioned to the AQCR from the State total by assuming that the relative proportions of AQCR to state fuel use remained constant from 1972 to 1973.

Initial results of this study indicated that the degree-day factor "dd", in the growth equation overestimated the effects of degree-day differences. Indications were found [27] that this factor should not be linear but rather a logarithmic function of degree-days. A regression performed on independent fuel use totals indicated that the equation

$$dd^1 = 1.2 \log(dd) + 1$$

fit well the variations in space-heating fuel use in New England.

Table 3-2 in Section III presents projected annual fuel totals for 1972 through 1974 and a comparison with Bureau of Mines data for 1972 and 1973.

8. Fuel Quality Survey

The extent to which fuel did not conform to SIP regulations during the winter of 1973-74 and an estimation of the sulfur content of the non-conforming fuel was determined by a survey of the major fuel distributors and users in the area. These data were used to create the actual emissions inventory for 1974. The results of this survey are contained in Appendix B-3. The final emissions inventory for each year including the effects of nonconforming fuel are presented in Table 3-4 of Section III.

B-2. FUEL CONSERVATION

Estimates of the impact of fuel conservation efforts on total fuel usage for each fuel type in the MBAQCR were compiled by surveying major fuel users and suppliers in the region. The survey group was chosen to provide information from a broad cross-section of fuel use categories throughout the area. When available, published data were also used to aid in quantifying the conservation efforts.

1. Distillate Oil

The New England Fuel Institute (NEFI) has compiled figures on total distillate oil use in Massachusetts in calendar years 1972 and 1973 [32]. These data reveal sales of distillate oil dropped 2.3 percent in 1973 from 1972 levels. No 1974 data were available.

In March 1974, NEFI reported [33] that conservation and weather combined achieved over a 20 percent reduction in distillate oil consumption in New Englnad last winter. More recently, NEFI has reported [32] that conservation measures affected a 14.8 percent reduction and warmer weather a 6.7 percent reduction in distillate oil usage in New England last winter. The Better Home Heating Council estimated [4] reductions of 10-15 percent in distillate use in Boston due to conservation measures alone. Northeast Petroleum reports that distillate oil deliveries to more than 900 retail dealers they supply in Massachusetts were down 15-17 percent during the 12-month period starting October, 1973.

From these data, conservation of distillate oil was assumed to be ten percent of total fuel conumption during the last quarter of 1973 and 15 percent in 1974.

2. Residual Oil

NEFI statistics for residual oil use in Massachusetts indicate total sales in calendar year 1973 fell 2.1 percent from 1972 levels. NEFI does not have any information regarding conservation of residual oil last winter in New England.

The regional director of the Federal Energy Administration (FEA) in Boston, Mr. Robert Philpott, has stated [34] that the effectiveness of conservation efforts has not been studied so far.
An individual effort worth noting was MIT's residual oil usage which dropped 6 percent in 1973 from 1972 levels and fell an additional 23 percent in 1974. MIT's fuel use in the emissions inventory was adjusted to reflect these specific data.

Monthly totals of Boston Edison's production of electricity fell from predicted levels in late 1973 and early 1974. New England Power Co. did not reply in this area. Electrical power generation sources burn 78 percent of the residual oil used by point sources in Metropolitan Boston. Assuming Boston Edison's figures are representative of all electrical power usage in Metropolitan Boston, fuel conservation efforts accounted for a nine percent reduction in electrical power fuel use during the fourth quarter of 1973 and a four percent decrease in 1974. The effect of degree-days on these totals was assumed to be negligible.

Of all fuel suppliers surveyed, only Northeast Petroleum and Union Petroleum could provide information on trends in residual oil deliveries last winter. Northeast reports that residual oil deliveries in Boston were down 10-12 percent during the 12-month period starting October 1973. During this time period, degree-day totals were about 5 percent below normal. Union reports residual oil deliveries in Boston were down about 25 percent last winter. NEFI estimates degree-day totals last winter were about 7 percent below normal. Assuming these dealers service mostly small source users of residual oil(i.e., area sources), the degree of conservation attributable to these sources was an 8 percent reduction in the last quarter of 1973 and 12 percent in 1974.

