THE MODELING OF AIRCRAFT DEICING FLUIDS DEPOSTION

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ABSTRACT

Glycol deposition near aircraft during deicing operations has become an important consideration at major airports. A sampling process was used to quantify glycol deposition from deicing operations at a major international airport. The resulting data indicate that glycol deposition was different for the two types of aircraft used in this study (DC-9 and 757). The main reason appears to be the height of release. Atmospheric dispersion modeling was not performed because of the nature of the deposition mechanisms (i.e. overspray and mists). Based on the collected data, deposition modeling was conducted using three mathematical modeling approaches and the best overall model was found to be a power series. The developed model predicts downwind ground level concentrations of Type I, propylene glycol. In addition to downwind distance, wind speed was incorporated into the model by normalizing the measured deposition concentrations by their corresponding average wind speeds. Separate models were developed for each aircraft, but the engine conditions were aggregated to obtain average models.

INTRODUCTION

Concerns have been raised at a major international airport over deicing operations at newly proposed sites. Concerns stem from the deposition of deicing fluid due to overspray and wind-carried mist (fine droplets) which could result in excessive ground concentrations at critical locations. To investigate the deposition characteristics of the fluid on the surrounding areas, several test sprays were conducted on two aircraft types: a

DC-9 and Boeing 757. Quantification of fluid deposition (in mass per unit area) allowed models to be developed to predict worst case downwind deposition for varying distances.

As alluded to, the deposition occurs in two ways; direct spray from the nozzle (overspray) and mists carried by the local wind. The overspray from the nozzle results in a large quantity of glycol being deposited near the aircraft in a short period of time. The mist is created either from spray impact on the aircraft surface or from the high pressure nozzle itself. This mist is carried by wind currents to greater distances than the direct spray. Fortunately, mists represent a much smaller fraction of the total deposition than that due to the direct spray.

This paper reports on the measurement and modeling effort of the glycol deposition. The final, developed model is presented.

BACKGROUND
The fluids commonly used in deicing operations are actually of two types: Aircraft deicing fluids (ADF) and aircraft anti-icing fluids (AAF) (McCready 1998). The most commonly used ADF is a Type I mixture of 50% water and 50% propylene (or ethylene) glycol by weight. This fluid is essentially used to melt and remove ice that has already accumulated on the outer surfaces of the aircraft and helps prevent additional accumulation. In contrast, a Type IV AAF is used to prevent ice from forming on an aircraft. This anti-icing agent is applied as a gel to literally coat the aircraft. The terms "Type I" and "Type IV" are Society of Automotive Engineers (SAE) nomenclature used to identify application conditions. Type I refers to applying fluids at higher than ambient temperatures and Type IV refers to applying fluids at ambient temperatures. Since only propylene glycol was used during testing at MSP (no ethylene glycol or Type IV AAF), "glycol" will be used throughout the rest of this paper to refer to the Type I propylene glycol mixture.

Propylene glycol (1,2-Propanediol) has an extremely low vapor pressure of 1 mm Hg at $45.5^{o}C$, and a high boiling point of $189^{o}C$ (Lide 1992). These properties result in the evaporation rates being quite low with little evaporation after a deicing event. Puddles usually form during deicing and the deposited glycol can be collected with a vacuum and consequently, recycled, or captured by sewers for treatment as wastewater. The concerns of this study was the resulting wet surfaces around the aircraft that could result in a potential safety hazard for vehicles due to a loss of surface friction. This primary reason, as well as some secondary reasons, resulted in this study to allow prediction of glycol deposition near the deicing operations.

METHODOLOGY
Glycol spraying was conducted on two different aircraft (McDonnell Douglas DC-9 and Boeing 757) under several different conditions. The various test scenarios are presented in Table 1. The power on state refers to an idling condition where the aircraft engines are operating at a low level. In contrast, the breakaway (power out) state refers to a higher level that is required to move the aircraft. The table shows that a total of 12 runs

corresponding to 9 actual sprayings of aircraft were conducted. The three non-spraying runs refer to blank samples taken for quality assurance purposes. The test sprays indicated in Table 1 refer to runs where the travel distances of the direct sprays were determined. All tests were conducted between 12 midnight and 6 AM for safety purposes. Different engine states for the DC-9 (off , on, and breakaway) and the 757 (off and breakaway) were also tested to determine their effects on deposition. No testing was done of the 757 with engines on because this is not done due to impacts on the engines. Three deicing vehicles were in use during each spraying run, and the operators of the deicing equipment were instructed to conduct the sprayings as if under a severe situation (i.e. heavily ice-coated aircraft). The sampling was passive in that local air patterns were not influenced.

