

ACRP

SYNTHESIS 6

AIRPORT
COOPERATIVE
RESEARCH
PROGRAM

Impact of Airport Pavement Deicing Products on Aircraft and Airfield Infrastructure

A Synthesis of Airport Practice

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Impact of Airport Pavement Deicing Products on Aircraft and Airfield Infrastructure

A Synthesis of Airport Practice

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SUBJECT AREAS

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AIRPORT COOPERATIVE RESEARCH PROGRAM

Airports are vital national resources. They serve a key role in transportation of people and goods and in regional, national, and international commerce. They are where the nation's aviation system connects with other modes of transportation and where federal responsibility for managing and regulating air traffic operations intersects with the role of state and local governments that own and operate most airports. Research is necessary to solve common operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the airport industry. The Airport Cooperative Research Program (ACRP) serves as one of the principal means by which the airport industry can develop innovative near-term solutions to meet demands placed on it.

The need for ACRP was identified in *TRB Special Report 272: Airport Research Needs: Cooperative Solutions* in 2003, based on a study sponsored by the Federal Aviation Administration (FAA). The ACRP carries out applied research on problems that are shared by airport operating agencies and are not being adequately addressed by existing federal research programs. It is modeled after the successful National Cooperative Highway Research Program and Transit Cooperative Research Program. The ACRP undertakes research and other technical activities in a variety of airport subject areas, including design, construction, maintenance, operations, safety, security, policy, planning, human resources, and administration. The ACRP provides a forum where airport operators can cooperatively address common operational problems.

The ACRP was authorized in December 2003 as part of the Vision 100-Century of Aviation Reauthorization Act. The primary participants in the ACRP are (1) an independent governing board, the ACRP Oversight Committee (AOC), appointed by the Secretary of the U.S. Department of Transportation with representation from airport operating agencies, other stakeholders, and relevant industry organizations such as the Airports Council International-North America (ACI-NA), the American Association of Airport Executives (AAAE), the National Association of State Aviation Officials (NASAO), and the Air Transport Association (ATA) as vital links to the airport community; (2) the TRB as program manager and secretariat for the governing board; and (3) the FAA as program sponsor. In October 2005, the FAA executed a contract with the National Academies formally initiating the program.

The ACRP benefits from the cooperation and participation of airport professionals, air carriers, shippers, state and local government officials, equipment and service suppliers, other airport users, and research organizations. Each of these participants has different interests and responsibilities, and each is an integral part of this cooperative research effort.

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FOREWORD

*By Staff
Transportation
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Airport administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to the airport industry. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire airport community, the Airport Cooperative Research Program authorized the Transportation Research Board to undertake a continuing project. This project, ACRP Project 11-03, "Synthesis of Information Related to Airport Practices," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an ACRP report series, *Synthesis of Airport Practice*.

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

This synthesis reports on how airports chemically treat their airport pavements to mitigate snow and ice, and the chemicals used; reviews the effects of pavement deicing products (PDPs) on aircraft and airfield infrastructure; and describes critical knowledge gaps in the subject. This report is technical in nature. Effects of PDPs on airport components include description of catalytic oxidation of carbon-carbon composite brakes, cadmium corrosion, and chemical interaction of aircraft deicing and anti-icing fluids on airfield infrastructure, including concrete and asphalt pavements and metal and composite fixtures such as runway lights.

Information used in this study was acquired through a comprehensive search of literature sources. Also, a survey was distributed to airframe and aircraft component manufacturers, airport infrastructure managers, air carriers, military aviation groups, deicing and anti-icing manufacturers, and industry and government organizations. Additional information, including the types of PDPs used by approximately 100 airports and contact information from the 50 busiest U.S. airports and select foreign airports, was acquired from the 2006 EPA Airport Deicing Questionnaire.

Xianming Shi, Western Transportation Institute, Montana State University, Bozeman, Montana, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

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IMPACT OF AIRPORT PAVEMENT DEICING PRODUCTS ON AIRCRAFT AND AIRFIELD INFRASTRUCTURE

SUMMARY

Airfield pavement deicing and anti-icing are essential activities to maintain safe winter operations of the aviation industry. Airfield pavement deicing products (PDPs) traditionally consisting of urea or glycols have become less popular owing to their adverse environmental impacts. New PDPs have emerged as alternatives that often contain potassium acetate (KAc), sodium acetate (NaAc), sodium formate (NaF), or potassium formate (KF) as the freezing point depressant. When it comes to airfield pavement deicing and anti-icing there are no simple solutions to the competing, and sometimes conflicting, objectives of aircraft safety, environmental regulatory compliance, materials compatibility, and operational implementation viability.

The objectives of this synthesis are to report how airports chemically treat their airfield pavements to mitigate snow and ice, and the chemicals used; review damage reported to aircraft components and airfield infrastructure in association with the use of traditional or modern PDPs; and identify critical knowledge gaps on these subjects.

Information was acquired through a comprehensive literature search and from a survey. In addition, responses representing approximately 100 airports were gathered from a 2006 EPA questionnaire, which indicated that KAc and sand are most widely used at U.S. airports for snow and ice control of airfield pavements, followed by airside urea, NaAc, NaF, propylene glycol-based fluids, ethylene glycol-based fluids, and others.

Catalytic oxidation of aircraft carbon-carbon composite brakes resulting from airfield PDPs has become a growing concern to be monitored in the ever-changing operation environment. As nontraditional chemical contaminants, modern PDPs may be responsible in recent years for the more rapid structural failure of carbon-carbon composite brakes. To avoid potential safety implications, this concern has to be mitigated through more frequent proactive maintenance and inspection activities incurring high direct and indirect costs.

Although the fundamental mechanisms of catalytic oxidation by PDPs are well understood in well-controlled laboratory settings, and advances in technologies for its prevention and mitigation have been made in the last decade or so, the problem seems far from solved. There is still a need to establish a comprehensive PDP catalytic oxidation test protocol. Furthermore, research is needed to better understand relationships between brake design, anti-oxidant treatment, and PDP contamination as factors in catalytic oxidation.

Field reports increasingly suggest that contact with modern PDPs promotes damage to aircraft components, especially cadmium (Cd)-plated components. Until recently, the principal evidence connecting alkali-metal-salt PDPs with Cd-plating corrosion has been that a trend of increased reports of the latter occurred concurrently to the introduction of the former.

Although the fundamental mechanisms of Cd corrosion in water are relatively well studied, the link between alkali-metal-salt-based PDPs and Cd-plating corrosion has yet to be experimentally validated and thoroughly investigated. There is still a need to establish a comprehen-

sive metallic corrosion test protocol for PDPs. More research is needed to better understand the interactions among the aircraft component design, the corrosion-inhibiting compounds used, and the contamination of PDPs in the processes of metallic corrosion. Finally, there is still a lack of academic research data from controlled field investigation regarding the aircraft metallic corrosion by PDPs.

Alkali-metal-salt-based PDPs accelerate the precipitation and buildup of thickener residues from modern aircraft deicing/anti-icing fluids (ADAFs). The contamination effects of ADAFs have been well-observed, but not yet thoroughly quantified. Acquisition of hard data will assist in the generation of inspection schedules and may spur development of improved thickener formulae for ADAFs. Research will be needed to better understand the interactions between ADAFs and PDPs, as new ADAFs and PDPs are continually introduced to the market.

The last decade has seen an increase in alkali-silica reaction (ASR) occurrence with the use of alkali-metal-salt-based deicers applied on airfield portland cement concrete pavements. Limited laboratory studies indicated that these modern PDPs could cause or accelerate ASR distress in the surface of portland cement concrete pavement by increasing the pH of concrete pore solution. Therefore, there is a need for research data from controlled field investigations regarding the effects of alkali-metal-salt-based PDPs on concrete pavement. Furthermore, it is essential to unravel the specific mechanism by which alkali-metal-salts cause or promote ASR.

Concurrent with the use of acetate and formate-based deicers in the 1990s, asphalt pavement in Europe saw an increase in pavement durability problems. The damaging mechanism of asphalt pavement by modern PDPs appeared to be a combination of chemical reactions, emulsification, and distillation, as well as the generation of additional stress inside the asphalt mix.

There is a need for research data from controlled field investigations regarding the effects of alkali-metal-salt-based PDPs on asphalt pavement. Furthermore, there is a need to unravel the specific mechanisms by which alkali-metal-salts and other PDPs (e.g., bio-based deicers) deteriorate asphalt pavement.

Other airfield infrastructure that comes into contact with PDPs includes ground support equipment, signage, lighting, and other electrical systems. Empirical evidence exists indicating that PDPs are responsible for damaging such infrastructure. However, no academic peer-reviewed scientific information could be found to corroborate these empirical observations.

CHAPTER ONE

INTRODUCTION

This report provides the synthesis of results from ACRP Project S10-03. This introductory chapter, describing the purpose and background of the report, provides the context for the remaining chapters.

PURPOSE OF SYNTHESIS

This synthesis reports on how airports chemically treat their airfield pavements to mitigate snow and ice, and the chemicals used; reviews damage to aircraft components and airfield infrastructure in association with the use of traditional or modern pavement deicing products (PDPs) (for simplicity, this document uses the terms “deicer” and “pavement deicing products” for all chemical products used for deicing and anti-icing operations); and identifies critical knowledge gaps on these subjects. Field reports of the aviation industry increasingly suggest that the use of PDPs, including alkali acetate and alkali formate products (such as sodium- and potassium-acetate-, and formate-based products), on aprons, runways, and taxiways may result in damage to various aircraft and airfield infrastructure under certain conditions.

BACKGROUND

Airfield pavement deicing and anti-icing are essential activities in maintaining the aviation industry’s safe winter operations. The general preference for aviation’s winter maintenance practices is anti-icing with approved chemicals to prevent the bonding of ice and pavement—a more proactive approach than deicing or sanding. For anti-icing, liquid chemicals are preferred for their better dispersion and adherence, because solid chemicals can be easily scattered by wind, aircraft, and ground support vehicles. For deicing, chemicals are applied to melt ice and disrupt any bond to the pavement, whereas sand can increase the frictional characteristics of the surface (“Airport Winter Safety and Operations” n.d.). Mechanical methods can reduce the amount of deicing chemicals applied; however, care must be taken to avoid polishing ice and creating a hazard that is more difficult to treat (*Pro-Act Fact Sheet* . . . 1998).

The traditional airfield PDPs consisting of urea or glycols have become less popular owing to their adverse environmental impacts. New PDPs have emerged as alternatives that often contain potassium acetate (KAc), sodium acetate (NaAc), sodium formate (NaF), or potassium formate (KF) as the freezing point depressant. KAc, NaAc, and NaF are more expen-

sive, but also more effective than urea at lower temperatures (–20°F, 10°F, and 5°F, respectively) (*Pro-Act Fact Sheet* . . . 1998). In Canada, the general consensus was that the increased effectiveness and simultaneous reduction in environmental problems justifies the increased cost of using new PDPs (Comfort 2000).

Airports and airlines deal with multiple objectives and are challenged with multiple constraints when it comes to airfield pavement deicing and anti-icing. First, aircraft safety (and mobility) is of the highest priority, which at times demands large quantities of PDPs to be used for snow and ice control on airfield pavements. Because passenger and flight crew safety is of paramount importance, the aviation regulators and airframe and aircraft component manufacturers strive to ensure the highest standards possible. For instance, critical control systems for aircraft are designed with an “extremely remote” probability of failing, which is one-in-one-billion (10^{-9}) flights (National Academy of Engineering 1980). Aircraft safety is also ensured by mandating regular regimes of inspection, maintenance, and replacement of aircraft brakes and components to manage the highly improbable but potentially catastrophic risks.

Second, environmental regulatory compliance is an important objective as a result of requirements of the Clean Water Act and National Pollution Discharge Elimination System permits for stormwater discharges. Officials at more than half of the airports that responded to a 2000 U.S. General Accounting Office survey indicated that it was getting much more difficult to balance environmental concerns with their airport’s operations (General Accounting Office 2000). The EPA is in the process of developing effluent limitation guidelines for airport deicing and anti-icing operations that may pose additional challenges for airports and airlines in achieving environmental compliance. The use of liquid glycol-based and solid urea deicers has received particular scrutiny owing to the high biochemical oxygen demand [BOD, often measured as 5-day BOD (BOD_5 in mg/L)] exerted on receiving bodies of water. Depleted oxygen levels can threaten aquatic life, whereas the ammonia by-product of urea is toxic to aquatic organisms (*Pro-Act Fact Sheet* . . . 1998). Although glycol-based deicers are increasingly less commonly used for pavement deicing, urea was still used by more than one-third of the 50 busiest airports in 2000 (General Accounting Office 2000) and more than one-third of the airports that reported using chemical deicers by a more comprehensive

EPA survey in 2006. The reduced oxygen demand by acetate- and formate-based deicers compared with urea is evident in Table 1, as reported as chemical oxygen demand. Testing for chemical oxygen demand is faster than standard BOD tests and indicates the theoretical maximum oxygen that would be consumed; BOD is related more to biological decomposition.

Third, materials compatibility between PDPs and the aircraft and airfield infrastructure is yet another objective. Field reports suggest that the use of modern PDPs, including alkali acetate and alkali formate products on aprons, runways, and taxiways may result in the need for more frequent maintenance and inspection for various aircraft and airfield infrastructure. Such PDPs have recently been reported to corrode or degrade cadmium or aluminum components and carbon-carbon (C/C) composite brakes of aircraft. Often mixed with corrosion inhibitors, KAc and KF were reported to degrade insulation in aircraft electrical systems. Existing research has indicated that KAc and KF may cause accelerated structural degradation of C/C composite aircraft brakes as a result of the catalytic oxidation by the potassium cation, which may result in reduced brake life and introduce the possibility of brake failure during aborted take-off. KF was found to cause corrosion to landing gear and associated wiring of some Boeing airplane models. Other examples of damage potentially associated with the use of PDPs include reports of corrosion in landing gear joints, electrical wire bundle degradation, corrosion of runway lighting fixtures, and damage to airfield pavements. Airfield pavement damage has been observed in both asphalt and concrete runways. Evidence of the former is more widely reported in European airports; however, laboratory tests worldwide have shown emulsification of asphalt and the disruption of asphalt-aggregate bonds. Extensive laboratory testing of concrete pavement has shown an increase in alkali-silica reactivity and the need for improved standardized tests for aggregate selection and mix design.

Finally, operational implementation viability is another constraint for airports and airlines to consider. The FAA prescribes a list of chemicals that are approved for the snow and ice control of airfield pavements, which limits options of chemicals being used as PDPs. The approval of PDPs by the FAA advisory circular ("Airport Winter Safety and Operations" n.d.) is currently based on two specifications of the SAE through Aerospace Material Specifications (AMS). Approved glycol- and potassium-acetate-based fluids must meet SAE AMS 1435B, Fluid, Generic Deicing/Anti-icing, Runways and Taxiways.

TABLE 1
CHEMICAL OXYGEN DEMAND FOR RUNWAY DEICERS

Deicers	COD	COD
	[g(O ₂)/kg dry deicer]	(kg/10 hectare surface)
Potassium Formate	190	285
Potassium Acetate	653	1,134
Urea	2,133	5,365

Adapted from Sava (2007).

Approved airside urea, calcium magnesium acetate, sodium formate, and sodium acetate products must meet SAE AMS 1431C, Compound, Solid Runway and Taxiway Deicing/Anti-icing. Airside urea must also meet the military specification MIL SPEC DOD-U-10866D, Urea-Technical ("Airport Winter Safety and Operations" n.d.). In addition, more costly PDPs must be justified and programmed into operating budgets. The costs associated with both aircraft and airfield maintenance and alleviating the environmental impacts of PDPs must be balanced in decision making for deicing and anti-icing operations. Alternative PDPs may also pose new challenges related to rules of practice and training.

The previously mentioned multiple dimensions of this complex problem define the context of this synthesis. There are no simple solutions to the competing, and sometimes conflicting, objectives of aircraft safety, environmental regulatory compliance, materials compatibility, and operational implementation viability.

ACRP has two airfield deicing research projects underway at this time: ACRP Project 02-01, *Alternative Aircraft and Airfield Deicing and Anti-Icing Formulations with Reduced Aquatic Toxicity and Biochemical Oxygen Demand*, which responds to the voiced need for new formulations of aircraft and airfield deicers that combine safety, performance, and materials compatibility with environmental stewardship and cost-effectiveness. The identification of new formulations will be based primarily on reduced toxicity and BOD₅ and evaluated based on their performance, efficiency, material compatibility, and environmental, operational, and safety impacts. Airports of all sizes and operational levels are reporting increased difficulty in balancing environmental concerns during their operations (General Accounting Office 2000). ACRP Project 02-02, *Managing Runoff from Aircraft and Airfield Deicing and Anti-Icing Operations*, will provide an array of planning guidelines with best management practices useful for the implementation of site-specific solutions for the collection of deicer runoff while still maintaining safe aviation. These guidelines can provide sound technical information in support of the ongoing effort by the EPA to establish effluent guidelines for discharges of deicing runoff.

To avoid duplication, this synthesis strictly limits this report to how airports chemically treat their airfield pavements to mitigate snow and ice, and chemicals used; reviews damage reported to aircraft components and airfield infrastructure in association with the use of traditional or modern PDPs; and identifies critical knowledge gaps on these subjects. Such information is expected to provide a holistic view of airfield pavement deicing and anti-icing operations and assist in the design of new deicer formulations.

METHODOLOGY

This synthesis was primarily based on a critical review of literature and a formal survey with follow-up interviews.

Literature Review

Information was assembled through a comprehensive search of literature and data sources to review damage reported to aircraft components and airfield infrastructure in association with the use of traditional or modern PDPs and to identify critical knowledge gaps on this topic. The search was carried out using a variety of tools, including TRIS online, Google Scholar, SCIFinder Scholar, Google, etc. Relatively limited information in academic peer-reviewed literature was found and thus industry peer-reviewed publications and reports published by the FAA, aircraft brake manufacturers, airframe manufacturers, airlines, airports, and PDP manufacturers were incorporated in the review process with caution. Information sources included, but were not limited to:

- U.S. General Accounting Office—results from a survey of the nation's 50 busiest commercial service airports.
- SAE Working Groups (A-5A Brake Manufacturers, G-12F Catalytic Oxidation, G-12F Cadmium Corrosion, and G-12F Fluid Residues).
- SAE specification documents AMS 1431 and AMS 1435.
- JÄPÄ—Finnish De-icing Project reports.
- Innovative Pavement Research Foundation (IPRF).
- Industry groups such as the ACI-NA, AAAE, NASAO, and ATA.
- Government groups such as the FAA, Transport Canada, and U.S. Air Force.
- Airlines [Alaska Airlines, American Airlines, ANA, British Airways, Continental Airlines, FlyBe, KLM, Northwest Airlines, SRTechnics (formerly Swissair), Stockholm–Arlanda, and United Airlines].
- Airframe and component manufacturers (Airbus, Boeing, Bombardier, Honeywell, Goodrich, and Messier–Bugatti).
- PDP manufacturers (ADDCON Nordic, Clariant, Cryotech Deicing Technology, Dow Canada, Kilfrost, and Old World Industries).

Survey

With the support of the ACRP project manager and technical panel members, a portion of the responses to the 2006 EPA

Airport Deicing Questionnaire were received, including the type of PDPs used by approximately 100 airports (including urea, KAc, NaAc, NaF, ethylene glycol-based fluids, propylene glycol-based fluids, and others), and contact information from the 50 busiest U.S. airports that reported using PDPs as well as several foreign airports including CPH (Copenhagen, Denmark), LGW (London–Gatwick, United Kingdom), and OSL (Oslo, Norway).

The EPA questionnaire did not provide information specifically related to the effects of PDPs on aircraft and airfield infrastructure. Thus, a survey was created under the guidance and review of the technical panel members to solicit input from many stakeholder groups: airframe and aircraft component manufacturers, airport infrastructure management, air carriers, military aviation, and industry and government groups. Early in the survey (see Appendix A), respondents were directed to any of four sections based on their role in the field of aviation: aircraft component manufacturing, airport management, PDP manufacturing, or air carriers. There were 43 responses to the ACRP survey. The distribution of responses based on perspective is shown in Figure 1, with more detailed information of survey respondents available in Appendix B.

ORGANIZATION OF SYNTHESIS

The following chapter will describe the use of PDPs at airports based on results from the 2006 EPA questionnaire and the ACRP survey distributed for this synthesis. Chapter three offers detailed information about the effects of PDPs on aircraft, including catalytic oxidation of C/C composite brakes, cadmium corrosion, and interaction with aircraft deicing and anti-icing fluids. Chapter four presents the currently available information on the effects of PDPs on asphalt and concrete airfield pavements, as well as the limited information available on other airfield infrastructure. These chapters describe the problems attributed to PDPs with possible scientific mechanisms of damage, as well as mitigation measures and knowledge gaps. Finally, chapter five summarizes the findings related to the effects of PDPs on aircraft and airfield infrastructure.

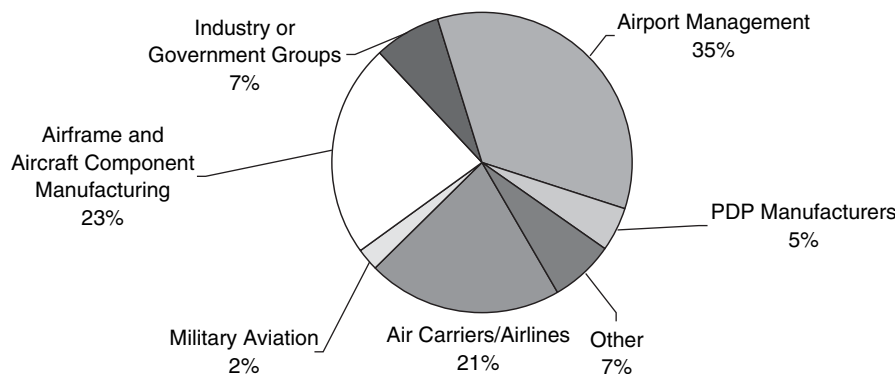


FIGURE 1 Classification of survey respondents.

USE OF AIRPORT PAVEMENT DEICING PRODUCTS AT AIRPORTS

The EPA is in the process of developing effluent guidelines for airport deicing. To this end, industry questionnaires were distributed and site visits and wastewater sampling were conducted. Based on responses to the in-depth questionnaire distributed in April 2006 to 152 airports, 130 of the 139 respondents conducted deicing activities (Strassler 2006). Detailed responses concerning the type and amount of deicers applied at 102 airports were acquired by the ACRP synthesis team. As shown in Table 2, approximately 100 of the airports applied deicers during the 2004/2005 winter season. KAc and sand were used by a majority of airports, 68 and 62 responses, respectively. Approximately 100 airports indicated the use of mechanical methods and 7 of these airports did not use any chemicals or sand. Thirty-nine airports reported using two different materials, 32 used three, and 18 used only one. Of the 18 airports that indicated using only one type of chemical, half used KAc, six applied sand, two applied airside urea, and only one used propylene glycol-based fluids.