3. Natural Gas

Boston Gas officials reported [34] that natural gas usage dropped 10-20 percent in Boston in 1974 from 1973 after correcting for weather effects.

Due to the similarity of user types, the effects of conservation of natural gas were assumed to be the same as those for distillate oil, i.e., 10 percent at the end of 1973 and 15 percent in 1974.

4. Gasoline

Data from the Massachusetts Department of Corporations and Taxes indicate that total gasoline consumption in Massachusetts rose 3.1 percent from 1972 and essentially returned to 1972 levels in 1974.

B-3. REGULATORY AND VARIANCE IMPLEMENTATION

Estimates of the extent to which SIP variances, granted as a result of the energy shortage, were implemented were made through a survey of major fuel users and distributors in the MBAQCR. Results of a similar survey conducted by the Massachusetts' BAQC have been used to supplement the information received by Walden, and the BAQC information was assumed to be correct whenever conflicting information was received from an individual contact.

The following subsections (A&B) summarize the results of the survey by fuel type. Results are in the form of scaling factors, i.e., the ratio of the average emission rate of the pollutant for actual and for full variance implementation to that of the SIP Regulation, assuming constant fuel use.

A. Sulfur Dioxide Scale Factors

1. Distillate Oil

The associated variance relaxed the SIP Regulation statewide to allow use of 0.5 percent sulfur distillate oil (0.5% S) instead of 0.3 percent sulfur fuel.

For actual variance implementation, the scaling factor of 1.02 was determined from the survey results. An analysis by the BAQC suggests approximately 9 percent of distillate used was nonconforming at about 0.37% S. This would also imply use of a scaling factor of 1.02.

For full variance implementation, distillate emissions were multiplied by 1.67.

2. Residual Oil

The associated variances were only granted to certain sources and in general allowed use of 1.0% S instead of 0.5% S residual oil in the core and 2.2% S instead of 1.0% S residual oil outside the core area.

Residual oil use during the winter of 1973-74 in the Metropolitan Boston AQCR can be categorized as follows:

		10^3GAL/YR	% OF TOTAL
Point Source	Granted Variance	1,078,479	56.2
Point Source	No Variance	88,355	4.6
Area Source	Granted Variance	127,748	6.7
Area Source	No Variance	623,712	32.5
		1,918,294	100.0

a) Point Sources

Table 3-3 in Section III presents the actual and full variance sulfur contents of residual oil used by point sources that were granted variances.

b) Area Sources

For actual variance implementation, a scaling factor of 1.13 was determined from survey results for sources in the core, 1.00 for sources out of the core.

For full variance implementation, residual area sources emissions were multiplied by 1.18. Although full variance implementation would be expected to more than double emissions, only 17 percent of residual area sources were granted variances.

3. Coal

The only variance associated with coal was to allow units 1, 2, and 3 of New England Power Co.'s Salem Harbor Plant (point sources) to burn 2.5% sulfur and 15% ash coal instead of residual oil after Jan. 23, 1974.

For actual variance implementation, coal with an average sulfur content of 0.77% was burned in units 1, 2, 1nd 3. No change in this factor, to account for oil usage in January, 1974, is necessary due to the low sulfur content of the coal that was burned. The scale factor for actual implementation is 1.05.

For full variance implementation, 2.6% sulfur residual oil could have been used from Jan. 1 through Jan. 22, 1974, and 2.5% sulfur coal from Jan. 23, 1974, through March 31, 1974. To account for this split, coal combustion was used in the inventory for units 1,2, and 3, and SO_2 emissions were multiplied by 0.94 to account for the 22 days of lower emissions from oil. The net scale factor was then 3.2.

B. Particulate Scale Factors

1. Distillate Oil

No increase in particulate emissions was assumed to result from full or actual variance implementation.

2. Residual Oil

No increase in particulate emissions was assumed to result from full or actual variance implementation.