Table 1. Test Scenarios

Run	Aircraft[a]	Engine State	Spray Time	Comments
0	None	N/A	N/A	Q/A Blanks
1	DC-9	Off	4 min	Quick Spray
2	DC-9	Off	8 min	Extended Spray
3	DC-9	On	7 min	Extended Spray
4	DC-9	On + Breakaway[c]	7 min	Extended Spray
5	None	N/A	1 min	Test Spray
6	None	N/A	N/A	Q/A Blanks
7	757[b]	Off	9 min	Extended Spray
8	757[b]	Off	7 min	Extended Spray
9	757[b]	Off + Breakaway[c]	4 min	Quick Spray
10	None	N/A	1 min	Test Spray
11	None	N/A	N/A	Q/A Blanks

[a]The DC-9 sprayings were conducted on the first night and the 757 on the second night.
[b]The 757 was not sprayed with the engine on due to safety concerns.
[c]Breakaway (pull-out) power was used immediately after spraying.

The actual collection of glycol was accomplished through the use of teflon coated collection trays, each 0.127 m^2 (1.37 ft^2) in area. These trays were strategically located downwind of the aircraft as shown in Figure 1. The same orientation, as shown in Figure 1, was used on both nights although the second night was a mirror image of the first. However, in both cases, the aircraft faced into the wind at a 45 degree angle. Site A was collected only at the end of each day's samplings (i.e. after all the runs had been completed for one type of aircraft) in an effort to determine the buildup due to multiple deicing runs. Sites B and C were placed side-by-side to assess data collection precision.

Site D was elevated to 3 m (10 ft) above ground level to help determine vertical distribution. Sites A-F were at a 45° offset from the aircraft's longitudinal axis and directly downwind. Sites G and H were at a 90° angle from the aircraft longitudinal axis and used to measure possible upwind deposition. Sites I, J, and K were along the longitudinal axis of the aircraft to allow the deposition due to jet blast to be evaluated. In addition, Sites I, J, and K allowed the impact from engine jet blast on glycol re-entrainment to be evaluated.