The type of PDP chemical or material used by airports based on their size classification: large-, medium-, small-, and non-hub, is presented in Table 2. Only the non-hub airport size was associated with less than 50% usage of KAc. Of all the airside urea in use, most (74%) was applied at non-hub airports.

Many of the respondents to the EPA questionnaire (49) also provided the amounts of chemicals applied during the

2002/2003, 2003/2004, and 2004/2005 winter seasons. These amounts are shown in Table 3 for the corresponding number of airports providing this information. The liquid chemicals were generally applied at 50% concentration; a few airports specified other concentrations.

The selection of PDPs by airport staff can be based on many factors, including cost, effectiveness, environmental impact, risk of corrosion (to metals), and electrical conductivity. Sixteen respondents to the ACRP survey chose to rate the importance of these five factors and any other criteria considered in the selection of PDPs at their representative airport. Numeric values were assigned to the level of importance based on the range of response options:

- 1 = Unimportant,
- 2 = Not very important,
- 3 = Important
- 4 = Somewhat important, and
- 5 = Very important.

Numerically, the average importance ranged from 3.5 to 4.9 across the criteria factors, with “effectiveness” ranked as the most important criterion and “electrical conductivity” as the least. The effectiveness criterion also exhibited the lowest standard deviation, with “corrosion risk” being the highest (Figure 2). Interestingly, no airport selected “unimportant” or “not very important” for any of the criteria options in the survey, highlighting the challenges and dilemmas faced by the

TABLE 2
TYPE OF PDP USED AT U.S. AIRPORTS DURING 2004/2005 WINTER SEASON

Chemical/Material	Size Classification				Total
	Large Hub (17)	Medium Hub (21)	Small Hub (19)	Non-Hub (44)	
Airside Urea	4	6	6	14	30
Sodium Formate	1	6	3	3	13
Sodium Acetate	7	8	6	6	27
Potassium Acetate	14	18	16	20	68
Propylene Glycol-Based Fluids	3	0	2	4	9
Ethylene Glycol-Based Fluids	1	0	1	1	3
Sand	12	15	10	25	62

Notes: Data based on a subset of the data from the 2006 EPA questionnaire.
Some airports used more than one PDP.

TABLE 3
AMOUNT OF DEICERS APPLIED AT THE REPORTING U.S. AIRPORTS DURING THREE
WINTER SEASONS

	2002/03		2003/04		2004/05	
	No. Airports	Amount	No. Airports	Amount	No. Airports	Amount
Chemical/Material						
Airside Urea (pounds)	14	2,056,988	16	4,330,356	17	2,451,914
Potassium Acetate (gallons)	35	4,146,441	36	4,598,292	36	2,792,393
Sodium Acetate (pounds)	13	5,068,222	12	5,764,147	16	4,365,449
Sand (pounds)	25	29,413,920	26	27,949,397	32	34,372,627
Sodium Formate (pounds)	5	248,283	6	486,813	7	365,073
Ethylene Glycol-Based Fluids (gallons)	1	373,185	1	151,118	1	261,887
Propylene Glycol-Based Fluids (gallons)	4	225,800	4	226,200	4	256,537

Note: Data based on a subset of the data from the 2006 EPA questionnaire.

airports pertinent to snow and ice control. A European airport filled in two “other” criteria: (1) impact on asphalt pavement and (2) impact on working environment, both considered “very important.”

The high use of KAc at airports is consistent with both the general FAA preference to anti-icing practices and its more benign environmental impact compared with urea and gly-

cols. The next chapter will discuss the impacts of PDPs on aircraft components. Although corrosion risk and electrical conductivity were judged least important compared with the other factors, the average response was still above “important.” However, their relative importance to airport staff implies that any new PDP formulations must not sacrifice effectiveness or environmental liability in looking for PDPs that may be more compatible with aircraft components.

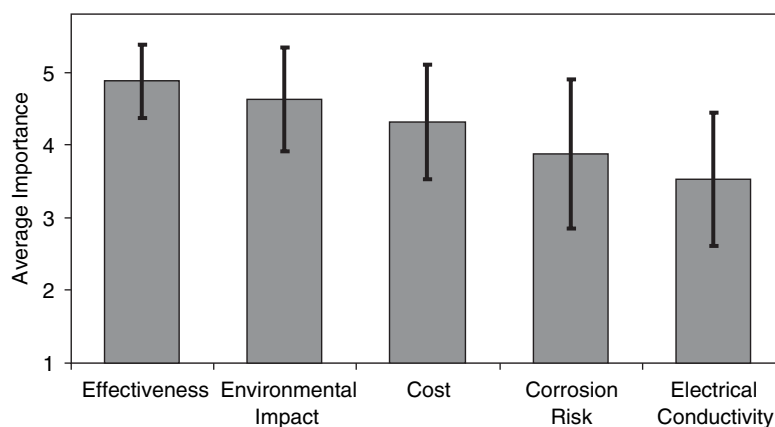


FIGURE 2 Importance of various criteria considered by airports for PDP selection; bars represent two standard deviations.

EFFECTS OF PAVEMENT DEICING PRODUCTS ON AIRCRAFT COMPONENTS

Alkali-metal-salt-based PDPs such as KAc and KF entered the European market to a significant extent in the mid- to late-1990s (approximately 1995 for KAc and 1998 for KF). A few years later, these modern PDPs entered the U.S. market. In both cases, these salts were introduced as alternatives to urea and glycols used in traditional PDPs for freezing point depression to mitigate the environmental concerns related to airfield deicing and anti-icing operations. It became apparent soon after their introduction that these new deicers presented new challenges. For instance, introduction of the alkali-metal-salts as PDPs coincided with the increased frequency of failures and returns of aircraft carbon-carbon (C/C) brakes, whereas aircraft C/C brakes had not changed significantly since their introduction in mid-1980s. Aircraft C/C composite brakes mainly consist of a carbon matrix reinforced by carbon fibers (either woven or randomly dispersed). In 1985, Airbus Industries introduced the first Messier-Bugatti production carbon brakes on the A310-300 and A300-600 aircraft (http://www.messier-bugatti.com/article.php3?id_article=180). Other issues concerning the aircraft durability and operations have also contributed to the debate surrounding the use of such PDPs.

The following sections of this chapter will discuss the effects of PDPs on aircraft components, including catalytic oxidation of C/C composite brakes, corrosion of aircraft alloys (with a focus on cadmium plating), and interaction with aircraft deicing and anti-icing products.

CATALYTIC OXIDATION OF CARBON-CARBON COMPOSITE BRAKES

Composites of a carbon matrix reinforced by carbon fiber (C/C composites) possess excellent mechanical and thermal properties. These C/C composites are much lighter than steel, maintain a near-constant friction coefficient over a broad temperature range, possess a much higher heat capacity and thermal conductivity than steel, and have tensile strength generally twice that of steel at elevated temperatures. Owing to their advantages over metallic friction materials, C/C composites have been increasingly used on aircraft brakes (Chai and Mason 1996). Since their aviation debut aboard the Concorde and the Vickers Super VC-10 ("Company History" 2007), there has been a general transition from metallic brakes to C/C composite brakes on modern medium and large aircraft (Chai and Mason 1996).

The typical C/C composite brake assembly consists of a primary thrust stator and multiple stator disks in an alternating stack with multiple rotor disks (Figure 3). The floating stators are kept from rotating with the motion of the landing gear wheel by interlocking stator tenons and torque tube splines, while the similarly keyed rotors rotate with the wheel. When activated, an annular piston assembly presses the thrust stator into the stack, causing very high friction force between the rotors and stators. Such friction can cause the carbon discs to reach 400°C–600°C in normal operations and up to 1400°C in some extreme cases such as in the event of refused take-off (Wu 2002).

A known drawback of C/C composites is their susceptibility to thermal oxidation at brake operating temperatures. At temperatures above 400°C, the reaction of carbon with oxygen can easily occur and thus wears the unprotected C/C composites. Existing research has demonstrated that oxidation (gasification) is the predominant mechanism for weight loss (an indicator of loss in structural integrity) of the C/C composites under high-energy brake operation conditions (Wu 2002). These conditions led to the popular practice of protecting the surface of C/C composite brakes with anti-oxidant coatings. As such, thermal oxidation usually will not occur until the anti-oxidant layer is disrupted. Dynamometer testing at 50% relative humidity and 100% normal aircraft landing energy led to significant oxidation of friction layer and friction debris samples obtained from commercially available C/C composite brake material, accompanied by the release of gaseous H₂O, CO₂, and CO (Penszynska-Bialczyk et al. 2007). Therefore, some level of thermal oxidation is expected and effective oxidation protection is essential to the design of C/C composite brakes.

As commercial and military aviation use of C/C composite brakes continues to grow, so does the scope of challenges associated with the technology. Alkali-metal-salt contaminants (e.g., sodium from the marine environment and potassium from cleaning and deicing chemicals) can reach the carbon surface and act as catalysts to facilitate oxidation of C/C composite brakes under conditions milder than those required for thermal oxidation. Concerns have been raised about the effect of modern PDPs (mainly alkali-metal-salts) on aircraft brakes.

The rest of this section will synthesize the information on the validity and nature of the effect of modern PDPs (primar-

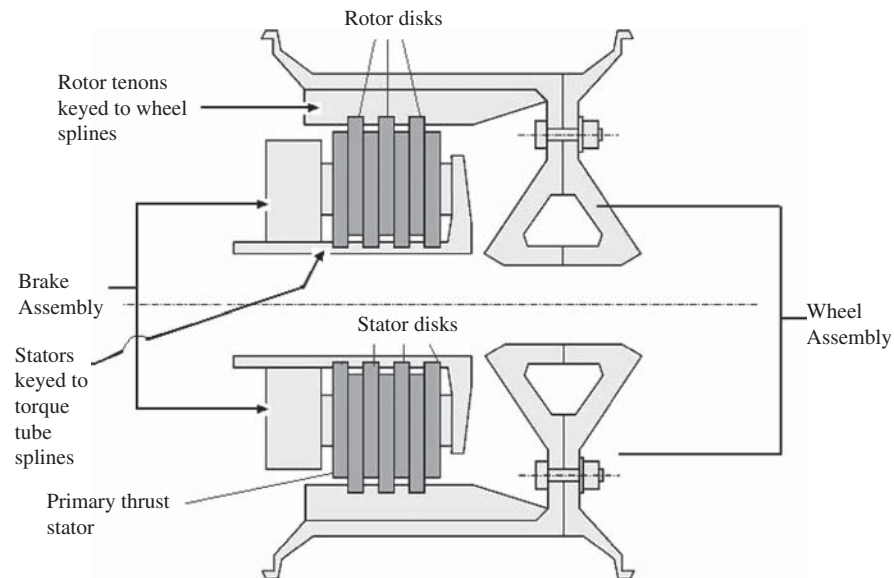


FIGURE 3 Typical airplane wheel and brake configuration: cross-sectional view.

ily alkali metal salts) on aircraft brakes, describe the related standards and test protocols, discuss ways to prevent and mitigate such effects, and identify knowledge gaps.

Validity of the Effect of Modern Pavement Deicing Products on Aircraft Brakes

Thermal oxidation is the primary design specification governing durability of aircraft C/C composite brakes. This is substantiated by data from Goodrich's Problem Analysis Report System, which has monitored failures and premature removals of C/C composite brakes (McCrillis 2007). Whereas thermal oxidation can be seen uniformly at the hottest brake

locations, catalytic oxidation typically corresponds to localized regions in cooler brake locations in contact with contaminant residue (e.g., aft aircraft positions) (Walker 2007). Figure 4 illustrates some C/C brake damage attributed to catalytic oxidation.

Catalytic oxidation of C/C composite brakes owing to air-field PDPs has become a growing concern to be monitored in the ever-changing operation environment (McCrillis 2007). As nontraditional chemical contaminants, modern PDPs may be responsible for the more rapid structural failure of C/C composite brakes in recent years. To avoid potential safety implications, this concern has to be mitigated through more

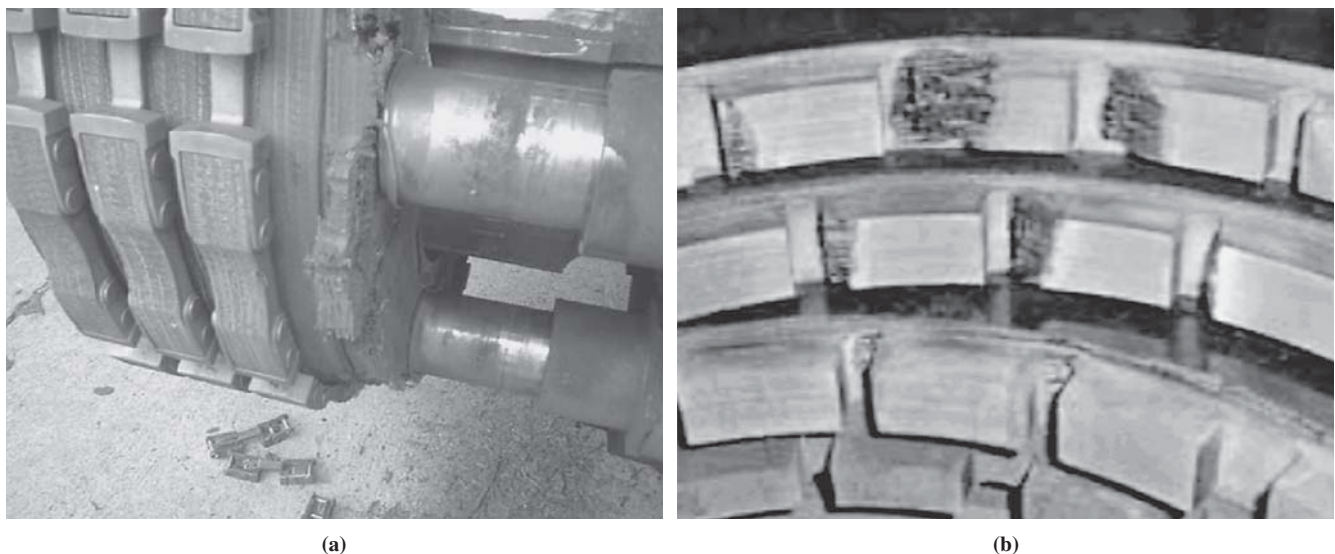


FIGURE 4 Carbon-carbon brake damage attributed to catalytic oxidation: (a) oxidized rotor drive lugs, (b) oxidized stator tenons (courtesy: Continental Airlines).

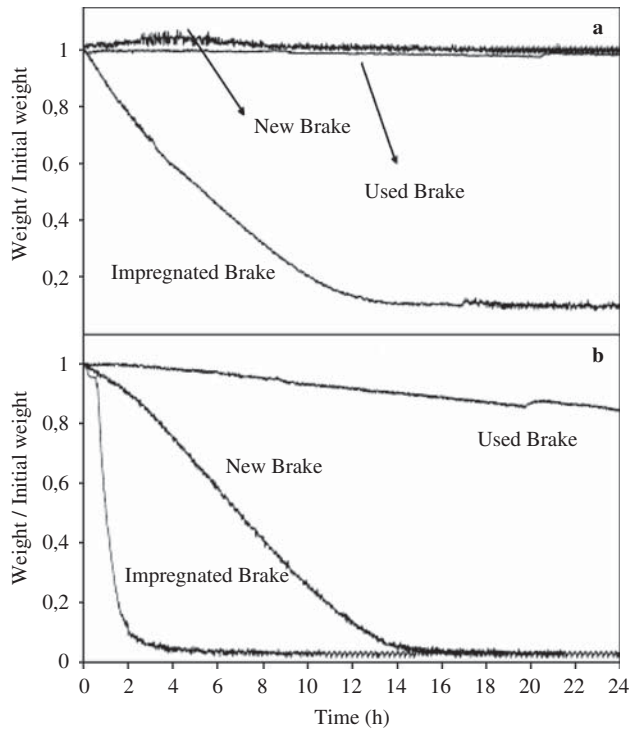


FIGURE 5 Weight loss curves of samples of new, used, and KAc-impregnated aircraft brakes obtained by TGA at 500°C (a) and 600°C (b) [adapted from Carabineiro et al. (1999)].

frequent proactive maintenance and inspection activities incurring high direct and indirect costs.

A growing body of field evidence from airline operators suggests that the use of KAc and KF on airfield pavements leads to catalytic oxidation of C/C composite brake components. The thermogravimetric analysis (TGA) data in Figure 5 illustrate the catalysis of carbon oxidation by potassium species, with the new brake samples impregnated with KAc showing high-oxidation reactivity at relatively low temperatures (Carabineiro et al. 1999). The TGA data in Table 4 also

illustrate the catalysis of carbon oxidation by a KAc-based PDP, with the C/C composite samples impregnated with the PDP showing a higher oxidation rate and a higher weight loss at lower temperatures (Filip 2007).

As the brake frictional characteristics are changed by the use of alkali-metal-salt-based PDPs, airline operators are concerned over the adverse effect of such PDPs on the braking performance and safety of aircraft (Jansen 2007). In addition to reduced brake life, such effect introduces the possibility of brake failure during aborted take-off, with the concomitant risk of fire from hydraulic fluid released during such an event.

Since 2003, Dunlop has analyzed the contamination of material samples of heat packs returned for service using the induction coupled plasma spectroscopy (Hutton 2007). A plain geographic trend can be seen (as shown in Table 5), with those aircraft operated in Northern Europe experiencing the highest rates of potassium contamination and those operated in Southern Europe and the Mediterranean region experiencing the lowest rates of contamination. According to Dunlop (Hutton 2007), this trend corresponds to the reported frequency of catalytic oxidation in the BAe 146 fleet operated throughout Europe—highest in Nordic countries where KAc and KF are regularly used for snow and ice control and lowest in Southern European countries where PDPs are not needed. Although aircraft are moving objects exposed to various PDPs, climatic conditions, and maintenance practices at different airports, the contaminants encountered other than PDPs often are essentially the same type of fire extinguishing or cleaning fluids as defined in the manufacturers' consumable materials list of allowable materials. Therefore, PDPs play a key role in the trend seen in Table 5.

Evidence from aircraft operators and manufacturers in North America, Europe, and Asia corroborate the role of PDPs in catalytic oxidation of C/C composite brakes. Irregular C/C composite brake wear and damage has been reported on virtually every aircraft platform equipped with them by international and regional carriers (Duncan 2007). ACRP survey

TABLE 4
TGA DATA AS A FUNCTION OF C/C COMPOSITE
AND DEICER CONTAMINATION

Sample	Onset of Oxidation (°C)	Maximum Rate of Weight Loss (% per min)	Weight Loss (%)
Virgin HWCCA	447	0.617	45
HWCCA+ PDP	421	0.902	71
Virgin HWCCD	382	0.619	53
HWCCD+ PDP	325	0.720	76

Adapted from Filip (2007).

Note: HWCCA, HWCCB, and HWCCD stand for different C/C composite materials, specifically for Carbenix™ C2000 2D pitch/charred resin, Carbenix™ C2000 2D-modified pitch/charred resin, and Carbenix™ 400 3D PAN/CVD, respectively.

TABLE 5
BAe 146 AIRCRAFT BRAKE CONTAMINATION ANALYSIS

Operator	Base of Operations (destinations)	No. of Aircraft	No. of Heat Packs Analyzed	Mean K Content per Sample (ppm)
A	United Kingdom (Europe)	20	101	547
B	Finland (Scandinavia, Europe)	9	44	2,183
C	Greece (Greek Islands, S. Europe)	6	42	74
D	Germany (Europe)	8	51	749
E	Germany (Europe)	5	18	991
F	Belgium (Europe)	31	93	563
G	Belgium (Europe)	11	32	991

Adapted from Hutton (2007).

respondents also indicated that no landing gear components made from C/C composite were immune to catalytic oxidation. Stators and related components tend to be more prone to catalytic oxidation than rotors, although rotors will readily load catalytic contaminants when the aircraft is stationary (Walker 2007). Direction of contaminants to brake parts can be influenced by landing gear design; redesign of landing gear on existing aircraft, however, is not practical.

Oxidation testing conducted jointly by the Center for Advanced Friction Studies (CAFS) at Southern Illinois University, Dunlop, Aircraft Braking Systems Corporation (ABSC), and Messier–Bugatti incorporated a range of materials, catalyst treatment methods, and heating temperatures (Table 6). Selected data regarding catalytic oxidation of unprotected C/Cs were presented at the SAE G-12 committee meeting in May 2007 (Filip 2007), and the results were predictably varied owing to differences in test methods employed in the lab-

oratories (Figures 6 and 7). Weight loss percentages recorded by Messier–Bugatti were much higher than those recorded in the other two laboratories—perhaps as a result of differences in heating temperature and air—which merit further investigation. Nonetheless, there was a consistent trend in weight loss data confirming the catalysis of contaminants for C/C oxidation. Figures 6 and 7 also indicate that the different C/C composite materials (both virgin and catalyst-loaded samples) experienced different levels of oxidation, which will be discussed later in this chapter.

Dunlop and ABSC are currently conducting catalytic oxidation round-robin testing for the SAE A-5 committee (Hutton 2007), and preliminary data from both laboratories indicate a significant increase in the oxidation of C/C in the presence of KAc and KF. In the most recent round of tests, uniform C/C coupons (material type not specified) were pre-treated with 25% (by weight of solution) KAc, KF, or urea; heated at 550°C for 4 h; and then weighed. The coupons treated with KF and KAc showed significantly higher weight loss than the control coupons, whereas those treated with urea showed weight loss similar to that of the control coupons

TABLE 6
TESTING PARAMETERS IN VARIOUS LABORATORIES

	CAFS	Dunlop	Messier–Bugatti
Sample	Cylinder, $D = 10$ mm, $H = 8$ mm, mass ~ 1.2 g	Cylinder, $D = 49.9$ mm, $H = 5.94$ mm, mass ~ 20 g	40 mm \times 40 mm \times 40 mm, mass ~ 50 g
		<i>With a KAc-based PDP—Cryotech E36</i>	
Contamination	Soaked for 60 min	Soaked for 30 min and dried at 150°C for 120 min	Impregnated under vacuum for 60 min and dried at 105°C for 120 min
Heating	700°C for 20 min, still air	550°C for 4 h, still air	650°C for 5 h, constant O ₂ partial pressure

CAFS = Center for Advanced Friction Studies.