3. Coal

The only variance affecting coal consumption during the energy shortage involved 15.6 percent ash coal burned in units 1, 2, and 3 of NEPCO's Salem Harbor Plant. The full and actual variance implementation cases for this facility are identical. The particulate emission rate for 15.6 percent ash coal is about 150 times greater than that for an equivalent quantity of oil. However, electrostatic precipitators used on these units resulted in a 92 percent reduction in particulate emissions. After adjusting for oil use during the first three weeks in January, plus the control efficiency of the precipitators, the net scale factor was 9.11.

APPENDIX C

MODELING ANALYSIS

C-1. AIR QUALITY MODEL AND SIMULATION SCALING PROCEDURE

A. Dispersion Model

References 28, 29, and 30 describe the basic Air Quality Display Model*, which was used in this analysis to predict ground level concentrations of TSP and SO_2 throughout the Metropolitan Boston AQCR. Consequently, an extended discussion of the model is not repeated here. However, several modifications to the basic form of the model were introduced in the analysis. These included:

· The Briggs plume rise equations were substituted for the Holland equation specified in the original model.

· A source contribution file was created to facilitate strategy simulations and to bypass the more costly control strategy approach of the IPP model.

The input data to the model included the STAR meteorological wind-stability data for each of the first quarters of 1972-1974 as recorded at Bsoton's Logan International Airport and the emissions inventories described in Section III.

The half-life of sulfur dioxide was assumed to be 0.5 hours in this study. This value, which is considerably less than the generally accepted value of three hours, was suggested by the Massachusetts Bureau of Air Quality Control (BAQC). This value of the half-life of SO_2 provided a better correlation with observed data in modeling runs of Metropolitan Boston performed by BAQC.

The effective stack height of each individual area source grid was computed by averaging the mean effective stack height of each of the following emissions categories, weighted by its relative emission strength within each grid.

---

* As incorporated in IPP.

Source Category	Mean Effective Stack Height (m)
Residential	15
Commercial-Institutional	47
Industrial	58
Incineration	23
Roadway	4

The mean effective stack heights were computed by the BAQC using average source parameters for each category and the Briggs' plume rise equations.

B. Scaling Procedure

The simulation of the no variance and full variance cases was performed by developing scale factors to reflect the change in emissions resulting from the various degrees of variance implementation. These scale factors were then multiplied by the corresponding source contribution and summed for each receptor to determine the change in concentration resulting from the simulation.

The basic scaling equation used was

$$\chi^*_{ik} = \sum_{j=1}^{N} \alpha_{jk}\chi_{ijk}$$

where

χ^*_{ik} = total contribution of pollutant k from all sources at receptor i under the strategy simulation

χ_{ijk} = contribution of pollutant k from source j to receptor i for 1974 actual conditions

α_{jk} = ratio of new emission estimate to original emission estimate for pollutant k and source j

N = total number of sources

The χ_{ijk} are contained on the source contribution file tape, and the α_{jk} are the scale factors for the no variance and full variance cases presented in Appendix B-3.

Walden

C-2. RECONCILIATION, VALIDATION, AND CALIBRATION

In order to calibrate the predictions of the air quality model, measurements of SO_2 and TSP concentrations recorded within the Metropolitan Boston AQCR were obtained from EPA and the Massachusetts Bureau of Air Quality Control (BAQC). The initial group of sampling receptors were carefully chosen to provide (1) a common measurement procedure, for SO_2 and TSP, i.e., the West-Gaeke bubble technique for measurement of SO_2 and the high volume sampler for measurement of TSP, and (2) a sufficient historical record, i.e., continuous operation from January 1972 through March 1974.

1. Sulfur Dioxide

a. Initial Reconciliation

Thirteen monitoring sites, listed in Table C-1, were initially selected for further study. Consultation with field personnel of the MBAQC indicated that the Government Center site was not to be considered representative of air quality in that area due to changes in air flow patterns induced by new multistory office construction in the area between 1972 and the present; all other sites were initially assumed to be representative of ambient air quality in the vicinity of the receptor.

