AIRBORNE OBSERVATIONS OF A SUMMERTIME, GROUND-BASED TRACER GAS RELEASE

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Abstract. Two research aircraft were equipped with real-time sulfur hexafluoride analyzers in support of the North Dakota/NOAA 1987 summertime weather modification research program. Sulfur hexafluoride (SF_6) was released from a ground location and the plume was detected by both aircraft on several downwind transects. The SF_6 plume was tracked to near the base of a developing thunderstorm by one of the research aircraft. Calculations were made of what the concentration of silver iodide (AgI) seeding material would have been had a seeding generator been operated concurrently with the SF_6 release. These calculations utilized the SF_6 release rate, an assumed AgI release rate, and the observed SF_6 concentrations.

1.0 INTRODUCTION

North American Weather Consultants (NAWC) has been a participant in the North Dakota/National Oceanic and Atmospheric Administration (NOAA) weather modification research program since 1981. This research is part of the larger NOAA/State research weather modification program being conducted in four states (Illinois, Nevada, North Dakota, Utah) described in Reinking (1985).

Part of the work in North Dakota has been concerned with the conduct of atmospheric tracer studies. These studies have been designed to study the transport and diffusion of a tracer gas, sulfur hexafluoride (SF_6), in summertime cumulus clouds. SF_6 is a manmade material used primarily as an electrical insulating gas for high voltage power transmission equipment. The background concentration of SF_6 is quite low being on the order of 1 part per trillion (ppt). Detection of SF_6 relies primarily upon two methods: gas chromatography and electron capture. Gas chromatography requires collection of air samples then subsequent analysis at a central location. Advances that began in the mid 1970's (Simmonds 1976) continued into the 1980's in utilizing the electron capture technique to develop real time SF_6 analyzers. Such an analyzer is described in Benner and Lamb (1985). An operational version of this analyzer (LBF-3), manufactured by Scientech Inc. of Pullman, Washington, has been utilized in the North Dakota tracer work since 1985. Results of the release of SF_6 from an airborne platform with detection by a second aircraft equipped with an LBF-3 real time analyzer have previously been reported (Griffith, 1985; Stith, **et al.**, 1986; Stith and Benner, 1987).

In the 1987 North Dakota research program a different type of experiment was conducted. It consisted of the ground release of SF_6 and utilized two different aircraft equipped with LBF-3 analyzers to document the transport and diffusion of the tracer gas. The LBF-3 real time analyzer has a response time of less than one second and a detection threshold of approximately 10 ppt.

There is an application of this type of experiment to the weather modification field. An often debated question is whether ground based silver iodide generators provide an effective means of modifying summertime cumulus clouds? Some research has been conducted to address this question (McPartland and Super, 1978; Heimbach and Stone, 1984). Much of the earlier research was conducted using an acoustical ice crystal counter normally referred to as an NCAR counter (Langer, 1973). The NCAR counter can be useful in documenting the presence of the silver iodide seeding material but its output is normally considered to be qualitative instead of quantitative with regards to the indicated ice crystal concentrations. The method described in this paper offers a quantitative manner of determining SF_6 concentration. The disadvantage becomes one of measuring the transport and diffusion of a tracer gas instead of the actual seeding material which necessitates the acceptance of certain assumptions such as the atmospheric transport and diffusion of small particulate and gas molecules will be the same. It should be noted that the earlier cited works often found silver iodide nuclei at cloud base level.

2.0 INSTRUMENTATION

Two aircraft utilized on the 1987 North Dakota/NOAA research program were equipped with LBF-3 analyzers. One was the South Dakota School of Mines and Technologies' armored T-28 research aircraft. The other was the University of North Dakota's Citation II cloud physics aircraft. Both aircraft carried a variety of state and cloud physics instrumentation in addition to the LBF-3 analyzer.

The University of Illinois' CHILL radar was also in place for the research program. Special rawinsonde observations were made from the project headquarters located at the Dickinson, North Dakota Airport.

3.0 FIELD PROCEDURES

The ground release of SF_6 gas was made from the Dickinson FAA vortac station located 8 km south of the city and 3 km northeast of the Dickinson Airport. The release was conducted from 1407 to 1450 (all times in MDT) on June 19, 1987 by directly venting one pressurized bottle of SF_6 after another resulting in a continuous release of SF_6 into the atmosphere. Four partially full cylinders were vented in this manner releasing a total of 29.4 Kg of gas. The resulting average release rate was 40.9 Kg hr^{-1}.

Flight plans were adopted to utilize both research sampling aircraft. The T-28 took off from the Dickinson Airport at 1417 MDT and flew along an arc downwind of the release point at a distance of 8-10 km. The initial (lowest) sampling altitude for both aircraft was 1.1 km MSL (approximately 350 m AGL). The T-28 flew transects at increasingly higher altitudes in approximately 150 m steps. The T-28 was then flown to higher altitudes to conduct an altitude sensitivity test of the LBF-3 analyzer. The T-28 landed at 1555.

The Citation II took off from the Dickinson Airport at 1350 and initially flew along an 18 km arc downwind of the release point. The Citation II also flew at increasingly higher altitudes with time. The altitude step increases averaged 150-200 m. The Citation made one pass at approximately 27 km downwind of the release site. This pass was made near the base of a developing thunderstorm. Subsequent sampling in this cloud was not conducted since it developed to a stage considered unsafe for aircraft penetration. The Citation II was then flown to higher altitudes to perform sensitivity tests of the LBF-3 analyzer versus altitude. The Citation II landed at 1620.

4.0 RESULTS

Table 1 provides the hourly weather observations taken at the FAA Flight Service Station located at the Dickinson Airport. The weather conditions during the release consisted of cloudy skies, a surface temperature of 26°C and surface winds from the southeast gusting to 25 knots. A special project rawinsonde was released from the Dickinson Airport at 1200 MDT. This sounding indicated upper level winds were consistently from the southeast averaging 10 ms^{-1}. The sounding also indicated conditional convective instability was present.

A summary of the CHILL radar observations for this day indicated shower and thunderstorm activity developed at approximately 1200 MDT west and northwest of Dickinson and drifted slowly east. A thunderstorm developed on the southern end of the convective area and moved north-northeast skirting the Dickinson Airport and moving north of Dickinson.

Table 1

Weather Observations
FSS Dickinson, North Dakota - June 19, 1987

Time (MDT)	Sky Condition Visibility (miles)	Temperature (°C)	Wind	Remarks
1254	55SCT E120 Bkn2500VC	27	140/15G25	RWU SW WSW
1357	E55BKN 120 OVC	26	140/15G23	RWU SW NW
1458	E 60BKN 120 BKN	24	160/15G26	RWU WN ONCL LTGCG
1545	E65 BKN 120 OVC	26	100/12G19	RWU W-NW-N BINOV
1651	65 SCT 120 SCT	26	140/14G23	MDT CU ALQDS

Both aircraft detected the SF_6 plume a number of times. Figure 1 shows several intercepts of the SF_6 plume by the Citation II aircraft between 1430 and 1500. Table 2 summarizes the SF_6 plume encounters for each of the aircraft. The T-28 first encountered the SF_6 plume at 1423 at a downwind distance of 8.8 km and an altitude of 1050 m (all altitudes MSL). This was 16 minutes after the release began. A calculation of the transport speed of the SF_6 plume from the release site indicates that the leading edge of the SF_6 plume should have traveled approximately 12 km in 16 minutes (16/60 hr. x 12.5 ms^{-1}). The first plume encounter by the T-28 was at a downwind distance of 8.8 km which indicates it encountered the plume shortly after plume passage through the downwind arc. In a similar manner the Citation II first observed the SF_6 plume at approximately 1434 at an altitude of 1140 m and a downwind distance of approximately 18 km. This was 26 minutes after the SF_6 release began. The transport of the leading edge of the SF_6 should have reached 19.5 km (26/60 hr. x 12.5 ms^{-1}) within 26 minutes.

Both aircraft encountered the SF_6 plume on each succeeding pass following initial detection. Figures 2 and 3 provide the aircraft flight tracks for the two hours of interest (1400 to 1500 and 1500 to 1600, respectively). Each circle with a cross-hair indicates the location of an SF_6 plume encounter. Figures 2 and 3 indicate the SF_6 was transported towards the northwest in agreement with the upper level winds observed on the 1200 Dickinson rawinsonde.

Table 2 contains maximum observed SF_6 concentrations and plume widths associated with ± 3 sigma y from the Gaussian centerline location. Pasquil-Gifford diffusion equations (Gifford, 1961) were used to calculate the maximum concentration at the same distance downwind as the observations and ± 3 standard deviations from the calculated values. Figure 4 provides a comparison of the 3 sigma values versus the Pasquill-Gifford calculated values for diffusion in the vertical (σ_z) for two different stability classifications (C and D). Figure 5 provides similar

Table 2

SF_6 Plume Information From the T-28 and Citation II June 19, 1987

T-28

Begin Time	End Time	Altitude (m)	Width[1] (m)	Downwind Distance (km)	Maximum SF_6 Conc. (ppt)
1423:24	1423:37	1050	1170	8.8	419
1428:09	1428:22	1070	1170	9.9	167
1430:36	1430:47	1210	990	8.3	221
1438:11	1438:29	1390	1620	8.1	538
1446:24	1446:38	1550	1260	9.2	388
1451:39	1452:02	1560	2070	10.4	717
1501:03	1501:20	1680	1530	9.5	117
1504:17	1504:35	1690	1620	9.1	251

Citation II

Begin Time	End Time	Altitude (m)	Width[1] (m)	Downwind Distance (km)	Maximum SF_6 Conc. (ppt)
1433:53	1434:15	1140	1673	18.0	41
1441:10	1442:19	1140	5021	18.2	100
1450:04	1451:13	1130	5232	17.9	87
1455:15	1455:51	1280	2705	17.8	27
1501:05	1502:26	1490	6220	17.5	204
1506:24	1507:22	1700	4334	17.7	122
1511:37	1512:04	2420	2134	17.5	32
1521:46	1522:07	2560	1622	16.5	21
1527:56	1528:25	2570	2323	26.3	37

1: Widths are corrected plume width i.e., width normal to wind direction at the given altitude.

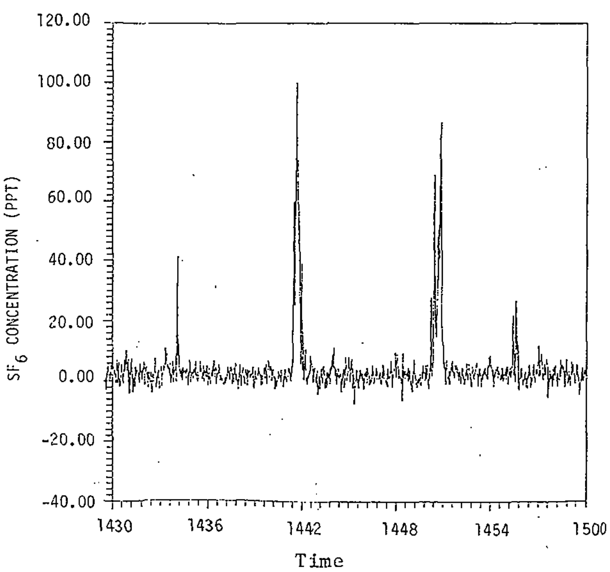

Figure 1 SF_6 Plumes Detected by the Citation II During the Period 1430-1500 MDT.

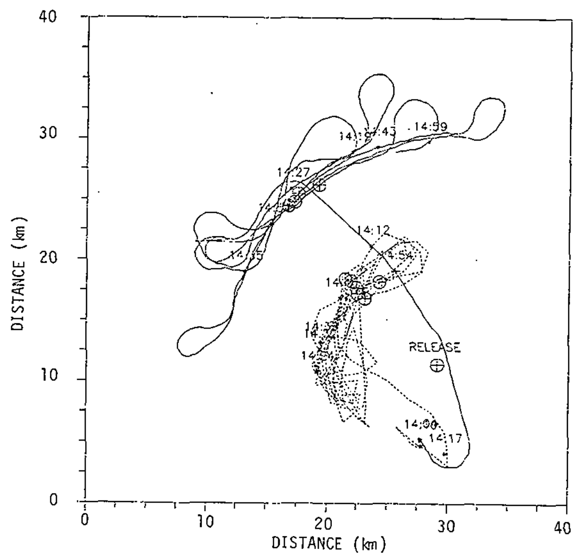

Figure 2 Flight Tracks, Hour 14, Citation II (solid line) and T-28 (dashed line). Times Plotted Above Flight Tracks. Release Site and SF_6 Plume Locations Depicted by Cross Hair Within a Circle.

information for horizontal diffusion (σ_Y). These figures suggest relatively good agreement between the observed and predicted values. From Table 2 it is seen that the SF_6 plume expanded to approximately 2 km in width at an altitude of approximately 1500 m 10 km downwind from the release. The plume expanded to 6 km in width 17 km downwind at a similar altitude. The flight pattern of the T-28 obviously did not approach plume top since the maximum SF_6 concentrations were relatively high (100-700 ppt). The Citation apparently did fly near plume top part of the time. At approximately 17 km downwind the plume top was near 2500 m (or approximately 1750 m above ground level).

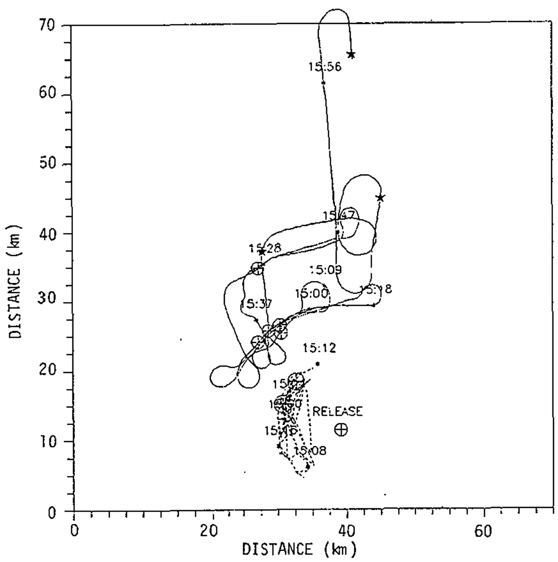

Figure 3 *Flight Tracks, Hour 15, Citation II (solid line) and T-28 (dashed line). Times Plotted Above Flight Tracks. Release Site and SF_6 Plume Locations Depicted by Cross Hair Within a Circle.*

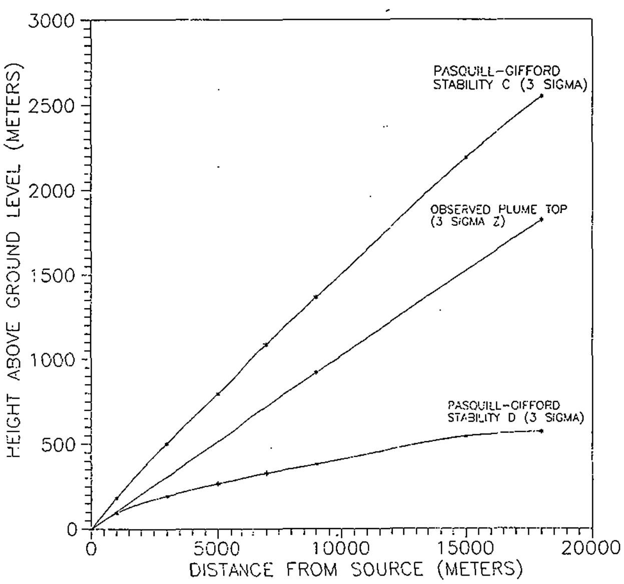

Figure 4 *Comparison of Pasquill-Gifford Vertical Dispersion Coefficients (Sigma Z) With Plume Dimension Data as Measured From Aircraft.*

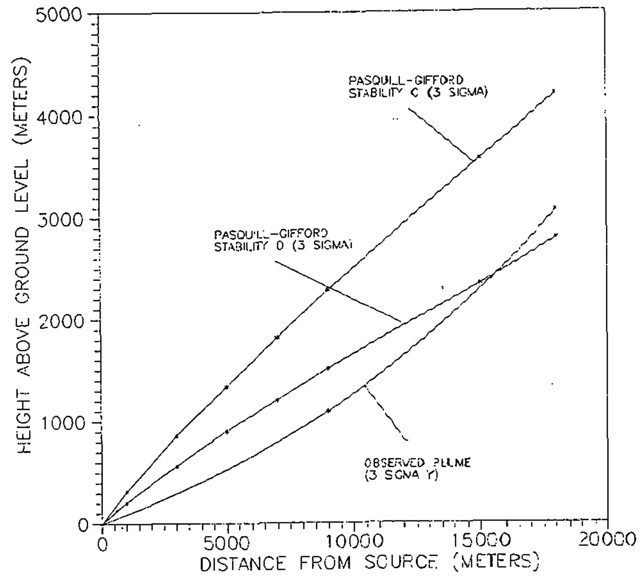

Figure 5 *Comparison of Pasquill-Gifford Horizontal Dispersion Coefficients (Sigma Y) With Plume Dimension Data as Measured From Aircraft.*

The observed one second SF_6 concentration data from the T-28 and Citation were plotted on a vertical display and the data were contoured. Some smoothing was performed in contouring the data. Figures 6 and 7 provide this information. The dashed lines represent the actual flight tracks from which the data were derived and contoured. These plots were prepared normal to the mean wind direction in order to present a true depiction of the plume dimensions.

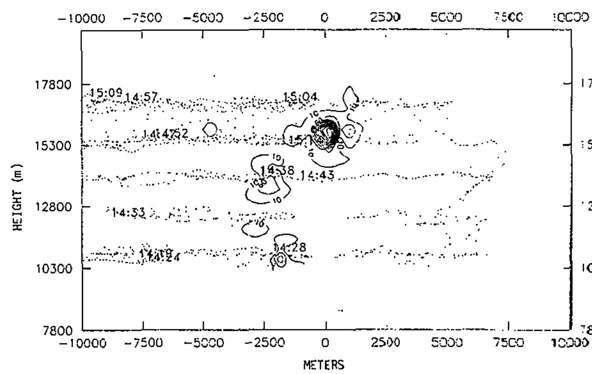

Figure 6 *T-28 Vertical Cross Section, 8-10 Kilometers From Release.*

The last sampling of the SF_6 plume by the Citation II aircraft occurred at 1428 at a downwind distance of approximately 27 km. This observation was in close proximity to the base of a developing thunderstorm. The altitude was 2.6 km and the maximum observed SF_6 concentration was 37 ppt (Table 2). A ratio technique, which had previously been used in the analysis of an airborne SF_6 release (Griffith, 1985), was utilized to examine possible seeding material concentration. This ground release

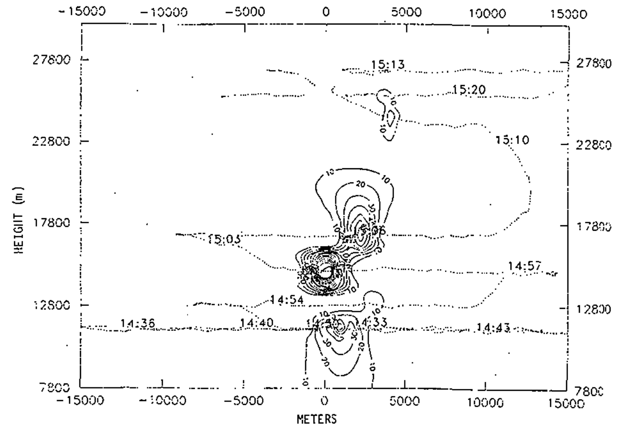

Figure 7 *Citation II Vertical Cross Section, 18 Kilometers From Release.*

experiment did not include the release of any seeding material. The tracer data can, however, be utilized to calculate what the concentration of seeding material would have been based upon a standard ground generator seeding rate. In these calculations it was assumed that a NAWC ground based generator was used emitting 25 g of silver iodide (AgI) per hour. The following equation was utilized:

$$\chi\,AgI = \frac{\chi\,SF_6 \cdot QAgI}{QSF_6}$$

Where:

χAgI = Calculated concentration of AgI

χSF_6 = Observed concentration of SF_6

$QAgI$ = Source strength of AgI

QSF_6 = Source strength of SF_6

In the case of the 37 ppt data point the calculated AgI concentration was 1.84×10^{-13} gl^{-1}. NAWC's ground generator was tested in the Colorado State University (CSU) cloud simulation laboratory in 1982 (Finnegan, 1982). The effectiveness of this generator under natural draft conditions with 1.5 gm^3 liquid water content was determined for several different cloud temperatures. Test results using maximum fan conditions would have been preferred but data were not available for the NAWC generator for some temperatures of interest. If the above calculated concentration is multiplied by the CSU effectiveness factors then the number of ice crystals produced can be calculated. Table 3 provides this information for several different cloud temperatures and for two different AgI production methods. DeMott **et al.**, (1983) demonstrated that a silver iodide-silver chloride complex produced higher nucleation efficiencies than pure silver iodide nuclei. NAWC's generator was tested with a 20 mole solution of NH_4CLO_4 added to the standard AgI, NH_4I solution. This solution, when vaporized, results in the AgI AgCl complex nuclei.

Table 3

Calculated Effectiveness (Ice Crystals) For NAWC Ground Based Generator at Different Temperatures and For Two Different Silver Iodide Production Methods

Cloud Temperature (°C)	Pure AgI (Crystals/1)	AgI·AgCl Complex (Crystals/1)
-6°	0.003	0.3
-8°	0.4	14
-10°	85	104
-12°	121	---

The calculations in Table 3 do not account for any dilution of the SF_6 (or AgI) as it ascended from +10°C (the temperature at the highest observation point near cloud base) to the colder temperatures where the silver iodide would become effective ice nuclei. The aircraft was not able to penetrate the developing thunderstorm so the actual concentration of SF_6 at colder temperatures is unknown. Considerable dilution of the SF_6 (and AgI) would be expected. The calculated ice crystal concentrations in Table 3 are therefore too high.

5.0 SUMMARY

A ground release of sulfur hexafluoride (a tracer gas) was tracked by two research aircraft during the 1987 North Dakota/NOAA summertime weather modification research program. Each aircraft carried a real-time SF_6 analyzer which provided considerable information on the SF_6 plumes. These analyzers had a response time of less than one second and a threshold of detection of approximately 10 ppt.

The plume dispersed in the horizontal and vertical in close agreement to standard Gaussian equation predictions. The top of the SF_6 plume was tracked to near cloud base of a developing thunderstorm. Observed SF_6 concentrations at this point were used to calculate what silver iodide concentrations would have been had silver iodide been released concurrently from the ground along with the SF_6. This calculated concentration was converted to estimates of the number of effective AgI nuclei for different temperatures and two different means of generating the AgI nuclei. The temperature of the last observation near cloud base was at +10°C. The material would have had to be transported vertically another 2.5 km to reach the threshold of AgI nucleation (-6°C). Consequently, the calculations of effective nuclei made from the cloud base observation are too high since considerable plume dispersion would be expected in the 2.5 km of vertical transport.

Direct observations of the in-cloud concentrations of the SF_6 were not possible due to aircraft safety considerations. Additional experiments of this type with in-cloud SF_6 detection (and possibly ice crystal concentration measurements if silver iodide was released concurrently) would provide useful information regarding the feasibility of ground based seeding of summertime convective clouds.

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