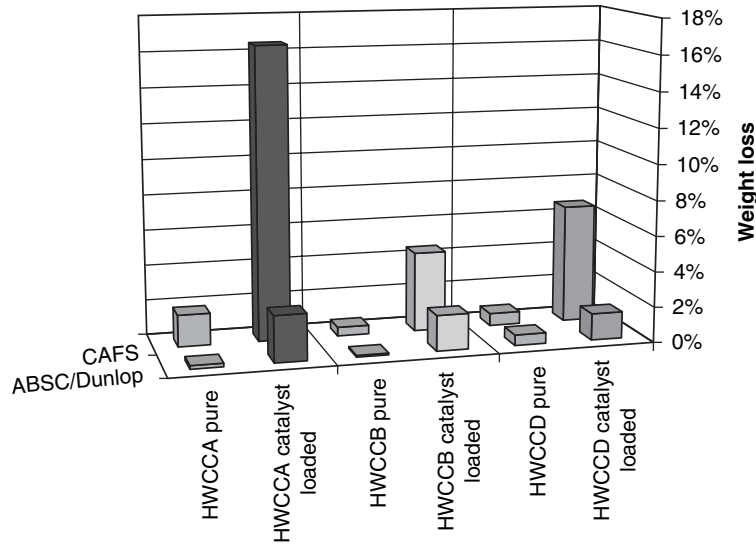


FIGURE 6 Selected results from carbon oxidation testing by Center for Advanced Friction Studies (CAFS) and Aircraft Braking Systems Corporation (ABSC)/Dunlop [adapted from Filip (2007)]. HWCCA = Carbenix™ C2000 2D pitch/charred resin, HWCCB = Carbenix™ C2000 2D-modified pitch/charred resin, and HWCCD = Carbenix™ 400 3D PAN/CVD.

(Figure 8). Although KAc- and KF-treated coupons experienced higher weight loss in the ABSC laboratory than in the Dunlop laboratory, the results demonstrated the roughly equal effectiveness of both potassium salt deicers as catalysts for carbon oxidation.

Nature of the Effect of Modern Pavement Deicing Products on Aircraft Brakes

Existing research in the laboratory has demonstrated the catalytic effects of potassium, sodium, and calcium on carbon oxidation (Lang and Pabst 1982; Krutzsch et al. 1996; Wu 2002). Oxygen transfer and electron transfer are the two gen-

eral mechanisms proposed to account for the catalytic effects of metals, oxides, and salts in carbon oxidation (Walker et al. 1968). At approximately 800°C the diffusion of oxygen through the surrounding gas to the carbon surface becomes the limiting step for thermal oxidation (Wu 2002). At typical peak operating temperatures for C/C aircraft brakes (near 500°C), the alkali-metal-salt-based PDPs (e.g., KAc) are known to decompose to alkali metal carbonates and oxides (e.g., K_2CO_3 and K_2O). The active species (S) are believed to serve mainly as “more effective adsorption and dissociation agents for the gaseous reactant than carbon itself” and to transfer the adsorbed oxygen (O) to the carbon (C). They can go through an oxidation-reduction cycle, as represented here (Wu 2002):

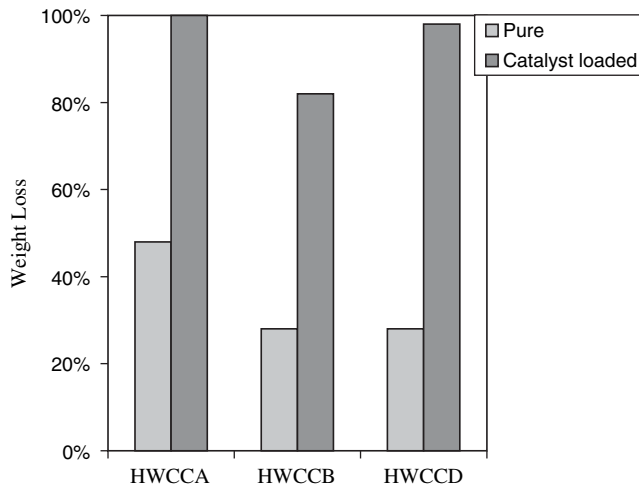


FIGURE 7 Selected results from carbon oxidation testing by Messier-Bugatti [adapted from Filip (2007)].

Such an oxygen-transfer mechanism has been supported by laboratory investigation pertinent to this subject. Environmental scanning electron microscopy experiments demonstrated that K-oxide particles very effectively catalyzed the gasification of isotropic carbon fibers in a C/C composite. In situ X-ray diffraction experiments suggested that a K-peroxide acted as the reactive intermediate species (Carabineiro et al. 1999). Experimental observations and molecular orbital (MO) calculations supported Wu's (2002) theory as follows: the presence of catalyst or inhibitor on carbon materials affects the oxidation behavior by influencing the concentration and stability of two types of oxygen complexes on the carbon surface during the C-O₂ reaction.

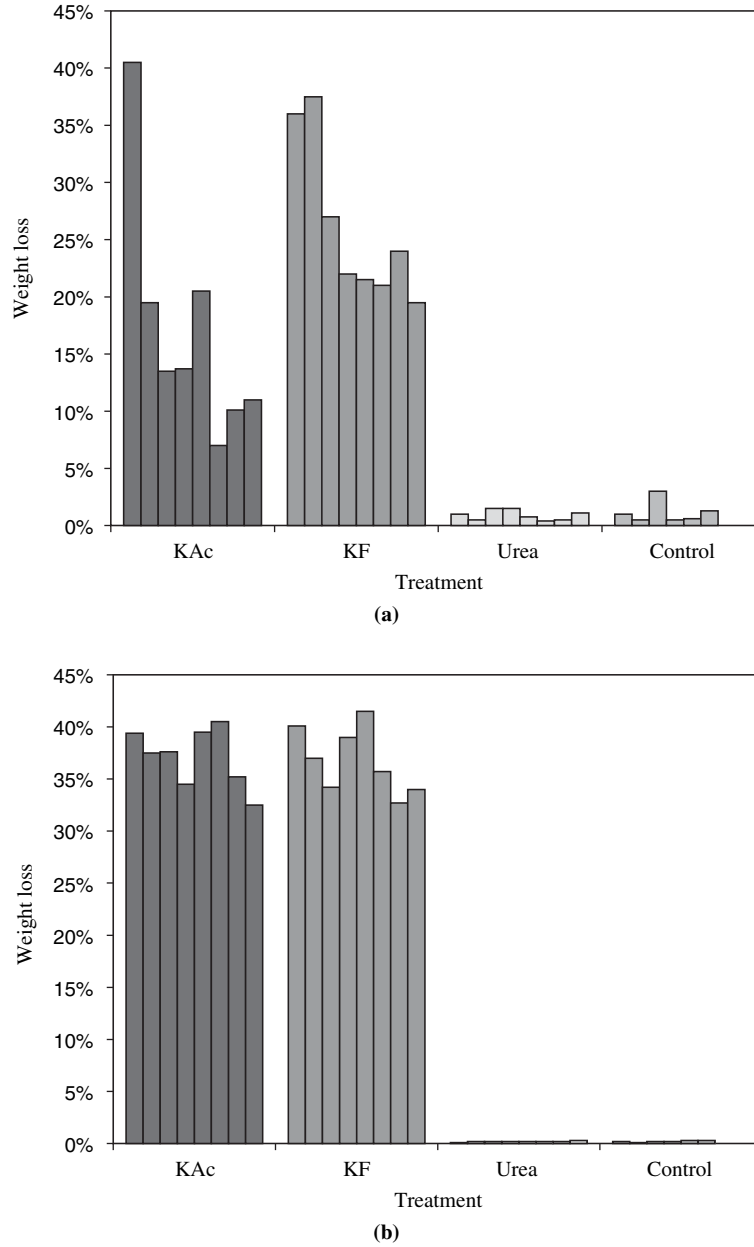
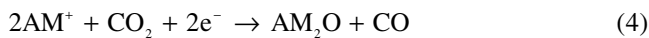


FIGURE 8 Weight loss of C/C after heating at 550°C for 4 h: (a) Dunlop data; (b) ABSC data [adapted from Hutton (2007)].

The electron-transfer mechanism, on the other hand, suggests that catalysts [e.g., alkali metals (AM)] have unfilled electron shells and accept electrons from carbon matrix, as represented here (Filip 2007):



This wetting ability (or lack thereof) is also relevant in the catalysis of C/C composites. The low melting temperatures

of K salts and their decomposition products—all below 600K (or 327°C)—allow them to migrate easily on the carbon surface and form good interfacial contact with it (Wu 2002; Wu and Radovic 2005), facilitating oxygen transfer (Figure 9a). In some cases heavy catalyst loading may retard the activity of K species by “crowding” particles on the carbon surface (Figure 9b). Calcium oxide, with a melting point higher than 1500K (or 1227°C) (Wu 2002), relies on initial loading and impregnation to achieve the necessary surface contact. As oxidation proceeds, immobile calcium oxide may act as a barrier for additional catalysts, lowering the oxidation rate (Figure 9c). This retarded reaction recommends Ca-based PDPs as less detrimental to C/C aircraft brakes than K-based PDPs (Wu and Radovic 2005).

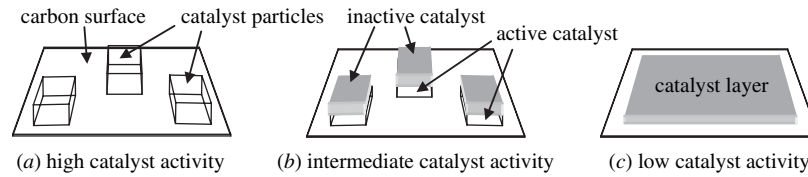


FIGURE 9 Catalyst loading and activity on brake surface [adapted from Wu and Radovic (2005)].

Several other less-studied factors also deserve attention. Temperature has been observed to play a role in governing the intensity of catalytic oxidation. Walker et al. (1997) observed a threshold of between 650°C and 700°C where the reaction rate of catalytic oxidation of C/C friction material in the presence of KAc drops off dramatically. Electrical conductivity may also be an important factor, as it appears to reflect catalytic potential in common pavement deicers. Conductivities of KAc and KF compared with that of urea appear to mirror relative catalytic abilities of these deicers (Table 7).

Standards and Test Protocols

SAE AMS 1431C and AMS 1435B are the accepted standards for solid and liquid pavement deicers, respectively. Neither currently contains requirements for C/C catalytic oxidation testing. The SAE G-12 Carbon Oxidation Working Group is in the process of refining a carbon compatibility test protocol with assistance from the SAE A-5A Brake Manufacturers Working Group for inclusion in the next revision of both standards.

Boeing provides for testing of runway and facility deicers in its comprehensive test protocol for the Evaluation of Maintenance Materials, Specification D6-17487. The current revision of the protocol, released in 2003, specifies details for testing solid and liquid deicers, but does not address their roles in C/C composite catalytic oxidation. Boeing has no plans at this time to add catalytic oxidation testing to D6-17487, citing a requirement included in every Boeing brake assembly engineering drawing: “. . . that the brake be designed to be compatible with different materials including runway de-icer fluids” [M. Arriaga, Boeing Company, personal communication, July 2007].

In addition, the SAE A-5A Working Group is in the process of developing an oxidation test method for anti-oxidant (AO)-treated coupons and the details are summarized as follows. C/C composite brake material will be cut from production discs and tested in the configuration of cylinders. A generic AO treatment based on mono-aluminum phosphate, phosphoric acid, and water (to be determined) will be used to simulate the application of the AO protection system. Although AO treatments are typically applied to nonfriction surfaces only, it is proposed to cover all surfaces of the test coupon to demonstrate the effect of the AO treatment. Dipping coupons in the AO treatment is proposed because it is less operator-sensitive than other application methods (e.g., brushing and spraying). The AO treatment will then be cured by heating the coupons at a ramp rate of 60°C/h to 300°C/h in air and at 300°C for 1 h. The AO treatment will be made centrally before the test coupons are distributed to test facilities. To test the catalytic oxidation, runway deicing solutions will be used at 25% w/w concentration. The weight loss of the AO-treated coupons will be tested under the same temperature for the testing of bare carbon; that is, 1022°F ± 10°F or better (550°C ± 5°C) in still air (SAE A-5A . . . 2007).

As discussed previously, there were large variations observed in the carbon oxidation testing results from different laboratories. These variations highlight the need to develop reliable, standard testing procedures to evaluate the catalysis of PDPs for carbon oxidation, which would allow better practices in preventing or mitigating such catalysis. To ensure reproducible results, protocol parameters to be defined will include sample material, density, dimensions, coupon orientation, contamination concentration, temperature, duration, post-treatment, heating temperature, and ambient air velocity.

Prevention and Mitigation

There are potential opportunities for all stakeholder groups to collaborate in addressing the catalytic oxidation issue of C/C aircraft brakes with respect to aircraft and component design, brake testing, aircraft operations, airfield maintenance, etc. In the domain of brake technologies, chemical modification of C/C appears to offer greater potential than structural changes or defect elimination in mitigating catalytic oxidation (Filip 2007). Chemical modification generally involves the introduction of groups of atoms to reduce gasification of carbon, the reduction of catalyst mobility, and the formation of a

TABLE 7
ELECTRICAL CONDUCTIVITIES
OF PAVEMENT DEICERS

Electrical Conductivity 1% Solution	
Type	($\mu\text{S}/\text{cm}$)
Urea	18
KAc	~7000
KF	~9000

barrier for transport of oxygen and reaction products (Filip 2007). Defect elimination generally involves the reduction of C/C composite porosity and the elimination of active oxidation sites (by means of improved crystalline order of carbon and reduced defects) (Filip 2007). A firm understanding of the catalysis mechanism has nurtured development of various proprietary AO formulations tailored to material, environmental, and performance needs of specific brake and wheel designs. It is also recognized that catalytic oxidation of C/C composite friction material by some alkali-metal-salt-based PDPs—such as those based on KAc and KF—cannot be fully arrested in situ by current methods.

Dozens of U.S. and European patents have been assigned to formulae and methods for blocking active oxidation sites on and below the C/C composite brake material surface. The oxidation inhibiting composition usually penetrates at least some of the pores of the C/C composite and, once heated, forms a deposit within the penetrated pores and the surface of the C/C composite. For instance, Stover and Dietz (1995) and Stover (1998, 2003) created AO formulations primarily of phosphoric acid, metal phosphates, and aluminum and zinc salts in a polyol/alcohol base. Walker and Booker (2000) demonstrated the effectiveness of P-13 (a standard phosphoric-acid-based AO) and a potassium compound (KH_2PO_4) for inhibiting catalytic oxidation by KAc by blocking active oxygen transfer sites on the surface of C/C friction material. It was proposed that the addition of KH_2PO_4 blocked sites on the carbon surface that were particularly prone to “activation” by K catalysis. Phosphate-based AO paints are now a standard, effective tool in reducing catalytic oxidation (T. Walker, Honeywell International, personal communication, July 2007).

Wu et al. (2001) and Wu (2002) explored inhibition by phosphorus (P)- and boron (B)-deposition and B-doping in fine detail and reported several key findings. Data suggested the presence of two catalyst-deactivation mechanisms. Surface-deposited P and B compounds were found to block (with varying success) catalysts from contact with active oxidation sites on the carbon substrate. Thermally deposited P compounds were demonstrated to be effective in inhibiting the carbon oxidation catalyzed by KAc and calcium acetate (CaAc); and the characterization of P-deposited carbon samples and ab initio molecular orbital calculations both suggested that the inhibition effectiveness derived from the formation of possibly C-O- PO_3 groups and C- PO_3 groups (Wu and Radovic 2006), which preferentially block the active carbon sites (Wu 2002). The effect on K catalysis was much smaller owing to the high wetting ability and mobility of K species. Also suggested was the possibility that in sufficient concentration, these deposition compounds form stable oxide glazes over the friction surface, acting as an oxygen barrier. B-doping promoted better graphitization of the C substrate, denying free electron sites to catalysts. A secondary benefit to B-doping was the lower curing temperature (by 400°C–500°C) needed for satisfactory graphitization. Wu (2002) suggested that a

combined use of P and B might offer more effective inhibition of catalytic carbon oxidation than used individually (Wu 2002). Emphasizing the impossibility of eliminating K catalysis of C/C composites, an inhibition system employing a combination of painted or ceramic coatings on nonfriction surfaces, B-doped C/C substrate, and deposited P and/or B_2O_3 was suggested.

Application of the laboratory research has been met with mixed success. Industry experiments with B-doping have not shown promise (T. Walker, Honeywell International, personal communication, July 2007), although elemental B has been used successfully as a barrier coating. Brush-on phosphate AO coatings continue to be widely employed, with periodically improved formulations. These AO treatments typically include multiple cycles of a brush-applied or sprayed phosphate- or phosphoric acid-based coating on the C/C material, followed by high-temperature curing. In addition, a ceramic-based oxygen barrier coating is applied to nonfriction surfaces (Webb 2007). C/C composites composed of three-dimensional nonwoven fabric with preform chemical vapor deposition matrix have generally replaced those composed of chopped polyacrylonitrile (PAN) or pitch fibers, owing to the increased load-bearing and thermal properties of the former. Combinations of these advances have resulted in marked reductions in unscheduled replacements owing to catalytic oxidation.

Materials-deicer compatibility testing conducted by the Concurrent Technologies Corporation on behalf of the Air Force Research Laboratory in 2003 and 2004 included catalytic oxidation testing of four Honeywell C/C friction materials and three pavement deicers that were then new to the market or still in development (Concurrent Technologies Corp. 2004). For each contaminant, ten specimens—five brushed with Honeywell P-13 phosphate-based AO compound—of each friction material were soaked in deicer or deionized water for 20 min and dried in still air at 110°F (43°C) for 30 min. Specimens were then heated for two 4-h periods at 1300°F (704°C) and allowed to cool to room temperature in still air after each session. Three of the C/C materials were composed of chopped pitch or PAN fiber with a phenolic char chemical vapor deposition matrix, whereas the fourth material, Carbenix™ 4000, consisted of 3D needled, nonwoven PAN fabric with a chemical vapor deposition preform matrix. As shown in Figures 10 and 11, unprotected 3D PAN samples suffered weight and hardness losses similar to those of the other unprotected friction materials. In contrast, AO-treated 3D PAN samples experienced the lowest weight and hardness losses in the group. This observation suggests that even though the 3D material showed no inherent resistance to catalytic oxidation, one or more of its unique traits improved the performance of the AO surface treatment. Although the CTC report did not offer explanations for the favorable performance of the AO-treated 3D C/C composite material, implementation of this improved material in the field in

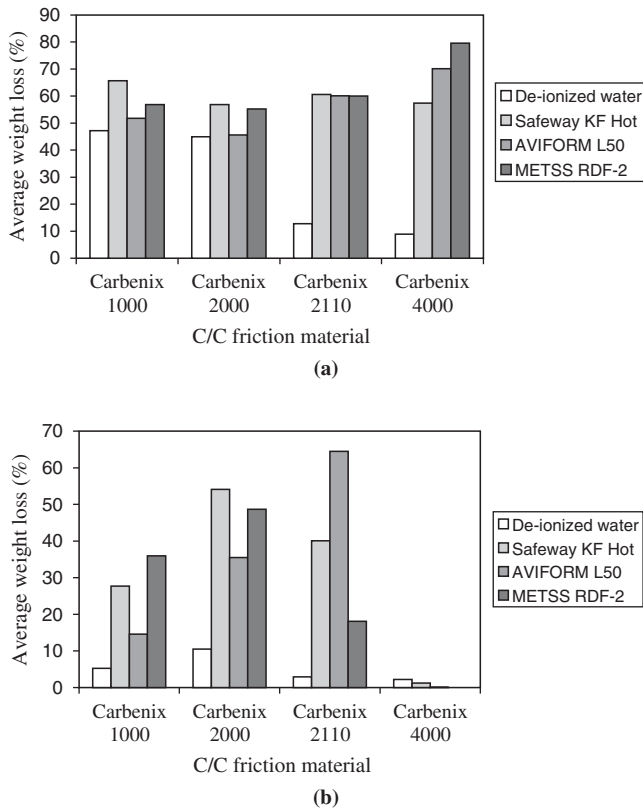


FIGURE 10 Average weight loss of (a) unprotected; (b) AO-treated C/C friction materials exposed to KF-based deicers and de-ionized water [adapted from Concurrent Technologies Corp. (2004)]. (Note: Carbenix™ is a Honeywell proprietary C/C material.)

concert with new AO systems has demonstrated similar margins of success. New brakes with a 3D PAN preform substrate and improved AO protection fitted aboard Boeing 767s led to a 90% reduction in brake removals before end-of-service life on those aircraft, and 3D PAN substrates have become the standard substrate on new C/C composite brake designs (Walker 2007).

Solid pavement deicer formulations were endorsed by several ACRP survey respondents as less aggressive catalysts, although no specific justification was provided. Catalytic oxidation of C/C brakes may also be mitigated by using more carbon-friendly PDPs on airfield pavements. Anhydrous betaine (*N,N,N*-trimethylglycine), a naturally occurring organic byproduct of sugar beet processing, is being developed with support from the Finnish Government and Finavia as a pavement deicer (Hänninen 2006; Simola 2006). Not yet commercially available, betaine has shown favorable results in metallic corrosion and deicing performance testing, and its low electrical conductivity also compares favorably with other deicers (Table 8). Betaine's relatively high BOD, nitrogen content (15% by weight), and high cost may present some challenges to using it as the sole freezing point depressant for PDPs.

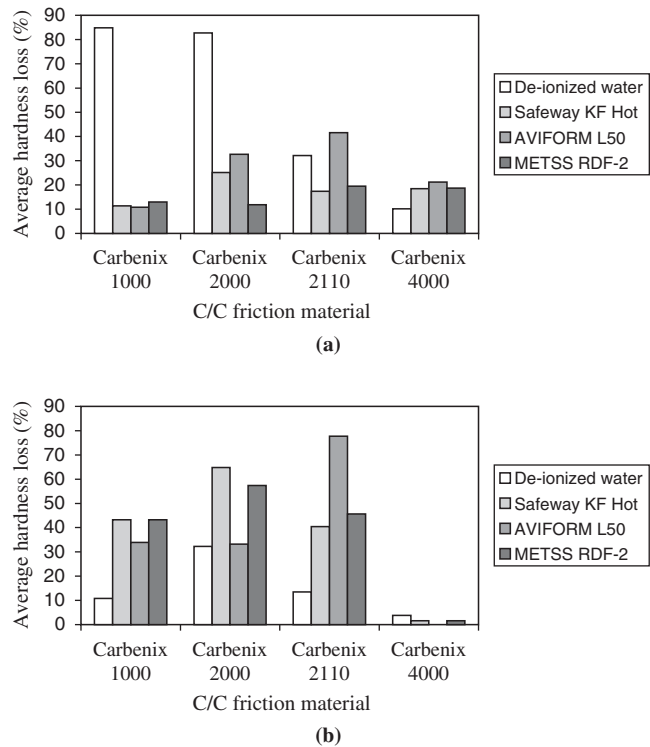


FIGURE 11 Average hardness loss of (a) unprotected; (b) AO-treated C/C friction materials exposed to KF-based pavement deicers and de-ionized water [adapted from Concurrent Technologies Corp. (2004)]. (Note: Carbenix™ is a Honeywell proprietary C/C material.)

