COMPARISON OF SILVER IODIDE OUTPUTS FROM TWO DIFFERENT GENERATORS AND SOLUTIONS MEASURED BY ACOUSTIC ICE NUCLEUS COUNTERS

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ABSTRACT. Field testing in late September 2009 permitted comparisons of the output of a WMI remote-controlled seeding generator burning a modern solution with an older style AgI generator and solution previously calibrated in the Colorado State University (CSU) Cloud Simulation Laboratory. That facility is no longer available for seeding generator calibrations. Acoustical Ice Nucleus Counters (AINCs), usually operated at -20°C, were used to monitor ice nucleus concentrations from passage of AgI lines released upwind by mobile generators towed approximately perpendicular to the prevailing wind direction. Considerable variability existed for total ice nuclei per AgI plume passage as could be anticipated given variations in atmospheric conditions. However, examination of all tests with useable data revealed no major difference between the outputs of the two generator types using different solutions. The WMI generator uses a newer solution, expected to produce ice nuclei which operate primarily by condensation-freezing in winter orographic clouds. It had yields in the -15 to -20°C range similar to the Montana State University Skyfire generator producing a relatively pure AgI aerosol likely to operate by contact nucleation. However, AINCs with standard configurations as used in this investigation cannot differentiate between ice nucleation processes. The observations also documented that a newly-manufactured AINC compares favorably with previously tested units. Recommendations are made for future testing expanded to warmer temperatures than practical with the standard configurations of the AINCs available for this study.

1. INTRODUCTION

Remote-controlled silver iodide (AgI) generators manufactured by Weather Modification, Inc. (WMI) are being operated at mountain locations as part of the randomized Wyoming Weather Modification Pilot Project (NCAR 2008). These units have not been calibrated for yield of ice nuclei (IN) per gram of AgI due to the unavailability of a suitable US facility such as the CSU Isothermal Cloud Chamber (ICC) previously used for this purpose (e.g., DeMott *et al.* 1995). During the past two winters, one of the AINCs used in this comparison has been operated at high elevation in Wyoming's Medicine Bow Range to detect IN produced by WMI ground-based generators as part of the randomized project.

The primary purpose of this paper is to compare WMI AgI ice nucleation activity with an older, calibrated generator, the Montana State University Skyfire (hereafter Skyfire) described by Super *et al.* (1972). Both the Skyfire, using a 2% AgI-NH_4I-acetone seeding solution, and one of the three acoustical ice nucleus counters AINCs used in this study was calibrated at the CSU Isothermal Cloud Chamber (ICC) as discussed by DeMott et al. (1995). These previous observations provide a quasi-standard with which the output of the newer equipment and solutions can be compared.

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The field approach discussed in this paper obviously lacks the repeatability and accuracy of earlier CSU laboratory results. Moreover, observations were made primarily at -20°C, the normal AINC cloud chamber operating temperature. Construction of a fixed dilution and testing facility even crudely approximating the ICC would require resources well in excess of those available for this study. While a large capacity fan was used by the ICC, natural wind and turbulence over miles diluted AgI aerosol to concentrations sufficiently low for observation by AINCs. Useful comparisons were obtained by the simpler field approach.

A secondary purpose of this paper is to compare three AINCs (a.k.a. NCAR counters). The oldest was built during 1976 under the supervision of the instrument's inventor, G. Langer. It is herein referred to as Unit 1, in order of production. Detailed discussions of the AINC have been provided by Langer *et al.* (1967) and Langer (1973). An improved AINC was built by J. Heimbach during 2006, which herein is called Unit 2. These two units were previously compared in the laboratory as discussed by Heimbach *et al.* (2008), therein called Unit 3-2 and the WMI unit, respectively. A third AINC, designated Unit 3 herein, was recently built by Heimbach for future use by Snowy Hydro in Australia (Huggins et al. 2008). All three AINCs were compared under field conditions during late September, 2009, near Fargo, ND, at the same time the IN sources were compared.

2. SPECIFICATIONS

Detailed specifications of Units 1 and 2 are presented in Table 1 of Heimbach et al. (2008). Unit 3 is similar to 2 except that its cloud chamber diameter is 17.8 cm (7 inches) rather than 20.3 cm (8 inches). Also, the Unit 3 sample intake is centered on the cloud chamber lid (as in Unit 1) rather than being offset 5.1 cm (2 inches) from the chamber wall in Unit 2. All 3 AINCs began counting ice crystals less than 30 sec after AgI input from a common manifold. Count rates rapidly increased after first detection and peak values were typically reached within 5-10 minutes depending upon AgI pass characteristics, especially concentration. Unit 3 always flushed out AgI plume remnants a little before the other AINCs.

Unit 1 was made for use in small aircraft. Accordingly, it has the smallest refrigeration compressor, smallest "footprint," and, more importantly, lacks a glycol pre-cooler and uses a smaller humidifier than the newer units. Observations presented by Heimbach *et al.* (2008) show that only about 50% of the Unit 1 cloud chamber volume was less than -6°C compared with 77% for Unit 2. In that study the latter unit measured greater AgI IN concentrations depending upon the AgI solution being burned, with the observed difference being greater when contact nucleation was presumed to occur, rather than condensation-freezing nucleation. It will be shown that total observed IN per AgI plume passage was consistently greatest from Unit 2 with the largest cloud chamber volume.

