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LAGRANGIAN MEASUREMENTS OF SULFUR DIOXIDE TO SULFATE CONVERSION RATES

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ABSTRACT

On the basis of Project MISTT data and proposed homogeneous gas phase oxidation mechanisms for sulfur dioxide, it has been suggested that the degree of mixing with background air, the chemical composition of the background air, and the intensity of the sunlight available are key factors determining the rate of sulfur dioxide to sulfate conversion. These hypotheses are examined in light of Lagrangian measurements of conversion rates in power plant plumes made during the Tennessee Plume Study and Project Da Vinci. It is found that the Lagrangian conversion rate measurements are consistent with these hypotheses. It has also been suggested that the concentration of ozone may serve as a workable surrogate for the concentrations of the free radicals involved in the homogeneous gas phase mechanism. Certain of the Lagrangian data indicate that this suggestion should be regarded with caution.

I. INTRODUCTION

Recently, Gillani and Wilson (1980) have presented evidence that plume effluent/background air interactions are of primary importance to sulfur dioxide to sulfate conversion in power plant plumes. They make a case that the character of the background air, particularly reactive hydrocarbon loading, and sunlight exposure play key roles in both aerosol and excess ozone generation in plumes. They also suggest that background ozone concentration may serve as a workable surrogate for the concentrations of the

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free radical species which are believed to be involved, but which are difficult to measure. These hypotheses are based on a presumed homogeneous gas phase oxidation mechanism involving photochemically generated free radicals, (Calvert, 1978; Eggleton, 1978), and upon observations made during Project MISTT (Wilson, 1978).

The sulfur dioxide to sulfate conversion rates cited by Gillani and Wilson are spatial averages over plume cross sections, and temporal averages over the transport time from the stack to the measurement cross section. This averaging may to some extent obscure the effects of plume-background mixing. Gillani and Wilson also cited data on the spatial distribution of aerosol and sulfur dioxide in plumes which qualitatively supports the conclusion that gaseous to particulate sulfur conversion proceeds more rapidly at the plume edge where mixing with background air is maximum. However, no quantitative conversion rates for plume edge were presented.

In the context of the Tennessee Plume Study and of Project Da Vinci (Zak, 1980) we have made a series of gaseous to particulate sulfur conversion rate measurements using a balloon-borne Lagrangian measurement platform (LAMP). These measurements include both daytime and nighttime data obtained at various positions between plume edge and plume centerline. The Lagrangian nature of the measurements eliminates some of the spatial and temporal averaging referred to earlier. An analysis of these results for the most part supports the hypotheses of Gillani and Wilson.

II. LAMP MEASUREMENTS

A. August 20, 1978

As part of the Tennessee Plume Study (TPS), two LAMP flights were made in the plume of the Cumberland Power Plant. This 2400 MWe, coal-fired TVA power plant is located on the Cumberland River near Clarksville, Tennessee. In these experiments the LAMP made use of a 10 m diameter helium-filled balloon about the size of a sport balloon. The instrumentation on the LAMP was automated, but an onboard pilot was needed to control

the balloon altitude. The LAMP experiments in support of the TPS are described in detail elsewhere (Gay, 1980).

For both flights, the LAMP was launched from a small parking lot about 400 m from the base of the 300 m tall Cumberland stacks. On August 20, the launch occurred at 1024 CDT. The structure of the winds aloft was such that the LAMP was immediately carried up into the plume, and rode embedded in the plume throughout the experiment, albeit not on plume center-line.

At the time of the launch, and for an hour or more before and after, sulfur hexafluoride tracer gas was injected into the Cumberland stacks. Syringe grab samples were periodically taken on board the LAMP, and later analyzed for SF_6 . The results are shown in Figure 1.