As early as 2002, a U.S. patent was under review for an aqueous liquid aircraft runway deicer composition featuring minimal catalytic oxidation effect on C/C composites. The composition contains 20%–25% w/w of an alkaline earth metal carboxylate, 1%–15% w/w of another alkaline earth metal carboxylate, 1%–35% w/w of an aliphatic alcohol, 0.01%–1% of an alkali metal silicate, and up to about 1% w/w of a triazole (Moles et al. 2002). Through partnership with DuPont Tate & Lyle Bio Products LLC, this evolved into a commercial product marketed by Cryotech (BX36), which now includes a bio-based active ingredient Susterra propanediol. Joint efforts by Honeywell and Cryotech led to preliminary testing of BX36, which showed less conductivity

TABLE 8
ELECTRICAL CONDUCTIVITY AND BIOLOGICAL OXYGEN DEMAND OF DEICERS

Deicer	Chemical Formula	Electrical Conductivity of	
		1% Solution ($\mu\text{S}/\text{cm}$)	BOD ₅ (mg O ₂ /g)
Betaine	C ₅ H ₁₁ NO ₂	99	759
KAc	CH ₃ COOK	~7,000	~300
KF	HCOOK	~9,000	~100
Urea	H ₂ NCONH ₂	18	~2,100

and more than 50% less catalytic activity and passed all AMS 1435A deicing criteria, including the proposed corrosion criteria (Boeing Method) (Walker 2007).

Knowledge Gaps

Although the fundamental mechanisms of catalytic oxidation by PDPs are well understood in well-controlled laboratory settings and advances in technologies for its prevention and mitigation have been made in the last decade or so, the problem appears far from solved. Action in the following areas may be beneficial for further advances.

There is still a need to establish a comprehensive PDP catalytic oxidation test protocol. To this end, a test protocol has been in development in the SAE G-12 Working Group since early 2003 and is currently being refined for inclusion to AMS 1431 and 1435. Incorporation of such a test protocol (including a conductivity test as suggested by several ACRP survey respondents) into AMS 1431C and 1435B will provide necessary guidance for developing the next generation of PDPs and C/C aircraft brakes. The proprietary nature of PDP and C/C aircraft brake technologies may hinder the development of such a test protocol, and the ever-changing nature of these technologies may entail continued efforts in updating the test protocol.

Furthermore, more research is needed to better understand relationships between brake design, AO treatment, and PDP contamination as factors in catalytic oxidation. PDP development is still an active field, and new products will continue to be introduced to the market. AO treatments designed to mitigate catalytic oxidation by PDPs are still immature and mostly proprietary.

CADMIUM CORROSION

Cadmium (Cd) had been the standard for protection of steel parts on aircraft wheels and brakes even before the 1980s. Cd-plating is the most popular surface treatment technology for corrosion protection of aircraft steel parts (e.g., airframe components and fasteners), which is of great importance to flight safety and aircraft durability. This is attributable to the unique combination of its excellent corrosion protection properties in traditional service environments and its other service characteristics. Cd-plating serves as a highly effective barrier coating, especially in the marine environments often experienced by aircraft. It also serves as a sacrificial coating to protect steel and features nonvoluminous corrosion products. Cadmium offers better corrosion resistance and a greater immunity domain than zinc (Badawy and Al-Kharafi 1998). Cadmium is also galvanically compatible with aluminum alloys (Baldwin and Smith 1996). Other attractive properties of Cd-plating include its good conductivity and surface lubricity, high ductility, solderability, and potential to be repaired in the field.

The main drawback of Cd-plating is the high toxicity associated with Cd and its compounds. Cadmium can accumulate in the human body with acute or chronic exposure, and eventually lead to softening of the bones and kidney failure in humans and many animals (“Metals as Toxins—Cadmium” 2007). In addition, the Cd-plating process often involves the use of toxic cyanide baths and the process itself can weaken steel components through hydrogen embrittlement if post-application precautions are not taken.

Despite the disadvantages of Cd-plating and a large body of research on its alternatives (Smith 1992; Baldwin and Smith 1996; Thomson 1996; Zhirnov et al. 2003), the desirable qualities of Cd-plating have yet to be matched or exceeded in a single alternative.

Field reports increasingly suggest that the contact with modern PDPs (such as potassium acetate- and formate-based products) promotes damage to aircraft components, including those that are Cd-plated. In April 2002, the Aerodrome Safety Branch under Transport Canada issued an Aerodrome Safety Circular, recommending that airport operators refrain from using deicing fluids containing KF on airside movement areas. The recommendation was based on a Boeing Service Bulletin indicating that all B737-600, -700, -700C, -800, and -900 airplane models were prone to suffer KF-promoted corrosion of electrical connectors located in the wheel well. In August 2004, Transport Canada cancelled the Circular, based on new evidence that the problem appeared to be limited to the Boeing 737, but suggested that airport operators inform air carriers serving their airport of the PDPs used on airside movement areas (Transport Canada . . . 2004). In September 2005, the FAA updated an existing airworthiness directive that applies to all Boeing B737-600, -700, -700C, -800, and -900 airplane models. The existing directive required “either determining exposure to runway deicing fluids containing KF, or performing repetitive inspections of certain electrical connectors in the wheel well of the main landing gear for corrosion and follow-on actions.” The amendment was prompted by anecdotal evidence showing similar corrosion effects of KAc-based PDPs and added a new inspection requirement and related corrective actions. The goal was to “prevent corrosion and subsequent moisture ingress into the electrical connectors, which could result in an electrical short and consequent incorrect functioning of critical airplane systems essential to safe flight and landing of the airplane” (“Airworthiness Directives . . .” 2005). The U.S. Air Force has found that KAc-based runway deicing fluids caused numerous problems with its aircraft components, mainly electronics (e.g., failure of switches and wire harnesses), likely owing to high conductivity of the deicers (“Runway Deicing . . .” 2007).

Cadmium corrosion has been observed in Continental Airlines (CO) and Scandinavian Airlines System 737-NG and CO EMB-145 MWW (main landing gear wheel well) electrical connectors, MWW components, and air conditioning bay packs. Aluminum corrosion has been observed in CO 737-NG

and other airline 737-Classic MWW and wing aluminum hydraulic lines. The PDPs were also suspected to cause the premature corrosion of landing gear joints, accelerate the degradation of electrical wire harness insulation, and promote the corrosion of aluminum belly skin (Duncan 2006). Similar effects have also been observed on ground support equipment (GSE) units. Among them, the foremost concern has been the effect of modern PDPs on Cd corrosion, although the other problems are more anecdotal and are more easily mitigated through better aircraft design or maintenance practices.

As such, the rest of this section synthesizes the information on the validity and nature of the effect modern PDPs (mainly alkali-metal-salts) on Cd corrosion, describes the related standards and test protocols, discusses ways to prevent and mitigate such effect, and identifies pertinent knowledge gaps.

Validity of the Effect of Modern Pavement Deicing Products on Cadmium Corrosion

Until recently, the principal evidence connecting alkali-metal-salt-based PDPs with Cd-plating corrosion has been a trend of increased reports of the latter occurring simultaneously with the introduction of the former (ACRP survey; Duncan 2006). In the United States, the introduction of alkali-metal-salt-based PDPs in recent years coincided with a rise in the number of reported cases of failed or replaced aircraft components resulting from Cd corrosion (Duncan 2006). A majority of the relevant reports involved mechanical and electrical connectors accessible to runway deicers through spraying or splashing, such as main landing gear wheel wells and air conditioning bays. Scandinavian and Northern European airports saw widespread corrosion of Cd-plated components and electrical failures on 737-NG aircraft in the 2000/2001 winter season, which Boeing attributed to their exposure to KAc- and KF-based PDPs (Hunter 2005). It is interesting to note that all PDPs used at these airports passed the Cd-corrosion test required by AMS 1435 and AMS 1431. The test protocol—ASTM F1111—involves the continuous immersion of Cd-plated steel specimens in the PDP for 24 h, which was later considered unable to simulate the field exposure conditions.

Boeing initiated round-robin testing based on ASTM F1111 Cd-plated steel specimens and a custom-designed Cd cor-

rosion test protocol involving cyclic immersion in the PDP for 31 days (instead of ASTM F1111, as discussed later). With the first round of tests since 2005, participating European and U.S. laboratories observed generally consistent mass *gain* patterns in Cd-plated coupons in the presence of KF (Nicholas 2007), and the experiment was redesigned and the second round of tests began in 2007. The material used was changed from F1111 Cd-plated steel to AMS QQ-P-416B Cd-plated steel. The test environment was adjusted to 90°F (32.2°C) and 30% relative humidity, and the test duration was reduced from 31 to 14 days. The number of brush strokes on the specimen was regulated at 12 stokes per side. Methanol was used to dry the specimen to ensure moisture removal. Data indicated a very reliable test within the same laboratory, but variations between laboratories. The latter was likely derived from deviations in detailed procedures (Nicholas 2007). The only anomalous weight gain (see Table 9, highlighted in bold) was attributed to an unidentified deviation in procedure. The next round of testing was planned for late 2007 and was to be conducted under significant changes in experiment design to further reduce variability between laboratories and to incorporate a fluid to simulate KAc-based PDPs (along with a KF-based fluid and urea as control) into the testing scheme.

Nature of the Effect of Modern Pavement Deicing Products on Cadmium Corrosion

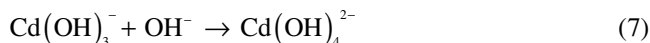
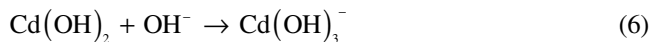
Because corrosion of metals is an electrochemical process, the thermodynamics of metallic corrosion is generally governed by the combination of pH of the electrolyte and electrochemical potential of the metal in the electrolyte. For the Cd-water system at 25°C, its potential-pH equilibrium diagram was established as early as the 1960s (Deltombe et al. 1966). Such theoretical predictions of corrosion and passivity were experimentally validated by testing the dissolution of Cd in solutions of pH 1–15. Consistent with the potential-pH equilibrium diagram, the immersion test results indicated significant corrosion of Cd in both acid (pH < 7) and highly alkaline (pH > 12) solutions and an intermediate region of a low corrosion rate of Cd near a pH of 12 (Tomlinson and Wardle 1975). It can be reasonably assumed that Cd in the first two solutions dissolved to Cd²⁺ and HCdO₂[−], respectively, whereas in the intermediate region it formed a passive layer of

TABLE 9
WEIGHT CHANGE OF CD-PLATED STEEL AFTER ROUND-ROBIN
TESTING IN KF, SPECIMEN SIZE 25.4 MM × 50.8 MM × 1.22 MM

Specimen Type	Weight Change of Specimens (g)				
	Lab A	Lab B	Lab C	Lab D	Lab E
ASTM F1111-02	−0.0114	−0.0919	+0.057	−0.0077	−0.0618
AMS QQ-P-416B	−0.0109	−0.0707	−0.0155	−0.0132	−0.0955

Adapted from Nicholas (2007).

$\text{Cd}(\text{OH})_2$. The formation of $\text{Cd}(\text{OH})_2$ or $\text{CdO} \cdot \text{H}_2\text{O}$ in neutral and alkaline solutions has been confirmed and this passive film may be unstable in highly alkaline solutions through the following reactions (Badawy and Al-Kharafi 2000):



In addition to pH, both the dissolved oxygen and temperature are expected to have an influence on the kinetics of metallic corrosion. The corrosion of Cd in water at pH 8.3–10.55 was found to proceed under cathodic control through the reduction of oxygen. The corrosion rate of Cd was reduced substantially by limiting the available oxygen in water or increasing concentrations of OH^- and CO_3^{2-} species (Posselt and Weber 1974). In another study, however, the presence of oxygen was found to passivate the Cd surface in neutral and alkaline solutions (Badawy et al. 1998). The electrochemical impedance spectroscopy data indicated the presence of two phase maxima in neutral solutions, signifying two consecutive charge transfer reactions with different time constants occurring at the Cd/electrolyte interface (Badawy et al. 1998). Similar to most chemical reactions, the rate of Cd corrosion usually increases with temperature.

Very little research has been conducted to investigate the mechanism of Cd corrosion or Cd-steel corrosion in the presence of alkali-metal-salts (e.g., KF and KAc), partly owing to the high toxicity associated with Cd and its compounds. It is known that the corrosion properties of Cd resemble those of zinc in the range pH 8–11, except for the higher corrosion resistance of Cd (Posselt and Weber 1974). As such, a recent laboratory study conducted at the Western Transportation

Institute might shed some light on the PDP effect on Cd-steel corrosion (Fay et al. 2007, with expanded dataset). The corrosion behavior of mild steel (ASTM A36) and galvanized steel (highway guardrail) was studied using various deicer products and analytical-grade KAc. For deicers diluted at 3% by weight or volume (for solid and liquid deicers, respectively), electrochemical testing of their corrosion to mild steel and galvanized steel showed that the acetates and formates (except the solid analytical KF) were much less corrosive to mild steel than the chloride-based deicers. Steel is considered to be passive when its corrosion current density $i_{\text{corr}} < 0.1 \mu\text{A}/\text{cm}^2$, and active corrosion occurs when $i_{\text{corr}} > 1.0 \mu\text{A}/\text{cm}^2$. As such, it can be concluded that the acetates and formates tested (except the solid analytical KF) were noncorrosive to mild steel, whereas the chloride-based deicers were very corrosive (as shown in Table 10). Nonetheless, the galvanized steel in the acetates and formates (except the solid NaF-based product) was found to be corroding at comparably high rates, as seen in the chloride-based deicers. The corrosion potential (E_{corr}) data shown in Table 10 indicate that acetates and formates (except the solid analytical KF) significantly shifted E_{corr} of mild steel to the noble direction, but failed to do so with E_{corr} of galvanized steel. The latter might be attributed to the presence of sacrificial zinc in the galvanized steel, which likely changed the potential-pH equilibrium of the steel and moved the metal from a passive state to an active corrosion state. It can be assumed that the sacrificial Cd in the Cd-plated steel plays a similar role to the sacrificial zinc in the galvanized steel when exposed to alkali-metal-salt deicers.

A few mechanisms may now be proposed that may be responsible for the effect of modern PDPs on the corrosion of Cd-steel aircraft components. First, PDP residues may be highly concentrated on localized areas of aircraft, owing to

TABLE 10
ELECTROCHEMICAL ANALYSIS OF DEICER EFFECT TO MILD STEEL (ASTM A36)
AND GALVANIZED STEEL (Guardrail)

	Deicer	Corrosion Rate (MPY)	E_{corr} (mV, vs. SCE)	i_{corr} ($\mu\text{A} \cdot \text{cm}^2$)
Mild Steel	MgCl_2 (liquid)	2.7 ± 1.1	-616.0 ± 1.8	6.0 ± 2.5
	Salt/Sand	2.5 ± 0.6	-764.3 ± 6.0	5.4 ± 1.3
	KAc (liquid)	$2.5\text{E-}03 \pm 9.1\text{E-}05$	-155.3 ± 30.2	$5.5\text{E-}03 \pm 2.0\text{E-}04$
	KAc (solid, analytical)	$2.5\text{E-}03 \pm 3.0\text{E-}04$	-132.3 ± 13.3	$5.5\text{E-}03 \pm 6.0\text{E-}04$
	NaAc (solid)	$7.1\text{E-}03 \pm 4.1\text{E-}03$	-204.3 ± 68.6	$6.8\text{E-}02 \pm 9.3\text{E-}02$
	NaF(solid)	$2.5\text{E-}03 \pm 2.1\text{E-}04$	-199.5 ± 12.0	$5.5\text{E-}03 \pm 6.0\text{E-}04$
	KF (solid, analytical)	8.5 ± 11.5	-598.0 ± 316.5	19.8 ± 23.9
Galvanized Steel	MgCl_2 (liquid)	1.7 ± 0.2	-1037.5 ± 5.0	3.5 ± 0.6
	Salt/Sand	$0.8 \pm 2.0\text{E-}02$	-1047.5 ± 5.0	1.6 ± 0.1
	KAc (liquid)	1.7 ± 0.6	-1032.5 ± 5.0	3.0 ± 0.9
	KAc (solid, analytical)	1.8 ± 1.2	-1050.0 ± 0.0	4.4 ± 1.3
	NaAc (solid)	0.9 ± 0.2	-1035.0 ± 19.1	1.8 ± 0.3
	NaF(solid)	$5.2\text{E-}02 \pm 5.9\text{E-}02$	-1003.3 ± 8.3	$0.2 \pm 9.1\text{E-}02$
	KF (solid, analytical)	1.6 ± 0.9	-1060.0 ± 0.0	4.1 ± 0.6

Note: 1 MPY = 1 milli-inch per year = 0.0254 mm per year.

the hygroscopic nature of these PDPs (e.g., KAc and NaF). This may lead to localized high alkalinity that can disrupt the passive film of $\text{Cd}(\text{OH})_2$ by means of the reactions in Eqs. 6 and 7. Second, the potential corrosion products (CdAc and CdF) are highly soluble in water, which may facilitate the corrosion of Cd-steel. Third, Cd serves as a sacrificial anode to protect the steel components and the corrosion of Cd may be accelerated by the high conductivity derived from its contamination by PDPs and the increasingly smaller area ratio of anodic sites (Cd) to cathodic sites (steel). Finally, the presence of PDPs might promote the hydrogen embrittlement of Cd-plated steel.

It should be cautioned no conclusions should be drawn about the corrosivity of PDPs without stating the specific deicer product and its concentration, the test protocol used (SAE, ASTM, National Association of Corrosion Engineers, or electrochemical test), and the type of metal tested.

Standards and Test Protocols

In May 2002, ASTM Committee F07 on Aerospace and Aircraft published an updated version of ASTM F1111-02, Standard Test Method for Corrosion of Low-Embrittling Cadmium Plate by Aircraft Maintenance Chemicals. As discussed earlier in this chapter, the testing parameters of ASTM F1111-02 have been considered insufficient for discriminating PDPs for their corrosivity, likely resulting from the relatively mild temperature (95°F or 35°C) and short, continuous immersion period (24 h). In response to this deficiency, Boeing developed its current Cd corrosion test (discussed later) and integrated it into the broader Boeing test protocol. Similar to those found in ASTM F1111-02, the plating specifications contained in the Boeing Cd corrosion test are intended to be used only for evaluation purposes and differ from those in AMS QQ-P-416 B, the accepted standard for electrodeposited Cd-plating in aerospace applications. AMS QQ-P-416 B references separate ASTM and NASA standards for determining corrosion resistance to salt spray, but does not set forth parameters for general corrosion testing such as those specified in ASTM F1111-02 or the Boeing protocol.

Boeing Document D6-17487, *Evaluation of Airplane Maintenance Materials*, contains a section (§20) specific to measuring the corrosivity of runway deicers to Cd-plating. The Boeing test sample specification was derived from the ASTM F1111 specification using a specimen size of 25.4 mm × 50.8 mm × 1.22 mm. The Boeing test protocol uses a 31-day cyclic immersion of Cd-plated steel in the electrolyte, instead of a 24-h continuous immersion used in the ASTM specification. Using this protocol, Cd-plated steel specimens were exposed to eight runway de-icing fluids and three control fluids, with three replicates in each solution. The test protocol was demonstrated to be capable of distinguishing the corrosivity of PDPs to Cd-plated steel, with a KAc-based PDP and a KF-based PDP being the most and the least corrosive, respectively (Hunter 2005).

The Boeing standard limits the Cd weight loss owing to corrosion to no more than 0.03 mg/cm², equivalent to no more than a 0.0077 g loss from a single test coupon. Because the majority of Cd weight loss occurs in the first 14 days of testing, Boeing reduced the test duration from 31 days to 14 days and plans to establish a new weight loss threshold level based on the revised test method.

Currently, the Boeing Cd corrosion test protocol is being modified. As discussed earlier, round-robin testing data indicated good consistency within the same laboratory, but revealed large variations between different laboratories. These variations highlight the need to develop reliable, standard testing procedures that can be used to evaluate the corrosivity of PDPs to Cd-plated steel, which would allow better practices for preventing or mitigating such corrosion. Details of the test protocol such as the Cd-plated steel material, dimensions, and configuration; specimen pretreatment and post-treatment; and testing environment (relative humidity, temperature, etc.) should be well-defined and controlled to ensure repeatable and reproducible results.

Prevention and Mitigation

There are potential opportunities for all stakeholder groups to collaborate to prevent and mitigate the effects of PDPs on aircraft components from aspects of aircraft and component design, aircraft operations, and airfield maintenance. Installation of TR (engine thrust reverser) cascades with improved design, replacement of Cd-plated connectors with stainless steel and anodized aluminum connectors, and application of corrosion-inhibiting compounds (CICs) are suggested by Boeing (Duncan 2006). Frequent inspection or online monitoring of corrosion-prone components, although costly, is another way to mitigate corrosion of Cd-plating and aluminum corrosion.

In the domain of CIC technologies there is still great potential for improvement. At this stage, the research has to build on the existing knowledge base of inhibiting Cd corrosion in the absence of PDPs. For instance, some quinoxaline derivatives (quinoxalidine acid, oxine, 2-methyloxine, and oxine-5-sulfonic acid) were found to form stable chelate compounds with Cd and thus inhibit the general corrosion of Cd (Kato et al. 1973). Quinoxaline, however, is a known hazardous air pollutant. Precoating the Cd surface with CO_3^{2-} or sodium metasilicate was reported to greatly reduce its corrosion rate (Posselt and Weber 1974). Triazoles are known to be effective CICs, but they have been banned in most Northern European countries owing to toxicity concerns (Duncan 2006).

Methanol, ethanol, isopropanol, and *n*-propanol were found to inhibit Cd corrosion in aqueous solution, and the electrochemical testing indicated their corrosion inhibition efficiency at 0.1 M to be 29.9%, 37.8%, 39.3%, and 98.6%,

respectively. The inhibition mechanism validated by surface analysis was proposed as follows. The alcohol molecules absorb on the active Cd sites by means of functional $-OH$ groups and stabilize the passive film, with their hydrophobic alkyl tails limiting the access of electrolyte to the metal surface. A concentration of ≥ 0.075 M of *n*-propanol in an alkaline solution ($pH = 13$) achieved 97% reduction in weight loss after a 180-min exposure. It should be noted that the experiment employed highly polished, spectroscopically pure Cd rods rather than AMS- or ASTM-compliant Cd-plated steel (Badawy and Al-Kharafi 1998, 2000).

Commercially available CICs for application to fasteners and other exposed metal are available in wipe-on, brush-on, and spray-on types (Groupe Meban 2007). Most employ an adsorption mechanism with an active ingredient(s) similar to *n*-propanol as described earlier, which blocks the active sites on the metal surface. As a secondary effect, the CIC base may then harden or dry on the metal surface, forming a temporary but durable physical barrier to salt spray, cleaners, and other contaminants. There is scant—if any—relevant research available to the public on the effectiveness of these CICs in mitigating Cd-plating corrosion, especially in the presence of PDPs.

In lieu of a comprehensive prevention solution to Cd-plating corrosion or a satisfactory Cd-plating replacement, shop-level mitigation practices such as additional and enhanced maintenance and inspection should help reduce the effects of PDPs on corrosion-prone Cd-plated steel aircraft components. Such best practices would also minimize the impact of PDPs on other aircraft components.

In addition, the corrosion of aircraft components (e.g., Cd-plating and aluminum parts) can be mitigated by utilizing less corrosive PDPs on airfield pavements. U.S. patents were granted in 2001 (USP 6287480), 2003 (USP 6623657), and 2005 (USP 7063803) for deicing formulae based on potassium succinate, succinic anhydride, and succinic acid. At least one potassium lactate formula has been marketed in the United States, but only to military facilities (Shi 2007). Such deicing compositions are claimed to be suitable and effective for airport applications in which corrosion of aircraft alloys and concrete runways are of concern, but they have not been tested at commercial airports. In addition, no testing in relation to C/C catalytic oxidation is known to have been conducted on these formulae.