Figure 1. Sample Locations
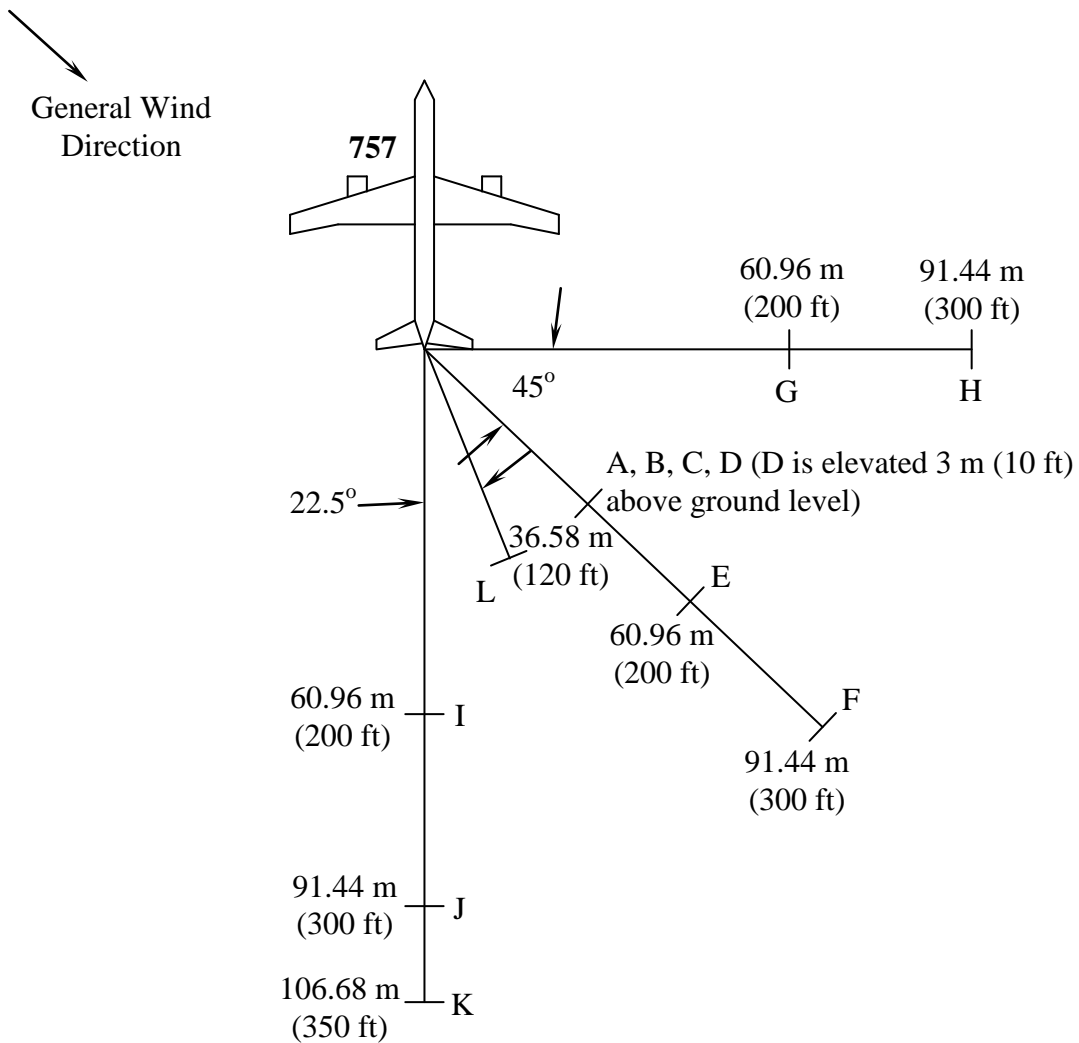
After each run, the teflon surfaces were rinsed with deionized water from teflon rinse bottles to remove glycol. The rinse mixture was captured in glass collection bottles. The

bottles had been previously baked to remove any organic residue. The use of teflon and glass surfaces was warranted to prevent contamination of samples since low level detection would be used.

The samples were analyzed at the University of Central Florida (UCF) for Total Organic Carbon (TOC). Since the teflon coated surfaces had been cleaned before each test and no other primary sources of carbon were nearby or upwind, the TOC was assumed to represent the glycol collected. TOC characterization tests of several samples were conducted to determine actual glycol results during TOC analysis. This allowed results from TOC testing to be applied directly to glycol capture through the use of a correction factor.

The result from a TOC analysis is essentially a concentration in mass per volume of the carbonaceous material in the sample bottle. Since the volume of the bottle and the collection area of the pan were known, the mass of the glycol, and hence, the deposition concentration in mass per unit area could be determined.

RESULTS OF MEASUREMENTS

During the tests, several observations were noted. First, the low evaporation rate of glycol was confirmed when the pavement surface was observed to still be damp from the first night's sprayings even after a vacuuming operation and 19 hours that included sunny and windy daytime hours. Second, testing verified that the direct spray could travel well over 30 m (100 ft). If an aircraft's vertical stabilizer is being treated, overspray is almost certain to occur as the leading and trailing edges are treated. Third, as expected, the overspray was observed to be dominant in its contribution to glycol deposition compared to the mists that were formed. Lastly, the engine operation mode was found to significantly affect glycol deposition but differently depending on aircraft type. The jet blast can cause mists to settle at a much farther distance than if the engines are off.

The characterization testing from the TOC testing, using pure glycol, indicated that a factor of 0.314 mg TOC per mg glycol occurred. This factor was used to determine deposition rates of glycol based on the measured TOC results.

