

Evaluation of the Environmental Impacts and Alternative Technologies of Deicing/Anti-icing Operations at Airports

By

Jui Shan Yong

*B.S in Environmental Engineering (2000)
University of Illinois at Urbana Champaign*

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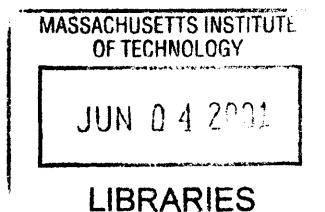
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Author.....
Department of Civil and Environmental Engineering

Certified by.....
David H. Marks
Morton '42 and Claire Goulder Family Professor of Engineering Systems
and Civil and Environmental Engineering

Accepted by.....
Oral Buyukozturk
Chairman, Departmental Committee on Graduate Studies

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I) ABSTRACT

Aircraft and airfield deicing/anti-icing are essential to safe airport operations during cold weather conditions. The regulatory bodies overseeing airports mandate that airlines and airports use chemical deicers/anti-icers for airport operations thus maintaining safety and reducing risks. However, such operations and the management of the associated contaminated storm water have come under close scrutiny during the past decade due to increasing public awareness of the potential environmental impacts of these chemicals and more strict environmental regulations.

In order to provide the reader with a brief but comprehensive overall guide to airport de-icing/anti-icing activities, this paper summarises the properties and environmental impacts of runway and aircraft de-icers/anti-icers such as biological oxygen demand, environmental fate, and aquatic/mammalian toxicity. Comparative analyses between these chemicals, taking into account the overall environmental impacts together with the chemical costs and remediation costs, will be discussed and recommendations provided. Engineering solutions as well as strategies to mitigate and reduce the deicing/anti-icing issues at airports will be looked at, such as product minimisation and substitution, and alternative technologies to complement present deicing/anti-icing operations. Recommendations for airports include the ways to reduce de-icing chemical use, better staff training and incorporation of alternative de-icing technologies. Recommendations for research include the development of environmentally sound de-icing chemicals with a focus on chemical additives and alternative de-icing technologies.

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II) INTRODUCTION

The presence of snow, ice, or slush on runways or aircraft frequently causes hazardous conditions that can contribute to aircraft accidents, delays, diversions, and flight conditions. Ice is detrimental to aircraft because it adds weight, distorts airfoil shapes, and may damage propellers, turbine, rudders, and other parts of the craft when dislodged during takeoff. Runway surfaces must provide sufficient traction to safely land and stop aircraft. Additionally, poor traction is a hazard to vehicles and ground crews in apron and service areas (1). Consequently, deicing or anti-icing of aircraft and runways are the key components in assuring cold weather aircraft safety, with human safety being an overriding concern at most airports.

Airport deicing and anti-icing practices fall into two general categories: aircraft and runways. Typically, airline and fixed based operators (i.e., contract service providers) are responsible for aircraft deicing/anti-icing operations, while airports are responsible for the deicing/anti-icing of airfield pavements.

Airline operators and airlines use deicers and anti-icing materials to control icing. Deicers are applied to aircraft and runways to facilitate melting and removal of accumulated ice, snow and frost. Anti-icing material are also applied to aircraft to extend holdover time, which is the estimated time an application of anti-icing fluid will prevent the formation of frost or ice, and the accumulation of snow and slush on the protected surfaces of the aircraft. Holdover time begins when the final application of the de-icing/anti-icing fluid commences, and it expires when the de-icing/anti-icing fluid applied to the aircraft loses its effectiveness (1). Once the holdover time of an aircraft is exceeded, it cannot be allowed to take off and has to be de-iced again.

In the United States, deicing procedures are overseen and regulated by the Federal Aviation Administration (FAA). The FAA incorporates criteria specified by professional associations such as the Society of Automotive Engineers and the United States

Department of Defense into the process for approving deicing chemicals. The criteria used by the FAA include:

- Maximal freezing point depression at reasonable cost
- Low fire hazard
- Non-corrosive to aircraft metals
- Inert to aircraft paint, plastic windows, gaskets and elastomers
- Minimal toxicity to ground crew and applicators

However, FAA does not evaluate the environmental impacts of deicing chemicals selected for use in deicing aircraft and airport surfaces. It is the responsibility of federal and state environmental regulatory agencies to evaluate the environmental impacts of these deicing and anti-icing chemicals and to regulate their discharges accordingly. Most deicing events occur during winter storms, so the runoff from the storm serves as the vehicle for transporting the deicing chemicals off the airfield and into the local receiving waters. Most existing federal and state regulations do not include limits on deicing chemicals in the stormwater discharges. Without discharge limits, airports have been freely discharging stormwater contaminated with deicing/anti-icing chemicals.

Because most airports were built long before environmental regulations for polluted water runoff were in place, the infrastructure needed to control the large quantities of deicing/anti-icing fluids used by many airports is often non-existent. According to FAA, 70% of the US population resides within 20 miles of at least one of the 538 commercial airports (2). A large percentage of primary hub commercial airports (97% in 1996) are located to adjacent environmentally sensitive areas (i.e., water bodies such as wetlands, rivers, coastal areas, creeks and lakes (3). Thus given that many, if not most of the airports in the US are sited along waterways, the control and disposal of deicing/anti-icing chemicals constitutes a significant water pollution issue.

As the amount of air travel has increased, the volume of deicing chemicals used and discharged into the environment has also increased, with the resulting attention by

regulators on the potential negative environmental impacts of de-icing chemicals. As the negative impacts have become more apparent, the public has begun to take a more active role in requiring airports to control deicing/anti-icing chemical discharges. This is evidenced by several citizen lawsuits filed by the Natural Resources Defense Council (NRDC) regarding current de-icing practices and their impacts on the environment.

Thus airports are now under pressure to try control the impact of deicing/anti-icing chemicals on stormwater while maintaining safe and economically viable air transportation.

III) BACKGROUND On De-icing/Anti-icing

Federal Aviation Regulations (FAR) established by the U.S. Federal Aviation Administration (FAA) prohibit takeoff when the frost, ice, or snow adheres to the airplane wings, propellers or control surfaces. This is known as the *Clean Airplane Concept*. These Federal Aviation Regulations also prohibit takeoff any time that frost, ice, or snow can reasonably be expected to adhere to the airplane, unless the operator has an approved ground deicing/anti-icing program.

Deicing/Anti-icing of aircraft

Deicing and anti-icing of aircraft remove and inhibit for a period of time, the formation of ice and snow on wings, fuselages, and other parts of the airplane that provide lift during takeoff. Common practice is to deice (remove accumulation) then anti-ice (protect from further accumulation) aircraft before takeoff.

Aircraft deicing processes as practiced at Logan airport are briefly described as follows. Deicing fluids are usually applied to the aircraft as a hot mixture under pressure using a nozzle mounted on a vehicle. The pressure of the liquid hitting the surface of the aircraft mechanically removes snow and ice, which is also melted by the solution. The deicing and anti-freeze properties of the compound also further remove the snow and ice. Between 20% to 50 % of the deicer that is applied to the aircraft is estimated to remain, meaning that as much as 80% of the fluid can end up as runoff. In addition, the amount of deicing used on an individual aircraft can range from 10 gallons to several thousand gallons for a small corporate jet to a large commercial aircraft (5). This procedure is performed by the airline or by a service company.

Tenant aircraft deicing operations primarily utilize either ethylene or propylene glycol mixed equally with water applied from tank trucks that have spray nozzles on extendable booms to reach all necessary portions of the aircraft. Deicing is usually performed immediately before departure from the gates or hangars (4).