PDPs with low electrical conductivity have been suggested to potentially pose less risk for aircraft components as well as C/C composite brakes. PDPs based on betaine (a bio-based freezing point depressant and corrosion inhibitor with low electrical conductivity) have been developed in Finland and are qualified for AMS 1435A certification owing to low corrosivity. In addition to its high cost, however, betaine's relatively high BOD and nitrogen content may present some challenges, as discussed earlier (Duncan 2006).

The U.S. Air Force suggested adding the solution conductivity test (ASTM D1125) to AMS 1431 and AMS 1435 as a required test for PDPs. In addition, other tests such as wet arc propagation resistance (SAE AS4373, Method 509), immersion volume swell (SAE AS4373, Method 601), bend (SAE AS4373, Method 712), and voltage withstand (SAE AS4373, Method 510) were suggested to be added to AMS 1431 and AMS 1435 if possible (USAF Research Laboratory 2007).

Knowledge Gaps

Although the fundamental mechanisms of Cd corrosion in water are relatively well studied, the link between alkali-metal-salt-based PDPs and Cd-plating corrosion has yet to be experimentally validated and thoroughly investigated. Action in the following areas may be beneficial for further advances in mitigating the effects of PDPs on Cd-plating and aircraft alloys in general.

First, there is still a need to establish a comprehensive metallic corrosion test protocol for PDPs. To this end, a Cd corrosion test protocol has been in development in the SAE G-12 Working Group since 2003 and is currently being refined for inclusion to AMS 1431 and AMS 1435. Incorporation of such a test protocol (including a conductivity test as suggested by several ACRP survey respondents) into AMS 1431C and AMS 1435B will provide necessary guidance for developing the next generation of PDPs and aircraft components. The proprietary nature of PDP and aircraft components may hinder the development of such a test protocol, and the ever-changing nature of these technologies may entail continued efforts in updating the test protocol. For instance, the need for an acceptable alternative to Cd-plating has led to extensive research on this subject and several promising alternatives such as Zn-Ni-P (Veeraraghavan et al. 2003), Zn-Sn-P (Zhirnov et al. 2006), and Zn-Ni (Thomson 1996; Claverie and Chaix 2007).

Second, more research is needed to better understand the interactions among the aircraft component design, the CICs used, and the contamination of PDPs in the processes of metallic corrosion. This is further complicated because the use of Cd-friendly PDPs is still in the burgeoning stage and new products will be continually introduced to the market. Similarly, CICs designed to mitigate Cd-plating corrosion by PDPs are still immature and mostly proprietary. Furthermore, field corrosion of metals may be affected by component design and exposure conditions, and various other mechanisms that are unique to the operational environment (e.g., galvanic corrosion, pitting corrosion, crevice corrosion, stress corrosion cracking, corrosion fatigue, erosion corrosion, and microbially influence corrosion).

Finally, there is still a lack of academic research data from controlled field investigations regarding the aircraft metallic corrosion by PDPs, which would help differentiate the contribution of PDPs to such corrosion from other possible

contaminants in the field environment. One challenge is that aircraft are moving objects exposed to various PDPs and other contaminants, climatic conditions, and maintenance practices at different airports. For instance, Cd-plated steel was found to be affected by paint vapors (Brough 1987), by microorganisms in hydraulic fluids (Weyandt and Schweisfurth 1989), and by aircraft fuel additives (Hinton and Trathen 1992).

INTERACTION WITH AIRCRAFT DEICING AND ANTI-ICING FLUIDS

The SAE Aircraft Deicing/Anti-icing Fluid (ADAF) Specifications provide guidelines for the holdover time of Types I, II, III, and IV fluids (“FAA-Approved . . .” 2007). To meet these criteria, Types II, III, and IV fluids currently used for aircraft anti-icing contain thickeners to keep these fluids on surfaces after application. These thickeners are gel polymer additives known to gradually precipitate out of solution and form dry residues that can remain in aerodynamically quiet areas of the aircraft for long periods. If not discovered, these residues can accumulate over time, rehydrate and expand in rain or aircraft washes, and freeze during cold weather or high altitude flight. This can negatively affect in-flight handling of the aircraft if deposits occur on or near control surfaces or linkages. Initial research has shown that thickener separation is accelerated by contact between aircraft deicing fluids and runway deicing fluids (Ross 2006; Hille 2007). A typical aircraft deicing operation is shown in Figure 12.

The rest of this section synthesizes the information on the validity and nature of the interaction between modern PDPs and ADAFs, describes the related standards and test protocols, discusses ways to prevent and mitigate such interaction, and identifies pertinent knowledge gaps.

Validity of Interaction Between Modern Pavement Deicing Products and Aircraft Deicing/Anti-Icing Fluids

The first glycol-based, non-Newtonian ADAFs were introduced in the early 1960s. (“Non-Newtonian” describes a fluid that, when subjected to an external force, experiences increased viscosity until the external force is removed, upon



FIGURE 12 Typical aircraft deicing operation [adapted from Ambrose (2007)].

which it returns to its normal state. This characteristic allows most ADAFs to be applied easily and then resist being blown off the aircraft surface during flight.). Rates of in-flight incidents connected to thickener deposits from these deicers appeared to rise during the mid-1990s, shortly after the introduction of alkali-metal-salt-based PDPs (Ross 2006). A greater proportion of these reports appear to have come from European operators than from North America or Asia (Hille 2007). The geographic imbalance of these reports is believed to be connected to the general method of aircraft deicer application favored at European airports. In Europe, aircraft are treated in a single application with a solution of Type II fluid in hot water. The two-step method favored elsewhere consists of an initial application of heated Type I (nonthickened) deicing fluid, followed by application of a heated Type IV solution (Hille 2007). User experience has shown that application of the pure or diluted Type I fluid removes thickener residue from previous deicer applications.

The synergistic generation of residue when an ADAF on aircraft is splattered with modern PDPs (e.g., KAc and NaF) presents serious concerns about residue gel rehydration and refreezing in flight and has produced potentially dangerous rough residues on leading edge surfaces on aircraft. Aircraft and runway deicing fluids tend to mix in two different locations—the aircraft and the runway (Hille 2007). Aircraft deicer may run off the aircraft, mix with runway deicer, and then be splashed back onto another aircraft by landing gear spray or blown on by thrust reversers. Runway deicer may reach freshly applied aircraft deicer by the same means or from overspray during runway application. After mixing, the now less viscous aircraft deicer may remain in place or it may migrate to aerodynamically quiet areas through control surface gaps or vent holes, where thickeners can precipitate unnoticed.

Nature of the Interaction Between Modern Pavement Deicing Products and Aircraft Deicing/Anti-Icing Fluids

Thickeners used in aircraft deicers increase viscosity through charge–charge interaction; organic salts such as KAc and KF are known to disrupt this interaction (Ross 2006). In theory, contamination with KAc or KF should cause a measurable reduction in the viscosity of the aircraft deicer. Preliminary evidence shared with the SAE G-12 committee by Kilfrost, Ltd. appears to support this theory. Samples of Type II and IV aircraft deicer fluids contaminated with small amounts of KF- or KAc-based PDPs experienced immediate reductions in viscosity, followed quickly by precipitation of thickener additives. These laboratory data appear to corroborate anecdotal reports of increased rates of thickener residues in environments where alkali-metal-salt-based PDPs have been used. Nonetheless, this issue is being addressed by Kilfrost.

Kilfrost also gathered data on the effect of runway deicers on dried thickener residue. The thickener was observed to rehydrate only slightly in a 5% KF solution when compared

with the control. Immediately following this treatment, the same residue sample exceeded the control in weight gain when rehydrated with dematerialized water (Ross 2006). This suggests that not only do alkali-metal-salt-based PDPs accelerate the precipitation and buildup of thickener residues, but under the right conditions they may also encourage greater moisture uptake by the thickeners.

Standards and Test Protocols

There are two independent standards used to designate ADAFs for military and commercial use. The military specification—MIL-A-8243D—is entitled Anti-icing and Deicing-Defrosting Fluids and approves only propylene glycol-based fluids as Type I and ethylene glycol-based fluids as Type II to be used by the U.S. Air Force. The commercial specifications—SAE AMS 1424 (Type I) and AMS 1428 (Types II, III, and IV)—classify ADAFs based on their viscosity and hold-over properties, other than their chemical composition (*Pro-Act Fact Sheet* . . . 1998).

AMS 1428F is the accepted standard for SAE Types II, III, and IV thickened, non-Newtonian aircraft deicers, and there is no provision for testing compatibility with PDPs contained in the July 2007 revision of this standard. Likewise, AMS 1435, the SAE standard for liquid runway deicers, contains no provision for testing compatibility with ADAFs.

Prevention and Mitigation

Although interaction between runway and aircraft deicers is inevitable, there are opportunities to control the effects of the interaction. When applying runway deicer, extra care can be taken to avoid overspray around parked airplanes. Thickener residue can be reduced to a minimum through frequent inspection and cleaning of areas prone to buildup, such as spar areas and leading edge cavities. Dried residue can be rehydrated with warm water spray and then flushed or wiped away. Nonetheless, challenges remain for such operational practices in commercial aviation, in light of the financial and environmental constraints. In addition, spray from PDP pools is unpredictable during aircraft take-off and landing. Interaction with Type IV ADAFs has been seen to rapidly promote rough, persistent residue on wing leading edges with unfavorable aerodynamic properties.

Knowledge Gaps

The contamination effects of ADAFs by runway deicing fluids have been well-observed, but not yet thoroughly quantified. Acquisition of hard data will assist in the generation of inspection schedules (Hille 2007) and may spur development

of improved thickener formulae for ADAFs. To this end, the SAE G-12 Fluid Residues Working Group is leading research efforts in this field. Currently available thickeners were designed to enhance the holdover properties of ADAFs and did not take the potential interaction with PDPs into account. From a residue mitigation standpoint, air carriers and airports would be well-served by a controlled comparison of the single- and double-step processes currently favored for application of ADAFs to identify the most effective method for controlling thickener residue buildup.

Further research is needed to better understand the interactions between ADAFs and PDPs, as new ADAFs and PDPs are continually introduced to the market. For instance, environmentally benign alternatives to glycol-based ADAFs such as formulations based on glucose-lactate have been tested with promising results (“FAA-Approved . . .” 2007). In addition to the freezing point depressant and additives used, the interactions between ADAFs and PDPs may be affected by the aircraft type, maintenance and inspection practices, and weather (Ross 2006).

CONCLUDING REMARKS

The U.S. aviation industry as a whole has enjoyed greater pavement frictional characteristics (safety) and longer operating hours for aircraft (nonclosure of runways) because of the effectiveness of modern PDPs.

In spite of their environmental advantages over older formulae such as urea and glycols, alkali-metal-salt-based PDPs present new challenges to the aircraft operating and manufacturing industries. Table 11 summarizes the effects of modern PDPs on aircraft components, including the key findings and knowledge gaps.

It should be noted that the effects of modern PDPs on aircraft components lead to substantial financial consequences such as increased maintenance, inspection, and replacement costs and flight delay costs. Continental Airlines forecasted out-of-service and flight delay losses owing to catalytic oxidation of C/C aircraft brakes starting at \$200,000 and \$500,000 annually (Duncan 2006). Advances in anti-oxidant technology and C/C composite substrates are helping to control this figure. Corrosion of Cd-plating and aluminum parts by runway deicers requires modifications and repairs to components on, in, and around landing gear and wheel wells, with an the annual cost estimated at approximately \$1.3 million per national carrier for the foreseeable future (Duncan 2006). Increasing costs like these are making alternatives to Cd-plated steel such as anodized aluminum and stainless steel more attractive to manufacturers (Duncan 2006).

TABLE 11
SUMMARY OF EFFECTS OF MODERN PDPs ON AIRCRAFT COMPONENTS

PDP Impact	Information Sources	What Is Known	What Is Unknown
<i>Catalytic oxidation of carbon-carbon composite brakes</i>	<ol style="list-style-type: none"> 1. Academic-peer-reviewed literature 2. Industry-peer-reviewed publications and reports 3. Survey of stakeholder groups 	<ol style="list-style-type: none"> 1. A growing body of field evidence from airline operators suggests that the use of KAc and KF on airfield pavements leads to catalytic oxidation of C/C composite brake components. 2. Existing research in the laboratory has demonstrated the catalytic effects of potassium, sodium, and calcium on carbon oxidation. 	<ol style="list-style-type: none"> 1. There is still a need to establish a comprehensive PDP catalytic oxidation test protocol. 2. More research is needed to better understand relationships between brake design, AO treatment, and PDP contamination as factors in catalytic oxidation.
<i>Corrosion of aircraft alloys (with a focus on cadmium plating)</i>	<ol style="list-style-type: none"> 1. Industry-peer-reviewed publications and reports 2. Survey of stakeholder groups 	<ol style="list-style-type: none"> 1. Until recently, the principal evidence connecting alkali-metal-salt-based PDPs with Cd-plating corrosion has been a trend of increased reports of the latter occurring simultaneously with the introduction of the former. 2. Very little research has been conducted to investigate the mechanism of Cd corrosion or Cd-steel corrosion in the presence of alkali-metal-salts (e.g., KF and KAc), partly owing to the high toxicity associated with Cd and its compounds. 	<ol style="list-style-type: none"> 1. There is still a need to establish a comprehensive metallic corrosion test protocol for PDPs. 2. More research is needed to better understand the interactions among the aircraft component design, the CICs used, and the contamination of PDPs in the processes of metallic corrosion. 3. There is still a lack of academic research data from controlled field investigation regarding the aircraft metallic corrosion by PDPs.
<i>Interaction with aircraft deicing and anti-icing products</i>	<ol style="list-style-type: none"> 1. Industry-peer-reviewed publications and reports 2. Survey of stakeholder groups 	<ol style="list-style-type: none"> 1. Recent laboratory data appear to corroborate anecdotal reports of increased rates of thickener residues in environments where alkali-metal-salt-based PDPs have been used. 	<ol style="list-style-type: none"> 1. The contamination effects of ADAFs by runway deicing fluids have been well-observed, but not yet thoroughly quantified. 2. Further research is needed to better understand the interactions between ADAFs and PDPs, as new ADAFs and PDPs are continually introduced to the market.

EFFECTS OF PAVEMENT DEICING PRODUCTS ON AIRFIELD INFRASTRUCTURE

The use of traditional PDPs consisting of urea and/or glycols has become diminished on airfields as a result of their adverse environmental impacts. Modern PDPs often include KAc, NaAc, and NaF as the freezing point depressant, with other additives.

This chapter synthesizes the effects of airport PDPs on pavement and other airfield infrastructure. The results of the ACRP survey distributed for this project are assimilated within the sections concerning effects on concrete pavement, asphalt pavement, and other infrastructure. In addition to the information obtained from the survey, the majority of this chapter synthesizes published data from a comprehensive literature review.

PAVEMENT DEICING PRODUCTS EFFECTS ON AIRFIELD INFRASTRUCTURE: FIELD EXPERIENCE

This section reports on the field experience regarding the effects of PDPs on the durability of airfield infrastructure. It should be noted that any pattern derived from such field data should be treated with caution and needs validation from research conducted in a well-controlled laboratory setting because the durability of airfield infrastructure is affected by a wide variety of factors. The lack of documentation and/or control of other variables in the field environment presents a challenge for researchers to unravel the specific role played by the PDPs or to quantify their impact. For instance, the difference in the performance of portland cement concrete (PCC) pavements at two airports could be potentially attributed to the use of not only different PDPs, but also different types of aggregates (reactive vs. nonreactive), among many other variables (e.g., mix design, construction quality, climatic conditions, and traffic loading).

Telephone interview results of 12 (primarily Canadian) airports/airport authorities conducted by George Comfort in 2000 indicated increased use of alkali-metal-salt-based PDPs (KAc, NaAc, and NaF) over urea. A majority of respondents to the interview indicated that pavement damage was not attributed to deicers, whereas four respondents suggested that no conclusive statements could be made. A few isolated responses to the interview indicated that crack and joint sealant might be affected, although no conclusive statements could be made to implicate aircraft or airfield deicers. Additionally, two airports noted that KAc might provide an additional benefit of removing rubber buildup on runways (Com-

fort 2000). In a report produced by the Transportation Association of Canada, it is stated that with good pavement design and construction, the effects of winter maintenance chemicals may be minimized (“Synthesis of Best Practices . . .” 2003).

More recent field and laboratory experience, however, indicates probable impacts of alkali-metal-salt-based PDPs on both PCC and asphalt pavements (Nilsson 2003, 2006; Rangaraju et al. 2006; Pan et al. 2008). To reexamine the case, a portion of the survey for this synthesis was designed to gather input regarding the impacts of deicers on airfield pavement and infrastructure. The ACRP survey was distributed to professionals representing the 50 busiest airports in the United States, among others. A total of 17 respondents were directed to this section of the survey based on an assessment of their initial responses. Among them, 14 were employed by airports, 12 of which are in the United States. Three additional respondents represented the Swedish Civil Aviation Administration (whose responses were specific to the Gothenburg–Landvetter Airport), the Innovative Pavement Research Foundation (IPRF), and the FAA. As such, the survey results provide information from a total of 15 airports. Ten of these 15 respondents indicated that their job title contained the word “Environmental”; other key words included Manager, Director, Coordinator, Administrator, Supervisor, Program, Deicing, Operations and Maintenance, Compliance, and Wastewater. Often the respondents consulted their pavement engineers before responding to some technical questions in the survey.

Four airports responded with detailed information about the specific use of PDPs: the type, application rate, application frequency, and total amount applied for each of the previous five seasons. In general, the results indicated increased use of KAc and less or no use of urea. For those that reported using both NaAc and NaF, the former has been used more frequently in the recent seasons.

Even though most responses to the ACRP survey indicated little field observation or concern regarding the impacts of PDPs on the durability of airfield infrastructure, this may not necessarily represent the overall situation of U.S. airports considering the limited number of responses. Seven questions solicited information regarding the role of PDPs in deteriorating pavements, ground support equipment (GSE), lighting fixtures, signage, and other infrastructure assets; the lifespan and design and material changes of these were also

questioned. Blank or “no” responses were common in the questions concerning damage or deterioration of airfield infrastructure. However, some responses provided more specific information regarding impacts on concrete and asphalt pavements as well as on other airfield infrastructure.

IMPACT OF PAVEMENT DEICING PRODUCTS ON CONCRETE PAVEMENT

This section synthesizes the information on the impact of PDPs on concrete pavement. First, the potential role of PDPs in the deterioration of concrete pavement is described, in terms of both chemical and physical effects associated with the use of PDPs. The current understanding of the mechanisms of damage is then discussed, followed by the associated standards and test protocols, methods of prevention or mitigation, and finally knowledge gaps on this subject.

As identified by a recent literature review (Pan et al. 2006), the last decade has seen an increase in the premature deterioration of airfield PCC pavements with the use of alkali-metal-salt-based PDPs (Maxwell 1999; Barrett and Pigman 2001; Johnson 2001; Pisano 2004; Roosevelt 2004; “New Anti-icing System . . .” 2005; Pinet and Griff 2005). Such PDPs have been used more extensively and for more years in European countries for winter maintenance than in the United States. The degree of distress in the PCC pavements of European facilities ranged from mild to severe in terms of surface cracking and repair and rehabilitation efforts needed (Pan et al. 2006).

Recent research conducted at Clemson University found that the acetate/formate-based deicers could induce increased levels of expansion in concrete with aggregates susceptible to the alkali-silica reaction (ASR), and could trigger ASR in concrete that previously did not show susceptibility to ASR (Rangaraju et al. 2005, 2006; Rangaraju and Desai 2006). The laboratory results from a modified ASTM C1260 mortar bar test and a modified ASTM C1293 concrete prism test indicated that both KAc- and NaAc-based deicer solutions showed significant potential to promote ASR in mortar bar specimens that contained reactive aggregates. Such solutions were also found to cause more rapid and higher levels of expansion within 14 days of testing and to lead to lower dynamic modulus of elasticity, compared with 1N sodium hydroxide (NaOH) solution (Rangaraju et al. 2006). Increasing temperature or deicer concentration was found to accelerate the deleterious effects of deicers on the ASR in concrete.

Based on the responses to the ACRP survey, concrete life spans at U.S. airports varied from 20 to 50 years, and changes in mix design and construction are consistent with FAA specifications. Only isolated cases of KAc accelerating ASR in some concrete pavements were reported by the survey respondents, with freeze-thaw cycles also contributing to the damage. It should be cautioned, however, that among the more than 50 U.S. airports contacted, only 12 (along with 3 non-

U.S. airports) responded to the ACRP survey. Two respondents specifically referred to the interim FAA recommendations concerning ASR and deicers.

ASR is a chemical reaction between alkalis present in the cement paste and siliceous minerals in the reactive aggregates of PCC, which produces a hydrophilic gel that expands when sufficient moisture is available. Such internal expansive forces are deleterious to the concrete durability and can cause cracks in both the cement paste and aggregates. Failure of concrete structures later attributed to ASR can be dated back to the late 1920s (Pan et al. 2006). Typical ASR distress is manifested by cracking, popouts, and expansion (as shown in Figure 13). Cracks allow more water to enter the concrete, popouts create foreign object damage hazard, and expansion can damage adjacent pavements and structures. The increased alkali content of modern PCC, as well as the potential for additional alkali from fly ash, admixtures, aggregates, mix water, etc., is the outcome of the competing forces of air emission standards and high energy costs. Thus, the low-alkali cement of today has more alkali than cement manufactured before the 1970s, often around 0.6% sodium oxide equivalent ($\text{Na}_2\text{O}_{\text{eq}}$). Accordingly, aggregates that did not historically react to low-alkali cement may not have the same performance today (*Pro-Act Fact Sheet* . . . 2006).

In addition to ASR, physical distresses such as scaling and spalling are common forms of deterioration of hardened concrete (Figure 14a and b, respectively), and both can occur in the absence of deicers. Scaling is physical damage of concrete surface often shown as local flaking or peeling, owing to the hydraulic pressures from freezing-thawing cycles of concrete pore solution (ACI Committee 302 1996). Freezing of water in saturated concrete generates expansive forces that are detrimental to the concrete surface, especially when it is not adequately protected with entrained air. Similar to chloride-based salts, alkali-metal-salt-based PDPs may exacerbate scaling when used at a concentration high enough to induce osmotic pressure upon moisture (Pan et al. 2006). In addition, the application of deicers to pavements increases the rate of cooling, which increases the number of freeze-thaw cycles over ambient conditions and thus the risk for scaling (Mussato et al. 2005). The use of properly cured, air-entrained PCC can prevent scaling. Entrained air provides spaces within the concrete matrix for expanding water to move into, thereby reducing the potential stress and associated deterioration pertinent to freeze-thaw cycling. It is believed that high quality concrete with 5%–7% entrained air is more resistant to freeze-thaw cycles and scaling (Williams 2003).