Air quality monitoring using the bubbler method is usually performed for 24 hours once every six days, resulting in an average sampling frequency of five observations per month. Criteria for the representativeness of quarterly data were thus developed to exclude a quarterly (three-month) average if it was composed of less than three observations (or 60%) in any of the component months. Quarterly averages were computed by averaging the three monthly means, thus, preventing a bias caused by unequal numbers of samples among the months. A number of sites were excluded by the "three observation" criteria. These sites are annotated in Table C-1. Further study of the representativeness of monitoring sites indicated that two receptors, those in Quincy and Revere, were located on the roof of buildings only a few meters from the chimney of residual-oil burning boilers. These sites were also excluded from the validation process.

TABLE C-1

CONCENTRATIONS OF SULFUR DIOXIDE (SO_2) AND TOTAL SUSPENDED PARTICULATES MEASURED IN THE METROPOLITAN BOSTON AQCR (FIRST QUARTER)

	SO_2*			TSP*		
Site	1972	1973	1974	1972	1973	1974
Government Center**	--	66	33	--	--	--
Kenmore Square**	104	73	30	161	147	84
South Bay	39	68+	27	--	--	--
East Boston	39	22	15	--	--	--
Brookline	34	51	22	48	50	32
Medford	24	13+	33	--	--	--
Needham	13	18	19	41	39	29
Norwood**	17	34	34	42	67	42
Waltham	32	20	20	32	45	29
Woburn	17	--	31	--	--	--
Marblehead	--	--	17	--	--	--
Quincy**	50	58	36	55	55	56
Revere**	58	42	43	54	--	--

* units: $\mu g/m^3$

** excluded from validation due to localized source influence

\+ excluded from validation due to insufficient data (see text)

-- no data recorded

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An analysis of the measured SO_2 data was also conducted to determine the possible deviation of the true mean of SO_2 levels at a given site from the measured mean. The number of samples taken during a given quarterly period at a sampling station is usually less than 12. This may allow a large discrepancy to appear between measured and actual means. An analysis based on the observed standard deviation at each site indicated that at the 5 percent significance level, the true mean often could vary from zero to twice the reported mean. This indicates that some of the apparent error in the model predictions results from sampling error. Kenmore Square is an important exception to this observation. At this site, there were sufficient observations to indicate that the reported mean would not be significantly different from the true mean (although sampling at Kenmore was never conducted on Sunday). This implies that any difference between predicted and observed values at Kenmore are due to other factors, e.g., the inventory, the model, or micro-meteorological differences.

b. 1972 Validation Run

The 1972 first quarter emissions inventory was processed to predict SO_2 concentrations at the reconciled monitoring sites for the validation (see Table C-1). The initial run indicated that SO_2 concentrations were overpredicted by a factor of two and the correlation coefficient was about 0.7.

Analysis of the source contribution file for sulfur dioxide indicated that area sources relatively far from the receptor (15 km) were contributing more sulfur dioxide to the receptors than would be reasonably expected. Consultation with the Massachusetts Bureau of Air Quality Control (BAQC) indicated that they had experienced similar problems in modeling the Metropolitan Boston area as part of the Air Quality Maintenance Plan process. The Bureau indicated that reducing the half-life of SO_2 in the atmosphere from three hours to 0.5 hours resulted an a better correlation with observed data [35].

These initial validation steps also indicated that two sites, Kenmore Square and Norwood, were significantly underpredicted. This same result has been obtained in other attempts to model the Metropolitan Boston area [35] and has been attributed to a combination of sampling error, micrometeorology, and modeling error; these sites were, therefore, excluded from the validation step.