Sites A, B, and C had the highest glycol depositions most likely due to their proximity to the aircraft and the direction of the prevailing wind. Although site D was also close to the aforementioned sites, it did not experience as much deposition because it was elevated 3 m above the ground. This tends to point out the quick settling rates. The data also confirms the observation that the jet blast significantly affects the settling distance of mists. This effect is exemplified by the increase in deposition for sites downwind of the jet blast as the engine condition is changed from the off to the on condition (from run 2 to run 3), and from the off or on condition to breakaway (run 3 to 4 or run 8 to 9). The data also shows that when comparing different aircraft types (i.e. runs 2 and 7), the 757 deicing operations resulted in much greater deposition of glycol than that of the DC-9. This discrepancy is thought to be caused by the greater height and overall size of the 757 resulting in a higher release point causing greater areal dispersion of glycol and the engine

orientation. The DC-9 engines are located along the fuselage while the B757 engines are under the wings. The differences in the aircraft also resulted in different spray patterns as the results show. It should also be noted that the aforementioned comparisons were made for similar spray times. The difference in spray times for each runs are further elaborated in the discussion of uncertainties.

DEPOSITION MODELING

Atmospheric dispersion modeling was not applied in this situation because of the complexities (i.e. random droplet size) involved with deposition mechanisms. As previously discussed, deposition away from the aircraft occurs either through overspray which accounts for the bulk of the deposition or through mist settling. Further complications are that aircraft type and engine condition can also affect deposition. Accordingly, deposition models were developed separately for each aircraft to predict ground level deposition rates downwind of the aircraft. Due to the nature of the spraying operations, spray directions constantly change and are not included in the aforementioned models. All results in this study correspond to complete deicing operations on aircraft.

Modeling was accomplished by relating wind speed and distance to deposition concentration. Near site wind data were taken and compared to tower data for the two days of sampling. A normalization process was used in that deposition rates were divided by their respective average measured wind speeds. These normalized values and their respective deposition distances were regressed using different model forms:

$$\text{Polynomial:} \quad y = ax^2 + bx + c \qquad\qquad (1)$$
$$\text{Power Series:} \quad y = ax^b \qquad\qquad (2)$$
$$\text{Exponential:} \quad y = ae^{bx} \qquad\qquad (3)$$

The use of these model types was warranted due to the non-linear appearance of the plotted data (Figures 2 to 5). For each run, only data from sites within the corresponding wind direction were included in the regression analysis since this was the dominant deposition direction and represents the worst case scenario. Data was included if the site was within 30° ($\pm30^o$) of the wind direction. Sites within this angular band were assumed to be equally affected by the wind. In order to use data with similar test conditions, only runs 2-4 (DC-9) and 7-9 (757) were used in such a way that deposition was analyzed with and without the engine breakaway condition. All of this data corresponds to ground level receptor locations. Site D was the only receptor location that was raised (i.e. 3 m) above the ground. Since the data from this site was not considered sufficient to incorporate height into the deposition models and the primary concern in this study was ground deposition, the models developed in this study correspond to ground level depositions only.

The coefficients and goodness of fit criteria for the models are presented in Table 2. Although the polynomial models produced the highest coefficient of determination (R^2), the parabolic nature of the curves restricts its use to distances from zero to that corresponding to the minimum point on the curve. Therefore, these models could not be

used to represent the overall deposition mechanism. The coefficient of determination and the mean squared error (MSE) are similar for the power series and exponential models, but the power series models generally appear to produce the best results. The R^2 values for these models are acceptable (i.e. 0.6011 and 0.5757 for DC-9, and 0.6844 and 0.8025 for 757), and the relatively small root MSEs and the significance of the p-values (i.e. less than 0.05 for 95% confidence) indicate that using a power series model to predict glycol deposition is justified. Since the deposition concentrations were normalized with their corresponding wind speeds, the calculated results from the models must be multiplied by wind speeds. Therefore, the functional form of the recommended power series model would be as follows:

$$C = (ae^{bx})u \qquad\qquad (4)$$
$$\text{where} \quad C = \text{deposition concentration } (L/m^2)$$
$$x = \text{distance from aircraft (m)}$$
$$u = \text{wind speed (m/min)}$$
$$a, b = \text{coefficients (dimensionless)}$$

In order to visually compare the effects of different engine conditions, the data used in the regression analysis was plotted according to aircraft type and engine condition. While not shown here, the graphs support the initial observations that engine condition affects glycol deposition concentration. In general, deposition seems to increases as engine condition changes from the off to the on condition, and increases even further when breakaway power is applied. General models were developed by aggregating data corresponding to different engine conditions. However, breakaway power was thought to be significant, and an attempt was made to separate out its effects by deriving models corresponding to data sets with and without breakaway power (runs 4 and 9). corresponding to the use of breakaway power.