The ingress of chloride into concrete and subsequent reinforcement corrosion has been extensively studied, and these eventually lead to concrete cracking or spalling. However, little research has been conducted to examine the ingress of alkali metal salts (e.g., KAc, KF, NaAc, and NaF) into concrete or their interaction with metallic reinforcement.

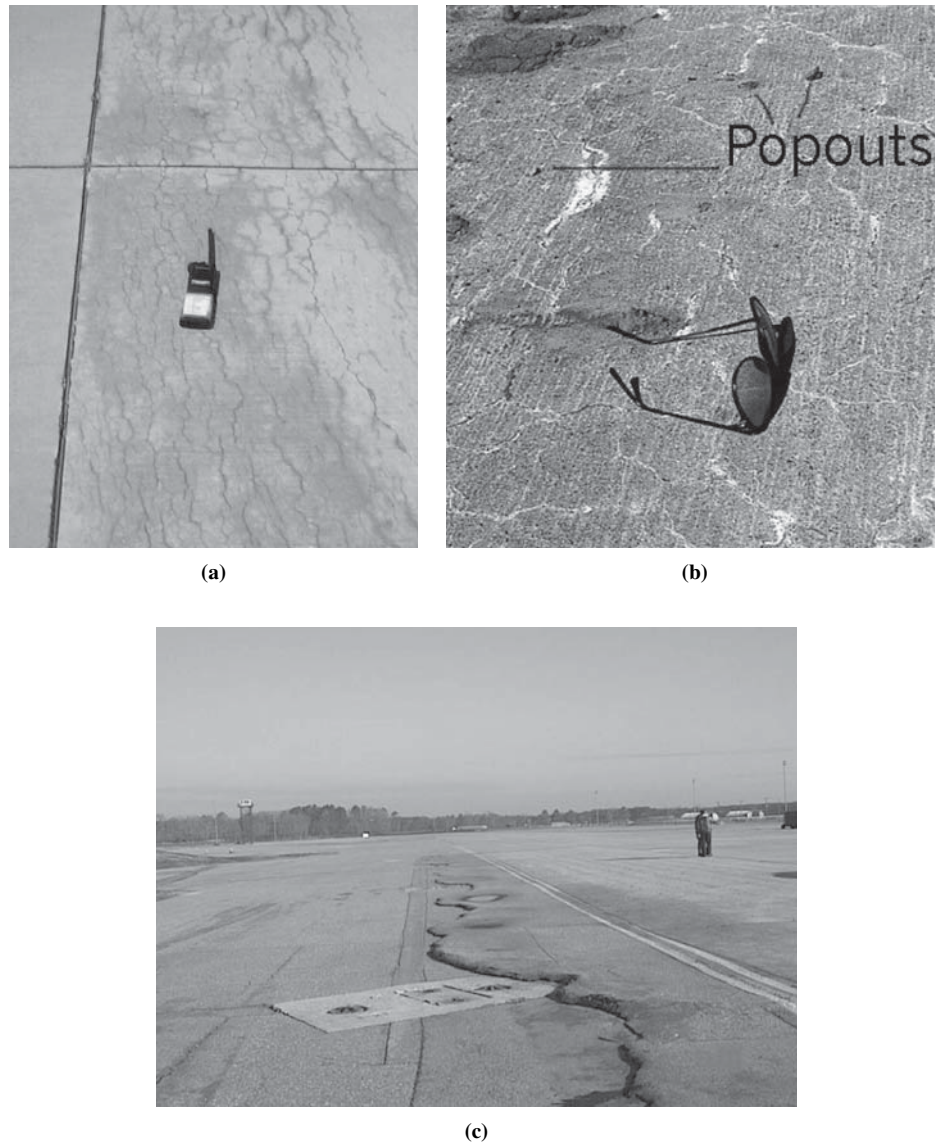


FIGURE 13 ASR-induced distresses at Air Force bases: (a) cracking, (b) popouts, and (c) asphalt shoulder heaving caused by ASR expansion in adjacent concrete [adapted from *Pro-Act Fact Sheet . . .* (2006)].

Interestingly, a very recent study reported the use of NaAc aqueous solution as a technology to reduce water permeability into PCC (Al-Otoom et al. 2007). The results indicated that the crystal growth of NaAc in concrete pores was relatively fast, which significantly reduced the water permeability of the concrete after only a 7-day treatment. The PCC samples tested were porous with the following mix design: a water-to-cement ratio of 0.65:1, an aggregates-to-cement ratio of 4.5:1, and a sand-to-gravel ratio of 1:2 (all by weight). The treatment of PCC by the NaAc solution did not significantly affect its freeze-thaw resistance or compressive strength, and only slightly increased the pH of the concrete. Overall, the treatment was demonstrated to be beneficial to the concrete's durability, especially at the optimum concentration of 20% NaAc (Al-Otoom et al. 2007). It is noteworthy that neither the details of aggregates used in the PCC

samples were provided, nor was any ASR testing conducted in this specific research.

Nature of the Effect of Modern Pavement Deicing Products on Portland Cement Concrete Pavement Deterioration

Limited existing laboratory studies indicated that alkali-metal-salt-based deicers could cause or accelerate ASR distress in the surface of PCC pavement by increasing the pH of concrete pore solution. PCC pavements that were otherwise resistant to ASR might show rapid deterioration when exposed to these high alkali solutions. The nature of the reactions associated with increased expansions in mortar bar tests to date remains unclear owing to limited research conducted on this topic. It was proposed that such deicers react with one of the major



FIGURE 14 Concrete scaling (a) and spalling (b) [adapted from Potomac Construction Industries (2007) and Cryotech Deicing Technology (2007), respectively].

hydrated products—calcium hydroxide— $\text{Ca}(\text{OH})_2$, and result in higher pH of the concrete pore solution. The high pH resulting from these interactions is likely to have an accelerating effect on the expansions as a result of ASR. This mechanism was substantiated by the SEM-EDX investigation of mortar bars after deicer immersion, which was unable to detect $\text{Ca}(\text{OH})_2$ in the cement paste (Rangaraju and Olek 2007).

There are other hypotheses that merit further investigation. A laboratory investigation using concrete samples obtained from existing Iowa highways suggested that magnesium and calcium deicers might accelerate highway concrete deterioration (Cody et al. 1996). Samples were experimentally deteriorated using wet–dry, freeze–thaw, and continuous soak conditions in solutions of magnesium chloride, calcium chloride, sodium chloride (NaCl), magnesium acetate (MgAc), magnesium nitrate, and distilled water. The magnesium and calcium salts were found to severely damage the concrete samples, whereas plain NaCl was the least harmful. This was possibly attributable to the reaction between magnesium and calcium cations (Mg^{2+} and Ca^{2+}) and the cement hydration products, or to the accelerating effect of these cations on the alkali-carbonate reaction if the concrete contained reactive dolomite aggregates.

Standards and Test Protocols

The U.S. Air Force requires that aggregates for new concrete pavements be tested according to ASTM C1260, Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method). Another standard, ASTM C1293, Standard Test Method for Determination of Length Change in Concrete Due to Alkali-Silica Reaction, is preferred but takes more than a year to complete. If it is not feasible to use only nonreactive aggregates, then mitigation methods are required. ASTM C1567, Standard Test Method for Determining the Potential for Alkali-Silica Reactivity of

Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method) or an equivalent test must be used.

In ASTM C1260, the samples are soaked for 14 days in a solution of NaOH. For the Air Force, mixtures that experience expansion greater than 0.08% require mitigation (*Pro-Act Fact Sheet* . . . 2006). The FAA has recommended that ASTM C1260 testing for new concrete pavement mixtures be modified by substituting a deicing agent for the NaOH solution, soaking for 28 days, and mitigating if expansion exceeds 0.10% (“Engineering Brief No. 70 . . .” 2005). Currently, these are interim recommendations until additional research is completed. The modifications to ASTM C1260, C1293, and C1567 are based on the research conducted at Clemson University. Additional research using these modified methods may be needed, especially for mitigation with lithium nitrate-based admixtures. The FAA will further refine the tests as part of the IPRF 05-7 project to make it a standard test method for evaluating the ASR susceptibility of PCC, which may be considered for inclusion to the SAE AMS 1435 and AMS 1431, along with ASTM C672, Test Method to Assess Scaling Resistance of Concrete Exposed to Deicers.

Prevention and Mitigation

To prevent or mitigate the effects of PDPs on concrete pavement, the first and most important countermeasure is to follow best possible practices in concrete mix design and construction. For instance, the mix design should take into consideration supplementary cementitious material to alleviate excess bleed water, aggregate blends that do not lack mid-sized aggregate, and suitable air void systems. Proper mix designs will allow easier placement and consolidation. In addition, good curing practices should also be followed (Van Dam et al. 2006). When possible, polymer sealants can be used to minimize the contact between PDPs and concrete pavement

and to reduce the ingress of water, PDPs, and other potentially deleterious contaminants into concrete.

ASR has been conventionally controlled by limiting alkali content in cement and selecting aggregates of good quality. Mortar bars prepared with nonreactive aggregates did not exhibit ASR distress when exposed to the standard NaOH or deicer solutions, even when high alkali cement (0.82% $\text{Na}_2\text{O}_{\text{eq}}$) was used in the mix (Rangaraju and Olek 2007). Based on these results, it appears that new concrete pavements should be prepared with nonreactive aggregates, if feasible. Nonreactive aggregates can likely be identified by a modified concrete prism test (ASTM C1293, with deicer soaking solution) in which expansion after one year is limited to 0.04% (Rangaraju and Olek 2007).

Furthermore, efforts have been made to mitigate ASR by adding various supplementary cementitious materials or chemical admixtures. Research sponsored by the FHWA used lithium compounds to successfully reduce ASR induced by deicers. However, for existing concrete pavement, it is unlikely that the solution will penetrate significantly, and the most benefit may only be seen on the surface with reduced debris generation (Folliard et al. 2003). The potential for mitigation of new concrete with lithium nitrate is more promising, although additional research is needed to determine the appropriate dosage (Rangaraju 2007). The toxicity and environmental effects of lithium nitrate have not been evaluated (*Materials Safety Data Sheet* 2006). The effectiveness of mineral admixtures was evaluated in reducing the ASR potential in the presence of KAc (Rangaraju and Desai 2006). The effectiveness of fly ash in mitigating ASR in the presence of KAc was found dependent on the lime content (Rangaraju and Desai 2006). Fly ash with lower lime content was more effective in reducing the expansions, and greater amounts of fly ash (up to 35% by weight) were needed to replace cement when more reactive aggregate was used. Ground granulated blast furnace slag with a replacement level of 50% was needed to mitigate the expansions; 40% replacement was found ineffective (Rangaraju 2007).

Knowledge Gaps

There is a need for research data from controlled field investigations regarding the effects of alkali-metal-salt-based PDPs on concrete pavement to help differentiate the contribution of such PDPs to concrete deterioration from other possible factors in the field environment. One challenge is that the durability of PCC pavement is often significantly affected by the mix design (water-to-cement ratio, type and amount of aggregates, air content, etc.), construction, curing and maintenance practices, exposure to various climatic conditions (e.g., wet-dry and freeze-thaw cycles), as well exposure to traffic loading.

Furthermore, there is a need to unravel the specific mechanism by which alkali metal salts cause or promote ASR.

Knowing the mechanism(s) of damage will provide necessary guidance for preventing or mitigating such distress and for developing the next generation of PDPs and airfield concrete pavement. Advances in technologies related to PDPs and concrete pavement will make both understanding their interaction and developing an appropriate compatibility test protocol a continued effort.

The IPRF closed a request for proposals in October 2006 to address these knowledge gaps. IPRF Project 01-G-002-05-7, Performance of Concrete in the Presence of Airfield Pavement Deicers and Identification of Induced Distress Mechanisms, continues the investigation by Dr. Rangaraju that has previously implicated acetate/formate-based deicers in the ASR increase in airfield pavements. Another IPRF project that recently underwent a request for proposals is Project 01-G-002-06-5, Role of Dirty Aggregates in the Performance of Concrete Exposed to Airfield Pavement Deicer, which will examine the possibility of increased alkali content on dirty aggregates and its role in concrete durability in the presence of PDPs.

IMPACT OF PAVEMENT DEICING PRODUCTS ON ASPHALT PAVEMENT

This section will synthesize the information on the impact of PDPs on asphalt pavement. First, the potential role of PDPs in the deterioration of asphalt pavement is described. The current understanding of the mechanisms of damage is then discussed, followed by the associated standards and test protocols, methods of prevention or mitigation, and finally knowledge gaps.

In addition to the effects of PDPs on PCC pavement, their effects on asphalt pavement are also of increasing concern. Canada's contribution to this research subject began in the 1990s with a laboratory study comparing cores of asphalt mix immersed in distilled water and a 2.5% urea solution. After one freeze-thaw cycle, there was significantly more loss of indirect tensile strength in the sample immersed in urea compared with the one in distilled water. Field experience did not coincide with these findings, but later studies continued to include urea among the other deicers evaluated (Hassan et al. 2000, 2002b).

A laboratory study found that the use of PDPs (NaCl, KAc, NaF, as well as urea) was damaging to both aggregates and asphalt mixes (Hassan et al. 2002a). The PDPs were tested at a concentration of 2% of full saturation, previously determined to be a critical concentration capable of the greatest damage. Limestone and quartzite aggregate samples subject to freeze-thaw testing showed more serious damage in all deicers than in distilled water, as measured by accumulated weight loss. Aggregates immersed in urea exhibited the most weight loss for both types, whereas the least damaging deicer for limestone was NaCl and for quartzite was KAc. Asphalt pavement samples taken from the Ottawa Macdonald-Cartier International Airport were subjected to freeze-thaw cycles in closed

containers. After 25 and 50 cycles, indirect tensile strength, elastic modulus, and penetration tests were performed. The indirect tensile strengths of the samples exposed to deicers were mostly higher than those exposed to distilled water. The lowest average elastic modulus was associated with the samples in urea and visual inspection indicated significant damage by urea. Based on weight measurements and density calculations, the asphalt mix sample immersed in NaF experienced the most disintegration after 25 cycles, whereas urea (followed by KAc) was the most detrimental deicer after 50 cycles. Exposure to freeze–thaw cycles and deicers was found to affect the viscosity of the recovered asphalt binder and the gradation of recovered aggregates. The freeze–thaw cycles seemed to result in soft asphalt binder, whereas the deicers caused asphalt hardening. However, the authors noted that these findings were inconclusive owing to the difficulties involved in testing and the inaccuracies in measuring the viscosity of the recovered asphalt. Overall, this laboratory investigation found urea to be the most detrimental deicer, whereas the other deicers “induced relatively small damage, comparable to that caused by distilled water” (Hassan et al. 2000). However, it was noted that chemical reactions would occur slowly at the temperatures involved in this study and that damage in the field could occur as a result of reactions between PDP residues and asphalt during hot summer temperatures (Hassan et al. 2000).

A follow-up study was conducted at higher temperatures on asphalt pavement samples taken from the Dorval International Airport (Montreal, Canada) to clarify the role played by the PDPs (NaCl, KAc, NaF, as well as urea) in asphalt deterioration, and to determine whether the damage was attributable to the physical freeze–thaw action. Only 15 freeze–thaw cycles were performed before subjecting some samples to 40 wet–dry cycles at 40°C. This research confirmed the previous finding that softening occurs during freeze–thaw and exposure to deicers causes hardening. After the freeze–thaw and wet–dry cycles, the samples in NaAc showed the lowest strength, followed by those in NaF. Interestingly, all samples showed increased strength after the warm wet–dry cycles and all except NaF and NaAc showed increased elasticity after the warm wet–dry cycles. However, the dry samples not exposed to freeze–thaw or wet–dry cycles had the greatest elasticity and nearly highest strength. Overall, the Canadian studies did not indicate significant damaging effects of KAc and NaF on asphalt pavement (Farha et al. 2002; Hassan et al. 2002a). It should be cautioned, however, that these results were based on laboratory experiments on only two samples of asphalt pavement and the mix design for each pavement was undeterminable from the reports. Additionally, the deicer concentration was low (2%), which may not be conducive to simulate years of field exposure by means of accelerated laboratory testing.

Concurrent to the use of acetate/formate-based deicers in the 1990s, asphalt pavement in Europe saw an increase in pavement durability problems. At some Nordic airports, these

problems emerged as degradation and disintegration of asphalt pavement, softening of asphalt binders, and stripping of asphalt mixes occurring together with loose aggregates on the runways (Nilsson 2003; Pan et al. 2006; *Seminar on the Effects of De-Icing Chemicals on Asphalt* 2006). Such problems were not identified before the airports changed from urea to KAc- and KF-based deicers (Pan et al. 2006). In 2001, serious asphalt durability problems were identified at airports in Nordic countries that used acetate/formate-based PDPs (Pan et al. 2006). Heavy binder bleeding and serious stripping problems were observed occurring together with loss of asphalt stability. Soft, sticky, and staining binder came to the surface, often leaving strong stains on electrical devices and on the airplanes. The binder of the asphalt base layer was “washed” off, and the aggregates experienced severe loss of strength. In the laboratory, the tests indicated chemical changes in the binder after exposure to the deicer, in the form of emulsification, distillation, and an increased amount of polycyclic aromatic hydrocarbons (PAHs). A field investigation was conducted thereafter confirming the deleterious effects of acetate-based deicer on asphalt pavement. The bitumen and the mastic squeezed to the surface of the core, and the concentration of the deicer had a clear influence on its solubility. Some bitumen was dissolved into the pore liquid, and pure stone particles were found inside the core. The limestone filler was found fully dissolved by the PDP liquid and the rest of the mastic became brittle and grey-colored. A large increase in the porosity of asphalt was also noticed.

To address the concerns over acetate-based deicers affecting asphalt pavement, a joint research program—the JÄPÄ Finnish De-icing Project—was established to conduct extensive laboratory and field investigations on this subject. The goal of JÄPÄ was to provide answers to three fundamental concerns: how the damages are generated, how to determine the compatibility between asphalt and de-icing materials, and how to prevent damages by mix design (Pan et al. 2006). The research showed that formate/acetate-based deicers significantly damaged asphalt pavements. The damaging mechanism seemed to be a combination of chemical reactions, emulsification, and distillation, as well as generation of additional stress inside the asphalt mix. Asphalt binders soaked in the deicer solution were found to have lower softening points and tended to dissolve at temperatures as low as 20°C. Asphalt mixes soaked in the deicer solution were found to have lower surface tensile strength and lower adhesion (Nilsson 2003; *Seminar on the Effects of De-Icing Chemicals on Asphalt* 2006). It seemed to be clear that deicer (formate or acetate), water or moisture, and heat were necessary for the damage to occur. In the field, such damages mainly occurred during the repaving process or on hot summer days with residual deicers from the winter season, as dynamic loading and unloading reduced the time it took for damages to occur.

Recent laboratory studies by a research group at Montana State University were able to reproduce acetate-induced emul-

sification of asphalt similar to the field observations at Nordic airports (Pan et al. 2008). Aqueous solution tests of asphalt binder in water and four NaAc solutions of different concentrations (5%–40%) showed a bilinear trend of weight loss increasing with the NaAc concentration. Both visual inspection and optical microscopy (as shown in Figure 15) indicated that a significant amount of asphalt emulsification occurred in NaAc, but not in water or aqueous solutions of NaCl or NaOH with a pH of 9 (equivalent to the measured pH of 40% NaAc solution). For the two tested asphalt binders, PG 58-22 exhibited slightly higher emulsification than PG 67-22. In the calcium magnesium acetate aqueous solution, asphalt emulsification occurred similarly to that in NaAc. These results confirmed that asphalt emulsification should be attributed to the acetate anion, CH_3COOH^- and excluded the possibility that high alkalinity was responsible for the asphalt emulsification in NaAc. Asphalt emulsification also occurred in a NaF aqueous solution and more detailed laboratory testing is being conducted.

The effects of NaAc on asphalt mixes were examined by conducting a modified ASTM D 3625-96 Boiling Water Test, which was originally designed to test the susceptibility of asphalt mixes to moisture damage, by accelerating the effect of water on bituminous-coated aggregate with boiling

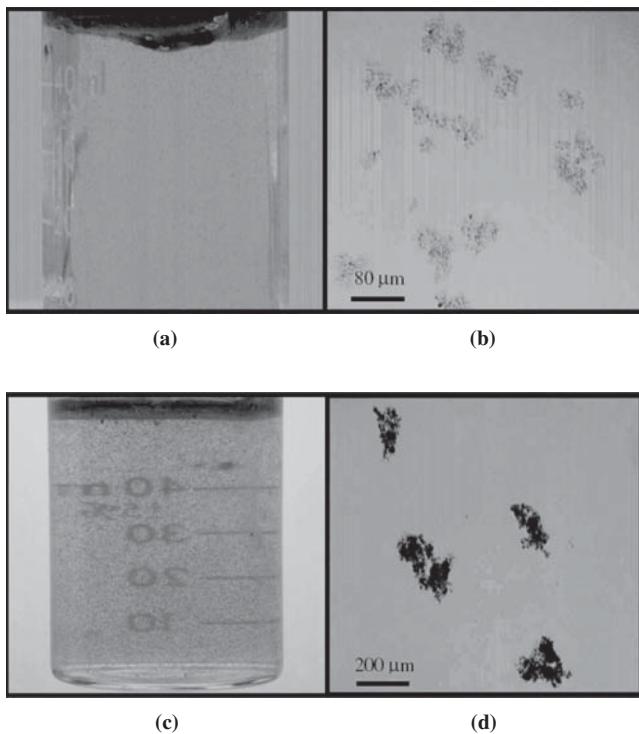


FIGURE 15 Digital photos (*left*) and optical microscopic images (*right*) showing the suspension solution of asphalt subsequent to the 60°C aqueous solution test. (a) and (b) Twenty-four hour reservation of 60°C aqueous solution test with the 20% acetate concentration; (c) and (d) Twenty-four hour reservation of the 60°C aqueous solution test with the 40% acetate solution [adapted from Pan et al. (2007)].

water. Stripping occurred for both crushed gravel and limestone aggregate particles included in the asphalt mix exposed to NaAc, suggesting that aggregate properties play at most a secondary role in asphalt emulsification (Pan et al. 2008). As indicated in Figure 16a, significant amounts of aggregates were stripped after exposure to the NaAc solutions and the aggregate stripping followed a bilinear trend with weight loss increasing with the NaAc concentration.

Phase I of Airfield Asphalt Pavement Technology Program Project 05-03: Effect of Deicing Chemicals on HMA Airfield Pavements includes a literature review, interviews with 36 airports that use deicers and have asphalt pavement, as well as laboratory testing. Seven airports indicated that pavement deterioration had occurred, but the cause was unknown except in one case that was most likely attributable to the type and source of asphalt binder and aggregate. Preliminary laboratory testing was conducted of asphalt pavement samples composed of either a chert gravel or diabase with two binders (PG 64-22 and PG 58-28) exposed to KAc and NaF. The presence of PAHs was inconclusive after vacuum-induced saturated samples were stored for 4 days at 60°C. However, significant generation of carboxylate salts had developed after the asphalt mixes were exposed to the deicers, although this may not be related directly to deicer-induced damage. Indirect tensile strength tests showed PG 64-22 to be “somewhat more resistant” (Advanced Asphalt Technologies 2007) and that chert gravel had significantly less strength when exposed to deicers compared with water. A long-term durability test developed by Advanced Asphalt Technologies also showed chert to be very susceptible to moisture damage, particularly when exposed to KAc or NaF. Soundness tests of both types of aggregate in magnesium sulfate, KAc, and NaF were acceptable and also showed that direct attack on the aggregate by the deicers was not occurring (Advanced Asphalt Technologies 2007).