A second validation run using the 1972 first quarter inventory and the above changes resulted in a statistically significant linear regression correlation coefficient of 0.86 and a significant improvement in the degree of overprediction. A regression analysis of the measured (Y) versus predicted (X) concentrations for the seven reconciled sites yielded the following line of best fit:

$$Y = 0.60X + 10.$$

However, since the natural background for SO_2 is approximately zero, and the predicted intercept is only 10, the forced zero-intercept form of regression analysis was used. The results of this analysis indicated the line of best fit:

$$Y = 0.86X$$

with a correlation coefficient of 0.75, which is also statistically significant.

c. 1973, 1974 Validation Runs

The 1973 and 1974 first quarter inventories were each processed to provide predictions of air quality at the reconciled monitoring sites in Table C-1. Regression analyses of these predictions versus measured data indicated that the 1973 line of best fit was statistically the same as that for 1972. However, the correlation coefficient for this year was 0.54 using the slope-intercept method, and 0.48 using the slope-forced-zero-intercept procedure. Neither of these values is statistically significant, considering the size of the data sample analyzed.

In 1974, SO_2 levels at many of the air quality receptors in the MBAQCR were below the minimum sensitivity level of the monitoring instrument (25 $\mu g/m^3$). Thus, differences among measured means may not represent true variations. An analysis of the 1974 first quarter measured data indicates extreme scatter in these values.

The expected spatial distribution of SO_2 concentrations where the mean is greater in urban areas and lower in suburban areas is not apparent in the 1974 data. Two urban sites, East Boston and South Bay, located only five kilometers apart, reported concentrations of 15 $\mu g/m^3$ and 27 $\mu g/m^3$, respectively, in 1974, whereas each site had reported 39 $\mu g/m^3$ in 1972. Kenmore Square, an urban site, averaged 104 $\mu g/m^3$ in 1972; Norwood, a suburban site, averaged 17 $\mu g/m^3$. In 1974, Norwood was actually higher than Kenmore Square, 37 $\mu g/m^3$ versus 30 $\mu g/m^3$.

This extreme variance in spatial and temporal patterns of measured data has been inexplicable. Thus, an extremely poor correlation was obtained when attempting to validate the 1974 measured versus predicted concentrations. However, a visual study of the data indicates that the 1972 line of best fit provides a reasonable fit of the 1974 data.

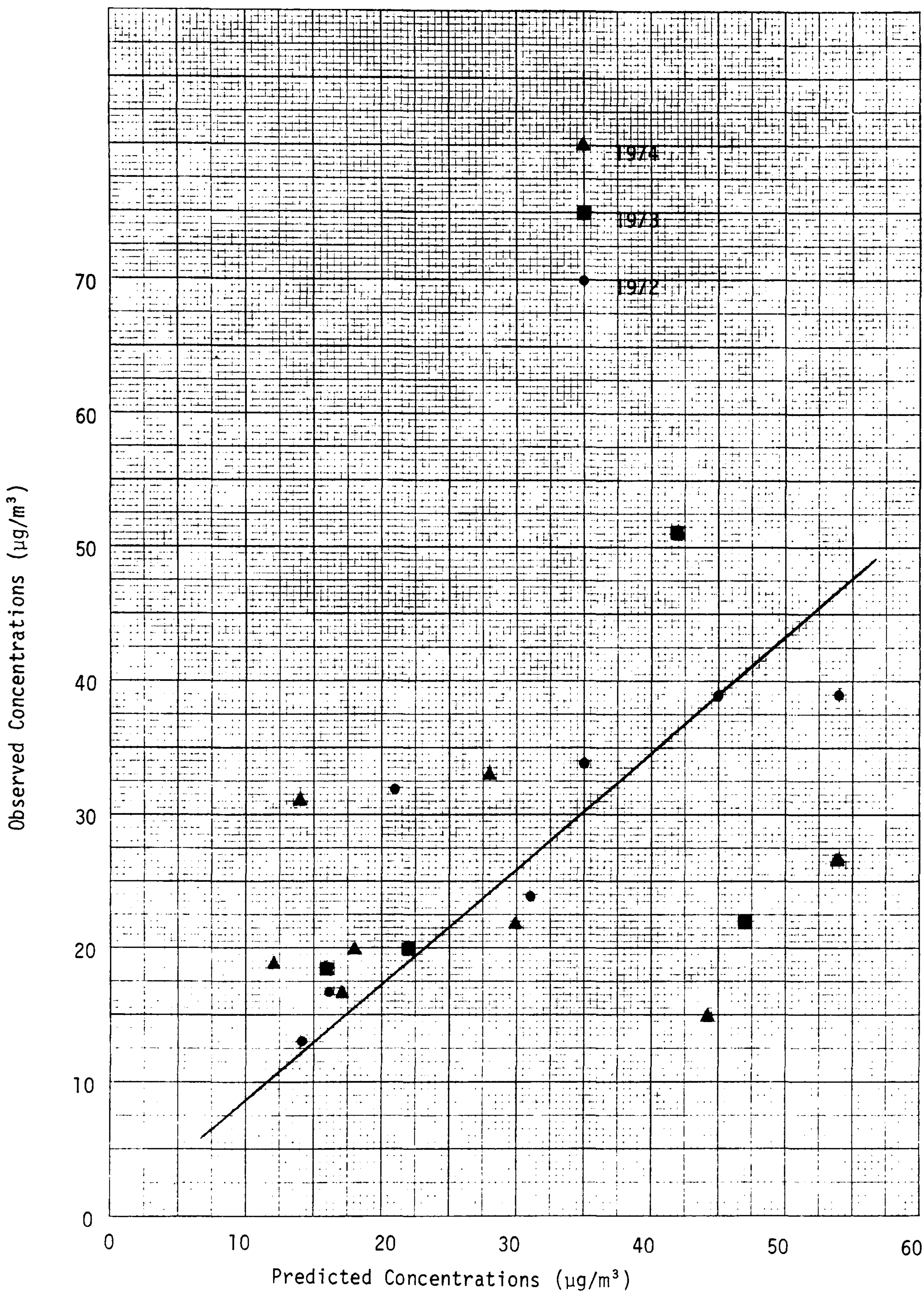
Figure C-1 presents the results of the validation for each year and compares these observations to the 1972 line of best fit, i.e., the forced-zero intercept, which was used for calibration.