DISCUSSIONS OF UNCERTAINTY
The precision involved with the sample collection was determined by comparing duplicate samples from the same collection bottle, and also by comparing samples taken from adjacent locations (i.e. sites B and C). The results of the duplicate sample comparisons provide an indication of analytical (measurement) error reported as a relative percent difference (RPD). In contrast, the results of the adjacent sample data provide errors associated with field sampling procedures. The average analytical and sampling RPDs (4.46% and 17.42%, respectively) give an overall indication of acceptable precision.

The accuracy of the data was characterized by quantifying glycol recoveries from known samples. Since glycol concentrations in field samples were unknown prior to laboratory analysis, they were inappropriate for determining accuracy. Therefore, samples fabricated in the laboratory were used. To determine analytical accuracy, a known concentration was spiked with a known quantity of glycol. This glycol was taken directly from the

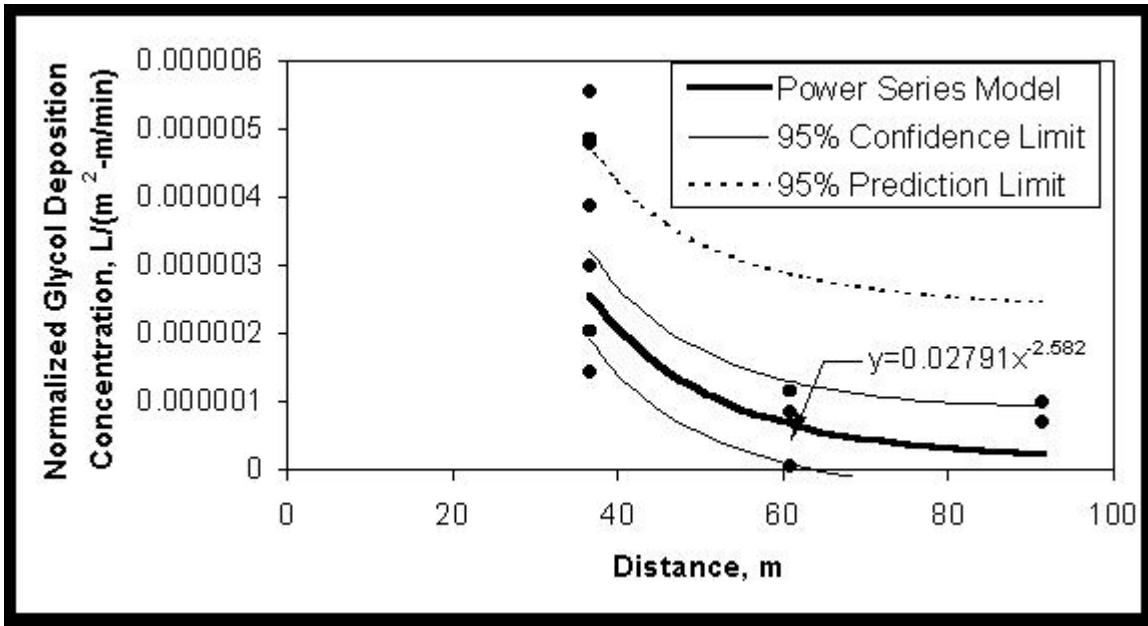Figure 2. Deposition Model for the DC-9 without Breakaway Data

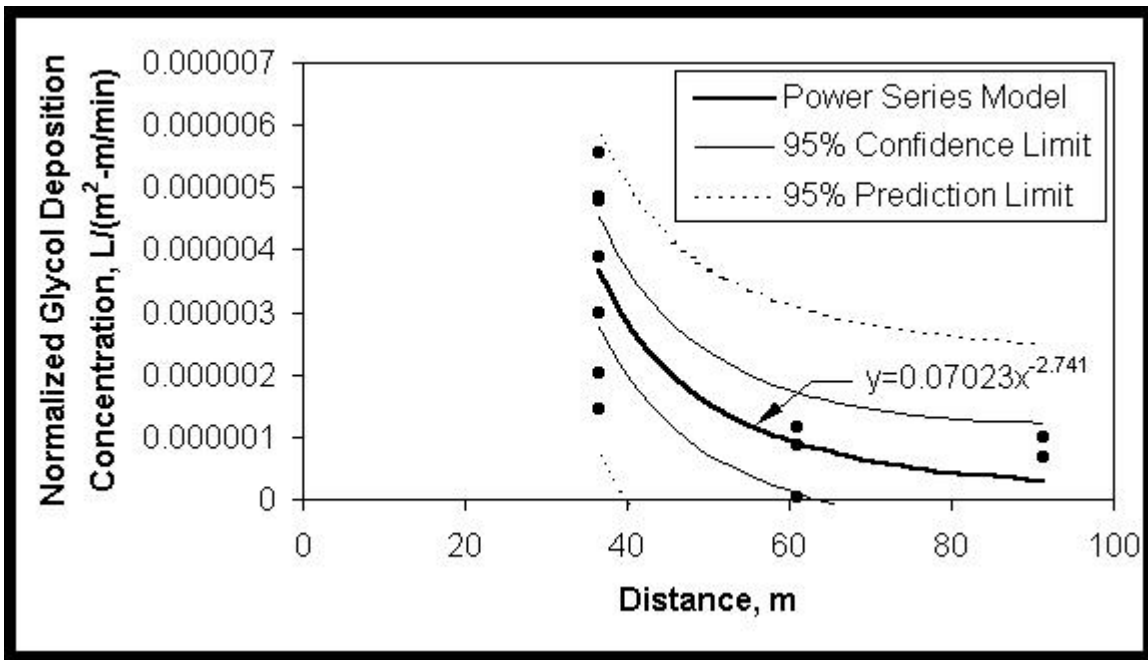Figure 3. Deposition Model for the DC-9 with Breakaway Data

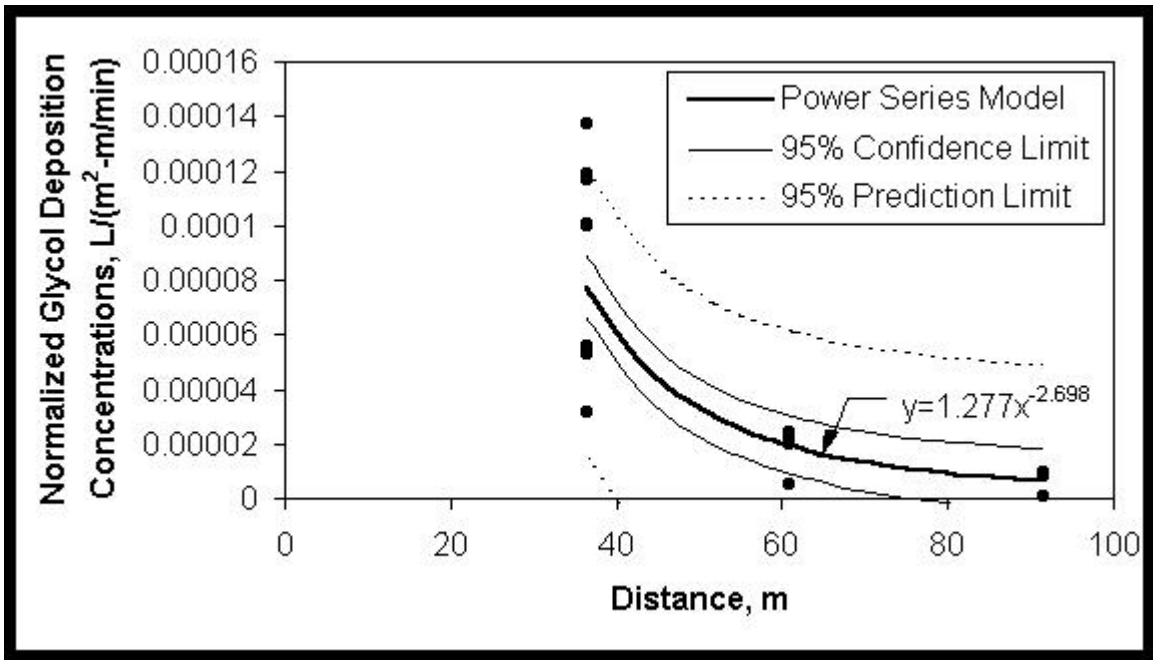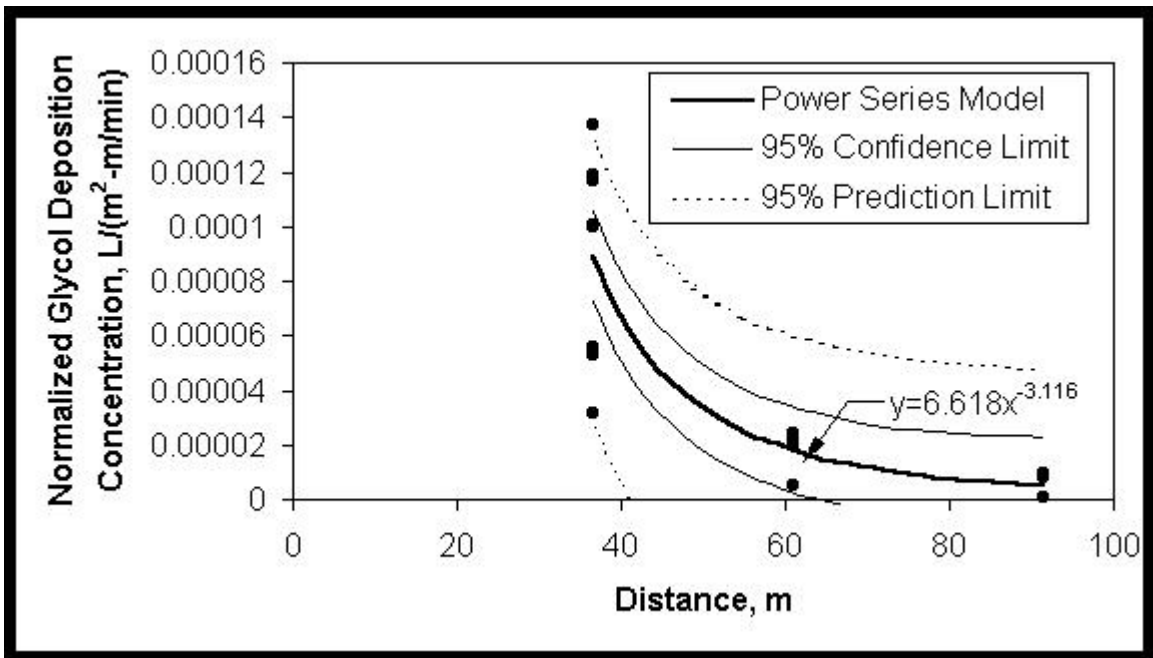Figure 4. Deposition Model for the 757 without Breakaway Data

Figure 5. Deposition Model for the 757 with Breakaway Data

spray trucks on site to ensure consistency such that the same glycol mixture was used for both quality assurance testing and field sampling. Sampling accuracy was determined by reproducing field sampling procedures in the laboratory but under controlled conditions. A known glycol quantity was applied to a sampling apparatus which was then rinsed using procedures employed in the field to generate a sample for analysis. The recovered sample was compared to the known quantity placed on the apparatus. Temperature was also varied to see if it had any effect on recovery. The average recoveries of 105.15%, 93.69%, and 85.05% indicate reasonable levels of analytical and sampling accuracy for the lab.

In analyzing the samples collected in the field, contamination had to be quantified. Both opened and unopened blank bottles were analyzed to show that the TOC, and hence, the glycol levels in these blanks were virtually zero (i.e. below the detection limit). Blanks collected from washings at the beginning of a sampling day and second washings after a spray run were used to determine detection limits. The term, detection limit, as used here refers to a contamination level that makes a data value unusable if it is below the detection limit. The average value for the blanks at the beginning of the first and second day (run 6) of sampling were 0.56 mg/L and 0.88 mg/L (as pure propylene glycol), respectively. To be conservative, the second day's value (0.88 mg/L) was used as the detection limit for all of the samples collected on the first day. The determination of the detection limit for the second day is more complicated. The detection limit of 0.88 mg/L is appropriate for the first run (run 7) on the second day, but not for runs 8 through 10 because runs 7 through 9 appear to have produced high concentrations that were not uniformly experienced at all sites. Thus, the use of a single detection limit was not considered appropriate. Instead, blank levels after the second day (run 11) of sampling were used as the detection limits based on site location:

Site A	32.46 mg/L
Site B	35.45 mg/L
Site C	128.49 mg/L
Site D	12.49 mg/L
Site E	21.80 mg/L
Site F	14.19 mg/L
Site G	0.72 mg/L (use 0.88 mg/L)
Site H	0.37 mg/L (use 0.88 mg/L)
Site I	1.68 mg/L
Site J	0.65 mg/L (use 0.88 mg/L)
Site K	0.94 mg/L
Site L	243.39 mg/L

All of the aforementioned detection limit values were used in classifying data as being real or below detection, and hence, invalid if the measured values were less than those shown.

A discrepancy that needs to be addressed concerns the fact that the models were derived from the values which were based on varying spray times. Although the usage of only runs 2-4 and 7-9 minimizes the variation in spray times, the differences can still be problematic since glycol usage, and hence, deposition rates are directly related to spray times. The most significant difference occurred when comparing runs 7 and 9 (9 and 4 minutes, respectively) which would reasonably be considered significant. However, the subjective nature of spraying operations by human operators tends to diminish the importance of the difference in spray times. During deicing processes, it was noted that spraying was not continuous; rather, the operators would intermittently discontinue spraying for up to several seconds in order to reposition the spray vehicle and spray personnel bucket. The inconsistencies in these off-times also reduced the possibility of using exact spray times for a field use model. Furthermore, the time spent deicing different sections of an aircraft may not be consistent. Therefore, even if the spray times were equal for two runs, the amount of glycol sampled at the same site could be different. Considering these factors, the deposition models developed in this study should be considered as estimation tools for predicting average deposition concentrations.

CONCLUSIONS

From observations and the collected data, direct sprays were found to reach distances of up to 53.3 m (175 ft). At these distances, it was clear from observations that most of the deposited glycol reached the ground very quickly while a fraction was carried further downwind as mist. Although deposition due to mist appeared to be relatively small, even mist depositions can become significant as they add up over time. A strong factor affecting deposition concentration is the initial height of the spray. With a higher nozzle position, deicing a 757 appears to produce greater glycol deposition with distance than a DC-9. Also, increasing receptor height appears to dramatically decrease the deposition rate as shown with site D which was raised 3 m (10 ft) above ground level. It is also important that deposition is affected by engine mode. However, more data will be required to better quantify this finding. The deposition models were developed separately for each aircraft since the spray height appeared to affect deposition. Power series models appeared to produce the best overall results. They generally had the highest R^2 values and their coefficients tested significant with p-values less than 0.05.

In order to obtain an overall deposition concentration for several consecutive deicing operations at the same location, the concentrations measured or predicted could be multiplied by the number of aircraft (taking into account that different aircraft will produce different concentrations). This simple method is reasonable since glycol evaporation is negligible. The movement of aircraft and other vehicles would have to be taken into account since they will carry off some of the deposited glycol.

RECOMMENDATIONS

Abatement at the deicing site is suggested in two steps. First, spray crews should be instructed to spray at a downward angle when possible and to spray at the minimum height where good coverage still occurs. Second, the data from the elevated site show that even at closer distances (here 36.6 m; 120 ft) deposition is generally less than one-

fourth the ground level deposition. This implies that a blast fence could be effective in reducing the impact away from the aircraft. In addition, a typical blast fence with wide slot openings is not recommended. The fine mist could easily travel through these slots carried by the drag force of the wind. Many designs are possible, but for each, the wind flow should be forced to make abrupt changes in direction in an attempt to capture the mists using impaction.

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KEY WORDS

Aircraft, glycol, deposition, modeling, airports, deicing fluids