Aircraft deicers are classified into four classes/types and they are Type I, Type II, Type III and Type IV. Not all types are currently being used. These fluid types vary by composition, holdover times (Holdover time is the period between the time of aircraft deicing fluid (ADF) application and time of takeoff; function of ambient temperature, precipitation, and ADF type and mixture strength.) and contains either ethylene glycol or propylene glycol, water and additives. Type I is the most commonly used fluid and is used only for the deicing or removal of ice, snow and frost from the aircraft parts and is a relatively thin liquid. Type II, III, and IV were developed for anti-icing and contains thickeners that helps form a film on the aircraft that increases holdover time and protects against re-icing and is relatively more viscous. These fluids being thicker and more viscous, clings to the aircraft, protects surfaces longer, and allows for longer holdover times than Type I.

FAA regulations do not stipulate which fluids should be used but recommend that commercial carriers and owners of private aircraft use fluids that meet the standards set, certified by the Society of Automotive Engineers (SAE) and approved by FAA. Type II and Type IV fluids were designed for use on all aircraft while Type III fluids were designed for use on smaller, commuter aircraft. In the US, most of the larger airlines use Type IV fluids exclusively for anti-icing because of its increased holdover times, but due to cost considerations, many smaller and regional airlines use Type II fluids as Type IV fluids require specialized application equipment.

Deicing/Anti-icing of runways

Deicing and anti-icing of runways involves the removal of snow/ice on the ground and the prevention of its' accumulation such that the pilot has enough friction for takeoff, landing and braking.

The runway deicing/anti-icing process typically includes mechanical removal of snow and ice using plows, brushes, and blowers, followed by the application of sand or chemical deicing/anti-icing agents.

This operation can be divided into the deicing of roadways and the deicing of taxiways and runways. For roadways, the practice is similar to public roadways, where a combination of rock salt (sodium chloride) and sand is used for both deicing and anti-icing purposes. Salt and sand are not, however, considered suitable for runway deicing due to corrosive and mechanical effects on aircraft. At Logan airport, on the taxiways and runways, a combination of ethylene glycol, urea and water in liquid form are applied under the trade name UCAR used both for anti-icing and deicing purposes although the majority of applications are for de-icing. The weight ratio is approximately (4):

- Ethylene glycol 50%
- Urea 25%
- Water 25%

It is applied by rear-mounted spray equipment attached to trucks at standard manufacturers application rates that range from 0.5 and 1.5 gallons per 1,000 square feet of runway surface depending on ground conditions. Additionally, urea in solid “prill” form and sand may be used occasionally for deicing purposes and to increase runway friction and braking action, respectively.

IV) ENVIRONMENTAL ASPECTS

i) Introduction

The primary environmental aspect of the deicing operation is the generation of spent aircraft deicing fluids (ADFs). Deicer fluid generated from the aircraft surfaces and the runway surfaces are transported to drains that function to direct the fluids to onsite water treatment facilities such as storm drains and paved surfaces. The storm drains and paved surfaces discharge the fluid to the local waterways or groundwater as sheet runoff. In some cases, deicing fluids are released directly to the environment as runoff to surface waters and infiltration to groundwater.

When released to the environment, ADFs are generally biodegradable with some components requiring more oxygen to biodegrade than others. However, the biodegradation of glycols released into the aquatic environment, which is variable relative to temperature, can be rapid and extremely oxygen demanding. Thus glycol contaminated stormwater runoff can deplete dissolved oxygen levels and threaten oxygen dependent aquatic life forms and also may have toxic effects on life forms present. Subsequently, the principal environmental impact of deicing fluids would be the biochemical oxygen demand (BOD) associated with the deicer fluids in the runoff.

BOD is the measure of the amount of dissolved oxygen needed to break down (or oxidize) a substance. A high BOD means that large amounts of dissolved oxygen in a water body must be used up to oxidize the substance, thereby lowering the dissolved oxygen levels available for fish and other aquatic organisms to breathe. For these reasons, fish kills have been associated with discharges of deicing chemicals and other environmental impacts associated with deicing chemicals include algal nuisances, odors, and contaminated surface water and groundwater drinking water systems (1).

In addition to the oxygen demand associated with deicing compounds, urea releases ammonia when it breaks down and heavily loads receiving waters with nitrogen

(4). Ammonia is an environmental concern because it contributes to nitrogenous oxygen demand and is potentially hazardous to aquatic life. Excessive urea in receiving streams often accelerates algal blooms in warmer months, due to additional nitrogen available (5). Algal blooms consume large amounts of oxygen, resulting in even greater reduced dissolved oxygen concentrations in streams and may cause eutrophication in lakes.

Potassium acetate-based deicers places a significant and much lower oxygen demand on receiving waters than urea does and does not result in ammonia and pH increase associated with urea. For this reason, certain airports use this deicer to reduce the environmental impact caused by urea.

Considering just deicer fluids by themselves, they are also moderately toxic to humans (9). Irritation to the skin and eyes upon contact is usually experienced (10). Oral ingestion may cause abdominal discomfort and pain, dizziness, and effects on the central nervous system and kidneys (9). However since these fluids are diluted with water, it is unlikely that deicing personnel would ingest anything close to a lethal amount. In addition, there is also a potential for volatile organic emissions to the air from the application of fluids to the planes and runways. But since the amount of glycol that vaporizes is usually small, the VOCs' emission to the air is insignificant and this together with the oral ingestion of the deicer fluids, is not a potential environmental problem (17).

It should also be noted that these deicing/anti-icing fluids are known to contain a variety of additives, including wetting agents, fire suppressants, and potentially toxic corrosive inhibitors. Many of these additives are many times more toxic and harmful to the environment than the primary constituents of ADFs, namely ethylene and propylene glycol. Since formulations are usually trade secrets, this increases the difficulty in accessing the true environmental impacts or toxicity effects caused by these additives.

Sand, while not degradable, can clog storm drains and contaminate water bodies through increased erosion and sediment built up.

The general summaries of environmental impacts due to the presence of ADFs in the airport stormwater runoff are:

1. Aquatic life effects such as fish kills, growth of biological slimes, elimination of aquatic life, stressed invertebrate communities, and impaired fisheries
2. Effects on wildlife, birds and cattle
3. Human health problems (worker and human exposure – headaches and nausea)
4. Aesthetic effects (odor, color and foaming.)
5. Effects on quality of receiving waters (low DO, high BOD, organic enrichment), groundwater, water supplies, and soils.

Thus airport runoff that usually contains significant amounts of deicing material cannot be normally discharged directly into the environment but must be instead has to be contained and treated to reduce the pollutants before release into the environment

ii) *Environmental Impacts of Chemical Deicers & Anti-icers*

a) *Introduction*

The Federal Aviation Administration, who sets the standards for aviation safety for all the airports through the United States, has approved only two aircraft deicing chemicals; ethylene glycol and propylene glycol. Only six other chemicals have also been approved for airfield surface de-icing and they are ethylene and propylene glycols, sodium formate, sodium acetate, potassium acetate and calcium magnesium acetate.

Glycols are effective deicers and constitute the bulk of chemical deicers used in the country but have recently come under scrutiny because of their potential adverse environmental effects. This phenomenon could be due to the increased use of these chemicals as deicers in the last decade. The principal environmental effects resulting from glycol discharge are high aquatic toxicity and biochemical oxygen demand in the surrounding waters that serves as the main transport media for the glycols once they are

released into the environment. Glycol pollution of air and soil are relatively insignificant in comparison to that of water.

In this section, we will look at the environmental effects of glycols and other chemical deicers on the aquatic environment, beginning with fate and transport in the environment, followed by toxicity and then biochemical oxygen demand.

b) Fate, Transport & Degradability in the Environment

1) Glycols

During applications of deicing fluids to the aircraft, up to 80% of the solution is capable of falling off onto the pavement surface, either through overspray or during taxi and takeoff (18).

These glycol fluids have low vapor pressure and high solubility (*Table 1*) as indicated by the low Henry's constants indicating that the glycols will not readily volatilize to the atmosphere from the surface water. Volatilization is favored when heating occurs but precipitation (e.g., rain, snow) will remove most of any vapor released to the environment. When applied, there may not be any precipitation to remove the glycols, but the glycols are also readily broken down by means of photochemical oxidation. Propylene glycol has a half life of 0.8 days and ethylene glycol has a half life of 0.3 to 3.5 days (18). Glycols have also high mobility in soils due to their low organic carbon partition coefficients (K_{oc}) (*Table 1*) (18).

Some of the physical and chemical properties are summarized in the table below.

Table 1: Physical and Chemical Properties of Ethylene and Propylene Glycol

PROPERTY	ETHYLENE GLYCOL	PROPYLENE GLYCOL
Molecular Weight	62.07	76.11
Color	Colorless	Colorless
Physical State	Liquid	Liquid
Melting Point	-11.5 deg C	-60 deg C
Boiling Point	198 deg C	187.6 deg C
Density @ 20 deg C (g/cm ³) @ 30 deg C (g/cm ³)	1.1135 1.1065	1.0361 No data
Odor	Odorless	Odorless
Odor Threshold	No data	No data
Solubility: water at 20 deg C	Miscible with water	Miscible with water
Organic Solvent(s)	Soluble in lower aliphatic alcohols, glycerol, acetic acid, acetone; Slightly soluble in ether; practically insoluble in benzene, chlorinated hydrocarbons, petroleum ether, oils	Soluble in alcohol, ether, benzene; slightly soluble in acetone, chloroform
Partition Coefficients Log Kow Log Koc	-1.36 0.592	-0.92 0.88
Vapour Pressure at 20 deg C	0.06 mm Hg	0.07 mm Hg
Henry's Law Constant (H): @ 25 deg C	2.34 x 10 ⁻¹⁰ atm-m ³ /mole	1.2 x 10 ⁻⁸ atm-m ³ /mole

Source: Table 3-2 (18)

Biodegradation plays a major role in removing residual glycol from soil. At concentrations of less than 6000 mg/kg in soil, ethylene glycol was found to have a biodegradation rate of 3.0 mg/kg in soil/day at -2 deg C and 19.7mg/kg soil/day at 8 deg C. Propylene glycol degraded at a rate of 2.3 mg/kg soil/day at -2 deg C and 27.0 mg/kg soil/day at 8 deg C (18).

Ethylene and propylene glycols reach groundwater and surface water near airports as a result of spills, runoff and discharge. Estimates in the U. S Toxic Release Inventory (TRI) indicate that 1.2 million pounds of ethylene glycol were released to surface waters

nationwide (18). Estimates of released propylene glycol are not included in the TRI because TRI reporting of propylene glycol is not required.

In laboratory experiments, glycols undergo rapid biodegradation in surface water. The half-life of ethylene glycol in surface water is estimated at 2-12 days under aerobic conditions and 8 – 48 days under anaerobic conditions (18). Propylene glycol has an estimated half-life of 1-4 days under aerobic conditions and 3-5 days under anaerobic conditions. Ethylene glycol undergoes complete biodegradation in surface waters in 14 days at 8 deg C (18). Glycols do not undergo significant abiotic transformation in water, and they tend to be resistant to hydrolysis (18).

The data depicting the half-lives of ethylene and propylene glycol under aerobic and anaerobic conditions are summarized in *Table 2* below. Note that these data were not conducted under the same laboratory conditions and may not be directly comparable.

Table 2: Half Lives of Glycols

Glycol Type	Half-Life		
	Aquatic		Soil
	Aerobic Conditions	Anaerobic Conditions	
Ethylene Glycol	2 to 12 days	4 to 48 days	0.2 to 0.9 days
Propylene Glycol	1 to 4 days	3 to 5 days	Equal to or slightly less than in water

Source: (18)

As indicated by the glycol’s low octanol/water partition coefficients in *Table 2*, glycols do not significantly bioconcentrate or biomagnify in animals or plants. Since glycols are very soluble in water, biodegradation is the most important process that breaks down ethylene and propylene glycol.

Ethylene and propylene glycols place a high demand for oxygen on the environment as aquatic organisms degrade them. Ethylene glycol has a reported freshwater 5-day biochemical oxygen demand (BOD5) ranging from 400,00 to 800,000 mg/L (19), and a marine BOD5 of about 260,000 mg/L (20). Both the freshwater and marine BOD5 for propylene glycol can exceed 1,000,000 mg/L (19,20) thus indicating

that propylene glycol does exert a higher oxygen demand on the receiving waters. These oxygen requirements are very high and as a comparison, domestic sewage has a BOD5 of approximately 200-300 mg/L (21). As a result, they can significantly affect or threaten aquatic life in streams that are not high in dissolved oxygen by depleting the available oxygen. These data are summarized in *Table 3* below.

Table 3: BOD5 of Glycols in Various Waters

Chemical	Freshwater BOD5 (mg/L)	Marine BOD5 (mg/L)
Ethylene Glycol	400,000 – 800,000	>1,000,000
Propylene Glycol	1,000,000	>1,000,000
Domestic Sewage	200 – 300	N.A

Source: (19, 20 and 21)

BOD5: 5 Day Biochemical Oxygen Demand

2) *Formulated Products and Additives of Propylene and Ethylene Glycol*

As discussed earlier, both pure propylene and ethylene glycol will exert a higher oxygen demand on the receiving waters, as they are more concentrated. Because, the additives constitute a small portion of ADFs (typically less than 2%), the chemical additives should not cause a significant increase in the oxygen demand of these products. However, some of the additives may be toxic to the microorganisms that biodegrade them and thus inhibiting the biodegradation of the ADFs, and therefore reducing the measured BOD in experiments.

Like pure propylene and ethylene glycol, the glycol portion is not expected to bioaccumulate and will rapidly biodegrade. A summary of BOD5 and COD (Theoretical Chemical Oxygen Demand) results for Type I, II and IV ADFs are shown below (*Table 4*). Although the ultimate BOD values for ADFs are still less than that of their corresponding pure glycols respectively, formulated fluids still pose an oxygen depletion threat on receiving streams.

Table 4: BOD5 of Formulated Deicers

Fluid Type	COD	BOD: 5days	BOD: 10days	BOD: 15days	BOD: 20days
Type I – EG based (concentrate)	1,260,000	873,000	1,070,000	NA	1,210,000
Type II – PG based (concentrate)	1,400,000	840,000	NA	NA	NA
Type II – PG based	NA	730,000	NA	NA	NA
Type IV – EG based	945,000	463,000	576,000	775,000	935,000
Type IV – PG based	794,000	520,000	NA	NA	785,000

Note: All units are in mg/L

Sources: (22, 24, 25, 26 and 27)

Although present in small amounts, fluid additives may impact the biodegradability of ADFs. Limited data is available to assess the impact of ADF additives on the fate of ADFs. From Cornell et al. who performed tests on the degradation of formulated fluids with tolyltiazoles (TTZ), it was found that TTZ has a significant impact on the degradation rate. With TTZ present at concentrations that might be found in airport soils, the pseudo-first order biodegradation rate constant for a propylene glycol-based ADF (containing TTZ) was approximately three times smaller than that of pure propylene glycol. The degradation rate also decreased as TTZ concentration increased (14, 28).

3) Urea

The low octanol/water partition coefficient (-1.52 at 20 to 25 deg C) indicates that it is not likely to bioaccumulate. Also, it is not likely to volatilize due to the low Henry's constant, though it readily leaches from the soil into the surface and groundwater (16).

Excessive urea in receiving streams often acts as a fertilizer and accelerates algal blooms in warmer months due to additional nitrogen available that comes from the chemical reactions of urea in water. Such algal blooms consume large amounts of oxygen, resulting in even greater reduced dissolved oxygen concentrations the receiving waters and may cause eutrophication in lakes (4). This also leads to the death of other

species plants and animals that require high levels of dissolved oxygen. Decaying algae in turn also consumes oxygen and can cause odor problems

Urea has a BOD₅ of about 20,000 mg/L (1). However as it breaks down to ammonia, the BOD₅ of urea increase to about 2,000,000 mg/L (4). An important factor to consider is that the degradation of urea to ammonia is very dependent on temperature and negligible degradation occurs at temperatures of less than 8 deg C. Therefore, while the urea of urea may cause potential problems to the aquatic environment due to ammonia formation, it may not be as large a concern during the winter months as it would be during the spring or winter months. These values are represented in Table 5 on page 19 as a comparison to other deicing chemicals.

4) *Potassium Acetate*

All forms of potassium acetate are readily biodegradable and has a tendency to degrade well at lower temperatures. It exerts a BOD that is much lower than other runway deicers (e.g., urea). Reported BOD₅ values are in the range of 0.14 to 0.30 grams of oxygen per gram of potassium acetate (22) or 300,000 mg/L (23) are represented in Table 5 on page 19. Independent studies conducted by vendors of potassium acetate have indicated that 100% of potassium acetate will degrade in 20 days at temperatures down to 2 deg C, while only 2% of urea will degrade in 20 days (23).

5) *Calcium Magnesium Acetate (CMA)*

CMA is also readily biodegradable and exerts a BOD₅ of 540,000 mg/L (1) and these values are represented in Table 5 on page19.

6) *Sodium Acetate*

Sodium acetate is readily biodegradable even at low temperatures and it exerts a BOD₅ of 580,000 mg/L (23) and these values are represented in Table 5 on page19.

7) *Sodium Formate*

Sodium formate is also highly biodegradable and its' BOD5 is 120,000 mg/L (4) and these values are represented in Table 5 on page 19.

Table 5: Summary of the BOD5 of certain chemicals

Chemical	BOD 5 (mg/L)
Urea	20,000
Ammonia	2,000,000
Potassium Acetate	300,000
Calcium Magnesium Acetate	540,000
Sodium Acetate	580,000
Sodium Formate	120,000

Sources: (1,23 and 24)

c) Toxicity

i) Introduction

Typically for aircrafts, glycol deicers are manufactured as a mixture of glycol, water, and other additives such as corrosion inhibitors, surfactants and wetting agents. The toxicity exhibited by the ADFs is in part due to the presence of the glycols (which typically make up 45% to 65% of the total fluid by weight), but is also due to the additives contained in the fluids. Although additives comprise of a small percentage of ADFs, they may be responsible for a disproportionate share of the toxicity of the ADFs.

Several toxicity tests have been performed using pure ethylene and propylene glycol but a few studies have been performed using formulated ADFs. Thus when referring to glycol toxicity, usually the toxicity of the pure product (without addition of water or additives) is referred to. However, the pure substance is never used on the

aircraft and airfields. While the toxicity levels of the manufactured glycols are more appropriate in evaluating the deicers' potential environmental impacts, determining the toxicity of these glycol mixtures are difficult with the toxicity varying for each mixture. It should also be noted that many of the formulations considered as trade secrets. Some information is also available on the types of compounds that may be included as additives in ADFs, though it is the pure substance that is being considered.

The toxicity of pavement deicing agents are primarily due to the application of glycols and urea although at the present moment, there are more benign pavement deicing agents currently being used.

Pavement or runway deicers may cause significant adverse environmental effects, although many airports are beginning to use less harmful agents. The FAA has approved the following pavement and runway deicers: urea, ethylene glycol, potassium acetate, calcium magnesium acetate (CMA), sodium acetate and sodium formate. Alternative agents that may be used are isopropanol and propylene glycol. Salts including magnesium chloride, sodium chloride, and potassium chloride are not approved for use in aircraft operational areas since they are corrosive to aircraft. Sand is occasionally used to increase friction and improve aircraft braking performance. The specifications for these agents are set by the SAE or the United States military (MIL-SPEC).

1) *Propylene and Ethylene Glycol*

The toxicity of propylene and ethylene glycol shall be written together as a form of comparison.

There is a common perception that propylene glycol is less toxic to wildlife than ethylene glycol, although they are similar in chemical and physical properties. This is probably due to the fact that the Food and Drug Administration (FDA) has classified propylene glycol as "generally recognized as safe" (GRAS) for use in food or food products (9) and the Cosmetics, Toiletries, and Fragrances Association (CFTA) has

approved propylene glycol in cosmetics products up to concentrations of 50% (9). In addition, ethylene glycol is considered as a hazardous air pollutant (HAP) by Congress and is required to be reported for use under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) if certain amount is released to the environment in a limited time (10).

Both ethylene and propylene glycol exhibit similar aquatic toxicity characteristics. Acute tests were performed on both freshwater and marine aquatic life to determine the lethal concentration (LC50) for the mortality for 50% of the sample population over a short period of time. The standard method then of comparing toxicity among chemicals is to compare the LC50 values for a common species. The greater the LC50 value of a chemical, the lower is its toxicity. In general, any material with an LC50 above 1000mg/l is considered relatively harmless, as depicted in the *Table 6* below (9).

Table 6: Classification for Aquatic Toxicity Rating Scale

<u>Classification</u>	<u>LC₅₀ Value (mg/L)</u>
Super Toxic	<0.01
Extremely Toxic	0.01 – 0.1
Highly Toxic	>0.1 – 1.0
Moderately Toxic	>1.0 – 10
Slightly Toxic	>10 – 1000
Practically Non-toxic	>100 – 1000
Relatively Harmless	>1000

LC50 = Lethal Concentration 50
 mg/L = milligrams per liter
 Source : (9)

Table 7 summarizing the LC₅₀ for four freshwater and marine organisms is located below, with brine shrimp being the only marine organism of the four species. It can be seen that these toxicity values fall well into the “relatively harmless” range and that are similar for both chemicals that are fairly non-toxic to the aquatic environment.

Table 7: Summary of LC values for pure glycols

Organism	Exposure time (hours)	LC ₅₀ (mg/l)	
		Propylene Glycol	Ethylene Glycol
Water Fleas (<i>Daphia magna</i>)	48	43,000(10)	54,700(10)
Fathead Minnows (<i>Pimephales promelas</i>)	96	>62,000(11)	81,950(11)
Algae (<i>Selenastruma capricornutum</i>)	24	19,000(10)	7,900(10)
Brine shrimp	24	>10,000(12)	>20,000(12)

LC₅₀ = Lethal Concentration 50

mg/L = milligrams per liter

Source : (10), (11) and (12)

For mammalian toxicity, there are three main exposure routes for ethylene and propylene glycol: inhalation, oral and dermal (through skin adsorption).

Inhalation and dermal exposure to ethylene glycol are not expected to exhibit toxic effects (13). Data based on human oral exposure (accidental or intentional) of ethylene glycol are available, and several animal studies have been used to corroborate the findings (13). When ingested, ethylene glycol quickly breaks down in the body to form chemicals that crystallize and affect kidney functions, and acidic chemicals that alter the body's normal chemical balance.

Inhalation, oral and dermal exposure to propylene glycol are not expected to lead to toxic effects, although some data suggest that oral exposure to propylene glycol may cause allergic reactions with minor side effects (13). Propylene glycol also readily breaks down in the body but does not form any crystals or acidic chemicals in the body (13).

Unlike aquatic tests, tests performed on humans or animals using ethylene or propylene glycol almost always focused on either ethylene or propylene glycol, but not both, and hence were performed under various conditions. Thus the mammalian toxicity results of both are not as comparable as the aquatic results. It is also important to

recognize that more studies have been performed using ethylene glycol than propylene glycol.

2) *Formulated Products and Additives of Propylene and Ethylene Glycol*

Formulated glycol deicers are more toxic than pure glycols, sometimes by order of magnitude. This can be attributed to the additives that are added to these glycol mixtures and this information for the same exposure time is summarized in the table below.

One type of additive is a group of compounds known as tolytriazoles, including 4(5)-methylebenzotiazole (MEBT) and 1H-benzotriazole (BTZ). As compared to the other formulated deicers in the table below, MEBT is the most toxic of them all, and it has roughly 3 orders of magnitude greater than the toxicity of either glycols alone for Water Fleas (*Daphia magna*). These values are summarized in *Table 8* below for easier reading.

Table 8: Summary of LC50 values for pure and formulated glycols and additives

Chemicals	LC50 (mg/l)		
	Water Fleas (<i>Daphia magna</i>)	Fathead Minnows (<i>Pimephales promelas</i>)	Algae (<i>Selenastruma capricornutum</i>)
Propylene Glycol	43,000 (10)	>62,000 (11)	19,000 (10)
Ethylene Glycol	54,700 (10)	81,950 (11)	7,900 (10)
Propylene Glycol Formulated Deicer	~3,500 (14)	~2,000 (14)	NA
Ethylene Glycol Formulated Deicer	400 (15)	240 (15)	NA
MEBT	74 (14)	NA	NA

LC50 = Lethal Concentration 50
 mg/L = milligrams per liter
 Source : (10), (11), (14) and (15)

Little mammalian toxicity data is available for tolytriazoles, although it is considered harmful if swallowed and may cause irritation on contact (14).

3) Urea

Urea is typically applied in granular form to the pavement and runway areas. It is a fertilizer and is relatively non-toxic at high doses. However, it degrades by hydrolysis to carbon dioxide and ammonia that can be very toxic to aquatic organisms even at low concentrations. Once ammonia is formed, it remains in solution as ammonia or its ionized form (NH₄⁺), biologically converts to other nitrogen forms (e.g., NO₃ or N₂), or volatilizes to the air.

Urea is considered non-toxic to aquatic organisms but it can irritate the nose and throat, causing a sore throat, sneezing or coughing, and shortness of breath in humans (16). Chronic and acute exposure in high concentrations may cause eye damage, skin redness or rash (dermatitis), or emphysema (17).

Ammonia in its unionized form is one of the urea byproducts that may have adverse aquatic effects and its aquatic toxicity is much greater than that of urea. Some values for the aquatic toxicity of urea and ammonia are shown in the *Table 9* (17).

Table 9: Summary of LC values for urea and ammonia

Organism	LC50 (mg/l)	
	Urea	Ammonia
Water Fleas (<i>Daphia magna</i>)	>10,000 (24 hour exposure)	189 (48 hour static test)
Fathead Minnows (<i>Pimephales promelas</i>)	N.A	0.73 –3.4 8.2 (hard water) (96 hour exposure)
<i>Tilapia mossambica</i>	22,500 (96 hour exposure)	N.A

LC50 = Lethal Concentration 50
 mg/L = milligrams per liter
 Sources: (16) and (17)

4) *Potassium Acetate*

Potassium acetate is currently one of the most commonly used runway and pavement deicers based on EPA-sponsored site visits, although many airports have expressed concern that it may degrade insulation in electric systems (e.g., runway lights).

It is applied in liquid form and is slightly flammable as well as corrosive and thus is mixed with corrosive inhibitors. It is a common food additive and is relatively non-toxic to mammals in small doses although it may cause eye irritation (17). Data for potassium acetate-based deicers are presented in *Table 10* below.

Table 10: Summary of LC values for potassium acetate based deicers

Organism	Exposure time	LC ₅₀ (mg/l)
Water Fleas (<i>Daphia magna</i>)	48 hours	>3,000
Fathead Minnows (<i>Pimephales promelas</i>)	7 days	>1,500
Rat	24	>5,000 (Lethal Dose in mg/Kg)

LC₅₀ = Lethal Concentration 50
mg/L = milligrams per liter
Source : (17)

5) *Calcium Magnesium Acetate (CMA)*

Calcium Magnesium Acetate (CMA) is applied in solid granular form and is an effective anti-icer that is relatively non-toxic to the environment although it has high costs. Unlike magnesium chloride and other salts, it is not corrosive and therefore does not contain corrosive inhibitors. The aquatic and mammalian toxicity is summarized in *Table 11* below.

Table 11: Summary of LC values for CMA

Organism	Exposure time	LC50 (mg/l)
Water Fleas (<i>Daphia magna</i>)	48 hours	>1,000
Rainbow Trout (<i>Oncorhynchus mykiss</i>)	96 hours	>1,000
Rat	LD 50 (Oral) LD 50 (dermal) 4 hour (inhalation)	>5,000 (in mg/Kg) >5,000 (in mg/Kg) 4.8

LC50 = Lethal Concentration which kills 50% of the test organisms.

LD50 = Lethal Dose which kills 50% of the test organisms

mg/L = milligrams per liter

Source : (17)

6) *Sodium Acetate*

Sodium is typically applied in solid form and is “relatively harmless” according to the US Fish and Wildlife standards (17). It is not considered hazardous but may irritate the skin on contact or irritate the respiratory tract following inhalation of dust. Acute aquatic and mammalian toxicity are summarized in *Table 12* below.

Table 12: Summary of LC values for Sodium Acetate

Organism	Exposure time	LC50 (mg/l)
Water Fleas (<i>Daphia magna</i>)	48 hours	2,400
Fathead Minnows (<i>Pimephales promelas</i>)	24 hours	2,750
Rat	LD 50 (Oral)	3,530 (in mg/Kg)

LC50 = Lethal Concentration which kills 50% of the test organisms.

LD50 = Lethal Dose which kills 50% of the test organisms

mg/L = milligrams per liter

Source : (17)

7) *Sodium Formate*

Sodium formate is typically applied in a pellet form and is mixed with corrosion inhibitors to meet specific requirements. Thus we are looking more at a formulated deicer. Significant exposure to sodium formate deicer may adversely affect people suffering from chronic disease of the respiratory system, skin, and/or eyes. Toxicity data from a sodium formate deicer manufacturer is summarized in *Table 13* below.

Table 13: Summary of toxicity values for Sodium Formate Deicer

Organism	Exposure time	LC50 (mg/l)
Water Fleas (<i>Daphia magna</i>)	24 hour EC50	4,800
	48 hour EC 50	4,400
Zebra Fish	96 hour LC50	100
Rat	LD 50 (Oral)	>2,000(in mg/Kg)

EC 50 = Median Effective Concentration which is the concentration that causes a specified effect in 50% of the organisms.

LC50 = Lethal Concentration which kills 50% of the test organisms.

LD50 = Lethal Dose which kills 50% of the test organisms

mg/L = milligrams per liter

Source : (17)

d) Nuisance Odors

Several airport authorities have reported onion-like nuisance odors associated with groundwater and/or stormwater from airports contaminated with propylene glycol (1). Traces of organic sulfur compounds and inorganic sulfate and sulfide ions were also detected in these contaminated waters (1). Laboratory experiments by Camp, Dresser and Mckee then suggested that reduced sulfur compounds resulting from the anaerobic decomposition of propylene glycol in the presence of sulfur, caused such odors. Control samples in the absence of propylene glycol did not produce such an odor (1). Camp, Dresser and Mckee then hypotesized that ethylene glycol could possibly be contributing to these odors although the study that they carried out did not demonstrate this.

e) Nuisance Bacterial Growth

There also have been several documented cases of bacterial slimes growing in glycol-contaminated waters. For example, “biological slime” has been reported to be growing where propylene glycol-contaminated stormwater has pooled on the ground surface (1). In addition, the nuisance bacteria *Sphaerotilus* has been found to be growing in ethylene glycol-contaminated waters by the Kentucky Department of Environmental Protection (19). This bacteria flourishes in water bodies with high carbon content and low dissolved oxygen levels (which are typical of waters contaminated with glycol) and grows rapidly under these oxygen depleted conditions (19). The bacterium then grows in long streamers attached to the streambed and can suffocate the benthic organisms and take over the entire ecosystem (19). The decomposing bacterium in return then places a high oxygen demand on the system and gives off foul sulfide odors (19).

V) POLLUTION PREVENTION

i) Introduction

Local environmental problems such as fish kills and odor problems combined with EPA's storm water program have prompted the airports and airlines to investigate a wider range of pollution prevention practices designed to eliminate or minimise the environmental impacts of deicing/anti-icing fluids (ADFs) without compromising safety.

There are four basic approaches that can be summarised as a guide to reduce pollution for aircraft or airfield deicing/anti-icing operations:

- Adoption of alternative chemicals that are less harmful to the environment through the development of more environmentally benign fluids.
- Minimisation and reduction of the amount of fluids applied through the development of better staying fluids, improved application methods, alternative/innovative deicing/anti-icing technologies, good maintenance and preventive practices.
- Development of collection and disposal strategies that prevent the release of ADF-contaminated waste water to the environment.
- Development of ADF recycling systems.

However, it should be noted that the pollution prevention practices selected by an airport or airline for use at a particular airport often depend on a variety of factors, including climate; total amount of chemicals being applied; number of airlines; aircraft fleet mix; costs; existing infrastructure; availability of land and many more. Also, the different regulations of each of the statutory boards governing each country may also account for the differences in deicing/anti-icing practices in different countries for example, Europe and the US.

ii) *Evaluation of Aircraft Deicing/Anti-icing Chemicals and Alternatives.*

Currently the FAA has only approved the use of propylene and ethylene glycol to remove snow and ice from aircraft. Propylene glycol use has also increased because of aquatic toxicity concerns from the use of ethylene glycol, even though propylene glycol has a higher BOD.

Because chemical deicers dissipate rapidly (slip off from aircraft surface), reapplication is often required if the aircraft does not take off within a specific time frame after which the glycol loses its effectiveness, known as the holdover time. Thus, to help increase holdover times and thus reduce the amount of chemical deicers applied, thickening agents are added to the glycol mixture. Based on the quantity of thickening agents, this then classifies the different deicing solutions to the different type I, II, III and IV as highlighted in the section regarding background information on deicing/anti-icing. Thus, the trend towards greater use of Type IV fluids which have the greatest viscosity/thickness and are less likely to shear off a plane should reduce the amount of deicing/anti-icing chemicals released into the environment.

One of the plausible solutions to the environmental problems with glycol-based ADFs is the replacement with more environmentally benign products. Most of the current research is thought to be in the preliminary stage and it is likely to be sometime before a suitable replacement is found. Substitute products need to be more biodegradable and less toxic than the current glycol-based ADFs and have to also be less toxic than current products. They have to be noncorrosive to aircraft parts and economically viable. This meaning that they have to be inexpensive and at least as effective in maintaining air safety as the glycol-based fluids they replace. Based on literature and experiments, two alternative chemicals, isopropanol and diethylene glycol seem suitable alternatives and will be discussed below.

However, since the FAA has only approved two aircraft deicing chemicals, airlines and airport authorities have little choice, let alone flexibility. The primary advantage of using glycols then would be their effectiveness and ability to melt snow quickly and their main disadvantage would be their potential environmental impact. Now, we shall look at isopropanol and diethylene glycol as possible alternatives.

a) *Isopropanol*

Isopropanol is another freezing point depressant is currently used by the US Air Force as a pavement deicer, but is not currently an SAE- or FAA approved freezing point depressant for aircraft deicing. Although it is highly flammable and cannot meet the SAE specifications without the addition of fire suppressants, it may be a viable alternative due to it's low cost and effectiveness as an alternative freezing point depressant. Research is currently being carried out on the use of isopropanol for aircraft deicing.

Isopropanol is a colourless, flammable liquid that has a slight odour resembling ethanol and acetone (28). Many industries including chemical and pharmaceutical manufacturing use it for solvent applications and is also commonly used as a deicing agent in liquid fuels (28). In pure form, it has a freezing point of approximately -88.5 deg C(28).

Available aquatic toxicity data show that isopropanol exhibits aquatic toxicity at concentrations similar to but slightly less than glycols and is also considered "relatively harmless"(30). It is also considered toxic if ingested in large enough doses, or through the subcutaneous route. Experimentally it has been shown to be teratogenic and cause negative reproductive effects and is an eye and skin irritant (28).

Isopropanol is also highly soluble in water and is not likely to bioaccumulate (16). It also has a theoretical oxygen demand, which is significantly higher than that of glycols though it has a very high rate of biodegradation (28). Thus this rapid biodegradation of isopropanol that combined with a high theoretical oxygen demand, can greatly reduce

oxygen levels in receiving streams and would result in greater oxygen depletion than either ethylene or propylene glycol which does not really make it a good substitute.

b) Diethylene Glycol

Diethylene glycol is an SAE-approved freezing point suppressant for use in ADFs; however, no ADFs that are primarily diethylene glycol are currently approved for use in the US. Diethylene glycol-based deicing fluids are more commonly found in Europe, although some formulations used in the United States may contain a small portion of diethylene glycol.

It is a clear, colourless, syrupy liquid that may be used as an anti-freeze, but is more commonly used in the petroleum refining industry as a solvent extractor (28). In its pure form, it has a freezing point of approximately -10 deg C (28).

It exhibits similar toxicity characteristics to ethylene glycol but it has a higher minimum freezing point temperature that does not make it a favourable alternative at this time. However, traces of diethylene glycol may be commonly found in ethylene glycol-based ADFs (29).

Like ethylene glycol, it can be fatal if ingested but is not as toxic to humans or mammals via other exposure routes (28). It is also an eye and skin irritant that can cause degenerative changes in the kidneys, liver, respiratory failure, and brain damage among others (28).

A primary advantage of diethylene glycol is that though it is not as easily biodegradable as propylene and ethylene glycol, it is not likely to volatilise into the air or bioaccumulate and it undergoes hydrolysis in water, easily which is a very important fate process in the surrounding environment (9,28,36).

In summary, diethylene glycol may be a viable substitute for ethylene and propylene glycol, more so than isopropanol. However, it does not offer any environmental benefits over the glycols, currently in use in the U.S. Aquatic and mammalian toxicity are similar to that of ethylene glycol and diethylene glycol requires the same amount of oxygen to degrade as ethylene and propylene glycol, but it degrades more slowly. This results in a smaller daily oxygen demand over a longer period of time and does not strain oxygen levels as much as the other glycols because oxygen demand is more gradual.

iii) Evaluation of Airfield Deicing/Anti-icing Chemicals and Alternatives

Currently the FAA approved airfield surface deicers are urea, sodium acetate, sodium formate, calcium magnesium acetate and potassium acetate (21) and researchers are currently testing several chemical alternatives to these, although none have been approved yet.

Because individual airports, airfields, and airlines present their own unique operational demands and meteorological conditions, deicing activities vary greatly from one region and airport to the next. The choice between a solid and liquid chemical is based on factors specific to each airfield and includes local temperature, precipitation amounts, and budgetary needs. However, when evaluating the use of a deicing chemical, the factors to considered include the following (8):

- Ice melting efficiency: chemicals with greater melting efficiency can decrease the amount of chemical applied.
- Corrosiveness: chemicals cannot contain any ionic salts or constituents that can be corrosive to aircraft surfaces, or equipment.
- Application and handling: the application rates will differ for different chemicals and some might require specialised equipment for application.
- Environmental effects: the environmental impacts as a result of usage have to be considered.

- Cost effectiveness: costs versus long term benefits have to be evaluated.

A comparison between the presently approved airfield deicing and anti-icing chemicals and their advantages and disadvantages will be discussed below, starting with the table beneath that summarises the characteristics of FAA-approved deicing chemicals. These are the physical states of the chemical (solid or liquid), the lowest effective temperature at which they are still effective, unit cost as means of comparison, amount applied per area and the cost per area.

Table of FAA-Approved Runway Deicing Chemicals

Chemical	Solid / Liquid	Lowest Effective Operating Temperature (Degree Celsius)	Unit Cost	Application/ 1,000 s.f.	Deicing Cost/ Acre
Urea	Solid	-7	\$229/ton	16 lbs	\$80
Sodium Acetate	Solid	-12	\$1,360/ton	11 lbs	\$326
Sodium Formate	Solid	-15	\$1,260/ton	6 lbs	\$165
Calcium Magnesium Acetate	Solid	-7	\$700/ton	16 lbs	\$244
Potassium Acetate	Liquid	-12	\$2.5/gallon	0.6 gallons	\$65
Propylene Glycol	Liquid	-7	\$4/gallon	1 gallon	\$175
Ethylene Glycol	Liquid	-7	\$2/gallon	1 gallon	\$85

Note: Temperatures are approximate. Specific vendor formulations and mixtures will have different operating temperatures.

Source: (35)

Now looking at these chemicals starting with urea, one finds out that it is the most widely used runway deicer across the United States because of it's low cost and excellent

performance as depicted in the table. This has resulted in many alternative runway-deicing chemicals being measured against urea due to its widespread use (4). However, the downside to it is its environmental impact and noted in the section above when discussing biological oxygen demand, urea has a BOD of 2 million parts per million and degrades to form ammonia.

However, the performance results of sodium acetate have indicated improved deicing capabilities as compared to urea and reacts faster and most efficiently with packed ice and snow (4). It also has application quantities two-thirds less as compared to urea. The huge disadvantage is that it costs three times more than urea as depicted above in the table where this cost comparison already takes into account the reduced quantity of chemical required as compared to urea. But the good thing is that the cost of sodium acetate continues to decrease as usage increases (4).

Next looking at sodium formate, one will find that the advantages as compared to urea include that it is more effective at lower temperatures, has a 40 to 60 percent reduction in volume needed, has a lower BOD, has irregular shaped crystals which prevent shearing off surfaces due to wind and a neutral pH which reduces potential for corrosion of metal aircraft components (8). However, the disadvantages include a slightly lower performance than sodium acetate and costs about 1.5 times more than urea (35).

Calcium magnesium acetate is not really that widely used at airports due to its slow reaction time with ice and spherical shape which facilitates the blowing off of this chemical after application to runways by strong winds (8). However, recent product developments have enabled CMA to be produced in angular form that allows the chemical to stay in place. Cost comparison to sodium formate shows that it is similar in that aspect.

Advantages of potassium acetate over glycol and urea include more efficient melting of snow and ice at lower temperatures, while maintaining friction on the airfield surface following application (23). Although it has a high BOD, it tends to degrade well

at lower temperatures unlike other deicing chemicals that require higher temperatures to degrade. An independent study by a potassium acetate vendor showed that 100% of potassium acetate will degrade in 20 days at temperature less than 2 deg Celsius as compared to 2% of urea under the same conditions (21). The cost of potassium acetate is also similar to propylene glycol and the cost comparison is based on an effective application rate of 60 % that of propylene glycol (21).

Although propylene and ethylene glycol are mainly used for aircraft deicing, they are also commonly used in conjunction with airport surface deicing solids and is usually used for pre-wetting of the solids in drier conditions. This pre-wetting enables the solid to become more cohesive and remain on the runway for longer periods of time (21). And the primary advantage to glycol is its effectiveness at lower temperatures.

iv) *Alternative Deicing/Anti-icing Minimisation Methods*

To reduce the environmental impacts of deicing/anti-icing chemicals, which is achieved by indirectly reducing the amount of deicing/anti-icing fluids used, certain alternative deicing/anti-icing minimisation methods may be carried out or used to complement the deicing/anti-icing operations. Some of these methods are thus discussed below.

1) *Preventive anti-icing*

Preventive anti-icing is the application of glycol-based anti-icing fluid prior to the start of icing conditions or a storm event to limit ice and snow built-up and facilitate its removal. The principal advantage of this is an overall reduction in the volume of glycol-based fluids applied to the aircraft. However to be effective as a preventive, anti-icing fluids must be applied to aircraft prior to the advent of icing conditions or a storm event and one major drawback would be the problem of obtaining accurate weather forecasts containing enough information for operations personnel to make informed decisions. Inaccurate forecasts may result in unnecessary anti-icing.

The U.S Air Force has experimented with preventive anti-icing techniques and has concluded that they can be effective in reducing the volume of fluid applied to the aircraft, provided operations personnel carefully co-ordinate their activities with local weather reports (34). But due to concerns that anti-icing fluids may degrade aircraft parts, particularly those made from composite materials, when the fluids are left on for extended periods, the U.S Air Force has not implemented widespread use of preventive anti-icing practices (22).

2) *Infrared Deicing*

The FAA has approved the use of infrared (IR) heating to de-ice aircraft instead of using deicing chemicals. The first operation was installed at Buffalo International Airport in New York. Here, aircraft are taxied or towed into a canopy area that directs IR energy at areas of the aircraft which require deicing and the ice absorbs the heat and melts without the aircraft being heated (6). Following deicing, a light film of Type I or II glycol is often applied to the aircraft to allow for some holdover time.

An IR system used only to de-ice general aviation aircraft (non-commercial aircraft) at a second facility located at Rhineland-Oneida County Municipal Airport in Wisconsin cost \$1.2 million to construct. Once in place, it allowed the municipal airport to reduce glycol use by approximately two-thirds (7).

Larger systems can be designed to de-ice commercial aircraft for an approximate construction cost of \$2.5 million. Once in place, an IR deicing system can deice a commercial aircraft for approximately \$500. The cost to deice the same commercial aircraft jet with conventional glycol is approximately \$5,000 (8).

3) *Forced Air Blast Deicing*

Force air-blasting uses compressed air combined with a fine spray of glycol deicing fluid to blow off snow and ice off the aircraft wings. This process has been observed to de-ice aircraft in half the time as compared to conventional spray trucks while using 70% less glycol per aircraft. The reduction in the cost of glycol amounts used can pay for the forced air system within one season of use (8). Such a system is operated from a mobile truck mounted unit and the cost to retrofit an existing truck is approximately \$100,000 (8).

This system is currently being used at Memphis Airport in Tennessee to deice Federal Express's aircraft. Also, according to Delta airlines that has introduced a forced air-blasting system to deice their aircraft at General Mitchell International Airport in Milwaukee, Wisconsin, this system has reduced their Type I glycol use by 50%. (X)

4) *Clean Wing Detection System*

This is a system designed by engineers to help pilots determine whether significant amounts of ice and snow have accumulated on the wings and thus the need for deicing. The Clean Wing Detection System uses sensors mounted flush on the aircraft skin to detect and measure the thickness of ice on the surfaces of the wings and also determines through its technology, all the common airplane surface contaminants, such as ice, snow, frost and deicing chemicals. In addition, the system also measures how well the applied anti-icing chemicals are working, which is another important criteria for determining whether another application of fluid is necessary (8). It should be noted that although the Clean Wing Detection System is not an alternative to the use of deicing chemicals, it should help prevent unnecessary deicing of aircraft, which should result in a reduction of the amount of ADFs being used.

5) *Upper Wing Heater System*

This system utilises thin pad heaters that are attached to the upper wing surface of the aircraft in front of the engines. The pad encapsulates the heater with aluminium sheets with an insulator to avoid heat loss to the wing and has heat sensors which activate a cockpit light when the temperature of the panel is above 5 degrees Celsius indicating that the ice is gone during the flight.

6) *Mechanical Methods*

Airfield Surfaces

All airports must employ mechanical methods to control snow and ice accumulation on airfield surfaces and these methods play an important role at airports to remove snow and ice from airfield surfaces. Use of mechanical methods to control ice and snow built-up results in less chemicals being applied and thus incur lower deicing/anti-icing costs and reduce the environmental impacts caused by these chemicals. Generally, conventional snow plows and other snow removal equipment like rotating metal brooms to physically remove built-up ice on airfield surfaces and mechanical blowers to dry surfaces to prevent refreezing are used. Sand is also a highly preferred airfield surface treatment to increase friction resistance because of its low cost and minimal environmental impact (1) as opposed to salt which cannot be used due to the corrosion of aircraft skin, turbine blades and other essential aircraft components.

Aircraft

Brooms and soft scrapers are some mechanical methods to remove accumulated snow and ice from aircraft. Most commercial airports do not use mechanical methods to deice the aircraft due to potential aircraft delays that may result and when performed

incorrectly, can damage aircraft antennas and sensors. Mechanical methods are generally only more practical for smaller aircraft; for large aircraft, they can be prohibitively time consuming and labour intensive. However, the U.S Air Force frequently uses such methods. They are able to engage in such techniques due to the number of personnel available to perform the work and the less pressing flight schedules (31).

In the midst of flights, the aircraft has to be able to deice their wings in order to be certified to fly in icy conditions. They do so through the means of routing heated engine exhaust (bleed air) through interior portions of the leading edge of aircraft wings and stabilizer surfaces, thus allowing in-flight anti-icing to occur. Most commercial jets use the bleed air system and smaller propeller aircraft uses a pneumatic system (rubber boots) that inflate along the leading edge of control surfaces, thus mechanically breaking up the ice as it forms (31).

6) *Solar Radiation*

At several U.S Air Force bases, aircraft are also parked strategically on ramps, orientated to maximize the melting of accumulated snow and ice by the sunlight. This method reduces the volume of aircraft deicing fluid used during the winter season, but is practical only for general aviation and certain military flights that can be delayed without negative economic or operational impacts (32).

7) *Hot water Deicing*

The FAA allows the aircraft to be deiced using hot water followed by the application of an anti-icing fluid when the ambient air temperatures are above 27 degrees Fahrenheit (33). However, none of the major U.S airlines currently uses this method because they believe it would compromise the safety of the passengers and ground operations staff. The airlines are concerned with flash freezing and the potential to build up thick layers of ice both on the aircraft and pavement. The water may also enter and freeze on flap tracks, elevators, and other parts of the aircraft, potentially affecting

aircraft handling and performance. The freezing of water in hoses, nozzles, and tanks when deicer trucks are not in use is also a concern.

8) *Physical covers – Hangar Storage and Aircraft Covers*

Many general aviation aircraft and some commuter and military aircraft are stored in hangars overnight and during storm events, thus eliminating the need for aircraft deicing. In addition, heated aircraft hangars are used to sometimes deice the aircraft. When hangar space is not available, aircraft covers or blankets are sometimes used as an alternative method to minimise frost, ice and snow accumulation on aircraft surfaces (4). Such covers, available in solid and mesh form, are typically more commonly used for small general aviation aircraft to protect the wings, tail, and engine heads. For both cases, anti-icing may be necessary in certain weather conditions to prevent the ice and snow from accumulating on aircraft surfaces during taxing and takeoff. However, due to the smaller volumes of ADFs required for application to the aircraft, the volume of generated ADFs contaminated stormwater is much less than if the aircrafts were to have been stored outside in the open without any physical cover.

VI) CONCLUSIONS

Thus the core problems associated with airport deicing/anti-icing chemicals can be summarised as follows:

- Limited selection of FAA-approved deicing/anti-icing chemicals: Due to lack of chemical choices in this field, airport authorities and airlines have limited flexibility in choosing chemical alternatives.
- Toxicity: Although the pure toxicity of the major substances (with the exception of urea) in deicing chemicals is not a major contributor to negative environmental impacts in receiving water, formulated deicers have been proven to have some escalated effects on some of the aquatic organisms. In addition, due to the lack of information about the composition of these formulated deicers, which are often, trade secrets, research on the toxicity of these formulations are often hindered.
- Biological Oxygen Demand (BOD): All approved deicing/anti-icing chemicals exerted elevated levels of BOD on the receiving water bodies and is one of the major related environmental problems.
- Necessity of deicing/anti-icing chemicals: It is currently impractical to deice without the use of chemicals
- Alternative technologies: Available technologies are currently at hand to reduce the amount of chemicals applied but not to solely replace chemical deicing.

There are a few options available to the airports and one of them would be *no action*, and allow the contaminated stormwater runoff to discharge into surface water bodies till the FAA or environmental groups issues ultimatums or bring legal action against them. Alternatively, the airports and airlines could look into using *alternative technologies and chemicals*, supplementing existing chemical deicing/anti-icing operations with these technologies and reducing volumes of chemical used. Alternative FAA-approved chemicals are available for runways but at the moment, none are available for aircrafts. *Collection and treatment* is another one of the options, where airports and airlines can opt to install stormwater and deicing chemical collection and treatment systems.

In the final section below, there are some recommendations which airlines or airport authorities can look into to try and alleviate the environmental impacts of deicing/anti-icing operations at airports. It is hopeful that in the future years, through breakthroughs in research or other means, the negative impacts of deicing/anti-icing operations at airports, pose no longer any threat to the environment without compromising the safety of humans or any other life forms.

I) RECOMMENDATIONS FOR REDUCING ENVIRONMENTAL IMPACTS ASSOCIATED WITH DEICING/ANTI-ICING.

a. Incorporation of Alternative Deicing Technologies and other Environmentally Friendly Techniques

Airports should incorporate alternative deicing technologies (some of which are highlighted in this paper, e.g., infrared deicing) into deicing operations. The incorporation of these technologies will aid in reducing the overall volume of deicing chemicals used and eventually discharged into the environment.

Additional sources of ADF discharges to the environment include spills from overfilling deicer truck tanks and leaks from worn or defective fittings on deicer trucks and other application equipment. These sources of ADFs can be greatly reduced by regular maintenance and checking of the equipment or through the fitting of more environment friendly equipment like dripless fittings or automatic filling shut-off valves. Locating ADF storage tanks within the boundaries of designated aircraft deicing/anti-icing collection and containment areas can also reduce unnecessary releases of ADFs.

b. Personnel Training & Experience

An important factor affecting the efficiency of aircraft and airfield deicing/anti-icing operations, which has been overlooked by the airport authorities and airlines, is the training and experience of personnel involved in aircraft and airfield deicing/anti-icing. Most airlines and airport authorities do not have employees dedicated to such operations and often use temporary staff or ground operations personnel (e.g., baggage handlers, mechanics) to carry out such operations. In addition, due to low pay and poor working conditions, employee turnover is usually high. As a result, a larger portion of the employees at airports who carried out such operations are newly hired, trained and inexperienced. Often, what results is the spraying of more ADFs than necessary or required. Even though the required training that these personnel have to undergo ensures

the safe operation of aircraft, this does not necessarily ensure efficiency at aircraft deicing/anti-icing. Well trained and experienced deicing/anti-icing personnel improve the efficiency of aircraft deicing/anti-icing operations and minimize the volume of fluid used, while ensuring passenger safety. Thus airlines and airport authorities have to find ways to decrease employee turnover and retain it's experienced personnel as well as ensuring that the training of new employees not only encompasses safe operations of airfield activities but also environmentally friendly pollution prevention techniques and awareness.

c. Additional Research

Due to the impracticability of deicing chemicals without the use of chemicals, I recommend the development of alternative deicer chemicals with lower biological demand and toxicity. Since deicing chemical toxicity increases drastically with the addition of additives, I would suggest focusing toxicity research more on formulated deicers and making the toxicity information more accessible to the proper authorities for evaluation.

Since the deicing is mandatory and impractical without use of chemicals, I recommend the continued development of alternative technologies to help complement the use of deicing chemicals. Thus, the overall chemical use can be reduced and the airport industry will have a wider range of effective options to use.

d. Collection and Treatment

Although, this paper did not go into depth about this option for helping to alleviate the environmental impacts of deicing/anti-icing operations, this is definitely a viable option for some airports and airlines. It should be noted that this may not be practical or necessary for all airports but based on regulatory trends, collection and treatment will most likely be required. However, due to the uncertainty of future regulations, the installation of collection and treatment systems may be premature,

meaning that these collection and treatment systems although adequate to prevent the discharge of deicing/anti-icing wastes into the environment, may not meet the requirements for future regulations. In addition, this may not be a feasible option for certain airports due to the large volume of contaminated stormwater that is generated from the large surface areas of the runway and also very dependent on the climate. None the less, this is still an alternative way that should be considered by airports to alleviate the environmental problems of deicing chemicals.

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