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A REGIONAL CHARACTERIZATION OF PARTICULATES IN NORTHEASTERN MINNESOTA

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Minnesota Environmental Quality Board
Regional Copper-Nickel Study
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INTRODUCTION TO THE REGIONAL COPPER-NICKEL STUDY

The Regi l Copper-Nickel Environmental Impact Study is a comprehensive examination of the potential cumulative environmental, social, and economic impacts of copper-nickel mineral development in northeastern Minnesota. This study is being conducted for the Minnesota Legislature and state Executive Branch agencies, under the direction of the Minnesota Environmental Quality Board (MEQB) and with the funding, review, and concurrence of the Legislative Commission on Minnesota Resources.

A region along the surface contact of the Duluth Complex in St. Louis and Lake counties in northeastern Minnesota contains a major domestic resource of copper-nickel sulfide mineralization. This region has been explored by several mineral resource development companies for more than twenty years, and recently two firms, AMAX and International Nickel Company, have considered commercial operations. These exploration and mine planning activities indicate the potential establishment of a new mining and processing industry in Minnesota. In addition, these activities indicate the need for a comprehensive environmental, social, and economic analysis by the state in order to consider the cumulative regional implications of this new industry and to provide adequate information for future state policy review and development. In January, 1976, the MEQB organized and initiated the Regional Copper-Nickel Study.

The major objectives of the Regional Copper-Nickel Study are: 1) to characterize the region in its pre-copper-nickel development state; 2) to identify and describe the probable technologies which may be used to exploit the mineral resource and to convert it into salable commodities; 3) to identify and assess the impacts of primary copper-nickel development and secondary regional growth; 4) to conceptualize alternative degrees of regional copper-nickel development; and 5) to assess the cumulative environmental, social, and economic impacts of such hypothetical developments. The Regional Study is a scientific information gathering and analysis effort and will not present subjective social judgements on whether, where, when, or how copper-nickel development should or should not proceed. In addition, the Study will not make or propose state policy pertaining to copper-nickel development.

The Minnesota Environmental Quality Board is a state agency responsible for the implementation of the Minnesota Environmental Policy Act and promotes cooperation between state agencies on environmental matters. The Regional Copper-Nickel Study is an ad hoc effort of the MEQB and future regulatory and site specific environmental impact studies will most likely be the responsibility of the Minnesota Department of Natural Resources and the Minnesota Pollution Control Agency.

A REGIONAL CHARACTERIZATION OF PARTICULATES IN NORTHEASTERN MINNESOTA

INTRODUCTION

Total suspended particulates (TSP) were sampled for comparison with federal and state air quality standards and for assessing present and projected environmental impacts. Readings in exceedance of these ambient standards have occurred in or near the Study Region. Both point sources, such as a smelter, and area sources, such as open pit mines and tailings basins associated with copper-nickel development, would be likely to cause increased particulate levels. Secondary development, such as expanded and new communities and increased automobile and truck traffic, may also contribute to increased particulate levels. Sampling and analysis of particulate data were designed to establish baseline levels for particulates, to establish differences currently existing between locations within the Study Region, and to determine what sources are currently contributing particulates. This last goal is particularly important as many sources that might result from copper-nickel development, such as mining, ore transport, tailing basins and secondary developments, will closely resemble existing sources. An evaluation of the contributions of these sources to present ambient levels will provide insight to the effects of additional similar sources from copper-nickel development.

The issue of regulations is important because much of the Study Region has been declared a non-attainment area for TSP; that is, concentrations of total suspended particulates (TSP) have exceeded the federal standards for ambient TSP concentrations. Existing particulate sources contributing to these exceedences are widespread and varied in type. Point sources include taconite processing plants, power plants, home heating, and, in the Duluth area, a whole range of industrial facilities. Taconite operations also contribute particulates through such activities as blasting, loading, hauling, dumping, and processing. Windblown particles from tailings basins, open areas and storage piles can account for a large portion of the emissions. Travel on gravel and dirt roads can produce large clouds of dust.

TSP concentrations were measured with high volume samplers (hi-vols) at sites representative of the various rural, industrial and community areas found in the Study Region. Sixteen locations were sampled, eleven in the Study Region and five in the Duluth area. Sampling site locations are shown in Figures 1 and 2 and are listed in Tables 1 and 2. Site descriptions can be found in Appendix 1. Samples were collected every sixth day following the U.S. Environmental Protection Agency schedule, and results were expressed as mean concentrations for each 24-hour period. Refer to the Air Quality Operations Manual for complete descriptions of sampling procedures. Sampling began at most sites on October 9, 1976, although the last site (Fernberg Road) was not operational until February 6, 1977. The final samples were taken on March 27, 1978. A maximum of ninety samples could have been taken at any site. The number of samples actually collected ranged between 86 (Hoyt Lakes Golf Course and Cloquet) and 63 (Hoyt Lakes Police Station). Missing values resulted from delayed startup at certain locations, weather problems, equipment failure, and illness of the field worker. Overall, 86% of the possible samples in the Study Region and 90% of the possible samples in the Duluth area were collected, a sufficient percentage for statistical analysis.

RESULTS

TSP data collected during the Study are presented in Table 3. Mean concentrations for the Study Area sites have been adjusted to eliminate bias due to missing values with a statistical model described in Appendix 2. Unless indicated otherwise, all annual means referred to in this report are the adjusted 1977 geometric means listed in Table 3. Time line plots of all TSP data are presented in Figures 3 through 18. Histograms illustrating the distribution of TSP concentrations at each sampling site may be found in Figures 19 through 22. A box plot, permitting easy comparison of results from all sites, is presented in Figure 23. This plot illustrates the median, quartiles, minimum value and maximum and second-highest sampled values for each site during 1977. Sample size is indicated below each site number.

1977 may not have been a representative year for particulate levels in the Study Region because of a strike against taconite mining opertions from August through December. This event very likely resulted in a significant reduction in the annual mean concentration at some sites. It should also be cautioned that the summary statistics found on the histograms may be biased because of missing observations.

COPPER-NICKEL STUDY REGION

Range of Impacts

Northeastern Minnesota experiences large temporal and spatial variations in particulate levels. Remote areas generally have quite low particulate concentrations and experience annual geometric mean TSP (total suspended particulates) levels in the 10 to 15 ug/m^3 range. During the base year 1977 with the taconite strike from August until December, the background sites at Fernberg Road, Kawishiwi Lab, and Toimi had adjusted annual geometric means of 10, 10 and 12 ug/m^3, respectively. These levels are far below the annual primary standard of 75 ug/m^3, and are typical of clean remote mid-continental areas (see Figures

24 and 25). 24-hour TSP concentrations in the remote areas were as low as an extremely clean 1 or 2 ug/m^3 and were rarely greater than 20 ug/m^3. The maximum measured 24-hour concentrations at Fernberg Road, Kawishiwi Lab, and Toimi during the study period October 1976 through March 1978 (excluding two very high levels at Kawishiwi Lab caused by digging near the sampler) were 66, 61 and 57 ug/m^3, respectively. These levels are far below the 24-hour primary standard of 260 ug/m^3.

The developed areas comprised of communities and industrial facilities have significantly higher particulate levels than do the remote areas. 1977 TSP geometric means in these areas were approximately two to five times those measured at the background sites. The highest 1977 geometric mean was the 54 ug/m^3, below the annual standard, measured at Virginia. As can be seen in Figures 24 and 25, mean TSP levels in the developed areas of the Study Region are in the range of those measured in non-severely impacted small to medium size cities generally larger than those of the Study Area.

Temporal variability at each site is evident in Figures 3 through 18. These plots of TSP concentrations over time clearly show the large fluctuations observed from sample to sample at the large community sites and the much smaller variability observed at the background sites. Standard deviations of the adjusted 1977 data varied from 13.5 ug/m^3 at the Fernberg Road background site to 66.1 ug/m^3 at Virginia. Variability this large is the result of a large number of sources in the immediate area as well as the effects of events such as the taconite strike in the second half of 1977.

That short term TSP concentrations can be quite high is also apparent from an examination of values exceeding the ambient 24-hour TSP standards. Levels at

Virginia (367 and 310 ug/m^3) and Hibbing (279 ug/m^3) exceeded the 24-hour primary standard (260 ug/m^3) which is not to be exceeded more than once per year at any site. These values and additional exceedances of the 24-hour secondary standard (150 ug/m^3) are shown in Table 4. No site in the Study Region was in violation of either the primary (75 ug/m^3) or secondary (60 ug/m^3) annual standard of TSP, however.

The second highest concentration at most sites was considerably higher than the mean, and, at most sites, was within about 20% of the highest value measured. This type of relationship indicates that most high values, while relatively uncommon, are part of the normal pattern and can be expected to recur occasionaly.

Community Impacts

It is apparent that the communities are the most impacted areas of the Study Region (see, e.g., Table 3). Community TSP levels very rarely fell below 10 ug/m^3 for a 24-hour sample and included most measured high values and exceedances of ambient standards. These community levels, varying from near background to well in excess of the 24-hour standards, were caused by varying mixtures of emissions from such sources as industry (including nearby mining), commerce, home heating, automobiles, and resuspension of dust from paved roads. Although these levels were measured at only one site per community, the sites were selected to provide measurements representative of each community.

The mining communities (those communities within a few kilometers of active mines) are generally more impacted than the non-mining communities because of the additional nearby emissions sources and exposed ground subject to wind erosion. Comparisons of the adjusted 1977 TSP concentrations in several communities (summarized with 1979 population figures in Table 5) demonstrates the influence of mining. For example, Virginia, a city with substantial nearby mining, had a 1977 TSP level of 54 ug/m^3 while Hibbing, with 30% greater population but no active local mining, had a mean of 37 ug/m^3. Among the smaller communities, Ely is fairly distant, is along an uncommon wind direction from the mines, and had a 1977 TSP mean of 22 ug/m^3. By comparison, Mountain Iron has about half the population of Ely but is adjacent to the Minntac taconite operation and had a mean level of 42 ug/m^3, about twice that of Ely. Hoyt Lakes is about the same size as Mountain Iron, but had a much lower TSP level of 30 ug/m^3. This difference may be attributed largely to Hoyt Lakes being about 8 km south of the Erie Mining Co. processing plant, much closer to active mining than Ely but more distant than Mountain Iron.

Community size, in addition to proximity to mining activity, can account for a substantial portion of particulate levels. The cumulative effect of the community sources in non-mining communities can be seen by comparing the adjusted TSP level of 22 ug/m^3 at Ely with that of 37 ug/m^3 at the much larger city of Hibbing. The importance of population to TSP levels without mining effects was demonstrated for the period August-October 1977 (no mining or snow cover) when the correlation of TSP with community population was 0.68. During the remainder of the mine strike with snow on the ground, the correlation went up to 0.78. This highly significant winter relationship may indicate the decreased importance of windblown dust and increased importance of home heating emissions during that time of the year.

The community size effect is also important for mining communities, but may be less apparent in areas of major mining impact. Virginia, for example, had a high TSP level and more exceedances of the TSP standards than did the much smaller community of Mountain Iron. These higher levels in the larger mining communities seem to result from the larger numbers of general community sources and the greater amount of mining activity usually found nearby.

Mining Impacts

Particulate emissions in a mining area are primarily large particles (greater than 1 um) generated by physical processes and emitted near the surface or from fairly short stacks (less than 50 m). These large particles have relatively high deposition velocities and, except during periods of very strong winds, usually deposit near the source.

TSP concentrations measured on mining property were about twice the background level but generally much lower than those in the communities during the study period. A comment should be made concerning data collected at the Erie Office. The sampler, located on a low rooftop about 1 km south-southwest of the processing plant and surrounded by mining operations and roads, had a 1977 mean TSP level of only 19 ug/m^3. This low value was strongly affected by the taconite strike that closed Erie Mining Company for five months that year. Most of the data were collected during the cold season when the narrow shaft furnace plume usually remained elevated near the source and only the low level emissions impacted the sampler. The pollution rose in Figure 27, which indicates the average TSP levels for 30^o wind sectors, shows that the highest average concentration was from the area of open pit operations to the west. During the warm season, the shaft furnace plume could be expected to mix to the ground much closer to the processing plant and have a larger near-source impact. The small amount of warm season data collected show the mean adjusted TSP level to have been 43 ug/m^3 between snowmelt and the onset of the taconite strike, much higher than during the winter. However, levels in most areas of the mines remained well below those found in the mining communities during the warm season.

Trace element concentrations at the Erie Office site averaged only about half those measured at the Dunka Road site on Erie Mining Company property for elements including iron, aluminum, silicon, sulfur, and arsenic (see section 3.5.2.1 of Volume 3-Chapter 3). The office did experience higher lead levels than did Dunka Road, possibly reflecting the nearby vehicular traffic at the office. The Erie Office values are probably not representative of the site, however, because of missing data and the mine strike.

Particulate concentrations within a mining area can be locally very high, however. The Dunka Road site had a mean TSP level of only 20 ug/m^3 and showed only a small impact from the direction of the Erie Mining Company processing plant 15 km to the west, but did demonstrate the high local concentrations that can be produced by unpaved roads. The highest concentrations at Dunka Road, including the maximum level of 243 ug/m^3, occurred on the infrequent days of heavy travel on an uncontrolled dirt road just west of the sampler. Dunka Road itself, about 100 m north of the sampler, had much more traffic and was on a major wind axis to the sampler. Concentrations from this direction were much lower than those from the west, largely as a result of Erie Mining Company's very effective chemical dust control program.

Loading, hauling, and dumping areas within the mines experience by far the highest short-term (on the order of a minute) concentrations in the Study Area. The University of Minnesota Mobile Laboratory (UMML) field study (Wilson et al. 1978) reported average volume concentrations of 355, 375, and 600 um^3/cm^3 (=ug/m^3 divided by density) for particles larger than 1 um during 3 passes of 85-

ton trucks at a distance of about 10 m. Three measurements taken during dumping of ore into a pocket loader while very light rain fell produced average volume concentrations of 160, 256, and 358 um^3/cm^3 at about 100 m. These operations emit large masses of coarse particles near ground level. The large particle sizes and low wind speeds frequently found in the pit areas allow most of the mass of particles to fall out very close to the sources.

The UMML study also found that mining sources such as ore dumping, processing operations, and tailing basins produce particles with iron-to-silicon ratios greater than one. Concentrations away from these operatins tend to be higher in silicon than iron, however, indicating the importance of local dust sources such as unpaved roads.

Blasting injects particles much higher into the atmosphere but occurs too infrequently to be a significant contributor to long-term particulate levels.

A brief summary of the types of minerals and their density ranges in the Duluth Gabbro may be informative at this point. The major and minor minerals in the Duluth Gabbro can be divided into silicates, oxides, and sulfides. Silicate minerals range in density from 2.6 to 3.8 gm/cm^3. The bulk of the silicates (greater than 60%) is made up of plagioclase (2.71 gm/cm^3), and the average density is 3.1 ± 0.2 gm/cm^3. The oxide minerals are ilmenite and magnetite (Fe-Ti oxides), and they have densities of 4.70 to 4.90 gm/cm^3. The sulfide minerals (chalcopyrite, cubanite, pentlandite, and pyrrhotite) have densities of 4.30 to 5.00 gm/cm^3. These ranges are summarized below:

Mineral Type	Density (gm/cm^3)
silicates	2.6 - 3.8
oxides	4.7 - 4.9
sulfides	4.3 - 5.0

Local and Regional Effects

Local and regional particulate impacts were investigated to determine source-receptor relationships. The investigation involved analysis of particulate sources, transport mechanisms, meteorological conditions (including the relationships between wind direction and TSP level reflected in the pollution roses and contribution roses presented in Figures 26 through 30), measured elemental concentrations, and the results of statistical modeling of the TSP data. The statistical modeling techniques and results are discussed in detail in Appendix 2.

The importance of nearby sources is apparent in the developed areas where measured TSP levels are generally easily explained by sources within a few kilometers of the sampling sites. Mountain Iron and Virginia, for example, were the two most impacted air quality sampling sites in the Study Area. Peaks on the Mountain Iron TSP rose are caused mainly by the Minntac processing plant 2 km to the north-northwest, the Minntac open pit to the north and northwest, local traffic and a tailing basin to the west-southwest, and particulate resuspension from streets to the south.

The Virginia TSP rose can be similarly explained by attributing peaks to the south to nearby mining operations and those to the west and northwest to the Virginia municipal power plant and the Minntac operation near Mountain Iron.

One effect of plume dispersion and the rapid deposition of large particles is to decrease the influences of the mines and communities on the background areas. The three remote sites were at different distances from and orientations to the developed areas. Yet they experienced similar mean and maximum concentrations, correlated above the 0.8 level with each other (see Table 6), and had very similar TSP roses (see Figure 28). The Fernberg Road and Kawishiwi Lab TSP roses, in fact, appear to be virtual twins. The Toimi TSP rose shows the small effect of the Mesabi Range area toward the northwest, as seen by comparing the virtually zero levels from the northeast quadrant with the low but significantly higher levels from the northwest quadrant. The average concentrations at Toimi from the direction of the mines to the northwest are actually lower than those measured on generally southerly flow. These strong similarities among the three sites suggest that particulate levels in the remote areas of northeastern Minnesota are very strongly influenced by regionwide events. Examples of regionwide events could occur when the entire region is under the impact of an air mass with high aerosol content from distant sources or strong winds to produce widespread blowing dust.

Although TSP concentrations are consistently high only near significant sources, the developed areas also make a significant contribution to the air quality of the entire Study Area. This influence on the very clean background air is apparent in the TSP roses for all three remote sites. Each site received contributions from the directions of the developed areas that, while quite low, were nevertheless much larger than those from the northeast. It is hypothesized that the particles arriving at these remote locations are primarily the smaller particles with lower deposition velocities and, therefore, greater potential for transport.

The strike against the taconite mining operations during August-December 1977 provided a unique opportunity to measure the impact of these operations on regional air quality. TSP concentrations in all portions of the Study Area decreased substantially during this period. Concentrations at the 11 sampling locations after the beginning of the strike and before the snow season decreased an average of 59% over the preceding spring and summer. Not surprisingly, the impact appeared to be the greatest at the locations on mining property, with the sampler at the Erie Mining Office showing a 76% drop. Areas showing less of an effect were the background sites, with a decrease of 46% at Kawishiwi Lab, and the largest communities, with decreases of about 45% at Virginia and Hibbing.

Perhaps the strongest indication of the importance of mining-related sources to the air quality of the entire Region, however, is that no site decreased by less than 45% during the strike. The differences in concentration between sampling location decreased substantially during the strike, though some significant differences between areas of the Study Area did remain. The TSP decrease was least in the larger communities, suggesting that particulate levels in these areas are strongly controlled by factors other than mining. The general level of activity within the communities, which may have increased while the mines were shut down, seems to be an important factor.

A summary analysis of possible contributors to the particulate levels observed at each sampling site is presented in Appendix 3.

Roads

Unpaved roads can be very significant sources of particulates over short ranges. Particles are lifted from gravel and dirt roads by vehicles and transported downwind. Relatively little road dust is lifted by wind alone. As discussed previously, the Dunka Road site demonstrated a large effect from a nearby uncontrolled dirt road and a much smaller effect from the chemically controlled Dunka Road. The UMML study (Wilson et al. 1978) measured average volumetric concentrations between 23 and 863 um^3/cm^3 for the plume of a single vehicle passing 110 m upwind of an unpaved road during light wind neutral to stable conditions. Concentrations increased rapidly with vehicle speed and decreased dramatically with distance from the road. TSP levels produced by road dust typically had low iron-to-silicon ratios (less than one) compared with ratios greater than one near mining sources where iron is in greater abundance.

The Toimi site is located near and west of a lightly traveled unpaved road. Concentrations from the east at the site were mostly low, indicating the need for moderately frequent travel to produce elevated TSP levels.

In addition to chemical control, nearby vegetation also controls the dispersion of dust lifted from roads. Trees and shrubs can decrease wind speeds and potential transport distance near a road. Trees also act as a filter to remove particles from a passing dust cloud. Strong winds, indicated to be at least 17 km/hr in the UMML study, can resuspend this dust and distribute it over a wider area than could have been possible during the initial suspension. Dense vegetation or the occurrence of precipitation can prevent additional dispersion of the intercepted dust.

Paved roads can also be important local sources of particulates in some communities where particles from nearby sources are deposited on the roads and resuspended by vehicles. Mountain Iron seems to show this effect. Particles from Minntac are deposited on the city streets and then resuspended by heavy automobile traffic. These particles are believed to contribute to the elevated TSP levels from the south at the Mountain Iron sampling site.

Long Distance Transport

Long distance transport of suspended particulates appears to be a major component of the regional background concentrations measured at the 3 remote sites. TSP pollution roses for all sites (Figures 26-28) show generally elevated concentrations from the south even where there are no known local sources, suggesting transport of particulates from distant sources. Possible source areas in the Upper Midwest include the urban/industrial areas of Duluth (about 80 km south of Hoyt Lakes), Minneapolis-St. Paul (about 300 km SSW of Hoyt Lakes), and Chicago (about 750 km SE of Hoyt Lakes). Recent research (see Lyons and Husar 1976; and Lyons, Dooley and Whitby 1978) has indicated that large masses of pollutants can be transported northward from the Ohio River and lower Mississippi River valley areas. These polluted air masses sometimes are transported to northern Minnesota before being forced eastward across the Great Lakes. Southerly winds are common in northeastern Minnesota in the summer and are responsible for a large portion of the annual background TSP level, as demonstrated by the strong TSP peaks on the contribution roses (Figures 29-30). Contribution roses are combinations of the particulate roses and wind roses and indicate the percentage of the annual TSP level arriving at the site from each wind sector.

The TSP roses also show elevated levels at Fernberg Road and Kawishiwi Lab under westerly winds. These levels probably represent medium range transport of particulates from the Mesabi Range communities and mines. These particulates, although from regional sources, produce smaller peaks in the contribution roses than those to the north-northwest or south because westerly winds are uncommon.

The possibility also exists for long distance transport of particulates from International Falls, 140 km northwest of Ely. International Falls has significant stack emissions (see emissions data in section 3.5.1.1 of Volume 3-Chapter3) and high ambient concentrations of particulates, and it is up the primary wind axis from the Study Area. Although concentrations from the northwest are low at most sites, they are generally significantly higher than the extremely low values measured from the northeast. Transport from International Falls would explain the enhanced background and the large northwest peaks on the contribution roses.

Duluth Area

The Duluth area is a special case in the analysis of northeastern Minnesota air quality. The size of the urban area, density of industrial sources, pollutant trapping effect of the steep topography, and complex meteorological regime warrant more intensive study than was undertaken here. However, the existing TSP data for representative sites allow some general conclusions to be drawn. TSP levels in the Duluth area (see Figure 22 and Table 3) are typically higher than those for similar types of areas in the Study Area. The Duluth International Airport site, atop the elevated terrain, for example, is generally considered a background site for that region. Yet it had a 1977 mean TSP level of 19 ug/m^3, nearly twice the Study Area mean background. This differential is expected to be smaller during a year of normal mining activity.

The other Duluth area extreme occurred at the West End site in the ore loading docks area. This site had a 1977 mean TSP level of 78 ug/m^3, much higher than any site in the Study Area, in excess of the 75 ug/m^3 annual standard, and in the realm of highly industrialized areas across the country. West End had one sample above the 24-hour primary standard and 9 other samples above the 24-hour secondary standard during the 18-month study period. As expected of a highly impacted location, West End had much higher concentrations of many trace elements, including iron, copper, nickel, lead, aluminum, and silicon, than did any Study Area site except for high lead, aluminum, and silicon levels measured at Babbitt. Arsenic, and to an extent phosphorus, concentrations were quite low at West End, however.

Between these two extremes are the residential areas in and around Duluth. Sites 7501, 7502, and Cloquet are all southwest of downtown Duluth and had similar 1977 geometric mean TSP levels of 38, 34, and 31 ug/m^3, respectively. These values are well below the annual standard and are similar to those found in the smaller mining and larger non-mining communities of the Study Area. The Duluth area also experienced much smaller variances of TSP level in residential areas than did similarly impactd areas in the Study Area. None of the 3 sites exceeded the 24-hour primary standard, but 7 exceedances of the secondary standard were recorded. The trend plots (Figure 32) show that the Duluth residential areas southwest of downtown have experienced a very significant decrease in mean and extreme TSP levels during the 1970s in response to decreasing emissions from a number of sources. Levels at the airport site have been much more steady, but may have experienced a small decrease during the same period.

Meteorological Relationships

Regional particulate concentrations are highly dependent on meteorological conditions, and relationships with wind direction have been discussed. Precipitation is also of major importance in reducing particulate levels. Rain has the immediate effect of removing particles from the atmosphere and wets the surface to decrease lift-off by wind and vehicles. Snow is generally less efficient at removing particles from the atmosphere, but is an excellent ground cover to prevent lift-off. Correlations between TSP and precipitation occurrence on both the day before and day of TSP sample collection were computed (see Appendix 2). Correlations at each site were negative, indicating that precipitation is associated with periods of low TSP levels. The large effect of snow cover in reducing ambient particulate concentrations is clearly seen in the time lines (Figures 3-18) and the adjusted mean TSP concentrations for each time period listed in Table 7. In general, TSP concentrations were much lower during snow cover for periods of both normal mining activity and the mine strike. This effect was smaller in the communities than at other sites, perhaps in response to home heating and commerce in communities during the winter and the importance of unpaved roads and windblown dust in rural areas in summer.

The overall effect of a very dry period, such as occurred during 1976, can be seen in the trend plots for Hibbing, Mountain Iron, and Virginia shown in Figure 31. Hibbing experienced a gradual decrease in TSP levels during the early 1970s, but showed a definite increase in 1976. Mountain Iron and Virginia, sites which revealed no clear trend during the 1970s, also experienced increased levels during 1976. Levels during 1977, a much wetter year that included the 5-month taconite strike, dropped back to the pre-1976 levels at each site. These results suggest the importance of ground sources of particles, such as windblown dust, and the possible impact of forest fires.

Wind speed was expected to have a noticeable effect on particulate levels, but a significant correlation between wind speed and TSP concentration was found at only one site (Virginia) in the Study Area. Correlations during a period of no snow cover or mining activity could be more conclusive, as could an assessment of wind speed dependent on wind direction, but the sample size was too small. It is known, however, that those sites near large potential area sources of windblown dust, Erie Office and Dunka Road, experienced generally low TSP levels. The few high concentrations at these two sites were caused mostly by the Erie Mining Company processing plant and road dust, respectively. The absence of high TSP levels from windblown dust is believed to be due to winter snow cover, frequent summer rainfall, and chemical dust control.

High Concentrations

The time lines (Figures 3-18), box plots (Figure 23), and histograms (Figures 19-22) all indicate that some high TSP concentrations, sometimes more than 10 times the annual geometric mean, occurred in most areas. Some of these levels occurred under normal conditions and can be expected to recur occasionally. For example, the narrow plumes from the Minntac and Erie Mining taconite processing plants occasionally impinge on the sampling sites at Mountain Iron and the Erie Office, respectively, for a sufficient amount of time to produce a large effect on the 24-hour TSP level. A similar effect occurs when an unusual wind direction brings aerosol-laden air to a normally clean area, such as when southwesterly winds transport particles from the developed areas of the Mesabi Range to Fernberg Road or Kawishiwi Lab. Intermittent sources can also produce these peak values, as when sporadic heavy use of the uncontrolled dirt road near the Dunka Road produced TSP concentrations as high as 243 ug/m^3. Combinations of mechanisms can also produce unusually high particulate levels. For example, a plume from a nearby source could impinge on a sampler during a period of elevated regional levels caused by long range transport or windblown dust. Such a combination may have been responsible for the highest TSP measurement at Ely High School (84 ug/m^3) on a day of high regional levels.

High TSP concentrations can also be caused by very unusual activity not likely to recur. Activities such as digging during utility work next to the Kawishiwi Lab and reroofing the Hoyt Lakes Police Station produced very high local TSP concentrations at those sites. The Hibbing site had one unexpectedly high measurement (279 ug/m^3) of undetermined origin, although local sources and forest fires are possibilities.

Summary

The air quality of the Study Area is generally characterized by very low particulate levels. The region is dotted with impacted areas caused by communities, mines, and unpaved roads. These impacted areas tend to be concentrated along the Mesabi Range near the mines and centers of population. Particulate concentrations in plumes from these developed areas decrease rapidly with distance, but have a discernible impact on air quality throughout the Study Area. The TSP background in remote areas is a product of very clean air entering the region from the north (especially the northeast), generally elevated levels from the south as a result of long distance transport, and impacts from distant mining areas and communities. Most impacts are suppressed considerably during periods of snow cover or rainfall.

The regional nature of most air quality impacts indicates that most of the area northeast of the Mesabi Range, including most of the BWCA, has generally very low particulate levels and probably exhibits patterns very similar to those observed at Fernberg Road. Exceptions undoubtedly occur near local sources such as cabins with fireplaces, campfires, and communities (especially Ely and Winton). Also, the southwest peak in the TSP pollution rose, caused by infrequent winds from the developed areas of the Iron Range, would be expected to decrease with distance northeast of the Fernberg Road site. The possibility exists of detecting contributions from such distant sources as Thunder Bay to the northeast and the Atikokan taconite plant to the north, but significant concentrations were not observed from those directions at Fernberg Road during the study.

The area south of the developed Mesabi Range area and away from the short-range Duluth/North Shore impact is probably impacted very similarly to Toimi. That is, the particulate levels are generally very low with the cleanest air coming from the northeast. A small impact from the direction of the Mesabi Range to the northwest is exceeded in total contribution by a wide angle of impact from the south. As there are few local sources, most of this southerly impact is probably from medium and long distance transport. Areas west of Toimi should experience a greater impact from mining and community activity than should areas farther east.

The region northwest of the Mesabi Range is virtually devoid of particulate sources for about 130 km to International Falls and probably has very low TSP levels except near the few small local sources. Levels may be somewhat higher than those found in similar remote areas northeast and south of the Range, however. Transport of dust from the mining areas is a much larger contributor to TSP levels when there is no snow cover, and the frequent southeast winds of summer may be responsible for higher remote TSP concentrations than those experienced at Fernberg Road. Concentrations of several particulate metals, including iron and aluminum that are major components of the mine-generated aerosol, were elevated at the Bear Head State Park site above levels at Fernberg Road and Toimi.

Empirical TSP Model

The analyses of data and familiarity with each site allow attributing the 1977 adjusted mean TSP level (non-adjusted level for Duluth sites) for each site to five major source categories: background (includes long-range transport, regionwide dust generation, and some minimum level of impact from distant regional sources), communities, mining/processing, unpaved roads, and unusual local sources. The ranges of impacts likely in northeastern Minnesota for these source categories in a year such as 1977 are as follows:

Estimated Contributions to Annual TSP (ug/m^3)

Background	10
Communities	10-30
Mining/processing	1-30+ (high very close to transfer points)
Unpaved roads	0-10+ (high very close to uncontrolled roads)
Unusual local sources	0-10

The actual level at a site can be estimated as the sum of the appropriate sources listed. It is very important to realize that these estimates are for a generally wet year with a long mine strike and are undoubtedly less than the values to be expected in a more normal year.

The above empirical model involves the apportioning of a geometric mean into arithmetic components, a procedure that is not valid mathematically. The scheme, however, does provide reasonable ranges of values for various types and degrees of air quality impact experienced in northeastern Minnesota. These values can be used in combination with the mechanisms discussed in this report and a great deal of caution to estimate approximate annual particulate levels in unsampled areas and for first-cut estimation of approximate levels to be expected near future development.

REFERENCES

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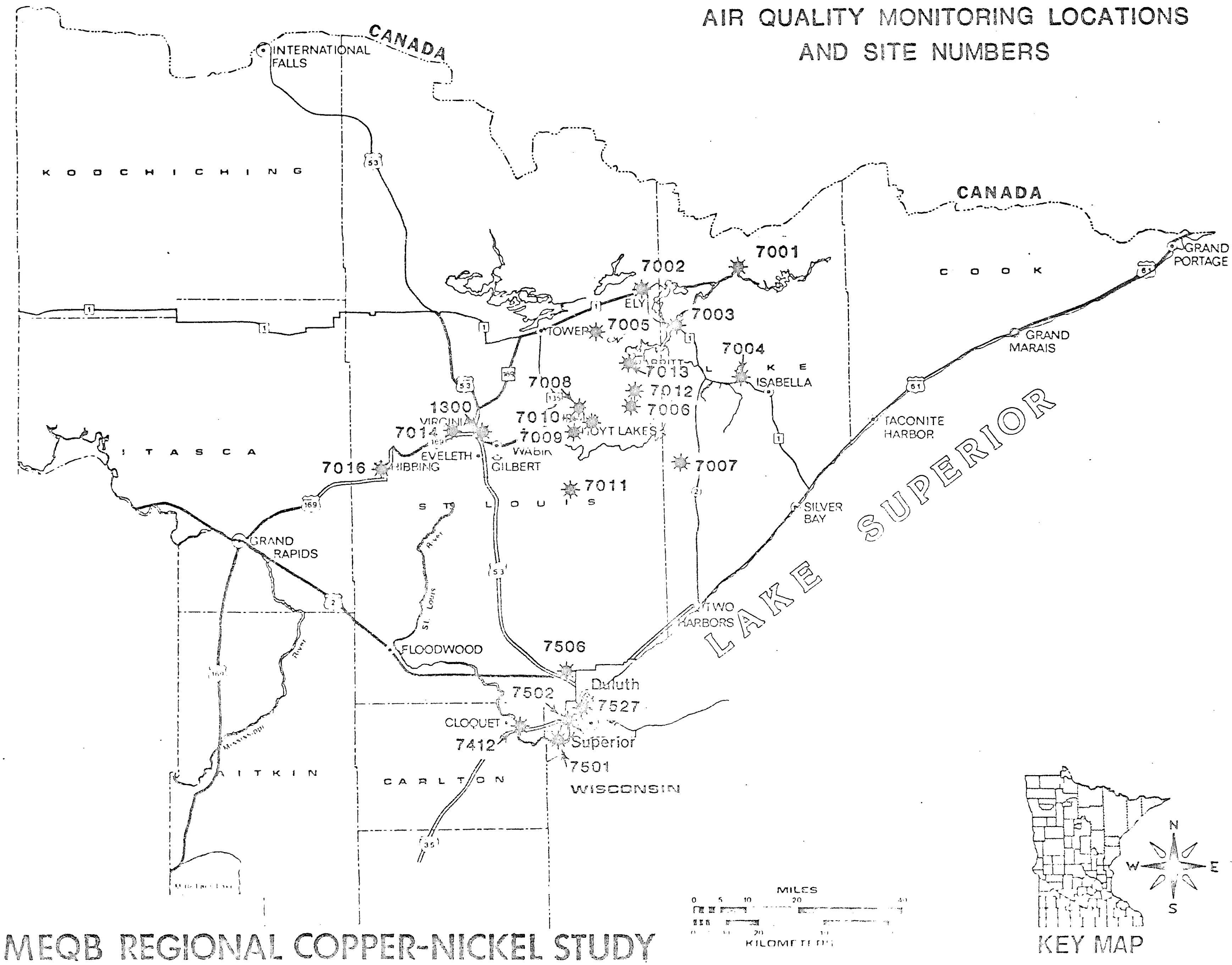
Lyons, W.A. and R.B. Husar. 1976. SMS/GOES visible images detect a synoptic-scale air pollution episode. Monthly Weather Review 104:1623-1626.

Lyons, W.A., J.C. Cooley and K.T. Whitby. 1978. Satellite detection of long-range pollution transport and sulfate aerosol hazes. Atmospheric Environment 12:621-631.

Wilson, J.C., K.T. Whitby, V.A. Marple and J.C. McCormack. 1978. Origins of coarse particles near and on the Iron Range of Minnesota. Regional Copper-Nickel Study, Minnesota Environmental Quality Board.

FIGURE 1

AIR QUALITY MONITORING LOCATIONS AND SITE NUMBERS



MEQB REGIONAL COPPER-NICKEL STUDY


DULUTH AREA
AIR QUALITY
SITE LOCATIONS
7506
7527
7502
7501
7412
DULUTH
LAKE SUPERIOR
WISCONSIN
DOUGLAS CO.
SUPERIOR
HERMAN
SOLWAY
MIDWAY
THOMSON
PROCTOR
SCALE OF STATUTE MILES

FIGURE 2

FIGURE 3

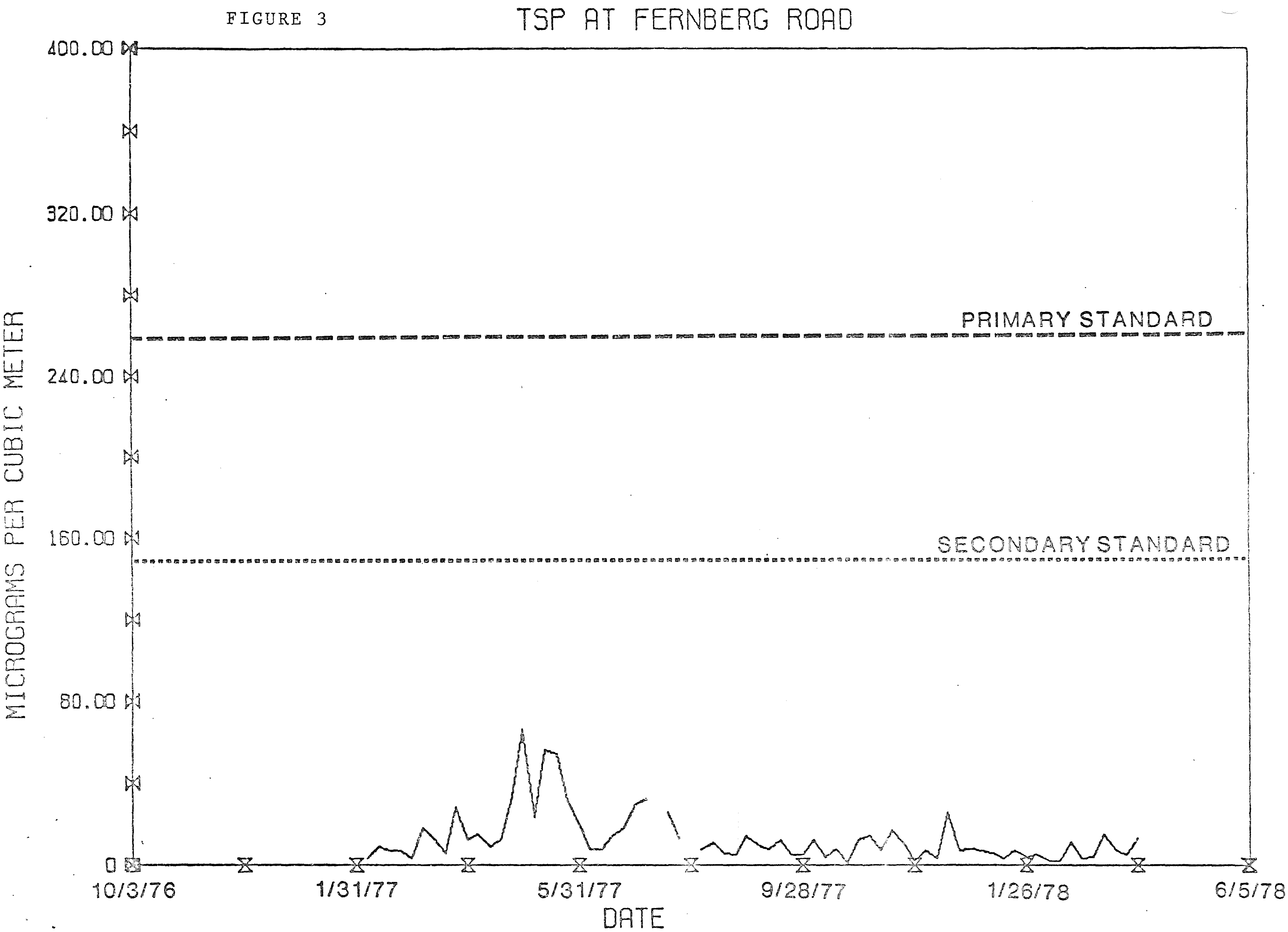

TSP AT FERNBERG ROAD
400.00
320.00
240.00
160.00
80.00
0
MICROGRAMS PER CUBIC METER
PRIMARY STANDARD
SECONDARY STANDARD
10/3/76
1/31/77
5/31/77
9/28/77
1/26/78
6/5/78
DATE

FIGURE 4

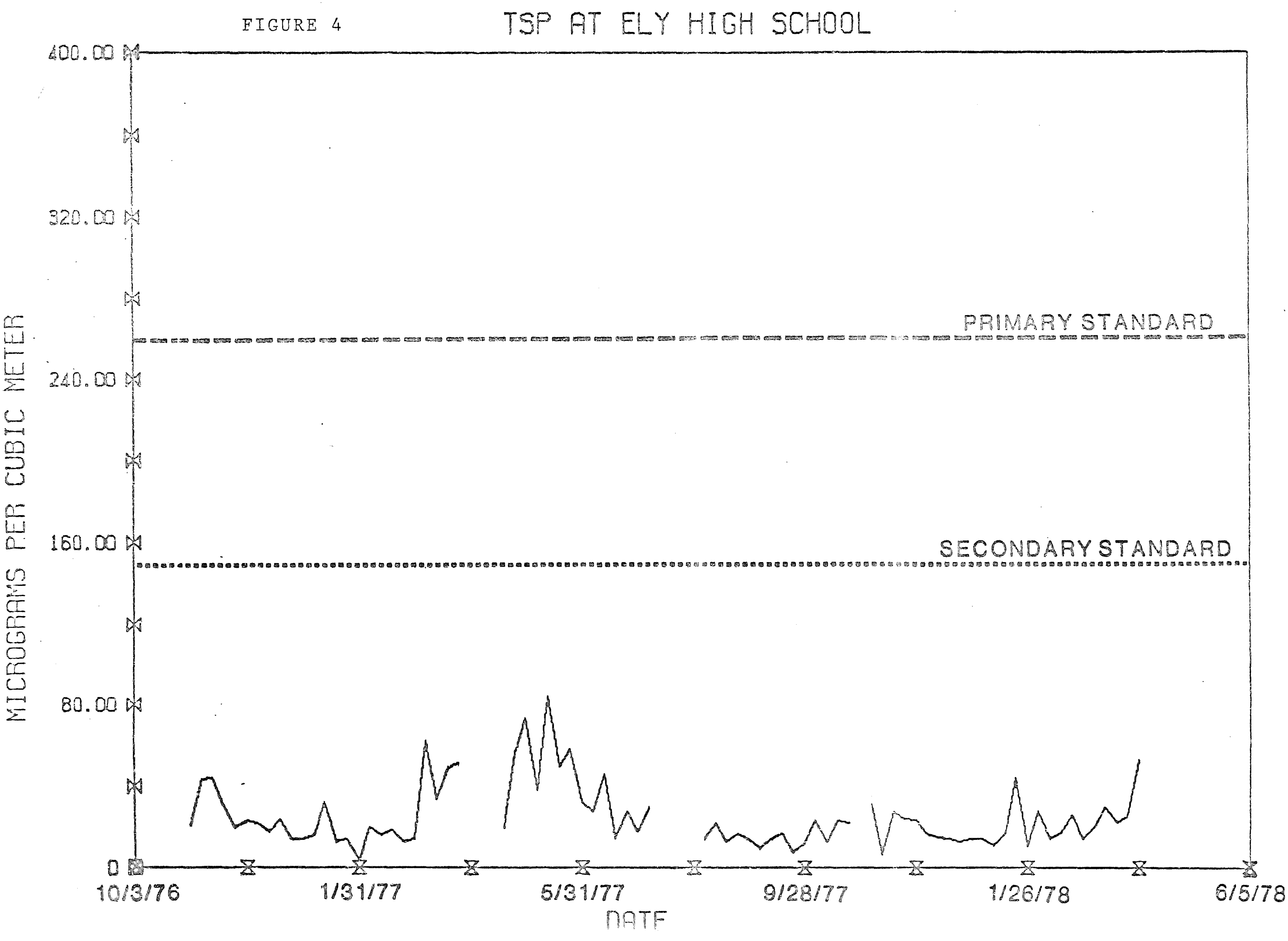

TSP AT ELY HIGH SCHOOL
MICROGRAMS PER CUBIC METER
400.00
320.00
240.00
160.00
80.00
0
PRIMARY STANDARD
SECONDARY STANDARD
10/3/76
1/31/77
5/31/77
9/28/77
1/26/78
6/5/78
DATE

FIGURE 5

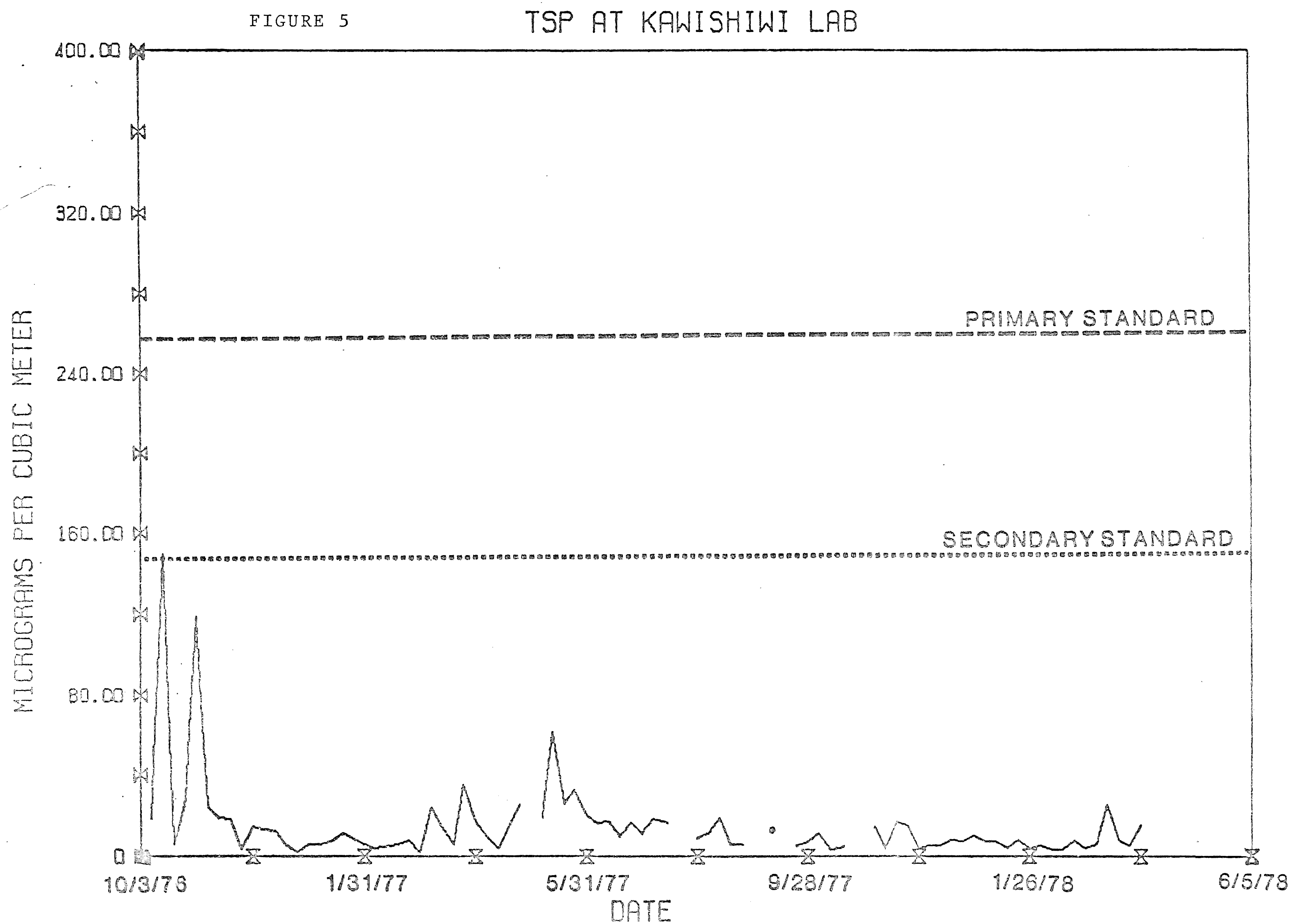

TSP AT KAWISHIWI LAB
400.00
320.00
240.00
160.00
80.00
0
MICROGRAMS PER CUBIC METER
PRIMARY STANDARD
SECONDARY STANDARD
10/3/76
1/31/77
5/31/77
9/28/77
1/26/78
6/5/78
DATE

FIGURE 6

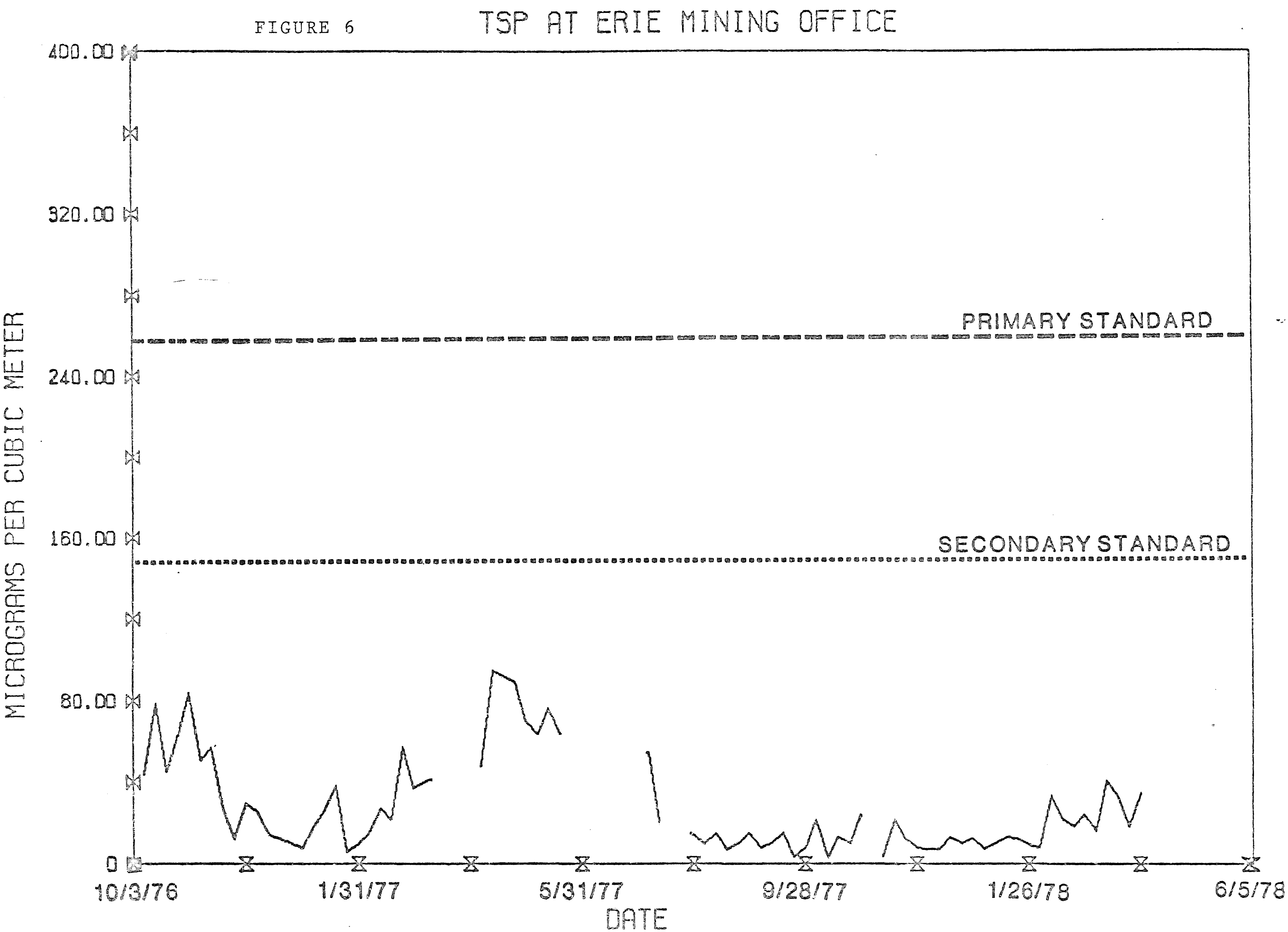

TSP AT ERIE MINING OFFICE
MICROGRAMS PER CUBIC METER
400.00
320.00
240.00
160.00
80.00
0
PRIMARY STANDARD
SECONDARY STANDARD
10/3/76
1/31/77
5/31/77
9/28/77
1/26/78
6/5/78
DATE

FIGURE 7

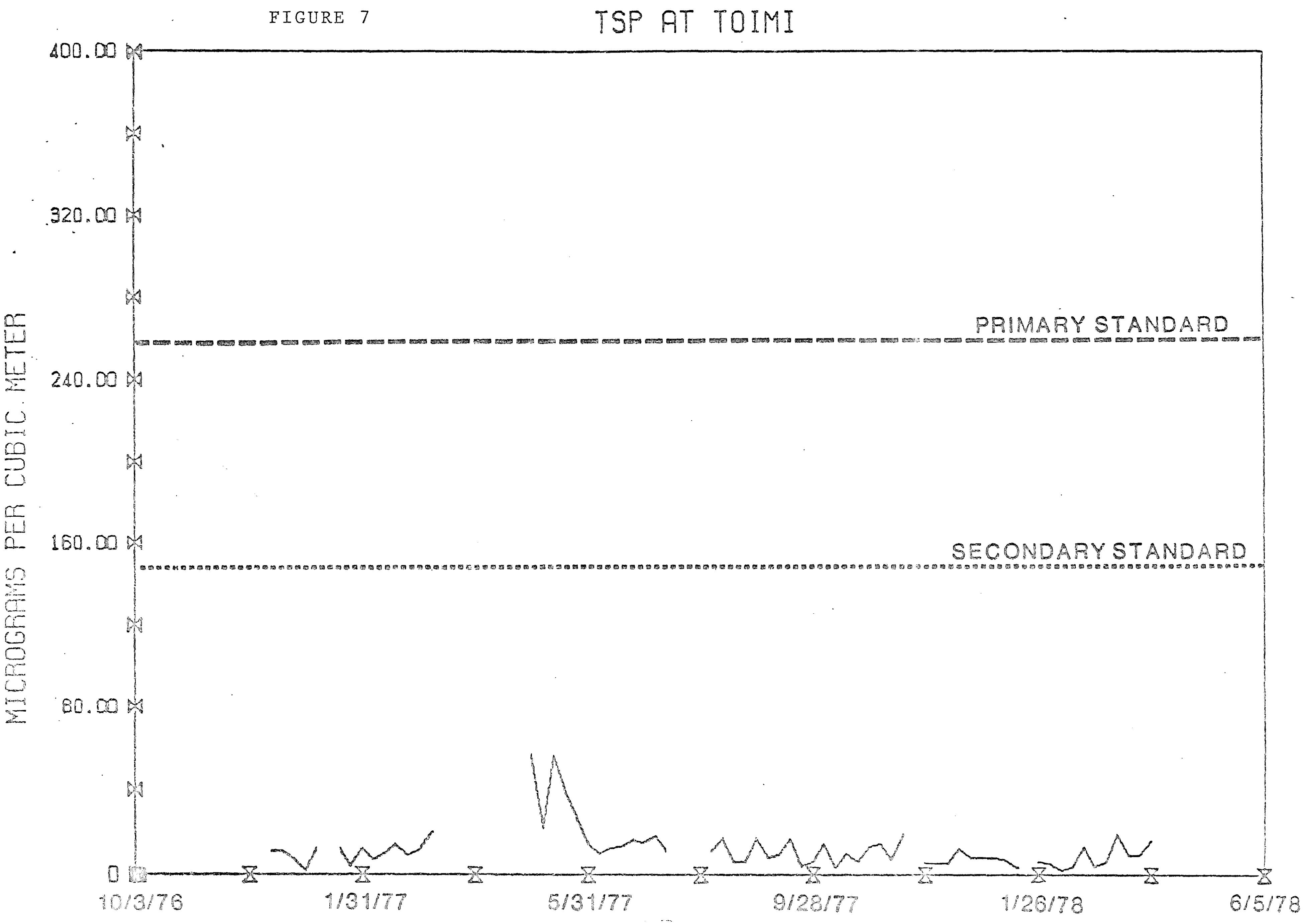

TSP AT TOIMI
400.00
320.00
240.00
160.00
80.00
0
MICROGRAMS PER CUBIC METER
PRIMARY STANDARD
SECONDARY STANDARD
10/3/76
1/31/77
5/31/77
9/28/77
1/26/78
6/5/78

FIGURE 8

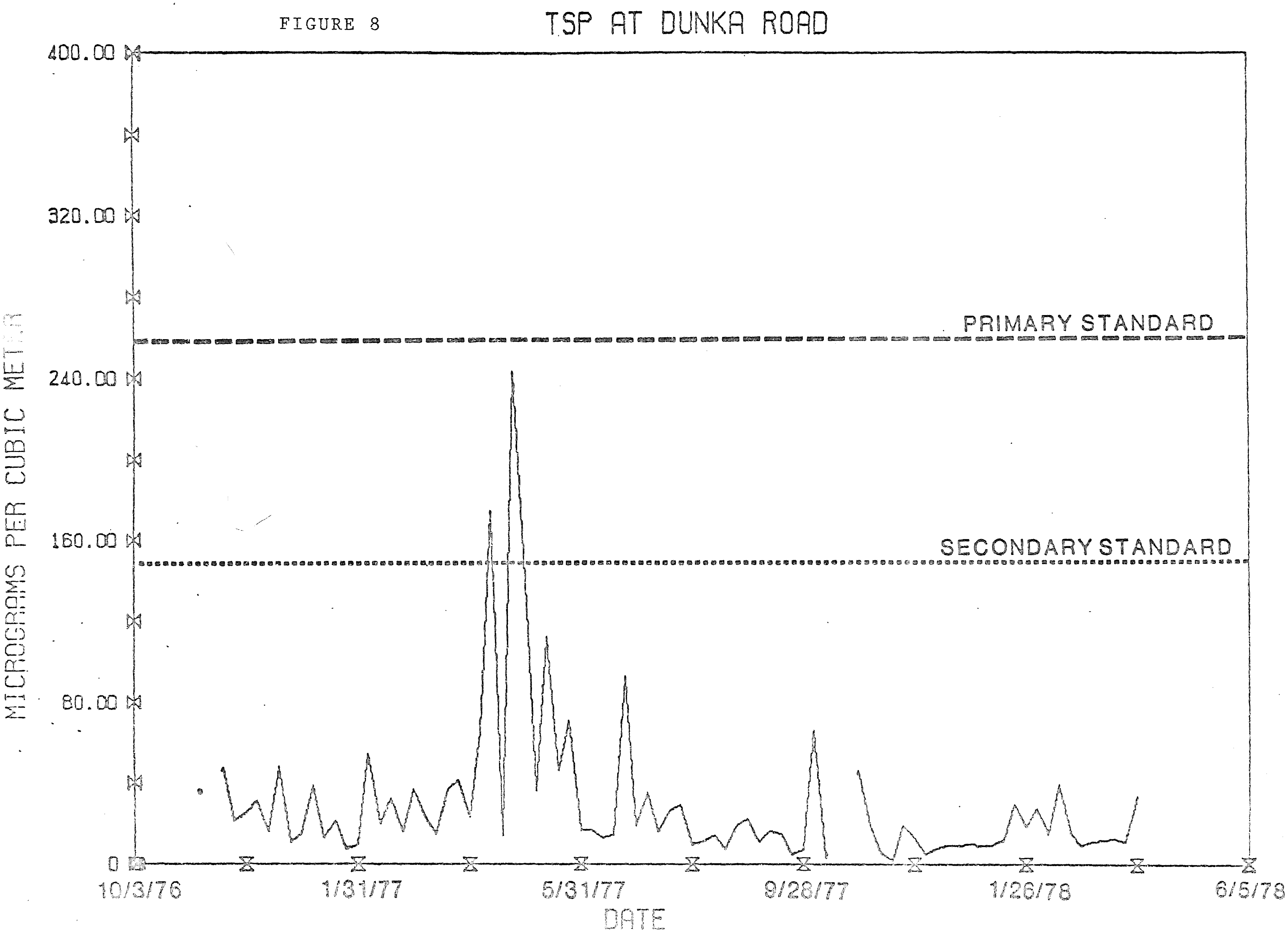

TSP AT DUNKA ROAD
400.00
320.00
240.00
160.00
80.00
0
PRIMARY STANDARD
SECONDARY STANDARD
MICROGRAMS PER CUBIC METER
10/3/76
1/31/77
5/31/77
9/28/77
1/26/78
6/5/78
DATE

FIGURE 9

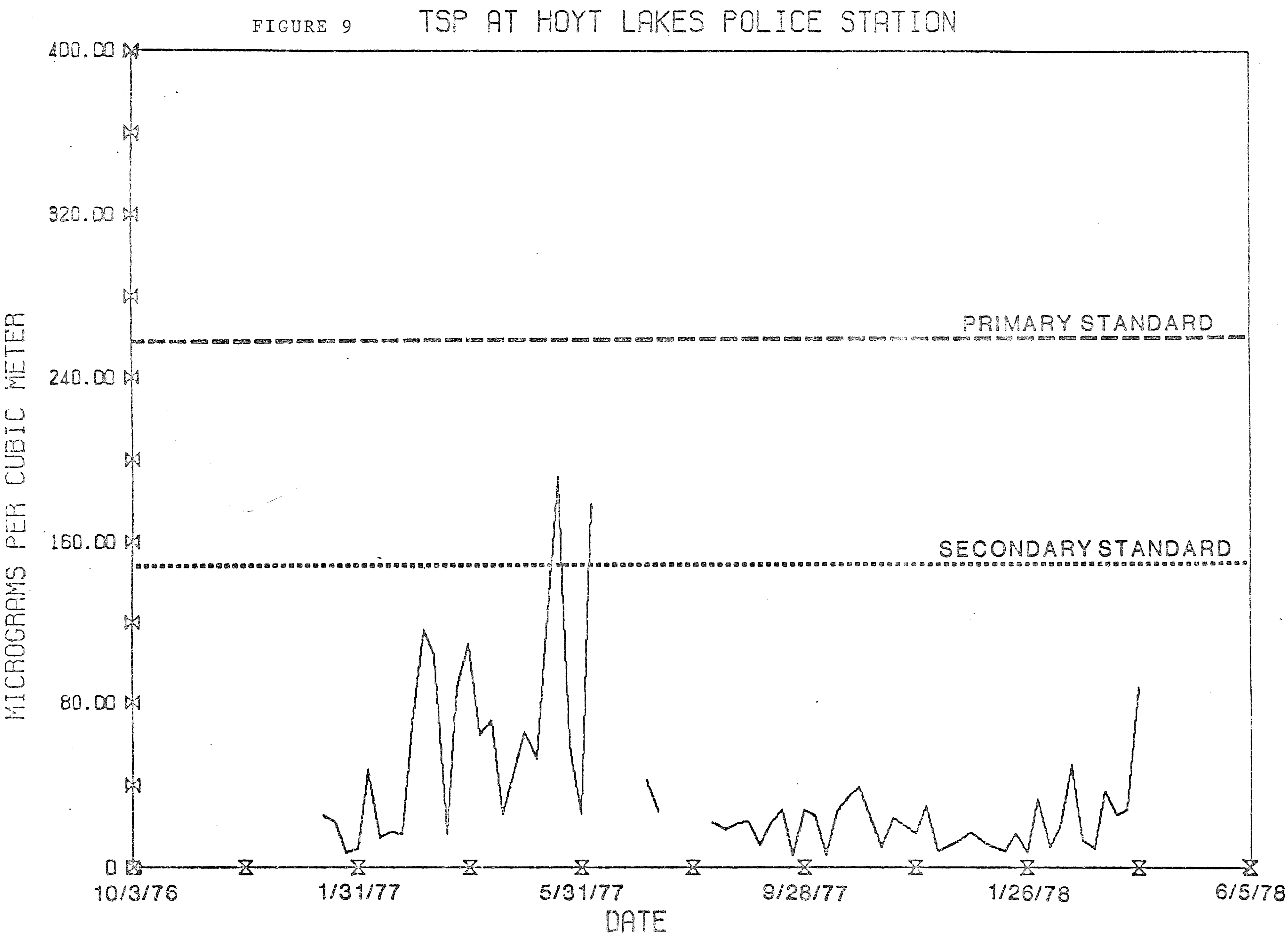

TSP AT HOYT LAKES POLICE STATION
PRIMARY STANDARD
SECONDARY STANDARD
400.00
320.00
240.00
160.00
80.00
0
MICROGRAMS PER CUBIC METER
10/3/76
1/31/77
5/31/77
9/28/77
1/26/78
6/5/78
DATE

FIGURE 10

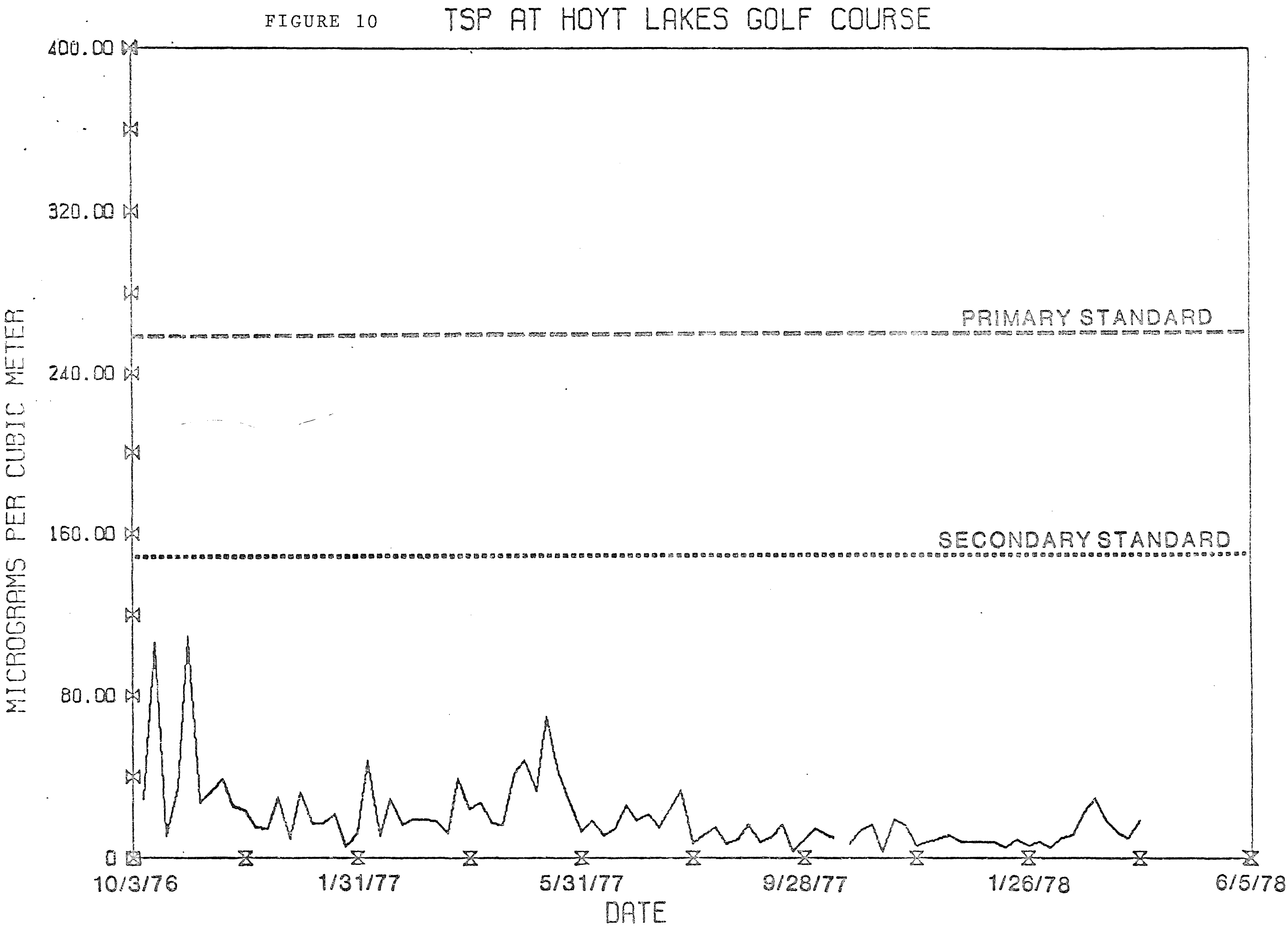

TSP AT HOYT LAKES GOLF COURSE
400.00
320.00
240.00
160.00
80.00
0
MICROGRAMS PER CUBIC METER
PRIMARY STANDARD
SECONDARY STANDARD
10/3/76
1/31/77
5/31/77
9/28/77
1/26/78
6/5/78
DATE

FIGURE 11

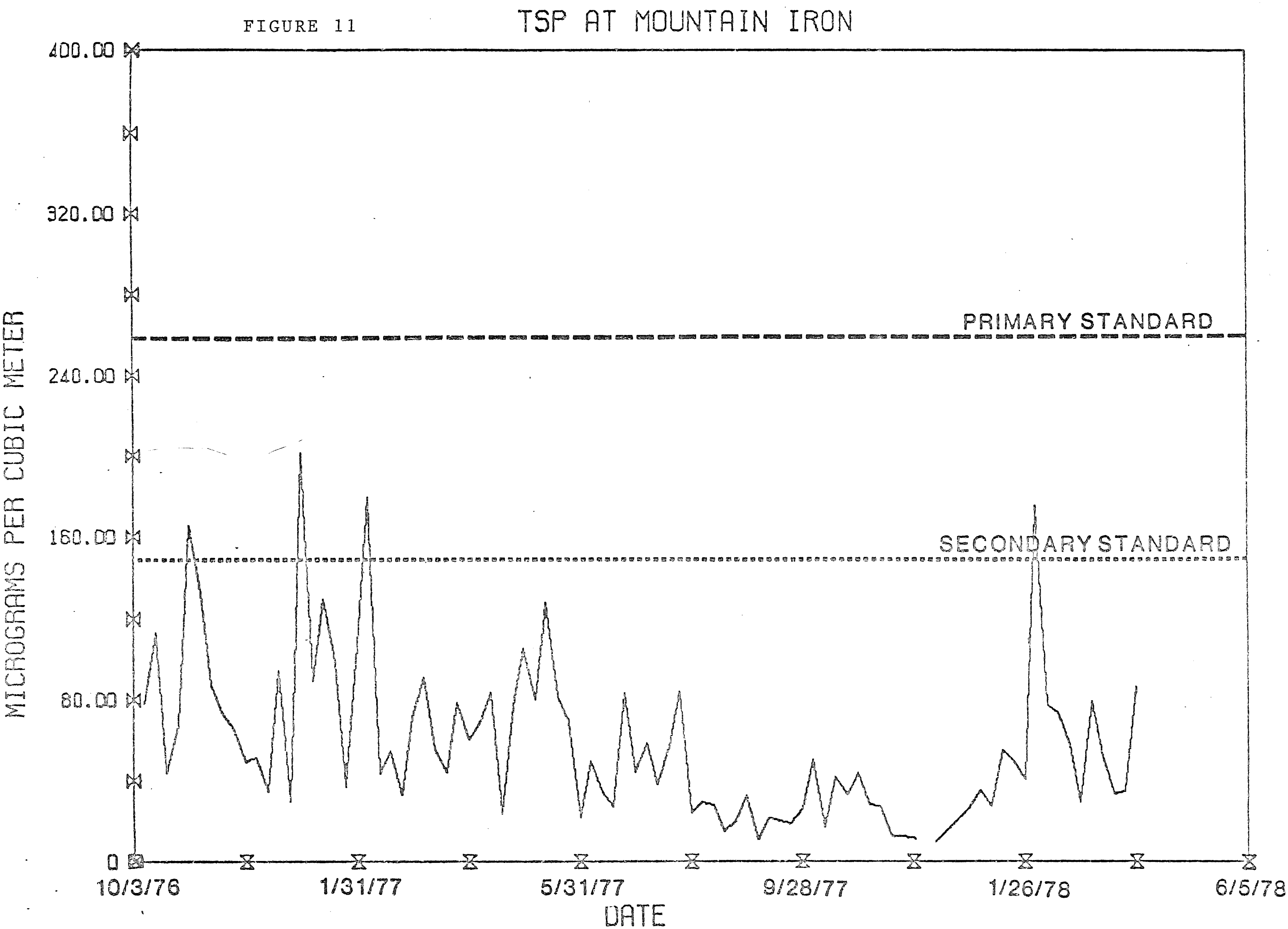

TSP AT MOUNTAIN IRON
400.00
320.00
240.00
160.00
80.00
0
MICROGRAMS PER CUBIC METER
PRIMARY STANDARD
SECONDARY STANDARD
10/3/76
1/31/77
5/31/77
9/28/77
1/26/78
6/5/78
DATE

FIGURE 12

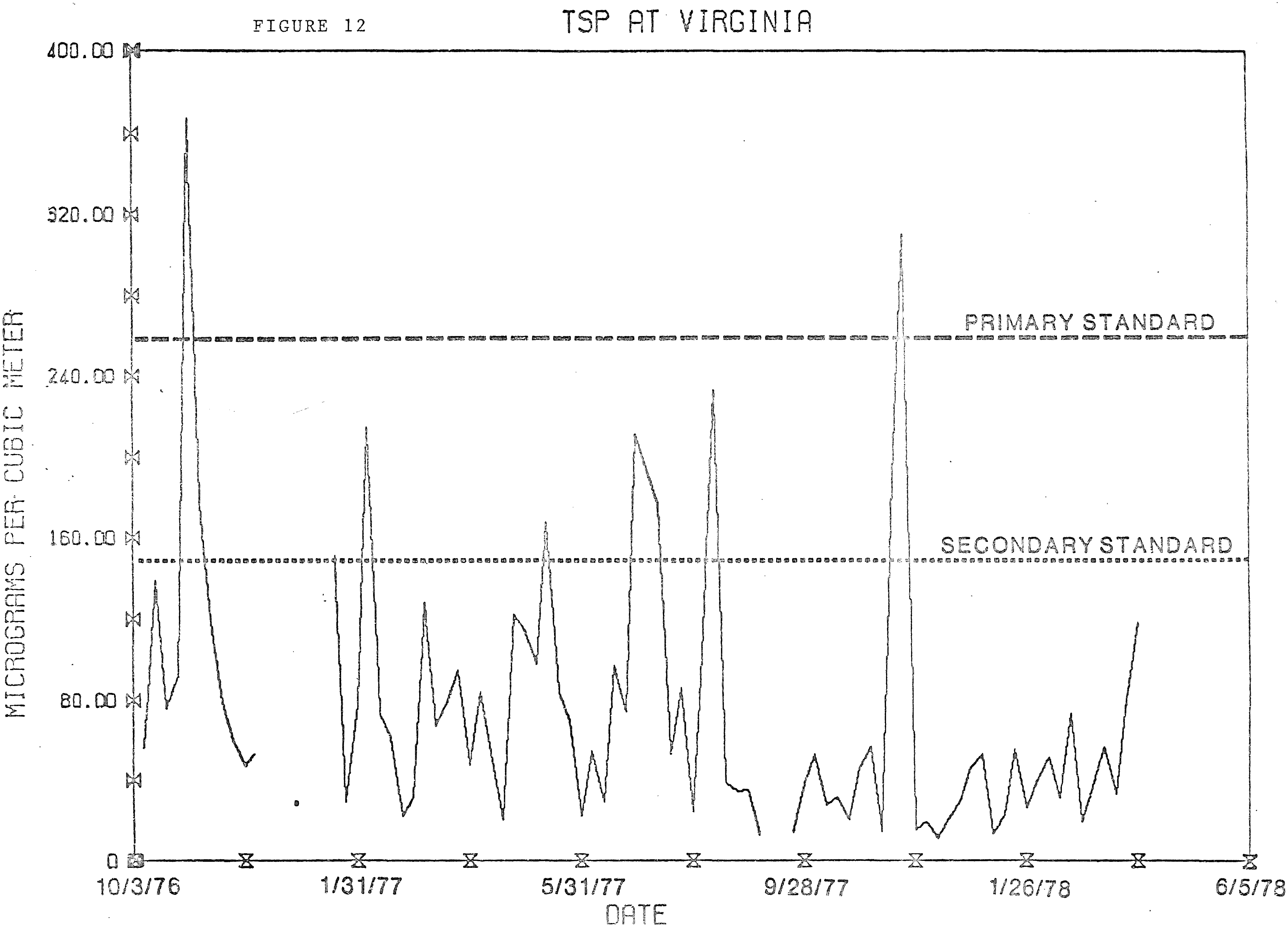

TSP AT VIRGINIA
PRIMARY STANDARD
SECONDARY STANDARD
MICROGRAMS PER CUBIC METER
400.00
320.00
240.00
160.00
80.00
0
10/3/76
1/31/77
5/31/77
9/28/77
1/26/78
6/5/78
DATE

FIGURE 13

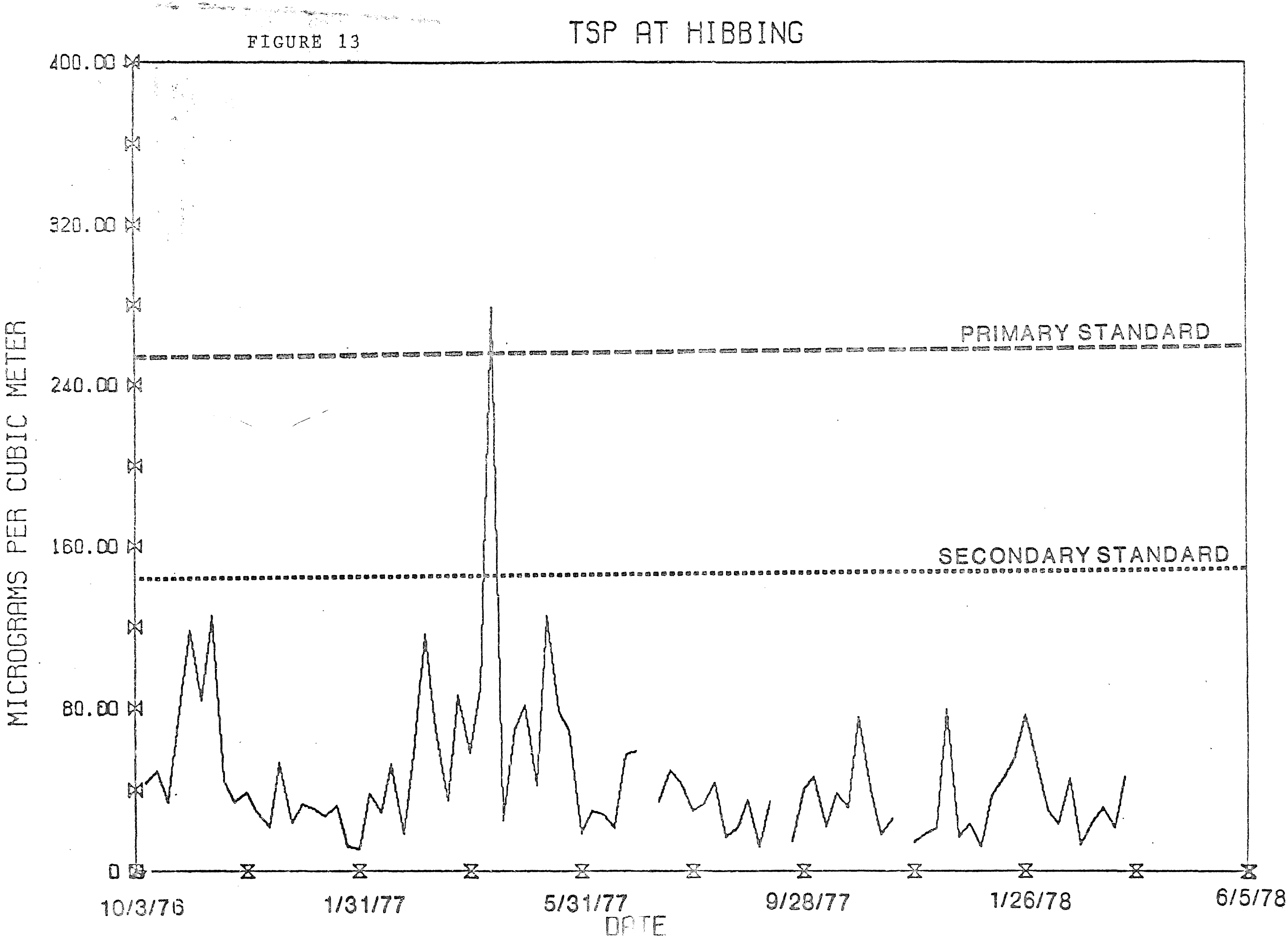

TSP AT HIBBING
400.00
320.00
240.00
160.00
80.00
0
MICROGRAMS PER CUBIC METER
PRIMARY STANDARD
SECONDARY STANDARD
10/3/76
1/31/77
5/31/77
9/28/77
1/26/78
6/5/78
DATE

FIGURE 14

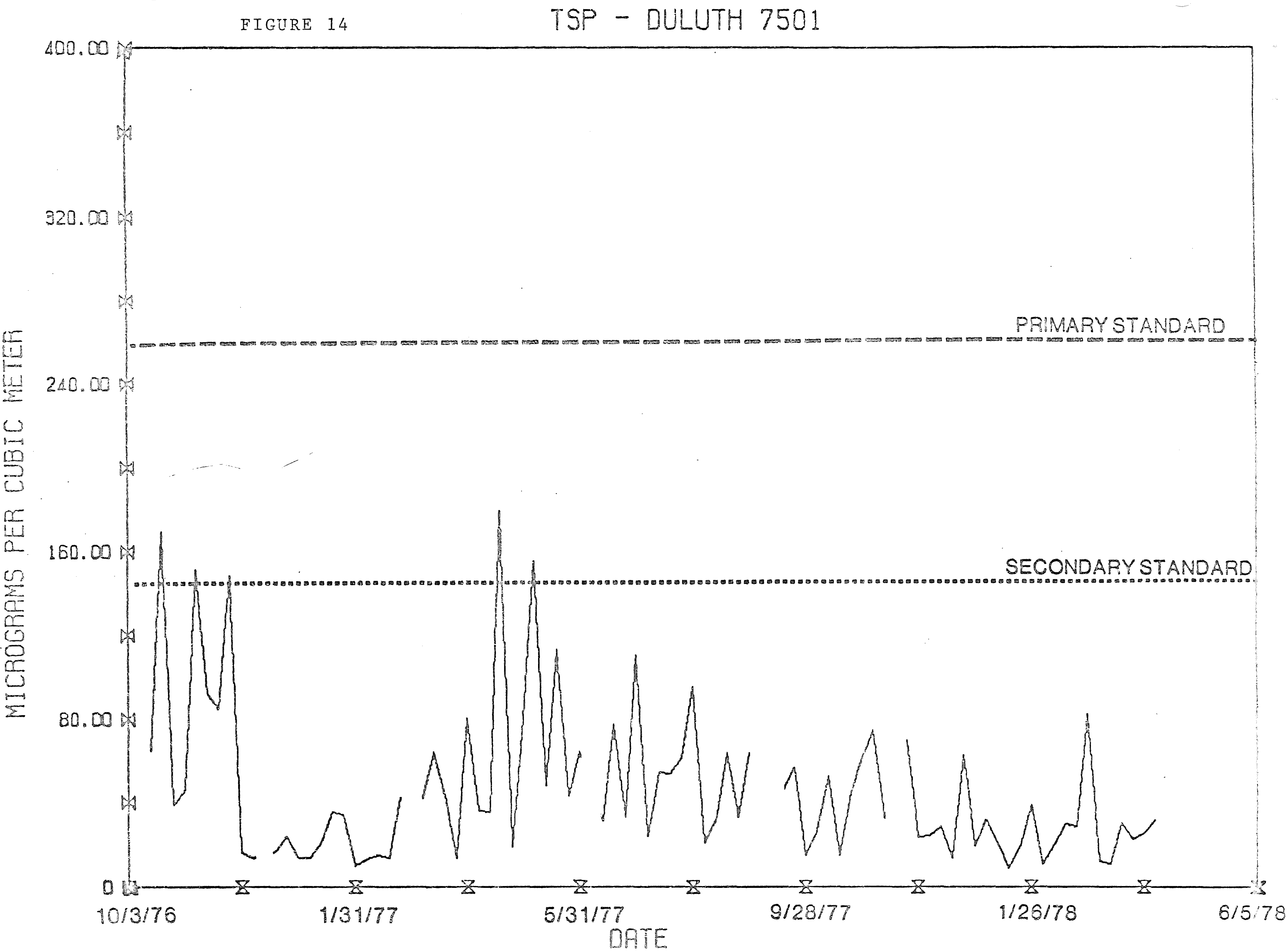

TSP - DULUTH 7501
400.00
320.00
240.00
160.00
80.00
0
PRIMARY STANDARD
SECONDARY STANDARD
MICROGRAMS PER CUBIC METER
10/3/76
1/31/77
5/31/77
9/28/77
1/26/78
6/5/78
DATE

FIGURE 15

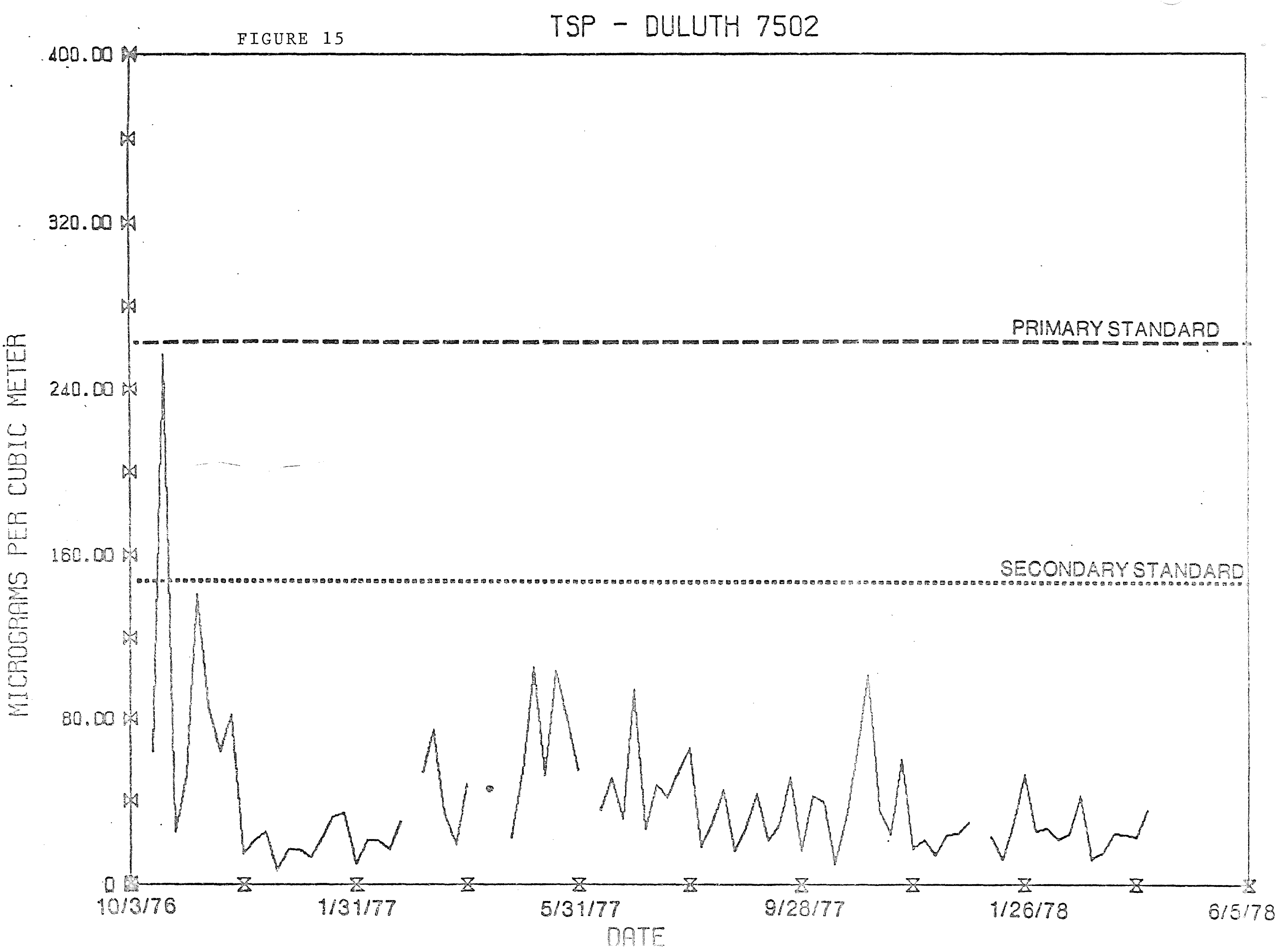
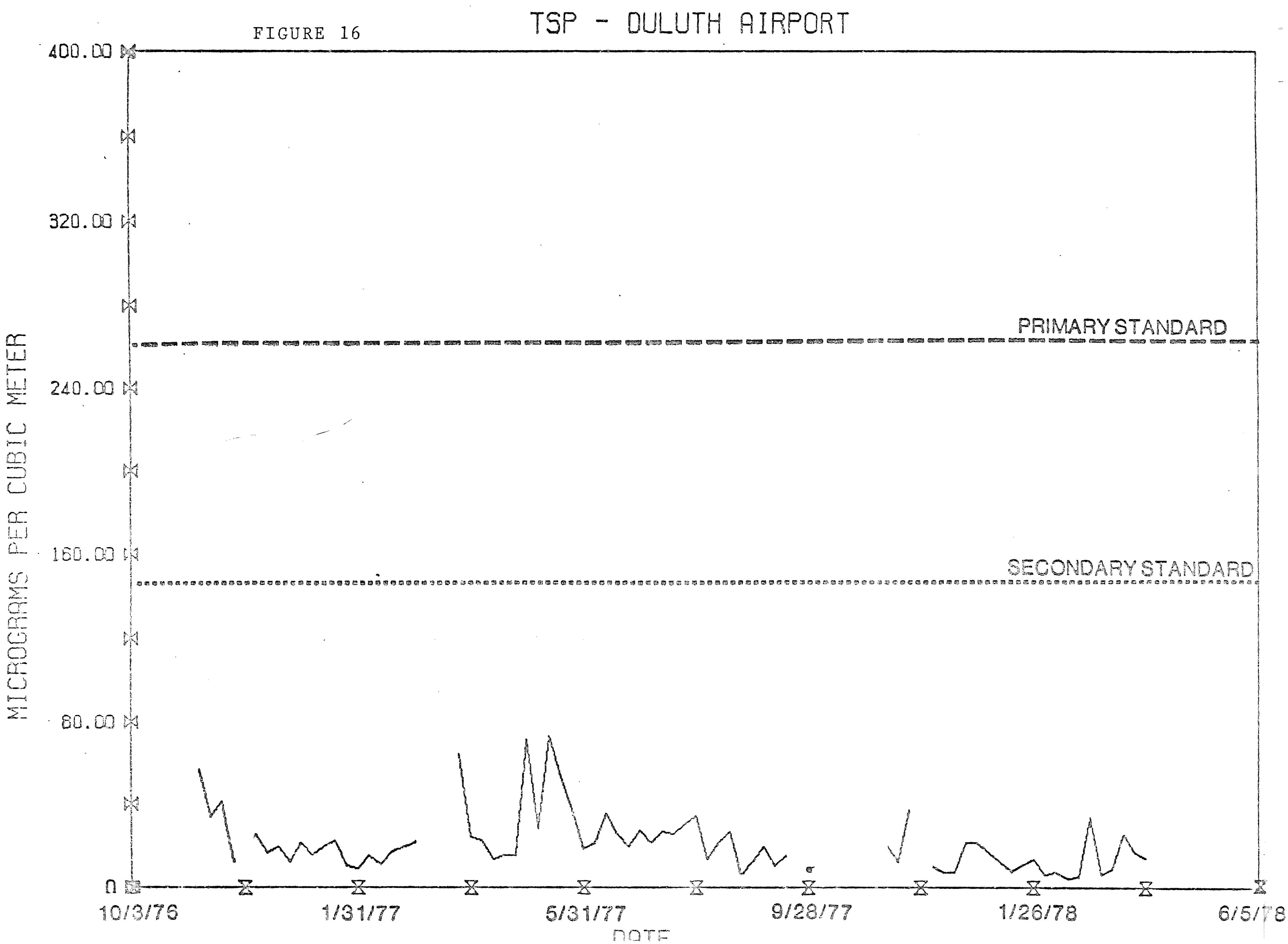

TSP - DULUTH 7502
400.00
320.00
240.00
160.00
80.00
0
MICROGRAMS PER CUBIC METER
PRIMARY STANDARD
SECONDARY STANDARD
10/3/76
1/31/77
5/31/77
9/28/77
1/26/78
6/5/78
DATE

FIGURE 16



TSP - DULUTH AIRPORT
MICROGRAMS PER CUBIC METER
400.00
320.00
240.00
160.00
80.00
0
PRIMARY STANDARD
SECONDARY STANDARD
10/3/76
1/31/77
5/31/77
9/28/77
1/26/78
6/5/78
DATE

FIGURE 17

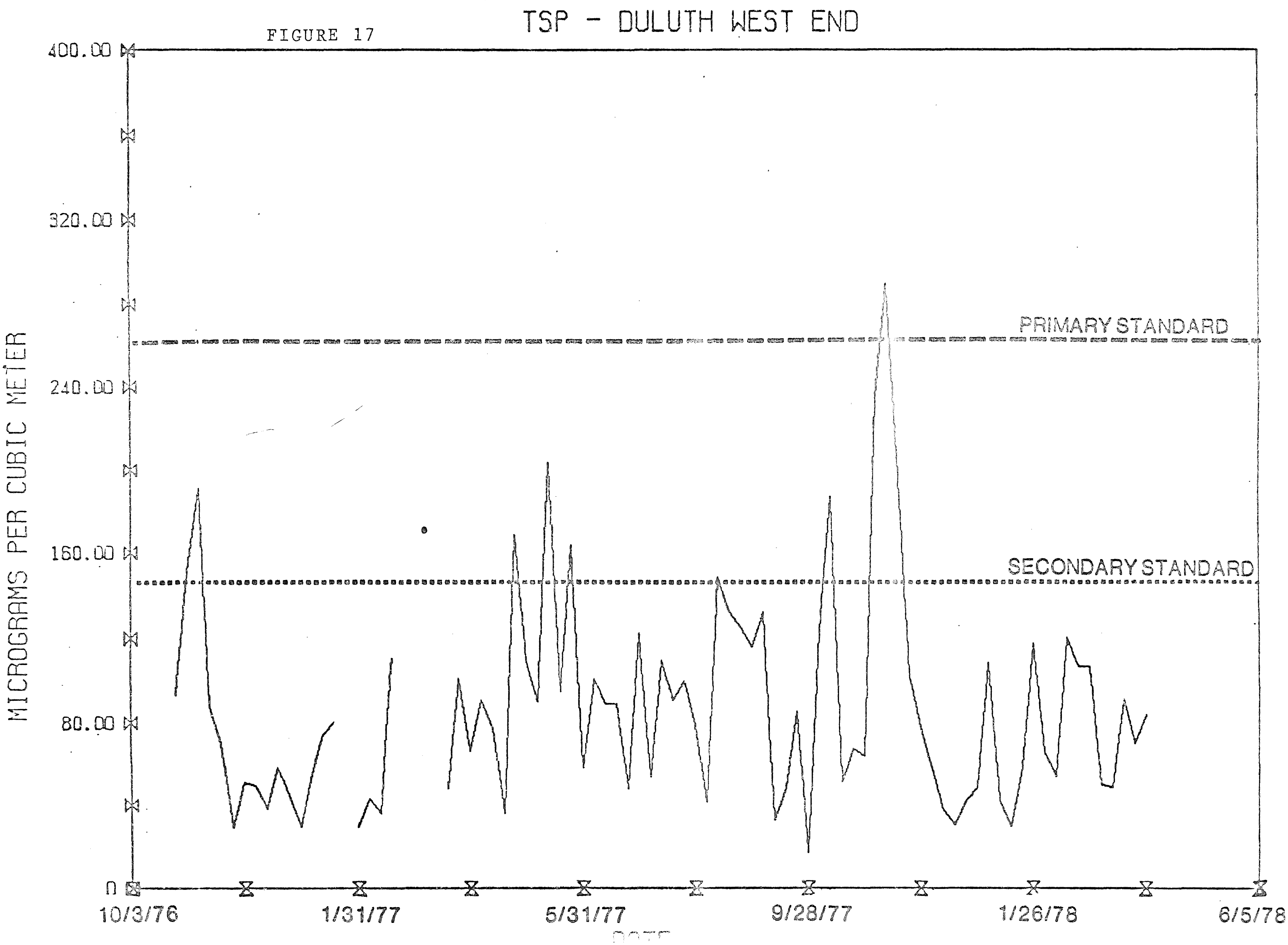

TSP - DULUTH WEST END
PRIMARY STANDARD
SECONDARY STANDARD
MICROGRAMS PER CUBIC METER
400.00
320.00
240.00
160.00
80.00
0
10/3/76
1/31/77
5/31/77
9/28/77
1/26/78
6/5/78

FIGURE 18

TSP - CLOQUET

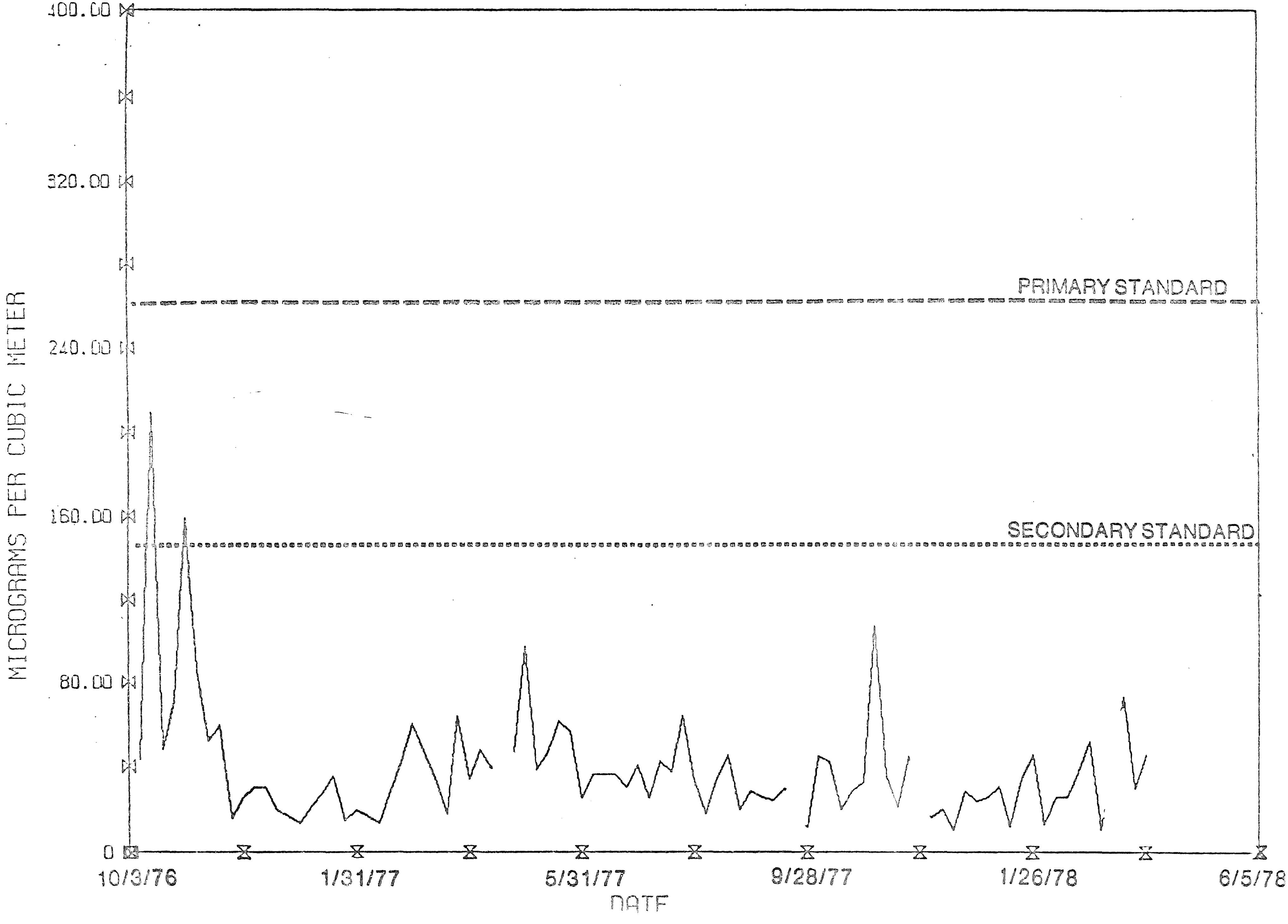
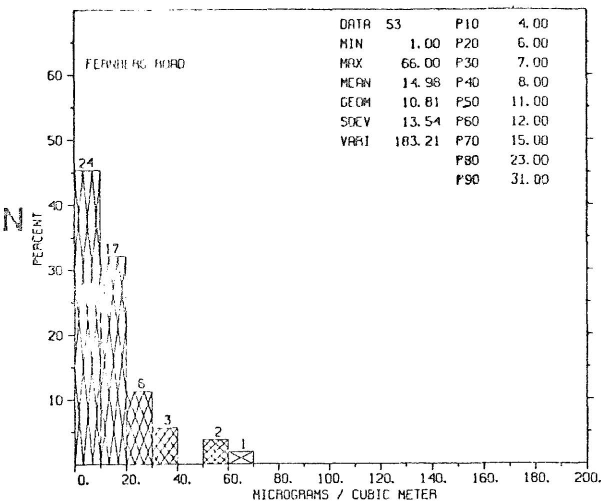
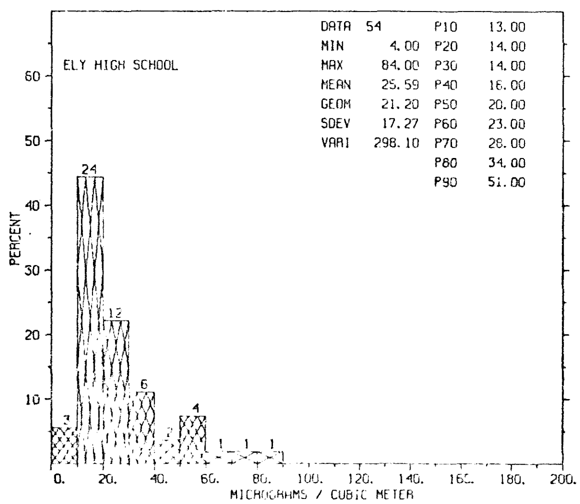
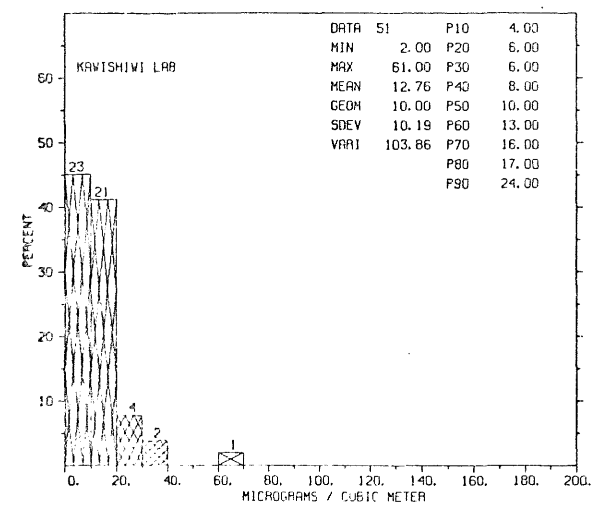


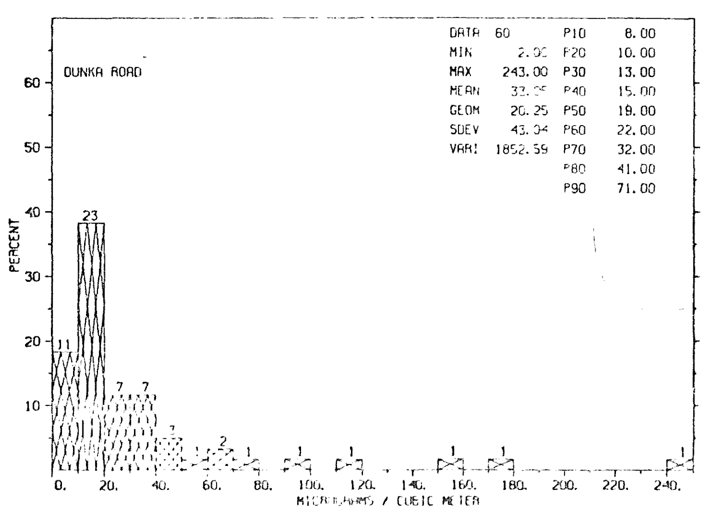
FIGURE 19

FREQUENCY DISTRIBUTION OF TOTAL SUSPENDED PARTICULATE CONCENTRATIONS FOR SELECTED SITES IN THE CU-NI STUDY REGION JAN-DEC 1977









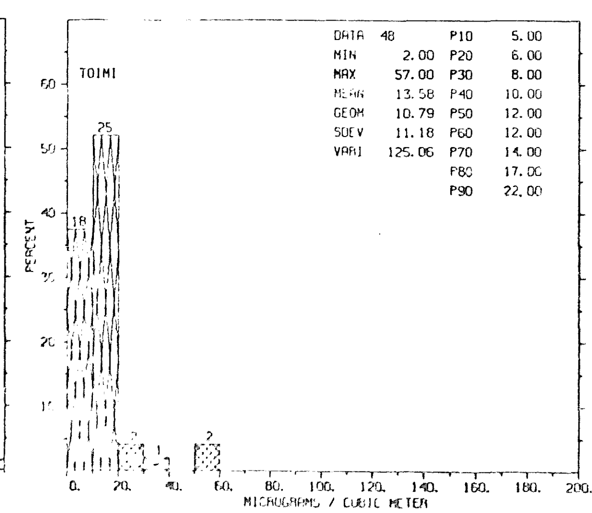


FIGURE 20

FREQUENCY DISTRIBUTION OF TOTAL SUSPENDED PARTICULATE CONCENTRATION FOR SELECTED SITES IN THE CU-NI STUDY REGION JAN-DEC 1977

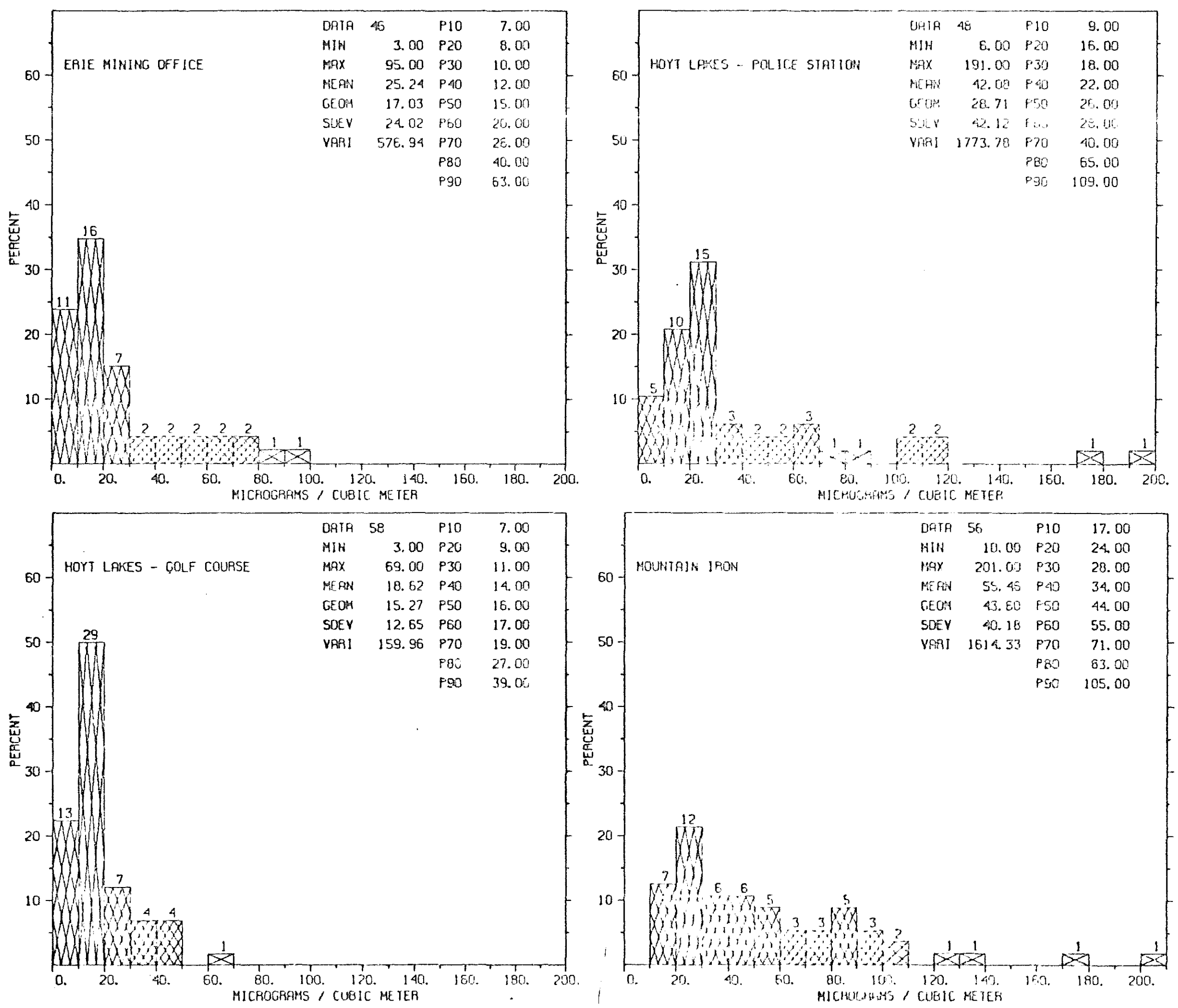
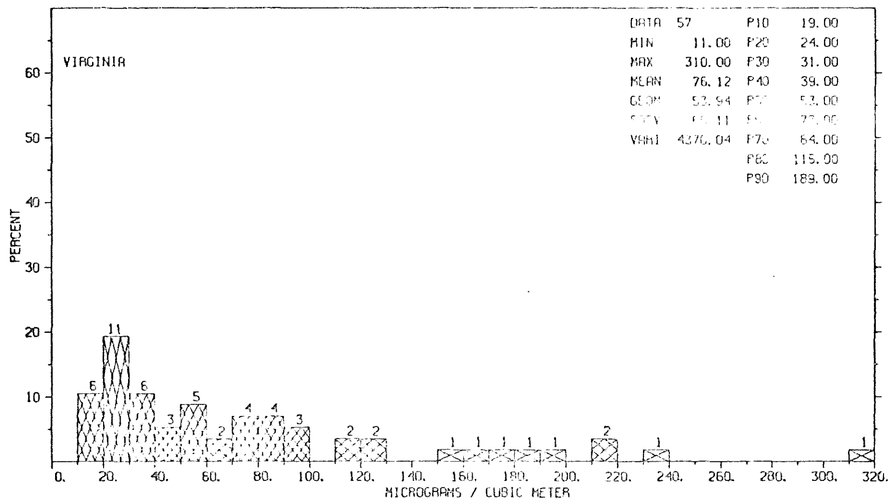


FIGURE 21

FREQUENCY DISTRIBUTION OF TOTAL SUSPENDED PARTICULATE CONCENTRATION FOR SELECTED SITES IN THE CU-NI STUDY REGION

JAN-DEC 1977



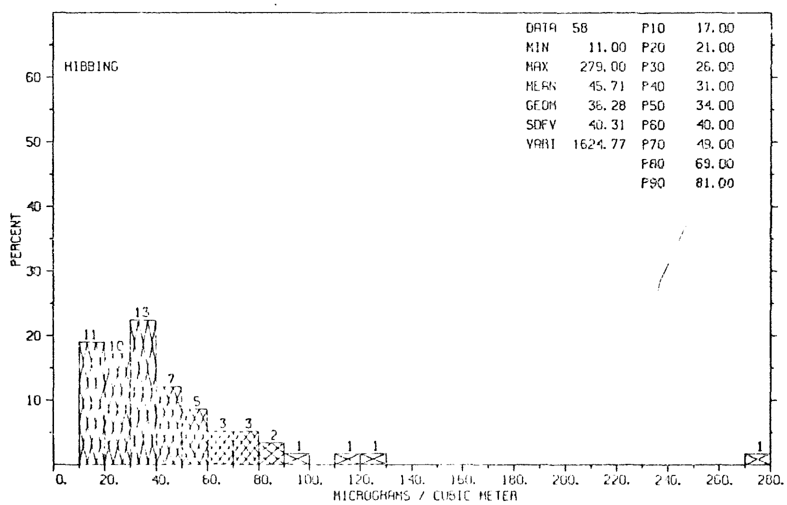
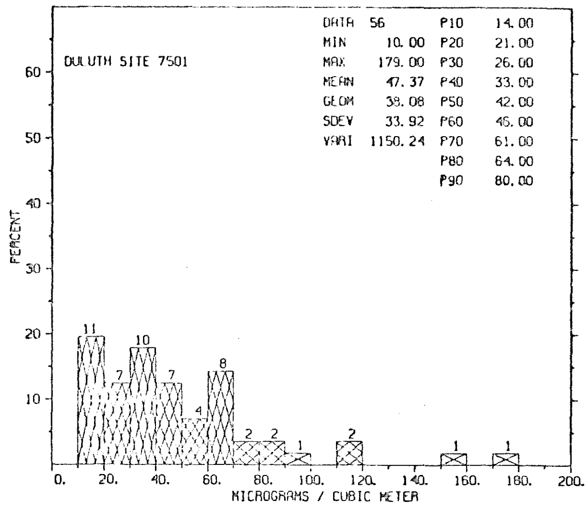
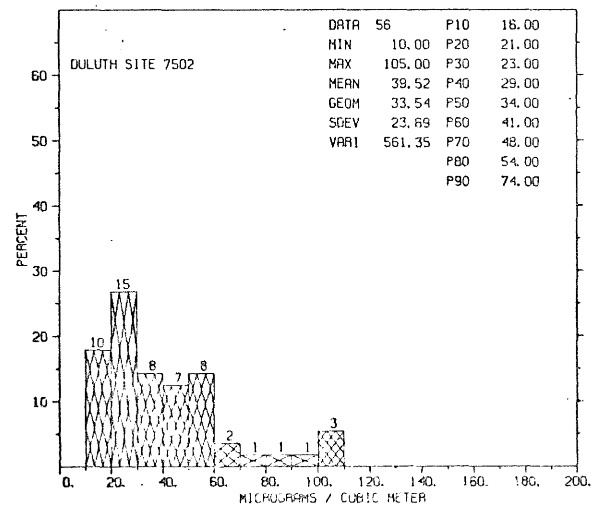
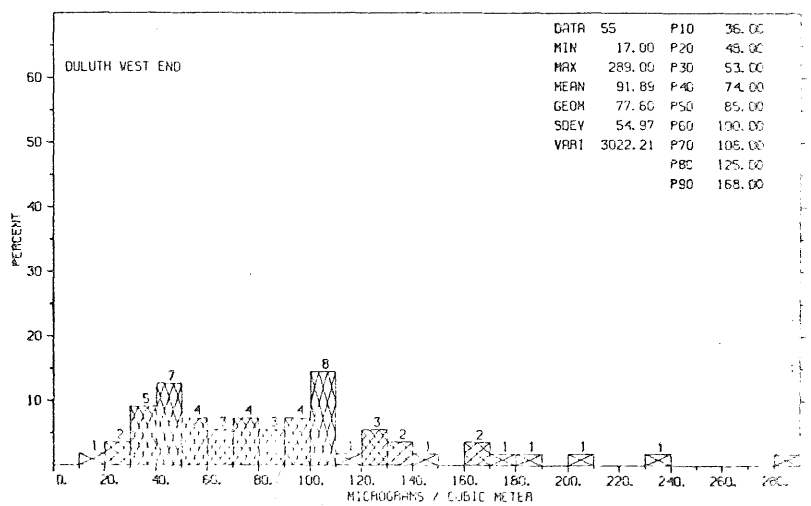


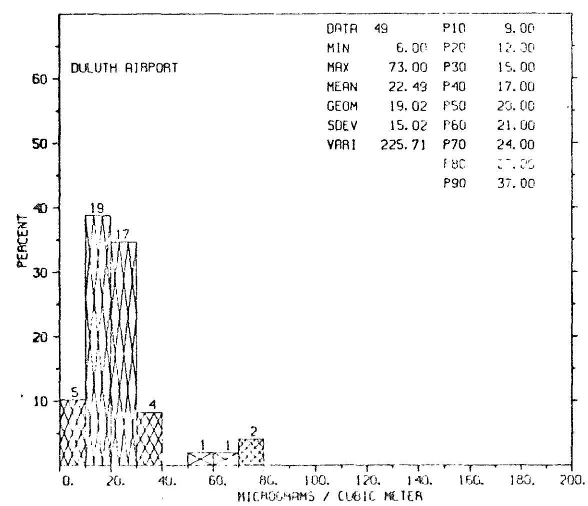
FIGURE 22

FREQUENCY DISTRIBUTION OF TOTAL SUSPENDED PARTICULATE CONCENTRATIONS FOR SELECTED SITES IN THE DULUTH, MN AREA JAN-DEC 1977









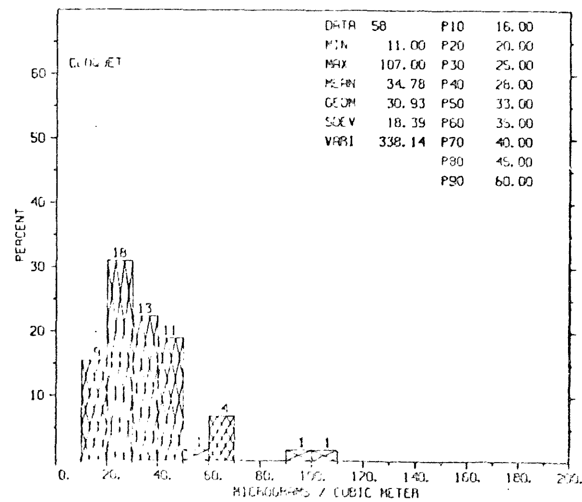


FIGURE 23 TSP READINGS JAN-DEC 1977

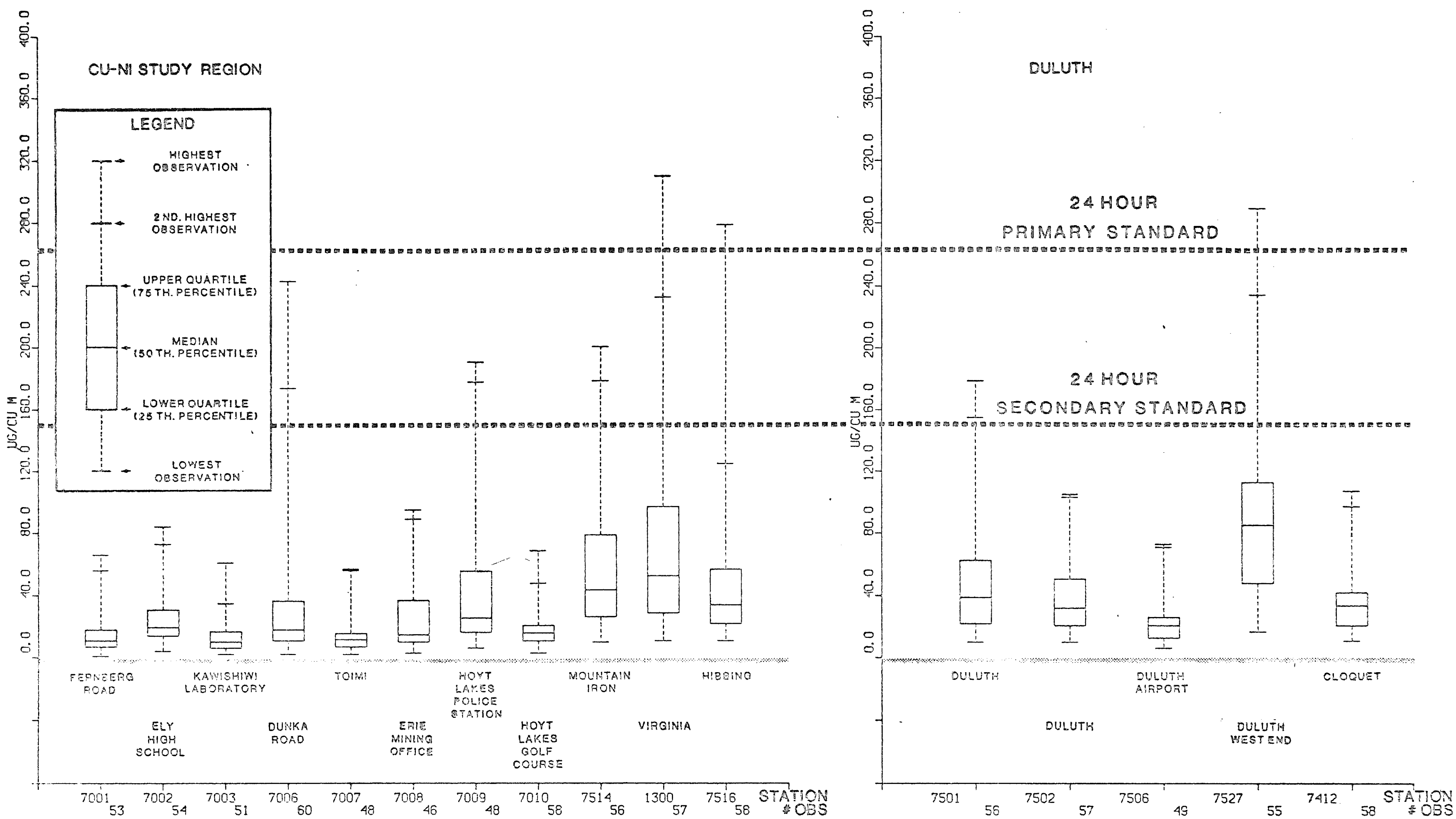
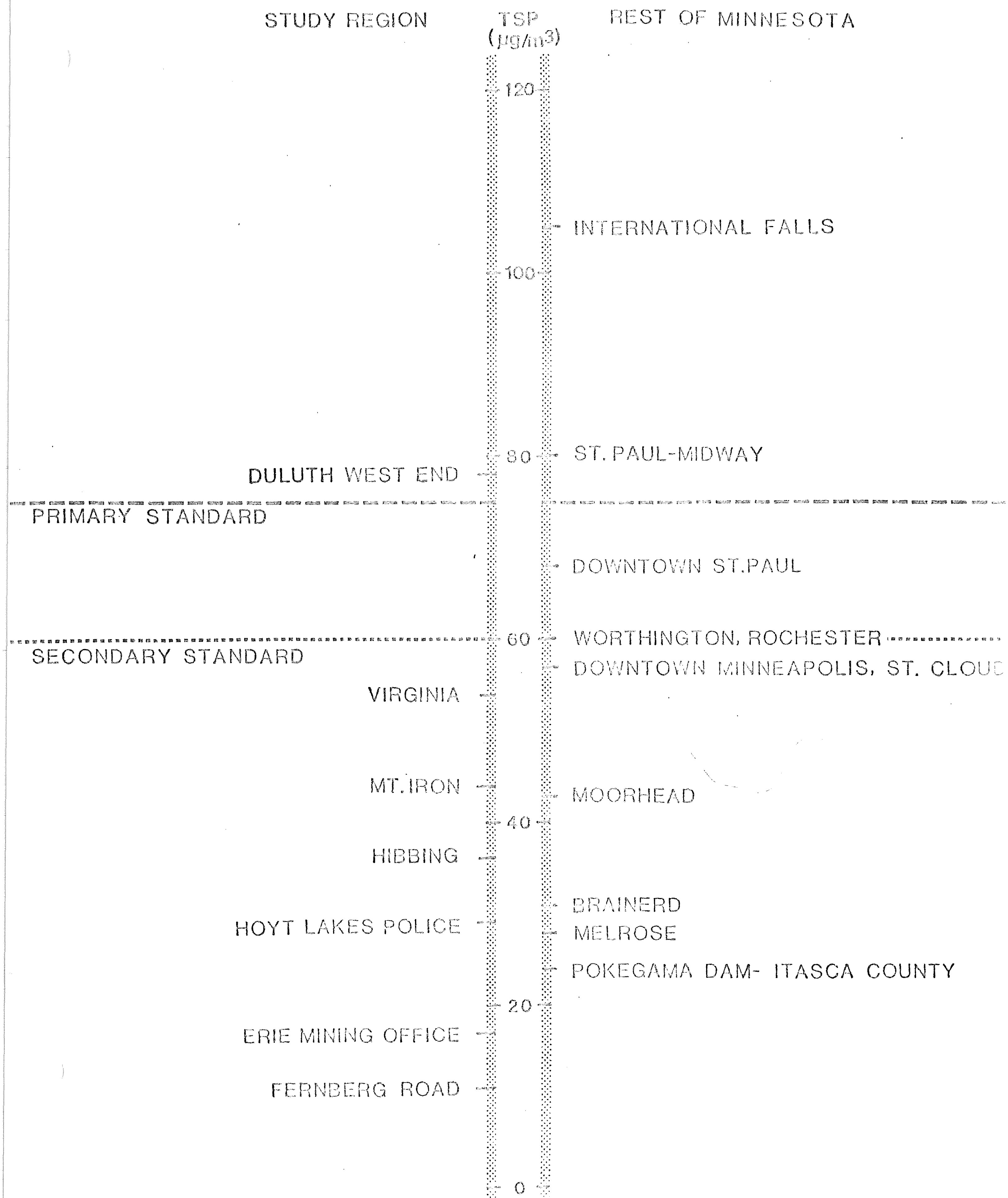
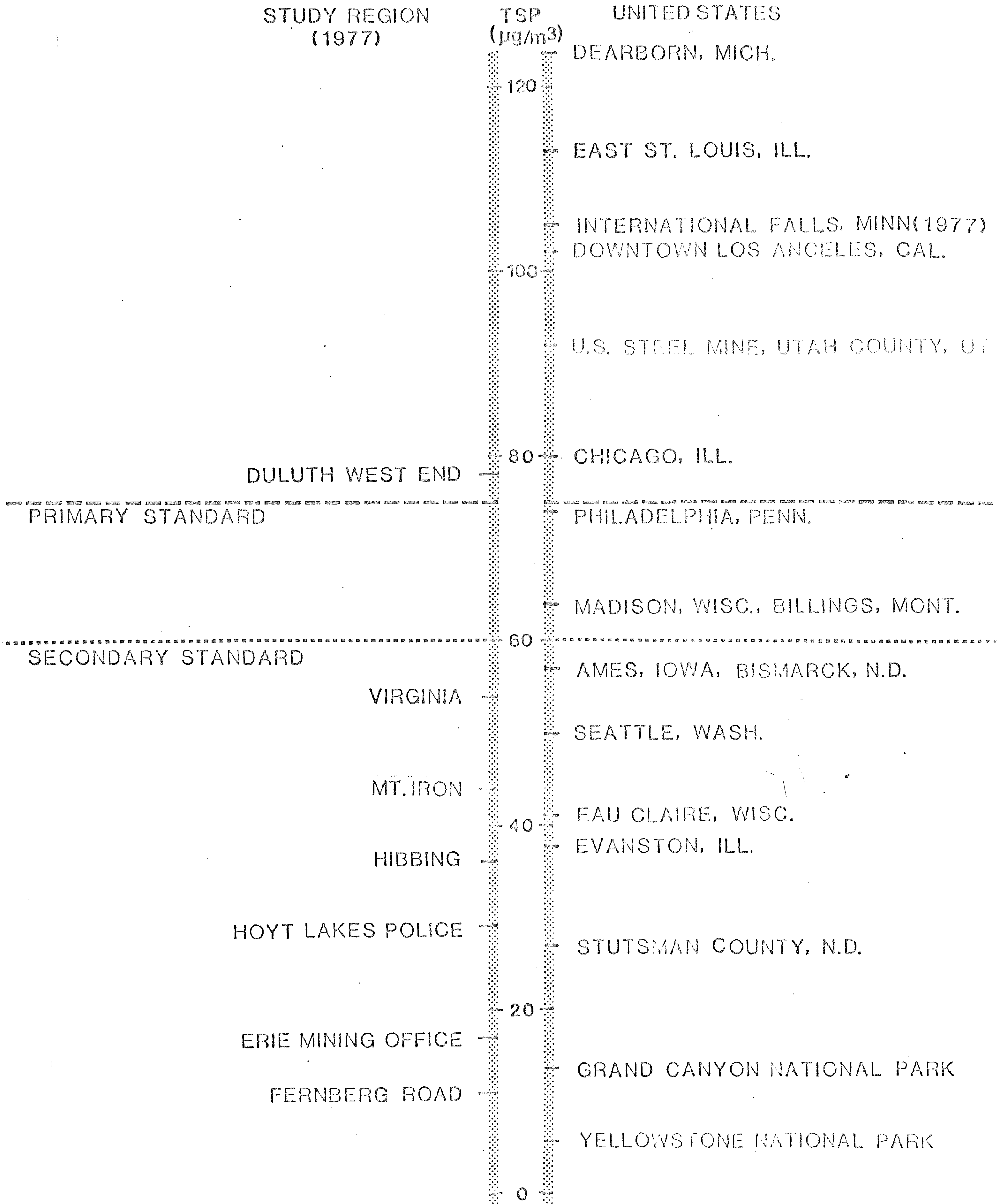


FIGURE 24: 1977 GEOMETRIC MEAN TSP CONCENTRATIONS IN MINNESOTA



SOURCE: MINNESOTA POLLUTION CONTROL AGENCY

FIGURE 25: 1976 GEOMETRIC MEAN TSP CONCENTRATIONS IN THE UNITED STATES

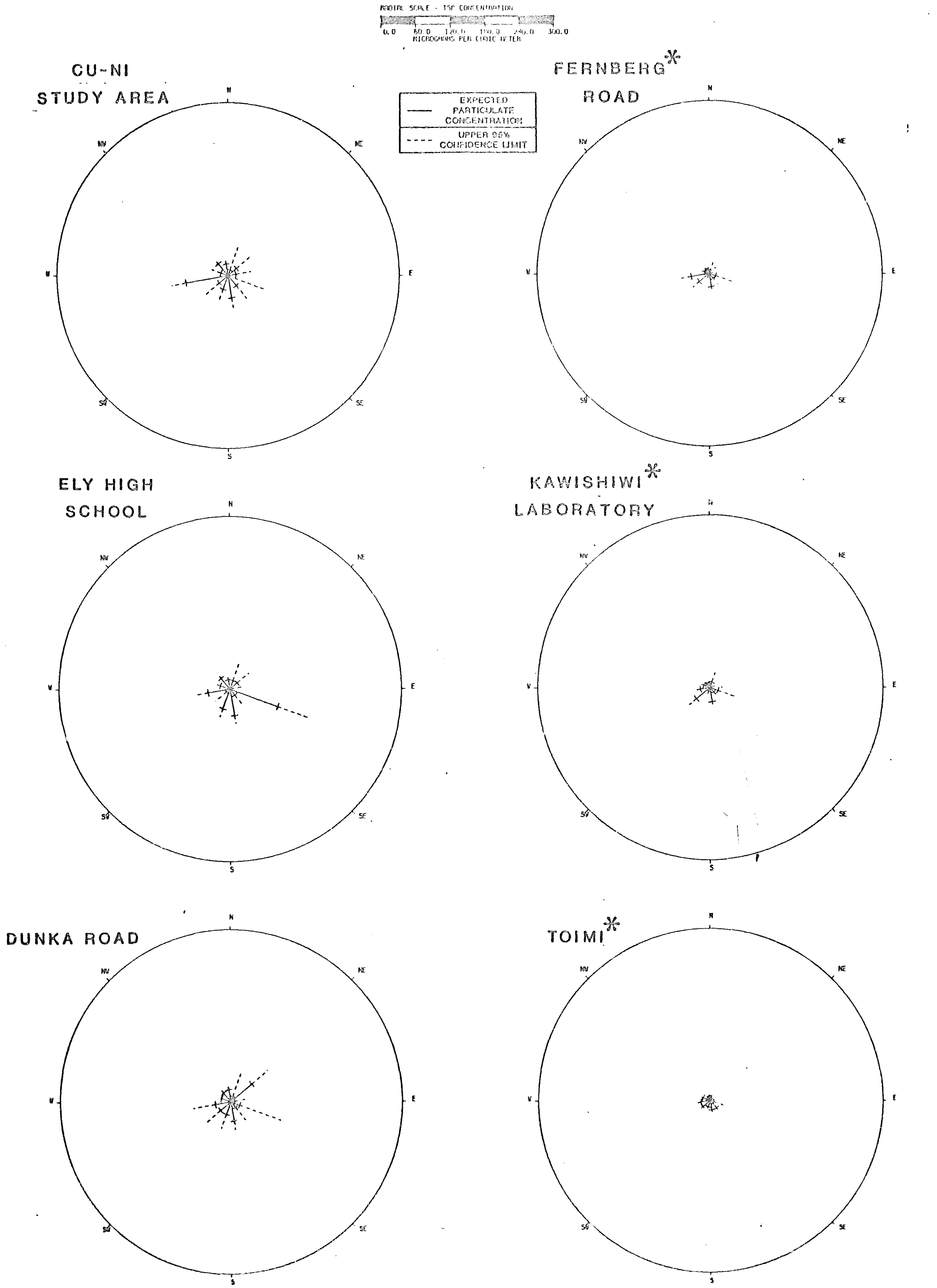


SOURCE: U.S. ENVIRONMENTAL PROTECTION AGENCY

FIGURE 26

TOTAL SUSPENDED PARTICULATE CONCENTRATIONS BY WIND DIRECTION

CU-NI STUDY REGION



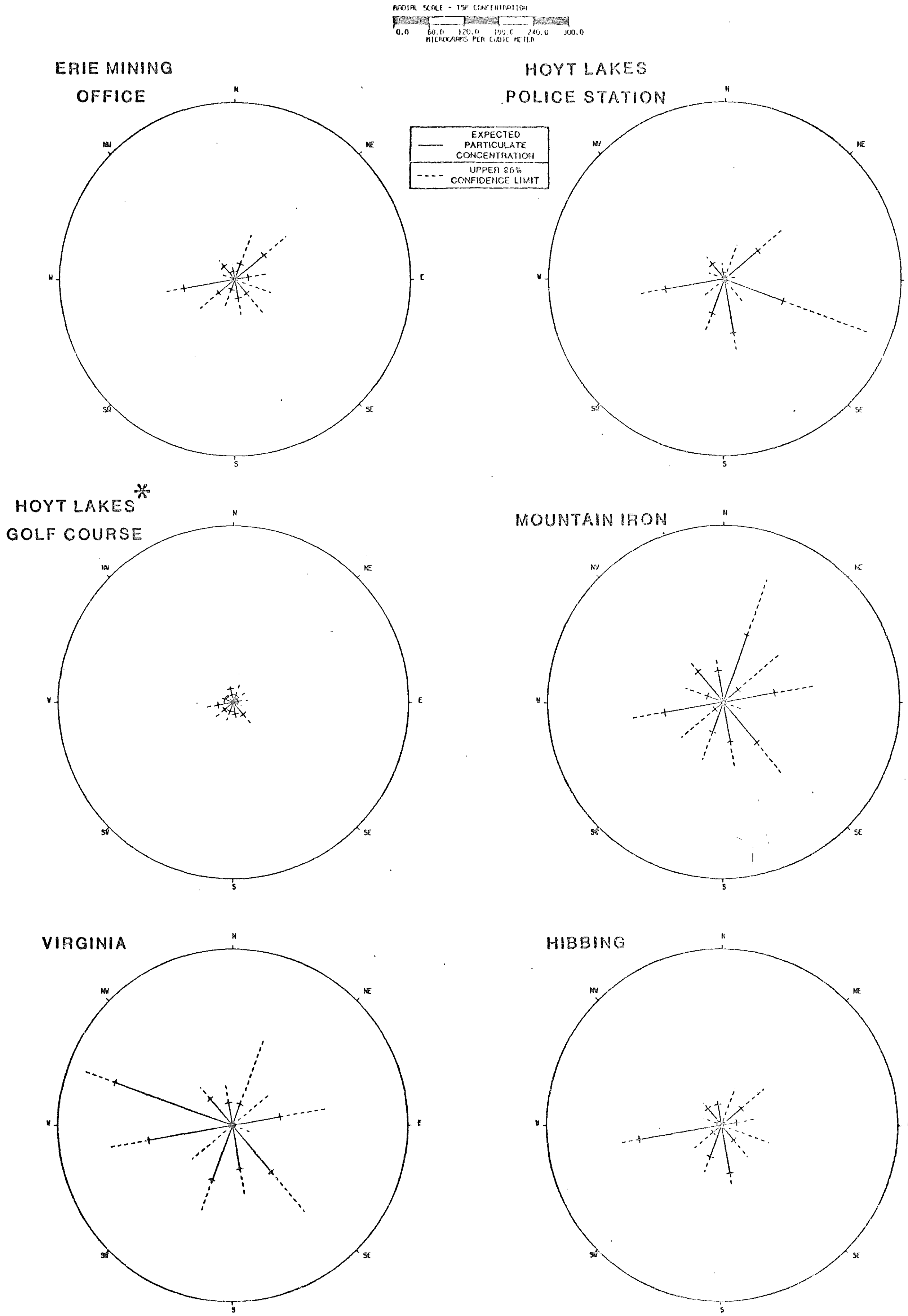
*-FOR EXPANDED SCALE; REFER TO FIGURE

INFORMATION PRESENTED WAS DERIVED FROM DATA COLLECTED BETWEEN OCT. 1976-MAR. 1978

FIGURE 27

TOTAL SUSPENDED PARTICULATE CONCENTRATIONS BY WIND DIRECTION

CU-NI STUDY REGION



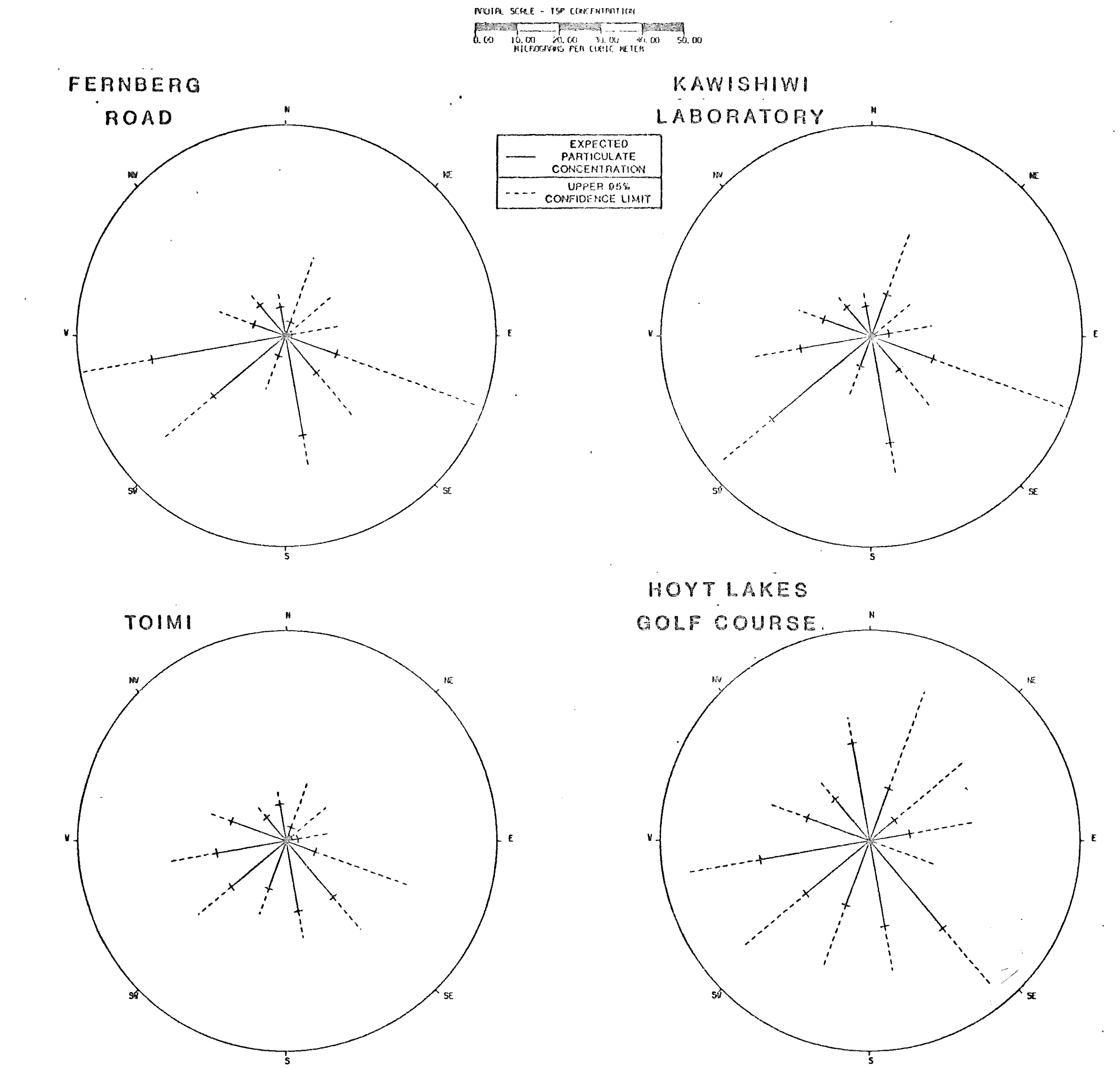
*-FOR EXPANDED SCALE; REFER TO FIGURE

INFORMATION PRESENTED WAS DERIVED FROM DATA COLLECTED BETWEEN OCT, 1976-MAR, 1978

FIGURE 28 EXPANDED SCALE

TOTAL SUSPENDED PARTICULATE CONCENTRATIONS BY WIND DIRECTION

CU-NI STUDY REGION

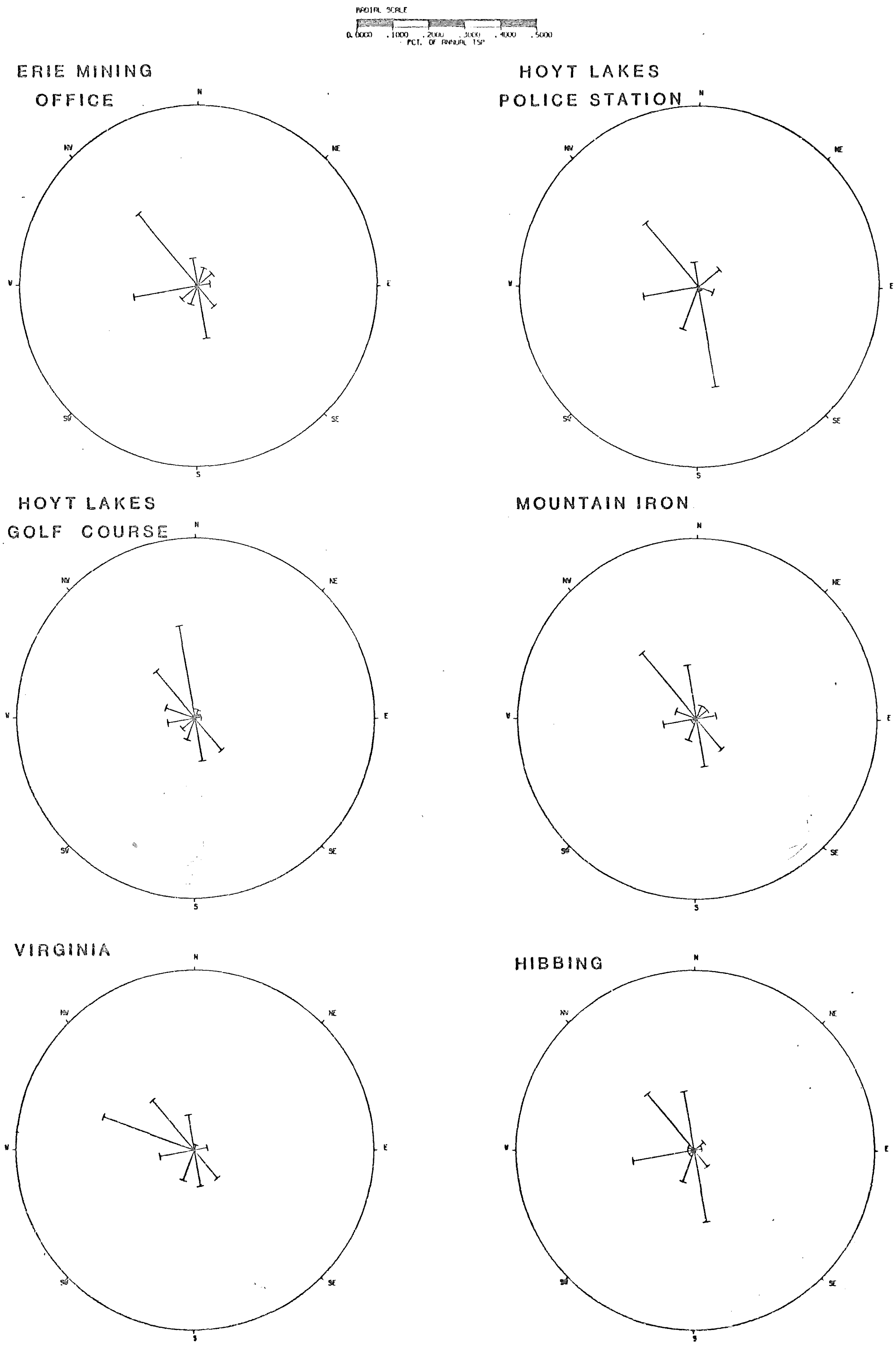


INFORMATION PRESENTED WAS DERIVED FROM DATA COLLECTED BETWEEN OCT, 1976-MAR, 1978

FIGURE 29

ANNUAL TSP CONTRIBUTION BY WIND DIRECTION

CU-NI STUDY REGION

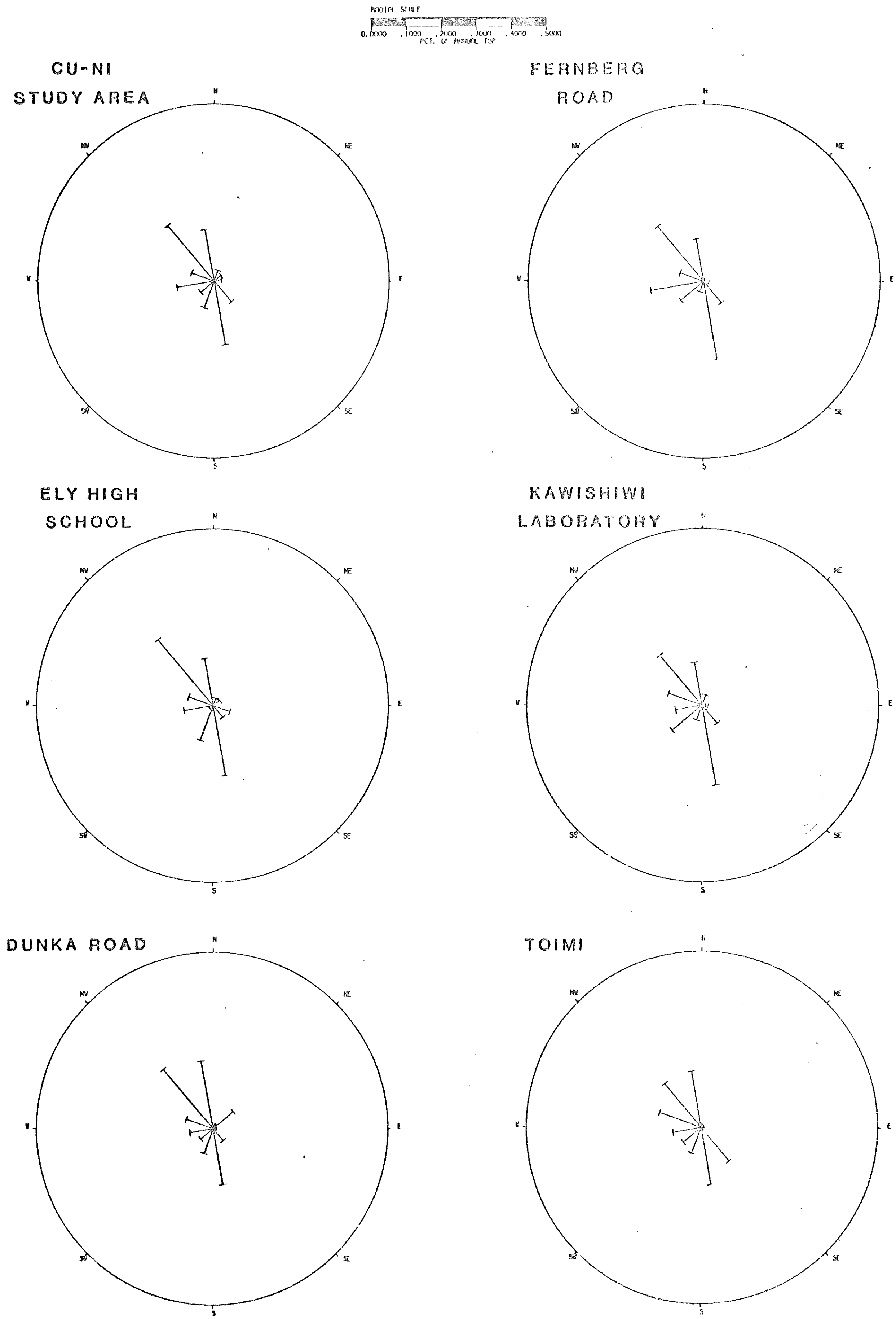


INFORMATION PRESENTED WAS DERIVED FROM DATA COLLECTED BETWEEN OCT. 1976-MAR. 1978

FIGURE 30

ANNUAL TSP CONTRIBUTION BY WIND DIRECTION

CU-NI STUDY REGION



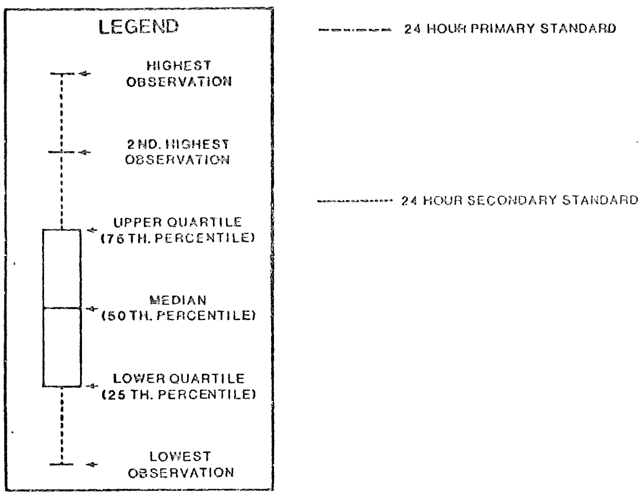
INFORMATION PRESENTED WAS DERIVED FROM DATA COLLECTED BETWEEN OCT, 1976-MAR, 1978

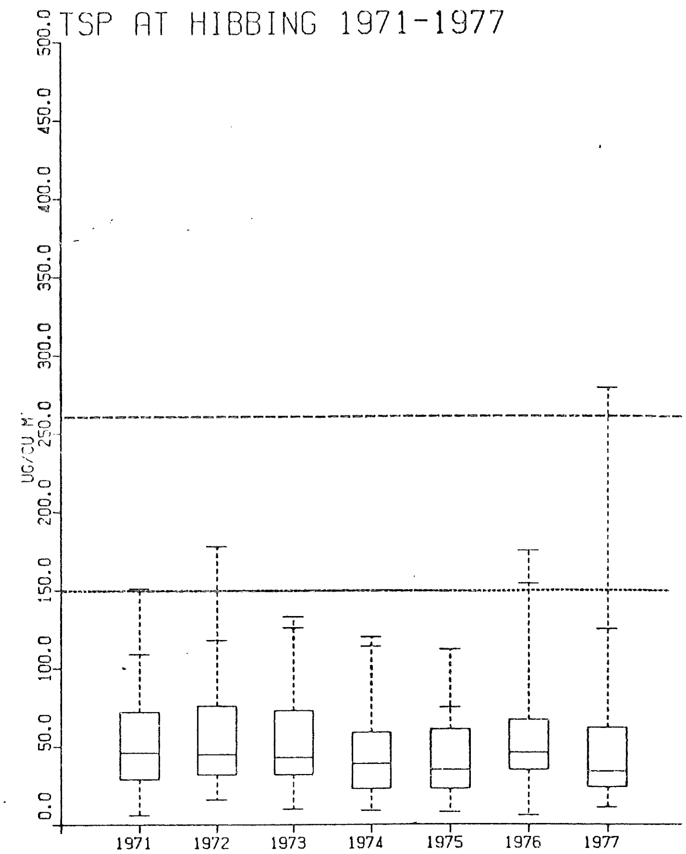
FIGURE 31

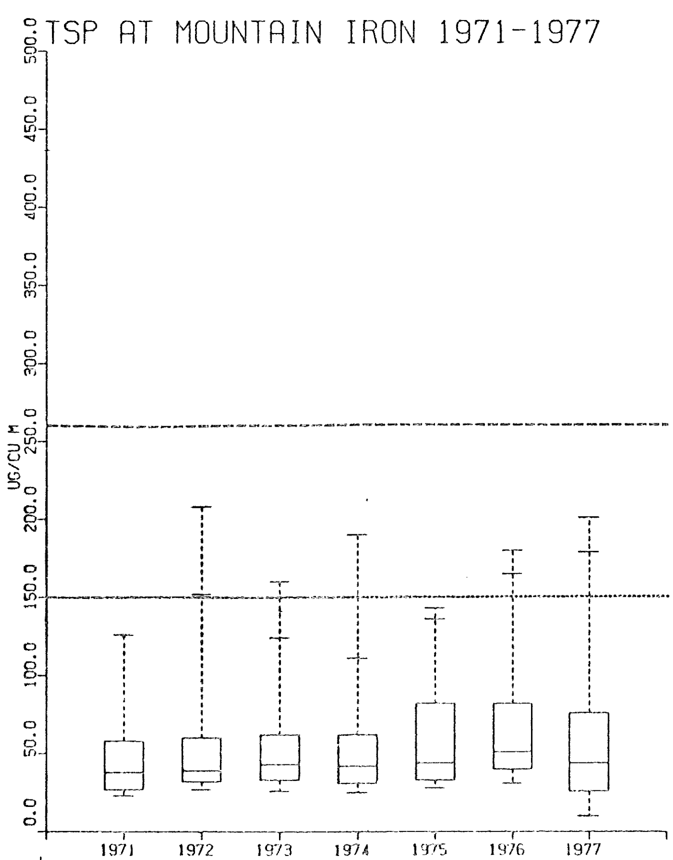
TRENDS IN TOTAL SUSPENDED PARTICULATES

(24-HOUR SAMPLES 1971-1977)

COPPER-NICKEL STUDY AREA







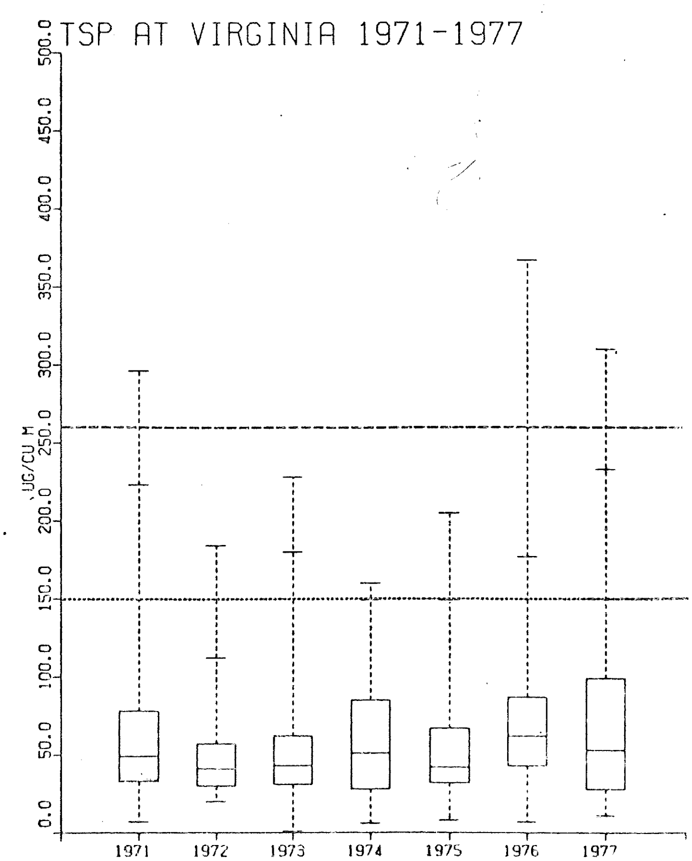
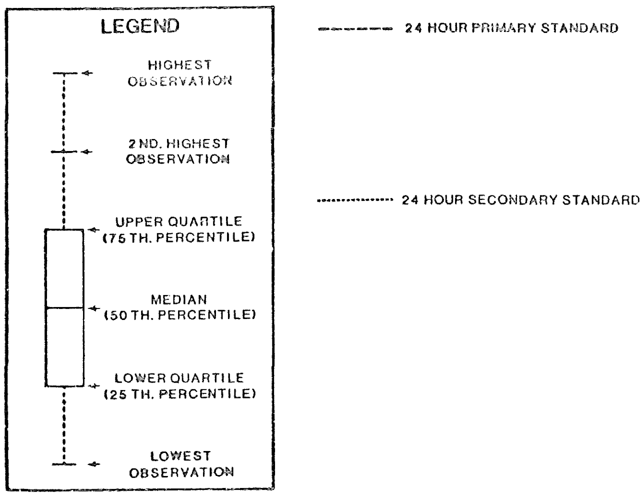


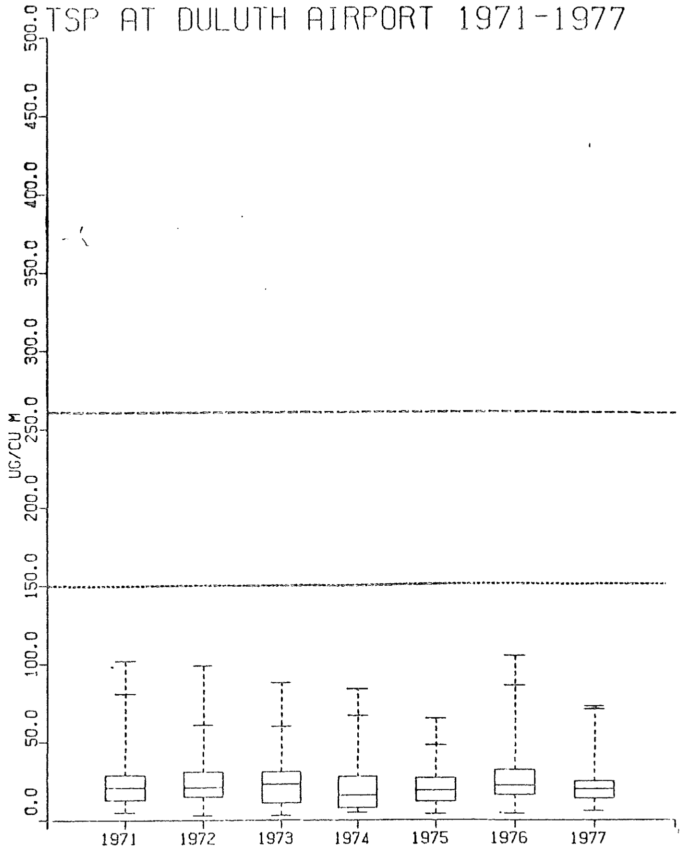
FIGURE 32

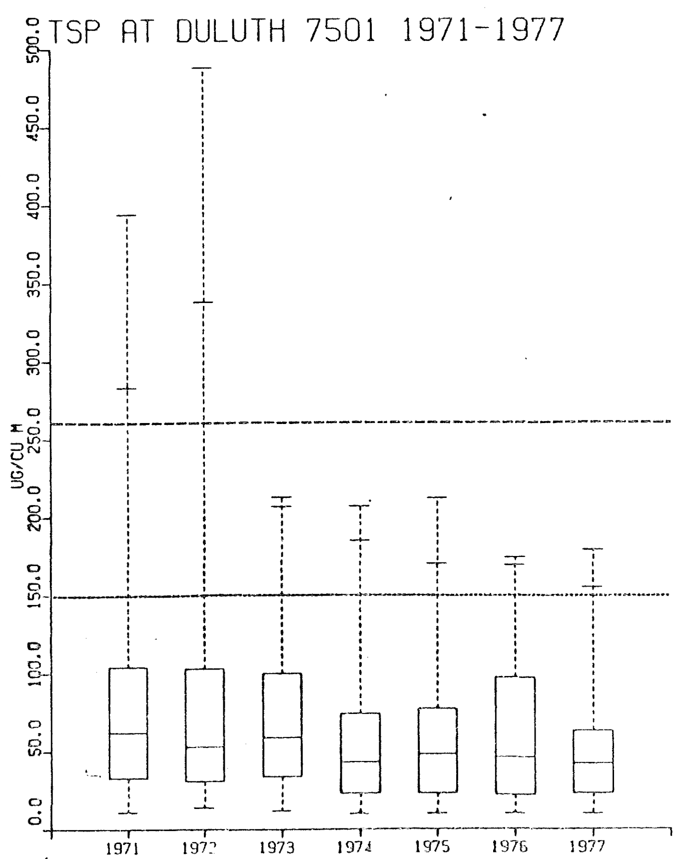
TRENDS IN TOTAL SUSPENDED PARTICULATES

(24-HOUR SAMPLES 1971-1977)

DULUTH AREA







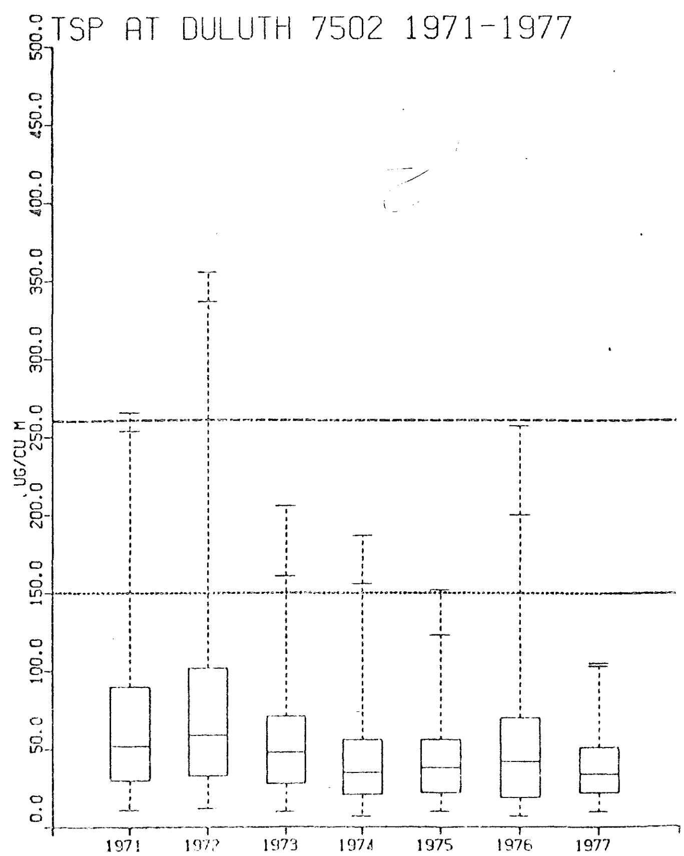


Table 1. Air quality sampling site instrumentation.

SITE NO.	NAME	STATUS[a]	HIGH-VOLUME SAMPLER	MEMBRANE SAMPLER	SO_2 & NO_2 (bubbler)	SO_2 (continuous)	EVENT RAIN SAMPLER	BULK DEPOSITION SAMPLER
7001	Fernberg Road	N,C	X	X		X		X
7002	Ely High School	N	X		X			
7003	Kawishiwi Lab	N	X		X		X	X
7004	Environmental Learning Center (ELC)	N		X	X			
7005	Bear Head State Park	N		X	X			
7006	Dunka Road	N	X	X	X			X
7007	Toimi	N	X	X	X			
7008	Erie Mining Office	N	X	X				
7009	Hoyt Lakes Police	P,C	X		X			
7010	Hoyt Lakes Golf Crs.	N	X	X	X		X	X
7011	Whiteface	N		X	X			
7012	Minnamax Office	N				X		
7013	Babbitt City Hall	N,C		X				
7514	Mt. Iron Post Office	P,C	X					
1300	Virginia City Hall	P,C	X					
7516	Hibbing	P,C	X					
7412	Scanlon	P,C	X	X	X			
7501	Duluth; 107th Ave.W.	P,C	X		X			
7502	Duluth; S.88th Ave.W.	P,C	X					
7506	Duluth Airport	P,C	X		X			
7527	Duluth West End	N,C	X	X	X			

[a]P = Site established prior to Regional Study.
N = New site for Regional Study.
C = Site continues to sample some parameters after Study sampling.

Table 2. Classification of air quality sampling sites.

TYPE	COPPER-NICKEL STUDY AREA	DULUTH AREA
Rural	Fernberg Road*	
	Kawishiwi Lab*	
	Environmental Learning Center	
	Bear Head Lake State Park	
	Toimi*	
	Hoyt Lakes Golf Course*	
	Whiteface	
	Minnamax	
Mining/Industrial	Dunka Road*	Duluth West End*
	Erie Mining Office*	
Community	Ely High School*	Cloquet*
	Hoyt Lakes Police Station*	Duluth 7501*
	Babbitt City Hall	Duluth 7502*
	Mountain Iron Post Office*	Duluth Airport*
	Virginia City Hall*	
	Hibbing Court House	

*TSP sampling site.

Table 3. Geometric mean total suspended particulates concentrations (ug/m^3).

	SAMPLED (1977)	ADJUSTED (1977)	ADJUSTED (all)
Study Area Sites			
7003 Kawishiwi Lab	10	10	10
7001 Fernberg Road	11	10	10
7007 Toimi	11	12	11
7010 Hoyt Lakes Golf Course	15	15	16
7008 Erie Mining	17	19	20
7006 Dunka Road	20	20	21
7002 Ely High School	21	22	23
7009 Hoyt Lakes Police Sta.	29	30	29
7516 Hibbing	37	37	37
7514 Mountain Iron	44	42	47
1300 Virginia	54	54	54
Duluth Area Sites			
7506 Duluth Airport	19		
7412 Cloquet	31		
7502 Duluth	34		
7501 Duluth	38		
7527 Duluth West End	78		

Table 4. Exceedances of 24-hour TSP secondary standard (150 ug/m^3).

SITE	NUMBER OF EXCEEDANCES	24-HOUR CONCENTRATIONS (ug/m^3)
Dunka Road	3	243, 174, 153
Hibbing	1	279*
Hoyt Lakes	2	191, 178
Mountain Iron	4	201, 179, 174, 165
Virginia	10	367*, 310*, 233, 214, 211, 193, 177, 177, 167, 151

*Also exceeds primary standard (260 ug/m^3).

Table 5. TSP data for selected area communities.

COMMUNITY	1976 POPULATION	ADJUSTED MEAN ANNUAL TSP (1977) (ug/m^3)	CHARACTER
Mountain Iron	3,756	42	mining (2-3 km)
Hoyt Lakes	3,722	30	mining (7-8 km)
Ely	4,961	22	non-mining
Virginia	11,730	54	mining (3-4 km)
Hibbing	16,126	37	non-mining

SOURCE: Bureau of the Census (1979). 1976 Current Population Reports, Series P-25, No. 762.

Table 6.

Correlations Between Study Area TSP Samping Sites	7001	7002	7003	7006	7007	7008	7009	7010	7514	1300	7516
7001 Fernberg Road		.73	.83	.53	.94	.67	.56	.73	.34	.39	.38
7002 Ely High School			.45	.57	.82	.65	.63	.47	.33	.30	.48
7003 Kawishiwi Lab				.39	.91	.59	.57	.88	.34	.50	.28
7006 Dunka Road					.77	.77	.38	.58	.35	.21	.63
7007 Toimi						.77	.58	.75	.25	.45	.67
7008 Erie Mining							.66	.68	.41	.43	.67
7009 Hoyt Lakes Police Sta.								.57	.36	.28	.48
7010 Hoyt Lakes Golf Course									.59	.56	.38
7514 Mountain Iron										.35	.39
1300 Virginia											.33
7516 Hibbing											

Correlations Between Study Area and Duluth Area Sites	7001	7002	7003	7006	7007	7008	7009	7010	7514	1300	7516
7501 Duluth	.33	.18	.11	-.01	.40	.29	.30	.14	-.08	.13	.07
7502 Duluth	.46	.36	.16	.10	.44	.34	.50	.15	.03	.19	.20
7506 Duluth Airport	.75	.60	.74	.32	.83	.52	.55	.66	.22	.35	.32
7527 Duluth West End	.25	.31	.32	.21	.27	.27	.15	.21	-.01	.23	.19
7401 Cloquet	.46	.37	.84	.32	.52	.63	.35	.74	.26	.40	.29

Table 7. Mean TSP concentrations per time period for all sites in the Study Area.

INTERVAL	DATES	EVENT	ADJUSTED MEAN TSP ($\mu g/m^3$)
1	10/9/76-11/20/76	Start up No snow cover	51.22*
2	11/26/76-3/7/76	Snow cover	18.97
3	3/14/77-7/24/77	Mining activity No snow	35.64
4	7/30/77-10/4/77	Mine strike	14.63**
5	10/10/77	Snow event	7.23
6	10/16/77-11/9/77	Mine strike No snow cover	16.68
7	11/16/77-12/15/77	Mine strike Snow cover	13.02
8	12/21/77-3/27/78	Mining activity resumed Snow cover	15.56

*Figure is unreliable because 3 sites were completely inoperable during this period.

**The mining strike began officially on August 1, but the mines were effectively shut down as of July 30. Samples taken on July 30 were included in the strike period.

APPENDIX 1

Air Quality Sampling Sites for Total Suspended Particulates

7001 Fernberg Road

Fernberg Road is a remote background site located on a hilltop about 25 km ENE of Ely near the boundary of the BWCA. The region is entirely forested except for the partially cleared area that the sampling station shared with a sheriff's communications tower. The dirt access road approaches the site generally from the NW, but it receives very little use in summer and is usually closed in winter. The high volume sampler (hi-vol) was mounted on the roof of a sampling shack 3 m above the ground.

7002 Ely High School

The high school is located in a residential area near the center of Ely. The hi-vol was located on the roof at about the same height as the school's chimney about 25 m to the S.W. The school burns fuel oil for heating. Mines in the area immediately surrounding Ely are abandoned.

7003 Kawishiwi Lab

The United States Forest Service Kawishiwi Laboratory is located on the South Kawishiwi River NE of the taconite mining operations. This is a forested area about 8 km SW of the BWCA. The hi-vol was locted on a 1-floor building. Potential local sources of pollutants are occasional vehicular traffic on the dirt access road and parking lot and occasional excavation near the building.

7006 Dunka Road

This site was located on Erie Mining Company property near Milepost 9, approximately 15 km east of their taconite processing plant. The hi-vol was mounted on a 2 m high stand about 100 m SE of Dunka Road and about 20 m NE of a dirt access road used mostly by large trucks during infrequent logging activity. Dunka Road handles a fair number of light vehicles (cars and pickup trucks), and chemical dust control is practiced. Some brush and trees are near the site, a large swamp begins a couple hundred meters to the south and southeast, and a forested area occasionally used for logging is about 1 km SW.

7007 Toimi

Toimi is a stand-mounted background site located on the west side of a little-used private gravel road. Low brush surrounds the site, and the area is mostly forested. This site is about 30 km SE (down the primary wind access) from Erie Mining and can be considered a test site for medium range transport of particulates from taconite mining and processing.

7008 Erie Mining Office

The hi-vol was located on the roof of the Erie Mining Company office building about 2.5 km SW of their tailings basin. The Erie taconite processing plant is on a small hill between the office building and the tailings basin. The building is surrounded by roads, railroad lines, active and abandoned open pits, storage piles, and mine dumps.

7009 Hoyt Lakes Police Station

The hi-vol was located atop the Police Station in a primarily residential area on the NW side of Hoyt Lakes. A nearby industrial facility is the Minnesota Power and Light (MP&L) generating station 1.5 km to the NW across Colby Lake. The Erie Mining Company mine and processing plant is approximately 8 km north.

7010 Hoyt Lakes Golf Course

The golf course is about 3 km east of the Police Station and about a kilometer east of the Hoyt Lakes residential area. The site is bordered by forest to the west and open golf course to the east. A small paved road to the golf course lodge passes 5 m to the east of the stand the hi-vol was on. The MP&L power plant is 4 km to the NW, and Erie Mining is 8 to 10 km to the NNW.

7514 Mountain Iron Post Office

The hi-vol is on the Post Office roof at the north edge of town within 200 m of the huge Minntac open pit and about 2 km SSE of the Minntac processing plant.

1300 Virginia City Hall

The sampler is located atop the 3-floor City Hall near downtown. A nearby source is the municipal power plant less than 0.5 km to the WNW. Mining occurs all around Virginia, with the largest nearby operations to the north and southeast. The Minntac processing plant is about 8 km to the WNW.

7516 Hibbing Court House

The sampling site is on the St. Louis County Court House about 1 km ENE of downtown. Highway 169 passes about 200 m west of the site. Most of the numerous iron mines in the Hibbing area are abandoned.

7412 Cloquet

The Cloquet sampler is located on top of a small sewage pumping station between Cloquet and Scanlon about 25 km WSW of downtown Duluth.

7501 Duluth

This Duluth site is on the roof of a home at 1329 107th Avenue West. The location is in a residential neighborhood approximately 1.5 km west of the U.S. Steel plant and 15 km southwest of downtown Duluth.

7502 Duluth

The Hi-vol is at ground level in a residential backyard at 414 South 88th Avenue West. The site is about 13 km SW of downtown, 2.5 km NNE of the U.S. Steel plant, and 3.5 km NE of site 7501.

7506 Duluth Airport

This ground level site is on the high ground 12 km NW of downtown and is considered the background TSP site for the Duluth area. The prevailing northwesterly winds and the steep slope up from the lakeshore to the east prevent most Duluth urban pollutants from reaching the site.

7527 Duluth West End

The West End site is on a small sewage pumping station in the taconite loading docks area of the Duluth harbor about 5 km SW of downtown. Nearby elevated railroad tracks and ore train unloading facilities could be expected to contribute to particulate loadings.

APPENDIX 2

Statistical Modeling of TSP Data

A major goal of the regional characterization of total suspended particulate data is the determination of patterns in spatial and temporal variablility. The establishment of these patterns is a useful tool for the identification of possible causal factors. The use of simple descriptive statistics is rarely adequate; to achieve these goals more complex statistical models are needed.

The models presented here are designed to achieve several goals:

1) Determination of significance of spatial and temporal variation.

2) Determination of how patterns in spatial variability change over time.

3) Assessment of the significance of specific events, particularly the mining strike (8/1/77-12/21/77) and snow cover (11/26/76-3/8/77 and 11/15/77-end of sampling).

4) Identification of those observations that cannot be explained on the basis of regional trends.

5) Establishment of relationships between air quality observations and meteorological conditions.

Much statistical analysis of air pollution data has employed a spectral analysis of time series (Phadke et al. 1973, Rao et al. 1976). This approach permits the identification of any cycles or periodicities in the data, and can aid in determining how different sampling stations relate to each other over time. It has proven to be a powerful method for the understanding of data sets where periodicities are expected to be small relative to the length of time of the study. This is not the case here.

Seasonal periodicities, particularly relating to snow cover, are highly likely, and eighteen months of study is not long enough to establish periodicities of this length. Diurnal cycles can also not be established as the readings are 24-hour averages. In addition, the data set contains a large number of missing observations, while spectral analysis works only with a relatively complete set of observations. Finally, to apply spectral analysis it is necessary to assume that the series is stationary; that aside from regular periodicities, there are no long-term trends in the data (Koopmans, 1974). The mine strike would seem to invalidate the assumption. For these reasons, spectral analysis was not employed.

The approach used is the development of a linear statistical model. This model takes the form

$$Yij = u + s_i + d_j + e_{ij}$$

where Y = observed TSP concentration at site i and time j
u = the overall mean TSP concentration for the region
s_i = the average deviation from the overall mean observed at site i
d_j = the average deviation from the overall mean observed at time j
e_{ij} = deviations from the overall mean at a particular site and time not accounted for by s_i and d_j.

To better understand the model, assume that there is an average background level of total suspended particulates in the Study Region. If a prediction had to be made for a particulate concentration without knowing the specific location and data for which the prediction were to be made, this average level would be a reasonable guess. Yet with more information we can make a better estimation. Variations from this mean can be placed in three categories. To begin with, it is clear that not all sites are the same. Sites located near particulate sources tend to run higher than the average background level, while those in relatively pristine areas will tend to have consistently lower particulate concentrations. Thus, if we know what location we are asked to make a prediction for, we can improve our guess by calculating the average value for that site rather than the entire region. In the model, the difference between the average for the whole region (u) and the average at each site is calculated. The average concentration at site i can then be expressed as $u + s_i$. S will be negative at sites with little pollution and positive sites strongly affected by particulate sources.

These estimates can clearly be improved if we take into account temporal variability. It is clear that on certain days particulate concentrations will be higher than average due to a particularly dirty air mass and on other days air over the entire region will be cleaner than usual because of air masses originating in unimpacted areas. We can then adjust the estimate by knowing whether the air on a given day was cleaner or dirtier than average and then substituting the regional average on the day in question for the regional average over the period (u). This can again be expressed mathematically as a deviation from the mean, where the average on day j is equal to the overall average (u) plus the deviation from this average on day j (d_j).

These factors can be combined. To obtain an estimate for a particular place at a particular time, we can start with the overall average (u). We can then adjust this if the day in question had dirtier or cleaner air than average ($u + d_j$). Finally, we can adjust if a site tends to have higher or lower than average particulate concentrations ($u + d_j + s_i$).

As an example, suppose we are interested in making a guess at what the TSP concentration was on a particular day when the sampler at a particular site was broken. We know from previous observation that the overall average concentration in the region is 45 ug/m^3. However, we also know from previous observations that this site tends to run on the average 10 ug/m^3 higher than the regional average. Our best guess, then, for the missing observation is $45 + 10 = 55$ ug/m^3.

However, from observations at other sites, we know that the air quality over the region was 20 ug/m^3 cleaner than average on this day. The estimate then becomes $45 + 10 - 20 = 35$ ug/m^3.

This is probably the best estimate available under the above circumstances, yet if we were to go through this procedure at a site and date for which a TSP reading was available, we might find a substantial difference between the value predicted by the above procedure and the actual reading. This is due in part to random fluctuation but is also due to a third sort of factor, namely some circumstance that is unique to a particular place at a particular time. Suppose, for example, a highway construction crew happened to be working near the site on that particular day. It is highly probable that the particulate concentration under these circumstances will be higher than normal, yet the effect will be highly localized. These sorts of effects concerning site i and day j are included in the model as e_{ij}.

The purpose of this analysis is to break a particulate reading down into several components. Estimation of the s_i terms enables us to identify which sites are consistently higher or consistently lower than average, and to quantify the magnitude of the difference between any two sites. The d_j terms provide an estimate of the magnitude of events affecting the entire region. Finally, identification of those samples with a high e_{ij} component provides a guide to the location of short term local effects.

Estimation of these effects is a fairly simple procedure. The easiest method would be to use the arithmetic mean of all observations as an estimate of u, the arithmetic mean of all observations at site i as an estimate for $u + s_i$ and the mean of all observations taken on day j as an estimate of $u + d_j$. This procedure would indeed yield maximum likelihood unbiased statistical estimates if there were no missing values in the data set (Scheffe, 1959). However, if the data are not complete, this procedure can lead to biased estimates. Suppose, for example, that readings on one day were missing from the three sites when TSP concentrations are usually lowest. An estimate for d taken on that day from the remaining eight locations would clearly be too high. The estimate must be modified to take missing values into account. This is essentially done by estimating the missing values in the manner described above and calculating means using these estimates. The statistical methodology for obtaining these adjusted estimates of u, s and d, while straightforward, involves development of a matrix notation too cumbersome to be present here. Detailed discussions can be found in Graybill (1961) and Scheffe (1959). Estimates of e_{ij} terms are obtained by taking the difference between the observed TSP concentration at site i on day j and the predicted value obtained from the equation

$$\text{Predicted TSP} = u + s_i + d_j$$

Estimates of e_{ij}, therefore, cannot be obtained for dates and sites where no TSP reading was taken.

Derivation of the estimates in this way also enables us to summarize results using an analysis of variance table. This has the advantage of permitting tests of the significance of the site and day effects. These tests will determine whether there is any statistically significant difference between sites or if they all behave alike. Similarly, we can test if any days are significantly different from any other or if regional effects tend to be constant. Analysis of this sort requires that certain assumptions be made involving normality of error (e_{ij}) terms and that the e_{ij} terms have the same variance for all sites and dates. A number of studies have shown that lognormal models are often appropriate for the description of air quality data (Larsen, 1971, 1973, 1974; Hunt, 1972; Neustadter and Sidik, 1974). Examination of frequency distributions of our TSP observations and the running of the model with several possible transformations of the data indicate that the lognormal model was indeed appropriate in this case, and that the assumptions outlined above were met under such a model. Accordingly, all analysis was done using log-transformed data. All mean values resulting from the model are thus geometric means.

The model was applied to the entire data set, and the analysis of variance table (Table 1) reveals the presence of highly significant spatial and temporal effects. Estimates of the site effects (Table 2) indicate the magnitude of the difference between extreme background sites (such as Fernberg Road) and community and industrial locations. Note that the geometric mean at the highest station (Virginia) is more than five times the mean reading obtained at Fernberg Road. Note also that no site was in violation of either the primary (75 ug/m^3) or secondary (60 ug/m^3) annual standard for TSP concentrations. Finally, a graph of the adjusted day means (Figure 1) shows the fluctuations observed over time.

Estimates of e_{ij} were computed for each observation. As these estimates are approximately normally distributed with mean 0 and variance 0.05 (from the analysis of variance), the upper 1% and 5% of the distribution can be calculated. Observations with e_{ij} estimates falling above these bounds may represent outliers, those points representing significant, short-term, local events. Note that a certain number of estimates of e_{ij} would be over these limits even if no such events occurred. If none of the events occurred, we would expect to find eight observations over the 1% limit. Fourteen were observed. It is likely, therefore, that some of these were true outliers. A list of observations falling above the 1% and 5% limit is found in Table 3.

Conditions in the Study Region were not constant over the sampling period. In particular, several events took place that had a potential effect on TSP concentrations over periods of several weeks or longer. Most notable were snow cover, which can be expected to reduce particulate concentrations by preventing liftoff, and the strike against taconite mining operations in the second half of 1977. Two questions relating to these events are of interest. First, what was the effect on the regional air quality? Secondly, did these events affect some sites differently than others?

These questions can be answered by running the model separately for each of the time periods in question. A comparison of the regional mean estimated at each time period will provide an answer to the first question. To answer the second, we need to take the ratio between the mean observed at each site and the regional mean. Comparison between site effects obtained from the same site during different events will not reveal if that site was affected differently than the rest of the region. Suppose, for example, that during the mining strike the adjusted mean at a station was 20 ug/m^3 while the regional mean was 30 ug/m^3. Suppose, also, that before the strike the mean at the same site was 30 ug/m^3 while the regional mean was 45 ug/m^3. Clearly, in this instance, the strike had an effect both on the region and the site. Note, however, that both the site and region decreased by the same percentage (33%) and during both periods, the ratio of the site mean to the regional mean was 2/3. This implies that the drop in TSP concentrations observed at the site during the strike was a reflection of the regional trend. However, if the mean at the site during the strike was 10 ug/m^3, we would conclude that the strike had a greater effect at this location than over the region as a whole, as the site showed a decrease of 66% as opposed to the 33% drop in the regional mean, and the ratio of the site mean to the regional mean decreased to 1/3.

Table 4 contains a list of the time periods considered and the mean TSP concentrations over the region during the period. It should be noted that the figures for period 1 (startup, no snow cover) may not be reliable and are definitely not comparable with the figures for other time periods. Three sites, including two background sites, were not operational during this period. The regional mean for this interval is probably biased as a result. It should also be noted that the date for the resumption of mining activities is approximate. Not all mining operations resumed at the same time, though most of the larger operations went back to work very close to December 21, 1977. A notable exception was Erie Mining, where activity was sporadic from December 21, 1977 until February 19, 1978, when normal activities resumed.

It appears that both snow cover and mining activity play an important role in determining particulate concentrations. Note that the adjusted geometric mean concentration at the eleven sampling sites increased by approximately 17 ug/m^3 in the period following snow melt in 1977. Note also the drop of 21 ug/m^3 following the cessation of mining activities. Only a slight drop (3 ug/m^3) was noted when snow cover was present during the mining strike, and only a small increase (2.5 ug/m^3) was noted when mining activity was resumed. It is possible that this last difference might have been greater had all operations resumed at the same time.

The analysis of variance results for each time period are found on Table 5. This table shows that both differences between sites and temporal differences were highly significant during each period in question. There is some evidence that there was, however, less variability between sites during the mining strike. The variance of site means in the period immediately before the strike (period 3, variance = 392.49) is significantly greater than the variance seen in the comparable period with no snow cover during the strike (period 4, variance =

110.37) ($F = 3.55$, $p < .05$). By contrast, no difference in the between-site variance was found for periods of snow cover and no snow cover. It appears, then, that mining activities play a major role in determining differences between sites.

Table 6 contains the site means for each period expressed as a percentage of the regional mean. These means are also graphed in Figure 2. Several interesting features may be discerned. The figures for periods 3 and 4 show that some sites were indeed disproportionately affected by the mining strike. In particular, the Erie Mining office went from 122% of the regional mean before the strike to 70% during the strike. Another location showing a drop in particulate concentrations greater than that seen over the region is the Hoyt Lakes Police Station (166% to 127%).

A few stations, however, did not show as great a drop as the regional average. Two of them, Kawishiwi and Toimi, were background sites, showing low concentrations throughout the course of the study. It is not surprising that mining activity would be of less importance at these loctions than at other sites in the region. The other stations where the decrease in TSP concentrations were less than average were the larger communities, Virginia (215% to 284%) and Hibbing (150% to 192%), suggesting that activities other than mining were of importance at these sites. It should be noted, though, that every station showed a drop in particulate concentrations after the strike began (Table 7, Figure 3), indicating that the air quality in all portions of the region is affected by mining activity.

The effect of snow cover also seems to vary from site to site. With the exception of Mountain Iron, all stations showed an increase in TSP concentrations from period 2 (mining, snow cover) to period 3 (mining, no snow cover). However, from periods 6 (no mining, no snow cover) to period 7 (no mining, snow cover) six stations showed changes of less than 2 ug/m^3. Of the remaining five, four (Dunka Road, Hoyt Lakes Police Station, Mountain Iron and Hibbing) decreased while one (Virginia) showed a substantial increase. It should be noted that the effect of snow cover does seem to be less in the communities. This may reflect an increase in home and business heating during the snow season. An exception to this trend is Ely, where it is likely that activity is substantially increased during the spring and summer. The large increase from period 2 to period 3 observed at Fernberg Road, a popular entry point to the Boundary Waters Canoe Area, may also reflect in increase in activity near this site following snow melt.

In an effort to further explore the relatonship between air quality in different portions of the region, correlation coefficients were computed between each pair of sites. The results (Table 8) seem to indicate that all stations in the region correlate most closely with the background sites (Fernberg Road, Kawishiwi Lab and Toimi). This suggests that whatever relationships exist between stations are due to regional trends and that those effects causing differences between stations are highly localized. Note, for example, that the highest correlations are found between the three background stations. Fernberg Road and Toimi, located 35 miles apart, have a correlation of .94. Developed sites that are very close together show little correlation. Note, for example, the correlation of .35 between Mountain Iron and Virginia, separated by only three miles. The communities do not correlate at all well with each other, and, in fact, show stronger relationships with the background sites.

Table 9, for purposes of comparison, shows the correlation coefficients between the Study Region sampling sites and five locations in the Duluth area.

Correlations between the Study Region sites and those two sites located away from the lakeshore in Duluth (Airport and Cloquet) are surprisingly strong; again, relationships are strongest between these two sites and the Study Region background sites. Correlations between the Study Region and the three Duluth sites near Lake Superior are weak, but again seem to be strongest with the background sites. The relatonship between these three Duluth sites and the Iron Range cities (Virginia, Mountain Iron and Hibbing) is virtually nonexistent.

However, overall correlations are not sufficient to illustrate the relationship between the Study Region and Duluth. Table 10 contains correlations between Study Region sites and Duluth sites when the wind at Hibbing was blowing from the south and southwest, from the Duluth area to the Study Region. For the purposes of this analysis, only those days when the wind was blowing from an arc between 150° and 240° for four or more daylight hours were considered. Nineteen sampling dates fell into this classification, comprising 21% of the total sample. Of these nineteen dates, only five occurred during the period of snow cover. Average wind speed on these days was 4.42 m/sec, slightly higher than the average wind speed at Hibbing of 3.95 m/sec (Watson, 1978).

The contrast between these correlations and the overall correlations is dramatic. Nowhere is this more important than at Mountain Iron. The overall correlation between Mountain Iron and Duluth West End is -.01, effectively non-existent. However, on the nineteen days with prevailing southerly and southwesterly winds, the correlation between these sites rises to .76, a very strong relationship. This pattern is not unique. Of the fifty-five possible correlations between Duluth and Study Region sites, fifty-two were higher when the wind was blowing from the Duluth area to the Study Region. Many of the increases are substantial. The relationship is most striking at Virginia and Mountain Iron, yet appears in other areas as well. The correlation between Duluth West End and Kawishiwi Laboratory, for example, was .32 overall, but rose to .62 when the wind was from the south. It appears, then, that particulate transport from the Duluth area and areas farther south can play a significant role in determining the air quality of the Study Region.

Relationship to Meteorological Factors

In an attempt to better explain spatial and temporal variations in total suspended particulate observations, statistical models were derived to relate the observations at each site to meteorological parameters. Particular attention was paid to wind direction, as analysis of the relationships between direction and particulate concentrations can suggest possible sources of particultes.

Some researchers (e.g. Samson, Neighmond and Yencha, 1975) have suggested using correlation coefficients as a measure of association between suspended particulates and wind direction. This method utilizes wind frequency distributions and involves the computation of correlation coefficients between 24-hour mean TSP concentrations and the wind frequency:

$$= \frac{\text{\# of hours wind blows from direction } i}{24}$$

for each wind direction under consideration. This method of direction-pollution association is viewed as an alternative to the "pollution rose" commonly used for this sort of model.

However, the pollution rose has an ease of interpretability that the displays of Samson et al. seem to lack. The figures plotted on a pollution rose represent the actual particulate concentrations expected when the wind is blowing from a particular direction. Correlation coefficients, while providing a measure of the strength of association between concentrations and wind directions, do not provide any indiction of the level of pollution expected. However, most pollution roses do not provide any indication of the strength of the association, or any indiction of the possible error in a plotted association.

The methodology presented here attempts to combine the best features of both methods. The method used is multiple regression analysis. Correlation analysis as used by Samson et al. essentially involves the computation of a separate bivariate regression model for each wind direction. Multiple regression results in one model account for all wind directions. The form of this model is:

$$TSP = \beta_1 D_1 + \beta_2 D_2 + \dots + \beta_n D_n$$

where D_i = expected TSP concentration when the wind is blowing from direction i.

The rationale for this model is simple. It states that the mean concentration over 24 hours will be an arithmetic average of the concentration observed from each wind direction weighted by the frequency of each wind.

The major computational task is estimation of the β_i terms. This can be done using standard regression analysis techniques (Draper and Smith, 1966). It is also possible to compute standard errors for these coefficients. By computing both the coefficient and its standard error, we estimate both the expected particulate concentration when the wind is blowing from a given direction and the deviation that might be expected from this estimate.

It is clear that the concentration observed when the wind is blowing from a given direction will not always be that predicted by the model. In fact, it may be very different. This is particularly true if short term local conditions exist that affect pollution readings for one or two sampling dates. An example of such a condition would be a construction project at or near a sampling location. If the wind blows from the construction site to the sampler during construction, pollution levels may well be much higher than would be observed under identical meteorolo[illegible]l conditions before or after construction. Identification of these atypical points ("outliers") is necessary for a complete analysis of suspended particulates data, and can easily be accomplished by examination of the residuals (difference between predicted and observed values) arising from the multiple regression models. Outliers can be detected using the Bonferroni criterion (Snedecor and Cochran, 1967; Weisberg, 1977). The models should be redone after outliers are deleted, as it is possible for one or two extreme values to grossly alter a regression estimate.

Models were constructed for all eleven Study Region sites at which TSP samples were taken. Wind data were obtained from the Hibbing airport. A wind rose for those dates on which TSP samples were taken is attached (Figure 4). It compares quite closely with the ten-year wind rose for the Hibbing airport (Figure 5), implying that the wind conditions for the study were typical of long term regional patterns. It must be assumed, however, that the wind data from Hibbing represent conditions throughout the Study Region. This assumption seems valid for general analysis.

It was decided to use only daylight hours to determine the wind frequency distribution, as nighttime winds were found to be light and highly variable. For modeling purposes, daylight was defined as the period between 6 AM and 6 PM. Furthermore, a better fit was found if only non-calm hours were used. The independent variables, then, represent the percentage of non-calm daylight hours during which the wind ws blowing from each direction. Wind was grouped into twelve thirty-degree intervals. All calculations were done using the computer program MULTREG, developed by the Department of Applied Statistics, University of

Minnesota (Weisberg, 1977). Pollution roses were generated by a FORTRAN program utilizing the CALCOM plotting package on the University of Minnesota Cyber 74 computer. A 95 percent upper confidence limit is plotted along with the pollution rose. This was computed using the formula:

$$U.L. = \beta + [s.e.(\beta)]\ t_{.05,df} \quad \text{(Snedecor and Cochran, 1967)}$$

where U.L. = upper confidence limit

s.e.(β) = standard error of estimated

$t_{.05,df}$ = 95th percentile from a t distribution with n-12 degrees of freedom (n = sample size).

The distance between the upper confidence limit and the estimated concentration was found to vary greatly. This implies that some of the expected concentrations are very accurately estimated. From other wind directions (those for which the difference between the upper confidence limit and the estimate is high) the estimates are not very accurate. The reasons for this lack of accuracy are three. First, and most difficult to estimate, is lack of precision in the data, most notably inaccuracies arising from applying Hibbing wind data to other locations. Secondly, pollution levels at a given wind direction may be highly variable. This cause tends to disappear after outliers are deleted. Thirdly, a glance at the Hibbing wind rose (Figure 5) will show that some winds are quite rare in the Study Region. In particular, winds from the northeast and southwest were rarely observed for more than one or two hours a day and on most days were not observed at all. There are simply too few observations at these wind directions to permit the derivation of a reliable estimate. In some extreme cases, this may even lead to negative estimates. These are statistical artifacts caused by a lack of data along with high variability at those observations that were made. We would expect those estimates to become positive and stabilize as the number of samples is increased. When a negative estimate was encountered in the models for the Study Region, the value 1 ug/m^3 was substituted as a reasonable minimum value.

To assess the importance of a suspended particulate source to a specific location, it is necessary to know both the pollution level that can be expected from the source and the frequency with which the wind blows from the source to the location under consideration. A pollution rose displays the former, a wind rose the latter. It is possible to combine the two by multiplying the expected particulate concentration at a given direction by the probability of the wind blowing from that direction. This number can then be standardized to obtain the expected percentage of annual pollution contributed from each wind direction. Specifically, the formula for the expected contribution from direction D_k is:

$$\text{Exp. Cont. } (D_k) = \frac{(\text{Concentration} \mid D_k)\ P(DK)}{\sum_{i=1}^{n} (\text{concentration} \mid D_i)\ P(Di)} \times 100$$

where Concentration $| D_k$ = expected TSP concentration when wind is blowing from direction k, and $P(D_k)$ = probability that wind is blowing from direction k.

Results

Pollution roses and contribution roses for each of the eleven Study Region TSP sites are presented in Figures 6 through 41. Two pollution roses are presented for each site, the first calculated from all observations and the second calculated after outliers had been deleted as described above. These outliers are listed in Table 11. The expected contribution roses often show peaks to the south and the northwest, reflecting the dominant winds. Sources to the east and northeast of a site are almost never important contributors, though they may cause isolated high readings.

A pollution rose for the region was constructed using results from the statistical model described earlier. Regional TSP readings were calculated as the sum of the overall mean (u) and the day effects (d_j). The resulting figures enable us to estimate trends in particulate concentrations affecting the entire region. Site differences and local effects have been removed.

The pollution rose shows that the largest regional effects occur when the wind is from the west and west-southwest. This most likely represents regional contributions from the densely populated areas of the Iron Range on the western fringe of the Study Region. It may also represent long range transport from agricultural areas. Another peak is seen from the south which may represent transport from the Duluth area or possibly more distant sources. The annual contribution rose shows that regional contributions reflect the wind rose with the bulk of particulates coming from the northwest and south and only insignificant contributions from northeast and east.

Meteorological correlations -- Although wind direction was considered to be the meteorological parameter of primary importance, corelations of total suspended particulate concentrations with wind speed and precipitation were also computed. Wind speed does not seem to be important, as a significant correlation between wind speed and TSP concentration was found at only one location (Virginia). A wind direction specific analysis of wind speed might have been more productive had sample size permitted. Precipitation was seen to have a greater effect. Correlations were computed between TSP and an indictor variable for precipitation. This varible took on the value 1 if precipitation occurred on the date in question and 0 if no precipitation was recorded. Correlations were computed for both precipitation on the day TSP samples were taken and the day before TSP samples were taken. In all cases, correlations between TSP and precipitation were seen to be negative, implying that precipitation is associated with lower TSP values and that the surface is a major source of particulates.

Unusual or Aberrant Observations (Outliers) -- Outliers among the TSP observations were detected by two methods. The first was from the statistical model, and the second was from the regression analysis that led to the pollution roses. A list of outliers from the statistical model may be found in Table 3 and a similar list from the pollution roses is presented in Table 11. These listings are not identical. This is because, in practice, each method is detecting a different sort of outlier.

The statistical model detects those observations not explained by the differences between sites or by regional trends. These outliers represent short-term, local effects. These could arise for two reasons. The first is what we hope to detect by this analysis, a short-term, local disturbance such as a forest fire, logging or construction. The second arises from a source almost always present, but where wind conditions that will transport material from the source to the site in question are very rare. A town located just west of a mine, for example, may almost never be affected by the mine because of the scarcity of easterly winds.

These latter points, however, will not show up as outliers in the regression (pollution rose) analysis. The regression analysis outliers arise from short-term local effects and from short-term regional effects. Unlike the statistical model, the regression analysis does not separate regional from local effects.

However, both models do detect those outliers resulting from short-term local sources. We can identify these by finding which observations appear as outliers in both models. Those observations that are outliers in the wind model but not in the statistical model represent short-term regional effects, while those outliers resulting from the statistical model but not from the wind regressions may represent high concentrations caused by rare wind patterns.

A list of outliers from both models is found in Table 12. Only 11 observations fall into this category, about 1% of the sample. It is worth noting that six of these observations were found in one two-month interval, from April 13, 1977 to June 6, 1977.

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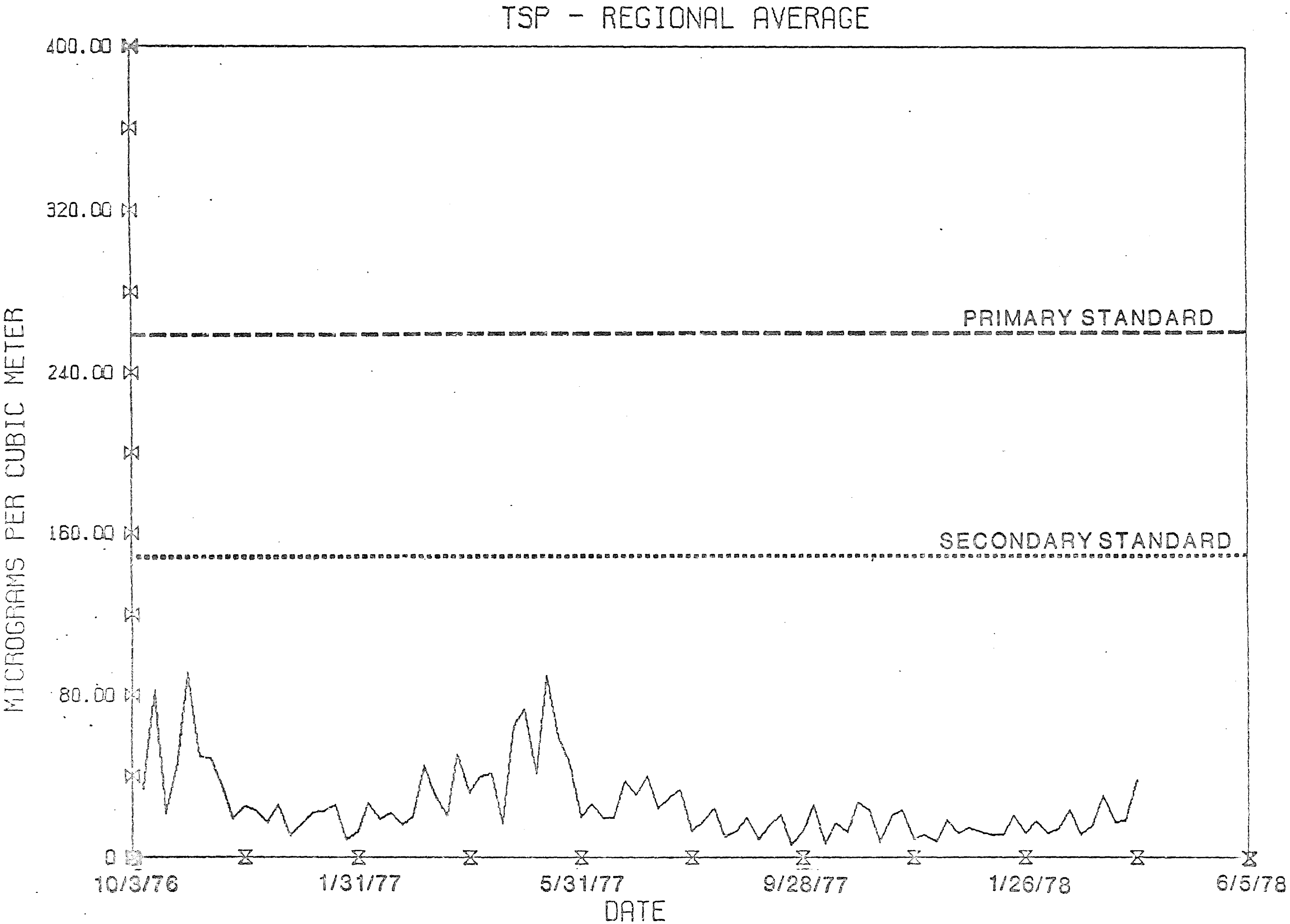
FIG. 1

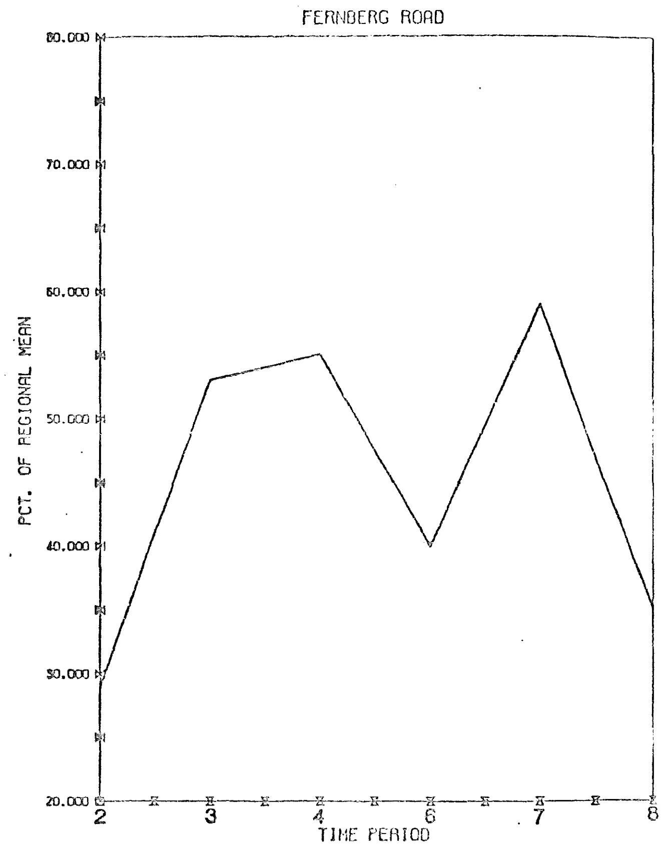


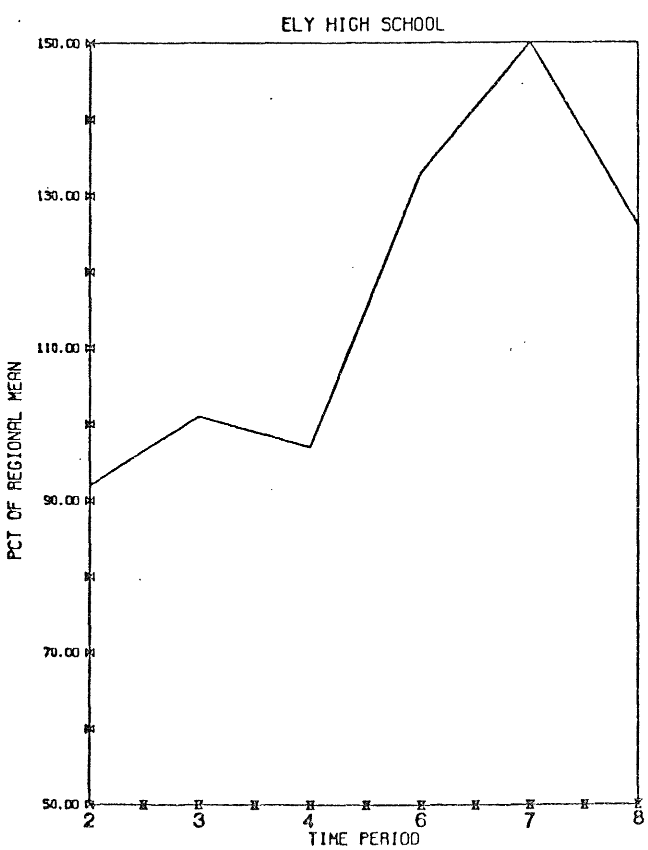
TSP - REGIONAL AVERAGE
400.00
320.00
240.00
160.00
80.00
0
PRIMARY STANDARD
SECONDARY STANDARD
MICROGRAMS PER CUBIC METER
10/3/76
1/31/77
5/31/77
9/28/77
1/26/78
6/5/78
DATE

FIGURE 2
PERCENTAGE OF REGIONAL TSP MEAN BY TIME PERIOD

LEGEND

TIME PERIOD	DATE
1	10/09/76-11/20/76
2	11/26/76-03/08/77
3	03/14/77-07/24/77
4	07/30/77-10/04/77
6	10/16/77-11/09/77
7	11/15/77-12/15/77
8	12/21/77-03/27/78





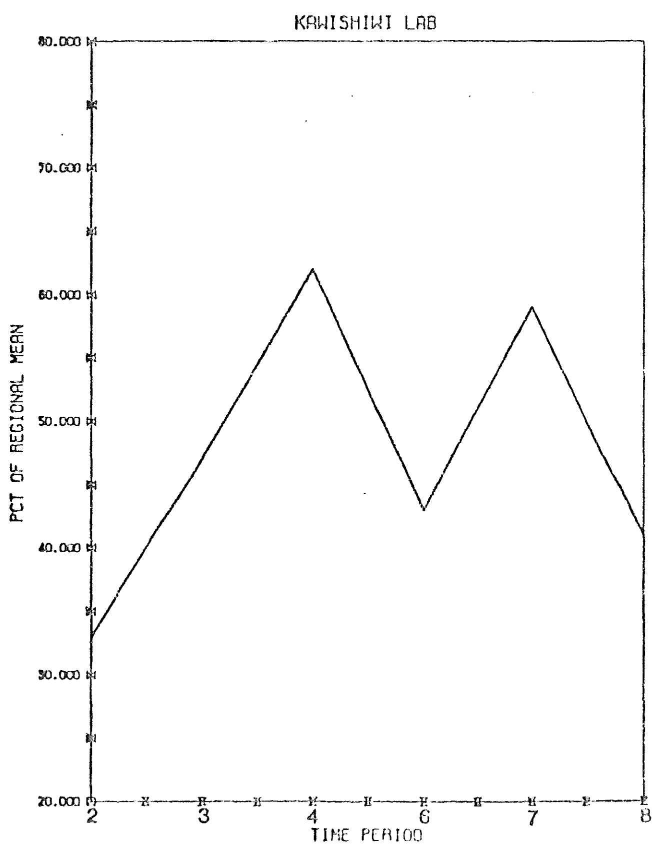
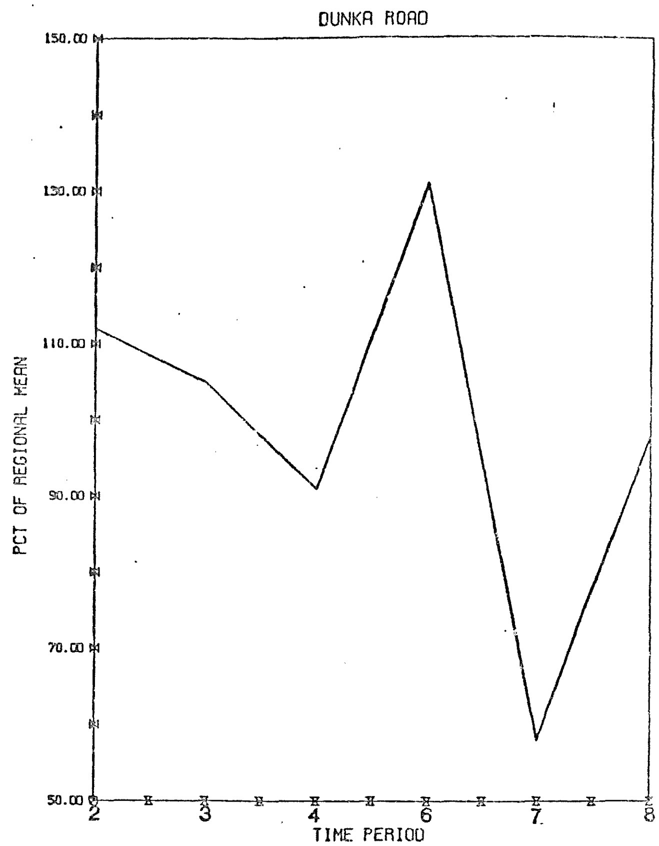
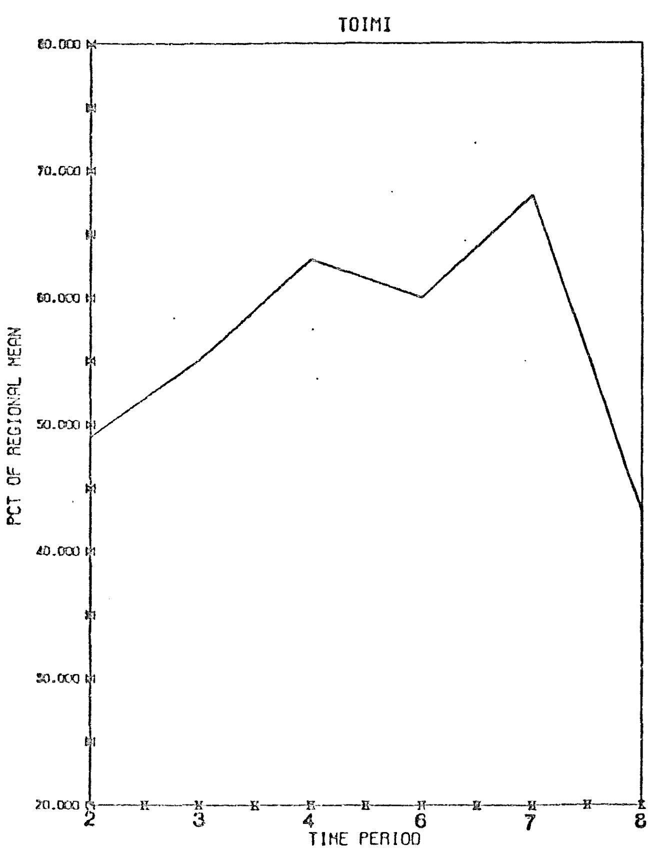


FIGURE 2
PERCENTAGE OF REGIONAL TSP MEAN BY TIME PERIOD

LEGEND

TIME PERIOD	DATE
1	10/09/76-11/20/76
2	11/26/76-03/08/77
3	03/14/77-07/24/77
4	07/30/77-10/04/77
6	10/16/77-11/09/77
7	11/15/77-12/15/77
8	12/21/77-03/27/78





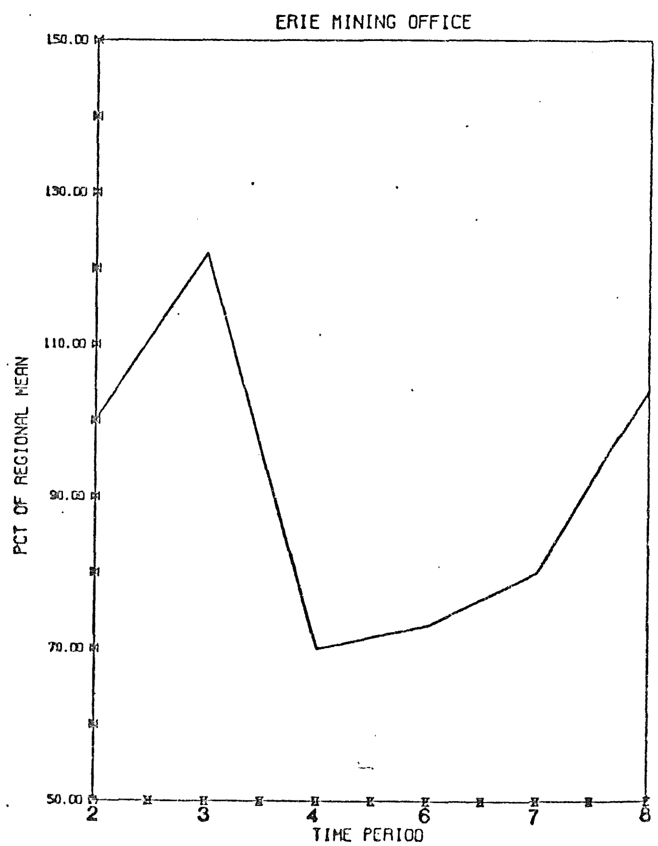
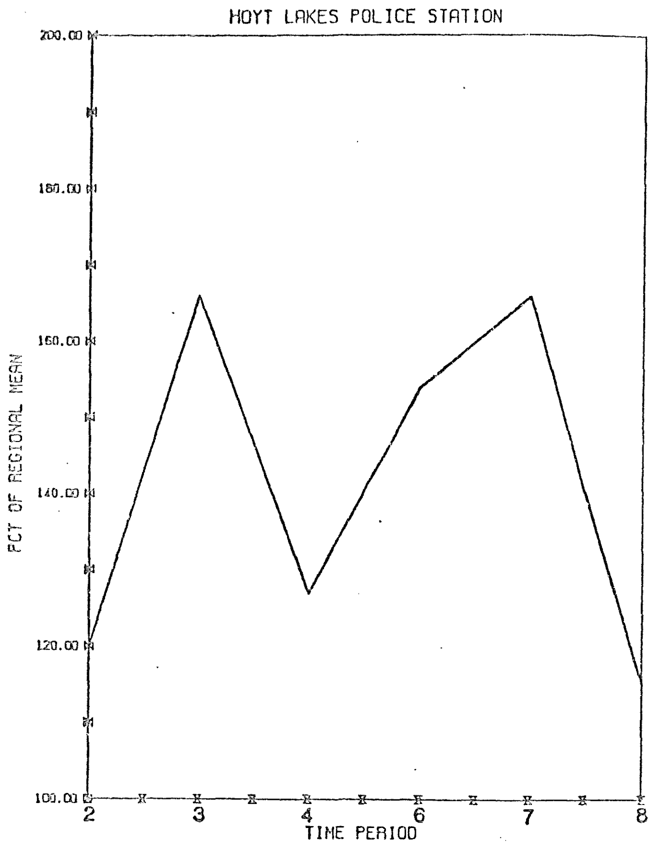


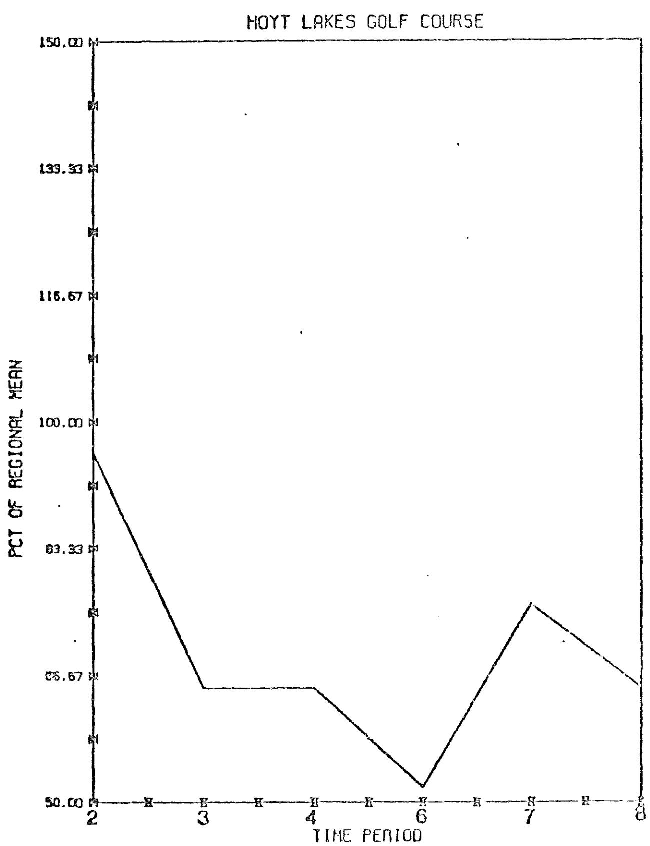
FIGURE 2.

PERCENTAGE OF REGIONAL TSP MEAN BY TIME PERIOD

LEGEND

TIME PERIOD	DATE
1	10/09/76-11/20/76
2	11/26/76-03/08/77
3	03/14/77-07/24/77
4	07/30/77-10/04/77
6	10/16/77-11/09/77
7	11/15/77-12/15/77
8	12/21/77-03/27/78





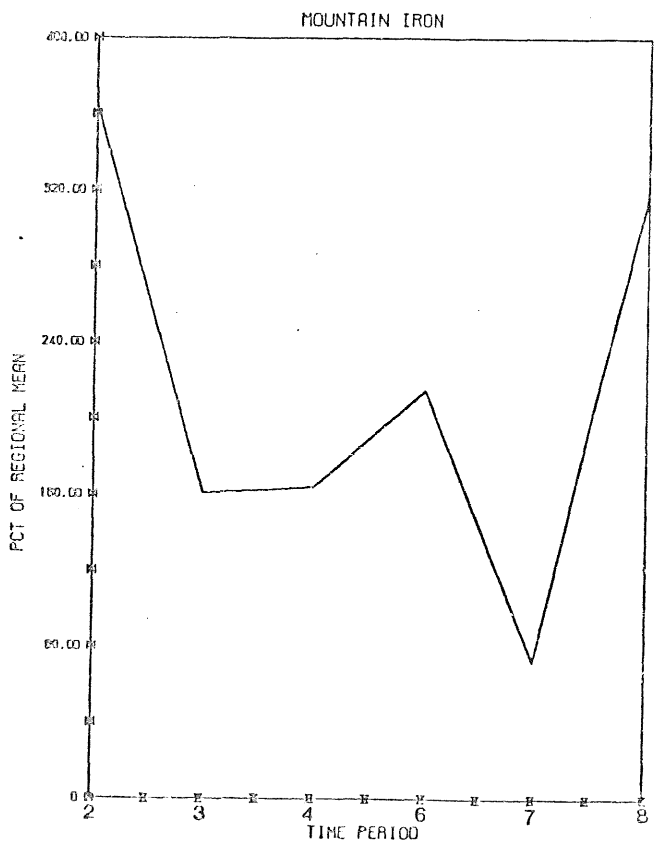


FIGURE 2
PERCENTAGE OF REGIONAL TSP MEAN BY TIME PERIOD

LEGEND

TIME PERIOD	DATE
1	10/09/76-11/20/76
2	11/26/76-03/08/77
3	03/14/77-07/24/77
4	07/30/77-10/04/77
6	10/16/77-11/09/77
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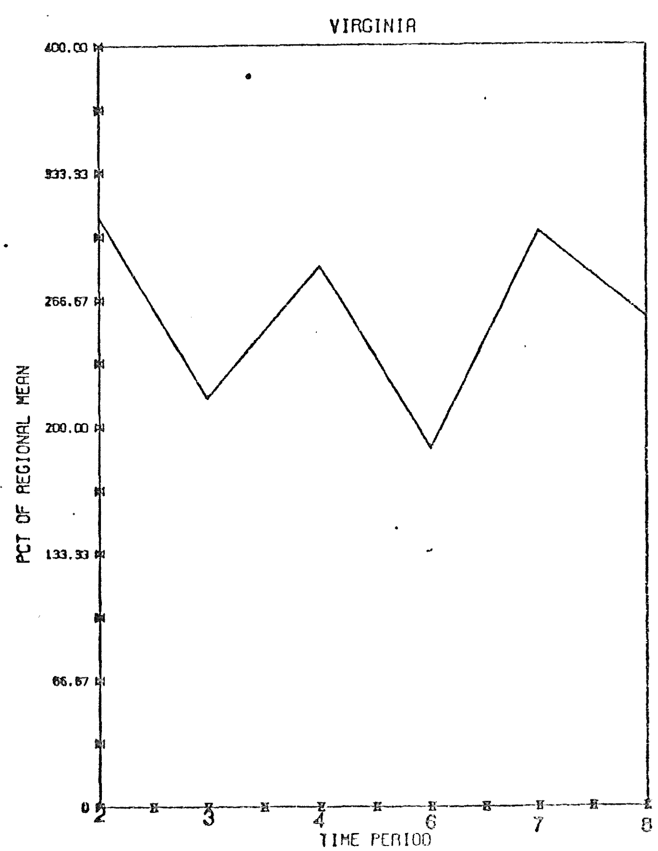
8	12/21/77-03/27/78



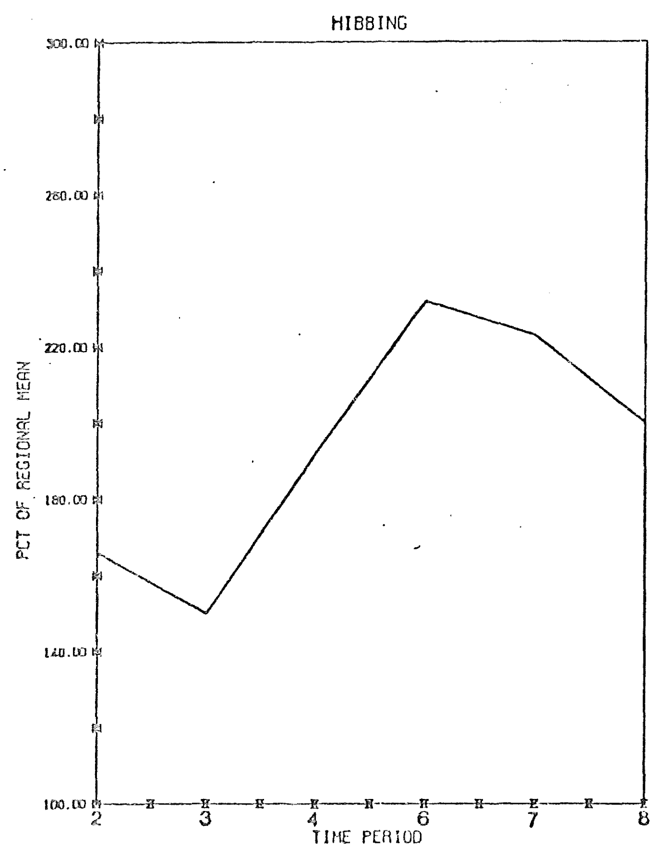


FIGURE 3 MEAN TSP BY TIME PERIOD

LEGEND

TIME PERIOD	DATE
1	10/09/76-11/20/76
2	11/26/76-03/08/77
3	03/14/77-07/24/77
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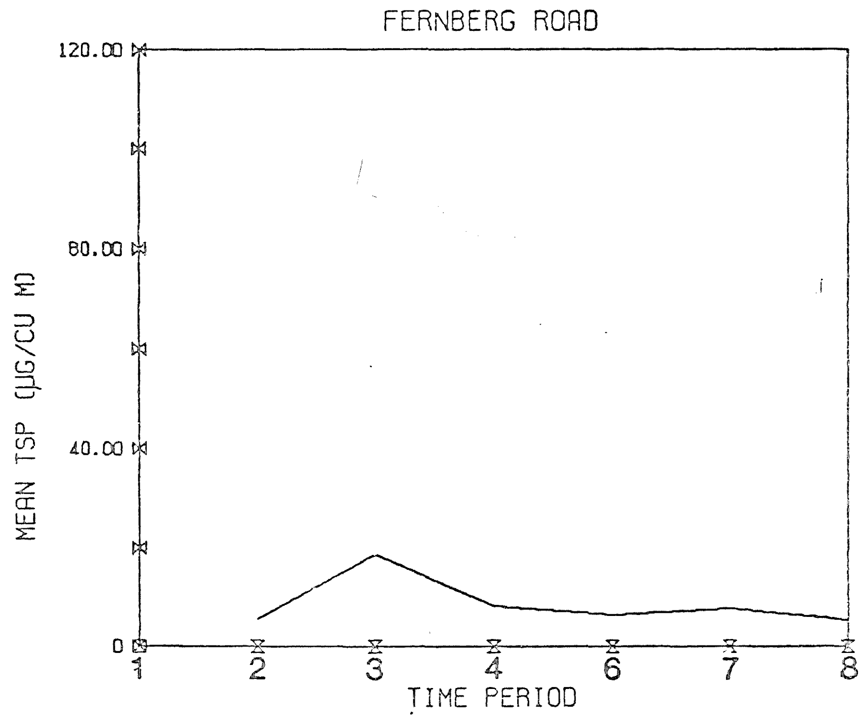
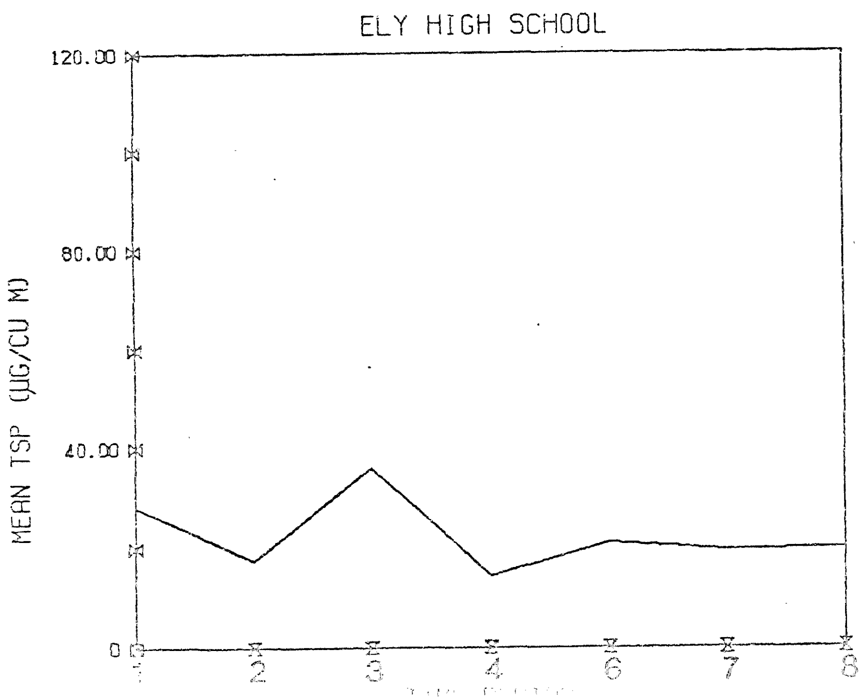
8	12/21/77-03/27/78





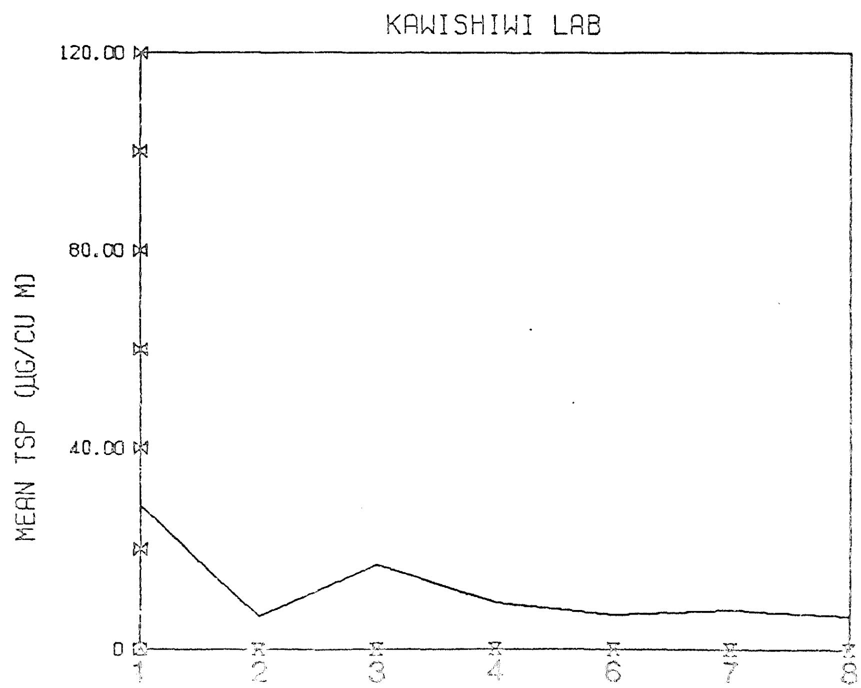


FIGURE 3 MEAN TSP BY TIME PERIOD

LEGEND

TIME PERIOD	DATE
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2	11/26/76-03/08/77
3	03/14/77-07/24/77
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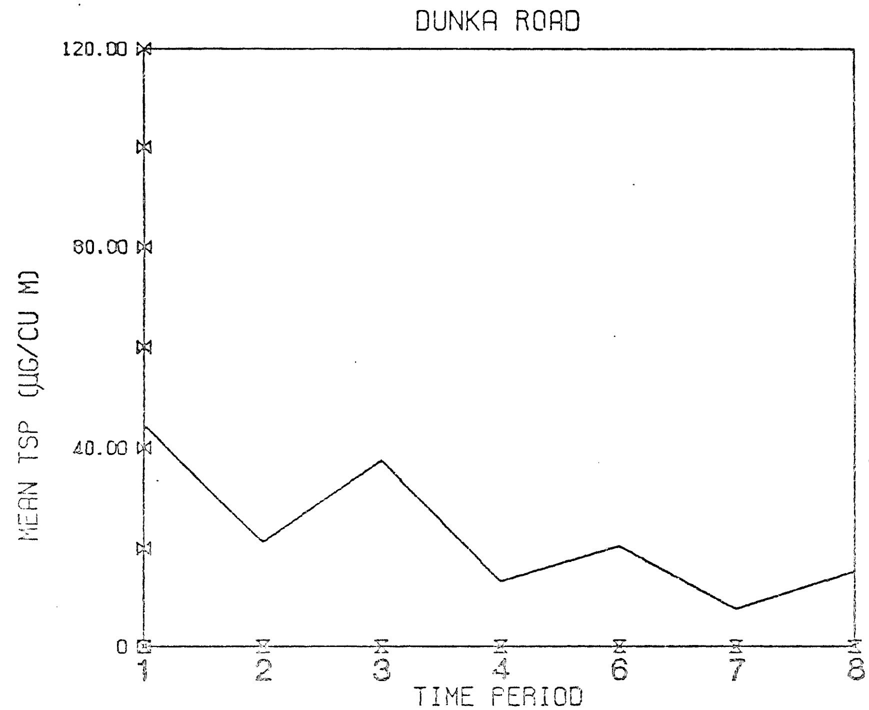
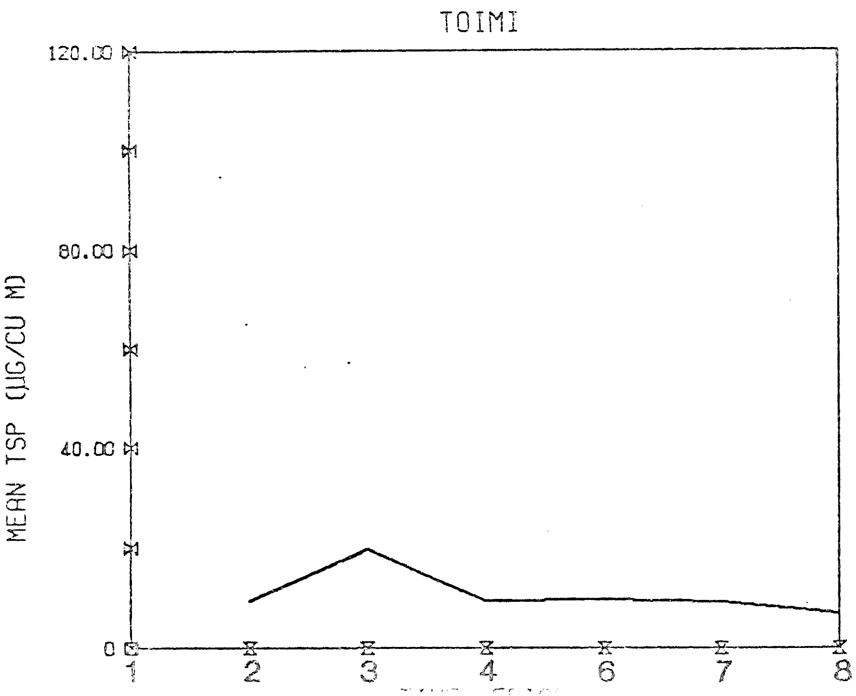
8	12/21/77-03/27/78





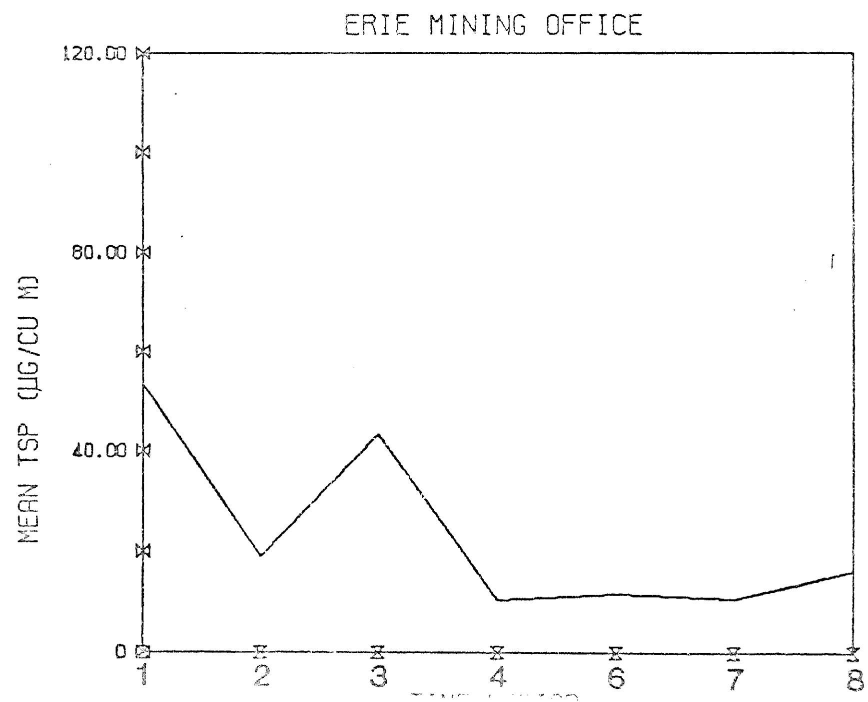


FIGURE 3 MEAN TSP BY TIME PERIOD

LEGEND

TIME PERIOD	DATE
1	10/09/76-11/20/76
2	11/26/76-03/08/77
3	03/14/77-07/24/77
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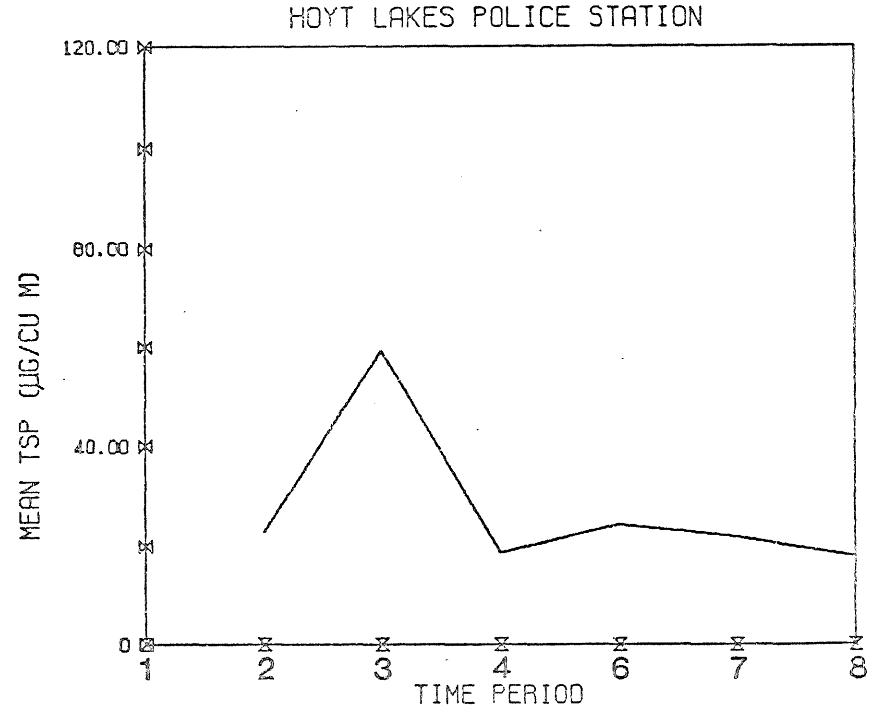
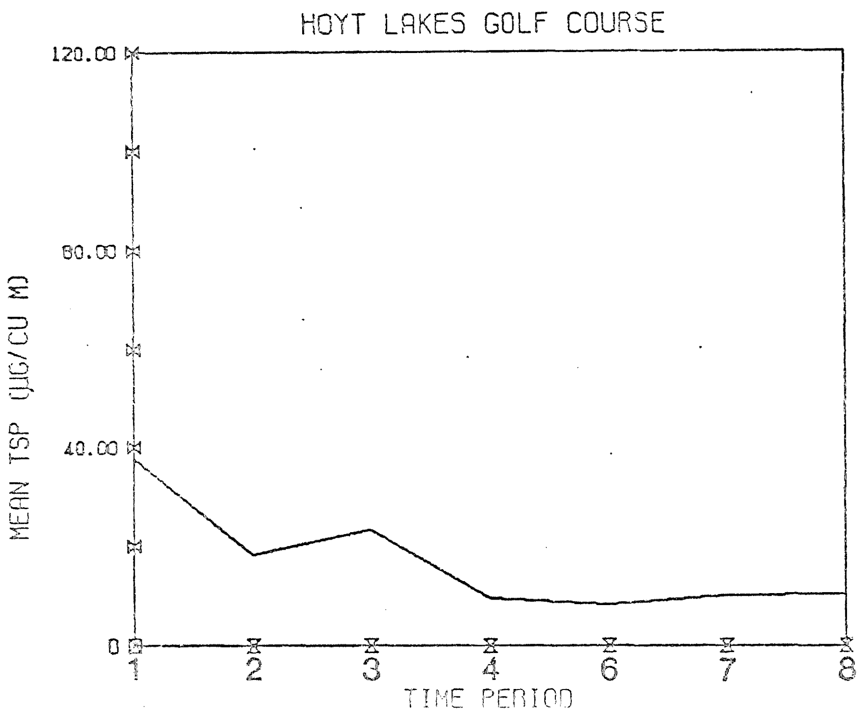
8	12/21/77-03/27/78





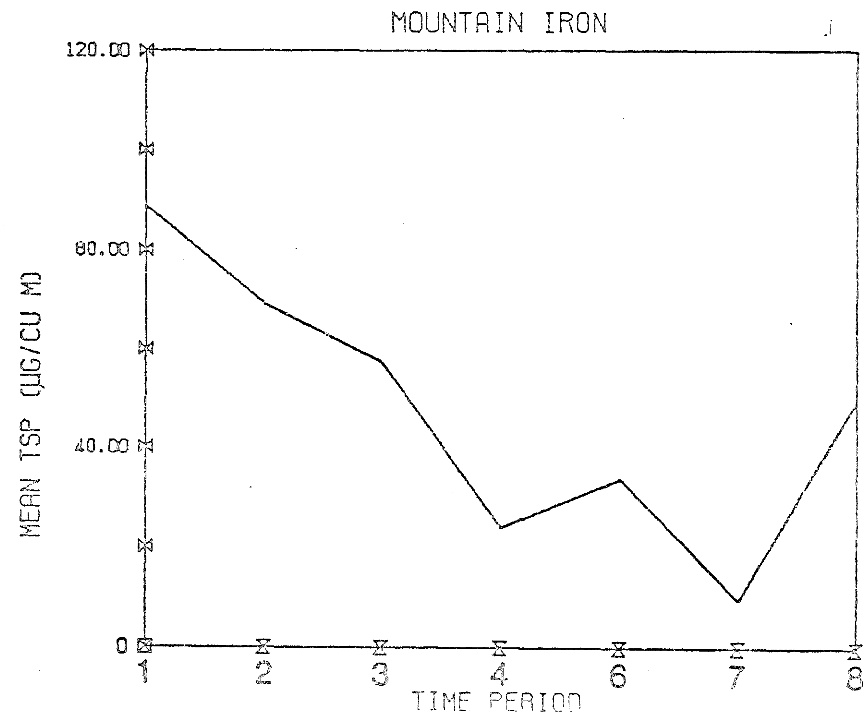


FIGURE 3 MEAN TSP BY TIME PERIOD

LEGEND

TIME PERIOD	DATE
1	10/09/76-11/20/76
2	11/26/76-03/08/77
3	03/14/77-07/24/77
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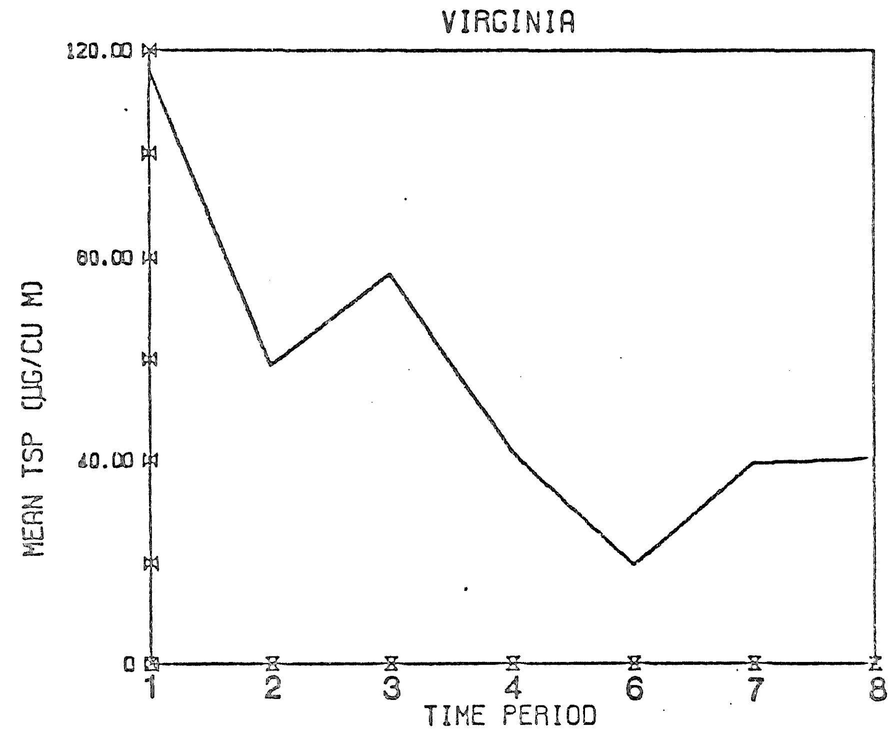
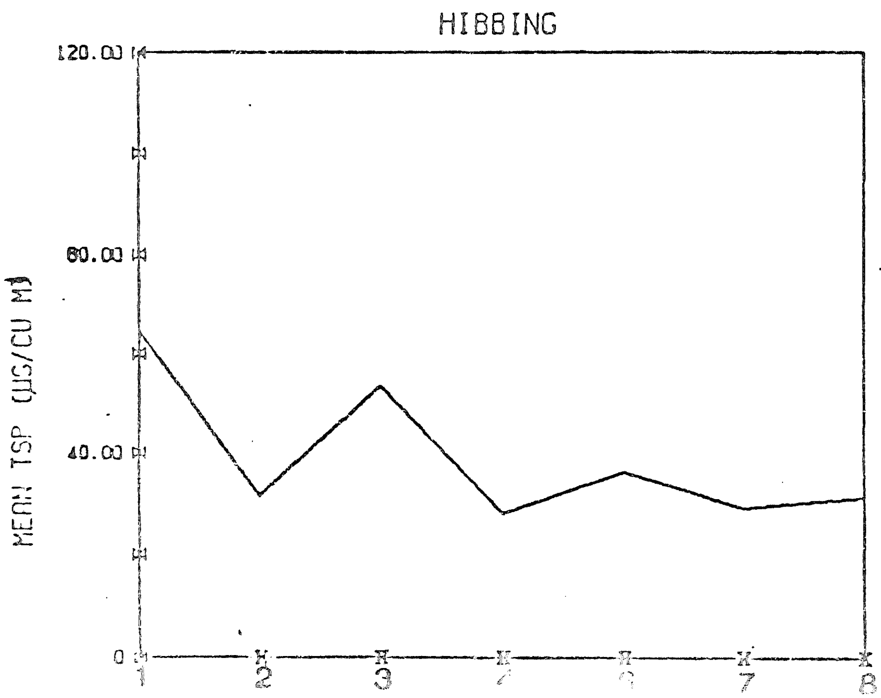
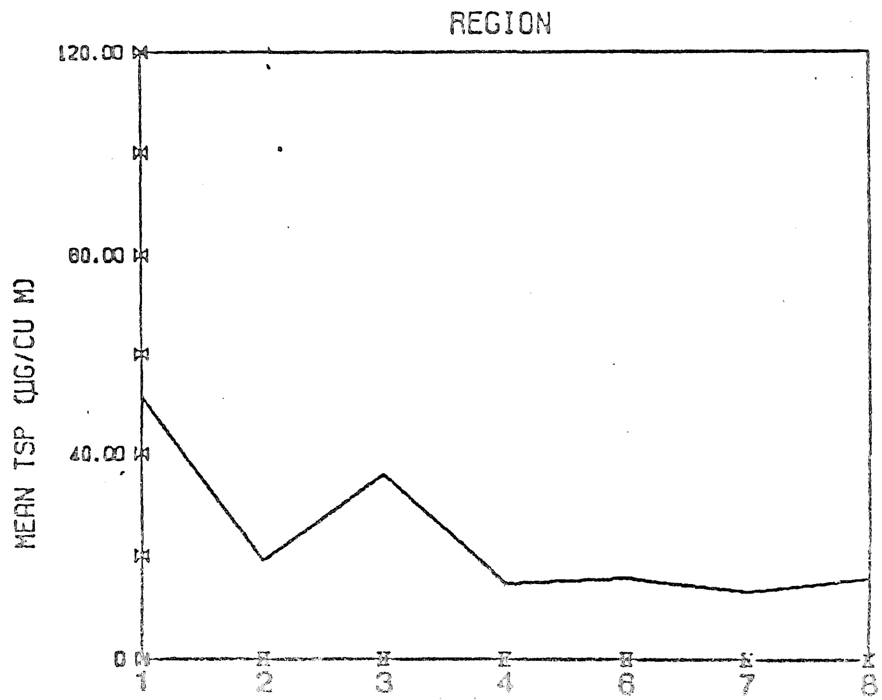






WIND [illegible]E FOR
TSP [illegible]ERVATIONS
1977 HIBBING WIND DATA

FIGURE 4

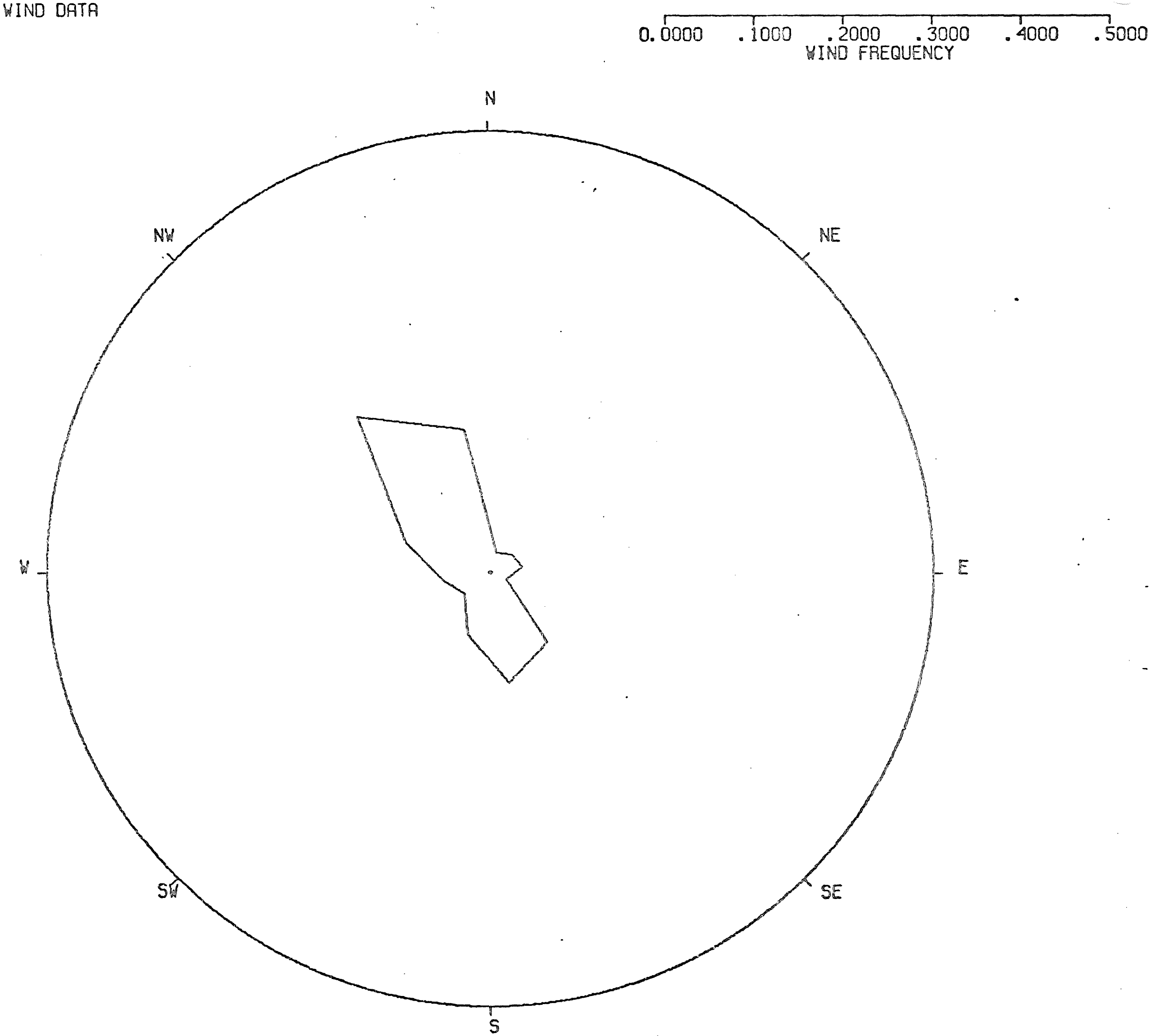
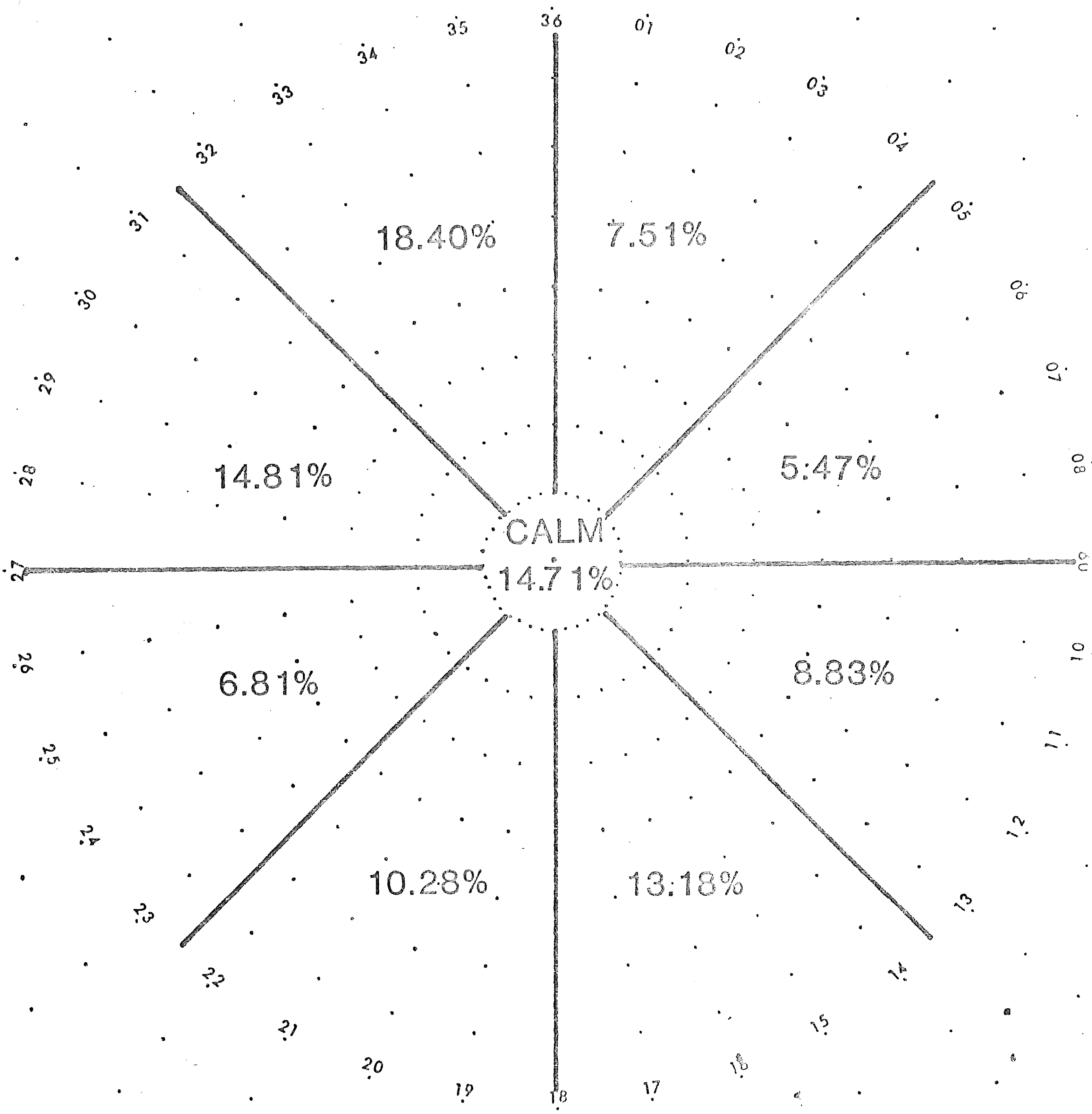


FIGURE 5

WIND DISTRIBUTION % FREQUENCY BY OCTANTS

HIBBING (1964 - 1973 DATA)



SOURCE: WATSON (1978)

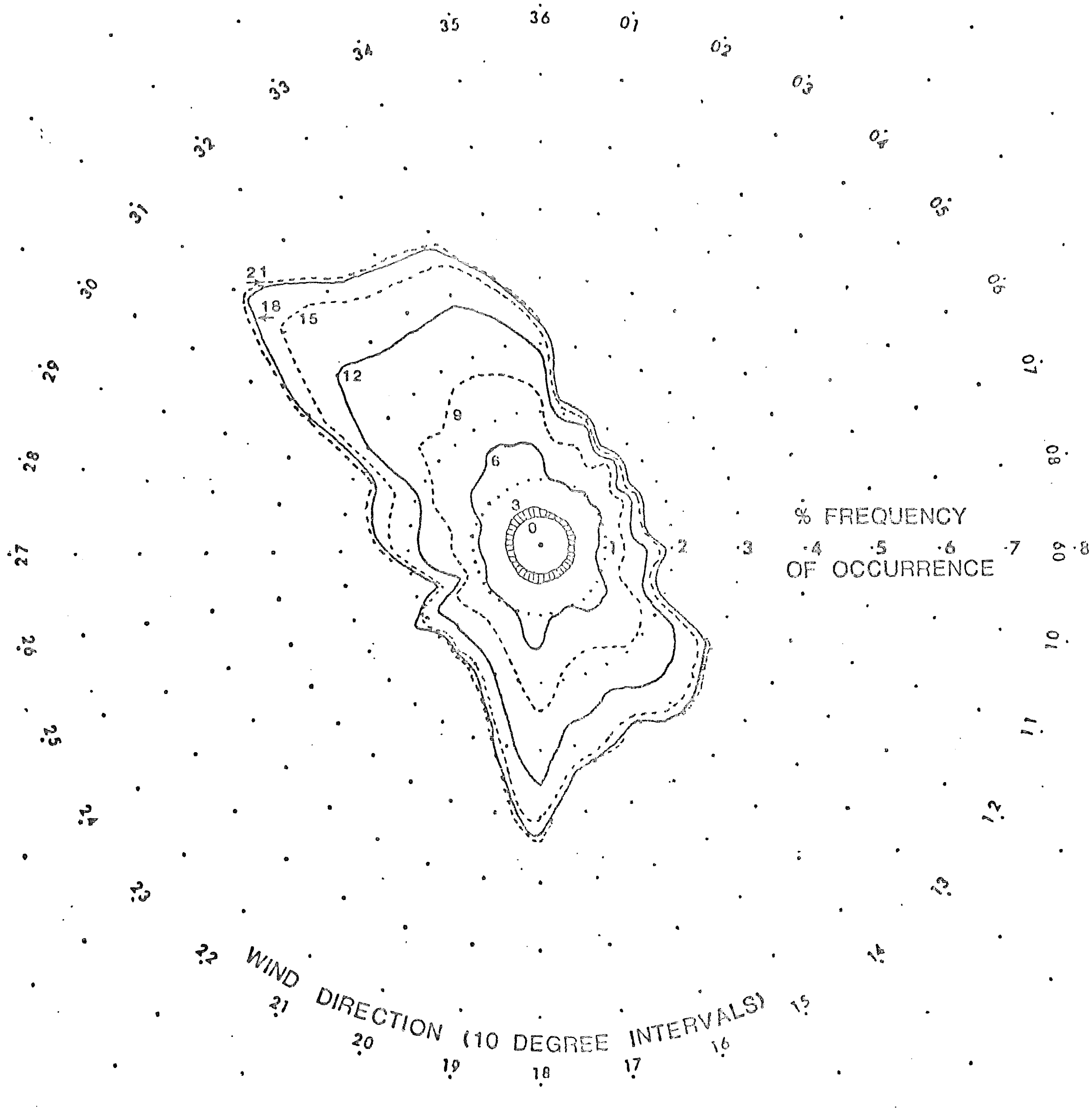
WIND ROSE

HIBBING (1964-1973 DATA)

(ISOPLETHS SHOW WIND SPEED IN M/SEC.)

FIGURE 5 (CONT.)

WIND ROSE
ANNUAL



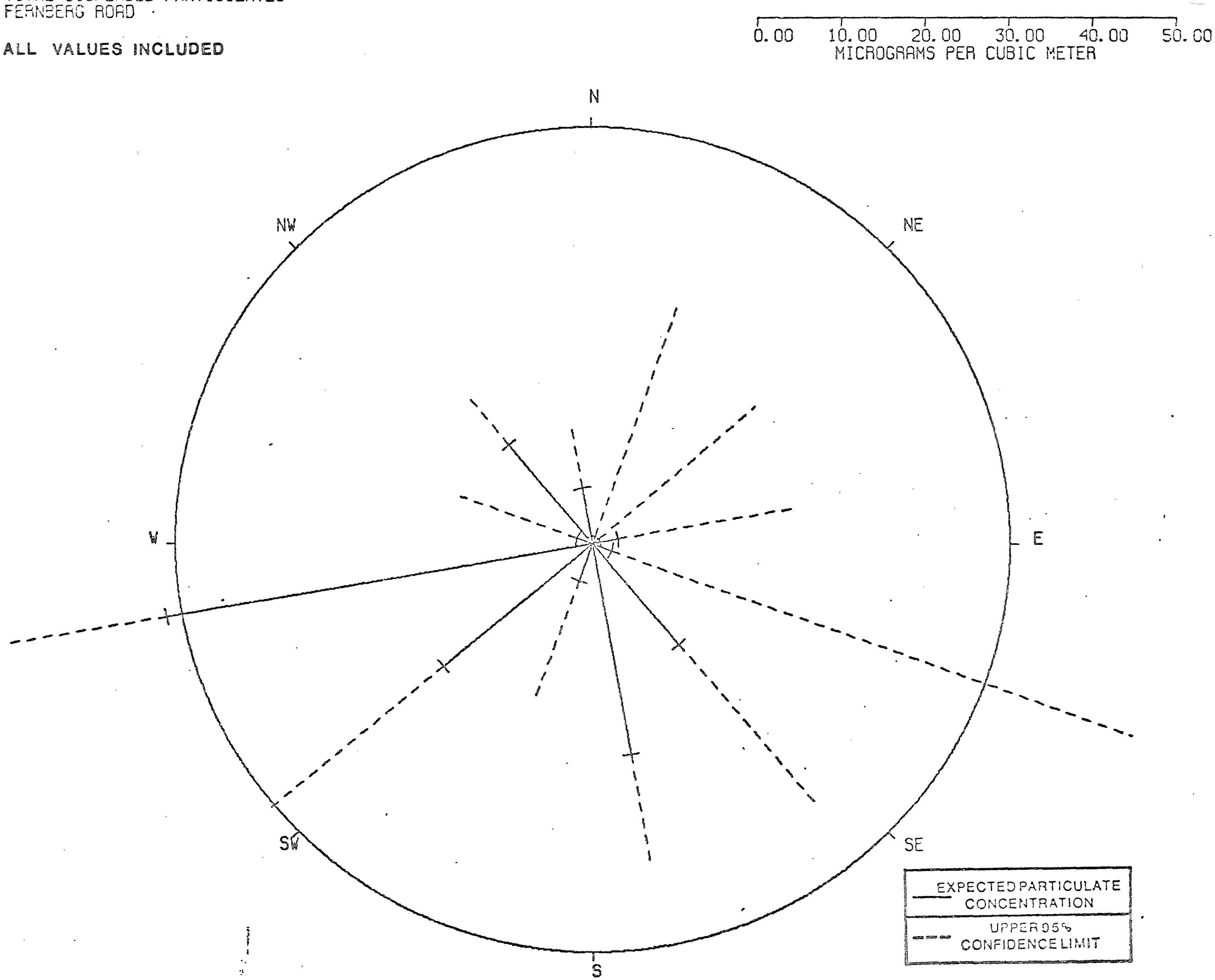
SOURCE : WATSON, (1978)

POLLU N ROSE FOR
TOTAL SUSPENDED PARTICULATES
FERNBERG ROAD

FIG. 6

ALL VALUES INCLUDED

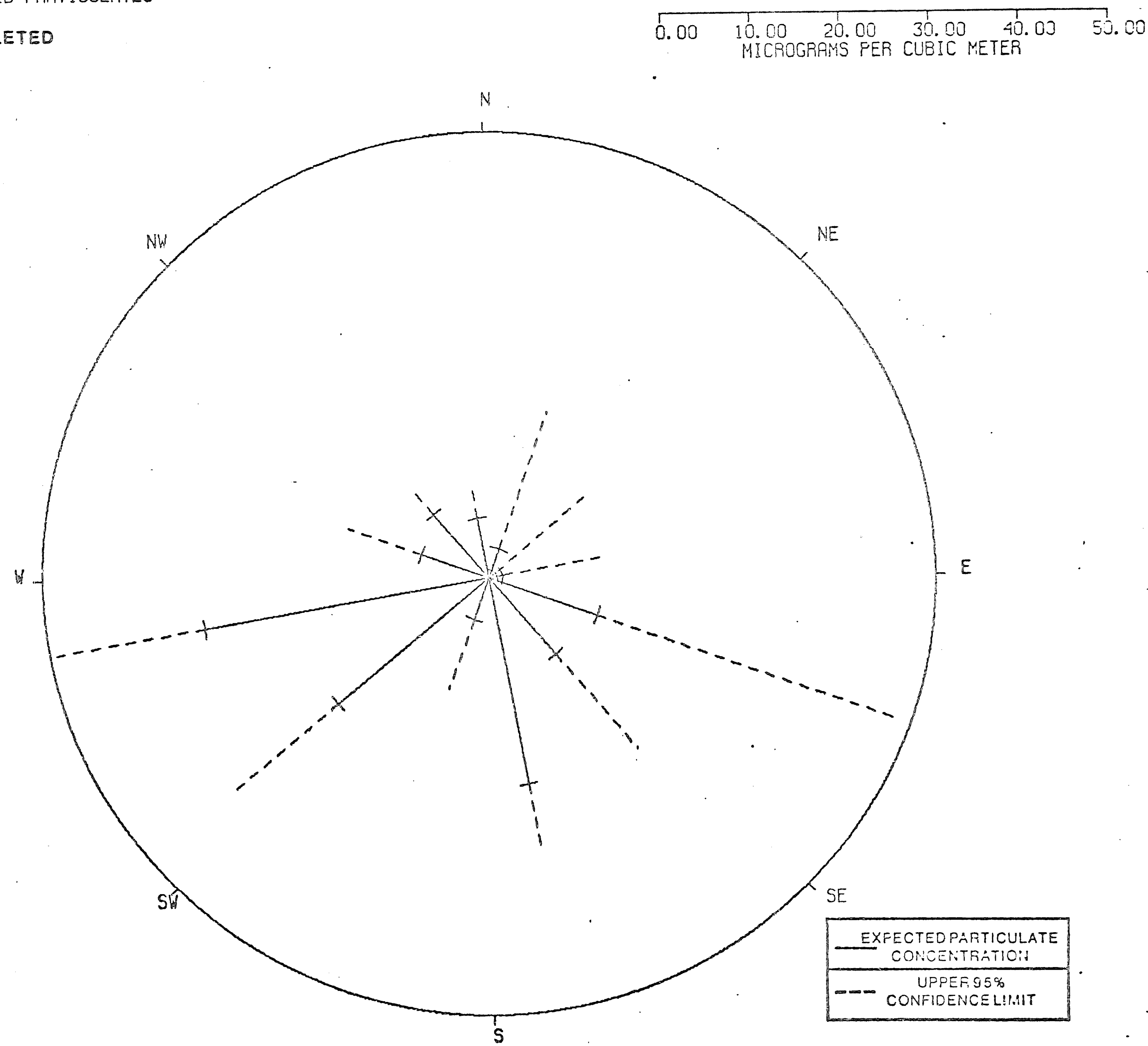
RADIAL SCALE - TSP CONCENTRATION



POLL[illegible]ON ROSE FOR
TOTAL SUSPENDED PARTICULATES
FERNBERG ROAD
OUTLIERS DELETED

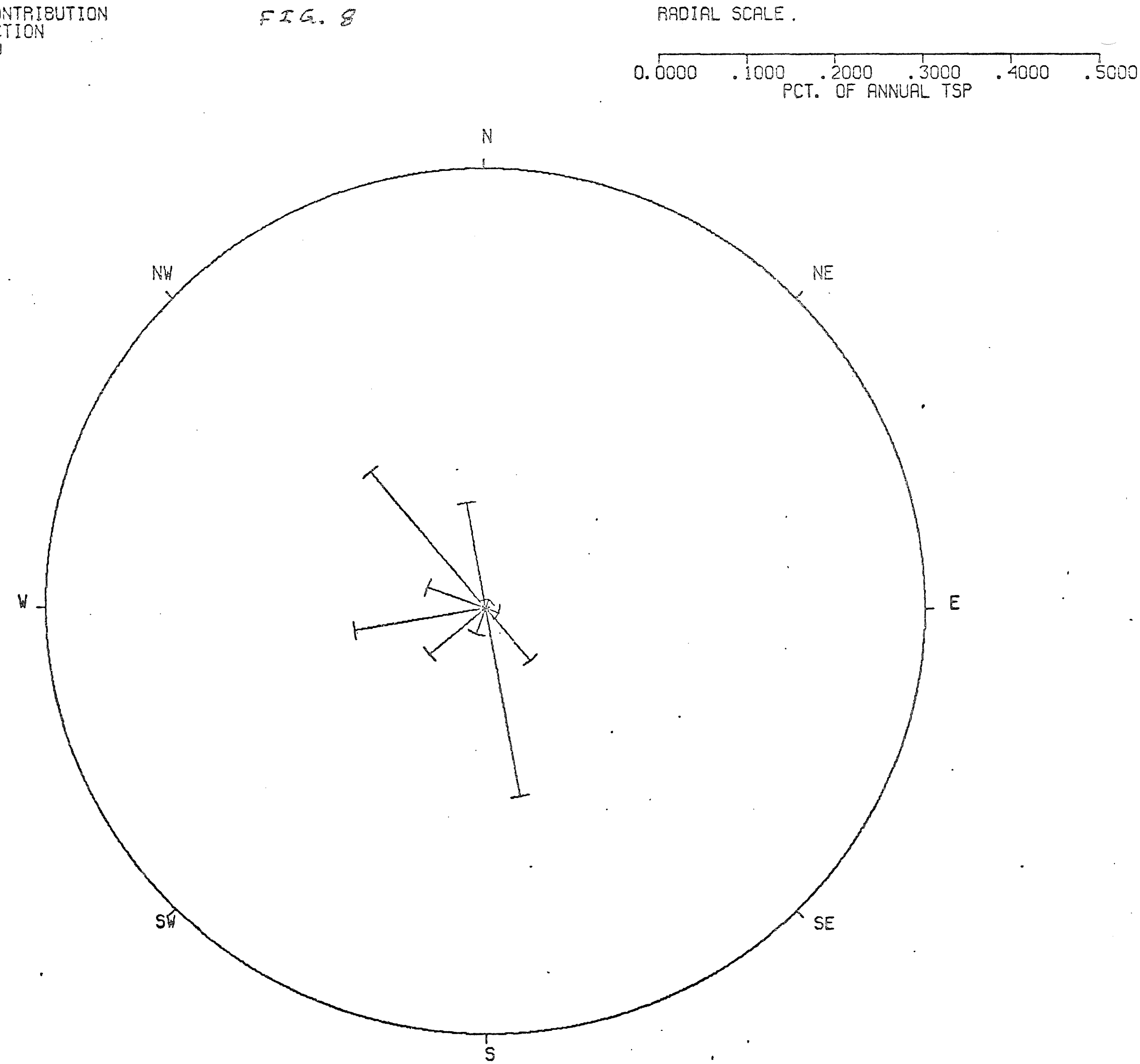
FIG. 7

RADIAL SCALE - TSP CONCENTRATION



ANNU[illegible] TSP CONTRIBUTION
BY [illegible] DIRECTION
FERNBERG ROAD

FIG. 8



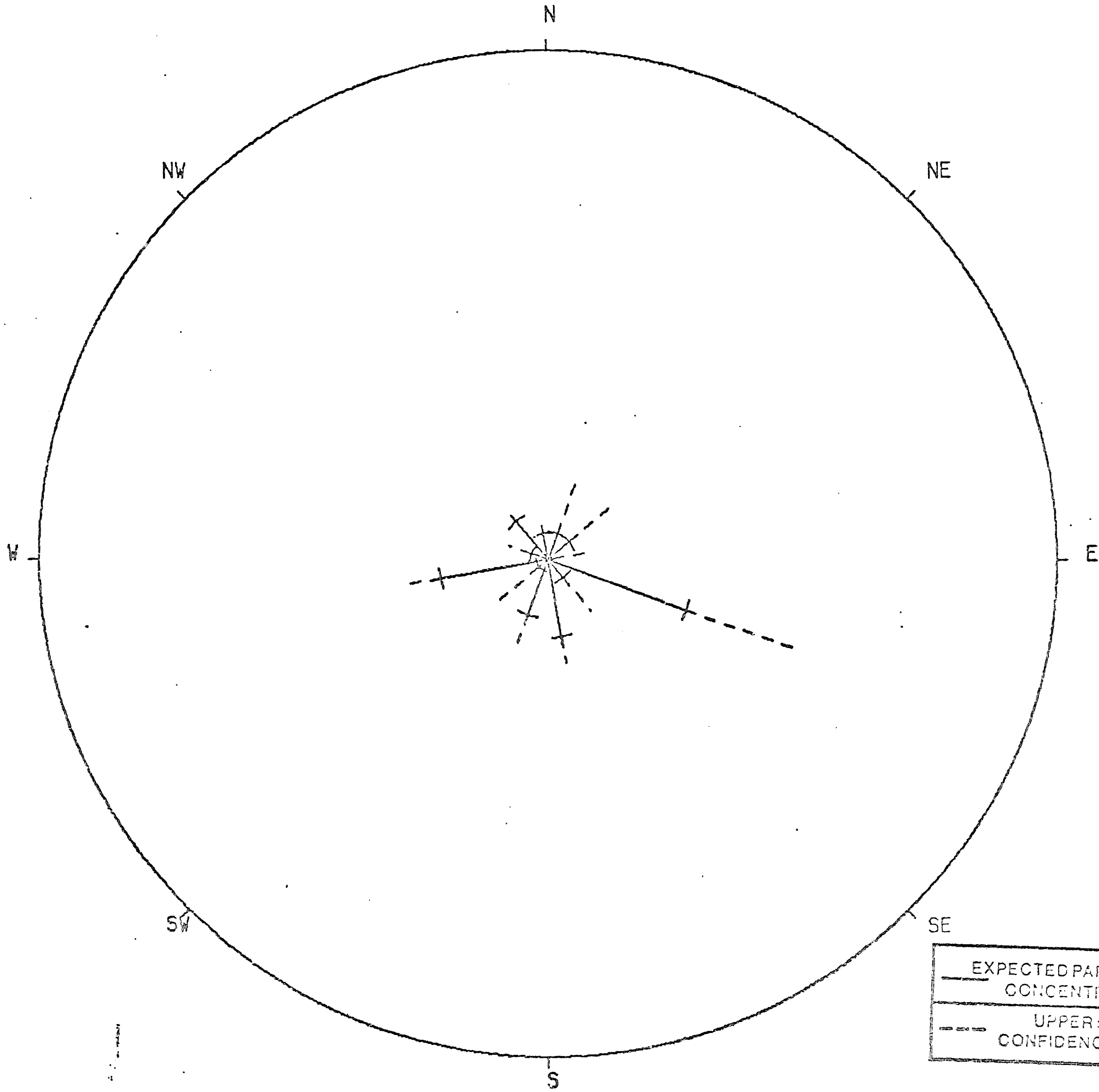
POLLUTION ROSE FOR
TOTAL SUSPENDED PARTICULATES
ELY HIGH SCHOOL

FIG. 9

ALL VALUES INCLUDED

RADIAL SCALE - TSP CONCENTRATION

0.0 60.0 120.0 180.0 240.0 300.0
MICROGRAMS PER CUBIC METER



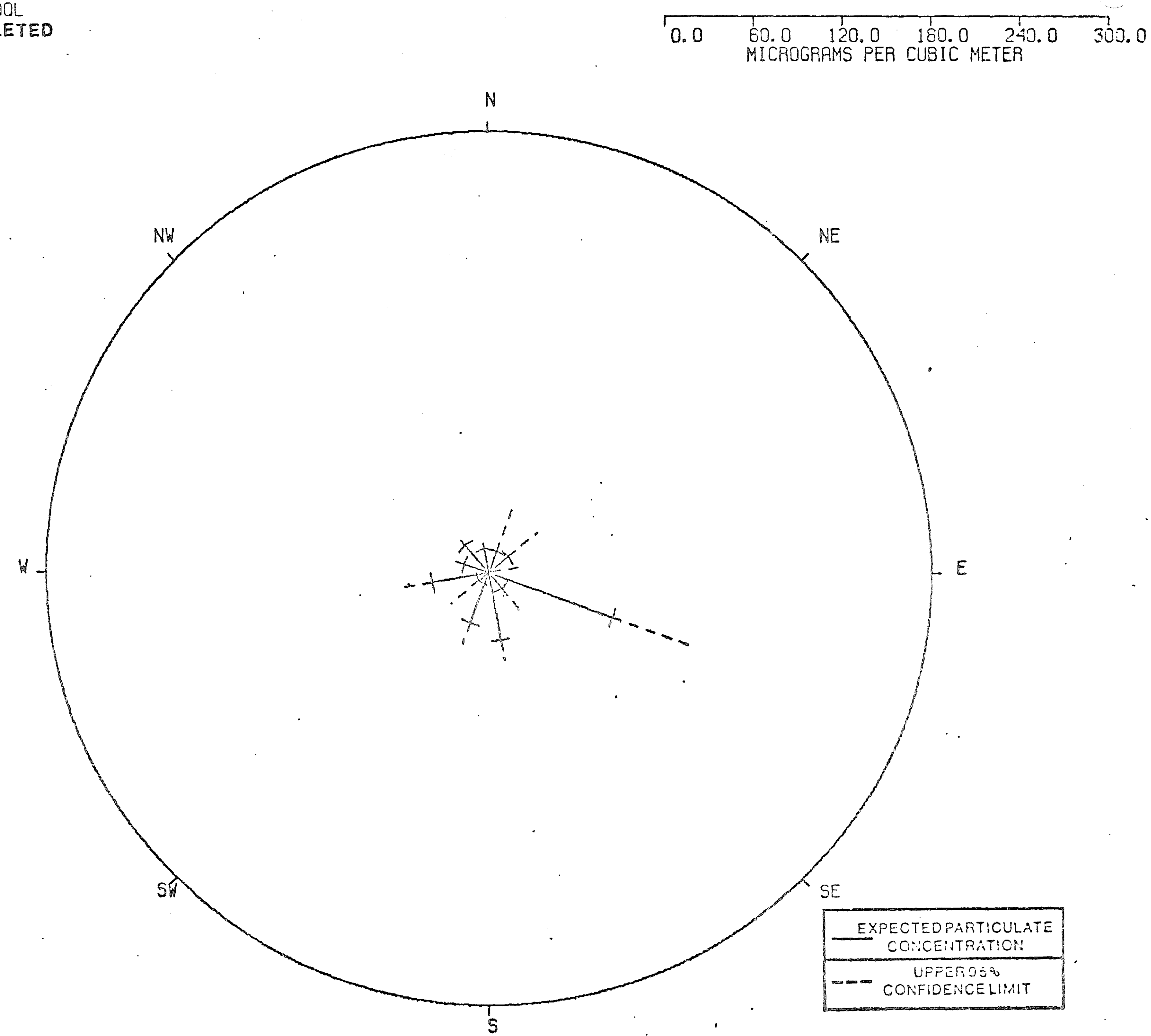
—— EXPECTED PARTICULATE CONCENTRATION

- - - UPPER 95% CONFIDENCE LIMIT

POLL ON ROSE FOR
TOT SUSPENDED PARTICULATES
FLY HIGH SCHOOL
OUTLIERS DELETED

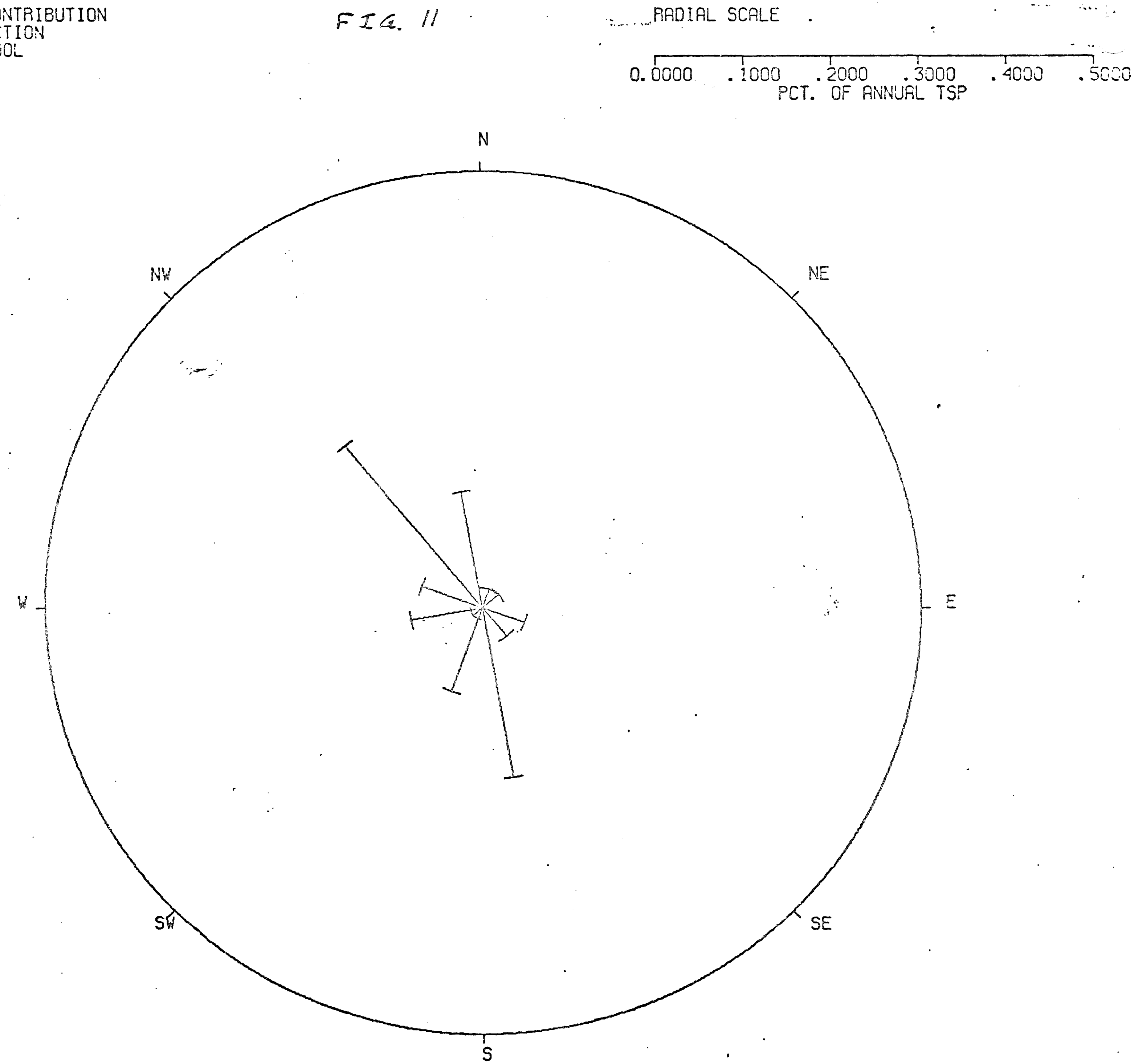
FIG. 10

RADIAL SCALE - TSP CONCENTRATION



ANNUAL TSP CONTRIBUTION
BY WIND DIRECTION
ELY HIGH SCHOOL

FIG. 11

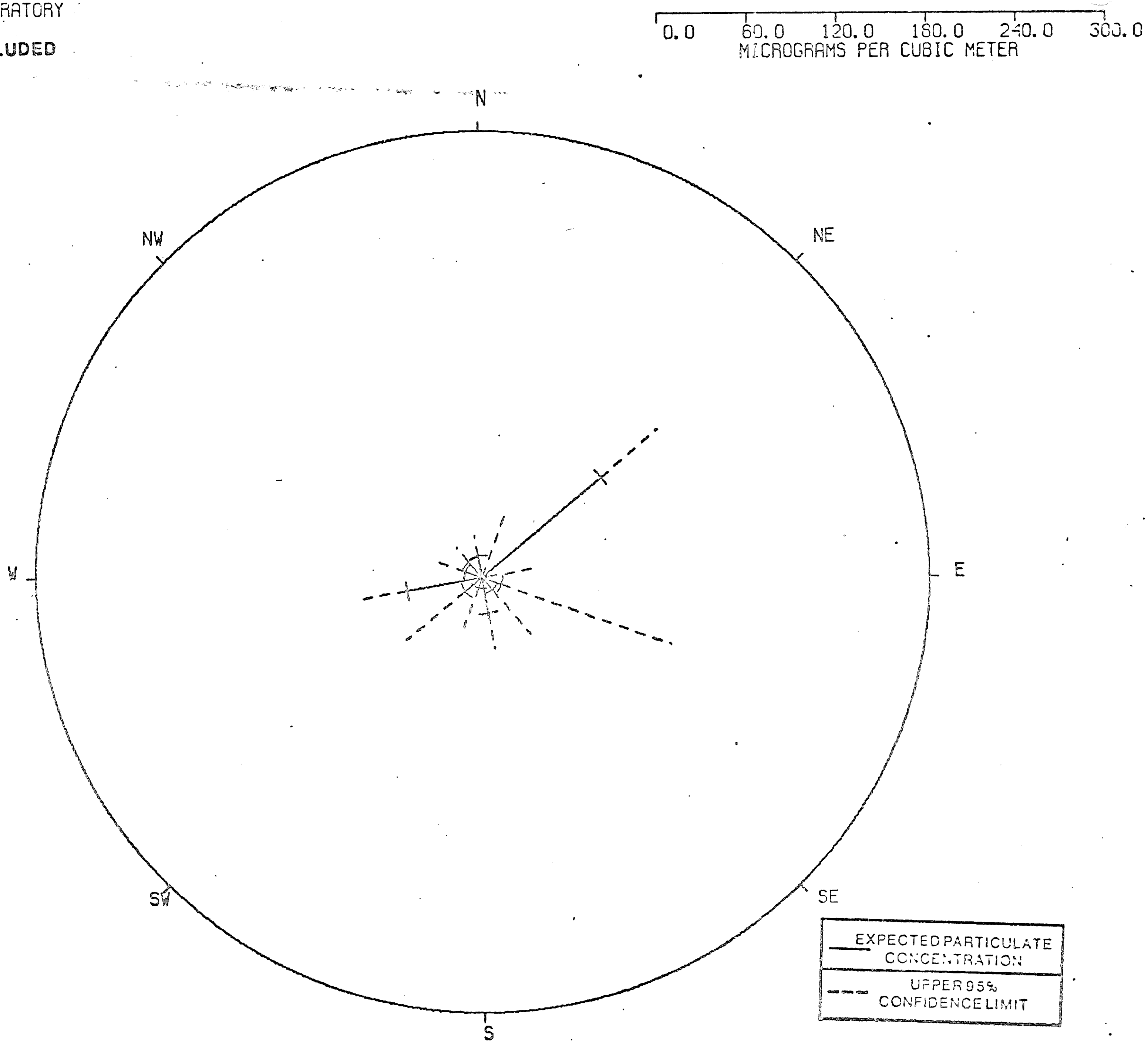


POL' TION ROSE FOR
TOT SUSPENDED PARTICULATES
KAWISHIWI LABORATORY

ALL VALUES INCLUDED

FIG. 12

RADIAL SCALE - TSP CONCENTRATION

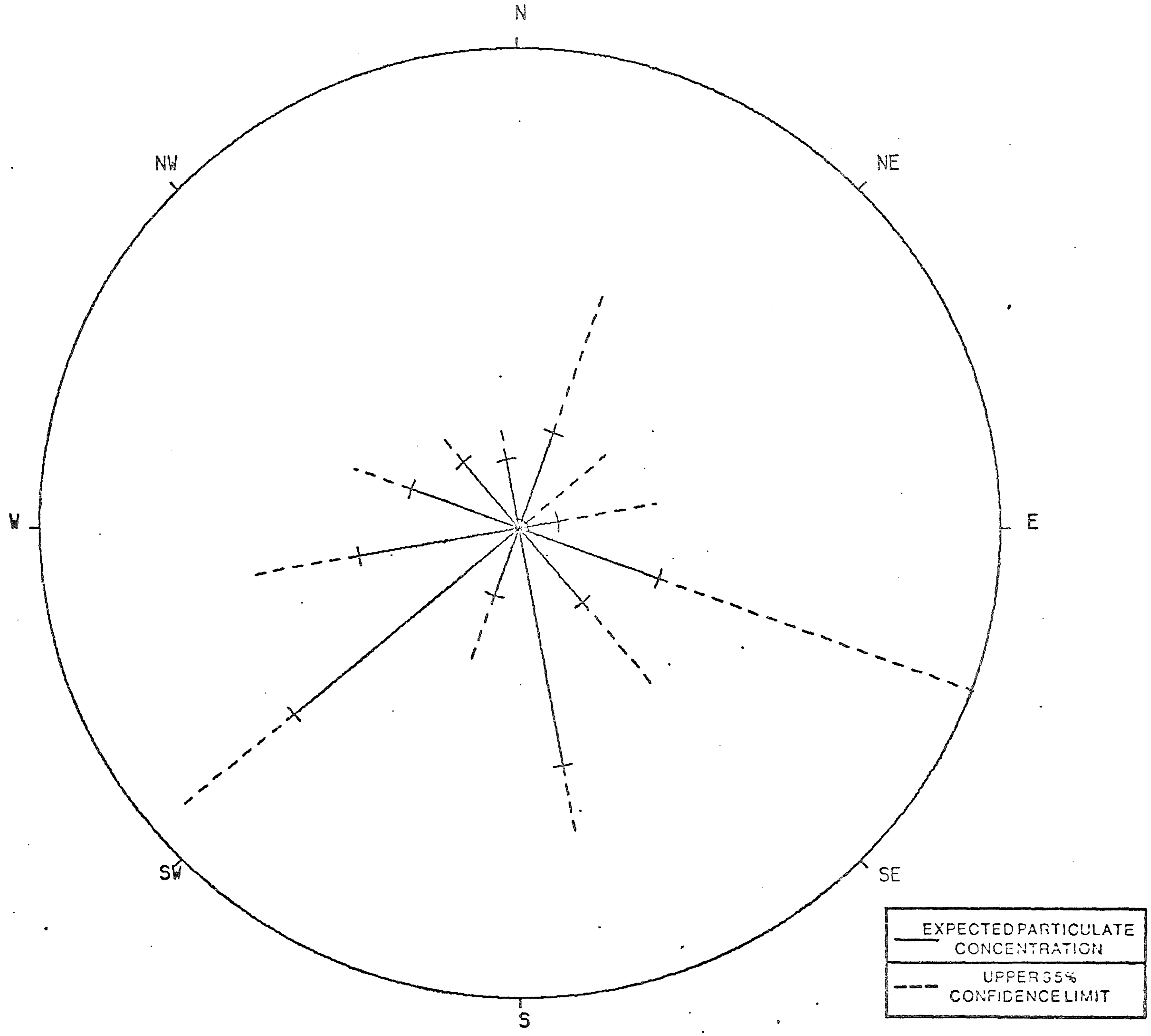


POLLUTION ROSE FOR
TOTAL SUSPENDED PARTICULATES
KAWISHIWI LABORATORY
OUTLIERS DELETED

FIG. 13

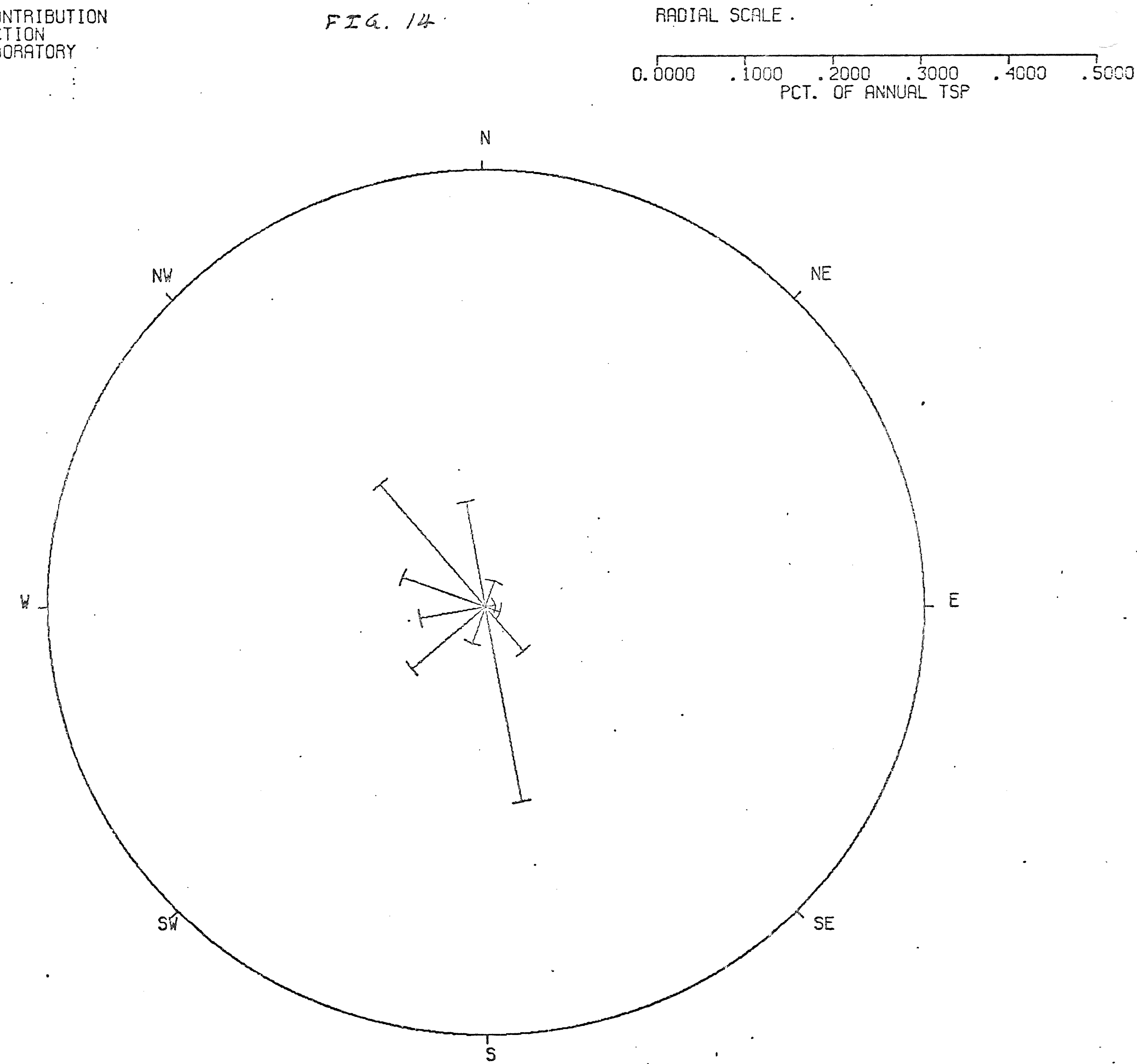
RADIAL SCALE - TSP CONCENTRATION

0.00 10.00 20.00 30.00 40.00 50.00
MICROGRAMS PER CUBIC METER



ANNU[illegible] TSP CONTRIBUTION
BY [illegible] DIRECTION
KAWISHIWI LABORATORY

FIG. 14



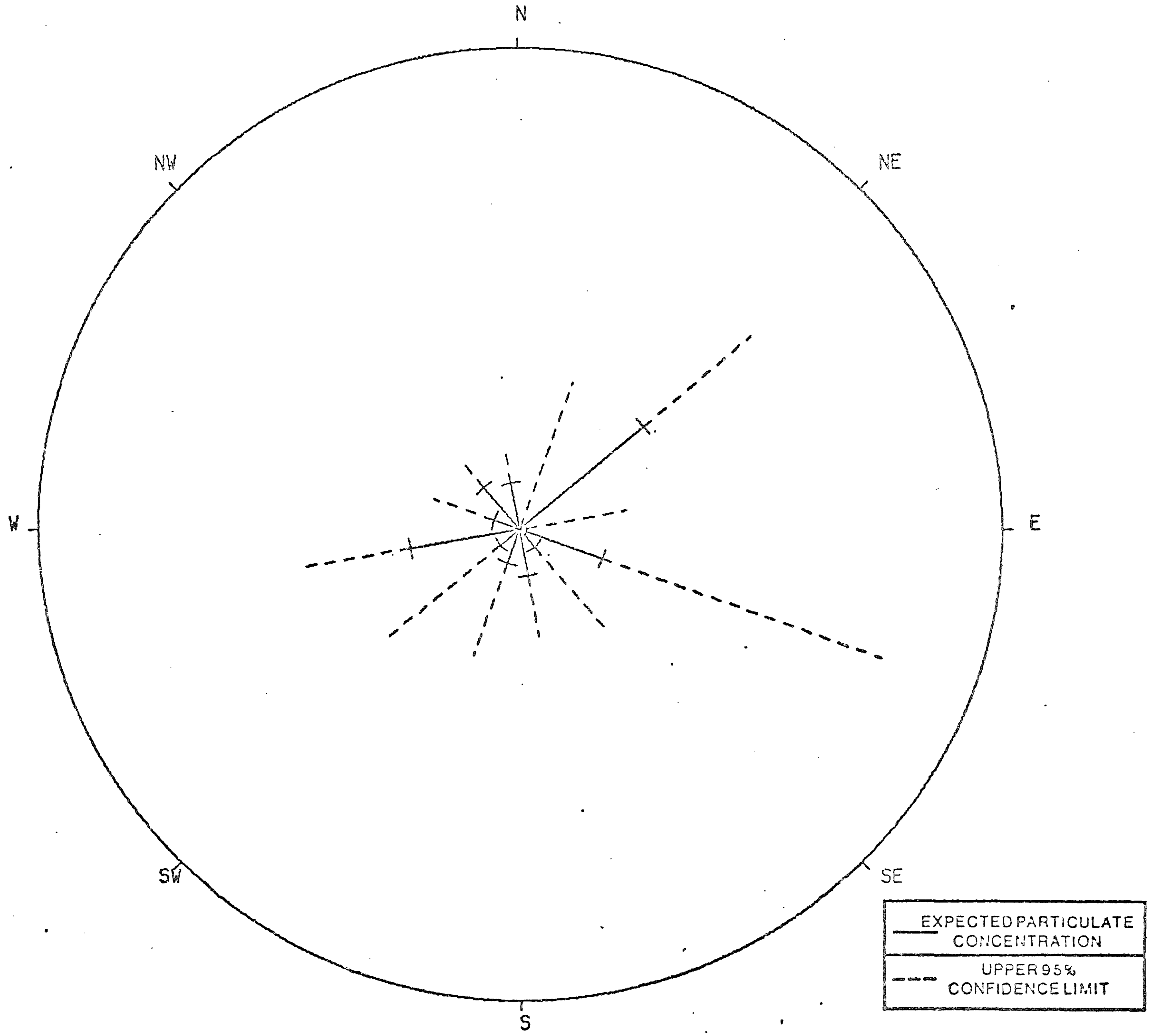
POLLUTION ROSE FOR
TOTAL SUSPENDED PARTICULATES
DUNKA ROAD

ALL VALUES INCLUDED

FIG. 15

RADIAL SCALE - TSP CONCENTRATION

0.0 60.0 120.0 180.0 240.0 300.0
MICROGRAMS PER CUBIC METER

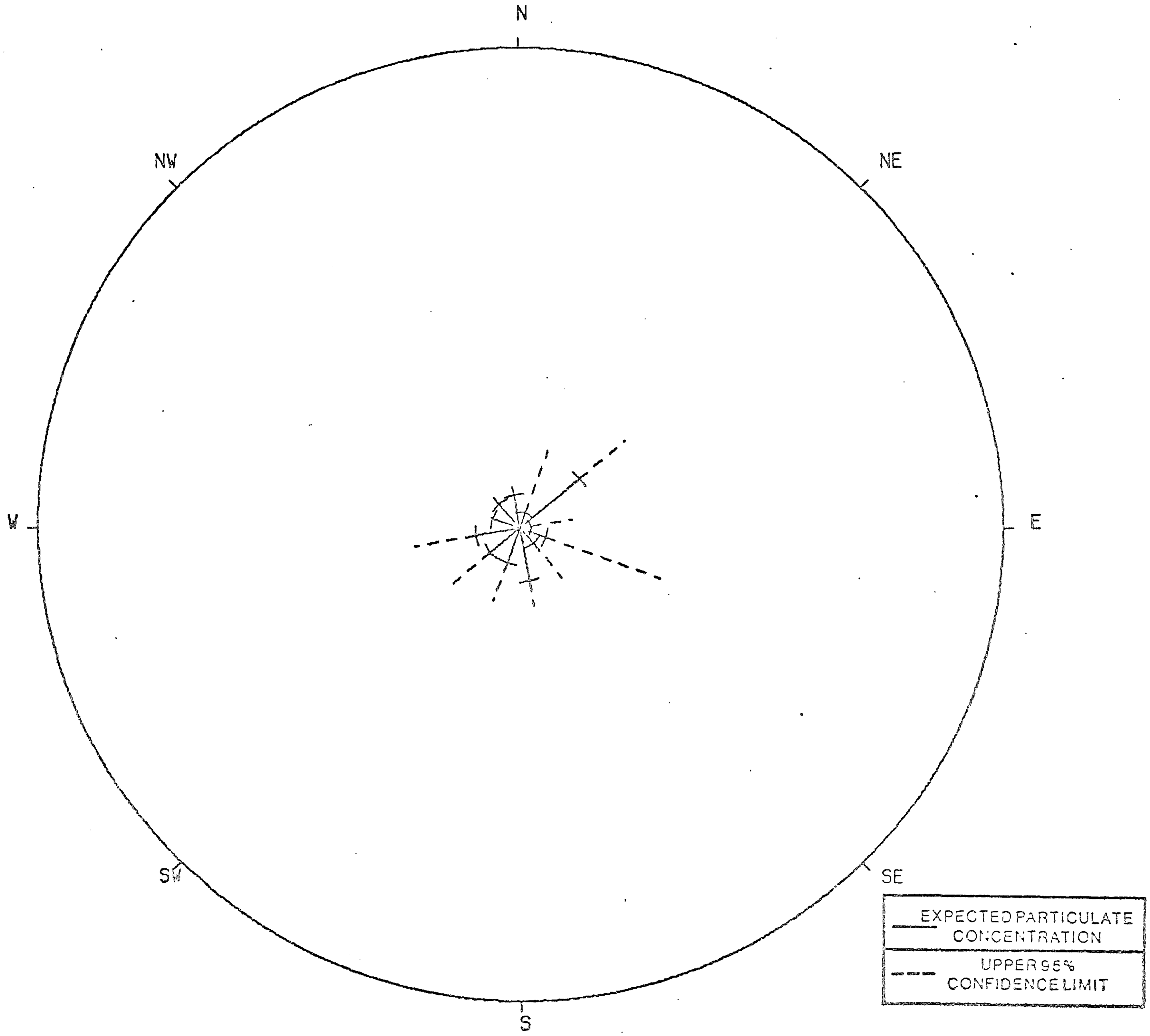


POLLUTION ROSE FOR
TOTAL SUSPENDED PARTICULATES
DUNKA ROAD
OUTLIERS DELETED

FIG. 16

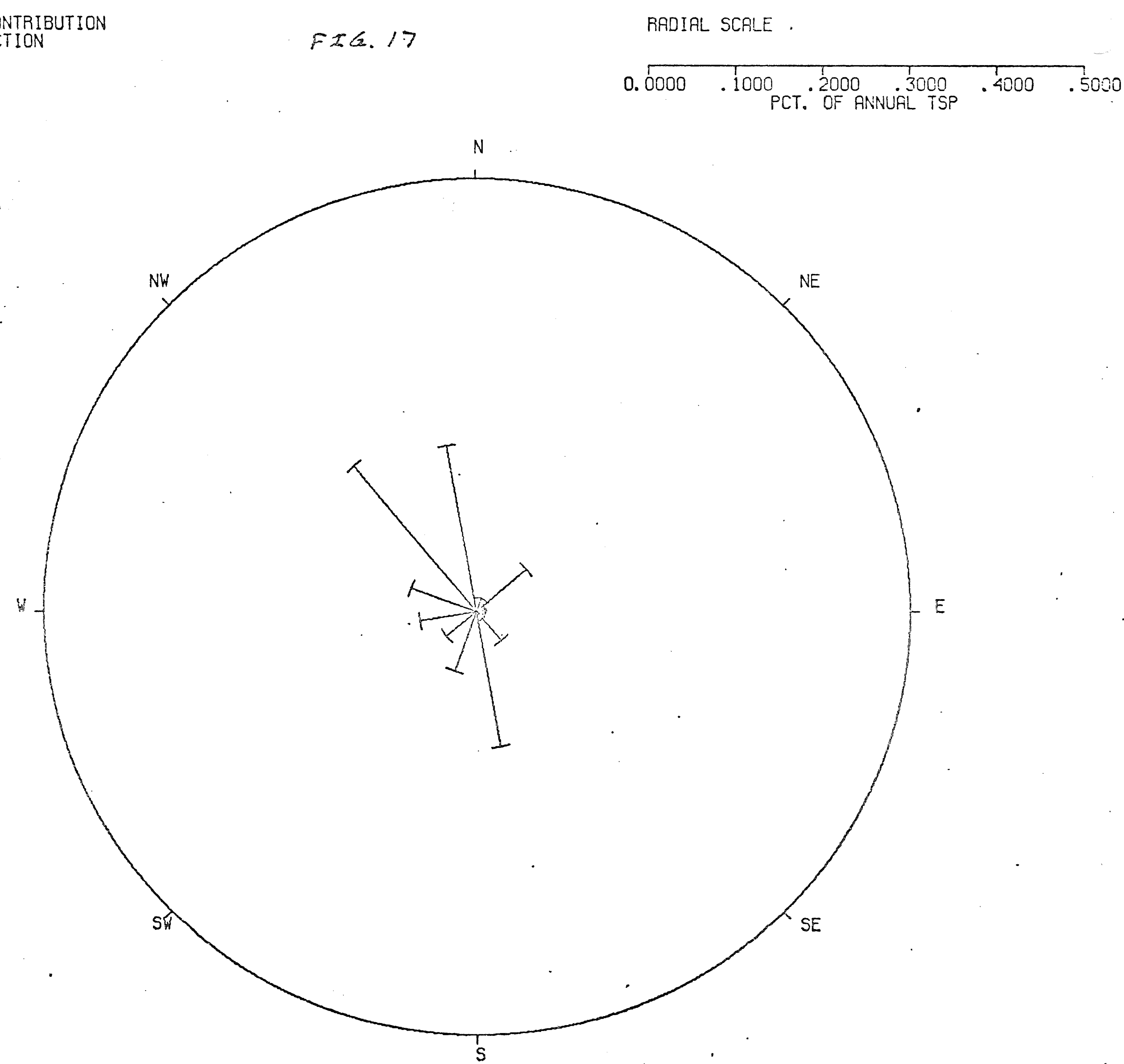
RADIAL SCALE - TSP CONCENTRATION

0.0 60.0 120.0 180.0 240.0 300.0
MICROGRAMS PER CUBIC METER



ANNUAL TSP CONTRIBUTION
BY W. DIRECTION
DUNKA ROAD

FIG. 17



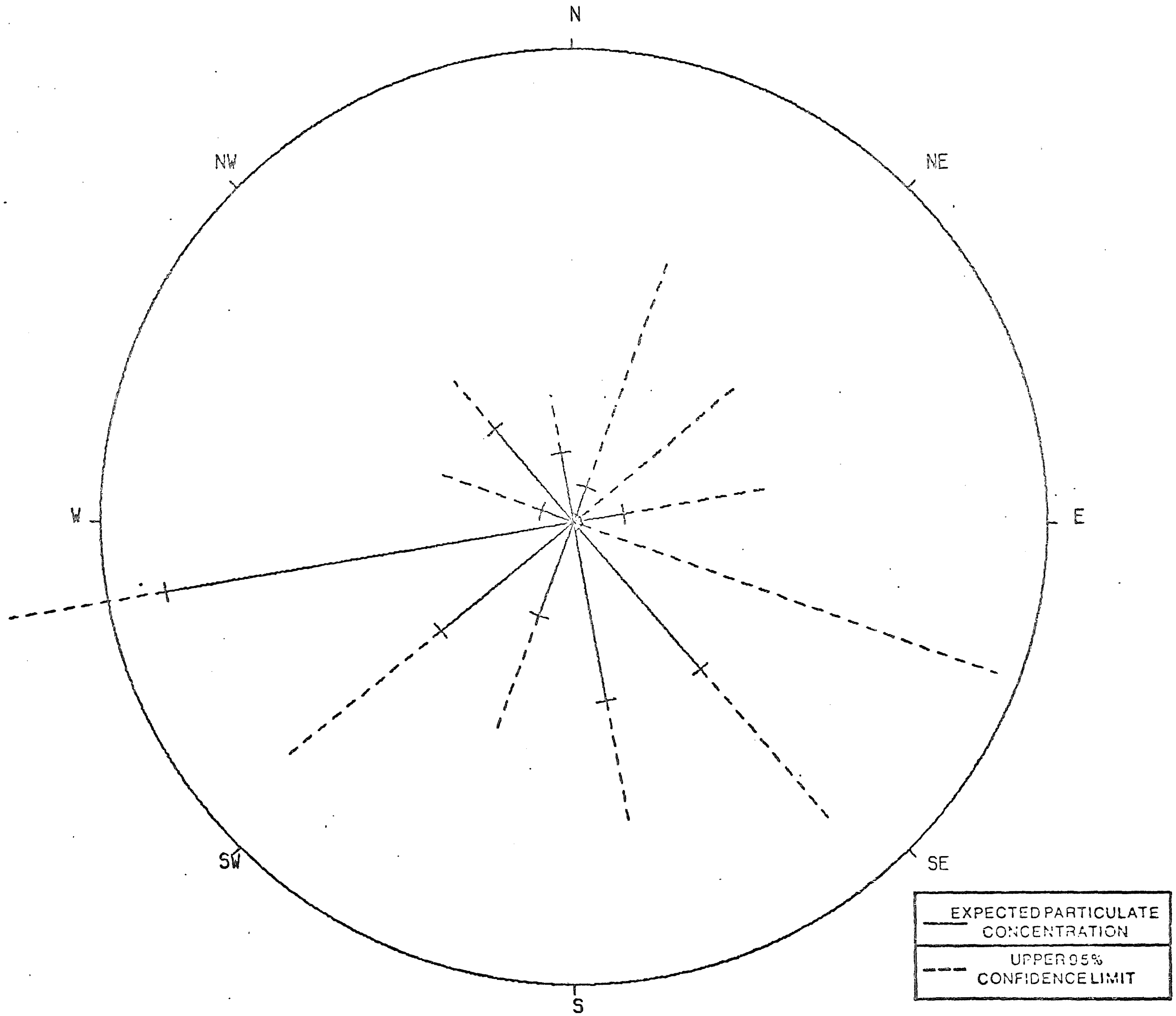
POL ON ROSE FOR
TOTA SUSPENDED PARTICULATES
TOIMI

ALL VALUES INCLUDED

FIG. 18

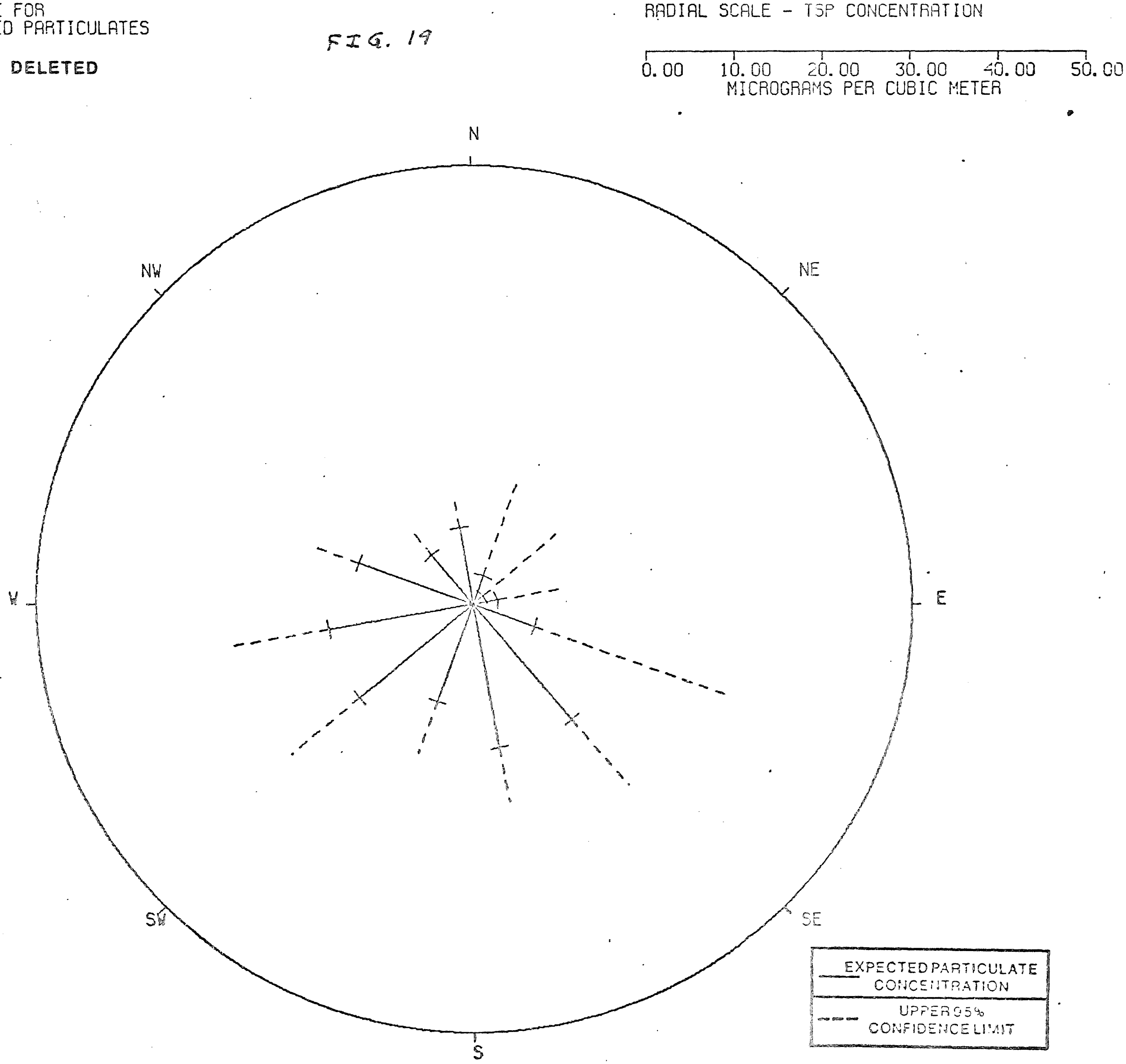
RADIAL SCALE - TSP CONCENTRATION

0.00 10.00 20.00 30.00 40.00 50.00
MICROGRAMS PER CUBIC METER



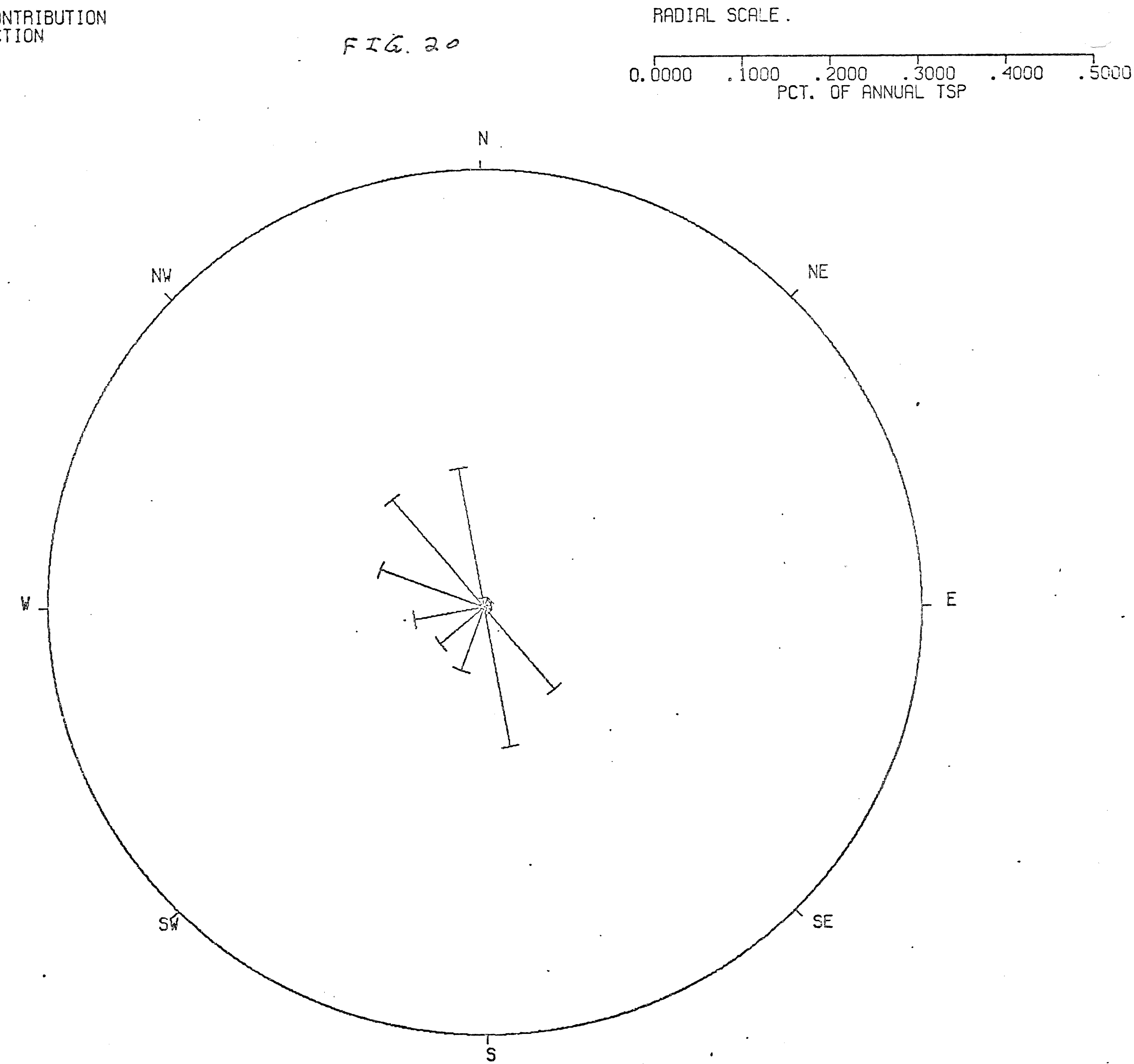
POLLUTION ROSE FOR
TOTAL SUS[illegible]ED PARTICULATES
TOIMI
OUTLIERS DELETED

FIG. 19



ANN[illegible] TSP CONTRIBUTION
BY [illegible] DIRECTION
TOIMI

FIG. 20



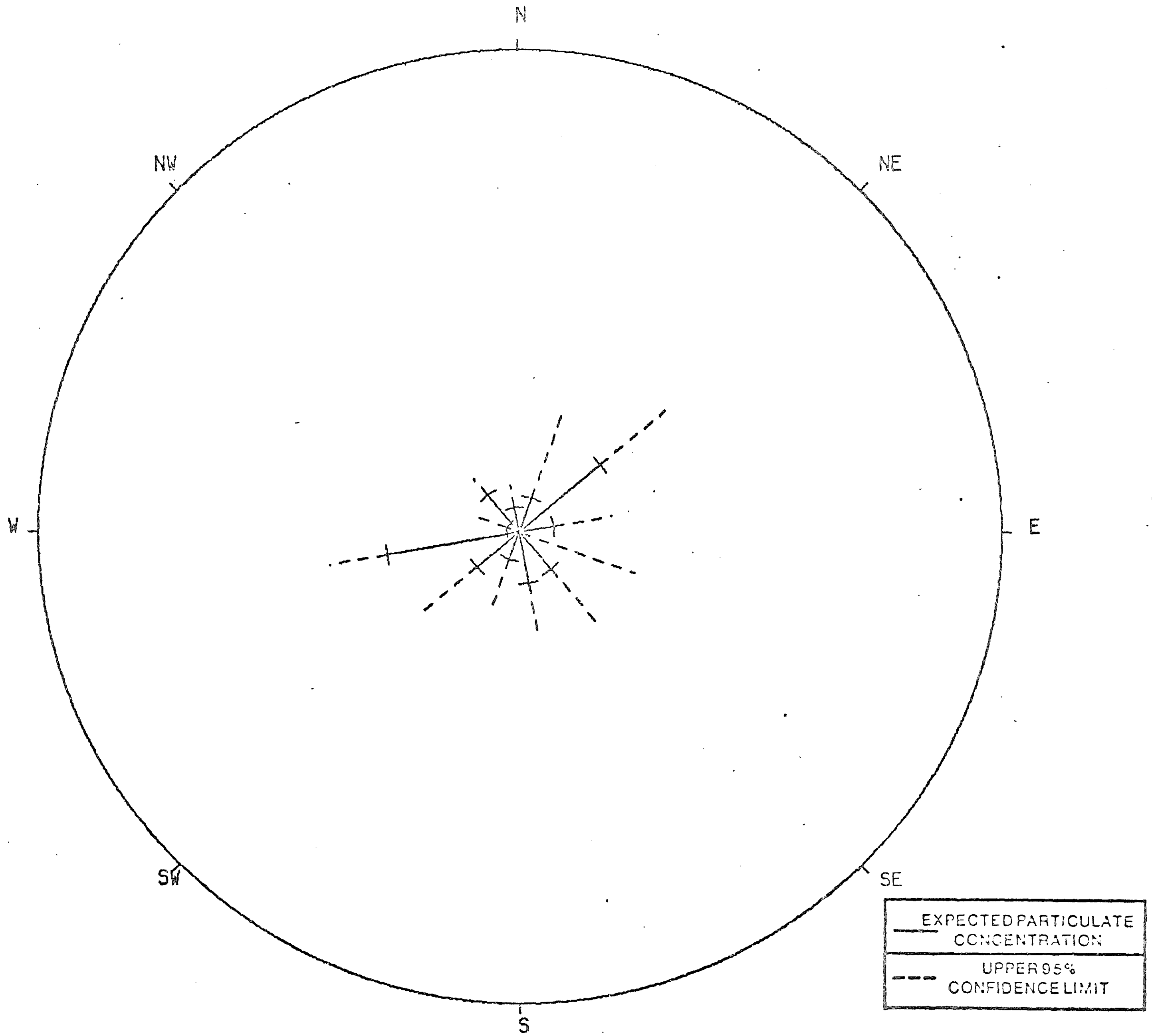
POLL[illegible]ON ROSE FOR
TOTAL SUSPENDED PARTICULATES
ERIE MINING OFFICE

ALL VALUES INCLUDED

FIG. 21

RADIAL SCALE - TSP CONCENTRATION

0.0 60.0 120.0 180.0 240.0 300.0
MICROGRAMS PER CUBIC METER

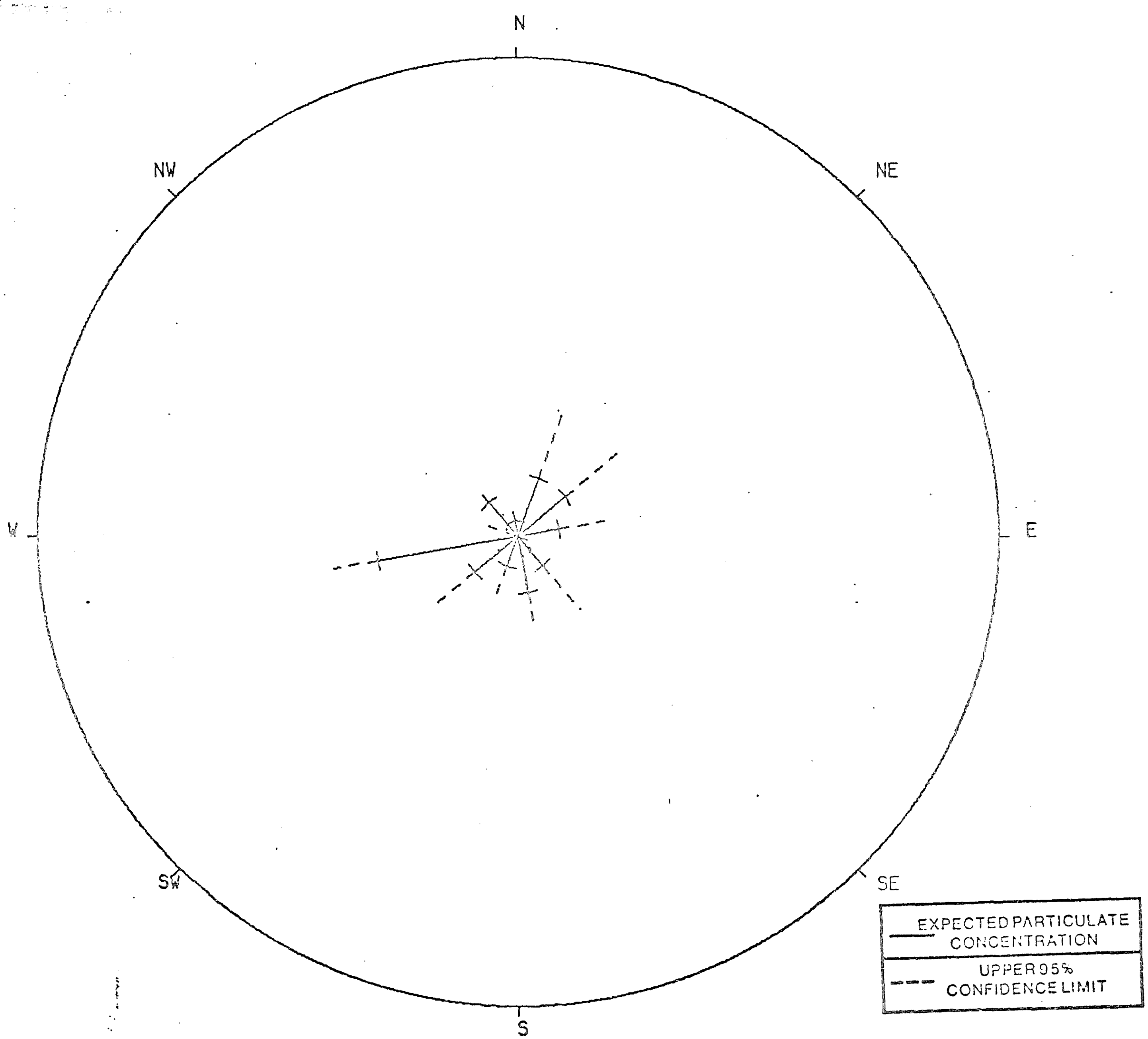


POLLUTION ROSE FOR
TOTAL SUSPENDED PARTICULATES
ERIE MINING OFFICE
OUTLIERS DELETED

FIG. 22

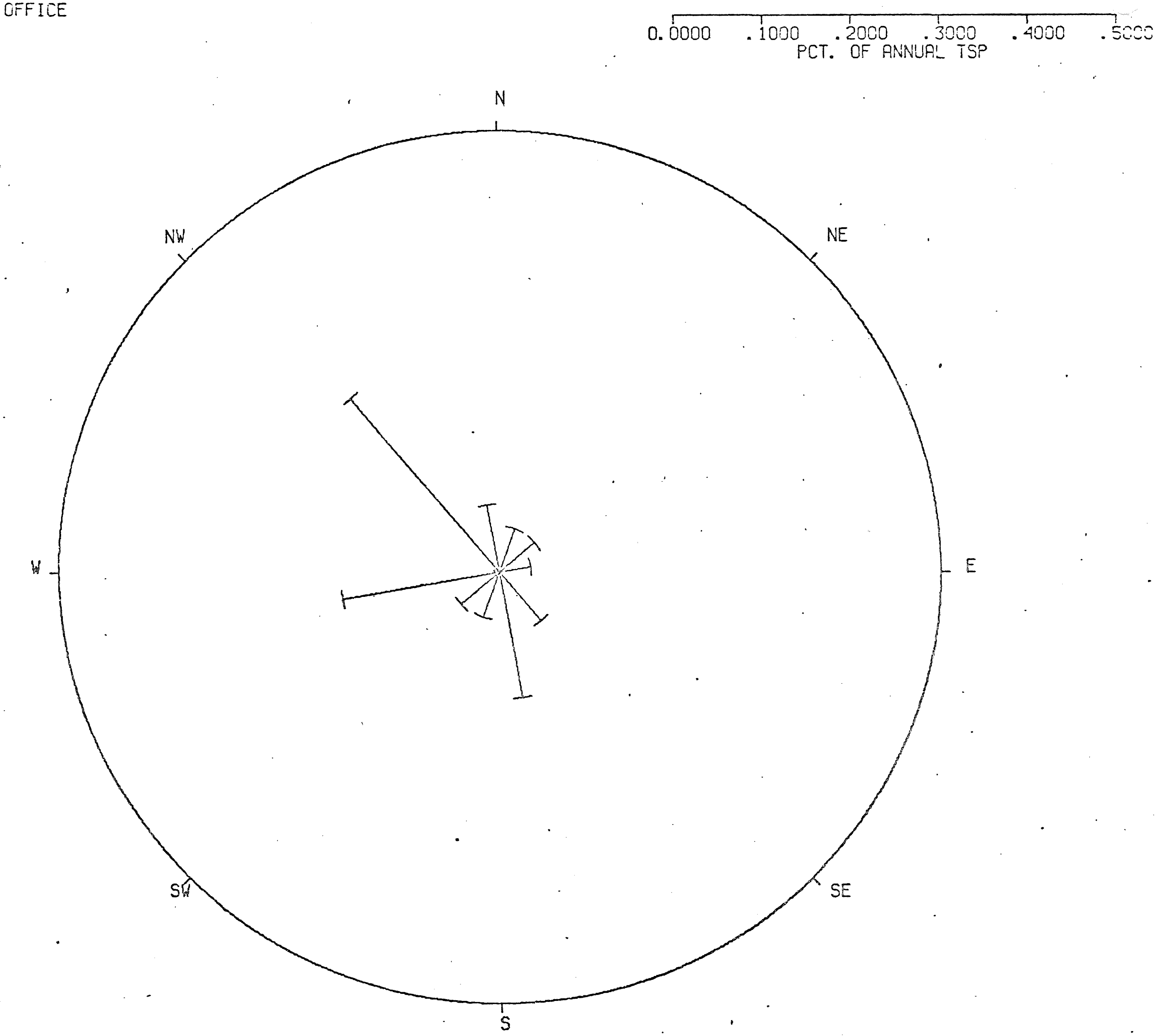
RADIAL SCALE - TSP CONCENTRATION

0.0 60.0 120.0 180.0 240.0 300.0
MICROGRAMS PER CUBIC METER



ANNUAL TSP CONTRIBUTION
BY WIND DIRECTION
ERIE MINING OFFICE

FIG. 23



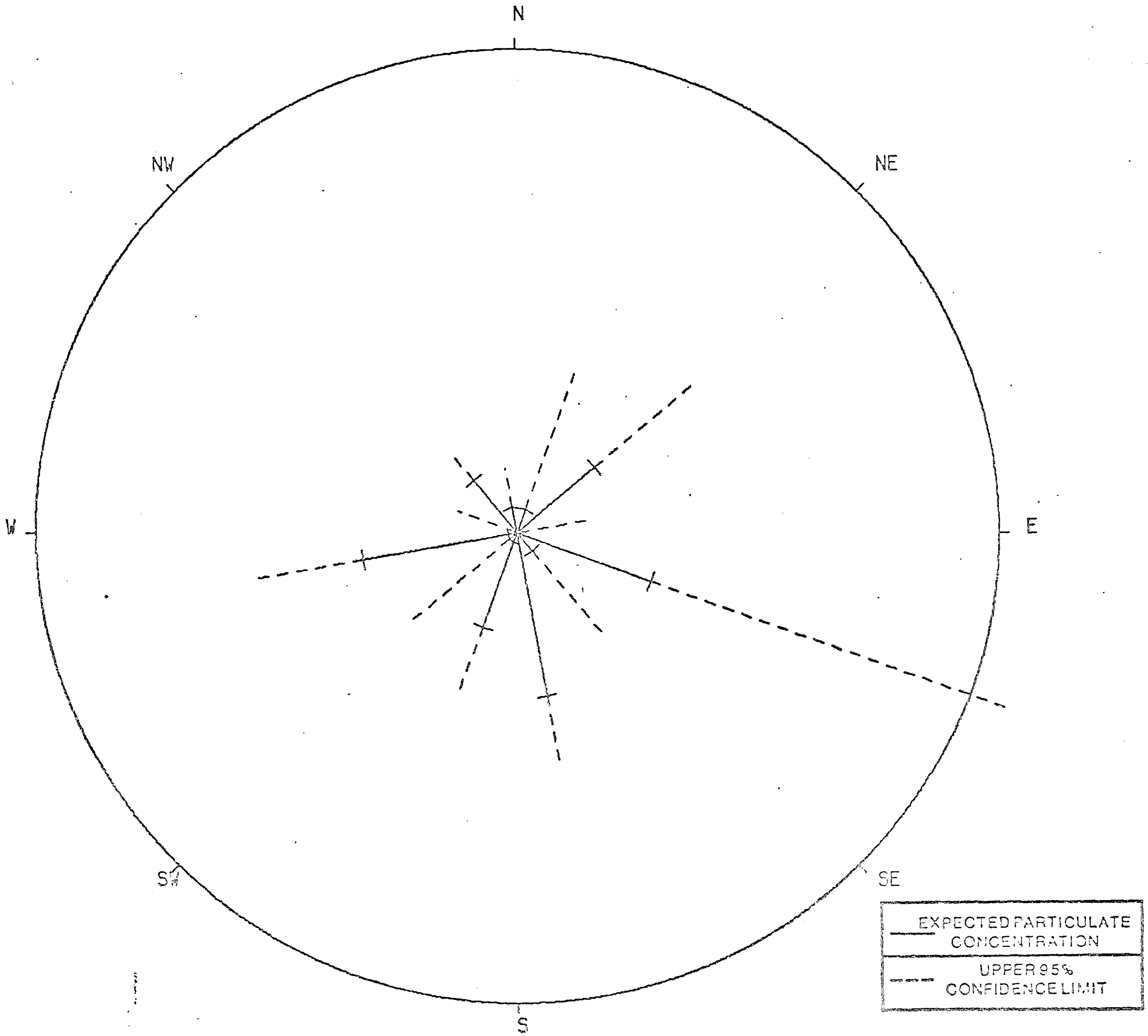
POLLUTION ROSE FOR
TOTAL SUSPENDED PARTICULATES
HOYT LAKES POLICE STATION

ALL VALUES INCLUDED

FIG. 24

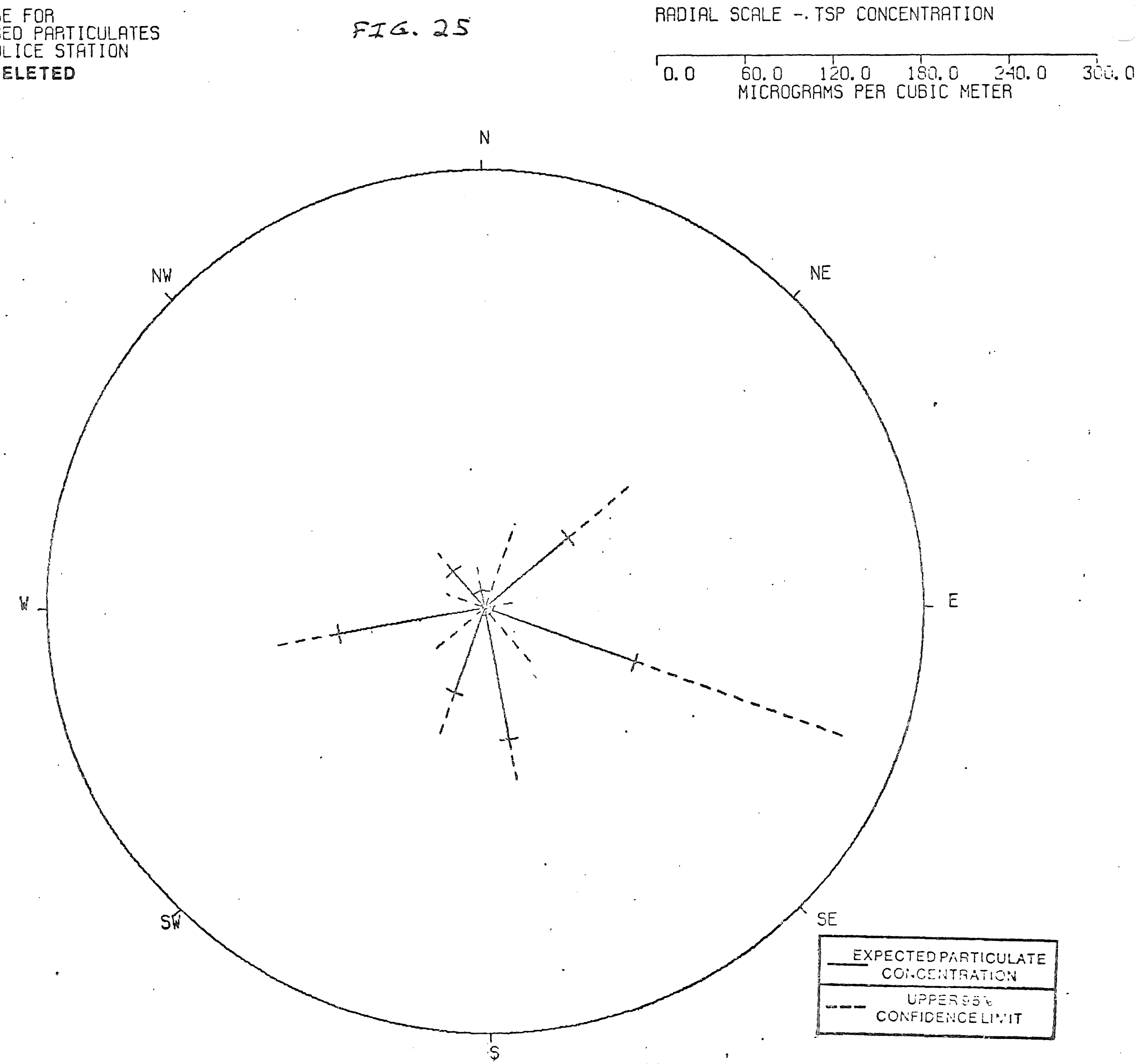
RADIAL SCALE - TSP CONCENTRATION

0.0 60.0 120.0 180.0 240.0 300.0
MICROGRAMS PER CUBIC METER



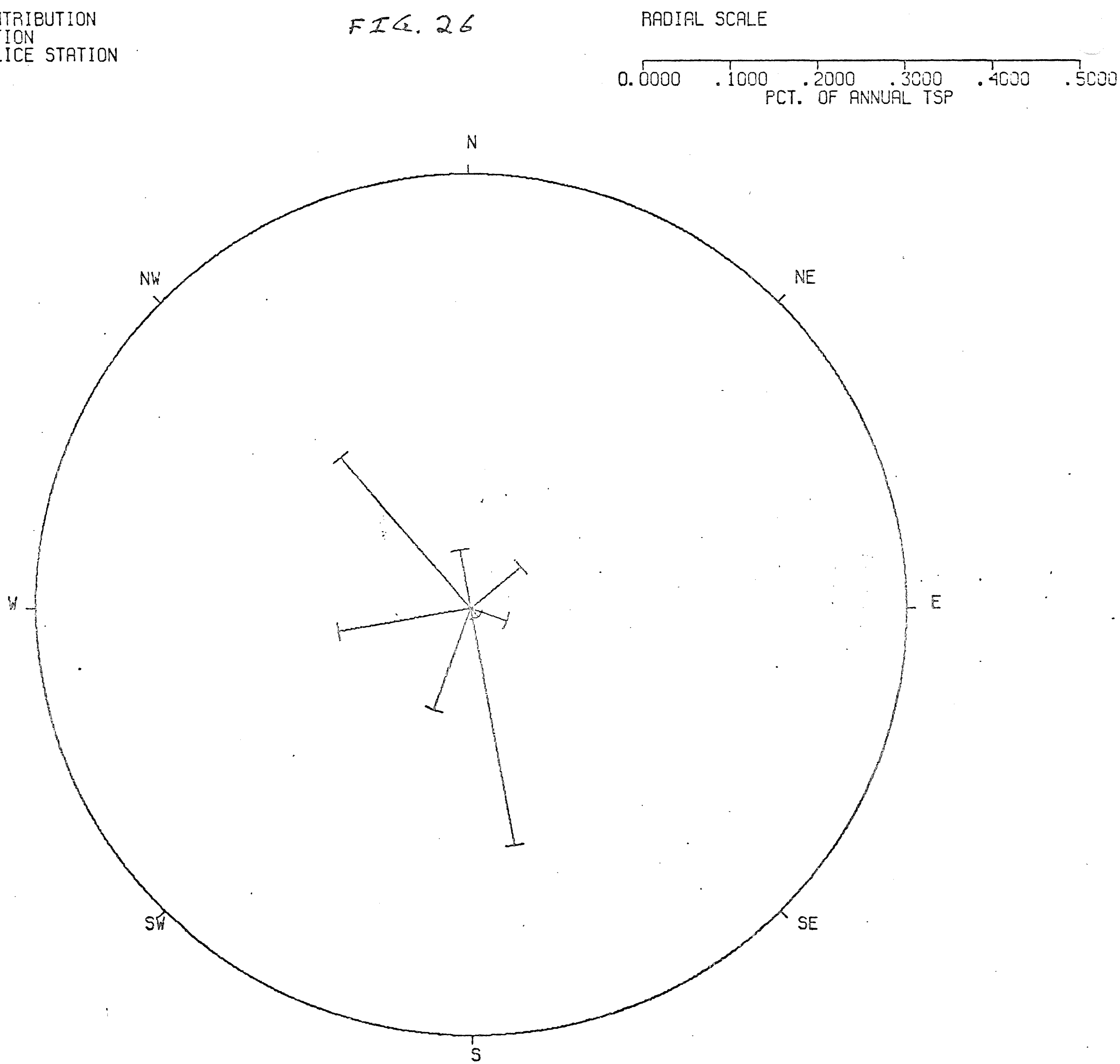
POLLUT[illegible] ROSE FOR
TOTAL SUSPENDED PARTICULATES
HOYT LAKES POLICE STATION
OUTLIERS DELETED

FIG. 25



ANNU TSP CONTRIBUTION
BY W DIRECTION
HOYT LAKES POLICE STATION

FIG. 26



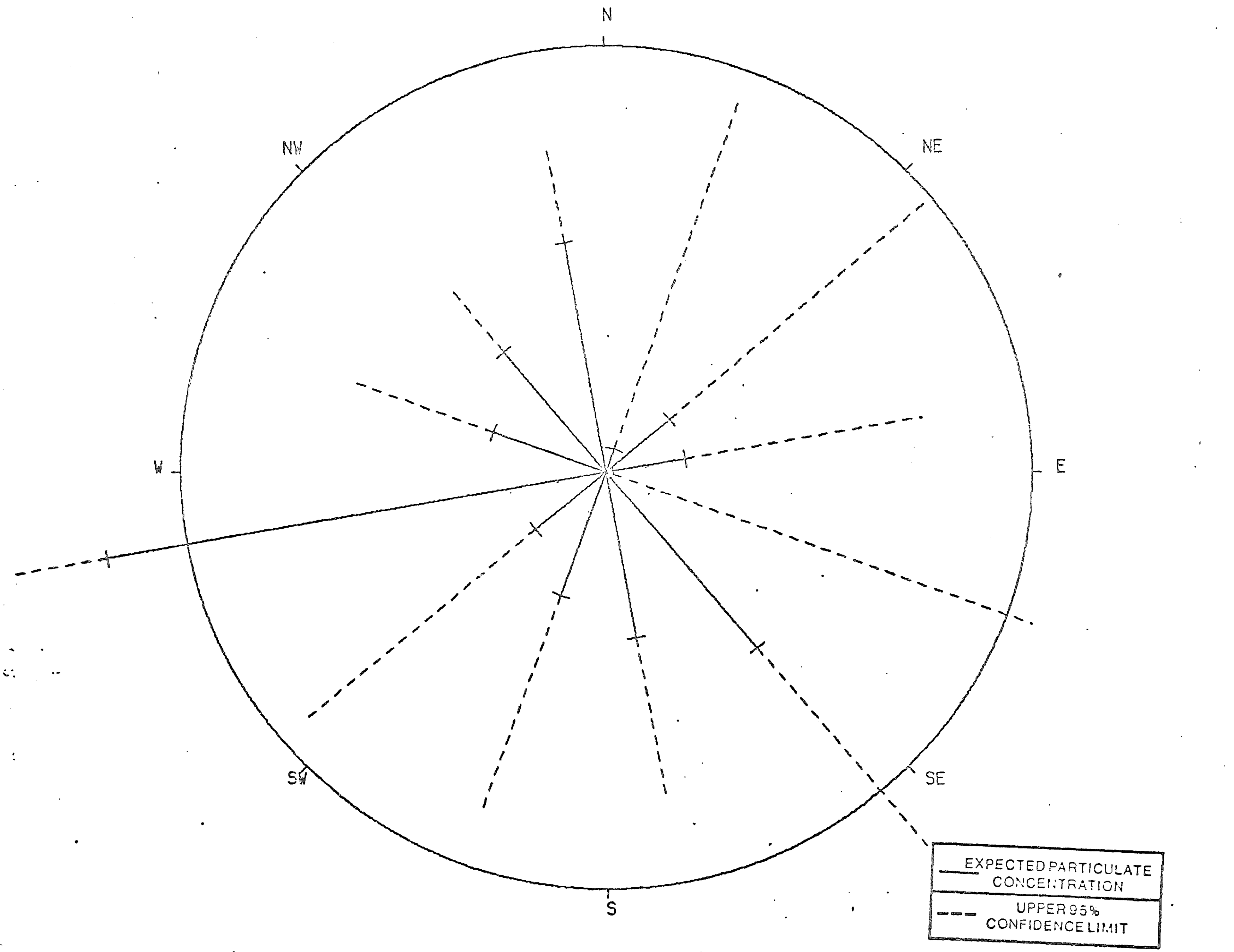
POLLUTION ROSE FOR
TOTAL SUSPENDED PARTICULATES
HOYT LAKES GOLF COURSE

FIG. 27

RADIAL SCALE - TSP CONCENTRATION

0.00 10.00 20.00 30.00 40.00 50.00
MICROGRAMS PER CUBIC METER

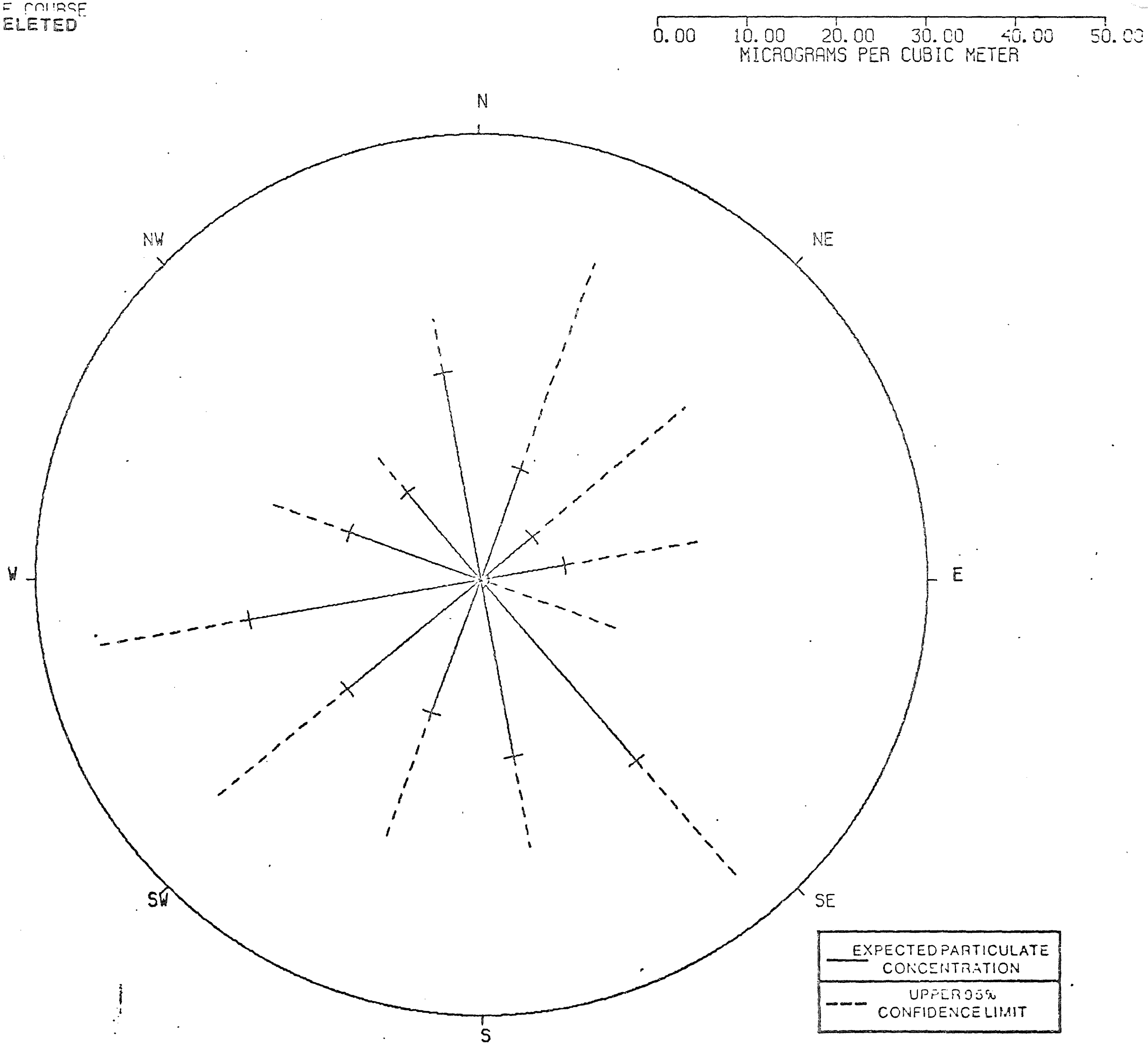
ALL VALUES INCLUDED



POLLUT[illegible] ROSE FOR
TOTAL SUSPENDED PARTICULATES
HOYT LAKES GOLF COURSE
OUTLIERS DELETED

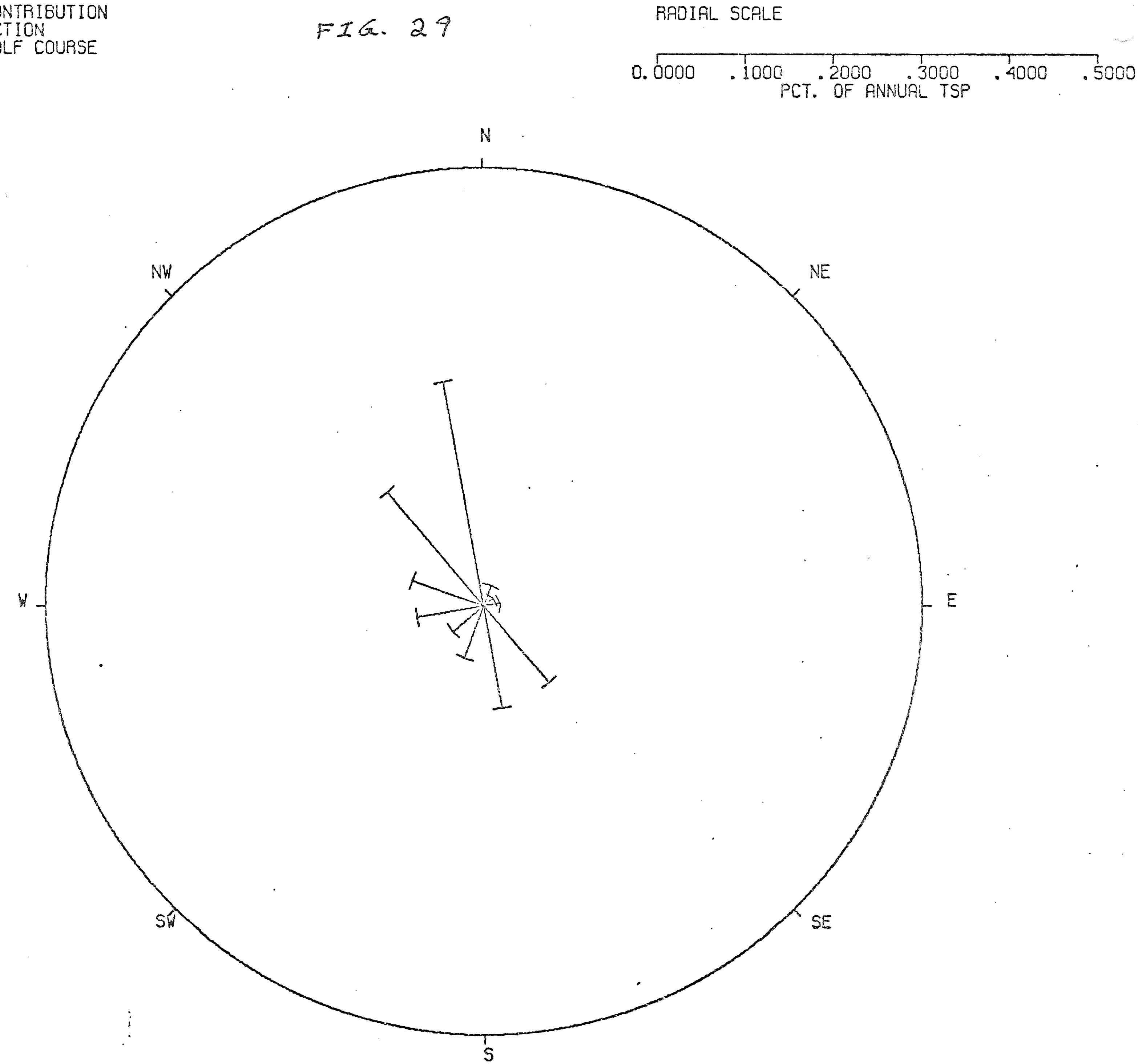
FIG. 28

RADIAL SCALE - TSP CONCENTRATION



ANNUAL TSP CONTRIBUTION
BY WIND DIRECTION
HOYT LAKES GOLF COURSE

FIG. 29



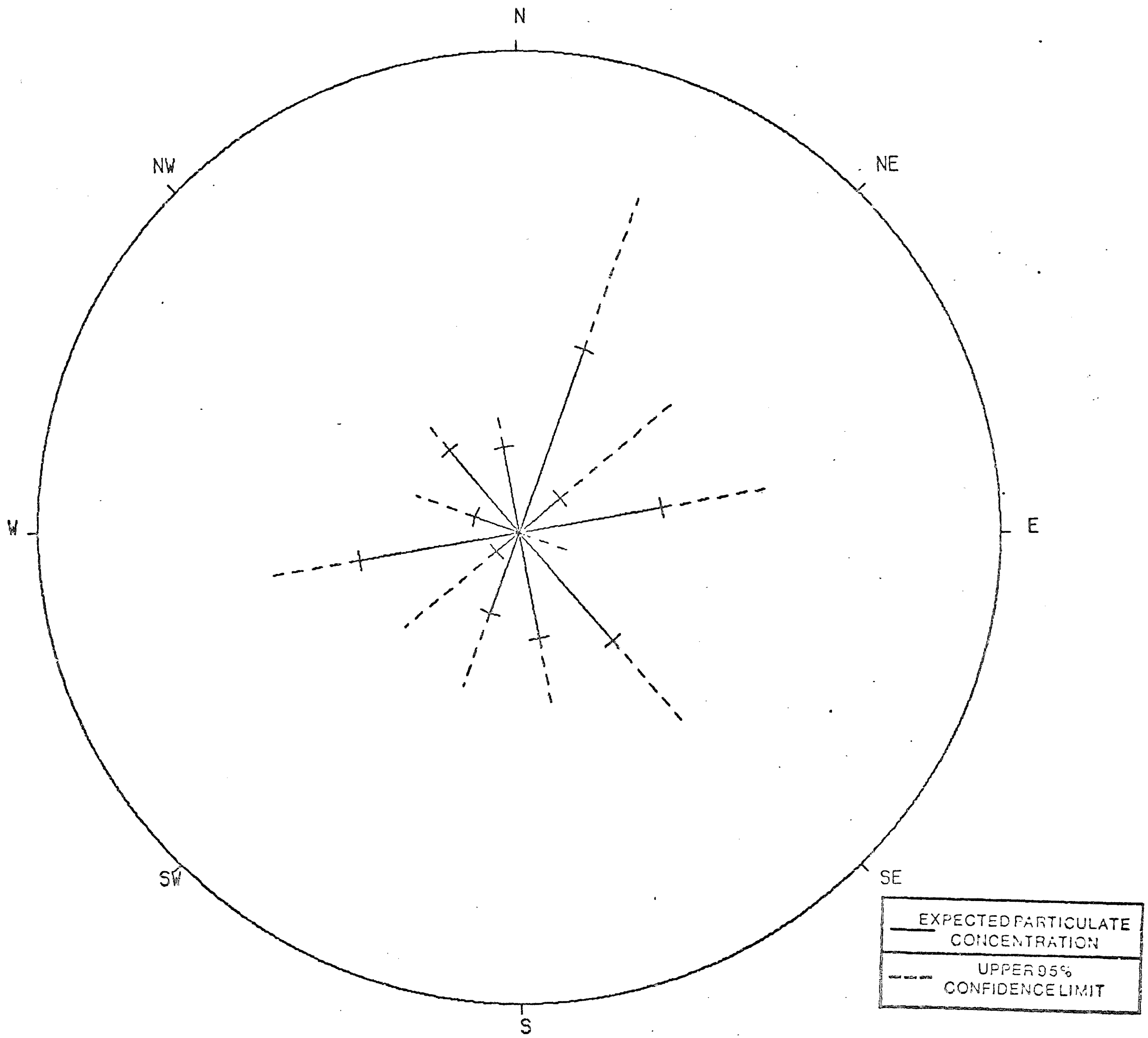
POLLUTIC OSE FOR
TOTAL SU...NDED PARTICULATES
MOUNTAIN IRON

ALL VALUES INCLUDED

FIG. 30

RADIAL SCALE - TSP CONCENTRATION

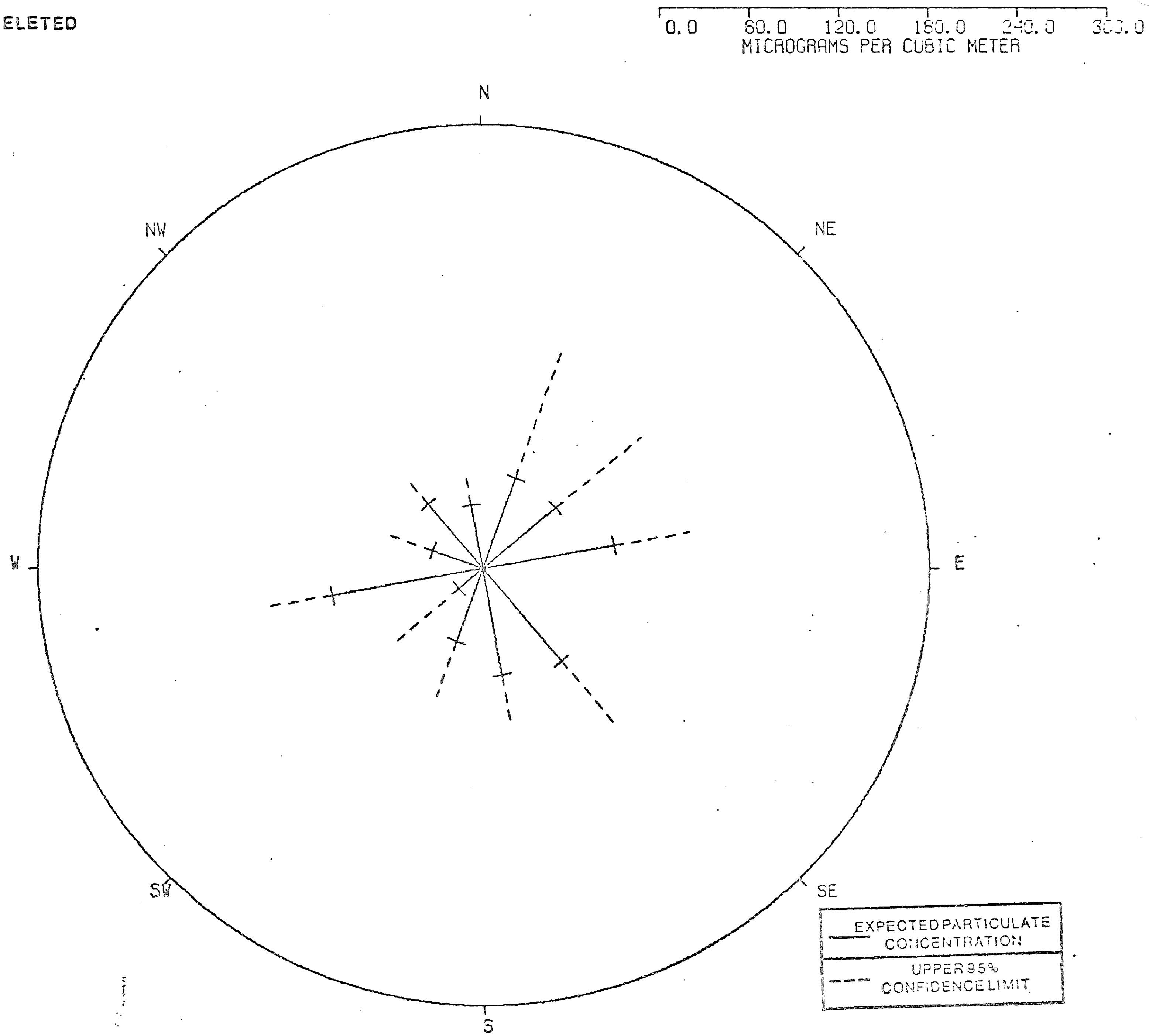
0.0 60.0 120.0 180.0 240.0 300.0
MICROGRAMS PER CUBIC METER



POLLUTION ROSE FOR
TOTAL SUSPENDED PARTICULATES
MOUNTAIN IRON
OUTLIERS DELETED

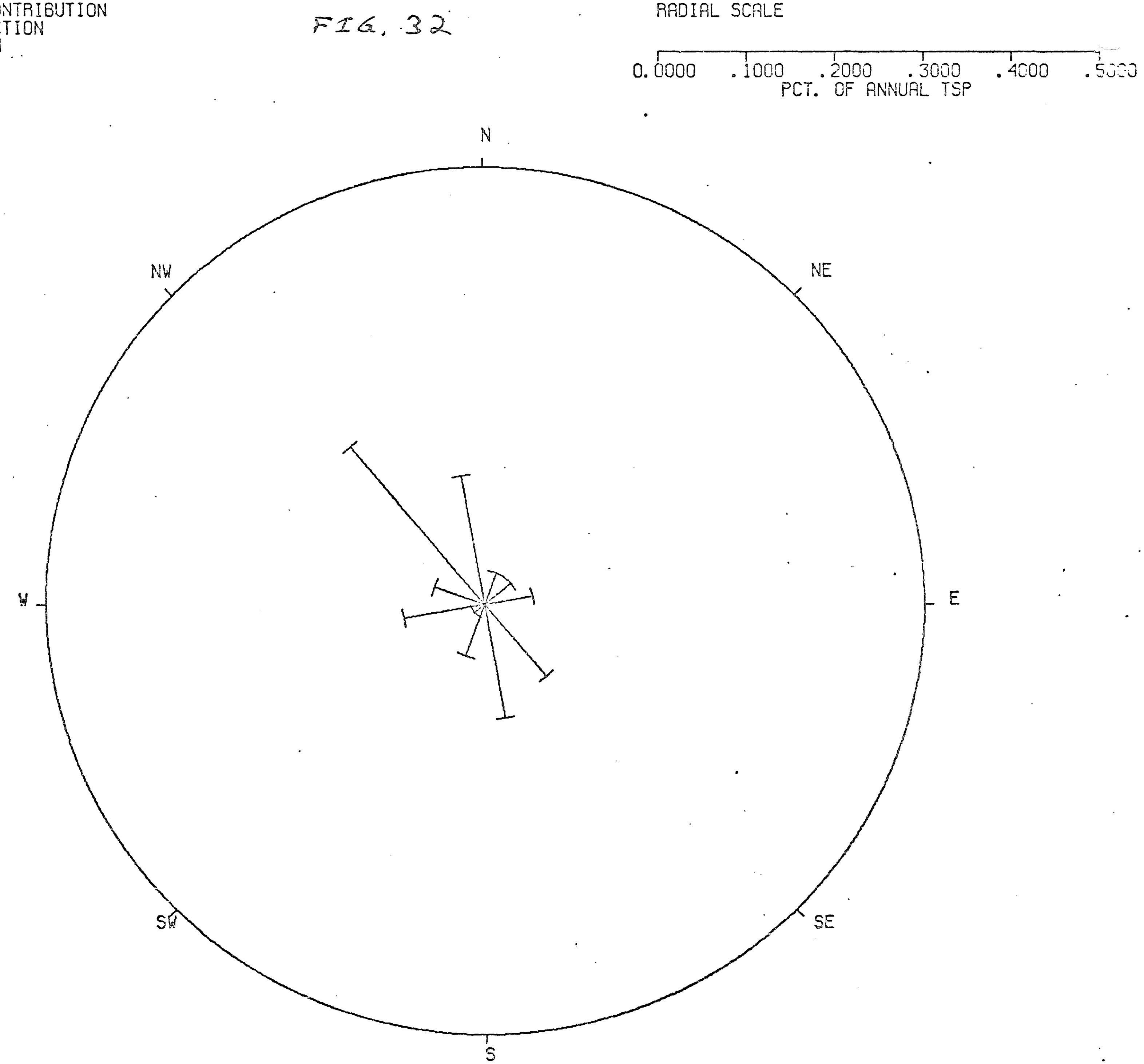
FIG. 31

RADIAL SCALE ~ TSP CONCENTRATION



ANNU TSP CONTRIBUTION
BY W DIRECTION
MOUNTAIN IRON

FIG. 32



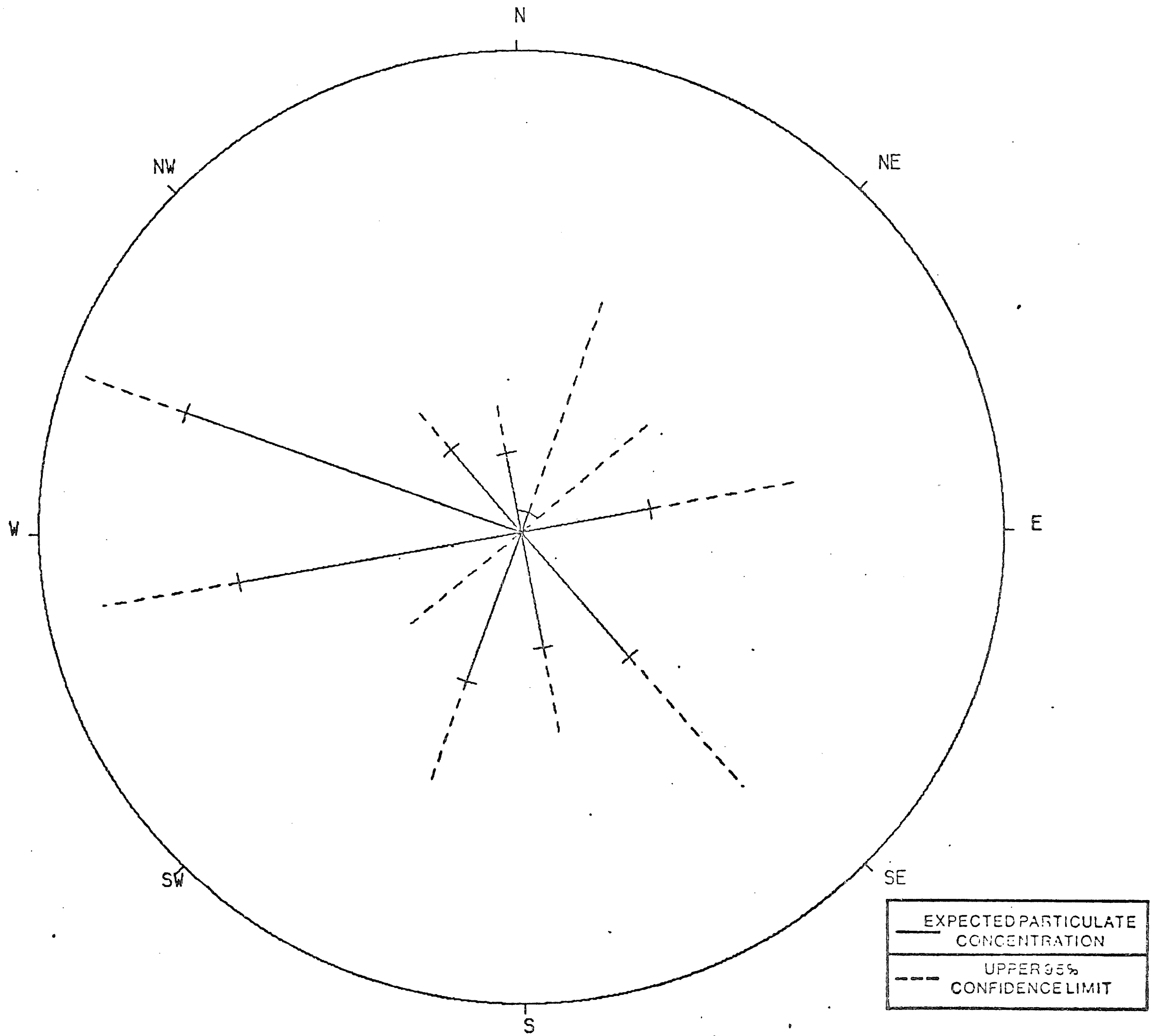
POLLUTI·N ROSE FOR
TOTAL ·PENDED PARTICULATES
VIRIGNIA

ALL VALUES INCLUDED

FIG. 33

RADIAL SCALE - .TSP CONCENTRATION

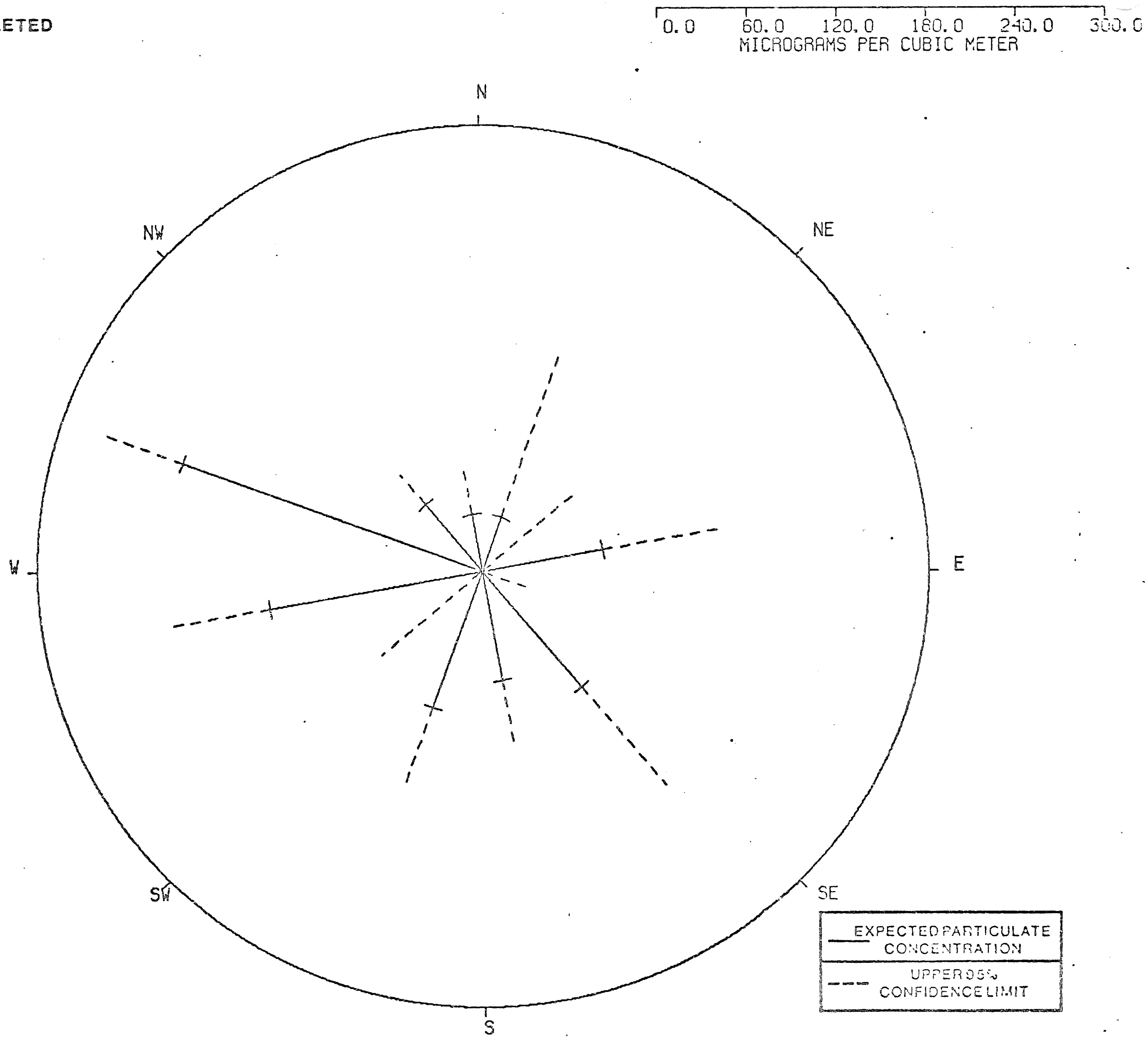
0.0 60.0 120.0 180.0 240.0 300.0
MICROGRAMS PER CUBIC METER



POLLUTION ROSE FOR
TOTAL SUSPENDED PARTICULATES
VIRGINIA
OUTLIERS DELETED

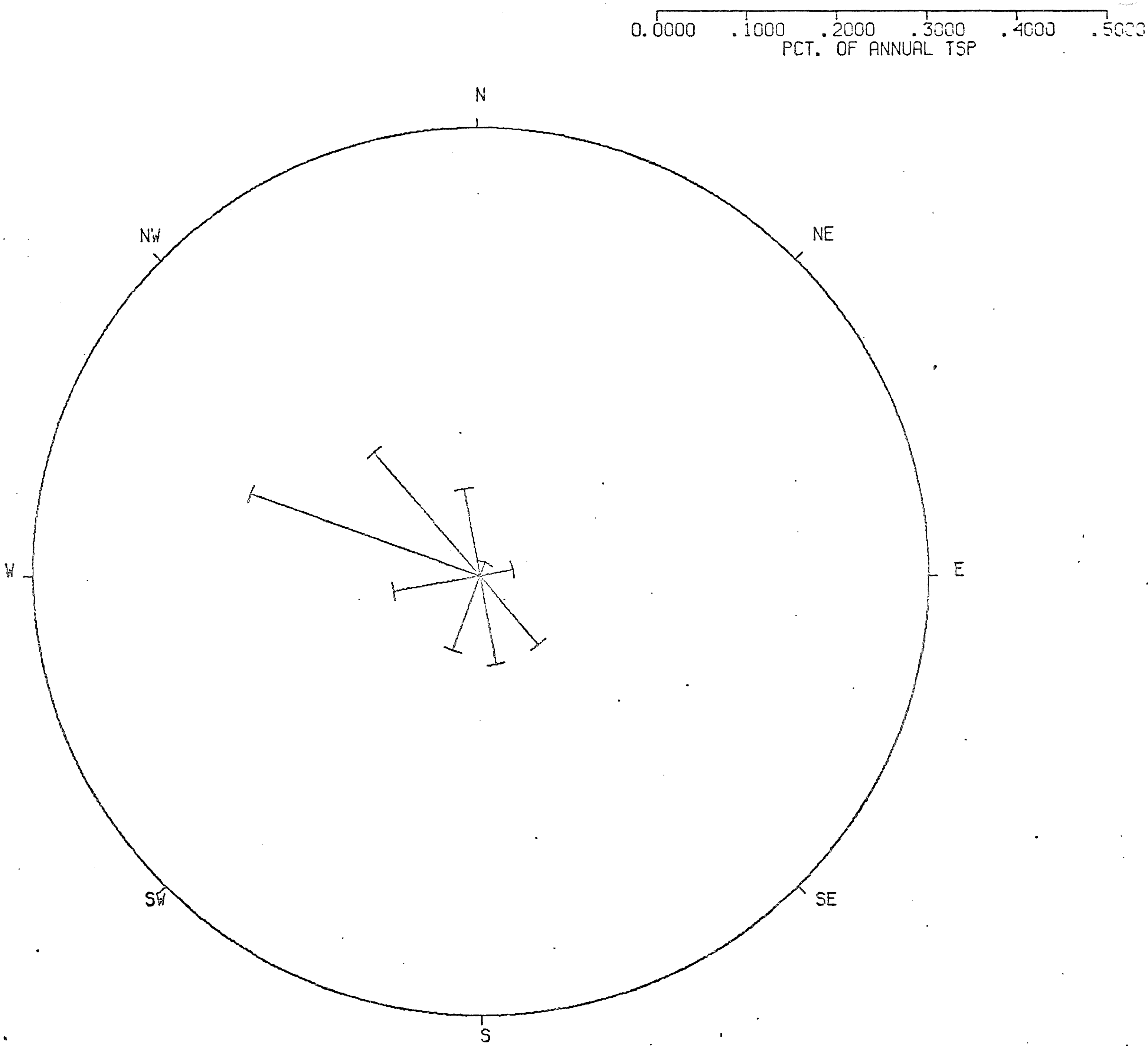
FIG. 34

RADIAL SCALE - TSP CONCENTRATION



ANNUA[illegible] TSP CONTRIBUTION
BY WI[illegible] DIRECTION
VIRGINIA

FIG. 35

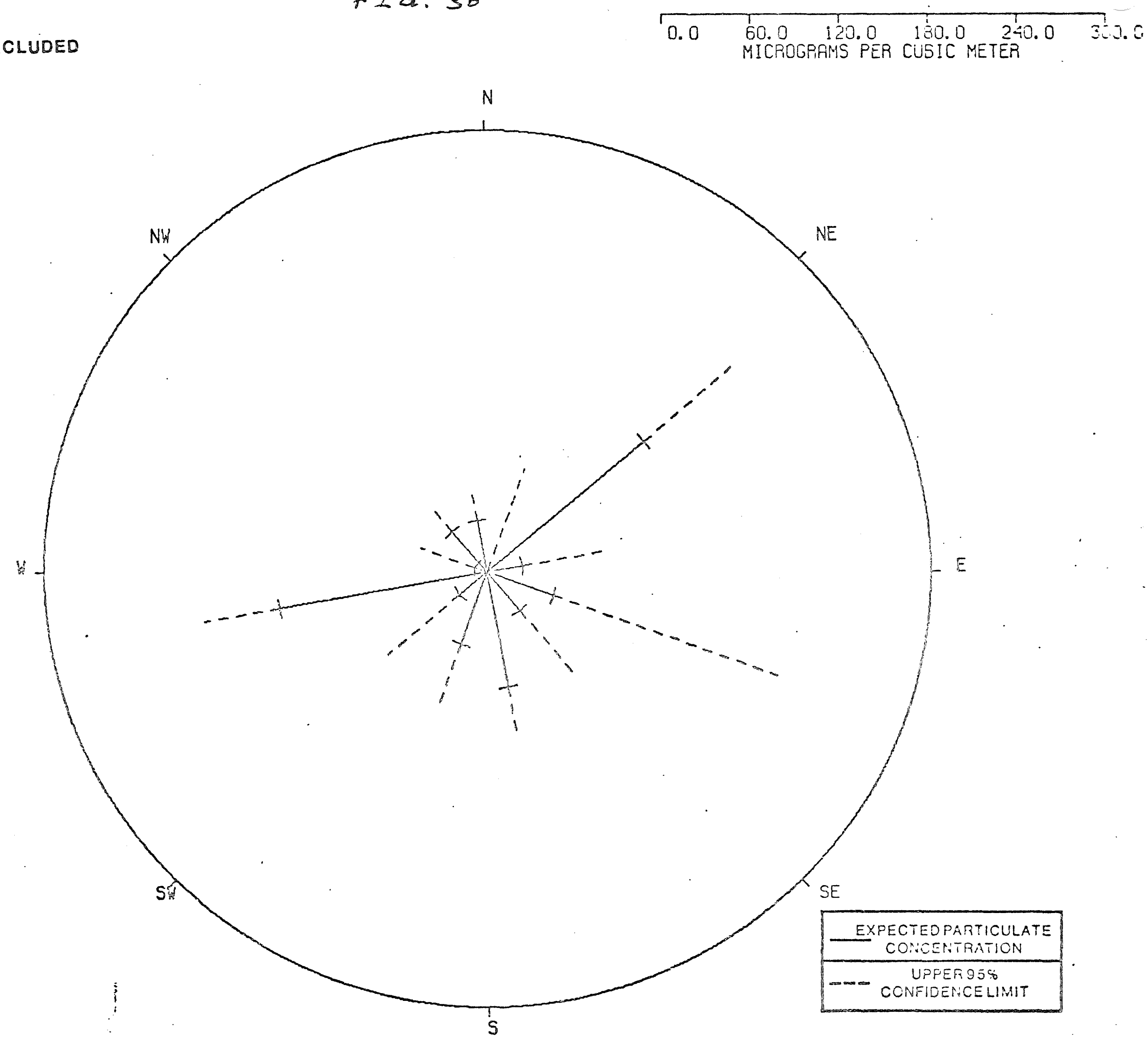


POLLUTION ROSE FOR
TOTAL SUSPENDED PARTICULATES
HIBBING

ALL VALUES INCLUDED

FIG. 36

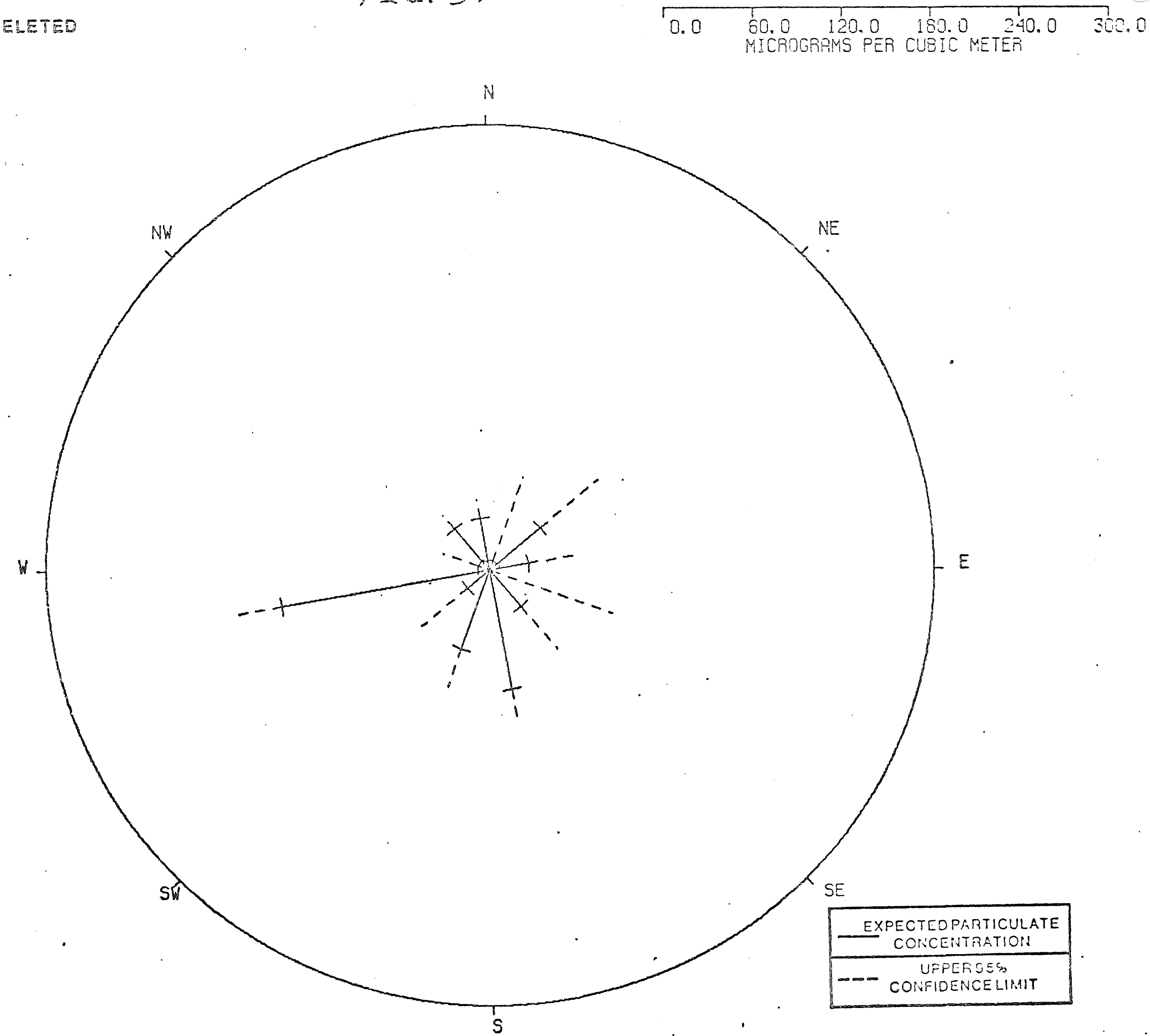
RADIAL SCALE - TSP CONCENTRATION



POLLUT' ' ROSE FOR
TOTAL 'PENDED PARTICULATES
HIBBING
OUTLIERS DELETED

FIG. 37

RADIAL SCALE - TSP CONCENTRATION

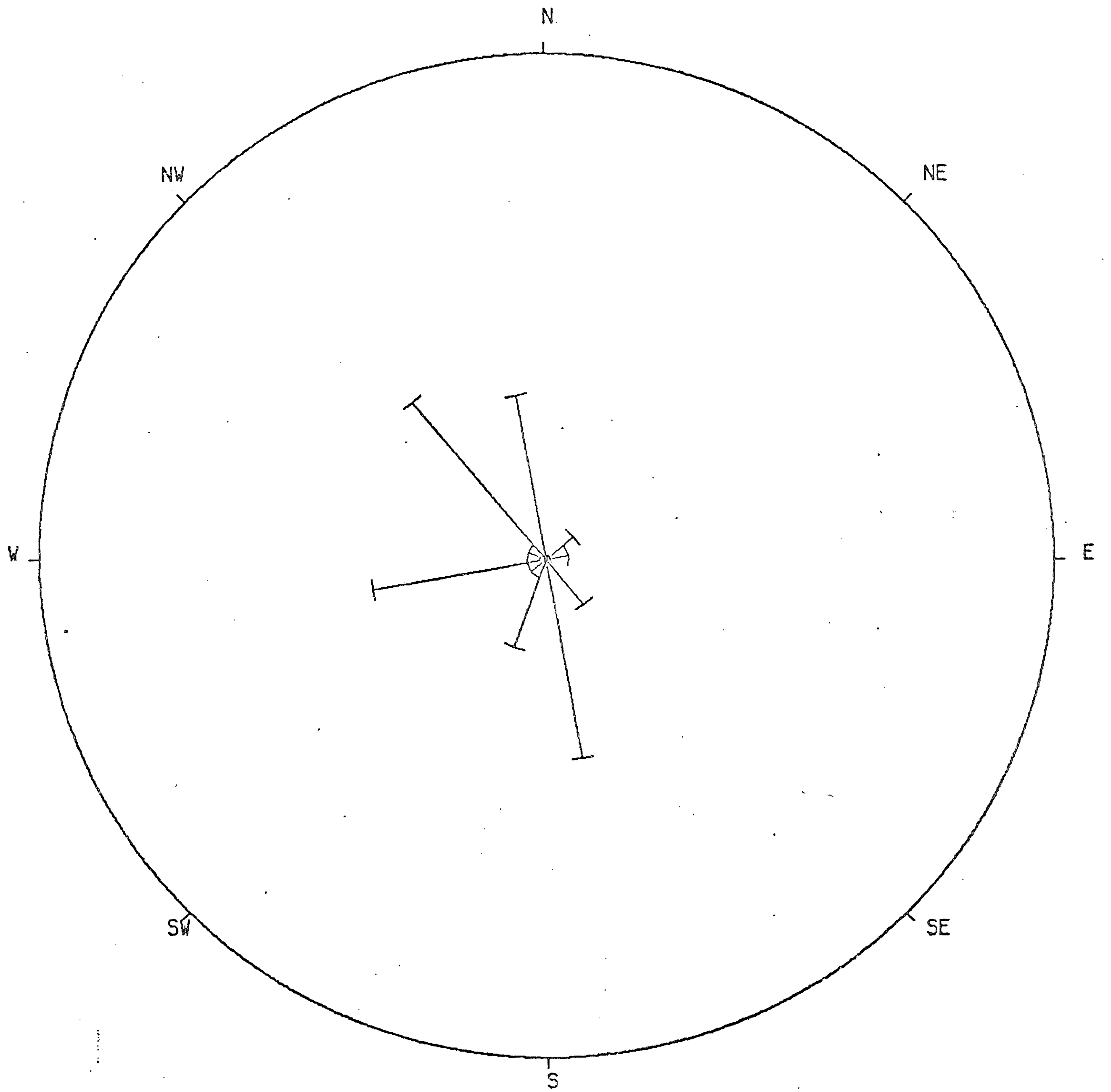


AN[illegible] TSP CONTRIBUTION
BY [illegible]D DIRECTION
HIBBING

FIG. 38

RADIAL SCALE

0.0000 .1000 .2000 .3000 .4000 .5000
PCT. OF ANNUAL TSP

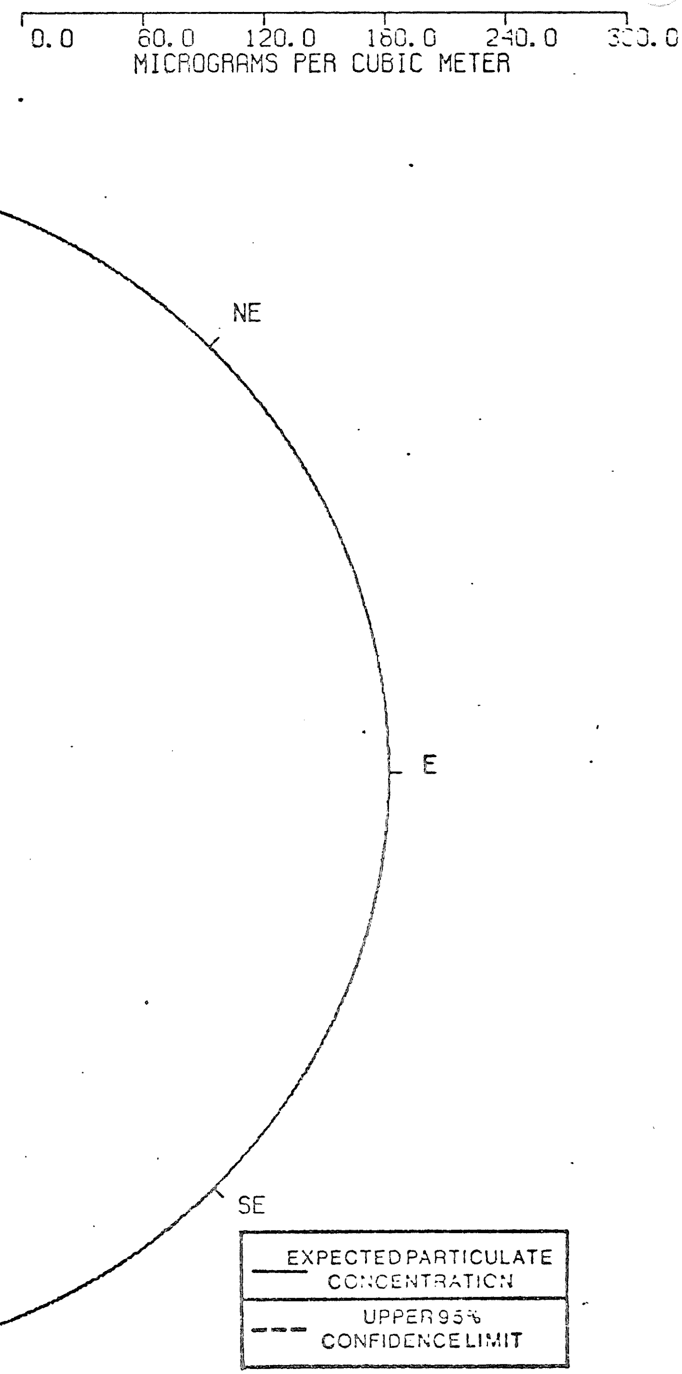


POLLUTION ROSE FOR
TOTAL SUSPENDED PARTICULATES
CU-NI STUDY AREA

ALL VALUES INCLUDED

FIG. 39

RADIAL SCALE - TSP CONCENTRATION



POLLUTION ROSE FOR
TOTAL SUSPENDED PARTICULATES
CU-NI STUDY AREA
OUTLIERS DELETED

FIG. 40

RADIAL SCALE - TSP CONCENTRATION

0.0 60.0 120.0 180.0 240.0 300.0
MICROGRAMS PER CUBIC METER

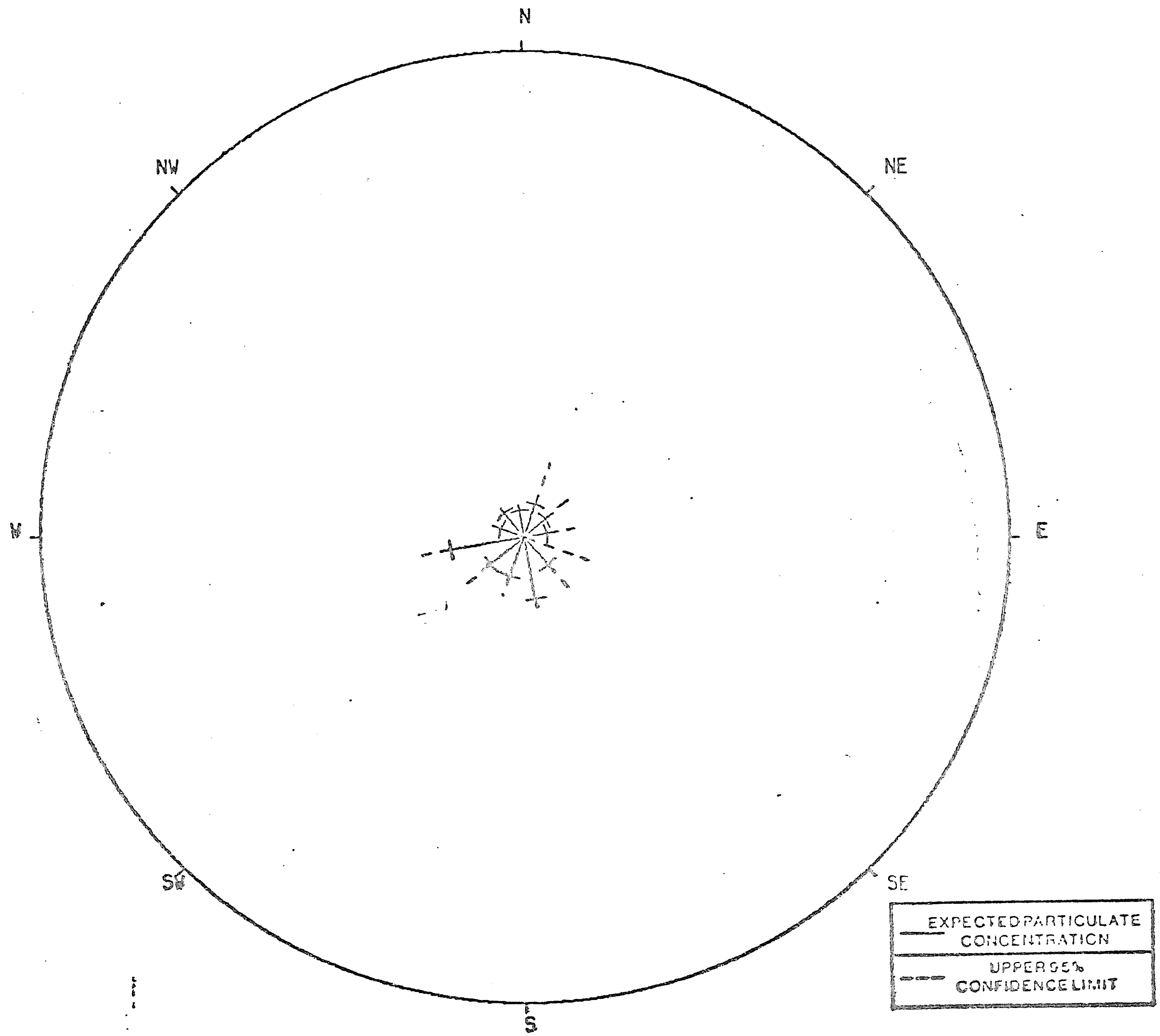


Table 1. Analysis of variance for total suspended particulates

All sites, all dates

Source	Degrees of Freedom	Mean Square	F
Days	89	0.613	13.13 ($p < .005$)
Sites	10	5.278	113.02 ($p < .005$)
Error	751	0.0467 (s^2)	

Table 2. Adjusted geometric means at TSP sample sites

All data

Site Number	Site Name	Mean TSP(ug/m^3)	Site Characteristics
7001	Fernberg Road	9.74	rural
7003	Kawishiwi Laboratory	9.83	rural
7007	Toimi	11.24	rural
7010	Hoyt Lakes Golf Course	15.56	near community
7008	Erie Mining Office	20.01	taconite mining
7006	Dunka Road	21.10	taconite mining
7002	Ely High School	22.61	community
7009	Hoyt Lakes Police Sta.	28.85	community
7516	Hibbing	37.48	community
7514	Mountain Iron	47.27	community
1300	Virginia	54.50	community
	Regional Mean	21.47	

Table 3. Potential outliers.

POINTS LYING ABOVE UPPER 1% OF DISTRIBUTION

Site	TSP (ug/m^3)	Date
Kawishiwi	150	10/15/76
Dunka Road	174	4/13/77
Dunka Road	243	4/25/77
Erie Mining Offc.	57	2/24/77
Hoyt Lakes Police	178	6/6/78
Mountain Iron	201	1/1/77
Mountain Iron	107	1/31/77
Mountain Iron	174	2/1/78
Virginia	214	2/6/77
	233	8/11/77
	189	11/15/77
	310	11/21/77
Hibbing	279	4/13/77
	76	1/26/78

POINTS LYING ABOVE UPPER 5% OF DISTRIBUTION

Site	TSP (ug/m^3)	Date
Fernberg Road	10	9/4/77
Fernberg Road	25	12/15/77
Ely High School	46	6/12/77
Ely High School	23	11/23/77
Kawishiwi Lab	119	11/2/76
Dunka Road	93	6/24/77
Dunka Road	66	10/4/77
Dunka Road	32	10/22/77
Dunak Road	39	2/13/78
Erie Mining Office	95	4/13/77
Erie Mining Office	33	2/7/78
Erie Mining Office	24	2/25/78
Hoyt Lakes Police Sta.	69	3/2/77
Hoyt Lakes Police Sta.	103	3/14/77
Hoyt Lakes Police Sta.	109	4/1/77
Hoyt Lakes Police Sta.	191	5/19/77
Hoyt Lakes Golf Course	32	1/1/77
Hoyt Lakes Golf Course	48	2/6/77
Hoyt Lakes Golf Course	22	2/25/78
Hoyt Lakes Golf Course	29	3/3/78
Mountain Iron	130	1/13/77
Mountain Iron	179	2/6/77
Mountain Iron	54	1/14/78
Mountain Iron	77	2/7/78
Mountain Iron	73	2/13/78
Mountain Iron	79	3/2/78
Virginia	151	1/19/77
Virginia	78	1/31/77
Virginia	211	6/30/77
Virginia	177	7/12/77
Virginia	114	8/5/77
Hibbing	79	12/15/77
Hibbing	45	1/14/78

Table 4. Mean TSP concentrations per time period for all sites in the Study Area.

INTERVAL	DATES	EVENT	ADJUSTED MEAN TSP (ug/m^3)
1	10/9/76-11/20/76	Start up No snow cover	51.22*
2	11/26/76-3/7/76	Snow cover	18.97
3	3/14/77-7/24/77	Mining activity No snow	35.64
4	7/30/77-10/4/77	Mine strike	14.63**
5	10/10/77	Snow event	7.23
6	10/16/77-11/9/77	Mine strike No snow cover	16.68
7	11/16/77-12/15/77	Mine strike Snow cover	13.02
8	12/21/77-3/27/78	Mining activity resumed Snow cover	15.56

*Figure is unreliable because 3 sites were completely inoperable during this period.

**The mining strike began officially on August 1, but the mines were effectively shut down as of July 30. Samples taken on July 30 were included in the strike period.

Table 5. Analysis of variance.

INTERVAL	TERM	MEAN SQUARE	DEGREES OF FREEDOM	F
1	Sites	0.3430	7	8.73 ($p<.005$)
10/9/76-	Days	0.2794	7	7.11 ($p<.005$)
11/20/76	Error	0.0393	39	
2	Sites	1.6216	10	34.72 ($p<.005$)
11/26/76-	Days	0.2546	17	5.45 ($p<.005$)
3/8/77	Error	0.0467	138	
3	Sites	1.0297	10	26.07 ($p<.005$)
3/14/77-	Days	0.3504	22	8.87 ($p<.005$)
7/24/77	Error	0.0395	178	
4	Sites	0.5708	10	27.44 ($p<.005$)
7/30/77-	Days	0.3219	11	15.48 ($p<.005$)
10/4/77	Error	0.0208	98	
6	Sites	0.3699	10	9.16 ($p<.005$)
10/16/77-	Days	0.4493	4	11.12 ($p<.005$)
11/9/77	Error	0.0404	34	
7	Sites	0.3650	10	5.08 ($p<.005$)
11/15/77-	Days	0.4055	5	5.64 ($p<.005$)
12/15/77	Error	0.0719	42	
8	Sites	1.7134	10	45.33 ($p<.005$)
12/21/77-	Days	0.2579	16	6.82 ($p<.005$)
3/17/78	Error	0.0378	155	

Table 6. Adjusted site means expressed as a percentage of regional mean for each time period.

SITE	TIME PERIOD OVERALL(%)	2	3	4	6	7	8
Fernberg Road	45	29	53	55	40	59	35
Ely High School	105	92	101	97	133	150	126
Kawishiwi Lab	46	33	47	62	43	59	41
Dunka Road	98	112	105	91	131	58	98
Toimi	52	49	55	63	60	68	43
Erie Mining Office	94	100	122	70	73	80	104
Hoyt Lakes Police	134	120	166	127	154	166	115
Hoyt Lakes Golf Crs.	72	96	65	65	52	76	65
Mountain Iron	220	365	161	164	215	72	318
Virginia	254	310	215	284	188	302	257
Hibbing	175	166	150	192	232	223	200

Table 7. Site means during each time period.

SITE	1	Snow 2	3	Mine Strike 4	6	Snow 7	8
Fernberg Road	--	5.50	18.59	8.05	6.27	7.68	5.45
Ely High School	23.17	17.45	36.00	14.19	20.85	19.53	19.61
Kawishiwi Lab	28.68	6.26	16.75	9.07	6.74	7.68	6.38
Dunka Road	44.56	21.25	37.42	13.31	20.54	7.55	15.25
Toimi	--	9.29	19.60	9.22	9.41	8.85	6.69
Erie Mining Office	53.27	18.97	43.48	10.24	11.45	10.42	16.18
Hoyt Lakes Police	--	22.76	59.16	18.58	24.15	21.61	17.89
Hoyt Lakes Golf Crs.	37.90	18.21	23.17	9.51	8.15	9.90	10.11
Mountain Iron	88.10	69.24	57.38	23.99	33.71	9.37	49.48
Virginia	116.27	58.81	76.63	41.55	29.48	39.32	39.99
Hibbing	64.54	31.49	53.46	28.09	36.38	29.03	31.12

Table 8. Correlations between study area TSP samping sites.

	7001	7002	7003	7006	7007	7008	7009	7010	7514	1300	7516
7001 Fernberg Road		.73	.83	.53	.94	.67	.56	.73	.34	.39	.38
7002 Ely High School			.45	.57	.82	.65	.63	.47	.33	.30	.48
7003 Kawishiwi Lab				.39	.91	.59	.57	.88	.34	.50	.28
7006 Dunka Road					.77	.77	.38	.58	.35	.21	.63
7007 Toimi						.77	.58	.75	.25	.45	.67
7008 Erie Mining							.66	.68	.41	.43	.67
7009 Hoyt Lakes Police Sta.								.57	.36	.28	.48
7010 Hoyt Lakes Golf Course									.59	.56	.38
7514 Mountain Iron										.35	.39
1300 Virginia											.33
7516 Hibbing											

Table 9. Correlations between study area and duluth area sites.

	7001	7002	7003	7006	7007	7008	7009	7010	7514	1300	7516
7501 Duluth	.33	.18	.11	-.01	.40	.29	.30	.14	-.08	.13	.07
7502 Duluth	.46	.36	.16	.10	.44	.34	.50	.15	.03	.19	.20
7506 Duluth Airport	.75	.60	.74	.32	.83	.52	.55	.66	.22	.35	.32
7527 Duluth West End	.25	.31	.32	.21	.27	.27	.15	.21	-.01	.23	.19
7401 Cloquet	.46	.37	.84	.32	.52	.63	.35	.74	.26	.40	.29

Table 10. Correlations between Study Area sites and Duluth sites when wind was from south for 4 or more daylight hours.

	7501 Duluth	7502 Duluth	7506 Duluth Airport	7527 Duluth West End	7401 Cloquet
7001 Fernberg Road	.49	.61	.67	.30	.63
7002 Ely High School	.33	.55	.84	.72	.74
7003 Kawishiwi Lab	.24	.36	.79	.62	.79
7006 Dunka Road	.08	.31	.67	.54	.62
7007 Toimi	.84	.84	.85	.48	.78
7008 Erie Mining	.54	.59	.87	.55	.88
7009 Hoyt Lakes Police Sta.	.70	.72	.72	.30	.67
7010 Hoyt Lakes Golf Course	.26	.31	.77	.39	.76
7514 Mountain Iron	.51	.67	.80	.76	.87
1300 Virginia	.44	.34	.33	.76	.50
7516 Hibbing	.15	.38	.63	.48	.57

Table 11. Outliers detected by pollution rose analysis.

SITE	DATE	TSP (ug/m^3)
Fernberg Road	4/25/77	33*
	5/1/77	66*
	5/13/77	56*
	5/19/77	54
Ely High School	5/1/77	73*
	5/13/77	84*
Kawishiwi Lab	10/15/76	150*
	11/2/76	119*
	5/13/77	61*
Dunka Road	4/13/77	174
	4/25/77	243*
	5/1/77	153
	5/13/77	112*
	6/24/77	93
Toimi	5/1/77	57*
	5/13/77	56*
	5/19/77	39
Erie Mining Office	4/13/77	95
	4/25/77	189*
Hoyt Lakes Police	5/19/77	191
	6/6/77	178
Hoyt Lakes Golf Crs.	10/15/76	106*
	11/2/76	109*
	5/1/77	48*
	5/13/77	69*
Mountain Iron	1/1/77	201
	2/6/77	179
	2/1/78	174
Virginia	11/2/76	367*
Hibbing	4/13/77	279
Region	10/15/76	
	11/2/76	
	4/25/77	
	5/1/77	
	5/13/77	

*Date was also outlier on regional pollution rose.

Table 12. Points detected as outliers by both analyses.

SITE	DATE	TSP (ug/m^3)
Kawishiwi Lab	10/15/76	150
	11/2/76	119
Dunka Road	4/13/77	174
	4/25/77	243
Erie Mining	4/13/77	95
Hoyt Lakes Police	5/19/77	191
	6/6/77	178
Mountain Iron	1/1/77	201
	2/6/77	179
	2/1/78	174
Hibbing	4/13/77	279

APPENDIX 3

Summaries of Directional Impacts at Individual Sampling Sites for Total Suspended Particulates

Fernberg Road (7001) -- The pollution rose shows a peak to the west-southwest, an uncommon wind direction, in the general direction of the town of Ely and the dirt road leading up to the site. A smaller peak to the south may indicate longer range transport from mining areas and more populated regions as there are no obvious local sources in these directions. The annual contribution rose shows the peak to the south to be the most important, contributing about 25% of the annual TSP.

Ely High School (7002) -- The most notable peak on the pollution rose lies to the east-southeast. However, there do not seem to be any significant local sources in this direction. A smaller peak to the west-southwest may result from emissions from the school heating plant stack. Other peaks are seen to the south, in the general direction of the eastern Iron Range. The annual contribution rose reflects the wind rose. Twenty-five percent of the annual particulate pollution at this site comes from the northwest, indicating the Ely business district as a source area. Concentrations from this direction are not high (<20 ug/m^3), but occur frequently.

Kawishiwi Laboratory (7003) -- Two peaks on the pollution rose are most noticeable, indicating sources to the south (average concentration of about 25 ug/m^3) and southwest (30 ug/m^3). These most likely indicate the nearby dirt laboratory parking lot to the southwest and the dirt road leading to the laboratory from the south. Transport from the Iron Range to the SW and distant urban sources to the south may account for a portion of these peaks, though it should be remembered that this location shows a smaller proportional decrease due to the taconite strike than did most other sites. Concentrations when the wind was blowing from the forested areas to the north, northeast and east were quite small. The annual contribution rose is again seen to reflect the wind rose, the bulk of the particulate matter coming from the south (25%) and the northwest (18%).

Dunka Road (7006) -- The pollution rose for Dunka Road shows elevated concentrations in the SW quadrant. These levels most likely result from the nearby dirt logging road and possibly from Erie Mining, more distant taconite operations, and communities. A peak from the northeast may result from Reserve Mining. The bulk of the total annual pollution comes from the north and northeast, reflecting, perhaps, dust from Dunka Road. Chemical dust control is practiced on the road but prevailing northwest winds may still make the road an important source for downwind locations.

Toimi (7007) -- The Toimi pollution rose is notable for the lack of distinct peaks. An area of higher concentration is found clockwise from the southeast to the west-northwest, indicating transport from distant roads and developed areas. The extremely low concentrations found when the wind is from the unpopulated areas to the northeast and east constitute the most notable feature.

Erie Mining Office (7008) -- The largest source indicated by the pollution rose at this site is the open pit mine located just west of the site. Other peaks are seen to the northeast and north-northeast, towards the tailings basin and processing plant. This is also in the general direction of the Reserve Mining operation, so longer range transport may be occurring. Some elevation of TSP levels is also seen to the south and southwest in the general directions of the communities of Hoyt Lakes and Aurora. Annual pollution is seen largely to come on the dominant northwest and south winds and from the mine area to the west. It should be noted, however, that Erie Mining Office is located at a gap in the Giants Range. This gap channels wind along more of a north-south axis than occurs at Hibbing, where the wind data were collected. Therefore, the peak indicated to the northwest probably represents the taconite processing facility to the north.

Hoyt Lakes Police Station (7009) -- Peaks at this site seem to reflect the influence of residential and industrial areas. The peak to the west possibly indicates the town of Aurora as well as possibly the large Iron Range cities; while peaks to the south and southwest point to the residential areas of Hoyt Lakes. These peaks may also reflect contributions from the Duluth area, as this site showed a fairly strong correlation with several Duluth sites. No obvious single soure accounts for the peak to the east-southeast, although local traffic and building sources may be the causes. The peak to the northeast is probably due to the Erie Mining operation. Over 40% of the annual particulate pollution at this site seems to come from the south. Other directions from which major contributions are made are the west and northwest.

Hoyt Lakes Golf Course (7010) -- Very few distinct features can be found on the pollution rose. Higher concentrations are found in a sector running clockwise from the southeast (from the paved road, possibly) to the west (from residential areas). The rest of the rose shows low concentrations, with the notable exception of a peak to the north towards Erie Mining. Particulates coming from this common direction comprise the most important contribution of any direction, accounting for about 25% of the annual particulate pollution at this site.

Mountain Iron (7514) -- Mountain Iron is one of the few locations with elevated concentrations coming from the northeast and north-northeast. These readings almost certainly result from the large Minntac open pit taconite mine and processing plant. Other notable features include peaks from the southeast, towards Virginia and Eveleth; the south, towards the center of Mountain Iron; and from the west-southwest, possibly resulting from the tailings basin and/or local traffic. The annual contribution rose shows that the single largest contribution again somes from the northwest, reflecting the prevailing wind. The relative infrequency of wind from the northeast minimizes the importance of the high concentrations seen from this direction.

Virginia (1300) -- Virginia recorded the highest daily level of total suspended particulates seen in the Study Region (367 ug/m^3) as well as the highest mean (54 ug/m^3). The pollution rose suggests the presence of sources in several directions, with the largest found on the dominant northwest and south wind axes. The largest peak lies to the west-northwest toward the Virginia muninicipal power plant and the Minntac operation at Mountain Iron. It is possible, in fact, that the Minntac processing plant contributes more particulate pollution to Virginia than to Mountain Iron due to the dominance of the northwest wind. Peaks also exist to the south and southeast. A large number of potential sources, including mining operations, the Virginia business district and the city of Eveleth exist in these directions.

Hibbing (7516) -- Hibbing is the largest city in the Study Area (Duluth is much larger but is outside the Study Region), yet there is very little active mining in the immediate area. It would be expected, therefore, that much of the TSP measured would come from general activity in the area. The pollution rose for Hibbing shows a large peak to the west-southwest, toward downtown Hibbing, and to the east toward the heavily traveled Highway 169. Other peaks are from the south. The annual contribution rose generally reflects the wind rose except for the strong west-southwest component.