Each ice crystal exiting the base of an AINC cloud chamber is rapidly accelerated then decelerated when passing through a Venturi tube glass sensor. This results in an audible "click" detected by a microphone connected to an electronic signal processor. Three nearly identical electronics units discriminated the respective acoustic signals. Each legitimate count triggered a TTL signal which was sent to a M300 data system for real-time display and archiving at 1 Hz. The electronics used with Unit 1 had a fixed delay of 7.0 msec and that used with Unit 2 was fixed at 8.2 msec. The adjustable delay of the package used with Unit 3 was set to 7.3 msec. These delays eliminated counting the first (loudest) echoes from the flat Plexiglas lid atop each chamber. Signal sensitivity is adjusted to eliminate "double counts" from much weaker second echoes and background noise. Given the delay times, maximum count rates ranged from 122 to 143 sec^{-1}. The true count rate is unknown when such high rates are encountered, so such periods must be rejected. The greatest unadjusted rate detected by any AINC during the 12 passes to be discussed in Tables 1 and 2 was 106 sec^{-1}, below allowed maximums.

It should be recognized that neither the ICC nor the AINCs mimic typical winter orographic clouds. Liquid water content (LWC) within the ICC was set to 0.5 g m^{-3} for the experiments reported by Garvey (1975), corresponding to about 2100 droplets cm^{-3} in the cloud chamber. Other reported experiments had generator yields also provided for a LWC of 1.5 g m^{-3}. New cloud droplets were continuously introduced to maintain LWC and ice crystals were frequently collected on microscope slides for up to 50 min after aerosol introduction. The ICC droplet concentration and LWC values were well above most winter measurements within orographic clouds of the Intermountain West (e.g., Rauber and Grant 1986).

Even higher droplet concentrations are required within AINC cloud chambers to enhance the probability of nucleation and ice crystal growth to detectable sizes (~ 20 μm) within the limited time available, typically about 1 min, before introduced aerosol and cloud exit the chamber. Table 2 of Langer (1973) indicated that for cloud and humidifier temperatures typically used in this paper, LWC varied from about 15 g m^{-3} at the cloud chamber top inlet to about 2 g m^{-3} by the bottom exit. Calculations and observations suggested typical droplet concentrations in the range 3 to 8 X 10^4 cm^{-3}. The purpose of the AINC was to force nucleation by whatever process in order to maximize detection of AgI aerosol concentrations.

These and other differences from natural clouds suggest considerable caution in directly applying ICC or AINC results to winter orographic clouds. As noted by Boe and DeMott (1999), "It has long been recognized that results from the CSU isothermal cloud chamber may not be entirely relevant to the behavior of ice nucleus aerosols in real clouds." But whatever the differences in cloud characteristics and nucleation modes, the ICC was the AgI generator and flare calibration standard for decades, providing the only comprehensive data base for comparisons among several AgI seeding devices and solutions. Comparisons between the ICC and two AINCs reported by DeMott et al. (1995) showed the latter sampled ice nucleus aerosols at about one-third of the ICC efficiency after dilution airflow corrections were made to the ICC. Agreement was closer (two-thirds) for raw ICC results commonly reported over the years.

3. EXPERIMENTAL DESIGN

All three AINCs were installed in close proximity (see Fig. 1) at the northeast corner of the Ice Crystal Engineering (ICE) manufacturing plant, located at 46.679° N latitude and 97.009° W longitude, 3.2 km (two miles) north of Kindred, ND, and 29 km (18 miles) southwest of Fargo, ND. Outside air was continually drawn through all-metal tubing, to minimize AgI wall losses, from a 3.4 m (11 ft) tower located about 6 m (20 ft) east of the northeast building corner. Sample air was drawn to each AINC from the common manifold by each unit's own vacuum pump, and the excess air was exhausted outside.

Silver iodide particles were released from a towed open flatbed trailer upon which were mounted two Skyfire generators with separate stainless steel solution tanks (see Fig. 2). One tank was for the 2% AgI-NH_4I-acetone seeding solution, historically used with these generators. The other tank contained a solution of 2% AgI-NH_4I-$C_6H_4Cl_2$-$NaClO_4$ in acetone, expected to produce condensation-freezing IN (DeMott 1997). The latter solution is used with WMI generators in the Wyoming project. For simplicity these will hereafter be referred to as Solutions S (for Skyfire) and W (for WMI), respectively. Also mounted on the trailer was a single WMI generator with separate stainless tanks for the respective solutions. All but a few successful plume releases used either the Skyfire generator with Solution S or the WMI generator burning Solution W.

With few exceptions the ICE facility is surrounded by a grid network of north-south and east-west roads with one mile (1.6 km) spacing. The terrain is flat and mostly covered by cropland with tree cover usually limited to local windbreaks for farms. No tree cover or other buildings exist near the ICE facility.

The experimental approach was to release AgI particles from between about 3.2-6.4 km (2-4 miles) upwind of ICE in a line as near to crosswind as practical. Ideally, similar plume characteristics would exist among the population of plume passages, and

Figure 1. The three AINCs. from left to right are: Unit 1 tested at the CSU ICC during 1994; Unit 3, newly constructed for the Snowy Hydro program in Australia by J. Heimbach (pictured); and Unit 2, the WMI counter. (Photograph by A. Super)

AgI IN totals could readily be compared for different configurations of generator and solution types. In reality, differences in wind speed and direction as well as atmospheric stability could be expected to result in substantial differences among plumes. While photo-deactivation has been shown to be minor with the Skyfire and Solution S (Super *et al.* 1975) its importance with Solution W is unknown. Sky conditions during AgI particle releases ranged from clear to overcast and both wind speeds and directions were wide-ranging. Consequently, substantial variability might be expected among the field observations as was observed.

In spite of the known shortcomings this was a practical approach to provide at least approximate comparisons between the previously calibrated Skyfire generator using Solution S and the much newer WMI generator with Solution W. A superior approach would have calculated AgI fluxes using an aircraft-mounted AINC flown across the wind at different altitudes from near ground level to above plume tops. That approach, used by Super *et al.* (1975), was impractical with existing time and resources. With the exception of construction of the two Skyfire generators using original blueprints, all equipment used in these tests was already available, most provided by WMI. That availability combined with considerable volunteer time and reduced fees by the authors made this investigation possible with limited available resources. More sophisticated and longer-duration testing was not feasible.

The usual experimental procedure was to make north-south or east-west passes with a pickup truck towing the seeding generator trailer upwind of ICE. Each pass was of sufficient length, typically 10 km (6 miles), to ensure that a portion of the released AgI line passed by ICE even with moderate wind direction changes. To maximize uniformity, passes were planned with the intention of placing the central portion of the AgI line plume at the ICE facility where the sampling occurred. The truck was driven as near to 8 m s^{-1} (18 mi h^{-1}) as practical, slow enough to avoid generator flameout but fast enough to accomplish multiple passes. This approach usually worked well

Figure 2. The flatbed trailer used for mobile releases of AgI during generator and solution comparison tests parked by the ICE facility. Two black MSU Skyfire generators are in the foreground with seeding solution being poured into a stainless steel tank by A. Super (left) and J. McPartland. The dark green WMI generator is mounted at trailer's rear. A silver wind shield used with a Skyfire is in front of the WMI unit. The extreme flatness of the terrain is evident; note the corn field in the background (right) of the photo. (Photograph by A. Super.)

except with light and variable winds. Frequent radio communication between the vehicle navigator and an AINC operator permitted real-time decisions for pass start and stop times and adjustments to pass locations to accommodate wind changes. Periodic wind estimates were made well upwind of the ICE building. These were supplemented by hourly data from the two nearest automatic weather stations operated by the North Dakota Agricultural Weather Network. These are "Leonard 5N" located 18.7 km (11.6 mi) at 289 degrees true from ICE and "Ekre" sited 20.0 km (12.4 mi) at 209 degrees from the AINCs.

4. TESTING SOLUTIONS AND AINC RESPONSES

A total of 13 plume passages were successfully detected on September 25, 26, 27 and 29, 2009. Observations from several other attempts were rejected because of generator problems or winds becoming too light and variable for AgI IN detection at ICE. Strong winds on the 27th precluded use of the Skyfires because of flame blowouts, but the WMI generator functioned well. Field sampling was not conducted on the 28th, which had continued strong winds.

Figure 3 illustrates the "classic" shape of an AgI plume (line passage) as observed by AINCs. In this case, Pass #4 (of Table 1), onset of plume detection was rapid and intense for all three AINCs which peaked simultaneously. Gradual decays followed as the plume of AgI aerosol passed the sampling input and then the cloud chambers flushed. This fast response, with rapid increase after initial AgI IN input, followed by holdup time in the cloud chamber is characteristic of AINCs as discussed by Heimbach et al. (1977).

The passage of a more complex plume is illustrated in Figure 4. In this case, Solution S was burned in a Skyfire generator. Dispersion and passage was more complex than that shown in Figure 3, with "shoulders" apparent during both onset and decay. Agreement in the maximum observed values was unusually close between Units 2 and 3 on this pass, for reasons not fully understood. The broader, apparently well-mixed plume likely resulted in part due to significantly lighter winds. Mean wind speed for this passage was only 7 miles per hour (3.0 m sec-1), compared to 17 mph (7.6 m sec-1) and 16 mph (7.2 m sec-1) for Passes 4 and 7, respectively. Final decay seems to be prolonged by persistence

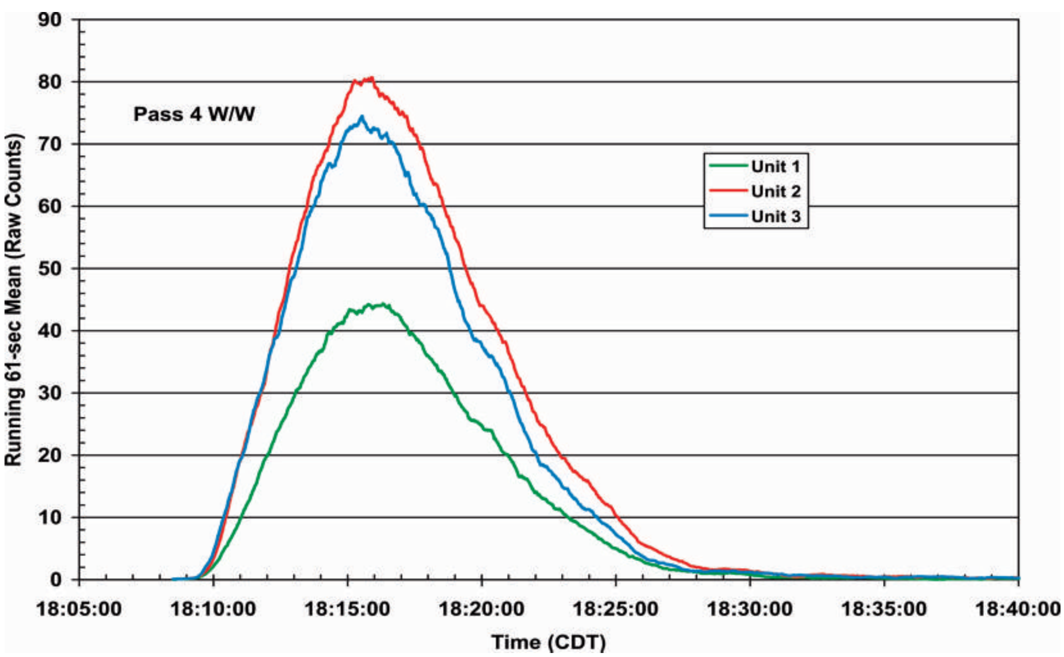

Figure 3. Running 61s means calculated from 1 Hz data (recorded acoustic counts) are shown from each AINC for Pass #4, the passage of an AgI line produced by combustion of Solution W in the WMI generator. Each AINC responded rapidly to AgI arrival at the sampling site. This rather dense but compact plume showed atypically close agreement between Unit 2 (Red), with largest cloud chamber, and Unit 3 (Blue). Unit 1 (Green), the oldest AINC, consistently measured lowest total counts in all passes. Maximum count rates were achieved about 7 minutes after plume arrival and more than 10 additional minutes were required to totally flush AgI remnants from AINC cloud chambers.

of a low but elevated background after passage of the primary plume.

Units 2 and 3 tracked unusually closely on this pass. Unit 1, with the smallest cloud chamber and no glycol pre-cooling, monitored the plume at lower concentrations by less than a factor of two.

Figure 5 shows a plume passage using Solution W in the WMI generator. Once again each AINC responded rapidly to AgI plume arrival and then required several minutes to totally flush out the seeding material and resulting ice crystals.

Table 1 summarizes the 12 successful field experiments. One pass on the 26th was excluded because the ice crystal count rate reached the maximum allowed by the associated electronics. Silver iodide IN arrival and departure (start and stop) times at ICE were estimated by reference to field notes, one minute count totals and raw second by second data. Arrival times are accurate because AINCs react to AgI IN presence in 1/2 minute or less. Departure times are much later than ends of AgI passage because of cloud chamber holdup times and the subjective nature of determining them, especially when new plumes occasionally arrived before natural background IN levels again existed. But in all cases indicated AgI IN concentrations were far below peak levels before arrival of the next plume and any errors in total counts should be minor. Further discussion of AINC response to sampled AgI particles is presented by Heimbach *et al.* (2008).

"Peak" in Table 1 refers to the minute (00~59 sec) with maximum counts detected by Unit 2 for each AgI line passage, minus 1 minute to allow for typical chamber holdup times before detection of high IN concentrations. Unit 2 always produced the greatest total counts per pass and is used as the standard in Tables 1 and 2 (but not Table 3). Peak minutes for the other AINCs were generally the same and never differed by more than a minute.

The nearest time and distance in Table 1 are estimates for when and where the mobile generators were closest to ICE based on local wind direction observations and assuming straight-line plume transport. In reality, plumes meandered, especially during lighter winds, and AgI IN from higher levels with stronger winds may have mixed to ground level. During Pass 1 the generator was upwind of ICE while in a rain shower, and other showers were nearby, so that plume trajectory is particularly uncertain.

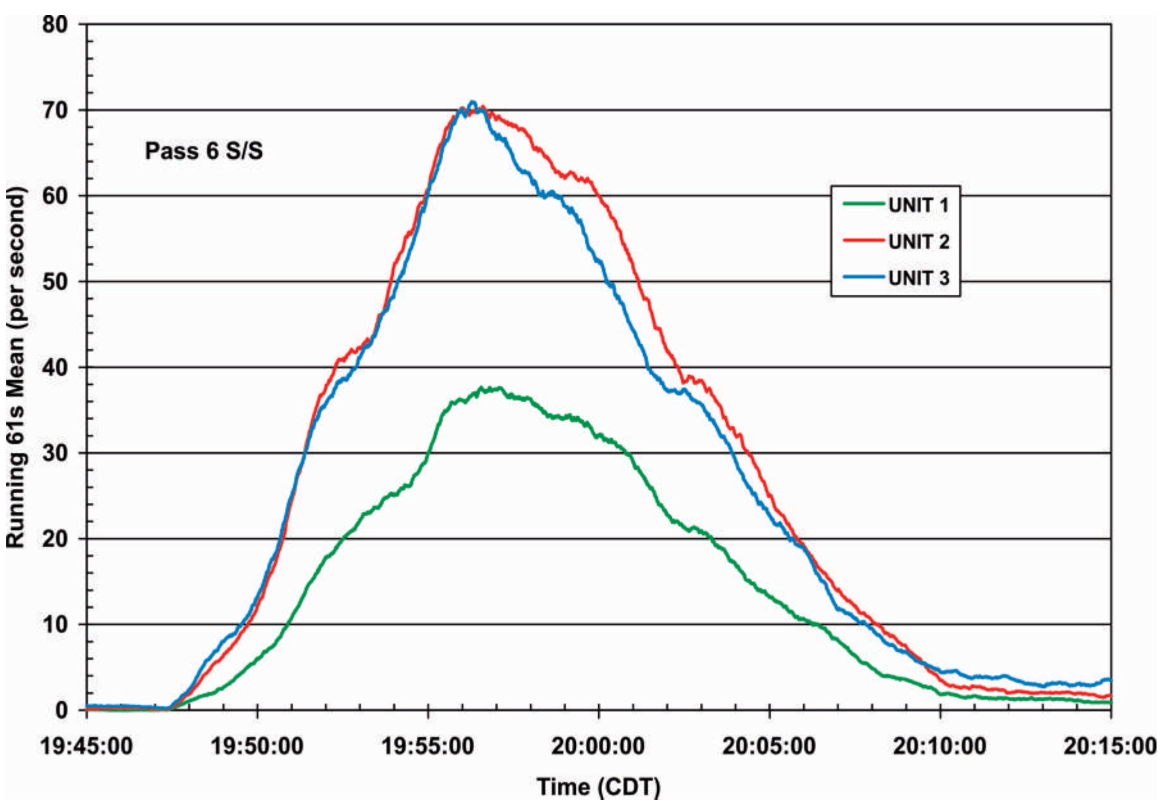

Figure 4. Similar to Fig. 3 but for Pass #6 showing plume passage produced by combustion of Solution S in the Skyfire generator. A broad plume resulted requiring about 10 minutes to reach peak count rates.

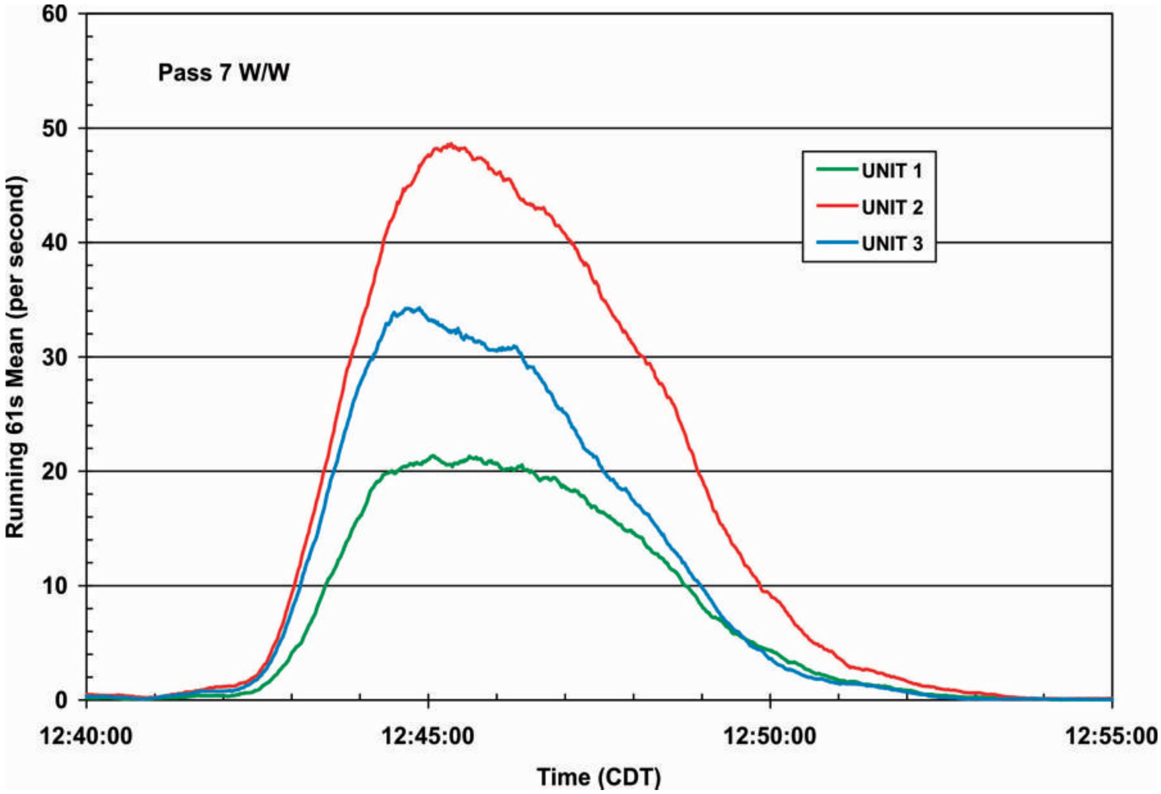

Figure 5. Similar to Figures 3 and 4 but for Pass # 7 produced by burning Solution W in the WMI generator. Each AINC responded rapidly to AgI arrival at the sampling site with peak count rates within ~3 minutes.

Table 1. Summary of mobile AgI generator passes, and generator and solution types during 25-29 September 2009. Generators are noted by S for Skyfire and W for WMI with the same letters used to denote solution types used. Other variables are discussed above. Wind directions are noted by SW for southwest, etc. Distance is in statute miles matching the road network spacing.

No.	Day	Start/Stop (CDT)	Heading	Gen./ Soln.	Nearest Time/Dist.	Peak (CDT)	Speed (mph)	Dir./Spd. (mph)
1	25	1639-1704	East	W/W	1651/2.2	1738	3	S/<5
2	26	1438-1452	West	S/S	1446/2.6	1457	14	SSW/10
3	26	1701-1716	East	S/W	1707/3.2	1726	10	SW/10+
4	26	1757-1813	West	W/W	1804/3.2	1815	17	SW/10
5	26	1817-1835	East	W/W	1826/3.2	1852	7	SW/5-10
6	26	1922-1935	East	S/S	1927/3.2	1956	7	SW/<5
7	27	1229-1249	North	W/W	1233/3.1	1245	16	WNW/18
8	27	1253-1318	South	W/W	1303/4.2	1317	18	NW/20
9	27	1338-1404	North	W/S	1351/4.2	1405	18	NW/20+
10	27	1411-1435	South	W/S	1421/4.2	1436	17	NW/20+
11	29	1133-1155	South	S/S	1146/2.1	1207	6	ESE/5+
12	29	1215-1238	North	S/S	1227/2.0	1254	4	E/<5

The right-most column of Table 1 contains local wind direction and speed estimates except that speeds on the 27th are based on hourly averages from the nearest upwind weather station (Leonard 5N) which showed some gusts in excess of 40 mph. These estimates are usually in reasonable agreement with "Speed" calculated from estimated time and distance when generators were nearest ICE, given uncertainties in actual trajectories.

Table 2 lists the passes in a different order, sorted by generator and solution type. Contrary to Figs. 3, 4 and 5, raw recorded counts for each second were corrected for coincidence losses caused by the electronic count integrators having a delay after each count; 7.0, 8.2 and 7.3 msec for Units 1, 2 and 3, respectively. Equation 1 was used:

$$X_{true} = X_{obs}/(1-[X_{obs}\ Y/1000]) \quad (1)$$

where X_{obs} is the counts (ice crystals) recorded in any given second and Y is the AINC-specific delay in msec. This is similar to equation (1) of DeMott *et al.* (1995) which was applied to one minute totals. In addition, summations of adjusted counts for each pass were normalized to 10 liters min^{-1} by equation 2:

$$\sum X_{normal} = \sum X_{true}\ (10.0/Q) \quad (2)$$

where Q is the sample flow for the particular AINC in liters min^{-1}. Sample flows were measured with a precision flowmeter and depended on the specific glass sensor flow, each hand-blown, less the filtered atomizer flow used to produce abundant cloud condensation nuclei for the moistened sample air. Sample flows were 10.3, 8.6 and 7.6 liters min^{-1} for Units 1, 2 and 3, respectively. Average AgI IN concentrations, effective at -20°C, are listed for Unit 2 by dividing total adjusted counts per pass by the minutes required for AgI nucleation and ice crystal transport through the AINC cloud chamber including flush time. This assumes the standard correction factor of 10 for ice crystals which do not reach the glass sensor because of losses to glycol-wetted chamber walls and bottom cone (Langer 1973).

Total adjusted Unit 2 counts for all passes are shown to range between 4339 and 109,743, a factor of 25, with a median near 23,000. A large range might be anticipated given the variability in transport and dispersion conditions among the passes. Excluding the lowest value, an obvious outlier, reduces the range to a factor of 7 with median of 24,722.

Table 2. Summary of Unit 2 total counts per pass by grouping of generator and solution types. Duration is the time from first AgI detection to return to background concentrations for each AINC. Average IN per liter is explained above. Total counts have been adjusted by equations 1 and 2. Total counts for Units 1 and 3 are presented as percentages of Unit 2. Mean values for the first two sets are in parentheses. Passes 10 and 12 began after first AgI detection once Unit 3 data were available (see footnotes).

Pass	Gen./ Soln.	Duration (min)	Ave IN $Liter^{-1}$	Total Counts Unit 2	Unit 1 (%)	Unit 3 (%)
01	W/W	21.52	698	15,029	34	77
04	W/W	33.45	3083	103,141	28	82
05	W/W	17.93	6120	109,743	29	79
07	W/W	9.73	2541	24,722	30	63
08	W/W	6.57	660	4339	36	73
		(17.84)	(2620)	(51,395)	(31)	(75)
02	S/S	11.72	1680	19,695	50	82
06	S/S	31.58	3305	104,379	30	95
11	S/S	12.35	4855	59,956	39	71
12*	S/S	14.57	1422	20,724	51	70
		(17.56)	(2816)	(51,189)	(43)	(80)
09	W/S	9.52	1882	17,918	43	93
10#	W/S	7.11	3516	25,000	46	98#
03	S/W	19.72	1057	20,839	35	89

* Unit 3 data unavailable until 7 min after AgI detected.

Unit 3 data unavailable until 2 min after AgI detected and different prototype electronics used with that unit only on this pass which had the highest Unit 3 percentage.

The average value for the passes using the WMI generator with Solution W is quite similar to that from the Skyfire generator with Solution S. The three passes (3, 9 and 10) using other combinations of generators and solutions are all within a factor of 3 of the other averages and similar to individual values within the aforementioned sample populations.

Comparison of average AgI concentrations (IN liter^{-1}) among all 12 plume passages reveals a range from 660 to 6120. All values are within a factor of 3 of the median of 2212. Averages are very similar for the two sets with more than two values.

The results can be considered encouraging in view of the wide range of encountered atmospheric conditions plus differences in generator design and seeding solution. To summarize the Unit 2 observations from Table 2, there appears to be little difference in -20°C yield between the generators tested whatever solution was used which cannot be explained by natural variability in atmospheric conditions.

Based on available AINC data it is concluded that combustion products from the WMI generator with Solution W, used by the Wyoming project, provides a similar yield of effective AgI IN to the older Skyfire unit burning Solution S. The latter produced a yield (effectiveness) of 8 X 10^{15} ice crystals per gram of AgI at -20°C for maximum tunnel flow (about 20 knots across the burner head) according to its most recent CSU ICC calibration (DeMott *et al.* 1995). This is a respectable yield judged against maximum draft calibrations for several ground generators presented by Garvey (1975) which included the Skyfire. DeMott *et al.* (1995) noted that the CSU calibration of the Skyfire generator over two decades later was in excellent agreement with the Garvey (1975) results.

5. COMPARISONS AMONG THE THREE AINCs

Table 2 provides comparisons of the oldest Unit 1 and newest Unit 3 AINCs with the consistently highest counting Unit 2. It will be recalled that Units 2 and 3 are similar regarding components, glycol precooling and cloud chamber dimensions except that Unit 2 has an 8 inch diameter chamber and that of Unit 3 is 7 inches. All three AINCs chambers have similar heights. Therefore, chamber volume is a primarily a function of the square of the radius so Unit 2 has a chamber volume approximately 31% larger than Units 1 and 3 (in inches, 16.0/12.25). Actual measurements including the bottom cones revealed Unit 2 was 41% larger in volume than Unit 3. The latter typically counted about 80% of the adjusted totals of Unit 2, or, in other words, Unit 2's observations averaged about 25% higher than those of Unit 3. It seems likely that much of the difference between these two otherwise similar units can be attributed to the larger chamber size of Unit 2 although differences in cloud condensation nuclei production, humidifier output and glass sensor characteristics may have also played roles. None of these factors can be precisely controlled with an AINC.

Unit 1's adjusted counts per plume passage averaged 37% of Unit 2's for all cases (median 36%). In addition to the smaller chamber volume than Unit 2, Unit 1 uses a smaller humidifier and lacks a glycol pre-cooler unlike the other two units. Unit 1's chamber cloud is visibly less dense than in the other units and, as previously noted, a substantially smaller portion of the chamber is cold enough for rapid ice nucleation and growth.

DeMott *et al.* (1995) noted that Unit 1 and a sister unit showed linear correlation coefficients usually above 0.90 during 1994 CSU ICC experiments, with differences usually less than 15%, so some scatter was experienced as seen in Table 2's percentages for Unit 1. It was also noted that those units detected about two-thirds of the raw ICC results commonly reported by the CSU facility over the years, but had about one-third of the efficiency of the ICC after dilution airflow corrections were applied to the ICC raw data. This suggests that Unit 2, which counted about 3 times the AgI-seeded ice crystals detected by Unit 1, would be in close agreement with corrected CSU ICC results if the latter were still available.

6. TEMPERATURE DEPENDENCE OF AINC RESPONSE

Continued strong northwest winds on 28 September precluded use of the Skyfire generators. Attempts were made to test AgI IN activity (yield) vs. cloud chamber temperature by maintaining Unit 3 at -20.0°C (all reported temperatures were measured near the chamber bottom) while operating the other two units at warmer temperatures. Generators were lit outside near the southeast corner of the ICE building (position shown in Fig. 2) for few minute periods and a 60 cc metal syringe was used to collect an AgI aerosol sample just above the burner head. The sample was immediately injected into a 5-gallon metal container and capped off. Although the generators were operated just downwind of the building, local turbulent mixing caused each burn to overwhelm Unit 3's capacity so usable data were not available. Good data were obtained from several tests by taking a metal syringe sample from the 5-gallon container and releasing the AgI-air mix just below the sample intake tube over about 15 seconds. A number of these attempts also exceeded Unit 3's capacity so those data were rejected.

Table 3 summarizes results of the 5 tests with usable data. Only Unit 3 was operated at -20°C so it provided the highest total counts, contrary to the results of Table 2. Consequently, Unit 3 is used as the standard for Table 3 whereas Unit 2 is the Table 2 standard. Start times were obvious from dramatic increases in the Unit 3 count rate and stop times indicate a return to background-level IN concentrations. Unit 2 and 1 were operated at -16°C and -15°C, respectively. Total counts per test were again adjusted using equations (1) and (2).

Additional adjustments were needed for Units 2 and 1 to compensate for AINC differences revealed in Table 2. On average, Unit 3 and Unit 1 counted 80 and 43% of Unit 2 totals for the Skyfire generator with Solution S. Corresponding values were 75 and 31% for the WMI generator with Solution W. Accordingly, adjusted Unit 2 values were decreased by multiplying by 0.80 or 0.75, depending upon generator and solution, and Unit 1 values were increased by factors of either 2.33 (100/43) or 3.23 (100/31). These adjusted values, listed in Table 3 as percentages of Unit 3 totals, are admittedly approximations given the scatter of individual comparisons in Table 2.

Unit 2's percentages ranged from 22 to 51% with a median of 39% and no obvious difference between generator and solution type. This suggests a yield near 3 X 10^{15} ice crystals per gram of AgI effective at -16°C. Unit 1 values at -15°C suggest better yields for the WMI generator with Solution W but only two data points exist.

The Skyfire generator calibration reported by DeMott *et al.* (1995) had values only for -6, -12 and -20°C for maximum tunnel draft. The -12°C value was 13% of the -20°C yield so the Unit 3 and 2 comparisons appear reasonable, suggesting a reduction to approximately 39% at 16°C. An earlier 1972 Skyfire calibration using 3% Solution S rather than 2% had observations at -15°C, -16°C and -20°C as well as warmer temperatures (Super *et al.* 1972; summary results in Garvey 1975). The -15°C value was 15% of that at -20°C, while the -16°C observations were near 35%. The results of Table 3 are in reasonable agreement with the CSU ICC calibrations. This agreement may be fortuitous given the limited data and variability among individual passes and tests.

A few attempts were made to compare Unit 3 at -20°C with Units 1 and 2 operated at -12°C. It was discovered that Unit 1 could not detect any AgI if warmer than -13°C. A single test provided useable Unit 3 data, not reaching its maximum count rate. The Unit 2 adjusted total count was only 1% that of Unit 3. Past ICC calibrations indicated -12°C values were about 10% those at -20°C. AINC cloud densities were very likely too low at -12°C for accurate IN observations. Special modifications would be required for adequate AINC operation at such warmer temperatures, not practical during these tests.

Langer *et al.* (1978) used AINCs to investigate AgI yield as functions of temperature and aerosol size between -14 and -20°C. AINCs can provide useful data to temperatures at least as warm as -8°C (Langer 1973) if modifications are made to maintain cloud density. One of the authors (Langer) noted necessary changes would include increasing humidifier temperature as cloud temperature increases. The glycol-water mixture specific gravity can be carefully maintained within a narrow range to minimize water vapor absorption. Larger AINCs than used in this study can eliminate the 90° glass elbow between chamber bottom cone and glass, thereby reducing ice crystal losses to impact and melt.

It would obviously be desirable to compare IN yields from the WMI and other generators burning modern solutions at moderately supercooled temperatures, especially in the -6°C to -12°C range. Supercooled liquid water is frequently found at such temperatures, near western mountain crests at temperatures sufficiently cold for AgI nucleation

Table 3. Summary of 28 September tests with Unit 3, 2 and 1 operated at -20°C, -16°C and -15°C, respectively. Total counts per test were adjusted by equations (1) and (2). In addition, Unit 1 and 2 totals were further corrected for differences among the AINCs discussed above.

Test	Gen./ Soln.	Duration (min)	Ave IN Liter^{-1} Unit 3	Total Counts Unit 3	Unit 2/ Unit 3 (%)	Unit 1/ Unit 3 (%)
A	S/S	8.51	7837	66,696	22	7
B	S/S	9.02	2578	23,257	40	11
C	S/S	8.52	2509	21,375	39	12
D	W/W	8.20	6952	57,004	33	37
E	W/W	8.52	3314	28,233	51	62

while seedable with ground-based generators. Future work should include such testing with modified AINCs. Size distributions of AgI aerosol should also be investigated given their importance in nucleation (Langer *et al.* 1978).

7. DISCUSSION

Silver iodide cloud seeding generators were calibrated over many years at special facilities, most commonly the Colorado State University CC. Such facilities are no longer available for that purpose in the US. This paper describes an affordable method of comparing a modern WMI generator and solution against an older Skyfire generator and solution last calibrated at the ICC during 1994 (DeMott *et al.* 1995).

Three AINCs were connected to a common source of outside air while sited in a building surrounded by a wide expanse of flat, open countryside in eastern North Dakota. They were used to monitor passages of AgI lines laid out about 3 to 6 km upwind by mobile generators towed approximately perpendicular to the prevailing wind direction. Most tests used either a Skyfire generator burning the 2% AgI-NH_4I-acetone seeding solution historically used with those units, or a solution of 2% AgI-NH_4I-$C_6H_4Cl_2$-$NaClO_4$ in acetone being used with WMI remote-controlled generators in a Wyoming randomized winter orographic experiment. Three AINCs were operated at their normal cloud chamber temperature of -20°C during AgI line passages. This allowed them to be inter-compared including a newly-manufactured AINC to be used in Australia. One of the AINCs was compared with the ICC with good results at the same time as the last Skyfire calibration.

Four sampling days had substantial variations in wind speed, direction, atmospheric stability and cloud cover. As would be expected, this resulted in a wide range of AgI IN totals per plume passage, and average concentrations, as observed during twelve tests with acceptable observations. However, average results were similar between the Skyfire generator and its usual solution and the WMI generator burning the newer solution used in Wyoming. Three tests used other combinations of generator and solution type and these were also in reasonable agreement with the other experiments. It is concluded that the available data set indicates no marked difference between the older ICC-calibrated Skyfire and solution and the WMI generator burning a modern solution as measured by AINCs with cloud temperatures maintained at -20°C.

Limited laboratory-type testing was done with the three AINCs operated at temperatures of -15, -16 and -20°C, respectively. These indicated warmer temperature yield decreases, relative to -20°C, for both generator and solution types in reasonable agreement with earlier ICC Skyfire tests. Attempts to compare yields at -12°C failed because special modifications are needed to operate AINCs at warmer temperatures in order to maintain an adequate cloud density. Past work has shown that reasonable results are possible with modified AINCs but such efforts were beyond the scope of this study.

Comparisons among the three AINCs document that the newest unit is in very good agreement with the WMI AINC when the difference in cloud volume (chamber diameter) is considered. The WMI and oldest (1976 vintage) AINC were recently compared (Heimbach *et al.* 2008) and the latter was previously tested at the ICC facility with good results (DeMott *et al.* 1995). The oldest unit lacks the glycol pre-cooler and larger humidifier of the two newer units and, consequently, consistently recorded lowest total AgI IN per plume passage. But any of the units are adequate for detecting AgI presence and approximate concentration effective at -20°C.

It is recommended that future testing be done at warmer cloud temperatures to provide yield verses cloud temperature curves between about -8°C (warmer if possible) and -20°C. At least one modified AINC would be used at warmer temperatures along with a standard AINC operated at -20°C for reference. These tests could be conducted in a laboratory setting with well-downwind generators briefly operated to provide AgI IN samples for storage in a large metal container to minimize coagulation losses. Diluted samples would later be injected into the AINCs. This approach is similar to that previously used at the ICC except AINCs would be substituted for the large Isothermal Cloud Chamber. While lacking ICC sophistication and reproducibility, the multiple AINC approach offers an affordable and practical alternative in the absence of available ICC-type facilities. Monitoring the size distribution of AgI aerosols should be part of future testing because of the importance of particle size in nucleation effectiveness.

Newer IN instruments exist which could be used in similar testing instead of AINCs if resources permitted. For example, Rogers *et al.* (2001) discuss a more sophisticated instrument with better controls. Whatever approach is used, future generator testing is needed, given the loss of CSU facilities for this purpose.

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