2. Total Suspended Particulates (TSP)

Seven monitoring sites were initially selected for further study. Table C-1 lists these sites. Criteria for excluding TSP monitoring data were identical to those used for SO_2 (see preceding subsection).

Exclusion of some sites in an initial reconcilation and of two others as a result of this validation analysis (see preceding subsection) resulted in only three usable monitoring sites, which is an inadequate basis for performing a meaningful regression analysis. However, due to the favorable agreement among the SO_2 regression parameters obtained in each of the years, it was decided to perform a validation by combining data from all three years for the three sites.

FIGURE C-1. SULFUR DIOXIDE



This regression provided a best line of fit of

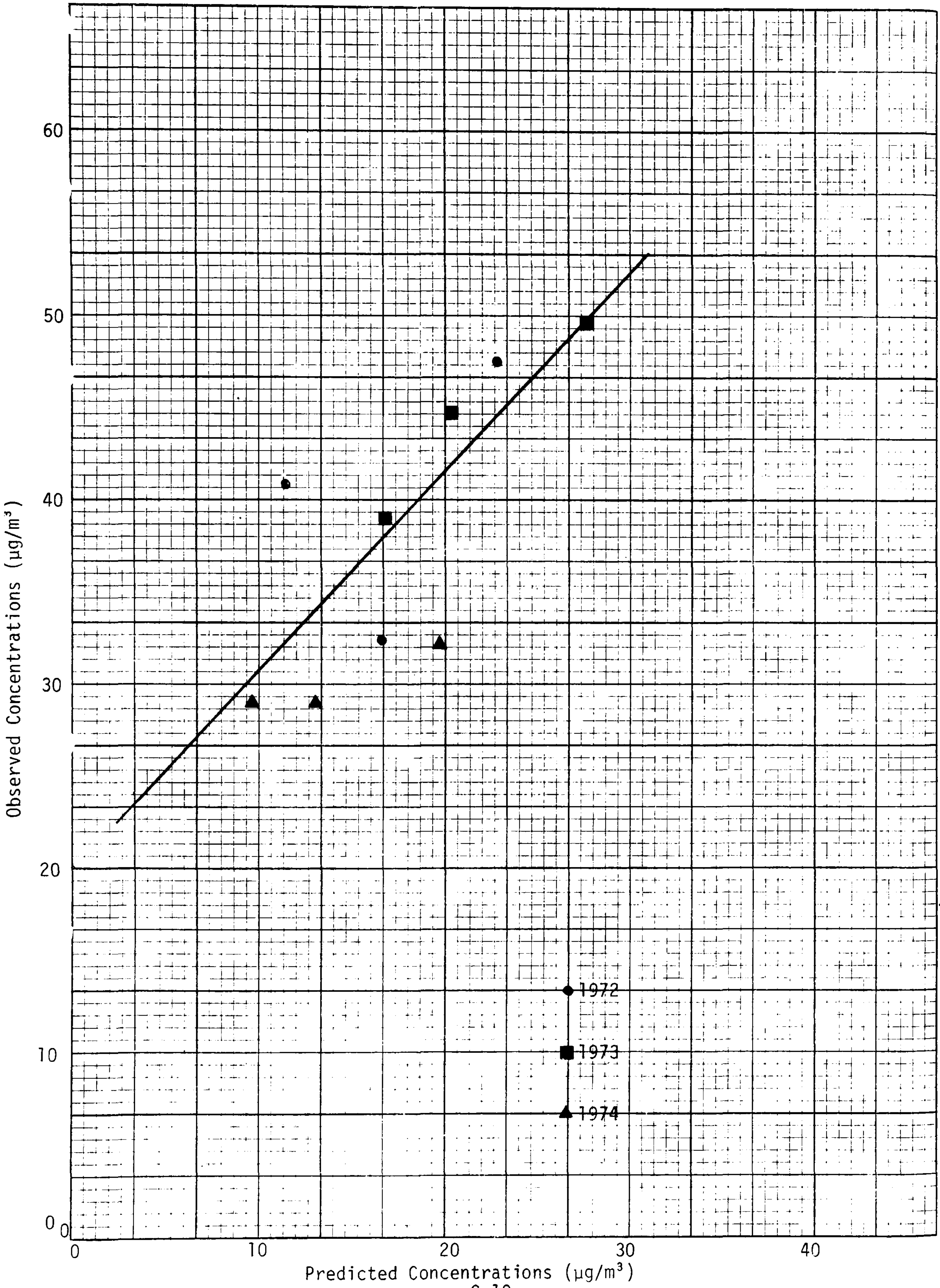
$$Y = 1.07\ X + 20$$

and a statistically significant correlation coefficient of 0.73.

This equation was used for the TSP calibration procedures.

The forced-zero-intercept regression was not used, due to the existence of a significant natural TSP background.

FIGURE C-2. TOTAL SUSPENDED PARTICULATES



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16. ABSTRACT

The purpose of this project was to evaluate the impact of the energy shortage on ambient sulfur dioxide (SO_2) and total suspended particulate (TSP) concentrations in a major urban area, Metropolitan Boston. A combined approach based on a statistical analysis of measured air quality data, regulatory and emissions analysis, and diffusion modeling of changes in ambient pollutant concentrations was used to attain this objective.

The objective of the air quality analysis was to identify and interpret changes in trends of measured SO_2 and TSP levels between January 1970 and March 1974 with regard to SIP regulations, variances granted because of the energy shortage, and meteorological conditions. The objective of the regulatory and emissions analysis was to develop quarterly emissions inventories for SO_2 and particulates in Metropolitan Boston for the period January 1973 to June 1974 to support the subsequent modeling analysis task. The objective of the diffusion modeling task was to obtain a clear understanding of the impact and potential impact of the energy shortage on air quality levels by isolating the relative effects of factors such as meteorology, growth and conservation, and variances on ambient SO_2 and TSP concentrations.

17. KEY WORDS AND DOCUMENT ANALYSIS

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