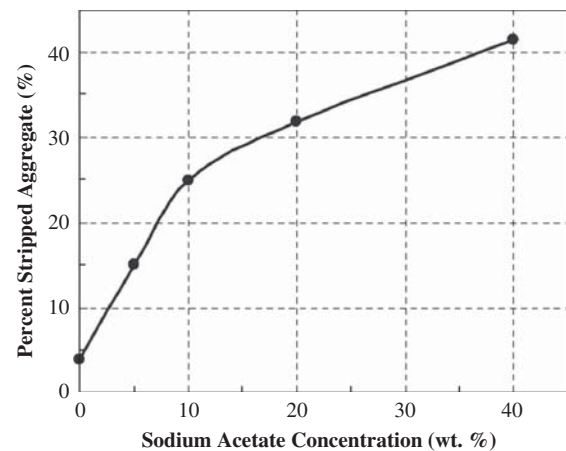


FIGURE 16 Percent stripped aggregates for an asphalt mix exposed to different NaAc solutions after the Modified Boiling Water Test [adapted from Pan et al. (2007)].

Nature of the Effect of Modern Pavement Deicing Products on Asphalt Pavement Deterioration

Canadian research demonstrating the damaging effects of urea on two types of asphalt pavement did not propose any mechanism or scientific explanation for the observations (Hassan et al. 2000, 2002b).

The JÄPÄ–Finnish De-icing Project studied the ingredient materials in asphalt pavement individually and their roles played in the damaging mechanism were ranked accordingly (Alatypö 2005). The detailed test results of each ingredient material are included as follows, as summarized by Pan et al. (2006).

Effects of Formate/Acetate-Based Deicers on Aggregates:

The main reason for pavement damages was not due to poor quality of aggregates. Mineral aggregate might be a reason secondary to asphalt binders in pavement damage. The decomposition level of acidic aggregates was higher than for caustic aggregates, but was still acceptable. However attention should be paid to the weathering resistance of aggregates used in airfields to extend the life span of asphalt pavements.

Physical Effects of Formate/Acetate-Based Deicers on Bitumen/Asphalt: (1) High density of deicer solution such as 1.34 kg/dm^3 for the 50 wt.% solution enabled the deicer solution to penetrate into bitumen by gravity. (2) Very low surface tension between deicer chemicals and asphalt facilitated stripping and emulsification of asphalt mixes. (3) Formate/acetate-based deicers had pH values usually between 9 and 11; and the higher the pH, the more aggressive the deicer would be. (4) Formate/acetate-based deicers were very hygroscopic, which kept the road surface constantly wet and retained water inside asphalt to overfill the air voids.

Chemical Effects of Formate/Acetate-Based Deicers on Bitumen/Asphalt: When exposed to deicers, composition changes of bitumen/asphalt occurred in the hydrocarbon classification C10-C40. When exposed to deicers, large organic molecules such as the PAHs grew in bitumen. Deicers in asphalt were found in both the liquid and gas phases. PAHs in the asphalt samples could migrate and become dissolved in the deicer.

Failure Process of Asphalt Pavements: Deicers migrate into the asphalt after application onto pavements and saturate asphalt mixes during the winter. The deicer solution intrudes into asphalt due to gravity and for other unknown reasons, especially when asphalt temperature rises significantly (a result of a hot asphalt layer laid or summer weather). Due to the low surface tension between deicers and bitumen, the deicers are absorbed in the bitumen that in turn starts to emulsify. It is possible that the chemical composition of the bitumen changes during emulsification. Due to emulsification the bitumen comes loose and the aggregate particles get cleaned, followed by bleeding and stripping.

Ongoing research by Advanced Asphalt Technologies currently suggests that the damaging mechanism is mainly a disruption of the asphalt-aggregate bond as a result of ASR. Expansive pressures typical of ASR-damaged concrete are not perceived to be the problem, but rather the bond disruption and increased susceptibility to moisture damage. Well-drained pavements may provide some protection because deicers are not applied during warm weather. Advanced Asphalt Technologies is currently working on Phase II that

includes more significant laboratory testing and field investigations (Advanced Asphalt Technologies 2007). However, the research by Pan et al. (2008) shows: (1) asphalt emulsification occurring to asphalt mixes with both reactive and non-reactive aggregates, and (2) asphalt emulsification not occurring in NaOH solutions of the same pH values as the NaAc solution. Thus, the research indicates that asphalt emulsification may be a more critical mechanism of asphalt mix deterioration than ASR unless very reactive aggregates are used in the asphalt mix.

Pan et al. (2008) proposed a detailed and specific mechanism of acetate-induced asphalt emulsification based on contact between acetate anions (CH_3COOH^-) and asphalt, which can be greatly increased at high summer and/or repaving temperatures owing to the tendency of asphalt to swell. For NaAc, aqueous solution tests of asphalt binder were performed at several concentrations and temperatures and the resulting suspended substance was examined using the Fourier Transform Infrared Spectroscopy. No significant amounts of new chemicals were identified, and intermolecular binding between the acetate anion CH_3COOH^- and the alkane component of asphalt was inferred (Pan et al. 2008). Van der Waals forces anchor the lipophilic organic chain (CH_3^-) of the acetate anion to the molecular chain of asphalt ($\text{CH}_3\text{--CH}_2^-$). At the same time, the hydrophilic polar end of the acetate anion (COO^-) forms hydrogen bonds with water molecules and pulls on the asphalt, overcoming the intermolecular forces within the asphalt. Asphalt emulsion is maintained by Brownian motion and repulsive forces on the flocules. The emulsification of asphalt reduces the asphalt-aggregate bond and can lead to adhesion failure in the pavement. There is also a potential that the aggregate preferentially bonds with the acetate anion, which has a higher polarity than the asphalt molecules.

Standards and Test Protocols

There are two existing Swedish test methods related to asphalt and deicers: the LFV Method 1-98, Bituminous Binders, Storage in De-icing Fluid, and the LFV Method 2-98, Effect of De-icing Fluid on the Surface Tensile Strength of Asphalt Concrete for Airfields—Adhesion Test. In 2006, results of round-robin testing of LFV Method 2-98 by seven laboratories were presented; however, the information was only available in the form of Microsoft PowerPoint Slides and thus difficult to follow. The confusion lies in the measurement units reported. The LFV 2-98 method indicates the surface strength at failure should be reported to the nearest 0.1 N/mm^2 , but the standard deviation of the round-robin test for repeatability was reported to be 130 N and 220 N for reproducibility (Nilsson 2006). One Norwegian airport reported the use of LFV Method 2-98, according to the ACRP survey results. The Aqueous Solution Test as developed by Pan et al. (2008) showed high efficiency in examining the emulsifiability of asphalt, and can be potentially established as a standard accelerating test. The other test—the Modified Boiling Water Test—also proposed by Pan et al. (2008) can be used as a rou-

tine laboratory test for evaluating suspicious asphalt mixes when exposed to alkali-metal-salt-based deicers.

Prevention and Mitigation

To prevent or mitigate the effects of PDPs on asphalt pavement, the first and most important countermeasure is to follow best possible practices in asphalt mix design and paving. Responses to the survey for this project point toward adoption of some of these preventive measures: one European airport reduced asphalt pavement air void to 3.0%; another European airport indicated that polymer-modified binder is used; and one U.S. airport changed the asphalt binder to PG 76-32, citing current FAA specifications. Nonetheless, the JÄPÄ Project research showed that the resistance of asphalt pavement to deicers can be improved only partially by mix design. According to the laboratory results, binders with high viscosity or polymer-modified binders were recommended when formate/acetate-based deicers were to be used. High-quality (sound) aggregates could also improve the durability of asphalt pavements in the presence of such deicers, and so did the aggregates with higher pH (Pan et al. 2006). It was recommended that the void contents of the asphalt mixes be kept low enough to limit deicer solution in pores. Other suggestions to prevent asphalt damages are summarized here (Valtonen 2006):

- Prefer harder bitumen (penetration max 70/100) or modified bitumen.
- Use alkaline aggregates and avoid limestone filler.
- Test the compatibility of the materials in advance.
- For security, do not use acetates and formates on asphalt structures.
- When repaving, mill away the wearing course containing residual deicers and do not use the recycled asphalt pavement unless confirming that it is not hazardous (Alatypö and Valtonen 2007).

Knowledge Gaps

Although it was observed in some Nordic airfields that exacerbated asphalt deterioration occurred with applications of alkali-metal-salt-based PDPs, thus far little observation has been reported in U.S. or Canadian airports. Significantly accelerated deterioration of asphalt pavements was found in laboratories when exposed to acetate/formate-based deicers. There is a need for research data from controlled field investigation regarding the effects of alkali-metal-salt-based PDPs on asphalt pavement, which would help differentiate the contribution of such PDPs to asphalt deterioration from other possible factors in the field environment. One challenge is that the durability of asphalt pavement is often significantly affected by the mix design, paving, and maintenance practices, the exposure to climatic conditions, as well as the exposure to traffic loading.

Furthermore, there is a need to unravel the specific mechanisms by which alkali metal salts and other PDPs (e.g., bio-

based deicers) deteriorate asphalt pavement. Knowing the mechanism(s) of damage will provide necessary guidance for preventing or mitigating such damage and for developing the next generation of PDPs and airfield asphalt pavement. Advances in technologies related to PDPs and asphalt pavement will make both understanding their interaction and developing an appropriate compatibility test protocol a continued effort.

IMPACT OF PAVEMENT DEICING PRODUCTS ON OTHER AIRFIELD INFRASTRUCTURE

Other airfield infrastructure that comes into contact with PDPs includes ground support equipment (GSE), signage, lighting, and other electrical systems. Empirical evidence exists indicating that PDPs are responsible for damaging such infrastructure. However, no academic peer-reviewed scientific information could be found to corroborate these empirical observations. The survey and other less technical information were heavily relied on in examining the case.

In July 2004, the United Kingdom Civil Aviation Authority issued a Notice to Aerodrome License Holders, the authority's standardized procedure for disseminating information about licensing of aerodromes, about the corrosion effects on ground lighting. Premature failure of an aeronautical ground lighting centerline fixture was partially attributed to a rubber removal cleaner; the cleaner destroyed the passivated corrosion protection layer and cracking formed. The cracking significantly reduced the strength of the fitting. However, it was thought that deicers could also produce a similar effect. The recommended action was to inspect fittings, repassivate if needed, and prevent fittings from contacting fluid with a pH outside of the range of 4 to 8.5 (Aerodrome Standards Department 2004).

In 2005, when one European airport switched from urea and ethylene glycol to formate-based products, corrosion of zinc-coated steel occurred on light fixtures, as well as on maintenance and ground operation vehicles. The same airport now uses stainless steel light fixtures instead of zinc-coated steel. Another European airport found that washing airport vehicles has decreased the corrosion effects, according to the responses to the ACRP synthesis survey.

The ACRP survey results indicated that lighting cable was also reported to deteriorate during or shortly following deicing events at two U.S. airports. One of these airports suspects that the aging of cable insulation plays a role in the deterioration. The other airport has upgraded to lighting cable with more resistance to deicers and is in the process of installing a system to remotely monitor the lighting electrical system.

The FAA has approved a test method for airport containers designed to serve as airport light bases, transformer housings, junction boxes, and accessories in the presence of

deicers containing KAc. A 50% KAc deicing solution is left in the base for 21 days at 194°F. To pass, the base must have no evidence of corrosion or leakage (“Specification for Airport Light Bases . . .” 2006).

Finally, the only other information found concerning deicers and airfield infrastructure is the possible reduction in safety from dirty light fixtures. In 2002, the airfield duty manager of the Manchester Airport in the United Kingdom mentioned “. . . that deicing fluid makes light fixtures sticky and more dirt sticks to them in the winter months” (Flight Safety Foundation Editorial Staff 2002).

CONCLUDING REMARKS

Both traditional and modern PDPs have been observed to react with major pavement materials and deteriorate the integrity of airport pavements. Deterioration of PCC pavements owing to

deicers is a complex process that involves chemical and physical alterations in aggregates and cement paste. Deterioration of hot mix asphalt caused or accelerated by the PDPs is a less explored area. In addition, current understanding of the impact of modern PDPs on both PCC and asphalt pavements is mostly based on macro-level observations and testing of properties, whereas mechanisms underlying the critical physical and chemical interactions are less known. Therefore, in-depth research using advanced techniques is needed to advance the knowledge base for better design, construction, and maintenance of pavement materials and to extend their service life in a cost-effective manner.

In spite of their environmental advantages over older formulae such as urea and glycols, alkali-metal-salt-based PDPs present potential problems for the airfield infrastructure. Table 12 summarizes the effects of modern PDPs on airfield infrastructure, including the key findings and knowledge gaps.

TABLE 12
SUMMARY OF EFFECTS OF MODERN PAVEMENT DEICING PRODUCTS
ON AIRFIELD INFRASTRUCTURE

PDP Impact	Information Sources	What Is Known	What Is Unknown
<i>Impact of PDPs on concrete pavement</i>	1. Academic-peer-reviewed literature 2. Industry-peer-reviewed publications and reports 3. Survey of stakeholder groups	1. The last decade has seen an increase in the premature deterioration of airfield PCC pavements with the use of alkali-metal-salt-based PDPs. 2. Limited existing laboratory studies indicated that alkali-metal-salt-based deicers could cause or accelerate ASR distress in the surface of PCC pavement, by increasing the pH of concrete pore solution.	1. There is a need for research data from controlled field investigation regarding the effects of alkali-metal-salt-based PDPs on concrete pavement. 2. There is a need to unravel the specific mechanism by which alkali metal salts cause or promote ASR.
<i>Impact of PDPs on asphalt pavement</i>	1. Academic-peer-reviewed literature 2. Industry-peer-reviewed publications and reports 3. Survey of stakeholder groups	1. Although it was observed in some Nordic airfields that exacerbated asphalt deterioration occurred with applications of alkali-metal-salt-based PDPs, there is thus far little observation reported in U.S. or Canadian airports. 2. Significantly accelerated deterioration of asphalt pavements was found in laboratories when exposed to acetate/formate-based deicers.	1. There is a need for research data from controlled field investigation regarding the effects of alkali-metal-salt-based PDPs on asphalt pavement. 2. There is a need to unravel the specific mechanisms by which alkali metal salts and other PDPs (e.g., bio-based deicers) deteriorate asphalt pavement.
<i>Impact of PDPs on other airfield infrastructure</i>	1. Industry-peer-reviewed publications and reports 2. Survey of stakeholder groups	1. Empirical evidence exists indicating that PDPs are responsible for damaging other airfield infrastructure (GSE, signage, lighting and other electrical systems).	1. No academic-peer-reviewed scientific information could be found to corroborate these empirical observations.

GSE = ground support equipment.

CONCLUSIONS

Responses representing approximately 100 airports were gathered from the recent (2006) EPA questionnaire, which indicated that potassium acetate (KAc) and sand are most widely used at U.S. airports for snow and ice control of airfield pavements, followed by airside urea, sodium acetate, sodium formate, propylene glycol-based fluids, ethylene glycol-based fluids, and other. Responses representing 12 U.S. airports and 3 non-U.S. airports were gathered from the ACRP synthesis survey distributed in this project to the 50 busiest U.S. airports among others. From the ACRP survey results, the selection of pavement deicing products (PDPs) by airport staff was based on many factors, including cost, effectiveness, environmental impact, risk of corrosion, and electrical conductivity. “Effectiveness” was ranked as the most important criterion and “electrical conductivity” as the least. The effectiveness criterion also exhibited the lowest standard deviation, with “corrosion risk” being the highest. Interestingly, the challenges and dilemmas faced by the airports pertinent to snow and ice control were highlighted because no airport selected “unimportant” or “not very important” for any of the criteria options in the survey.

Alkali-metal-salt-based PDPs such as KAc and potassium formate (KF) entered the European market to a significant extent in the mid- to late-1990s. A few years later, these modern PDPs entered the U.S. market. In both cases, these salts were introduced as alternatives to urea and glycols used in traditional PDPs for freezing point depression, to mitigate the environmental concerns related to airfield deicing and anti-icing operations. It became apparent soon after their introduction that these new deicers presented new challenges, to both the aircraft and airfield infrastructure.

• Catalytic Oxidation of Carbon–Carbon Composite Brakes

Thermal oxidation is the primary design specification governing durability of aircraft carbon–carbon (C/C) composite brakes. Catalytic oxidation of C/C composite brakes resulting from airfield PDPs has become a growing concern that needs to be monitored in the ever-changing operation environment. In recent years, as non-traditional chemical contaminants, modern PDPs may be responsible for the more rapid structural failure of C/C composite brakes. To avoid potential safety implications, this concern has to be mitigated through more frequent proactive maintenance and inspection activities incurring high direct and indirect costs. A growing body of field evidence from airline operators suggests that the use of KAc and

KF on airfield pavements leads to premature oxidation of C/C composite brake components. As the brake frictional characteristics are changed by the use of alkali-metal-salt-based deicers on airfield pavements, airline operators are concerned about the adverse effect of these PDPs on the braking performance and safety of aircraft.

There are potential opportunities for all stakeholder groups to collaborate to address the catalytic oxidation issue of C/C aircraft brakes, with respect to aircraft and component design, brake testing, aircraft operations, airfield maintenance, etc. In the domain of brake technologies, the combination of chemical modification of C/C with structural changes or defect elimination seems to offer promising solutions to mitigating catalytic oxidation. Catalytic oxidation of C/C brakes may also be mitigated by utilizing more carbon-friendly PDPs on airfield pavements.

• Cadmium Corrosion

Cadmium (Cd) plating is the most popular surface treatment technology for corrosion protection of aircraft steel parts (e.g., airframe components and fasteners). Field reports increasingly suggest that the contact with modern PDPs promotes damage to aircraft components, including Cd-plated components. Until recently, the principal evidence connecting alkali-metal-salt-based PDPs with Cd-plating corrosion has been the increasing number of reports of the latter occurring concurrently with the introduction of the former.

There are potential opportunities for all stakeholder groups to collaborate to prevent and mitigate the effects of PDPs on aircraft components, from aspects of aircraft and component design, aircraft operations, and airfield maintenance. In the domain of corrosion-inhibiting compounds, there is still great potential for improvement when it comes to mitigating the effect of PDPs on aircraft frames and components. Little academic research on interactions between alkali metal salts and Cd-plating is available, and still less is available on inhibition of these interactions. In lieu of a comprehensive prevention solution to Cd-plating corrosion or a satisfactory Cd-plating replacement, shop-level mitigation practices such as additional and enhanced maintenance and inspection should help reduce the effects of PDPs on corrosion-prone, Cd-plated steel aircraft components. Such best practices would also minimize the impact of PDPs on other aircraft components. In addition, the corrosion of aircraft components (e.g., Cd-plating and

aluminum parts) can be mitigated by using less corrosive PDPs on airfield pavements.

- **Interaction with Aircraft Deicing and Anti-Icing Fluids**

Thickeners used in modern aircraft deicing and anti-icing fluids increase viscosity through charge–charge interaction; organic salts such as KAc and KF are known to disrupt this interaction and cause a measurable reduction in their viscosity. Not only do alkali-metal-salt-based PDPs accelerate the precipitation and buildup of thickener residues, but under the right conditions, they may also encourage greater moisture uptake by the thickeners.

Although interaction between runway and aircraft deicers is inevitable, there are opportunities to control the effects of the interaction by means of enhanced operational practices. Nonetheless, challenges such as financial and environmental constraints remain for such operational practices in commercial aviation. In addition, spray from PDP pools is unpredictable during aircraft take-off and landing. Interaction with Type IV aircraft deicing and anti-icing fluids has been seen to rapidly promote rough, persistent residue on wing leading edges with unfavorable aerodynamic properties.

- **Impact of Pavement Deicing Products on Concrete Pavement**

The last decade has seen an increase in the premature deterioration of airfield portland cement concrete (PCC) pavements with the use of alkali-metal-salt-based PDPs. Such PDPs have been used more extensively and for more years in European countries for winter maintenance than in the United States. The degree of distress in the PCC pavements of European facilities ranged from mild to severe in terms of surface cracking, repair, and rehabilitation efforts needed. Limited existing laboratory studies indicated that alkali-metal-salt-based deicers could cause or accelerate alkali-silica reaction (ASR) distress in the surface of PCC pavement by increasing the pH of concrete pore solution.

To prevent or mitigate the effects of PDPs on concrete pavement, the first and most important countermeasure is to follow best possible practices in concrete mix design and construction. ASR has been conventionally controlled by limiting alkali content in cement and selecting aggregates of good quality. Furthermore, efforts have been made to mitigate ASR by adding various supplementary cementitious materials or chemical admixtures such as lithium compounds.

- **Impact of Pavement Deicing Products on Asphalt Pavement**

In addition to the effects of PDPs on PCC pavement, their effects on asphalt pavement are also of increasing concern. A laboratory study found that the use of PDPs (sodium chloride, KAc, and sodium formate, as well as urea) was damaging to

both aggregates and asphalt mixes. Concurrent to the use of acetate and formate-based deicers in the 1990s, asphalt pavement in Europe saw an increase in pavement durability problems. At some Nordic airports, these problems emerged as degradation and disintegration of asphalt pavement, softening of asphalt binders, and stripping of asphalt mixes occurring together with loose aggregates on the runways. Such problems were not identified before the airports changed from urea to KAc- and KF-based deicers. According to laboratory and field investigations conducted under a joint research program—the JÄPÄ Finnish De-icing Project—the damaging mechanism of asphalt pavement by modern PDPs appeared to be a combination of chemical reactions, emulsification, and distillation, as well as the generation of additional stress inside the asphalt mix.

To prevent or mitigate the effects of PDPs on asphalt pavement, the first and most important countermeasure is to follow best possible practices in asphalt mix design and construction. Responses to the ACRP survey for this project pointed toward adoption of some of these preventive measures: one European airport reduced asphalt pavement air void to 3.0%; another European airport indicated using polymer-modified binder; and one U.S. airport changed the asphalt binder to PG 76-32, citing current FAA specifications. Nonetheless, the JÄPÄ Project research showed that the resistance of asphalt pavement to deicers can be improved only partially by mix design. According to the laboratory results, binders with high viscosity or polymer-modified binders were recommended when formate/acetate-based deicers were to be used. High-quality (sound) aggregates could also improve the durability of asphalt pavements in the presence of such deicers, and so did the aggregates with higher pH. The void contents of the asphalt mixes were recommended to be kept low enough to limit deicer solution in pores.