Throughout the flight, specially prepared Brookhaven National Laboratory (BNL) tandem filter packs were exposed to obtain simultaneous measurements of the particulate and gaseous sulfur concentrations. The behavior of the ratios of particulate to gaseous sulfur concentrations is shown in Figure 2. The ratios correspond to 2 hour time integrated measurements plotted at the midpoint of the exposure time. A fourth measurement was made after the three shown here, but it was not included in the analysis because there is strong evidence that by that time, the LAMP had come under the added influence of a downwind power plant (Johnsonville).

The particulate to gaseous sulfur ratios were analyzed according to the method described in the following section. A curve was fitted to the experimental ratios which yielded an average conversion rate of 6.4% per hour over the period 1141-1541 CDT. The period from stack emission through the first measurement was separately analyzed. Assuming a particulate to gaseous sulfur ratio of 0.01 at the stack, the conversion rate over the initial period was 0.4%/hr, which suggests that during the initial period conversion was inhibited.

The conversion rates cited above are quoted without error bars, as is customary. However, on the basis of a crude error analysis, it is felt that using the methods described here, sulfur conversion rates are

typically measured with an uncertainty of $\pm 50\%$ at about the 90% confidence level.

During this experiment, the BNL Islander instrumented aircraft was also active. Data from this aircraft were used to determine the position of the LAMP within the plume relative to the centerline (Gillani, 1978, 1979). In late afternoon some time after these conversion rate measurements were made, the LAMP was found to be at about the 50% of maximum sulfur dioxide concentration point. However, by this time, Johnsonville was already contributing to the sulfur dioxide being measured at the LAMP, so the LAMP was somewhat further out on the edge of the Cumberland plume than this fact would suggest. A comparison of the sulfur hexafluoride measurements made on the LAMP and on the BNL aircraft (Sasaki, 1979) indicates that the LAMP was at a position corresponding to no more than 1/10 of the centerline concentration in the Cumberland SF_6 plume.

The BNL aircraft also took tandem filter pack data on particulate and gaseous sulfur concentrations. The aircraft data (which did involve spatial averaging) yielded a lower conversion rate by about a factor of two (Garber, 1979).

B. August 25, 1978

On this day, the LAMP was launched at 1018 CDT from the same small parking lot near the base of the Cumberland stacks. However, the rate of ascent and the structure of winds aloft were such that the LAMP remained completely outside of the plume for the first hour or so of flight. Thereafter, the spread of the plume engulfed the LAMP, but throughout the remainder of the experiment, the LAMP was on the extreme edge of the plume. Figure 3 shows the sulfur hexafluoride data.

Figure 4 presents the particulate to gaseous sulfur ratios evaluated for the period after the LAMP had entered the plume. The curve fitted to the ratio data yields a conversion rate of 2.7% per hour. However, the calculated conversion rate from the stack to the first measurement on the extreme edge of the plume is 16.6% per hour. While this number may be high, it does suggest that on the extreme edge of the plume, the conversion of

sulfur dioxide to sulfate was not initially inhibited as it was more deeply in the plume during the August 20 experiment.

While the potential sources of error will be discussed in more detail later, it should be remarked here that the calculated conversion rate for the initial period is more sensitive to background corrections than is the fit of measured ratio data.

The spatial relationship of the LAMP to the plume just before the first whiff of SF_6 was detected was documented by the Stanford Research Institute (SRI) mobile LIDAR (Uthe, 1979). The SRI researchers comment that the LAMP was outside the plume at the time of their observation. This is consistent with both the SF_6 and the SO_2 data. The position of the LAMP relative to the plume can also be judged by the SF_6 measurements from ground level traverses made by the Cal Tech auto (Sasaki, 1979).

The BNL aircraft was also active during this experiment. Here, however, the conversion rate calculated from the fitted LAMP data was in close agreement with the BNL conversion rate results averaged over the entire plume.

C. June 8, 1976

During the summer of 1976, two long range Lagrangian experiments were launched from near St. Louis under the auspices of Project Da Vinci. These earlier experiments employed a much larger balloon (approximately 20 m diameter), and a heavier, non-automated payload (Zak, 1980). The first experiment took place under near stagnation conditions in an air mass which contained a fairly heavy burden of aged pollutants.

The LAMP was launched from a small airport about 25 km west of the St. Louis city center. Launch occurred at 0856 CDT under sunny but hazy skies. The LAMP was carried by the winds to the southeast over suburban areas until about 1200 CDT, when its altitude was increased. At that time, it rose into an elevated layer with a higher concentration of SO_2 in which it rode to the north over the metropolitan area during the afternoon. The time history of the winds aloft suggest that the source of this SO_2 may have been the Meramec power plant 18 km to the south of the point at

which the altitude increase took place. Contributions from other sources to the south, such as the Rush Island power plant (40 km), or even sources further upwind cannot be ruled out. For simplicity's sake, we assume that the dominant source of the sulfur dioxide observed was Meramec. This assumption affects only the initial calculated conversion rate, not the conversion rate obtained by fitting the data.

For the Da Vinci experiments, sulfur dioxide concentration was measured in real time as well as by the BNL tandem filter technique. The real time data were provided by a TECO pulsed fluorescence SO_2 analyzer. Zero gas readings were taken once or more every hour, and used to correct for zero drift. All concentrations used were time averages typically over 5-20 minutes. Particulate sulfur measurements were made by XRF (X-ray fluorescence) and PIXE (Proton-induced X-ray emission) analysis of filter samples, as well as by the BNL method. The ratio data presented here makes use of TECO sulfur dioxide data, and the XRF particulate sulfur data where available. In one case where XRF data was lacking (June 9), PIXE data was used. Results from the BNL measurements can thus be independently checked.

From the particulate to gaseous sulfur ratio fit (Figure 5) we obtain a conversion rate of 8.5% per hour for the period 1222-1708 CDT during which the LAMP was over the St. Louis area. With the assumption that Meramec is the source of the measured SO_2 , one obtains a conversion rate of 6.1% per hour for the period from stack emission to the first measurement (1030-1222 CDT). If further upwind sources contributed substantially, the real conversion rate would be lower.

The 8.5% conversion rate is in moderate disagreement with the conversion rate calculated by BNL from the LAMP tandem filter pack data, $\leq 4\%$ per hour, (Forrest, 1979). The author feels that at the concentration levels observed in this experiment, the uncertainties in both data sets are relatively large, and this accounts for the discrepancy. However, the author also feels that the XRF/TECO data is somewhat more reliable. During a period when SO_2 measurements made on board the LAMP would be expected to approximately agree with ground level SO_2 measurements, the TECO measurements

did, but the BNL measurements were a factor of two higher. On the July 23 flight yet to be discussed, after the experiment proper was over, the balloon ascended above the mixing layer. The TECO showed SO_2 concentrations falling to zero as expected. The XRF measurements showed the particulate sulfur concentration also falling to zero. The BNL measurements did not.

D. June 9, 1976

Later during the same flight, the LAMP overflowed the Alton-Wood River refinery area. One or more plumes were encountered, the combined effect of which led to systematically varying SO_2 concentrations from midnight through 0500 CDT on June 9.

The behavior of the particulate to gaseous sulfur ratios is shown in Figure 6. The fit of the data yields a 1.1% per hour conversion rate over the period 0213-0422.

The LAMP overflowed the refinery area at about 2100 CDT, June 8. Assuming a particulate to gaseous sulfur ratio of 0.01 at the stack, the calculated conversion rate from the stack to the first ratio measurement is 0.7% per hour.

E. July 23, 1976.

On July 23, the LAMP was launched at 0725 CDT under brisk westerly wind and clear sky conditions from the same site as for the earlier Da Vinci experiment. The LAMP overflowed the city, passing within 2 or 3 kilometers of the city center.

At launch, the LAMP was approximately 14 km to the north of the Labadie power plant plume. By 1030 CDT, the Labadie plume had spread to the point that the LAMP was beginning to be influenced by it. For the remainder of the experiment, the LAMP remained in the Labadie plume.

During the afternoon, the sulfur dioxide concentration declined in a systematic way, reflecting further dilution of the Labadie plume. The behavior of the particulate to gaseous sulfur ratio is shown in Figure 7. A fit of the ratio data yields a conversion rate of 4.4% per hour over the interval 1332-1713 CDT. The calculated conversion rate from the stack

to the initial measurement yields an average of 3.4% per hour over the period 0630-1332 CDT. Of course, both of these conversion rates apply to the extreme edge of the plume.

Chang (1979) has calculated the conversion rate for the period 1100-1700 CDT using the BNL tandem filter data taken on board the LAMP. He finds the rate to be 4.2%/hour, in good agreement with results from the TECO and XRF data.

III. METHOD OF CONVERSION RATE CALCULATION

It has long been recognized that conversion rates may be calculated from the behavior of the ratio of particulate to total sulfur concentration (Alkezweeny, 1977; Chang, 1979). This method offers the advantage that in the absence of significant background concentrations, dilution effects drop out of the calculation. This is the case under the assumption that sulfur dioxide and particulate sulfur experience the same fractional dilution -- that is, if dilution reduces the concentration of one species by 10%, it also reduces the concentration of the other by 10%. In the presence of significant background concentrations, this assumption is not valid. This difficulty is usually overcome by subtracting off the background concentrations and dealing only with plume excess concentrations. This procedure implicitly assumes that the background SO_2 is negligible. Any particulate sulfur formed from background SO_2 is ascribed to conversion of the plume excess SO_2 . As long as plume excess sulfur dioxide greatly exceeds background, this is satisfactory. However, on the plume edge or far downwind across the whole plume, wherever the ratio of plume excess to background SO_2 is not large, this procedure can introduce significant error into the calculated conversion rate.

For this reason, a different method of calculating conversion rates was sought. It was found that an analysis based on the ratio of total particulate to total gaseous sulfur did provide an appropriate means of handling dilution in the presence of background at low plume excess concentrations. Dealing with the particulate to gaseous sulfur ratio has an additional advantage. This ratio is particularly sensitive to gas to

particulate conversion, since conversion affects both the numerator and the denominator of the ratio, and is less sensitive to other processes which affect only one or the other. In general, we have found that this method is quite insensitive to assumptions about ground removal rates, background levels, etc. It can be shown that in this ratio method these factors affect the calculated conversion rate in second order. Although the method used is described in detail elsewhere (Zak, 1980), it will be outlined here.

In analogy with the ratio techniques described by Alkezweeny (1977) and by Chang (1979), a differential equation is derived to describe the behavior of the ratio of particulate to gaseous sulfur concentrations in a Lagrangian volume. The solution to that equation is given by:

$$r(t) = -\gamma/(\gamma + \Delta\Delta) + \{r_0 + \gamma/(\gamma + \Delta\Delta)\} \exp\{(\gamma + \Delta\Delta)t\} \quad [1]$$

here r = concentration of particulate sulfur/concentration of gaseous sulfur, both expressed in μg sulfur per m^3 .

r_0 = initial value of r

γ = conversion rate

$\Delta\Delta = \Delta\beta + \Delta D$

here $\Delta\beta = \beta_g - \beta_p$; the ground deposition rate for gaseous sulfur minus the ground deposition rate for particulate sulfur.

Also $\beta_i = 36v_i/H$, where v_i = deposition velocity in cm/sec, and H = mixing height in meters for either gaseous or particulate sulfur.

ΔD = fractional rate of dilution of gaseous sulfur minus the fractional rate of dilution of particulate sulfur.

If background is negligible, or if this expression is applied to plume excess concentrations, ΔD may be taken to be zero, and dilution drops out. If, however, background is significant, ΔD must be calculated. Since the method for calculating ΔD is somewhat involved, the reader is referred to the detailed discussion cited earlier (Zak, 1980). The value of ΔD is assumed to be constant over the period of analysis and is set equal to its calculated average value over the period of interest. Once ΔD is obtained, the expression given in Equation 1 is used to fit a series of

particulate to gaseous sulfur ratio measurements. The conversion rate, γ , and the initial ratio, r_0 , are the fitting parameters.

If one chooses to evaluate the conversion rate from only two experimental ratios as was done for the initial periods from stack to first in-plume ratio measurement, fitting is inappropriate. Instead, one can use the equivalent expression given below to evaluate γ :

$$\gamma = \frac{\phi}{\Delta t} \ln \left\{ \frac{r_2 + \phi}{r_1 + \phi} \right\} \quad [2]$$

here

$$\phi = \gamma / (\gamma + \Delta \Delta)$$

$$r_1 = r \text{ at time } t_1$$

$$r_2 = r \text{ at time } t_2$$

$$\Delta t = t_2 - t_1$$

This expression is solved iteratively for a self-consistent value of γ . It is found that this expression for γ is quite insensitive to ϕ , and hence to the initial guess for γ . Thus the iteration converges rapidly.

For the initial period, we apply this expression to plume excess concentrations, taking $\Delta D = 0$. This cannot be avoided because, for this period, there is insufficient information available to calculate the ΔD required for applying this method to total concentration ratios. Thus the plume excess ratios and the calculated conversion rates are sensitive to the measured background concentrations used in determining them. In some cases, we have employed the concentrations measured before the LAMP encountered the plume as background data. In other cases, we have used out-of-plume aircraft measurements. A difficulty arises in that the analysis depends upon the implicit assumption that so-called "background" is spatially homogeneous, whereas in fact, background consists of the residue of far upwind source plumes, and it is not necessarily homogeneous. This difficulty is somewhat ameliorated in Lagrangian experiments, provided that the background used is that present in the volume of air in which the LAMP was embedded prior to influence by the source under study.

For afternoon convective periods, we used a sulfur dioxide deposition velocity of 1 cm/sec (Garland, 1978). For the June 9 nocturnal period, v_g was taken to be zero. For all calculations, v_p was set at $0.1 v_g$. For the Tennessee Plume Study experiments, we used an afternoon mixing height of 1 km (Gillani, 1979b). For the Da Vinci experiments, we used an afternoon mixing height of 2 km (Zak, 1980). In all cases, the precise choice of deposition parameters over a plausible range had little influence on the calculated conversion rates.

As long as the assumption is valid that plume excess sulfur dioxide and plume excess particulate sulfur dilute at the same fractional rate, the major sources of uncertainty in the calculated conversion rate are uncertainties in the measurements of the concentrations themselves. Fitting the expression in Equation 1 to several measured ratios reduces the impact of random measurement error. It should be noted, however, that the assumption of equal fractional dilution is probably not strictly valid. If the conversion rate does vary over the plume cross section as these and other results suggest, then the cross-sectional shape of the plume in SO_2 and in particulate sulfur will be different. Consequently, their concentration gradients will differ, and hence, their rates of dilution. Our crude error analysis includes an allowance for an arbitrarily assigned $\pm 50\%$ difference in the relative rates of dilution of gaseous and particulate sulfur. This provides a major contribution to the assigned $\pm 50\%$ uncertainty on γ at the 90% confidence level.

IV. DISCUSSION OF RESULTS

A summary of the conversion rates obtained by the LAMP under various conditions is presented in Table I. These results should be compared with the MISTT aircraft results presented by Gillani and Wilson (1980) in their Table I. In some 17 measurements, they found an average daytime conversion rate of 1.3% per hour. The average daytime conversion rate observed by the LAMP was 6.1% per hour. Even if one confines one's attention to the more reliable conversion rates obtained from the fitted data, one obtains

an average conversion rate of 5.5% per hour. This is about four times the average rate observed by Gillani and Wilson.

The difference between the average LAMP result and the average aircraft result can be accounted for in terms of the factors identified by Gillani and Wilson. First, and probably most importantly, the LAMP data is essentially characteristic of plume edges, with high background air to plume effluent mixing ratios, whereas the aircraft data is averaged over the entire plume cross section. For the one period in which the LAMP experienced a much lower background air to plume effluent mixing ratio, the observed conversion rate was much lower (0.4% per hour). Secondly, the nature of the background air encountered during the LAMP experiments favored more rapid conversion according to the criteria of Gillani and Wilson. The average background ozone concentration measured was about 105 ppb, whereas for the MISTT experiments, the average ozone concentration was about 70 ppb. Finally, the daytime periods over which conversion rates were measured by the LAMP either included, or were limited to the mid-day periods during which both irradiation and mixing were maximum, whereas the MISTT data includes early morning measurement periods which yielded below average conversion rates about equal to the nighttime rate observed by the LAMP.

It should be noted that the conversion rates measured by the LAMP in power plant plumes on plume edges are quite similar to conversion rates measured by aircraft in urban plumes (Miller, 1980). In fact, in at least two cases, the power plant plumes measured by the LAMP were embedded in an urban plume (6/8 and 7/23/76). This, too, is consistent with the Gillani and Wilson hypotheses in that in urban plumes, typically the mixing ratio of background air to effluent is quite high, as is the reactive hydrocarbon loading.

The LAMP nighttime conversion rate measurements, however, indicate that one suggestion of Gillani and Wilson should be taken with some caution. Gillani and Wilson suggest that ozone concentration could serve as a workable surrogate for the concentrations of the free radicals involved in the homogeneous gas phase oxidation of sulfur dioxide. The nighttime data indicate that although the oxidation rate falls markedly in the

absence of sunlight, the ozone concentration remains high. This is consistent with a photochemical source for the free radicals which is inoperative in the absence of UV radiation, and a different primary conversion mechanism operative at night. Although it is obvious that at night, ozone concentrations cannot be used as a surrogate for the pertinent free radical concentrations, there are likely many other situations in which the correlation is poor. Because ozone has an extremely long lifetime under fair weather conditions (Zak, 1980), high concentrations can persist long after the conditions favoring free radical generation have ceased to exist.

TABLE 1

CONVERSION RATES AND ATTENDANT CONDITIONS MEASURED BY LAMP

Experiment	Rate	Time	Plume Age	Excess SO ₂	Solar Irradiation ^a	O ₃ Conc. ^b	Temp. ^c	Rel. Hum. ^c	NMHC ^d	Comments
	(%/hr)	(CDT)	(hrs)	(ppb)	Ly/min	(ppb)	(°C)	(%)	ppm C	
<u>8/20/78</u>										
*Stack to 1st meas.	0.4%	1024- 1141	0 - 1.3	Stack - 480	1.0	-	20°	63%	0.9	mostly sunny
*Fitted ratio series	6.4%	1141- 1541	1.3 - 5.3	480 - 30	1.2	135	22°	58%	0.8	mostly sunny
<u>8/25/78</u>										
*Stack to 1st meas.	16.7%	1018- 1208	0 - 1.8	Stack - 20	.95	-	26°	42%	0.4	mostly sunny
*Fitted ratio series	2.7%	1208- 1535	1.8 - 5.3	20 - 14	.95	105	21°	35%	0.6	mostly sunny
<u>6/8/76</u>										
*Stack to 1st meas.	6.1%	1030- 1222	0 - 1.9	Stack - 10	1.2	95 - 120	-	-	-	sunny with haze

TABLE 1 (cont'd)

Experiment	Rate	Time	Plume Age	Excess SO ₂	Solar Irradiation ^a	O ₃ Conc. ^b	Temp. ^c	Rel. Hum. ^c	NMHC ^d	Comment
	(%/hr)	(CDT)	(hrs)	(ppb)	Ly/min	(ppb)	(°C)	(%)	ppm C	
*Fitted ratio series	8.5%	1222-1708	1.9 - 6.6	10 - 2	0.9	120 - 150	14°	70%	-	sunny with haze
<u>8/9/76</u>										
*Stack to 1st meas.	0.7%	2100-0213	0 - 5.2	Stack - 50	0	150	20°	53%	-	night
*Fitted ratio series	1.1%	0213-0422	5.2 - 7.4	50 - 35	0	150	20°	53%	-	night
<u>7/23/76</u>										
*Stack to 1st meas.	3.4%	0630-1332	0 - 7	Stack - 8	-	50 - 80	-	-	-	clear
*Fitted ratio series	4.4%	1332-1713	7 - 10.7	8 - 2	-	80 - 95	-	-	-	clear

- ^aFor the TPS experiments, the solar irradiation data was provided by the Tennessee Valley Authority, Gillani (1979b); for the 6/8/76 Da Vinci flight, this data was abstracted from Decker (1978).
- ^bFor the TPS experiments, the ozone data was provided by Brookhaven National Laboratories instrumented aircraft (Gillani, 1979a); for the Da Vinci experiments, it was provided by Sandia National laboratories onboard instrumentation (Zak, 1980).
- ^cFor the TPS experiments the LAMP temperature and relative humidity data were provided by Sandia National Laboratories in collaboration with the University of Denver; for the Da Vinci experiments, it was provided by Sandia in collaboration with the Atmospheric Sciences Laboratory and the University of Texas at El Paso.
- ^dThe non-methane hydrocarbon data comes from analysis of grab samples by the Research Triangle Institute taken on board the LAMP (Gay, 1980).

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CAPTIONS

- Figure 1 Sulfur hexafluoride concentration measured onboard the LAMP versus time during 8/20/78 experiment. SF_6 GC analysis courtesy of F. Shair of California Institute of Technology.
- Figure 2 Ratio of concentration of particulate sulfur to concentration of sulfur in form of sulfur dioxide observed on LAMP during 8/20/78 experiment. Data from analysis of BNL tandem filter packs.
- Figure 3 Sulfur hexafluoride concentration measured onboard LAMP versus time during 8/25/78 experiment. SF_6 GC analysis courtesy of F. Shair of California Institute of Technology.
- Figure 4 Ratio of concentration of particulate sulfur to concentration of gaseous sulfur observed on LAMP during 8/25/78 experiment. BNL filter pack data.
- Figure 5 Particulate to gaseous sulfur ratios measured on LAMP during 6/8/76 experiment. XRF analysis of filters for particulate sulfur courtesy of R. Giauque of Lawrence Berkeley Laboratory.
- Figure 6 Particulate to gaseous sulfur ratios measured on LAMP during 6/9/76 experiment. PIXE analysis of "streaker" samples for particulate sulfur courtesy of J. Winchester of Florida State University.
- Figure 7 Particulate to gaseous sulfur concentration ratios measured on LAMP during 7/23/76 experiment. XRF analysis of filters for particulate sulfur courtesy of R. Giauque of Lawrence Berkeley Laboratory.

LAMP SF6 TRACER MEASUREMENTS

8/20/78 SULFUR MOLE RATIOS (SO_4/SO_2)

fig 2.

LAMP SF6 TRACER MEASUREMENTS

8/25/78 SULFUR MOLE RATIOS (SO₄/SO₂)

6/8/76 SULFUR MOLE RATIOS (SO4/SO2)

6/9/76 SULFUR MOLE RATIOS (SO₄/SO₂)

7/23/76 SULFUR MOLE RATIOS (SO₄/SO₂)