- **Impact of Pavement Deicing Products on Other Airfield Infrastructure**

Other airfield infrastructure that comes into contact with PDPs includes ground support equipment, signage, and lighting and other electrical systems. Empirical evidence exists indicating that PDPs are responsible for damaging such infrastructure. However, no academic-peer-reviewed scientific information could be found to corroborate these empirical observations.

- **Looking to the Future**

When it comes to airfield pavement deicing and anti-icing there are no simple solutions to the competing, and sometimes conflicting, objectives of aircraft safety, environmental regulatory compliance, materials compatibility, and operational implementation viability.

The ACRP survey distributed for this project provided a forum to describe knowledge gaps and research needs, as well

TABLE 13
SUMMARY OF PDP EFFECTS, KNOWLEDGE GAPS, AND ONGOING RESEARCH

PDP Impact	What Is Known	What Is Unknown	Ongoing Research
<i>Catalytic oxidation of carbon-carbon composite brakes</i>	<ol style="list-style-type: none"> 1. A growing body of field evidence from airline operators suggests that the use of KAc and KF on airfield pavements leads to catalytic oxidation of C/C composite brake components. 2. Existing research in the laboratory has demonstrated the catalytic effects of potassium, sodium, and calcium on carbon oxidation. 	<ol style="list-style-type: none"> 1. There is still a need to establish a comprehensive PDP catalytic oxidation test protocol. 2. More research is needed to better understand relationships between brake design, AO treatment, and PDP contamination as factors in catalytic oxidation. 	<p>The SAE G-12 Carbon Oxidation Working Group is in the process of refining a carbon compatibility test protocol.</p> <p>The SAE A-5A Brake Manufacturers Working Group is in the process of developing an oxidation test method for AO-treated coupons.</p>
<i>Corrosion of aircraft alloys (with a focus on cadmium plating)</i>	<ol style="list-style-type: none"> 1. Until recently, the principal evidence connecting alkali-metal-salt-based PDPs with Cd-plating corrosion has been a trend of increased reports of the latter occurring simultaneously with the introduction of the former. 2. Very little research has been conducted to investigate the mechanism of Cd corrosion or Cd-steel corrosion in the presence of alkali metal salts (e.g., KF and KAc), partly owing to the high toxicity associated with Cd and its compounds. 	<ol style="list-style-type: none"> 1. There is still a need to establish a comprehensive metallic corrosion test protocol for PDPs. 2. More research is needed to better understand the interactions among the aircraft component design, the CICs used, and the contamination of PDPs in the processes of metallic corrosion. 3. There is still a lack of academic research data from controlled field investigation regarding the aircraft metallic corrosion by PDPs. 	<p>A Cd-corrosion test protocol has been in development in the SAE G-12 Cd Corrosion Working Group since 2003 and is currently being refined for inclusion to AMS 1431 and 1435.</p>
<i>Interaction with aircraft deicing and anti-icing products</i>	<ol style="list-style-type: none"> 1. Recent laboratory data appear to corroborate anecdotal reports of increased rates of thickener residues in environments where alkali-metal-salt-based PDPs have been used. 	<ol style="list-style-type: none"> 1. The contamination effects of ADAFs by runway deicing fluids have been well-observed but not yet thoroughly quantified. 2. Further research is needed to better understand the interactions between ADAFs and PDPs, as new ADAFs and PDPs are continually introduced to the market. 	<p>The SAE G-12 Fluid Residues Working Group is leading research efforts in this field.</p>
<i>Impact of PDPs on concrete pavement</i>	<ol style="list-style-type: none"> 1. The last decade has seen an increase in the premature deterioration of airfield PCC pavements with the use of alkali-metal-salt-based PDPs. 2. Limited existing laboratory studies indicated that alkali-metal-salt-based deicers could cause or accelerate ASR distress in the surface of PCC pavement, by increasing the pH of concrete pore solution. 	<ol style="list-style-type: none"> 1. There is a need for research data from controlled field investigation regarding the effects of alkali-metal-salt-based PDPs on concrete pavement. 2. There is a need to unravel the specific mechanism by which alkali metal salts cause or promote ASR. 	<p>IPRF Project 05-7: Performance of Concrete in the Presence of Airfield Pavement Deicers and Identification of Induced Distress Mechanisms and IPRF Project 06-5: Role of Dirty Aggregates in the Performance of Concrete Exposed to Airfield Pavement Deicer, both conducted by Clemson University.</p>
<i>Impact of PDPs on asphalt pavement</i>	<ol style="list-style-type: none"> 1. Although it was observed in some Nordic airfields that exacerbated asphalt deterioration occurred with applications of alkali-metal-salt-based PDPs, there is thus far little observation reported in U.S. or Canadian airports. 2. Significantly accelerated deterioration of asphalt pavements was found in laboratories when exposed to acetate/formate-based deicers. 	<ol style="list-style-type: none"> 1. There is a need for research data from controlled field investigation regarding the effects of alkali-metal-salt-based PDPs on asphalt pavement. 2. There is a need to unravel the specific mechanisms by which alkali metal salts and other PDPs (e.g., bio-based deicers) deteriorate asphalt pavement. 	<p>AATP Project 05-03: Effect of Deicing Chemicals on HMA Airfield Pavements, conducted by the Advanced Asphalt Technologies.</p> <p>RITA Project: Mitigation of Moisture and Deicer Effects on Asphalt Thermal Cracking through Polymer Modification, conducted by Montana State University.</p>
<i>Impact of PDPs on other airfield infrastructure</i>	<ol style="list-style-type: none"> 1. Empirical evidence exists indicating that PDPs are responsible for damaging other airfield infrastructure (GSE, signage, lighting and other electrical systems). 	<ol style="list-style-type: none"> 1. No academic-peer-reviewed scientific information could be found to corroborate these empirical observations. 	<p>N/A</p>

AO = anti-oxidant; CICs = corrosion-inhibiting compounds; ADAFs = aircraft deicing/anti-icing fluids; ASR = alkali-silica reaction; N/A = not available.

as potential challenges for the future of airfield pavement deicing and anti-icing. Some of the key findings from the survey and the literature review are summarized in Table 13.

A dominant theme throughout all the responses provided by airports was the challenge of needing environmentally benign products that are simultaneously safe for aircraft, pavement, and electrical systems. Several respondents indicated the need for standards concerning the compatibility of

deicers with airfield infrastructure and airframe materials, as well as standards for environmental effects of deicers. There was a strong call for best practices and new test methods with pass/fail criteria, but also skepticism about the actual impacts of PDPs and whether scientific data are truly available to confirm these impacts. One suggestion noted was to keep precise records of PDP use to develop the knowledge base needed to determine if PDPs are damaging aircraft and airfields.

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ACRONYMS AND ABBREVIATIONS

ABSC	Aircraft Braking Systems Corporation	K	potassium
ADAF	aircraft deicing/anti-icing fluid	KAc	potassium acetate
AMS	aerospace material specifications	KF	potassium formate
AO	anti-oxidant	Mg/L	milligram/liter
ASR	alkali-silica reaction	NaAc	sodium acetate
BOD	biochemical oxygen demand	NaF	sodium formate
BOD ₅	5-day BOD	P	phosphorus
C/C	carbon-carbon	PAH	polycyclic aromatic hydrocarbons
CIC	corrosion-inhibiting compound	PAN	polyacrylonitrile
CVD	chemical vapor deposition	PCC	portland cement concrete
GSE	ground support equipment	PDP	pavement deicing product
IPRF	Innovative Pavement Research Foundation	TGA	thermogravimetric analysis

APPENDIX A

Blank ACRP Survey

ACRP Synthesis 11-03, Topic S10-03: Impact of Airport Pavement Deicing Products on Aircraft and Airfield Infrastructure

The Airport Cooperative Research Program is conducting research on the state of the practice of airport de-icing. The objectives of this research are to report how airports deice their airfield pavements, identify chemicals used and amounts applied, review damage reported to aircraft components and airfield infrastructure in association with the use of traditional or modern pavement deicing products (PDPs), and identify critical knowledge gaps on this topic. The research is conducted primarily by a research team led by Dr. Xianming Shi at MSU Bozeman.

Please take a few minutes to complete this survey. Answer every question to the best of your knowledge. For the purposes of this survey, the term "PDP" includes any product applied to pavement for "de-icing" or "anti-icing" applications.

NOTE: Any information you provide in this survey will be held in strictest confidence. Contact information collected in this survey will be used only for the purpose of gathering follow-up information from participants and will not be shared with any person or group outside ACRP. Your cooperation will be of great benefit to this project, your organization and industry, and the entire aviation community.

Please fax the completed survey to Dr. Xianming Shi at (406) 994-1697, or use the answers on this handout to complete the online survey at <http://www.trb.org/ss/wsb.dll/24/PDPPilot.htm>.

Thank you.

Personal Information:

First Name: _____

Last Name: _____

Company/Organization: _____

Position: _____

Daytime Telephone No.: _____

In which sector of the aviation industry do you currently work:

- ☐ Airframe and/or aircraft component manufacturing—Go to Section 2
- ☐ Airport/airfield infrastructure management—Go to Section 3
- ☐ Charter, commercial, or corporate air carrier—Go to Section 4
- ☐ Industry or government group (e.g., FAA, ATA, SAE, etc.)—Go to Section 1
- ☐ Military aviation—Go to Section 1
- ☐ Other (please specify)—Go to Section 1—_____

ACRP Synthesis 11-03, Topic S10-03: Impact of Airport Pavement Deicing Products on Aircraft and Airfield Infrastructure

Section 1

Why are you interested in the topic of airfield de-icing and its impact on airfield infrastructure and aircraft components? Please be specific.

Please describe in as much detail as possible any initiatives or policies involving PDP application that you would like to see put in place or that have been proposed by air carriers, airports, or other organizations.

If you work in:

Military aviation, go to section 2.

an industry or government group, go to section 2

Other, go to section 6.

NOTE: After completing all relevant sections of this survey, complete section 8: General Questions.

Section 2

Please indicate which of the following attributes apply to your current or past roles at your government or industry group or military aviation unit.

	Current	Past	Never	If you checked "Current" or "Past":
Work with or at a specific airport or airfield	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Complete section 3.
Work for or with airframe or aircraft component manufacturing	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Complete section 4.
Work with charter, commercial, corporate, military, or other air carrier(s)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Complete section 5.
Work with PDP manufacturing and/or testing	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Complete section 6.

NOTE: After completing all relevant sections of this survey, complete section 8: General Questions.

Section 3: Airframes and Components

The following questions deal with airframe and component manufacturing and use.

What airframe(s) or component(s) manufactured or used by your organization are impacted by PDPs? What are the design life spans of these products?

Have the design or construction of materials used for your components changed over the years? If so, how?

Yes No Not sure

Comments:

Has your organization ever tested any measures designed to mitigate the impact of PDPs on your products? Please comment on success stories and lessons learned.

Yes No Not sure

Comments:

Has your organization conducted any scientific testing on the effects of PDPs on aircraft brakes (especially carbon brakes)? If so, is there a report available on the subject? If not, what type(s) of testing would you recommend? If you do not have the data, where might we obtain them?

Yes No Not sure

Comments:

From a materials selection viewpoint, please rank on a scale from 1 (no risk) to 10 (high risk) the potential risk of failure of your products when exposed to each the following types of PDP:

Urea	1	2	3	4	5	6	7	8	9	10
Glycols	1	2	3	4	5	6	7	8	9	10
Potassium Acetate	1	2	3	4	5	6	7	8	9	10
Sodium Acetate	1	2	3	4	5	6	7	8	9	10
Potassium Formate	1	2	3	4	5	6	7	8	9	10
Sodium Formate	1	2	3	4	5	6	7	8	9	10
Calcium Magnesium Acetate	1	2	3	4	5	6	7	8	9	10
Other (please specify)	1	2	3	4	5	6	7	8	9	10
Other (please specify)	1	2	3	4	5	6	7	8	9	10

Comments:

Has your organization ever conducted scientific testing on materials' compatibility with any PDP? If, so, is there a report available on the testing? If not, what type of testing would you recommend for products similar to yours?

Yes No Not sure

Comments:

Have you made suggestions to your customers regarding maintenance procedures for corrosion prevention?

Yes No Not sure

Comments:

Do you have any field evidence that your airframes or components were durable to one or more specific type of PDP? Please be specific as to time and place. Did you observe any consistent trends? Are there reports, presentations, photographs, or other documentation available?

Yes No Not sure

Comments:

Section 4: Airport and Airfield

The following questions deal with application of PDPs at airports and airfields and their effects on airfield infrastructure assets and aircraft components.

Please provide the following information about the airport or airfield at which you currently work:

Airport or airfield name

IACA airport code or USAF airfield code

City

State, Province, County, or Department

Country

Please rank the following criteria based on their importance in selecting a PDP for use at your airport or airfield. Describe criteria not specifically listed in the matrix in the box below and rank them using the "Other (#)" categories.

	Very Important	Somewhat Important	Important	Not Very Important	Unimportant
Corrosion risk	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Environmental impact	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Cost	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Effectiveness	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Electrical conductivity	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Other (1) (please specify)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Other (2) (please specify)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Comments:

How many different unique-trade-name PDPs were applied in the last five years? If you do not have the data, where might we obtain them?

Additional information:

Please describe typical climate conditions experienced at your airport or airfield. Please be specific as to temperature, humidity, precipitation (especially rainfall), and changes throughout the year.

Do you have field evidence linking seasonal changes in climate factors at your airport or airfield with changes in rates of deterioration of airfield pavements or corrosion of aircraft components, ground support equipment, lighting fixtures, signage, or other airfield infrastructure assets? If so, is there documentation available?

Yes No Not sure

Comments:

Based upon your experience, please discuss life spans of concrete and asphalt pavement materials, lighting fixtures, signage, ground support equipment, and other airfield infrastructure assets at your airport or airfield.

Have the mix design or construction practices for pavements at your airport or airfield changed over the years? If so, how? Please be specific. Where might we obtain data if you do not have them?

Yes No Not sure

Comments:

Have the design or materials used for lighting fixtures, signage, ground support equipment, or other airfield infrastructure at changed over the years? If so, how? Where might we obtain data if you do not have them?

Comments:

REMINDER: Don't forget to download the PDP application data form from the ACRP survey website, or download the form directly from this link:
<http://www.coe.montana.edu/wti/wwwshare/Corrosion/PDPData.xls>

Section 5: Air Carriers

The following questions deal with the effects of PDPs on charter, commercial, corporate, and military aircraft

Please list the aircraft models operated by your organization.

Of the airports to which your airplanes routinely fly, which airports apply PDPs to deice airfield pavements (runway, taxiway, aprons, etc.)? Are there concerns about any specific airport(s) with respect to PDP application?

Has your organization ever tested measures designed to mitigate the impact of PDPs on aircraft components or airfield infrastructure assets? Please comment on success stories and lessons learned.

Yes No Not sure

Comments:

Do you have any field evidence that a specific type of PDP caused or aggravated corrosion damage to components on your aircraft or reduced service life? Please be specific as to time and place. Did you confirm or suspect a mechanism for such corrosion or damage? Did you observe any consistent trends? Do you have any reports, presentations, photographs, cost information, or other documentation available on the subject?

Comments:

Has your organization conducted any scientific testing on the compatibility of PDPs with known susceptible aircraft components? If so, is there a report available on this testing? If not, what type(s) of testing would you recommend? If you do not have the data, where might we obtain them?

Yes No Not sure

Comments:

Has your organization conducted any scientific testing on the effects of PDPs on aircraft brakes (especially carbon brakes)? If so, is there a report available on the subject? If not, what type(s) of testing would you recommend? If you do not have the data, where might we obtain them?

Comments:

Do you have any field evidence that a specific type of aircraft component (e.g. airframe, landing gear, or related component) was durable after extended (i.e. years of) exposure to PDPs? Please be specific as to time and place. Did you observe any trend(s)? If so, is there any report, presentation, photograph, or other evidence available regarding the trend(s)?

Yes No Not sure

Comments:

Has your organization conducted any scientific testing on the compatibility of PDPs with known susceptible aircraft components? If so, is there a report available on this testing? If not, what type(s) of testing would you recommend? If you do not have the data, where might we obtain them?

Yes No Not sure

Comments:

Section 6: PDP Manufacturing

The following questions deal with the manufacture and testing of PDPs.

Please list the trade name of each PDP your organization manufactures or tests:

PDP #1

PDP #2

PDP #3

PDP #4

PDP #5

PDP #6

PDP #7

PDP #8

PDP #9

PDP #10

From a materials selection viewpoint, please discuss the potential risk from your product(s) to any known susceptible aircraft components or airfield infrastructure assets. Please be specific.

Has your organization conducted any scientific testing on the compatibility of your product(s) with known susceptible aircraft components and airfield infrastructure assets? If so, is there a report available on this testing? If not, what type(s) of testing would you recommend?

Yes No Not sure

Comments:

Has your organization conducted any scientific testing on the effects of your PDPs on aircraft brakes (especially carbon brakes)? If so, is there a report available on the subject? If not, what type(s) of testing would you recommend? If you do not have the data, where might we obtain them?

Yes No Not sure

Comments:

Do you have any field evidence that a specific type of aircraft component (e.g. airframe, landing gear, or related component) or airfield infrastructure asset was durable after years of exposure to your product(s)? Please be specific as to time and place. Did you observe any trends? If so, is there any report, presentation, photographic evidence, or other documentation available regarding the trends?

Yes No Not sure

Comments:

Do you have any field evidence that a specific type of aircraft component or airfield infrastructure asset was corroded, damaged, or suffered reduced service life due to your product(s)? Please be specific as to time and place. Did you confirm or suspect a mechanism for such corrosion or damage? Did you observe any consistent trends? Do you have any reports, presentations, photographic evidence, cost information, or other documentation available on the subject?

Yes No Not sure

Comments:

Do you know of any factors other than your product(s) which contribute to the reported damages? If so, please list them and rank their impact relative to that of your product(s) on a scale from 1 to 10.

Yes No Not sure

Comments:

Has your organization ever tested measures designed to mitigate the impact of your product(s) on aircraft components or airfield infrastructure assets? Please comment on success stories and lessons learned.

Yes No Not sure

Comments:

Do you have any field evidence that a specific type of aircraft component (e.g. airframe, landing gear, or related component) or airfield infrastructure asset was durable after years of exposure to your product(s)? Please be specific as to time and place. Did you observe any trends? If so, is there any report, presentation, photographic evidence, or other documentation available regarding the trends?

Yes No Not sure

Comments:

Section 7: Miscellaneous Questions

These questions cover knowledge of airfield de-icing practices that you may have gained during your employment in a sector of the aviation industry not listed in the previous question.

Do you know of any scientific testing conducted to determine the compatibility of PDPs with various known susceptible aircraft components or airfield infrastructure assets? If so, is there a report available on the testing? If not, what type(s) of testing would you recommend?

Yes No Not sure

Comments:

Are you aware of any field evidence that a specific type of aircraft component or airfield infrastructure asset was durable after years of exposure to PDPs? Please be specific as to when and where. Were any consistent trends observed? If so, is there any report, presentation, photographic evidence, or other documentation available?

Yes No Not sure

Comments:

Do you know of any field evidence that a specific type of PDP caused or aggravated corrosion damage to aircraft components or airfield infrastructure assets or reduced their service life? Please be specific as to time and place. Was there a confirmed or suspected mechanism for such corrosion or damage? Were any consistent trends observed? Are there reports, presentations, photographs, cost information, or other information available on the subject?

Yes No

Comments:

Are you aware of any known or suspected factors other than the presence of PDPs used contributing to the reported damage? If so, please comment and compare the impact of these factors to that of PDPs.

Yes No

Comments:

Are you aware of any testing of tested measures designed to mitigate the impact of PDPs on aircraft components or airfield infrastructure assets? Please comment on success stories and lessons learned.

Yes No

Comments:

Section 8: General Questions

Please list, rank, and discuss knowledge gaps and research subjects concerning PDPs and their effects that you feel need to be addressed.

Looking into the future, what do you see as potential challenges and solutions regarding this topic?

Please include any additional comments or suggestions not addressed by this survey.

Please fax the completed survey to Dr. Xianming Shi at (406) 994-1697, or use the answers on this handout to complete the online survey at <http://www.trb.org/ss/wsb.dtl/24/PDPPilot.htm>.

APPENDIX B

ACRP Survey Respondents

AIRPORT/AIRFIELD INFRASTRUCTURE MANAGEMENT (15)

Company/Organization	Position
Salt Lake City Department of Airports	Manager, Environmental Programs
Indianapolis International	Environmental Manager
Des Moines International Airport	Airport Environmental Manager
Port of Portland—Portland International Airport	Deicing Operations Manager
Alleghany County Airport Authority	Manager of Environmental Compliance
Massachusetts Port Authority	Assistant Director of Capital Programs and Environmental Affairs
St. Louis Airport Authority	Assistant Director, Operations and Maintenance
Maryland Aviation Administration	Environmental Program Manager
Flughafen Zuerich AG	Project Manager Waste Water
Metro Nashville Airport Authority	Assistant Manager Environmental Compliance
Reno-Tahoe Airport Authority	Environmental Compliance Coordinator
Wayne County Airport Authority	Environmental Program Administrator
Columbus Regional Airport Authority	Environmental Supervisor
Swedish Civil Aviation Administration	M. Sc. Project Manager
Oslo Airport	<i>not indicated</i>

AIRFRAME AND AIRCRAFT COMPONENT MANUFACTURING (9)

Company/Organization	Position
Boeing Aerospace	Senior Engineer
Airbus SAS	Manager, Electro-Mechanical Systems
Aircraftbraking Systems Corp.	Director, Customer and Technical Support
BCA/CAS/Airport Technology	Technical Analyst
BAE Systems	Senior Materials Engineer
The Boeing Company	Customer Service Engineer
Honeywell/Aerospace	Engineer
Honeywell	Staff Engineer, R&D
Messier-Bugatti	Friction Material Development

AIRCARRIER/AIRLINES (9)

Company/Organization	Position
Northwest Airlines	Engineer
UPS	Aircraft Engineer
All Nippon Airways	Development Engineering
Finnair	Service Manager, De-icing
SAS, Scandinavian Airlines	Materials and Process Engineer
British Airways	Senior Technical Engineer (Design)
American Airlines	Deice Engineering Specialist
KLM Royal Dutch Airlines	Systems Engineer
Continental Airlines	Senior Engineer

INDUSTRY OR GOVERNMENT GROUP (3)**Company/Organization**

Air Transport Association
 Innovative Pavement Research Foundation
 Federal Aviation Administration

Position

Managing Director
not indicated
not indicated

MILITARY AVIATION (1)**Company/Organization**

U.S. Air Force

Position

Environmental Engineer, AFMC Deicing POC

PAVEMENT DEICING PRODUCT MANUFACTURING (2)**Company/Organization**

The Dow Chemical Company
 Cryotech Deicing Technology

Position

Technical Service
 R&D Manager

OTHER (3)**Company/Organization**

VTI
 CH2M Hill
 Clemson University

Position

not indicated
 Principal Water Resources Specialist
 Associate Professor

Abbreviations used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI-NA	Airports Council International-North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation