FINAL REPORT

Demonstration of an Environmentally Benign and Reduced Corrosion Runway Deicing Fluid

ESTCP Project WP-0924

Mary T. Wyderski
Air Force/Aeronautical System Command

H. Nicholas Conkle
Melissa S. Roshon
Jeremy L. Craft
Satya P. Chauhan
Battelle

Version 2

January 2011

Note: this work was originally classified as Sustainable Infrastructure (SI) project SI-0924. In August 2010, after the testing had been completed and this report drafted, the project was transferred to the Weapon Systems and Platforms Projects (WP) area and the project re-numbered WP-0924. This Final Report was prepared, with the permission of ESTCP, following the SI Final Report guidelines rather that the WP guidelines.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
31-01-2011

2. REPORT TYPE
FINAL

3. DATES COVERED *(From - To)*
04-2009 to 08-2010

4. TITLE AND SUBTITLE
Final Report
Demonstration of an Environmentally Benign and Reduced Corrosion Runway Deicing Fluid

5a. CONTRACT NUMBER
FA8903-08-D-8779

5b. GRANT NUMBER
NA

5c. PROGRAM ELEMENT NUMBER
NA

6. AUTHOR(S)
M. T. Wyderski (Air Force/ASC); and H.N. Conkle, M.S. Roshon, J.L. Craft, and S.P. Chauhan (Battelle)

5d. PROJECT NUMBER
G006357

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
US Air Force/ASC: Wright-Patterson Air Force Base, OH 45433
Battelle: 505 King Ave., Columbus, OH 43201

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Enviromental Security Technology Certification Program: 901 North Stuart Street, Suite 303, Arlington, Virginia 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
ESTCP

11. SPONSORING/MONITORING AGENCY REPORT NUMBER
WP-0924

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This report presents the findings from a full-scale side-by-side demonstration of Battelle Runway Deicing Fluid (RDF) versus conventional potassium-acetate based RDF. The tests were conducted on a closed section of the Wright-Patterson Air Force Base runway using full-scale fluid application trailers. Anti-icing and deicing performance was based on runway friction rating, a measure of surface slipperiness, and holdover time. The two Battelle fluids tested met all acceptance criteria including lower aquatic toxicity (acute and chronic), similar oxygen demand, lower corrosion of aircraft components (cadmium-plated parts and carbon-carbon brake pads), and comparable runway friction and holdover time. A life-cycle cost analysis indicated that Battelle-RDFs were more cost effective due to lower fluid cost, lower maintenance costs due to reduced metal corrosion and braking system damage.

15. SUBJECT TERMS
Runway deicing fluids; bio-based deicing fluids; aquatic toxicity; oxygen demand; runway surface friction; holdover time; life cycle costs

16. SECURITY CLASSIFICATION OF:

a. REPORT	b. ABSTRACT	c. THIS PAGE
U	U	U

17. LIMITATION OF ABSTRACT
NA

18. NUMBER OF PAGES
121

19a. NAME OF RESPONSIBLE PERSON
Mary Wyderski

19b. TELEPONE NUMBER (*Include area code*)
(937) 656-5570

This page intentionally left blank.

TABLE OF CONTENTS

Page No.

LIST OF TABLES

LIST OF FIGURES

ACRONYMS

ABW	Air Base Wing
AFB	Air Force Base
AFCEE	Air Force Center for Engineering and the Environment
AFCESA	Air Force Civil Engineering Support Agency
AFI	Air Force Instruction
AFMC	Air Force Materiel Command
AFRL	Air Force Research Laboratory
AMS	Aerospace Materials Specification
ASC	Aeronautical System Center
ASMs	Aircraft Single Managers
ASTM	American Society for Testing and Materials
BOD	Biochemical Oxygen Demand
CRREL	Cold Regions Research and Engineering Laboratory
CFR	Code of Federal Regulations
COD	Chemical Oxygen Demand
CPSMR	Contractor's Progress, Status and Management Report
CWA	Clean Water Act
DoD	Department of Defense
ELG	Effluent limitations guidelines
ENV	Environmental
EO	Executive Order
EPA	United States Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
FAA	Federal Aviation Administration
FAME	Fatty Acid Methyl Ester
FFA	Free fatty acids
FPD	Freezing point depressant
gpy	gallons per year
GEN3	Trade name of Battelle-RDFs licensed to Basic Solutions North America Corp.
GEN3 64™	Battelle-RDF 6-4 formulation sold by Basic Solutions
GHG	Green house gas
HOT	Hold over time
IC_{25}	Inhibition concentration, calculated percentage of effluent at which the test organisms exhibit a 25% reduction in a biological function such as reproduction (as in the case of daphnids) or growth (as in the case of fish)
KAc	Potassium acetate
KFo	Potassium formate
LC_{50}	Lethal concentration where 50% of organisms die
LCC	Life cycle costs
LRB	Laboratory record book
MABS	Meggitt Aircraft Braking Systems
MSDS	Material Safety Data Sheet
MTMS	Military Test Method Standard
MTU	Michigan Technological University

NA	Not Applicable
NAAC	Sodium acetate (solid deicer)
NPDES	National Pollutant Discharge Elimination System
NSN	National stock number (or NATO stock number)
O_2	Oxygen
PG	Propylene glycol
PI	Principal Investigator
PNNL	Pacific Northwest National Laboratory
POC	Point of Contact
RCR	Runway condition rating
RDFs	Runway deicing fluid(s)
SAE	Society of Automotive Engineers
SAIC	Science Applications International Corporation
S&ICP	Snow and Ice Control Plan
SERDP	Strategic Environmental Research and Development Program
SMI	Scientific Materials International, Inc
USAF	United States Air Force
WP	Weapon Systems and Platforms
WPAFB	Wright-Patterson Air Force Base
WSSMs	Weapon Systems Single Managers

ACKNOWLEDGEMENTS

This project was conducted for the Environmental Security Technology Certification Program (ESTCP) by the US Air Force Aeronautical System Center (ASC) with the assistance of Battelle, Air Force Research Laboratory (AFRL), the Army Cold Regions Research and Engineering Laboratory (CRREL), and SAIC.

The project manager was Ms. Mary Wyderski. Technical and managerial contributions were provided by Dr. John Hall of the ESTCP program office.

Ms. Wyderski was supported by Mr. Don Tarazano and Mr. Nick Conkle. The members of the project team (minus the authors and the ESTCP staff) and their contributions are presented in Appendix A.

EXECUTIVE SUMMARY

Currently the DoD exclusively uses potassium acetate (KAc) based runway deicing fluids (RDFs) to deice and anti-ice military runways and taxiways. Commercial airports predominantly use KAc, but some also use RDFs composed of KAc plus propylene glycol (PG) or urea plus PG. These RDFs have environmental concerns due to toxicity as well as material compatibility problems due to corrosion of carbon brake-pad components and cadmium-plated landing gear and airfield lighting fixtures.

Under the SERDP project SI-1535, Battelle developed a series of effective bio-based RDFs to address these issues. Tests showed that the Battelle-RDFs met the mandatory Aerospace Material Specification 1435A specifications. It had reduced ecotoxicity and was compliant with all other environmental requirements. Also, it was found to be more compatible (i.e., less corrosive) with commercial aircraft materials (such as landing gear components) and Air-Force unique materials (e.g., infrared windows, low observable coatings). A full-scale demonstration was conducted with two Battelle-RDF formulations: 6-12 using a partially refined bio-based material and 6-3 using a fully purified bio-based material.

The objective of the demonstration was to show that an advanced RDF prepared from low-cost bio-based raw materials was less toxic, less corrosive, but as effective as commercial KAc liquid RDFs in airfield deicing and anti-icing. The two Battelle-RDFs were evaluated under anti-icing and deicing conditions on a runway at Wright-Patterson Air Force Base (WPAFB) during January and February 2010. Runway test sections 50-ft wide by 1,000-ft long were used in side-by-side tests of the Battelle-RDFs and Cryotech E-36 KAc RDF. Two commercial Batts deicing-fluid delivery trailers were used in the demonstration.

The tests produced sufficient data to conclude the demonstration was a success. Prior to the testing quantitative and qualitative performance objectives were established. The test results are summarized below:

- Quantitative
  - Environmental: 3 to 4 times less toxic
  - Oxygen demand: intermediate between KAc RDF and KAc+PG RDF
  - Corrosion: 60 to 80% less corrosive to cadmium-plated landing gear and carbon-carbon brake pad materials
  - Deicing and anti-icing performance: comparable to KAc RDF

- Qualitative
  - Ease of use: comparable to KAc RDFs
  - Maintenance requirements: comparable to KAc RDFs.

The Battelle-RDFs were found to be suitable as a drop-in replacement for KAc RDF. A manufacturing analysis indicated that the Battelle-RDFs had lower fluid costs. A life cycle cost estimate indicated that the Battelle-RDFs had slightly higher wastewater treatment costs (due to slightly higher BOD levels). But, these increased costs were insignificant compared to the savings from lower fluid cost and airfield and aircraft maintenance costs (due to reduced Cd and carbon-carbon brake pad corrosion).

To quantify the savings across the DoD, it was estimated that the military (primarily the Air Force) consumes approximately 1 million gallons of RDF each year. Usage is spread over 31 active USAF bases, 45 Air National Guard Bases, and 4 Air Force Reserve Command bases located in the northern half of the U. S. This compares to an estimated 8 million gallons of KAc RDF used at U. S. commercial airports. It was estimated that if a "typical" Air Force Base (using 31,000 gallons of RDF/year) switched to Battelle-RDF, the savings would be ~$92,000/year. The estimated savings grew to $2.9 million if the entire DoD switched, and $28 million if all DoD and commercial airports switched to Battelle-RDF.

It is important to move these advanced bio-based RDFs from the laboratory to the airfields and airports across the country. Users may express concern because the Battelle-RDFs are new and they may have reservations because of their potential damage to aircraft or weapon system components. These reservations should be allayed once the range of tests performed and the superior corrosion properties and comparable deicing/anti-icing performance of Battelle-RDFs are disseminated.

A major implementation issue is the manufacture and delivery of the RDF. Battelle is a research and development company and not an RDF vendor. This issue was resolved when Battelle licensed the technology to Basic Solutions North America Corporation. Basic Solutions distributes the Battelle-RDF 6-4 formulation under the trade name **GEN3 64™** (formulation 6-4 is similar to 6-12 and 6-3, except it has a higher bio-based content) and plans to offer **GEN3 63™** and **GEN3 6-12™** in the near future. During the 2009/2010 deicing season, 15 Canadian commercial airports and 4 U. S. commercial concerns used or tested **GEN3**. In all these commercial airport trials, **GEN3 64™** was used without modification to the storage tanks, transfer pumps, deicing fluid trailers, spray nozzles, or fluid delivery pumps. This supports the conclusion that Battelle-RDFs can be readily implemented as a drop in replacement.

Prior to use in the Air Force and the DoD, the fluid was reviewed and accepted by the Air Force Civil Engineering Support Agency, the Air Force agency that provides guidance on allowable liquid and solid RDFs. Now that it has been accepted, the Aircraft Single Managers (ASMs) and Weapons System Single Managers (WSSMs) can be notified that **GEN3** is approved for use. A National Stock Number (NSN) may be requested and secured to facilitate procurement. Finally, and most importantly, the ASMs and WSSMs will have to review the environmental, material compatibility, and performance data and accept **GEN3** for use on their aircraft and/or weapon system. In some cases, special material-compatibility concerns may delay acceptance; or additional material-specific testing may be required by a weapon system before acceptance.

1.0 INTRODUCTION

This Final Report is organized per the ESTCP Guidance for Sustainable Infrastructure (SI) Facilities and Energy projects. It consists of the following nine sections and two Appendices:

1. Introduction
2. Technology Description
3. Performance Objectives
4. Facilities/Site Description
5. Test Design
6. Performance Assessment
7. Cost Assessment
8. Implementation Issues
9. References

Appendix A: Points of Contact
Appendix B: Statistical Analysis of Performance Data.

1.1 BACKGROUND

Currently the Department of Defense (DoD) exclusively uses potassium acetate (KAc) based runway deicing fluids (RDFs) for their liquid pavement deicing needs to deice and anti-ice military runways and taxiways. Commercial airports predominantly use KAc but some also use RDFs composed of KAc plus propylene glycol (PG) or urea plus PG.

The DoD faces a significant environmental and military readiness problem due to the use of aqueous solutions of the KAc RDF. Originally the airports used urea or PG for runway deicing; however, due to the high biochemical oxygen demand (BOD) and high chemical oxygen demand (COD) of urea and PG, as well as the high ecotoxicity of urea, the DoD and most US commercial airports have switched to organic salts such as KAc. European airports use sodium or potassium formate runway deicers and anti-icer fluids. Studies now indicate that the acetate and formate deicers are more toxic than originally recognized [1].

While the acetate and formate deicers have a much lower BOD and COD than urea or PG, they are corrosive to aircraft components leading to military readiness problems. Recent testing by Air Force Research Laboratory (AFRL) indicates their compatibility with advanced DoD aircraft is questionable [2]. In recent Society of Automotive Engineers (SAE) G-12 Aircraft Ground Deicing Fluids Subcommittee meetings, there has been serious concern expressed about the more commonly used KAc and formate deicers because of the corrosion of very expensive carbon-carbon brake pads and associated components, as well as landing gear components containing cadmium.

These concerns are likely to lead to the use of larger quantities of toxic corrosion-inhibitors and/or the use of less corrosive but high-BOD/COD alternatives, such as PG or PG + acetate mixtures. Therefore, both the environmental and material compatibility concerns are currently threatening the runway maintenance and aircraft availability for both the DoD and commercial sectors.

As documented in the SERDP project SI-1535 final report, a series of effective RDFs were developed to address the environmental and material compatibility issues [3]. A multi-tiered approach was used to formulate RDFs with the ultimate objective of passing the mandatory Aerospace Material Specification (AMS) 1435A specifications as well as meeting or exceeding other key environmental, materials compatibility, and deicing performance requirements. The key to simultaneously improving the properties of and reducing the cost of RDF was to use low-cost, bio-based ingredients as a substitute freezing point depressant (FPD). Use of this bio-based FPD along with KAc and food-grade additives allowed the production of an environmentally friendly RDF that is more compatible with runway/pavement and aircraft components, meets all performance requirements, and costs less.

1.2 OBJECTIVE OF THE DEMONSTRATION

The objective of these tests was to demonstrate that an advanced RDF prepared from low-cost bio-based raw materials is less toxic, less corrosive, and as effective as commercial KAc liquid RDFs in airfield anti-icing and deicing at WPAFB.

1.3 REGULATORY DRIVERS

There are several drivers for implementing a new, more environmentally friendly RDF. Two are discussed below.

1.3.1 Water Pollution Reduction

The Clean Water Act (CWA) and its National Pollutant Discharge Elimination System (NPDES) (40 CFR 122.26) permit program requires facilities that discharge point source storm water to obtain an NPDES permit. All the RDF used for deicing/anti-icing runways and aprons enters the airfield water drainage system. For example, facilities discharging these pollutants at the WPAFB airfield are subject to storm water monitoring and reporting requirements per the WPAFB NPDES permit. The US EPA requested industry comments on new effluent limitations guidelines (ELG) in August 2009 [4]. This proposed guideline addressed wastewater collection practices used by airports and the treatment of those wastes. Specific to the discharge from RDFs, the EPA proposed a ban on the use of urea for runway deicing. However, there is likely to be pressure on the airport authorities in the future to control the toxicity of RDFs.

The regulations would be imposed when airports seek discharge permits from individual states. Many airports are already in compliance with proposed requirements, in response to local and state regulations.

The Draft ELG for Aircraft Deicing Fluids proposes to control discharges based on COD rather than BOD (there is no proposed BOD or COD limits proposed for RDFs). The EPA determined that COD is the better indicator for the following reasons:

- COD captures the oxygen demand from nitrogen and other organic components of the contaminated storm water that may not be represented in a BOD analytical result

- Toxic aircraft deicing fluid additive compounds in deicing storm water may have a negative and variable impact on the acclimation of the active cultures used in BOD analysis, making that method less accurate than a COD analysis

- COD analyses are simple to conduct and can be measured in real time, compared to the 5-day test required by the BOD_5 analytical method.

- The COD analytical method does not require measurement of the receiving water temperature.

On the other hand, current NPDES permits are primarily based on BOD_5. Therefore, we have referenced both COD and BOD_5 in this report.

1.3.2 Greening of the DoD

Three Executive Orders (EOs) dictate that federal agencies promote the increased use of bio-based materials, including:

1. EO 13134 “Developing and Promoting Biobased Products and Bioenergy,” President Clinton, 1999. This EO established a Council to encourage the use of bio-based products.

2. EO 13423 “Strengthening Federal Environmental, Energy, and Transportation Management,” President Bush, 2007. This EO instructs Federal agencies to conduct their environmental, transportation, and energy-related activities under the law in support of their respective missions in an environmentally, economically, and fiscally sound, integrated, continuously improving, efficient, and sustainable manner. The order encompasses a number of green acquisition programs including the encouragement of bio-based procurement.

3. EO 13514 “Federal Leadership in Environmental, Energy, and Economic Performance,” President Obama, 2009. This EO was signed to establish an integrated strategy towards sustainability in the Federal Government and to make reduction of greenhouse gas emissions a priority for Federal agencies. The EO requires Federal agencies to set a 2020 greenhouse gas emissions reduction target within 90 days; increase energy efficiency; reduce fleet petroleum consumption; conserve water; reduce waste; support sustainable communities; and leverage Federal purchasing power to promote environmentally-responsible products and technologies. This EO also requires agencies to conduct an annual greenhouse gas (GHG) inventory, including specified scope 1, 2, and 3 emissions categorizations by January 5, 2011, and annually thereafter. The push to reduce GHG reduction will support the use of bio-based fluids such as Battelle-RDF.

This page intentionally left blank.

2.0 TECHNOLOGY/METHODOLOGY DESCRIPTION

2.1 TECHNOLOGY OVERVIEW

2.1.1 Technology Description

Battelle's proprietary formulations and associated processes include applications for runway and pavement deicing [5-8]. Battelle's proprietary process is a novel chemistry (covered by U.S. Patent 7,048,871) and is based on altering the tail-end of the process for making fatty acid methyl ester (FAME) by transesterification of triglycerides typically derived from vegetable oil seeds or other fats [9]. While there is a well-established oleochemical industry based on this process, the use of FAME as a biodiesel is rapidly growing. By altering the transesterification (FAME/biodiesel production) process, Battelle has been able to make RDF formulations that address the current aircraft corrosion problems while providing environmental and cost benefits.

A typical process for making FAME (also used as biodiesel) is as follows:

$$\text{Triglycerides (fats/oils) + Methanol Catalyst} \xrightarrow{\text{NaOH}} \text{Fatty Acid Methyl Ester + Work By-Product}$$

A simple, atmospheric pressure process yields about 90% FAME. The spent sodium hydroxide (NaOH) catalyst is typically neutralized with hydrochloric acid (HCl) resulting in a side stream containing waste by-products, sodium chloride (NaCl) salt, methanol, water, and some free fatty acids (FFA). Currently, this by-product is used only after refining it into pure components by eliminating all impurities through an expensive, multi-step process and rejecting most impurities as hazardous waste. However, with increasing interest in biodiesel production in Europe and the U.S., there will be a glut of this side stream with no good outlet. Even at the current low levels of biodiesel production, the rate of by-product generation production is high enough to allow the production of 10 times more RDF according to the Battelle process than the total demand for RDF in the U.S. and Europe [10]. This side stream is typically unsuitable for making an RDF due to the presence of NaCl, FFAs, and color forming and odor emitting impurities.

In Battelle's process, the HCl acid is replaced with a suitable organic acid that not only neutralizes the NaOH, but also forms an effective deicing salt (e.g., an acetate or a formate salt) along with the bio-based FPD [9]. Furthermore, a simple process, based on the use of a proprietary Battelle absorbent, can be used to remove FFA and other organic impurities that cause slipperiness and impart objectionable color and odor, while retaining all of the deicing chemicals (bio-based FPD and sodium acetate/formate). Since these by-products from FAME/biodiesel production provides for a maximum of 8% organic salt, it is beneficial to add an additional organic salt to obtain improved deicing properties as well as to reduce BOD/COD. Because of the non-corrosive (actually corrosion inhibition) nature of bio-based ingredients such as the biodiesel by-product, an RDF is formulated without the need for exotic corrosion inhibitors. In this manner, an alternative RDF is made at a significantly lower cost than formulations made from pure components and other additives.

In particular, a biodiesel by-product was modified as a key ingredient. A simple process to treat such a raw material was first demonstrated at laboratory scale and then was scaled-up to 50-gallon batch scale. The RDFs made from a biodiesel by-product were compared to these made from pure (technical grade) ingredients employing identical compositions. These two types of RDFs were indistinguishable in terms of environmental, physical, deicing, and materials compatibility properties.

A total of six RDFs were thus formulated and fully certified under AMS 1435A under the SERDP program; Table 1 provides details of the RDFs of primary interest to the DoD.

Table 1. Description of Selected Certified Battelle-RDF Formulations

No.	Battelle-RDF Designation	Bio-based Freezing Point Depressant Purification	Secondary FPD	Applications
1	6-12	Low-cost purification for RDF-specific use	KAc	Deicing and anti-icing
2	6-2	Conventional; very high purity	KAc	Deicing and anti-icing
3	6-3	Conventional; very high purity	KAc	Deicing and anti-icing
4	6-4	Conventional; very high purity	KAc	Deicing and anti-icing

These formulations provide a range of chemical compositions that allow a user to select the desired environmental and materials property improvements as well as cost reductions. The two preferred RDFs were selected from this set:

- RDF 6-12: made from biodiesel by-products using a low-cost Battelle-developed purification process.
- RDF 6-3: made from highly purified biodiesel by-products.

These two formulations were selected because:

1. They were the most cost-effective formulations.

2. They represented two levels of biodiesel upgrading (minimal and full purification).

3. Both RDFs passed the Air Force’s Material Test Method Specification (MTMS) Tier-3 tests.

Therefore RDF 6-12 and RDF 6-3 were selected for the demonstration to allow testing of a range of RDF costs, and a range of bio-based FPD concentrations, while still meeting all environmental, materials compatibility, and performance requirements. Note: the two formulations were evaluated independently in side-by-side tests versus KAc in the demonstration program.

Table 2 provides a brief summary of the properties of the two selected formulations and alternative liquid RDFs. Note: much of the data was collected during SERDP project SI-1535 and is included as part of the performance findings discussed in a later section.

Table 2. Comparison of Two Battelle-RDF Formulations versus Commercial Alternatives

Parameter	RDF Designations			
	Battelle-RDF 6-12	Battelle-RDF 6-3	KAc	KAc+PG
BOD_5, kg O_2/kg fluid	Intermediate	Intermediate	Slightly lower	Highest
COD, kg O_2/kg fluid	Intermediate	Intermediate	Slightly lower	Highest
Acute toxicity	Lower	Lowest	Medium	Medium
Chronic toxicity	Lowest	Lower	Medium	Medium
Ice melting time, min	Comparable to KAc	Comparable to KAc	Comparable to KAc	Comparable to KAc
Friction	Comparable to KAc	Comparable to KAc	Not applicable	Slightly inferior to KAc
Brake pad life	Longer	Longest	Shortest	Intermediate
Life cycle cost vs. KAc	Lowest	Lower	Highest	Higher

2.1.2 Overall Schematics

Figures 1 and 2 contain flowsheets that show the differences between the state-of-the art for producing USP-grade refined bio-based components and the process for making RDF from biodiesel by-products. Figures 3 and 4 show schematics for the formulation of KAc-RDF and KAc+PG RDFs.

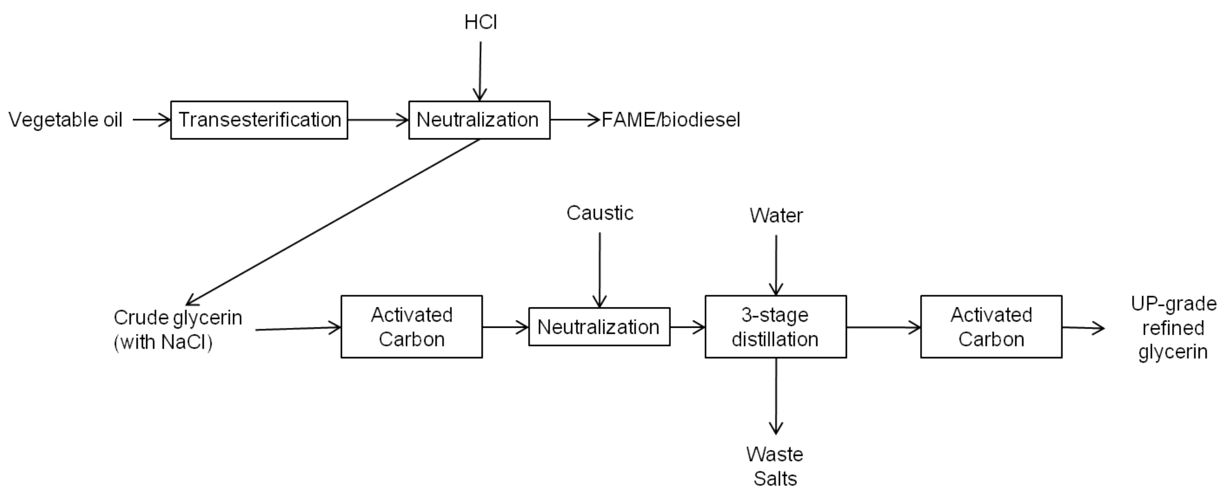


Figure 1. Typical FAME/Biodiesel Process

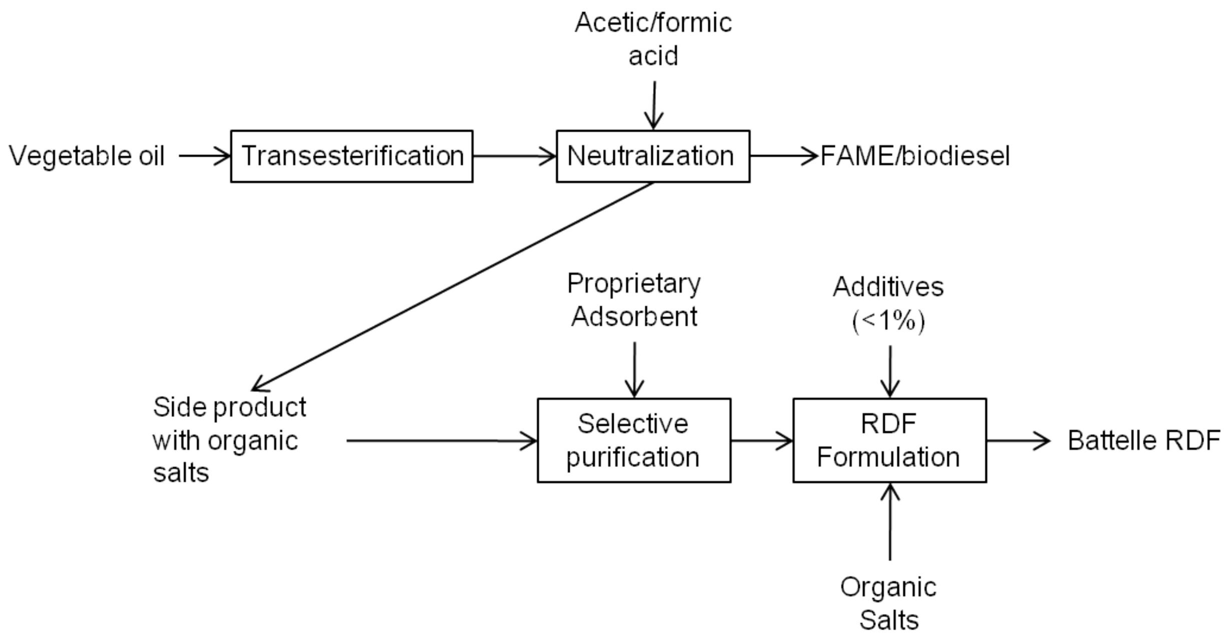


Figure 2. Battelle-RDF Process

RDF 6-12 was manufactured using biodiesel waste by-product after it was subjected to selective purification. RDF 6-3 was formulated with USP-grade refined components.

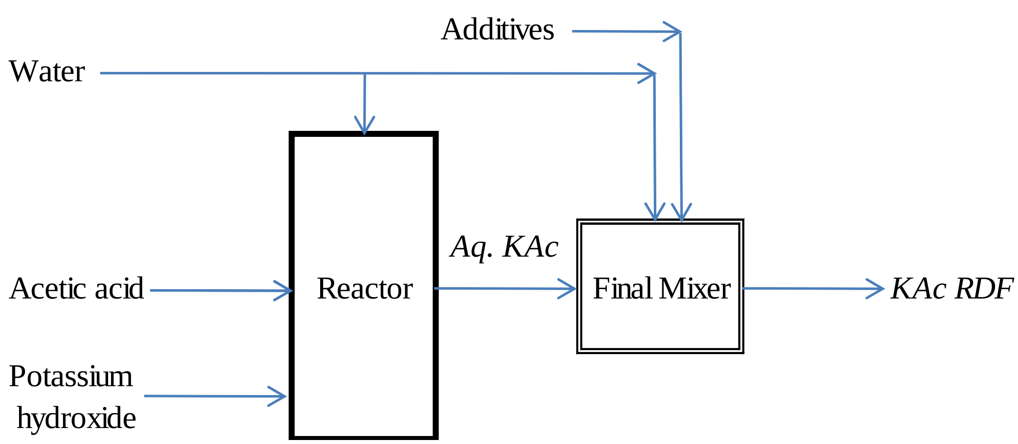


Figure 3. Potassium Acetate RDF Process

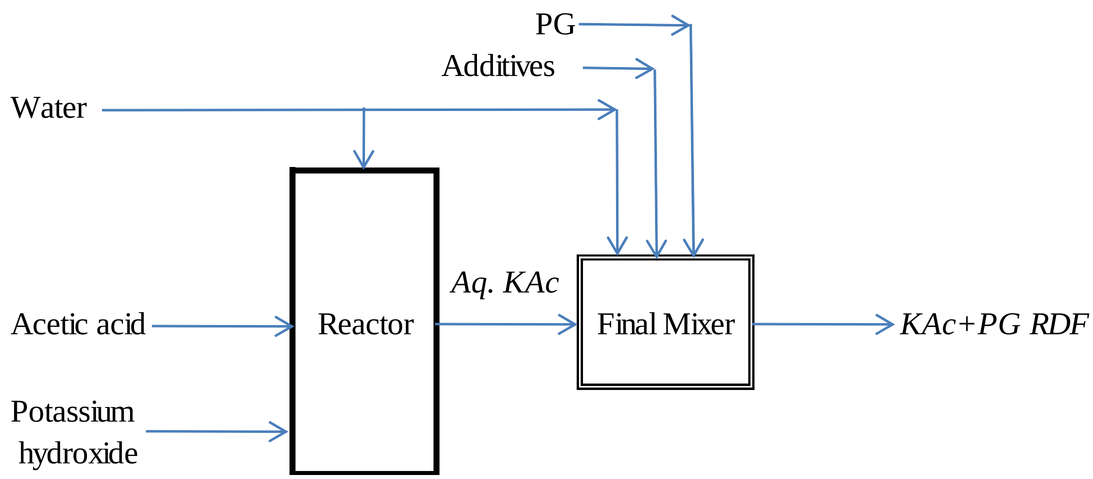


Figure 4. Potassium Acetate Plus Propylene Glycol RDF Process

2.1.3 Chronology

For the past nine years, staff members from Battelle and the Battelle-managed Pacific Northwest National Laboratory (PNNL) have been developing a variety of deicing/anti-icing fluids derived from renewable (bio-based) resources. Three patents were obtained in the 2006 – 2007 timeframe. In 2007, Battelle and PNNL began a SERDP project to optimize an RDF formulation. Over the next two years, over a hundred formulations were developed. Four were fully certified under AMS 1435A under the SERDP project and the top two were selected for this demonstration.

2.1.4 Expected Applications

It is expected that the Battelle-RDFs can be used interchangeably with liquid KAc and/or KAc+PG RDFs, i.e., serve as a drop in replacement for military or civilian liquid runway deicing and anti-icing fluids.

The two Battelle-RDF fluids have very similar environmental, physical, corrosion, and performance properties, so it is expected that either formulation could be selected. Of course, since RDF 6-12 is anticipated to cost less, it would be the preferred formulation. However, RDF 6-12 can only be prepared where formulators have access to biodiesel waste by-product produced using acetic acid as the neutralizing agent in the biodiesel operation. Other acids, such as HCl or sulfuric acid are frequently cheaper and, therefore, are more commonly used in biodiesel production, so not every biodiesel plant will generate acetate crude.

Battelle-RDF 6-3 will be used when only pure compounds are available.

2.2 TECHNOLOGY DEVELOPMENT

The Battelle-RDF technology was developed under a Battelle funded internal research and development program and was subsequently laboratory tested under the SERDP project titled “Development of an Environmentally Benign and Reduced Corrosion Runway Deicing Fluid,” SI-1535 [3].

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The advantages and limitations of the Battelle-RDFs and KAc RDF are noted below:

- Advantages: lower ecotoxicity, better corrosion properties, and lower life cycle costs
- Comparables: deicing, anti-icing, hold-over time, and friction properties
- Limitations: slightly higher BOD/COD.

More details are provided below.

2.3.1 Advantage – Lower Toxicity

The acute ecotoxicity, based on lethal concentration where 50% of the organisms die (LC_{50}) for *Daphnia magna* and fathead minnows, was less than half that of currently used RDFs due to elimination of toxic corrosion inhibitors. For chronic toxicity, we selected Inhibition Concentration. It is calculated as the percentage of effluent at which the test organisms exhibit a 25% reduction in a biological function such as reproduction (as in the case of daphnids) or growth (as in the case of fish). The Wisconsin State Laboratory of Hygiene measured for Inhibition Concentration during SI-1535 use. The chronic toxicity of Battelle-RDF 6-3 and 6-12 was two to ten times lower (i.e., IC_{25} values two to ten times higher) than for commercial KAc RDFs.

2.3.2 Advantage – Cadmium Corrosion

KAc and other organic-salt RDFs can aggressively attack Cd-plated parts, as well as certain other material materials included in the military test method standard (MTMS) protocol. The Battelle-RDFs were dramatically better than KAc RDFs with respect to Cd-plated parts and cast magnesium alloys. These preferred Battelle-RDFs were typically 75% to 80% less corrosive than currently used RDFs.

2.3.3 Advantage – Brake Component Corrosion

A key concern with KAc and other organic-salt RDFs is their aggressive attack on carbon brakes (due to catalytic oxidation). The Battelle-RDFs were dramatically better than KAc RDFs with respect to compatibility with carbon-carbon brake pads. The preferred Battelle-RDFs were typically 75% less reactive to carbon, and are thus projected to improve brake life from one year to about four years. A preliminary analysis indicated that the financial impact of this improvement were dramatic [11].

2.3.4 Advantage – Economics

A cost-benefit analysis conducted as part of this project showed that the Battelle-RDFs were not only cheaper than KAc or KAc+PG RDF alternatives, but also reduced aircraft/airport maintenance costs for a lower life-cycle cost.

2.3.5 Comparable – Performance

The Michigan Technological University (MTU) conducted deicing performance testing that covered ice melting, ice undercutting, and ice penetration [12]. Like the lab test, the demonstration testing indicated the Battelle-RDFs were comparable to KAc RDFs.

2.3.6 Comparable – Friction

The MTU, as well as FAA-performed, runway friction tests confirmed that Battelle-RDFs are as good as KAc RDFs and better than KAc+PG RDFs. The FAA issued a letter to all U.S. airports approving the use of all four Battelle-RDFs tested. Like the lab test, the demonstration testing indicated the Battelle-RDFs had comparable or better friction properties to KAc RDFs.

2.3.7 Disadvantage – Higher Oxygen Demand

U.S. airports are currently using KAc-based RDFs but are considering a move towards using mixtures of KAc and PG to reduce the corrosion of aircraft materials. The BOD/COD of the two Battelle-RDFs selected for the demonstration have oxygen demands that were slightly higher than KAc but lower than KAc+PG RDFs.

This page intentionally left blank.

3.0 PERFORMANCE OBJECTIVES

Based on preliminary data, the Battelle-RDFs may represent viable alternative RDFs, i.e., they may serve as an improved drop-in replacement for organic-salt based RDFs like KAc. Based on small-scale testing, the Battelle-RDF can reduce both environmental risks and costs while maintaining airfield anti-icing/deicing performance. But demonstration data were needed to verify the laboratory performance. Table 3 shows in brief each performance objective and its relevance; measurement metric; data requirement, including the method of collection; and success criteria, including calculations required. For quantitative objectives, the metric threshold (minimum acceptable) value is noted when applicable. Note: In some cases the threshold was established during the demonstration tests.

3.1 ACUTE AQUATIC TOXICITY

- Relevance of objective: Acute (i.e., short-term exposure) aquatic toxicity is critical to the environmentally-sound operation of DoD airports. RDF runoff may be collected for treatment, or diverted to local waterways. Excessively toxic fluids could cause problems at central wastewater treatment plants, or quickly lead to fish kills if discharged to local waterways.

- Metric description: LC_{50} for water fleas (*Daphnia magna*, 48-hr test period) and LC_{50} for fathead minnows (*Pimephales promelas,* 96-hr test period) were selected as the metrics for this objective.

- Data description: LC_{50} for the two noted species are determined as components of the AMS 1435A certification procedure. The higher the LC_{50} the less toxic the fluid. They are reported in mg/L.

- Success criteria: The Battelle-RDFs shall be considered acute-toxicity successes if their LC_{50} values for *Daphnia magna* and *Pimephales promelas*) were higher than the LC_{50} for KAc RDF.

- Status: The success criteria were met because the Battelle-RDFs LC_{50} values were higher than those for KAc RDF. More details are provided in Sections 5 and 6.

This page intentionally left blank.

Table 3. Performance Objectives

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives				
Environmental				
Safeguard waterways by lowering acute toxicity	LC_{50}, mg/L, water fleas (*Daphnia magna*, 48 hr)	Data on acute and chronic toxicity	LC_{50} higher than for KAc RDF (>1,000 mg/L)	Success
	LC_{50}, mg/L, fathead minnows (*Pimephales promelas*, 96 hr)		LC_{50} higher than KAc RDF (>1,000 mg/L)	Success
Safeguard waterways by lowering chronic toxicity	IC_{25}, mg/L, Ceriodaphnia magna		IC_{25} higher than KAc RDF (>800 mg/L)	Success
	IC_{25}, mg/L, Pimephales promelas		IC_{25} higher than KAc RDF (>300 mg/L)	Success
Safeguard waterways by controlling oxidative load	COD, kg O_2/kg RDF fluid	Wastewater treatment load and surcharge costs need for the life-cycle cost analysis	COD falls between KAc and KAc+PG RDF levels (i.e., between 0.3 and 0.73 kg O_2/kg RDF fluid)[(a)]	Success
	BOD_5, kg O_2/kg RDF fluid		Values fall between KAc and KAc+PG RDF levels (between 0.15 and 0.32 mg/L)[(a)]	Success
Corrosion of cadmium-plated parts				
Maintain life of Cd-plated landing gear and aircraft lighting components to ensure safe, extended operation	Weight change, mg/cm^2/24 hr	Data to estimate landing-gear component life needed for life-cycle cost analysis	Lower weight change, as determined by the AMS 1435A cadmium-corrosion test, when compared to KAc RDF	Success
Corrosion of carbon-carbon brake pad				
Maintain life of brake pads to ensure safe and extended operation	Weight loss, %	Data to estimate brake pad life needed for life-cycle cost analysis	Lower weight loss, as determined by the Honeywell brake pad protocol, when compared to KAc RDF	Success
Performance – during anti-icing (RDF dosage ~0.5 gal/ 1000 ft^2) [(a)]				
Maximize the amount of time runways and taxiways are maintained snow- and ice-free	Hold over time (HOT), minutes	Time the surface remains suitable for aircraft operation	Comparable or longer HOT, compared to KAc RDF	Success

(a) If the Battelle RDF COD or BOD_5 levels were at or below the KAc RDF levels, that would also be considered a "success."

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Maintain sufficient runway and taxiway friction values to ensure safe landings and taxiing	Friction coefficient expressed in terms of Runway Condition Rating (RCR)	Pavement surface friction data	Comparable or higher rating compared to KAc, RCR	Success
Performance – during deicing (RDF dosage ~2 gal/1000 ft^2) (a)				
Reduce time to prepare runways and taxiways for operation	Melting efficiency, minutes	Melting times, used to estimate relative fluid dosage requirements needed for life-cycle cost estimate	Comparable or shorter ice-melting times, compared to KAc-RDF	Success
Maintain sufficient runway and taxiway friction values to ensure safe landings and taxiing	RCR	Pavement surface friction	Comparable or higher rating, compare to KAc RDF	Success
Qualitative Performance Objectives(b)				
Ease of use	Ability of RDF operator to use the fluid as a drop-in replacement for KAc; expressed on a scale of 1 to 10	Feedback from operators on usability of the Battelle-RDF, including filling, fluid application, smell, etc.	Based on user surveys, achieve an equal or superior rating compared to KAc RDF (based on a minimum of two WPAFB RDF users and the Operations Chief's assessment of usability)	Success
Maintenance	Ease of maintenance; expressed on a scale of 1 to 10	Feedback from operators on ability to maintain runway deicing equipment when using Battelle-RDF, lack of corrosion or required modifications	Based on user surveys, achieve an equal or superior rating compared to KAc RDF (based on a minimum of two WPAFB RDF users and the Operations Chief's assessment of maintenance issues)	Success

(a) The quantitative assessment for anti-icing (hold-over time and RCR) and de-icing (melt time and RCR) was compared for the three RDFs. The estimated mean for each RDF, corrected for time of day effects, and estimated 95% confidence interval, again corrected for time of day effects, of the three RDFs during anti-icing and deicing tests was determined. If the Battelle-RDFs confidence interval exceeds the KAc confidence interval the fluid was considered superior, if the two intervals overlap then the fluid was classified as comparable. If the KAc interval exceeds the Battelle-RDF interval, with no overlap, the Battelle-RDF was considered inferior. An example is provided later in the text.

(b) The quantitative performance measures for ease of use and maintenance was compared for the three RDFs. KAc performance ratings was assessed by the observers and an average was calculated. Comparable data for the Battelle-RDFs was tallied. If the Battelle-RDFs' average values fall within the KAc RDF value ± two digits, then the Battelle-RDF was considered to have comparable performance.

3.2 CHRONIC TOXICITY

- Relevance of objective: Chronic (long-term) toxicity is also critical to the environmentally-sound operation of DoD airports. Wetlands and aquatic life can be adversely affected by exposure to seemingly low toxicity chemicals delivered over an extended period of time.

- Metric description: IC_{25} for *Ceriodaphnia magna* and *Pimephales promelas*.

- Data description: IC_{25} tests for the two noted species are conducted by the Wisconsin State Laboratory of Hygiene. The higher the IC_{25}, the less toxic is the fluid. They are reported in mg/L.

- Success criteria: The Battelle-RDFs shall be considered chronic-toxicity successes if their IC_{25} values for *Ceriodaphnia magna* and *Pimephales promelas* are higher than the IC_{25} for KAc.

- Status: The success criteria were met because the Battelle-RDFs IC_{25} values were higher than those for KAc RDF. More details are provided in Sections 5 and 6.

3.3 CHEMICAL OXYGEN DEMAND AND BIOCHEMICAL OXYGEN DEMAND

- Relevance of objective: When certain compounds are released into the environment, particularly organic compounds, chemical and biological reactions are initiated that strive to oxidize the compounds using the water's dissolved oxygen (O_2). Oxygen depletion can result, and cause toxic conditions leading to fish kills, putrid smells, or other undesirable consequences.

- Metric description: COD and BOD_5 are two measures of the amount of oxygen required to complete the oxidation reactions. High COD and BOD values indicate the potential for environmental problems.

- Data description: COD (also referred to as theoretical 5-day oxygen demand) and BOD_5 (determined after 5 days at a temperature of 20ºC) were determined as components of the AMS 1435A certification test procedure. From an environmental-impact point of view, the lower the number the better. These levels were reported in kg O_2/kg fluid.

- Success criteria: Both KAc and KAc-PG RDFs are used commercially at U.S. airports. The Battelle-RDFs shall be considered oxygen-demand successes if the COD and BOD_5 values for Battelle-RDF 6-12 and 6-3 are between the COD and BOD_5 levels of KAc RDF and KAc-PG RDFs.

- Status: The success criteria were met because the Battelle-RDFs COD and BOD_5 values fell between the COD and BOD_5 levels of KAc RDF and KAc-PG RDFs. More details are provided in Sections 5 and 6.

3.4 CADMIUM CORROSION

- Relevance of objective: Longer Cd-plated aircraft (landing gear) and airfield (light system components) life is important to improve flight readiness and lower maintenance costs. Cd corrosion related costs were factored into the life-cycle cost projections.

- Metric description: Corrosion of cadmium-plated parts, in weight change $mg/cm^2/24$ hour.

- Data description: Each Battelle-RDF and the KAc RDF were subjected to the AMS 1435A cadmium corrosion test. The weight loss for each fluid was compared to both the established limit and to each other.

- Data analysis: Lower weight loss was related to reduced aircraft and airfield maintenance requirements and reflected in the cost-benefit analysis figures.

- Success criteria: If the weight loss of either Battelle-RDF is more than 50% lower than the KAc RDF weight loss, both fluids were considered superior. If the weight loss is no greater than with KAc RDF, then it would be considered acceptable. Both cases would constitute a success.

- Status: The success criteria were met because the weight losses of each Battelle-RDF were more than 50% lower than the KAc RDF weight loss; thus both fluids were considered superior. More details are provided in Sections 5 and 6.

3.5 CARBON-CARBON BRAKE PAD CORROSION

- Relevance of objective: A significant reduction in brake-pad corrosion, translating into longer braking system life, is an important objective in terms of increased flight readiness and lower maintenance costs. In prior economic analyses, this has been the most significant factor in the projection of lower life-cycle costs for the Battelle-RDFs.

- Metric description: Corrosion of carbon-carbon brake pad coupons, in weight loss percent.

- Data description: Each Battelle-RDF and the KAc RDF were subjected to the Honeywell carbon-carbon brake oxidation test. The weight loss for each fluid was compared to the others.

- Data analysis: Lower weight losses were related to reduced aircraft brake-system maintenance requirements and reflected in the cost-benefit analysis figures.

- Success criteria: If the weight loss of either Battelle-RDF is more than 50% lower than the KAc RDF weight loss, the fluid would be considered superior. If it is no more corrosive, then it would be considered acceptable. Both cases would be considered a success.

- Status: The success criteria were met because the weight losses of both Battelle-RDFs were up to 50% lower than the KAc RDF weight loss (as measured by the Meggitt or Honeywell tests); thus both Battelle fluids were considered superior. More details are provided in Sections 5 and 6.

The previous environmental, cadmium-corrosion, and brake-pad corrosion quantitative performance measures were determined via laboratory testing, following established test protocol, during the SERDP program. The following quantitative field measures were conducted on full-scale equipment on the runway at WPAFB.

3.6 ANTI-ICING FRICTION VALUES

- Relevance of objective: An anti-iced surface must retain a high degree of friction to allow the aircraft to land safely without skidding or sliding off the runway. Therefore, assurance that the friction values are high is critical to a successful demonstration.

- Metric description: The friction coefficient expressed in terms of the Runway Condition Rating (RCR) was used to assess whether the objective was met.

- Data description: The Battelle-RDF was applied by one truck on the test surface. Simultaneously, KAc RDF was applied by a second truck onto a similar section of dry runway, under similar meteorological (temperature, wind, time of day, etc.) conditions. Water from a third truck was applied to the surface to simulate freezing precipitation. Data on runway friction, or slipperiness, was determined using a BOWMONK AFM2 de-accelerometer operated by staff of the 88th Air Base Wing. The truck was driven along the treated airfield and, when the brakes were applied, an RCR number was generated. The process was repeated every few hundred yards to generate multiple measures of the surface slipperiness during each test. Note: An average RCR value of >20 is categorized as "good," 13-19 as "fair," 6-12 as "poor," and 0-5 as "Nil" (no braking efficiency).

- Success criteria: The RCRs determined at multiple sections of the runway were accumulated and the estimated true mean and 95% confidence intervals for all three fluids were calculated. The Battelle-RDFs' confidence intervals were compared to the KAc RDF confidence interval. If the Battelle-RDF interval was higher than the KAc-RDF interval with no overlap, it was considered superior or, if the two intervals overlapped, then the Battelle-RDF was considered acceptable and the test a success. If the Battelle-RDF interval was lower than the KAc-RDF interval (with no overlap), then the Battelle-RDF fluid was considered inferior.

- Status: The success criteria were met because the confidence intervals for both Battelle-RDFs overlapped the KAc RDF confidence interval. More details are provided on these demonstration tests in Sections 5 and 6.

3.7 ANTI-ICING HOT

- Relevance of objective: RDFs are applied to deice or anti-ice runways and taxiways after (deicing) or prior to the arrival of ice and snow (anti-icing). Maintaining a snow- and ice-free surface is the primary function of an RDF.

- Metric description: The HOT, in minutes, was the metric that was used. It represented the time the airfield was considered ice and snow-free after application due to the melting action of the RDF.

- Data description: The test data collected during the anti-icing friction test (described above) were plotted and the time when the RCR values would reach a value of 9 (midpoint of the "poor" airfield friction RCR rating) was obtained. The minutes the surfaces remain suitable for aircraft traffic was determined.

- Success criteria: The HOT on the runway was calculated. If the Battelle-RDF HOT confidence interval was equal to or higher than the KAc HOT confidence interval then the Battelle-RDF was considered acceptable and the test a success.

- Status: The success criteria were met because the anti-icing HOT confidence interval for each Battelle-RDF overlapped the corresponding KAc RDF HOT confidence interval. More details are provided on these demonstration tests in Sections 5 and 6.

3.8 DEICING MELTING EFFICIENCY

- Relevance of objective: RDFs are applied to deice ice or snow-covered runways to melt the ice. Therefore, showing the ability of an RDF to melt ice quickly is a critical factor in a successful demonstration.

- Metric description: the melt efficiency, the time in minutes to melt through a fixed depth of ice or packed snow at a fixed RDF dosage, is the metric that was used.

- Data description: The surface was coated with water and allowed to freeze to a thickness of ~¼ inch. On subsequent days, each RDF was applied under similar meteorological (e.g., ice and snow thickness, temperature, wind) conditions, using similar dosage levels to the surface and allowed to work until the ice has de-bonded from the runway surface. Airfield staff assessed the times to melt through to the runway surfaces.

- Success criteria: If the time for the Battelle-RDFs to melt ice was faster, they would be considered superior. If they required an equal amount of time, then the Battelle-RDFs would be considered comparable. Both conditions would constitute a success.

- Status: the success criteria were met because the time-to-melt intervals for both Battelle-RDFs were comparable. More details are provided on these demonstration tests in Sections 5 and 6.

3.9 DEICING FRICTION VALUES

- Relevance of objective: A deiced surface must retain a high degree of friction to allow the aircraft to land safely without skidding or sliding off the runway. Therefore, assurance that the friction values are high is critical to a successful demonstration.

- Metric description: The friction coefficient expressed in terms of the RCR was used to assess whether the objective was met.

- Data description: The airfield was iced and coated with RDF as noted above. After the ice-to-surface bond was broken, airfield mechanical brooms were passed over the surface to remove all ice. Then data on runway friction were collected using the BOWMONK AFM2 de-accelerometer. The process was repeated every few hundred yards to generate multiple measures of the surface slipperiness during each test.

- Success criteria: The RCRs were accumulated and the estimated true mean and 95% confidence intervals calculated. The Battelle-RDF intervals were compared to the KAc RDF interval. If the Battelle-RDF confidence interval is higher than the KAc-RDF interval with no overlap, it was considered superior or, if the two intervals overlapped, the Battelle-RDF was considered acceptable and the test a success. If the Battelle-RDF interval was lower than the KAc-RDF interval (with no overlap), the Battelle-RDF fluid would be considered inferior.

- Status: The success criteria were met because the RCR intervals for both Battelle-RDFs overlapped the KAc RDF interval. More details are provided on these demonstration tests in Sections 5 and 6.

3.10 EASE OF USE

- Relevance of objective: For the Battelle-RDF to be accepted into DoD service, it should be usable as a drop-in replacement for KAc RDF.

- Metric description: Qualitative 1 through 10 ratings were generated by 88th Air Base Wing (ABW) staff and other knowledgeable observers. Each rater assessed both the KAc RDF and each Battelle-RDF. Areas of interest included filling, fluid application, and smell.

- Data description: The average ease-of-use rating for KAc RDF was computed. Then the average rating of each Battelle-RDF was determined.

- Success criteria: If the rating number of each Battelle-RDF is higher, or falls within 2 digits of the KAc RDF rating, the fluid was deemed a success. For example, if the average KAc RDF rating was 6, then a Battelle-RDF rating of 6 ± 2 (4 or higher) would constitute a successful fluid.

- Status: The success criteria were met because the ease of use intervals for both Battelle-RDFs overlapped the KAc RDF interval. More details are provided on these demonstration tests in Sections 5 and 6.

3.11 MAINTENANCE

- Relevance of objective: For the Battelle-RDF to be accepted into DoD service, it should not significantly increase user maintenance requirements.
- Metric description: Qualitative 1 through 10 ratings were generated by 88^{th} ABW staff and other knowledgeable observers for KAc RDF and each Battelle-RDF. Areas of interest included obvious corrosion/ deterioration of pumps, valves, seals, or fittings and the need for equipment modifications to facilitate use.
- Data description: The average maintenance ratings for KAc RDF were computed. Then the average rating for each Battelle-RDF was determined.
- Success criteria: If the rating number of each Battelle-RDF is higher, or falls within 2 digits of the KAc RDF rating, the fluid was deemed a success.
- Status: The success criteria were met because the ease-of-maintenance intervals for both Battelle-RDFs overlapped the KAc RDF interval. More details are provided on these demonstration tests in Sections 5 and 6.

4.0 FACILITY/SITE DESCRIPTION

WPAFB was chosen for this demonstration for four reasons:

1. Weather: Winter weather has cold temperatures with adequate snow and icy precipitation.

2. Facilities: Suitable test runways, deicing equipment, and trained RDF technicians were available.

3. Operations staff: WPAFB has an airfield operations crew that was enthusiastic about participating in the demonstration.

4. Air Force deicing expertise: WPAFB houses staff members from the ASC and AFRL, who have the Air Force responsibility to advise on aircraft and runway deicing technologies and operations.

4.1 FACILITY/SITE LOCATION AND OPERATIONS

WPAFB is located in Greene and Montgomery counties, eight miles northeast of the central business district of Dayton, Ohio, United States. Part of the base is located along the city limits of Riverside and is also adjacent to Fairborn and Beavercreek. The base is named after the Wright brothers, who used the Huffman Prairie portion of what became Wright-Patterson as their testing ground, and Frank Stuart Patterson (son and nephew of the co-founders of National Cash Register) who was killed on June 19, 1918, in the crash of his Airco DH.4 at Wilbur Wright Field.

WPAFB is the headquarters of the Air Force Materiel Command, one of the major commands of the Air Force. “Wright-Patt” (as the base is colloquially called) is also the location of a major USAF Medical Center (hospital), the Air Force Institute of Technology, and the National Museum of the United States Air Force, formerly known as the U.S. Air Force Museum.

It is also the home base of the 445th Airlift Wing of the Air Force Reserve Command, an Air Mobility Command unit that flies the C-5 Galaxy heavy airlifter. WPAFB is also the headquarters of the Aeronautical Systems Center (ASC) and the Air Force Research Laboratory (AFRL) [13]. From the 2008 Base Economic Impact Analysis, WPAFB has a total of 25,713 military, civilian, and contractor employees, an increase of almost 900 employees compared to 2007 numbers [14].

WPAFB has two major runways; Figure 5 is a photo of the airfield circa 2000. These runways support all types of aircraft from C-5 Galaxy heavy cargo aircraft to commercial Boeing 747s. The long runway is made of concrete and is 12,000-ft long by 300-ft wide. The short runway consists of an asphalt overlay and is 7,000-ft long by 150-ft wide. Testing sites were available on the 2,600-ft out-of-service portion of the long runway. No aircraft were used in the testing as this would have required extensive approvals and was not required for successful demonstration.

Currently the airfield uses two types of runway deicers: liquid KAc and solid sodium acetate (NAAC).

During the Fall 2007 to Spring 2008 deicing season, 14,200 gal of KAc and 90 metric tons of NAAC were used. Battelle-RDF was transferred from the 250-gallon shipment totes into one of WPAFB's RDF spray tankers for the demonstration.

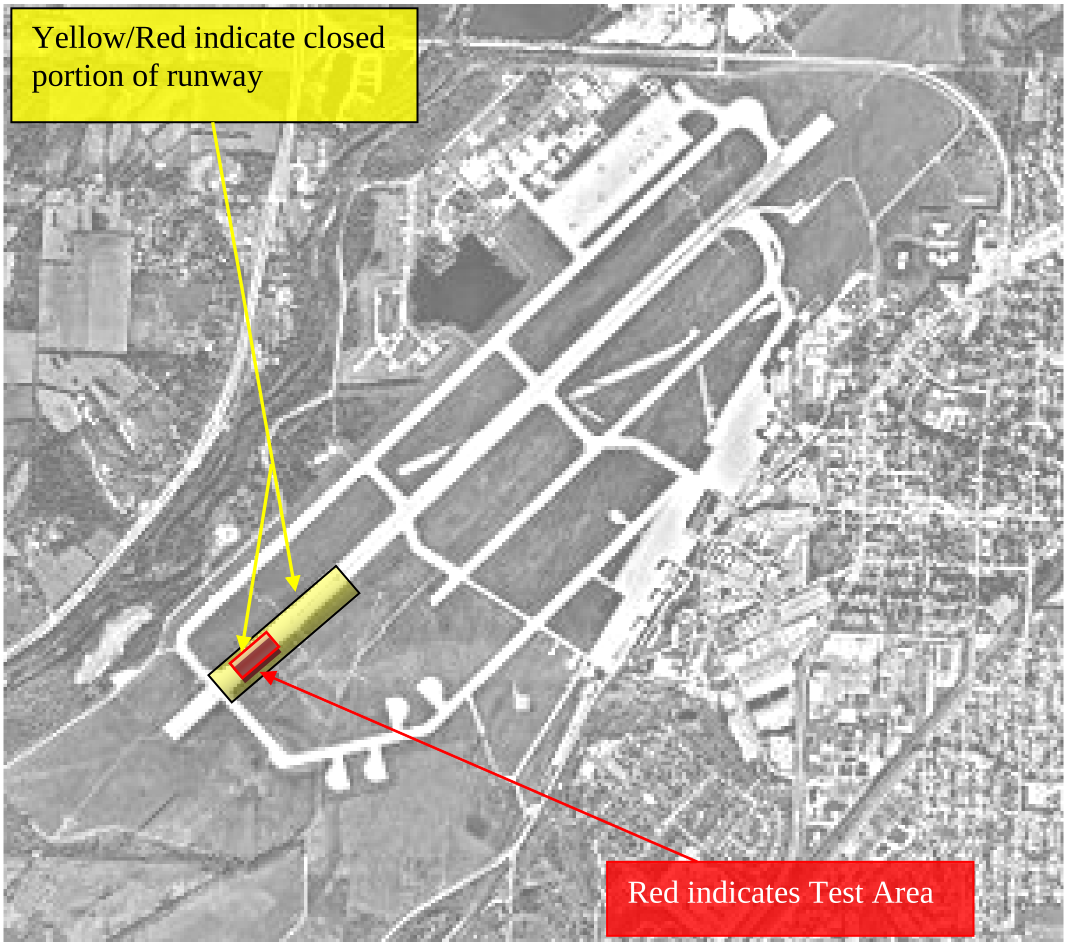


Figure 5. WPAFB Airfield Showing Sites for Demonstration Testing
[Reference 13]

Testing was performed at WPAFB following Air Force Instruction (AFI) 32-1002 "Snow and Ice Removal," [15]. It stipulated that installations with over 6 inches average annual snowfall maintain a Snow and Ice Control Plan (S&ICP) and form a Snow and Ice Control Committee. The S&ICP is tailored to meet local needs. It includes snowfall history, equipment and attachment inventory, equipment plowing patterns, team composition, materials and parts levels, and color-coded maps. Details on how the AFI and the S&ICP were implemented are provided in a subsequent section.

4.2 FACILITY SITE CONDITIONS

The weather in the Dayton area, and nearby WPAFB, in January and February is cold. The area receives several inches of precipitation as shown in Table 4. The base also typically receives several inches of snow as noted in Table 5.

Table 4. 2008/2009 Weather Conditions for Dayton Ohio [16]

Dayton Statistics	Nov	Dec	Jan	Feb	Mar
Temperature mean value, °F	43	32	26	30	41
High temperature mean value, °F	51	39	34	38	50
Low temperature mean value, °F	34	24	18	21	31
Precipitation mean monthly value, inches	3.2	3.1	2.2	2.3	3.6

Table 5. 2008/2009 Snowfall at WPAFB [17]

Winter Season, Start and End Year	WPAFB Snowfall, Monthly Value, inch [(a)]				
	Nov	Dec	Jan	Feb	Mar
2000-2001	0.1	9.3	1.5	2.0	0.8
2001-2002	0.0	1.8	4.5	1.5	1.9
2002-2003	1.8	4.6	10.1	15.7	0.3
2003-2004	0.0	2.9	3.2	0.9	7.0
2004-2005	0.0	14.9	4.6	2.5	1.2
2005-2006	1.7	7.6	0.4	1.2	3.0
2006-2007	0.0	0.0	2.8	8.5	0.0
2007-2008	0.0	6.1	1.3	9.1	14.0
2008-2009	0.0	0.0	13.8	0.4	0.0

(a) These figures depict snowfall levels and do not reflect rain or freezing rain requiring snow and ice control actions.

These conditions were suitable for an RDF demonstration. Conditions requiring both deicing and anti-icing were encountered during the demonstration period.

4.3 FACILITY APPROVALS

The tests followed AFI 32-1002; more specifically, the WPAFB S&ICP. AFI 32-1002 dictated the management team and the approval process. The plan was followed to get approval from the airfield owner, the Air Force Civil Engineering Support Agency (AFCESA), and the environmental office. Because the fluid was not used on an active runway, approval of the aircraft single managers was not required.

Dr. Craig Rutland, the US Air Force Pavement Engineer, and airfield surface expert from AFCESA, reviewed the proposed test plan and approved the demonstration.

Ms. Karen Beason from the 88th ABW environmental office reviewed the plan and prepared an Air Force Form 813 entitled “Preliminary Environmental Impact Analysis.” After consideration of the fluid environmental properties, the airfield RDF demonstration program was approved.

This page intentionally left blank.

5.0 TEST DESIGN

5.1 CONCEPTUAL TEST DESIGN

On a series of cold, wintery days in 2010, when temperatures were below freezing, water was applied to simulate ice storm conditions. Two WPAFB liquid deicing trucks spread the test RDFs across the parallel test areas. Anti-icing and deicing performance data were collected. Results for the Battelle-RDFs were compared to the performance of commercial liquid KAc runway deicing fluid (the RDF currently used at the base) under similar snow/ice/temperature conditions on adjacent sections of the closed runway at the WPAFB airport to assess relative effectiveness.

5.2 BASELINE CHARACTERIZATION

AFI 32-1002 provided directions for runway deicing and anti-icing practices and this served as the baseline operating conditions. The closed section of runway R-23, the 12,500-ft long runway, was selected as the single test site to demonstrate RDF performance. The available test section was 300-ft wide by 2,600-ft long; see Figure 5 presented earlier.

Tests followed AFI 32-1002 and more specifically the WPAFB S&ICP. The AFI provided guidance on the type of deicing chemical to be used and dosage rates (i.e., gal of liquid deicer per thousand square feet) as a function of operation (deicing versus anti-icing) and ice thickness; see Table 6 below.

Table 6. Suggested Potassium Acetate-Based RDF Dosage Rates in Kilograms Per 100 Square Meters (Gallons Per 1,000 Square Feet)
Reference [15]: AFI 32-1002 Table A2.4

Ice Thickness	Pavement Temperature		
	-1.1 °C (30 °F)	**-3.9 °C (25 °F)**	**-6.7 °C (20 °F)**
Less than 0.8 mm (1/32")	0.44 (0.9)	0.59 (1.2)	0.88 (1.8)
0.8 mm to 3.2 mm (1/32" to 1/8")	0.59 (1.2)	0.88 (1.8)	1.46 (3.0)
3.2 mm to 6.4 mm (1/8" to 1/4")	0.88 (1.8)	1.32 (2.7)	2.93 (6.0)

NOTE: When freezing conditions are expected, potassium acetate may be used as an anti-icer at the rate of 2 liters per 100 square meters (0.5 gallons per 1,000 sq ft).

As noted, the anti-icing dosage is ~0.5 gal/1000 ft^2. Deicing dosage depends on both ice depth and temperature, but is typically 2 gal/1000 ft^2. However, to provide an exact comparison on anti-icing and deicing effectiveness, side-by-side tests of Battelle-RDF and KAc RDF were conducted for anti-icing, using the prescribed RDF dosage. For deicing, testing were conducted using constant deicer dosage rates.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

5.3.1 Demonstration Set-Up

Prior to arriving at WPAFB, Battelle-RDFs 6-12 (1,000 gal) and 6-3 (3,000 gal) were manufactured by a toll producer under Battelle supervision. Table 7 shows the composition of each of these formulations and Figure 6 shows photos from the formulation and filling operations.

Table 7. Composition of Test RDFs

	Designation		
Additive	**RDF 6-12 Prepared from Biodiesel By-Product**	**RDF 6-3 Prepared from Pure Bio-based Material**	**KAc RDF**
Freezing Point Depressants Mixture	55.4%	58.4%	50%
Additives	0.8%	3.0%	~1%
Water	43.8%	38.6%	49%
pH	10.7	10.8	10.6

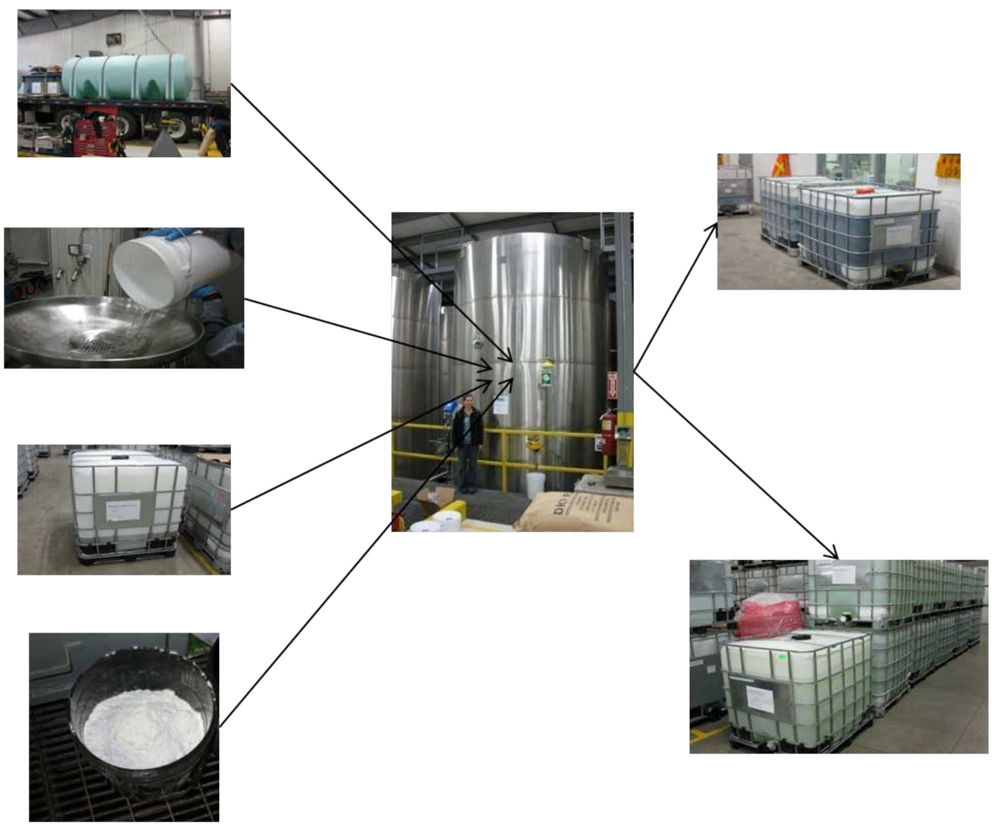


Figure 6. Battelle-RDF Formulation and Filled Totes

Left column (top to bottom): aqueous KAc solution, liquid additives, bio-based fluids, solid additives
Middle: mixing tank where ingredients were combined
Right column (top to bottom): RDF 6-12 (deep blue color), RDF 6-3 (uncolored RDF)

The Battelle fluid was delivered to the WPAFB airfield in sixteen, 250-gal poly totes. They were logged into the base Pharmacy. The ABW staff transferred two totes of each Battelle-RDF fluid and placed them inside a Battelle-supplied secondary containment berm. The commercial KAc RDF (E36® manufactured by Cryotech) used at WPAFB was supplied by the ABW for comparison testing.

5.3.2 Period of Operation

The demonstration was originally planned for a 5-day period in January 2010. However, actual testing was done in two phases. The side-by-side anti-icing tests were conducted on 12 and 13 January 2010. The deicing tests were conducted on 29 January and 26 February 2010.

5.3.3 Amount of Material Tested

Four thousand gallons of the two Battelle-RDFs were manufactured for the demonstration. Approximately 500 gal of each RDF was used in the anti-icing and deicing demonstrations.

5.3.4 Residuals Handling

RDF was sprayed on the runway to melt snow, ice, or frost. All of the fluid evaporated with little or no flow into wastewater drains. The small amount that may have made it to the collection drains was sent to the Dayton, OH, publically-owned treatment works for wastewater treatment.

Rinse waters from the RDF truck, generated from cleaning between different brands of RDF fluids were discharged into the hangar wastewater collection system.

5.3.5 Operating Parameters for the Technology

The test objective was to demonstrate that Battelle-RDFs 6-12 and 6-3 were as effective as commercial KAc RDFs in airfield anti-icing and deicing. Quantitative data and qualitative observations were collected to establish that the RDFs were as effective, were as easy to use, and had similar maintenance requirements.

5.3.6 Experimental Design

Prior to proceeding with the demonstration at WPAFB, both Battelle-RDFs passed all AMS 1435A certification testing. A “Fluid Qualification Report” was supplied to the base to document successful completion of all requirements [18].

The demonstration used Battelle-RDF 6-12 and 6-3 on the closed section of the long runway. To verify the laboratory runway anti-icing and deicing performance, a demonstration procedure used in prior full-scale RDF testing procedure developed by Battelle and Basic Solutions (an RDF vendor) was employed. The two Battelle fluids were evaluated for (a) anti-icing and (b) deicing at WPAFB. Two RDF fluid distribution “Batts Deicer Pro Series” trucks were used. The 750-gal capacity T-750 truck was filled with 500 gal of Battelle-RDF. The 1,100-gal capacity T-1100 sprayer was filled with 500 gal of the base-procured, standard KAc RDF (Cryotech E-36). Note: These trucks were calibrated at the beginning of the deicing season. The trucks use an application computer to automatically correct for speed in order to provide uniform gallon per thousand square feet coverage.

Table 8 lists the personnel involved in the demonstration and their roles and responsibilities.

Table 8. Job Descriptions and Responsibilities During Field Demonstration

Job Title	Assignee and Organization	Responsibilities
Principal Investigator (PI)	Mary Wyderski (AF/ASC)	Project manager responsible for all project deliverables. Coordinated all demonstration activities. Led kick-off and wrap up meetings each day.
Demonstration supervisor	Nick Conkle (Battelle)	Observed and documented findings. Filled out datasheets. Attended kick-off and wrap up meetings each day. Documented test procedures and findings.
Test support	Melissa Roshon and Kevin Rose (Battelle)	Collected observation data, filled out datasheets. Attended kick-off and wrap up meetings each day. Supported report preparation.
88th ABW demonstration coordinators	William Kassinos, Michael Patterson, and Jim Tufano (AF/88th ABW)	Coordinated 88th ABW demonstration activities and logistics. Filled out qualitative assessment. Assigned 88th ABW personnel their duties that day. Attended kick-off and wrap up meetings each day.
Deicing truck operator	Brian Robinson, Joseph Pugh, Derik Harlow, Tim Schwab Joe Fletcher, Jesse Pierson (AF/88th ABW)	Operated Batts deicing truck; aided in deicing fluid transfer; cleaned out the truck before and after demonstration; completed qualitative datasheet.
Friction measurement operator	Rome Alcantara (AF/88th ABW)	Operated Friction Test Unit and reported Runway Condition Rating (RCR); completed qualitative datasheet; attended kick-off and wrap up meetings each day.
Materials advisor	Elizabeth Berman (AFRL)	Observed operation with special attention to special materials; attended kick-off and wrap up meetings each day.
Runway advisor	Benny Preston (AFCESA)	Observed operation with special attention on airfield pavement impact; attended kick-off and wrap up meetings each day.
RDF advisor	Kelvin Williamson (Basic Solutions)	Assisted in testing based on experience gained as a RDF user and vendor
RDF advisor	Charles Ryerson (CRREL)	Observed operations with special attention to Army RDF issues.
Program support	Don Tarazano (SAIC)	Assisted PI; documented testing; attended kick-off and wrap up meetings each day.
Demonstration photographer and videographer	Melissa Roshon and Kevin Rose (Battelle)	Visually documented testing; attended kick-off and wrap up meetings each day.
Environmental advisor	Thomas Lorman (ASC/ENV)	Observed operation with special attention to environmental issues; attended kick-off and wrap up meetings each day.
Others	Grey Earley, William LaFountain, and Mike Sanders (AF)	Observed operations with special attention to Air Force Materiel Command issues.

Table 9 lists equipment requirements, purposes, operators, and suppliers used in the demonstration. All RDF fluids were used full strength.

Table 9. Required Equipment

Equipment	Purpose	Supplied by	Operated by
1,000 gallons of RDF 6-12 and 3,000 gal of RDF 6-3	Test fluids	Battelle	NA
1,000 gal of KAc RDF	Test fluids	WPAFB	NA
Runway deicing sprayers (Batts T-1100 and T-750; 1100-gal unit for KAc and the 750 gal unit for Battelle-RDFs)	Deicing fluid application	WPAFB	WPAFB staff
Friction tester (BOWMONK AFM2) and truck	Friction assessment	WPAFB	WPAFB staff
Observation truck	For airfield access to observe and measure deiced surface properties	WPAFB	WPAFB staff
Clipboards, pens, datasheets, other miscellaneous supplies	Document demonstration	Battelle (small items, such as tape and pens, may be supplied as needed by the base)	All observers
Secondary containment for fluid storage on base	Contain fluid in the unlikely event of a spill	Battelle	NA
Forklift	Gravity transfer of fluids to truck	WPAFB	WPAFB staff
Video, digital, and still photography equipment	Demonstration documentation	Battelle	Various AF and Battelle staff
Snow/ice characterization equipment (scale, ruler, thermometer, volumetric container, etc.)	Measure properties of snow and/or ice	Battelle	Battelle
Magnetic placards (2 for 6-12, 2 for 6-3, and 2 for KAc)	Attached to either side of each RDF truck to identify the fluid in each truck	Battelle	NA

5.3.7 Demobilization

Residual Battelle-RDFs in the Batts trucks were drained and sent to the base wastewater collection drain. The tanks on the trucks were filled with water and flushed into the drain at the hangar. Following cleaning, the tanks were refilled with KAc RDF to prepare the truck for normal usage.

At the conclusion of the demonstration, the remaining Battelle-RDFs were shipped back to the toll producer.

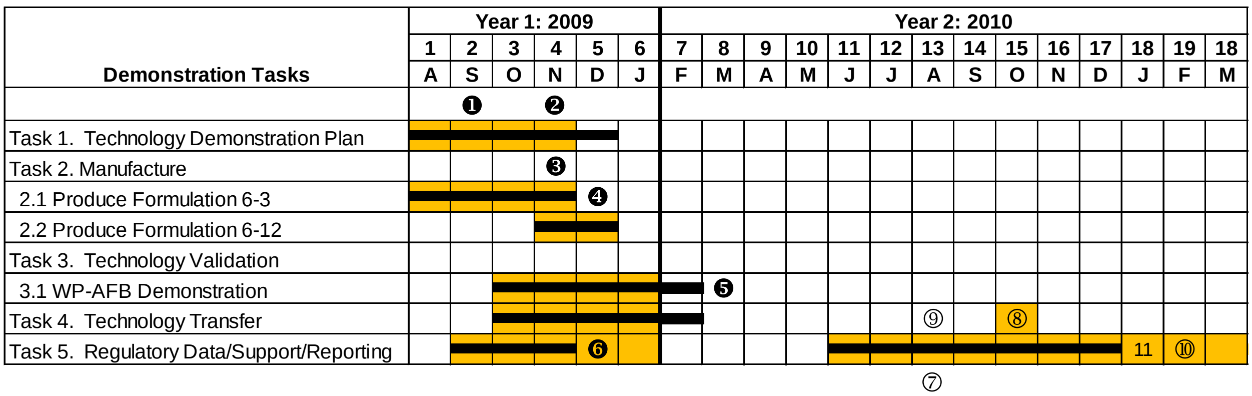
5.4 OPERATIONAL TESTING

5.4.1 Program Scope

The project included the following five tasks:

- Task 1: Technology Demonstration Plan.
- Task 2: RDF Manufacture.
- Task 3: Technology Validation.
- Task 4: Technology Transfer.
- Task 5: Regulatory Data/Support.

Figure 7 contains the overall program schedule and list of milestones. The technical approach for each of these tasks is described below.



Year 1 Milestone No.	Time, mo.	Year 2 Milestone No.	Time, mo.
1. Draft Dem/Val Plan	Completed	7. Draft Cost and Performance Report	Completed
2. Final Dem/Val Plan	Completed	8. Final Cost and Performance Report	30-Oct-10
3. Manufacturing protocol finalized	Completed	9. Draft Final Report	Completed
4. RDFs Produced	Completed	10. Final Report	1-Feb-11
5. Demonstration Test Completed	Completed	11. Final Briefing	1-Feb-11
6. Regulatory Review	Completed		

Figure 7. Revised Project Schedule

Task 1: Technology Demonstration Plan

A Technology Demonstration/Validation (Dem/Val) Plan, based on the ESTCP Sustainable Infrastructure, Facilities and Energy Projects, was prepared to communicate and guide all aspects of the manufacturing and field-testing activities [19]. This document established the objectives, test site activities, sampling and analysis requirements, data collection and analysis requirements, technical performance criteria, economic performance criteria, and quality assurance plans. The Demonstration Plan addressed both general DoD and site-specific issues.

Task 2: RDF Manufacture

In November and December 2009, Battelle manufactured 4,000-gallons of Battelle-RDF (3,000 gallons of Battelle-RDF 6-3 and 1,000 gallons of Battelle-RDF 6-12) for the demonstration. The fluids were stored in 250-gal totes. Battelle performed several QA tests (specific gravity and pH) to make sure the formulations were correct. The totes were delivered to WPAFB on 6 January 2010.

Both formulations were certified per AMS 1435A during the SERDP project, "Development of an Environmentally Benign and Reduced Corrosion Runway Deicing Fluid," SI-1535.

Task 3: Technology Validation

Ease of use, effectiveness, and compatibility with RDF deicing equipment were verified in this task. A single 1-week field trial was originally planned to conduct the field tests at WPAFB. However, due to the weather, the anti-icing tests were conducted in January and the deicing tests in late January and February 2010. Table 10 notes the time periods when the on-site WPAFB demonstration tests were conducted.

Table 10. Test Periods

Demonstration Efforts	Time Period (2010)
Anti-Icing	
6-3 vs. KAc	12 January
6-12 vs. KAc	13 January
Deicing	
6-3 vs. KAc	29 January
6-12 vs. KAc	26 February

The results of Tasks 2 and 3 were used to assess the Battelle-RDF life-cycle cost for deploying the bio-based RDF for military applications. The results are summarized in Section 7 of this report and described in greater detail in the Cost and Performance Report [20].

Task 4: Technology Transfer

The manufacturing technology is covered under Battelle patents (7,169,321; 7,105,105; and 7,048,871). Battelle and its potential commercialization partners worked with Air Force, Army, and Navy staff to maximize synergy within the DoD.

Results by organization are noted below:

1. Air Force:
   - Presented demonstration plan to Deicing Workshop
   - Presented data package to AFCESA for review and inclusion in AFI 32-1002.

2. Army: Briefed CRREL staff.
3. Navy: Determined there was no need for RDF as most naval installations are located near the ocean and RDF is not required.

Results of the runway deicing tests were published (numbers 1 through 4) or will be published (number 5) at the following forums to assist in the full-scale implementation of the technology:

1. Air Force Material Command Deicing Workshop, presentation, Dayton OH, 18 November 2009. [21]

2. ESTCP Partners in Environmental Excellence, poster session, Washington, DC, December 2009. [22]

3. SAE G-12 Aircraft Ground Deicing Fluids Subcommittee presentation, “Demonstration of Battelle-RDFs/ Basic Solutions Gen3 RDFs,” Berlin, Germany, May 2010. [23]

4. SAE G-12 Aircraft Ground Deicing Fluids Subcommittee presentation, “Gen3 – Airport Results 2009/2010,” Berlin, Germany, May 2010. [24]

5. International Conference on Aircraft and Engine Icing and Ground De-Icing, “Laboratory Testing and Field Demonstration of an Environmentally Benign and Reduced Corrosion Runway Deicing Fluid,” Chicago, Illinois USA, June 13-17, 2011.

Task 5: Regulatory Data/Support/Reporting

Ms. Wyderski, with the support of the SAIC representatives and Battelle, engaged the appropriate Program Managers, Base Managers, etc., at the outset of the project to gather their support so as to assure acceptance. They delivered a Fluid Qualification Report including independent laboratory test sheets showing that the two test fluids meet the AMS 1435A requirements, an MSDS for each fluid, and a draft demonstration test plan. Communications with test site environmental managers and risk management staff assured compliance with all regulatory requirements. No special exemptions or treatability study exemptions were required. The data generated by the testing provided the quantitative basis for communicating implementation plans with local and federal environmental agencies.

Reporting included preparation of ESTCP documents including the following:

1. Preparation of a milestone execution plan.

2. Submittal of information for the monthly financial reporting via the SERDP and ESTCP Management System (SEMS) web site.

3. Submittal of inputs for the quarterly technical and programmatic reports via SEMS.

4. Preparation of a Fact Sheet.

5. Participation in annual in-progress reviews in Arlington, VA.

6. Attendance at the annual ESTCP symposium in Arlington, VA.

7. Preparation of a draft and a Final Report per the ESTCP guidelines to summarize the demonstration plan, the activities, findings, and recommendations.

8. Preparation of a draft and final Cost and Performance Summary Report per the ESTCP guidelines to describe the technology, its advantages, cost for implementation, and techno-economic advantages.

9. Delivery of the Final Briefing in Washington, DC, as part of the ESTCP Conference on Partners in Environmental Technology Technical Symposium & Workshop.

The team also supplied documents noted in the Contract Data Requirements List to the AFCEE (Table 11).

Table 11. Contract Data Requirement List

Deliverable	Frequency	Year 1 Scope	Year 2 Scope
Project Planning Chart	Draft + Revisions + Progress and significant changes updated every 4 weeks	x	
CPSMR input	Every 4 weeks	x	x
Financial report input	Every 4 weeks	x	x
Presentation materials	Meeting minutes	x	x
Notification Requirements	Only as required	x	x
OSHA Reports	Only as required	x	x
Demonstration Plan	Draft + Revisions	x	
Fluid Qualification Report	Once	x	
Data Package	Once	x	
ESTCP Final Report	Draft + Revisions		x
ESTCP Cost and Performance Report	Draft + Revisions		x

5.4.2 Pre-Test Preparations

Prior to testing, the ABW staff performed the following pre-test steps:

- Emptied the Batts T-750 RDF sprayer trucks.
- Filled it with one tote of Battelle-RDF 6-3 (6-3 was selected because 3,000 gallons of this material were available); a hose to facilitate the transfer from the 250-gallon totes to the Batts truck was provided by Battelle.
- Attached a magnetic placard to the truck to designate it Battelle-RDF 6-3.
- Attached a magnetic placard to the conventional RDF truck to designate it KAc. The KAc RDF was placed in the Batts T-1100 sprayer truck.
- Collected a 1-L RDF sample from each truck; it was stored for further analysis (described later in section 5.6.1 of this report).

5.5 SAMPLING PROTOCOL

The two Battelle-RDFs were sampled after production and analyzed for specific gravity and pH per AMS 1435A to make sure the formulations were correct.

Multiple 100-mL samples were collected from the Battelle-RDF totes and analyzed at the toll-producer site for specific gravity and pH. Samples were collected from the Battelle-RDFs and KAc RDF deicing trucks during the fluid demonstration.

In addition, test data such as date, time, meteorological conditions, and application information were collected; a detailed discussion of anti-icing and deicing is presented in Section 5.6.5. Table 12 shows the protocol for extracting the quantitative performance data, including ice melting time, friction, and hold over time.

Qualitative data on ease of use and maintenance were also collected and are discussed in more detail in Section 5.6.6.

Table 12. Quantitative Data Collection Protocol

Test Type	Parameter	Parameter Description	Test Preparation	Collection Protocol
Anti-Icing	Hold Over Time (HOT)	Time surface remains suitable for aircraft landing	On two adjacent sections of runway, apply Battelle-RDF and KAc RDF during simulated ice storm (by applying water spray to the below freezing runway surface).	Collect RCR data using a de-accelerometer [(a)] Calculate HOT as the time from start of water application to time RCR falls below acceptable limits.
	Runway Condition Rating (RCR)	Measure of runway friction/suitability for landing		Collect RCR data.
Deicing	Melt time	Time to melt the ice to create an acceptable runway surface	On two adjacent sections of runway, apply water spray to make uniform iced runways. Apply Battelle-RDF and KAc RDF	Collect RCR data. Calculate melt time as the time required to transform the iced runway into one suitable for landing (based on RCR)
	RCR	Measure of runway friction/suitability for landing		Collect RCR data. Compare RCR data for the two RDFs

(a) BOWMONK AFM2 de-accelerometer was operated by staff of the 88th Air Base Wing. The truck was driven along the treated airfield and when the brakes were applied an RCR number was generated. The process was repeated every few hundred yards to generate multiple measures of the surface slipperiness during each test. Note: an average RCR value of >20 is categorized as "good," 13-19 as "fair," 6-12 as "poor," and 0-5 as "Nil" (no braking efficiency).

5.5.1 Calibration of Equipment

Prior to pH determinations, the Mettler-Toledo “Seven Go” pH meter was calibrated with a standard pH 10 buffer solution. Prior to specific-gravity determination the Mettler Toledo “Densito 30PX” instrument was calibrated with water at 60 ºF.

The application “dosage” rates of the RDF spray trucks (Batts Deicer Pro series T-750 and T-1100 sprayers) were calibrated at the beginning of the deicing season. The application rate was automatically corrected for speed to allow uniform gal/1000 ft^2 coverage regardless of the speed of the RDF truck.

The BOWMONK AFM2 friction tester was also calibrated at the beginning of the deicing season. Effective friction values were reported in terms of RCR.

5.5.2 Quality Assurance Sampling

Samples of each Battelle-RDF were collected and noted in a Battelle Laboratory Record Book (LRB). The samples were labeled with the sample designation (e.g., Battelle-RDF 6-12) along with the page number and line number. They were analyzed at the toll-production site for specific gravity and pH, for each lot, per the AMS 1435A required quality assurance program. Results were noted in the LRB.

A 1-L sample each of Battelle-RDF 6-12 and Battelle-RDF 6-3 were collected from the RDF truck. A 4-L sample of KAc was collected from the KAc-RDF deicing truck used during the tests. A chain-of-custody form was completed for these samples and placed in the sample-collection box. The box and the form were transported back to Battelle for analysis.

5.5.3 Sample Documentation

A product label was attached to each 250-gal tote of Battelle-RDF. In addition, each individual collection bottle was labeled with the sample designation (LRB page and line number) and the date.

A magnetic placard was attached to each deicing truck to allow easy identification of the RDF being applied.

All data were entered into a Battelle LRB.

Photographs and video were taken by Battelle and WPAFB staff and transferred to CDs and DVDs for permanent storage.

5.6 SAMPLING RESULTS

5.6.1 pH and Specific Gravity

The RDF samples were analyzed at the toll-producer site for specific gravity and pH; see Table 13. Battelle-RDFs and KAc RDF samples were also collected from the deicing trucks during the fluid demonstration task.

Table 13. Liquid RDF Samples Collected and Analyzed

Designation	Samples Collected During Fluid Formulation		
		Specific gravity, g/mL	**pH**
Battelle-RDF 6-12		1.256	10.86
Battelle-RDF 6-3		1.258	10.89
Designation	**Samples Collected During Field Demonstration**		
	Sample No. [(a)]	**Specific Gravity, g/mL**	**pH**
Battelle-RDF 6-12	52833-15-26	1.26440	10.74
Battelle-RDF 6-3	52833-83-28	1.26699	10.81
Cryotech E36 KAc RDF	52833-15-28	1.28669	10.59

(a) Lab record book number - page number - line number.

The results show that the fluid properties remain within the acceptable ± 0.5 pH units and ± 0.015 specific gravity units.

5.6.2 Acute Aquatic Toxicity

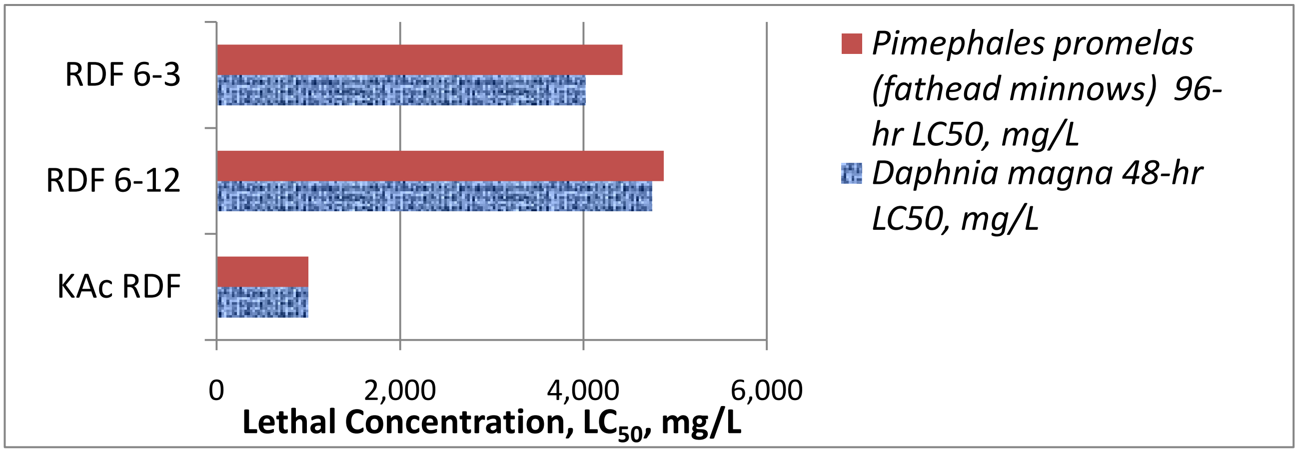
The RDF samples were analyzed by SMI Inc., as part of the AMS 1435A certification executed during the SERDP project, for acute ecotoxicity [3]. It was not necessary to repeat the certification testing for this ESTCP project. The LC_{50} concentration, the highest concentration in mg/L at which 50% of the test species die, was determined for two species:

- EPA 40 CFR 797.1300 Daphnid Acute Toxicity; *Daphnia magna* (water fleas) 48-hr LC_{50}
- EPA 40 CFR 797.1400 Fish Acute Toxicity; *Pimephales promelas* (fat minnows) 96-hr LC_{50}

Results are shown in Table 14 and graphically in Figure 8. The higher LC_{50} values for the two Battelle-RDFs, compared to the KAc-RDF, indicate that the Battelle-RDFs have a lower acute toxicity.

Table 14. Acute Toxicity Results

Sample	***Daphnia magna*** **(water flea) 48-hr LC_{50}, mg/L**	***Pimephales promelas*** **(fathead minnows) 96-hr LC_{50}, mg/L**
Commercial Acetate RDF	1,000 (Typical)	1,000 (Typical)
RDF 6-12	3,275	4,325
RDF 6-3	4,025	4,425



Note: Higher LC_{50} numbers correspond to lower toxicity

Figure 8. Acute Toxicity of Battelle-RDFs Shows Lower EcoToxicity

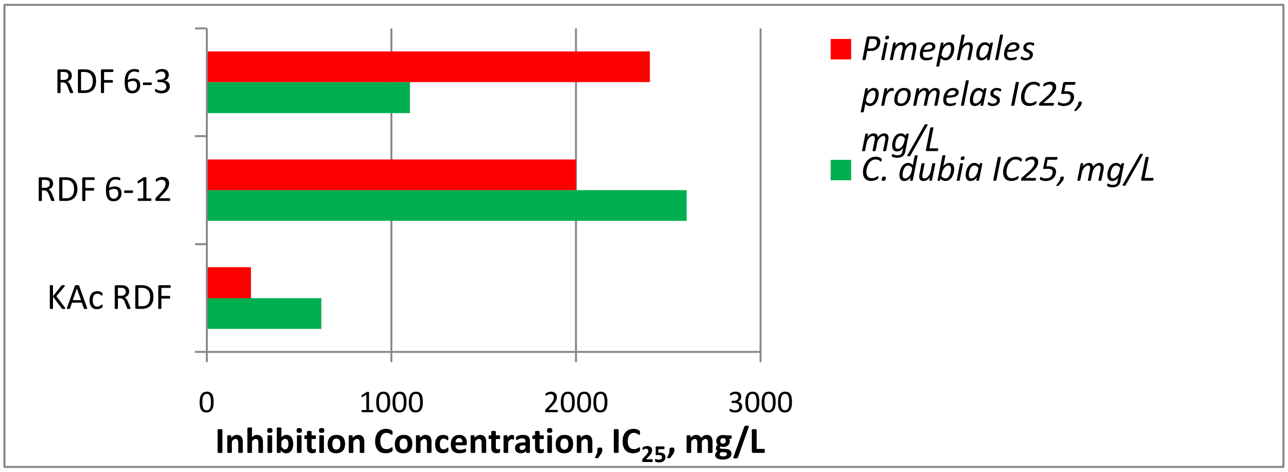
5.6.3 Chronic Toxicity

Battelle-RDF 6-12 and 6-3 were evaluated for chronic toxicity as part of the SERDP project [3]. The IC_{25} values were determined for *Ceriodaphnia magna* and *Pimephales promelas* by Wisconsin State Laboratory of Hygiene. The IC_{25} is the statistically determined concentration in mg/L that would theoretically result in a negative impact to 25% of the population of fish or daphnids. For fish, the endpoint is growth and for the daphnia it is the number of young produced.

Results are shown in Table 15 and graphically in Figure 9. The higher IC_{25} values for the two Battelle-RDFs, compared to the KAc-RDF, indicate that the Battelle-RDFs have lower chronic toxicities.

Table 15. Chronic Toxicity Results

RDF	***C. dubia*** **IC_{25}, mg/L**	***Pimephales promelas*** **IC_{25}, mg/L**
Commercial RDF #1	828	283
Commercial RDF #2	406	189
Battelle-RDF 6-3	1,100	2,400
Battelle-RDF 6-12	2,600	2,000



Note: Higher IC_{25} numbers correspond to lower toxicity

Figure 9. Chronic Toxicity of Battelle-RDFs Shows Lower EcoToxicity

5.6.2 Chemical Oxygen Demand and Biochemical Oxygen Demand

The RDF samples were analyzed for COD and BOD_5 by SMI Inc., as part of the AMS 1435A certification conducted during the SERDP project [3]. Results are shown in Table 16 and graphically in Figure 10. The values for the two Battelle-RDFs fall between KAc-RDF and KAc+PG RDF, which indicate that the Battelle-RDFs have an intermediate oxygen demand.

Table 16. Oxygen Demand Results

Sample	COD Kg O_2/kg	BOD_5 @ 20°C kg O_2/kg
Commercial KAc RDF	0.30 (Typical)	0.15 (Typical)
Commercial KAc+PG RDF	0.73 [(a)]	0.32 [(a)]
RDF 6-12	0.50	0.26
RDF 6-3	0.52	0.30

(a) From technical specification for Octagon Process's Octamelt (a KAc+PG RDF) [25].

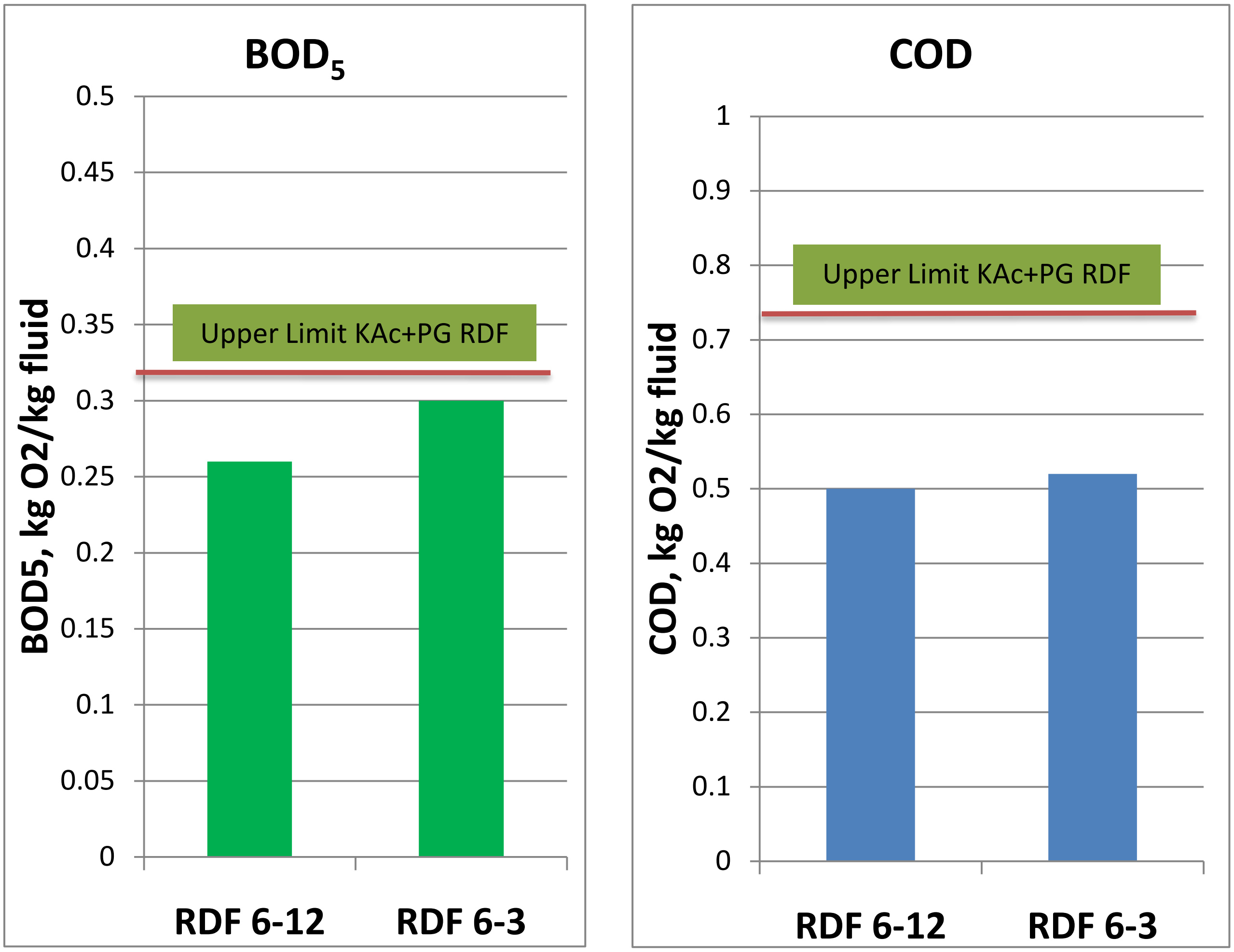


Figure 10. COD and BOD of Battelle-RDFs Shows Acceptable Oxygen Demand

5.6.3 Cadmium Corrosion

The RDF samples were analyzed for Cd corrosion by SMI Inc., as part of the AMS 1435A certification under the SERDP project [3]. Results are shown graphically in Figure 11. The 24-hour low-embrittling Cd corrosion rates for Battelle-RDFs are 60-75% lower than a typical KAc RDF.

In addition, a multi-cycle cadmium corrosion test was performed by Boeing on two preferred Battelle-RDF samples (RDFs 6-3 and 6-12) and compared to three formulations comparable to commercially used ones -- two based on potassium formate (KFo) and one on urea. As noted the RDFs are quite corrosive to Cd and are expected to fail the initial specs suggested by Boeing, though the specs have not yet been adopted. As shown in Figure 12, the Battelle-RDFs showed almost no corrosion compared to the formate deicers.

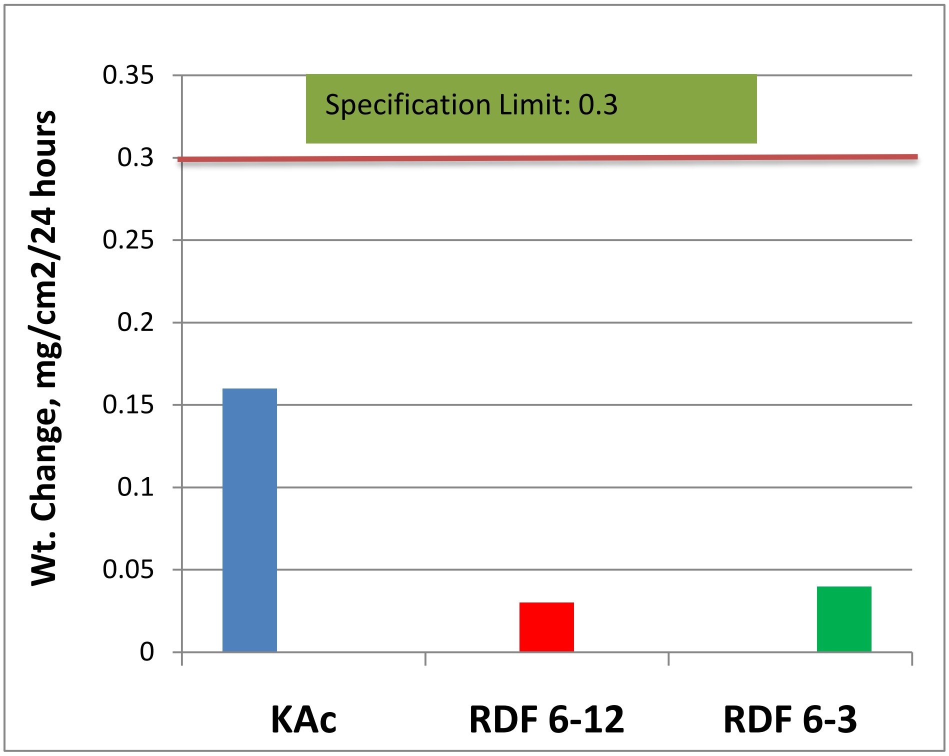


Figure 11. Cadmium Loss Data for Battelle-RDFs Shows Lower Corrosion Rates

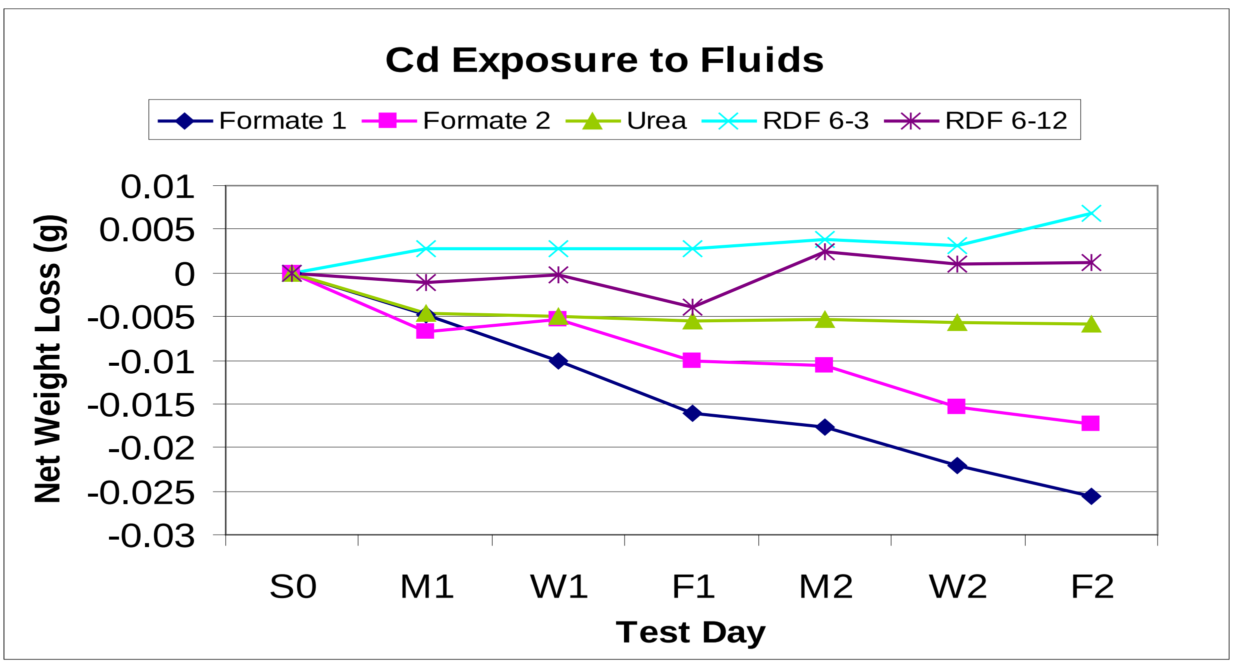


Figure 12. Multi-cycle Cadmium Corrosion Testing Show Lower Corrosion

5.6.4 Carbon-carbon Brake Pad Corrosion

The SAE Subcommittees A-5A (for aircraft brakes) and G-12 (for deicing fluids) developed a way to better analyze the data from the standard Honeywell in order to predict the propensity for catalytic oxidation of carbon brakes by RDFs. It is an ASTM-style test that is expected to be incorporated in AMS 1435A in the future.

Another company, Meggitt Aircraft Braking Systems (MABS), tested a variety of Battelle-RDFs using the method drafted by SAE subsequent to Honeywell testing. Materials included Carbenix® 4000 coated with primer (50/50 mixture of 85% phosphoric acid to 50% mono aluminum phosphate) antioxidant system. In the MABS-USA Meggitt test, the coupons were soaked in the RDF and dried for 4 hours at 80°C. They were then oxidized in flowing air for 24 hours at 550°C (1022°F). The weight loss was recorded after the coupons cooled. (Note: These samples were soaked in only a 50% deicer concentration whereas Honeywell's data are for 100% concentrated deicer.) Comparative normalized results, developed under the SERDP project, are shown in Figure 13 [3]. Both test methods confirm that Battelle-RDFs have a much lower catalytic oxidation activity than KAc or KFo RDFs.

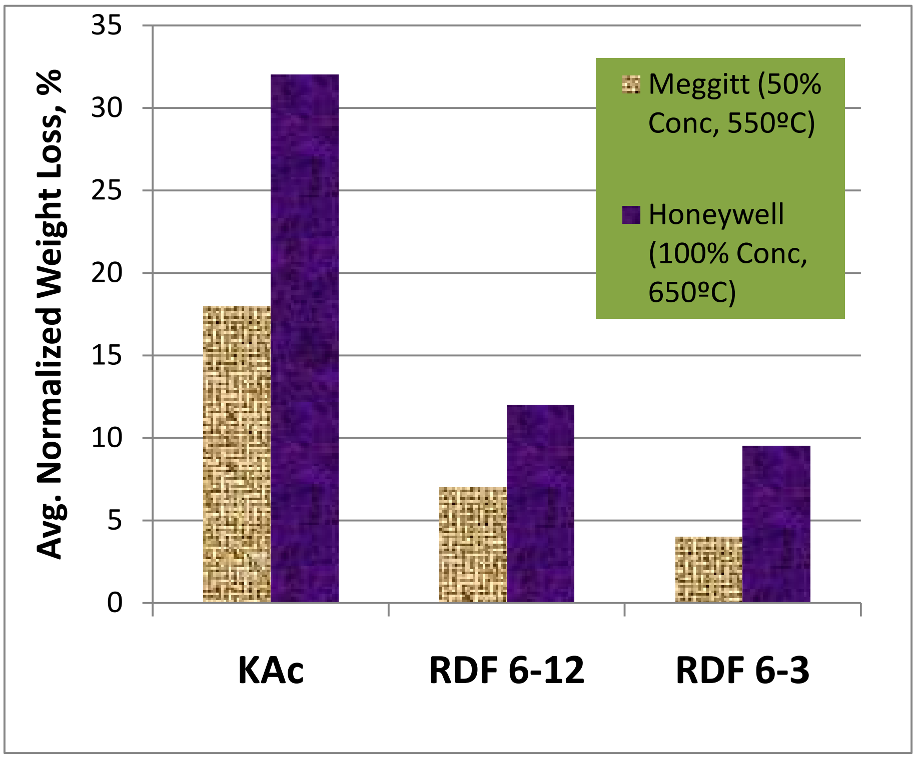


Figure 13. Brake Pad Loss Data for Battelle-RDFs Shows Lower Carbon-Carbon Corrosion

5.6.5 Anti-icing Tests

The first WPAFB RDF demonstration series covered anti-icing. Battelle-RDF 6-3 was tested on January 12, 2010, and RDF 6-12 was tested the following day. The test conditions and data collected are provided below. A discussion of the analysis of the raw data is provided in Section 6.

5.6.5.1 Battelle-RDF 6-3 versus KAc-RDF Anti-icing Tests

The anti-icing trial began in the morning to take maximum advantage of the coldest part of the day. The temperature was subfreezing with little wind. No freezing precipitation or snow was expected, so it was decided to simulate an icing event by the spray application of water. These conditions were judged suitable for assessing relative anti-icing performance of Battelle-RDF 6-3 and KAc-RDF.

The team was transported to the 300-ft wide by 2,600-ft long closed section of the long runway (R-23). Meteorological information (air temperature and wind speed and direction) was obtained from the WPAFB weather station. Surface and subsurface temperature data were obtained from probes maintained by the 88th ABW. Prior to fluid application, the test data were recorded; see Table 17 for the four tests. A schematic of the runway showing test areas 1 and 2 is shown in Figure 14.

The two runway-test sections were anti-iced per the dosage guidelines in Table 7 presented earlier (0.5 gal/1000 ft^2). The test was conducted as follows:

1. A 44-ft by 1,000 ft section, 45-ft left of the landing strip centerline was sprayed at 0.5 gal/thousand ft^2 with Battelle-RDF 6-3 using the Batts T-750 truck.
2. A 44-ft by 1,000 ft section, 90-ft left of the landing strip centerline was sprayed at 0.5 gal/thousand ft^2 with KAc RDF using the Batts T-1100 truck.
3. A 20-ft wide water spray was applied using a misting nozzle with a water rate of 1.25 gal/thousand ft^2.
4. Initial RCR runs were conducted but the surface was too dry to collect meaningful data.
5. Additional water was applied with an increased spray rate of 2.0 gal/thousand ft^2
6. RCR data was collected
7. Steps 5 and 6 were repeated until four water doses had been applied and the runway friction dropped.

The raw RCR data are shown in Table 18 and presented graphically in Figure 15. As noted, the RCRs in both cases dropped with elapsed time, indicating that the deicing fluid was being diluted and had lost some of its effectiveness. The significance of the data, in terms of friction and HOT, is discussed in Section 6.

Table 17. Anti-Icing Test Log

Pre-Test Data	Test Area 1 KAc RDF	Test Area 2 Battelle 6-3	Test Area 3 KAc RDF	Test Area 4 Battelle 6-12
Date	12 January 2010		13 January 2010	
Initial test RDF application start time	08:45	08:50	08:12	08:14
First test site	West of centerline	East of centerline	East of centerline	West of centerline
Runway surface temperature, °F	25		3; rose to 15 during test	
Air temperature, °F	21		9; rose to 13 during test	
Sky conditions (clear or cloudy)	Overcast		Overcast	
Wind velocity, knots/direction, °	3/330		2/140	
Condition of pavement surface prior to application	Dry		Dry	
Deicer fluid temperature, °F	~60		~60	
Comments	Problems were encountered with the first attempt; see below		Problems were encountered with the first attempt; see below	
	KAc application proceeded well	Battelle-RDF spray nozzles had been flushed with water; they froze. After thawing we re-tested	KAc application proceeded well	Battelle-RDF spray nozzles initially were not spraying uniformly; decided to repeat application
Test Variables	Test Area 1 KAc RDF	Test Area 2 Battelle 6-3	Test Area 3 KAc RDF	Test Area 4 Battelle 6-12
Application method (equipment)	T-1100	T-750	T-1100	T-750
Amount of snow/ice on surface, in.	0	0	0	0
Application rates of deicer fluids, gal/1000 ft^2 / spray width, ft	0.5/44	0.5/44	0.5/44	0.25/44
Amount of fluid applied, gal	~22	~22	~22	~11
Second test site	East side, 90 ft from of centerline	East side, 45 ft from of centerline	Same as above	Same as above
New test RDF application start time	09:53	09:50	08:40	08:35
Comments	RDF application looked uniform	RDF application looked uniform	An additional 0.25 gal/thousand ft^2 was applied to make total fluid applied ~0.75 gal/thousand ft^2	An additional 0.5 gal/thousand ft^2 was added to make total fluid applied ~0.75 gal/thousand ft^2
First water application – nozzle type	Misting droplets		8-mm droplets	
First water application time	09:55	09:52	08:48	08:46
First water application rates, gal/1000 ft^2 / spray width, ft	1.25/20		5/20	
Second, third, and fourth water applications – nozzle type	8-mm droplets		8-mm droplets	
Second, third, and fourth water application rates, gal/1000 ft^2 / spray width, ft	2.0/20		5/20	

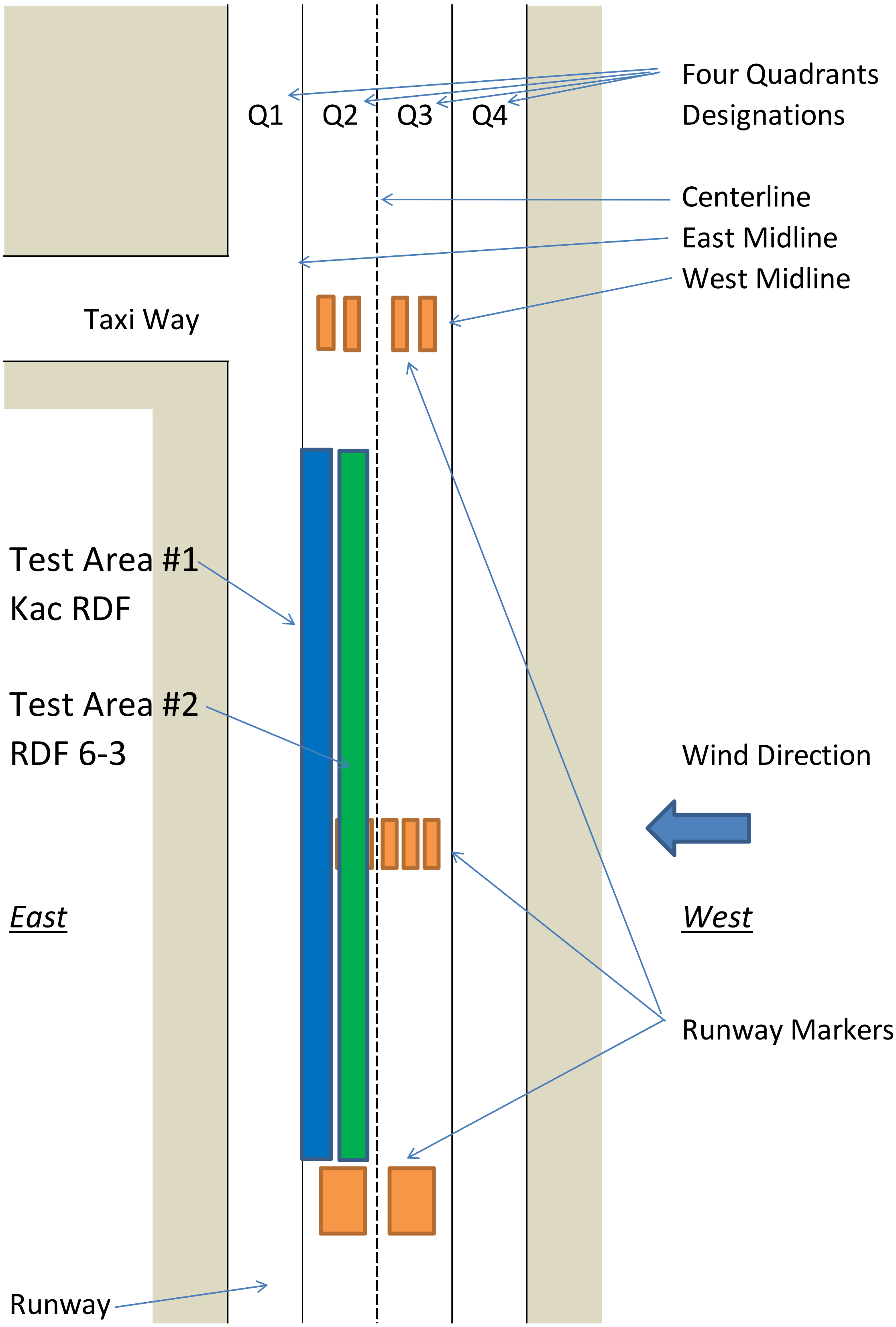


Figure 14. Test Areas 1 and 2 Used in Anti-Icing Tests on 12 January 2010

Table 18. Battelle-RDF 6-3 versus KAc-RDF Anti-Icing Data

RDF 6-3		KAc RDF	
Elapsed Time, min[(a)]	**Ruway Condition Rating**	**Elapsed Time, min[(a)]**	**Ruway Condition Rating**
29.00	13.80	29.00	10.67
29.50	10.20	29.50	9.80
30.20	12.77	30.00	4.83
36.00	11.10	37.00	8.90
36.50	7.90	37.50	7.47
37.00	9.07	37.90	8.23
42.00	9.87	43.00	8.50
43.00	9.27	43.50	6.87
43.50	12.57	43.90	5.87

(a) Time after first water application

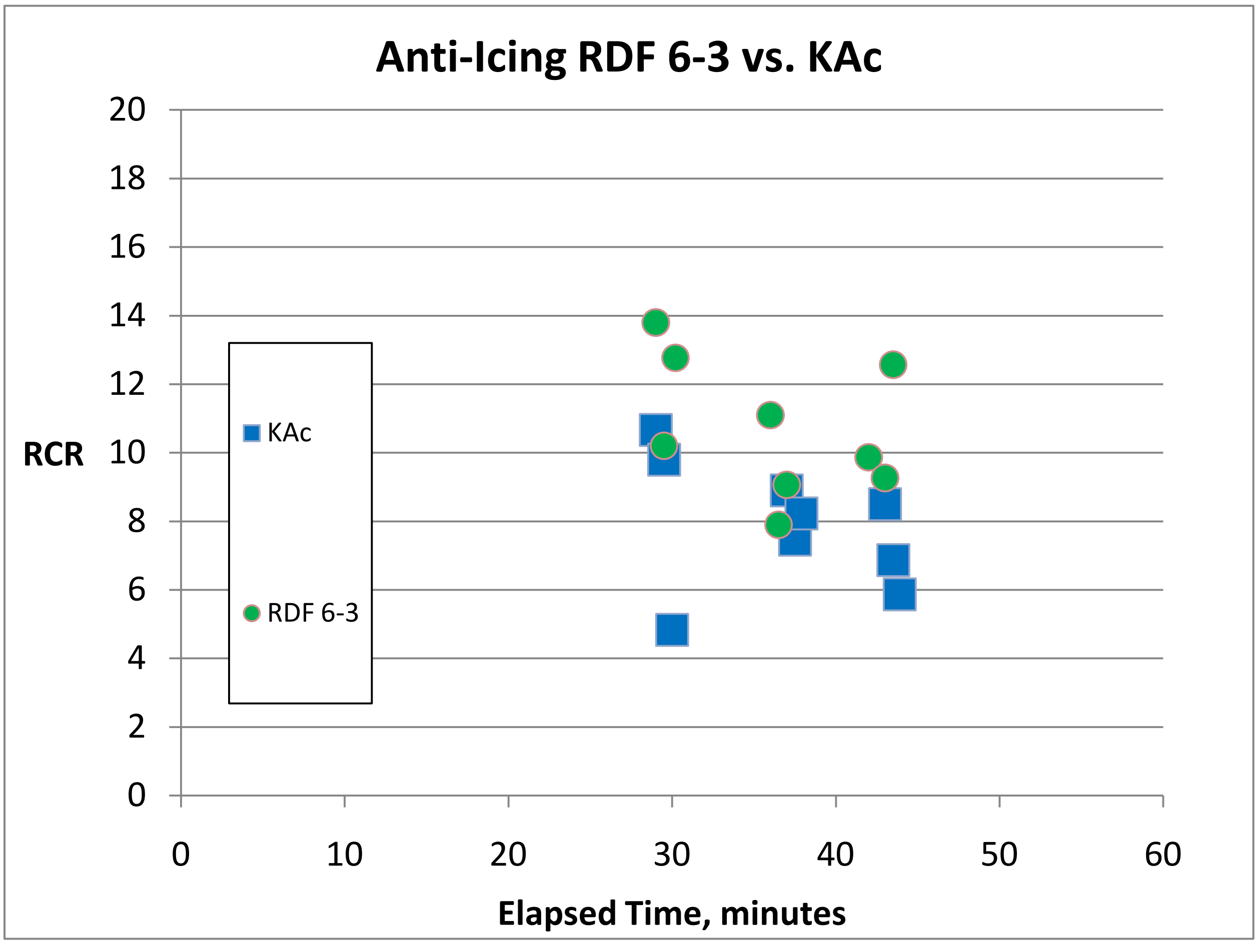


Figure 15. Anti-Icing RCR versus Elapsed Time for RDF 6-3 and KAc RDF

Photos of the first day of anti-icing testing are shown in Figure 16.

Top left: truck with Batts T-1100 trailer (KAc RDF)
Top right: T-750 trailer (RDF 6-3)
Middle left: water being applied to runway
Middle right: iced surface
Bottom: anti-iced runway after simulated ice shower

Figure 16. Photos of Test Site During RDF 6-3 Anti-Icing Tests

5.6.5.2 Battelle-RDF 6-12 versus KAc-RDF Anti-icing Tests

The second anti-icing trial began in the morning of January 13th to take maximum advantage of the coldest part of the day. The air temperature was much colder than in the first anti-icing test at 9ºF at 08:12; the surface temperature was 3 ºF but rose rapidly once the sun came up reaching 15ºF during the test. Fortunately, there was little wind. No freezing precipitation or snow was expected, so it was decided to again simulate an icing event by spraying water along the runway.

The team was transported to the closed section of the long runway and the test data were recorded. The plan was to anti-ice the two runway-test sections (test areas 3 and 4) per the 0.5 gal/1000 ft^2 dosage guidelines in Table 7 presented earlier. A schematic of the runway showing test areas 3 and 4 is shown in Figure 17.

See steps below:

1. A 44-ft by 1,000 ft section left (east) of the landing strip centerline was sprayed with KAc RDF using the Batts T-1100 truck.
2. A 44-ft by 1,000 ft section right (west) of the landing strip centerline was sprayed with Battelle-RDF 6-12 using the Batts T-750 truck.
3. Problems with the uniformity of the RDF 6-12 spray coverage was experienced and both fluids were re-applied to the runway strips to achieve a consistent, total 0.75 gal/thousand ft^2 dose.
4. Water spray was applied using a spray unit with a water rate of 5 gal/thousand ft^2.
5. More water was applied at the same rate.
6. RCR data were collected on both strips.
7. Steps 5 and 6 were repeated until four water doses had been applied and the RCR dropped to near 6 (i.e., to an unacceptable friction level).

The raw RCR data are shown in Table 19 and presented graphically in Figure 18. As before, the RCRs dropped with elapsed time showing the RDFs were losing their effectiveness during this simulated ice storm. An analysis of relative effectiveness, in terms of friction and HOT is discussed in Section 6.

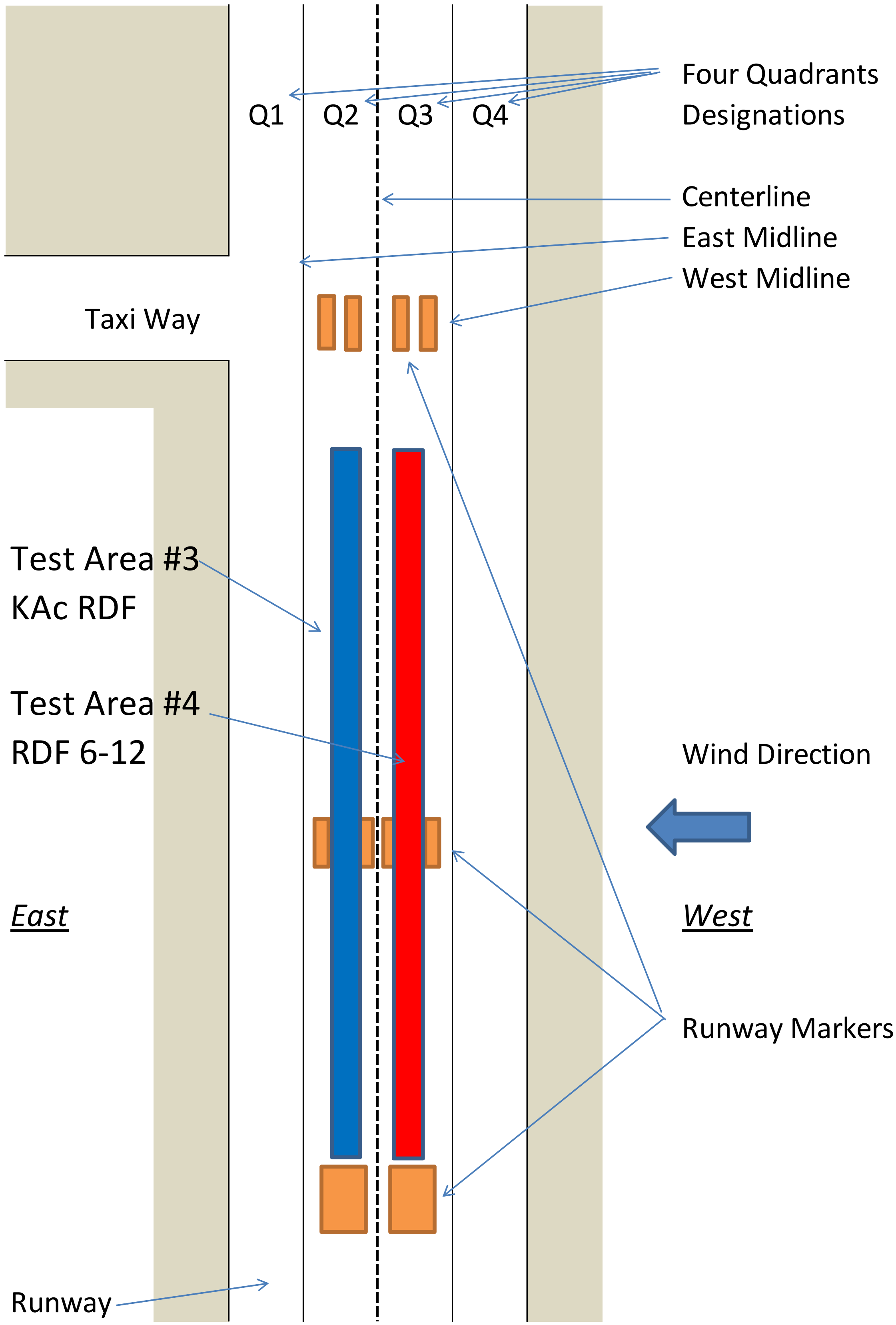


Figure 17. Test Areas 3 and 4 Used in Anti-Icing Tests on 13 January 2010

Table 19. Battelle-RDF 6-12 versus KAc-RDF Anti-Icing Data

RDF 6-12		KAc RDF	
Elapsed Time, min[(a)]	Ruway Condition Rating	Elapsed Time, min[(a)]	Ruway Condition Rating
12.00	14.03	12.00	11.33
13.00	15.60	12.50	12.67
13.50	13.40	12.90	13.17
21.00	7.77	19.00	9.40
21.50	9.97	20.00	9.33
23.00	12.53	20.50	11.97
27.00	6.17	25.00	11.57
27.50	6.60	25.50	6.63
27.90	9.97	25.90	9.50
34.00	6.50	31.00	4.50
34.50	7.17	32.00	6.03
34.90	8.57	33.00	6.03
41.00	6.83	39.00	5.83
41.50	7.60	39.50	6.27
41.90	6.93	40.00	6.53

(a) Time after first water application

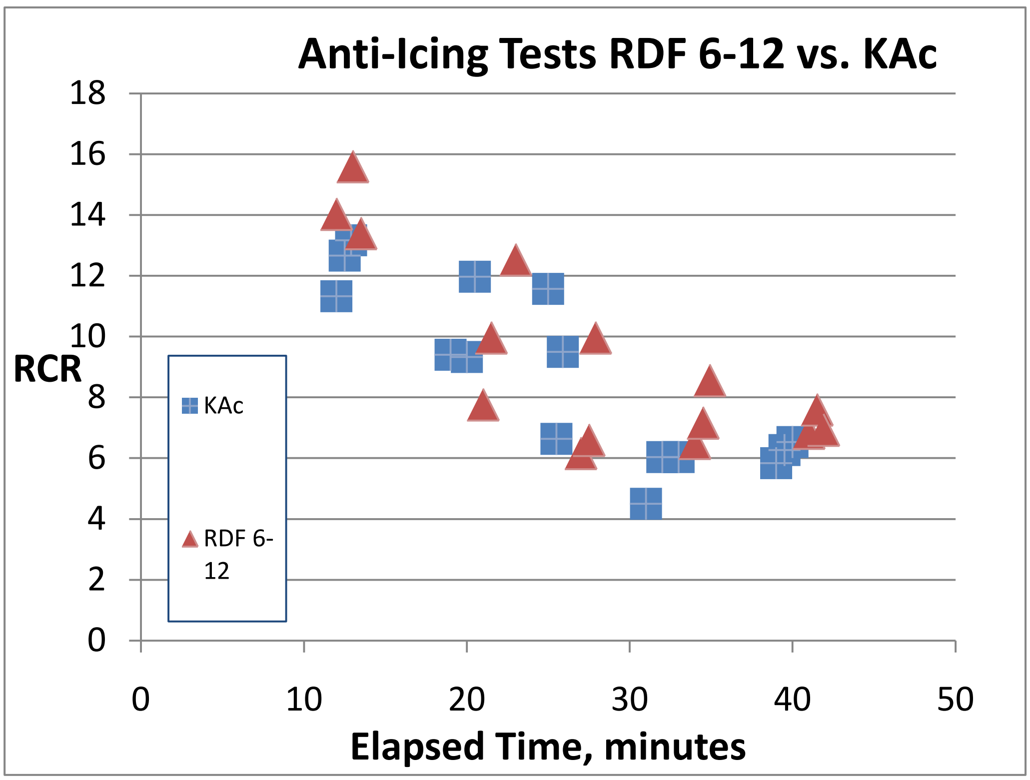
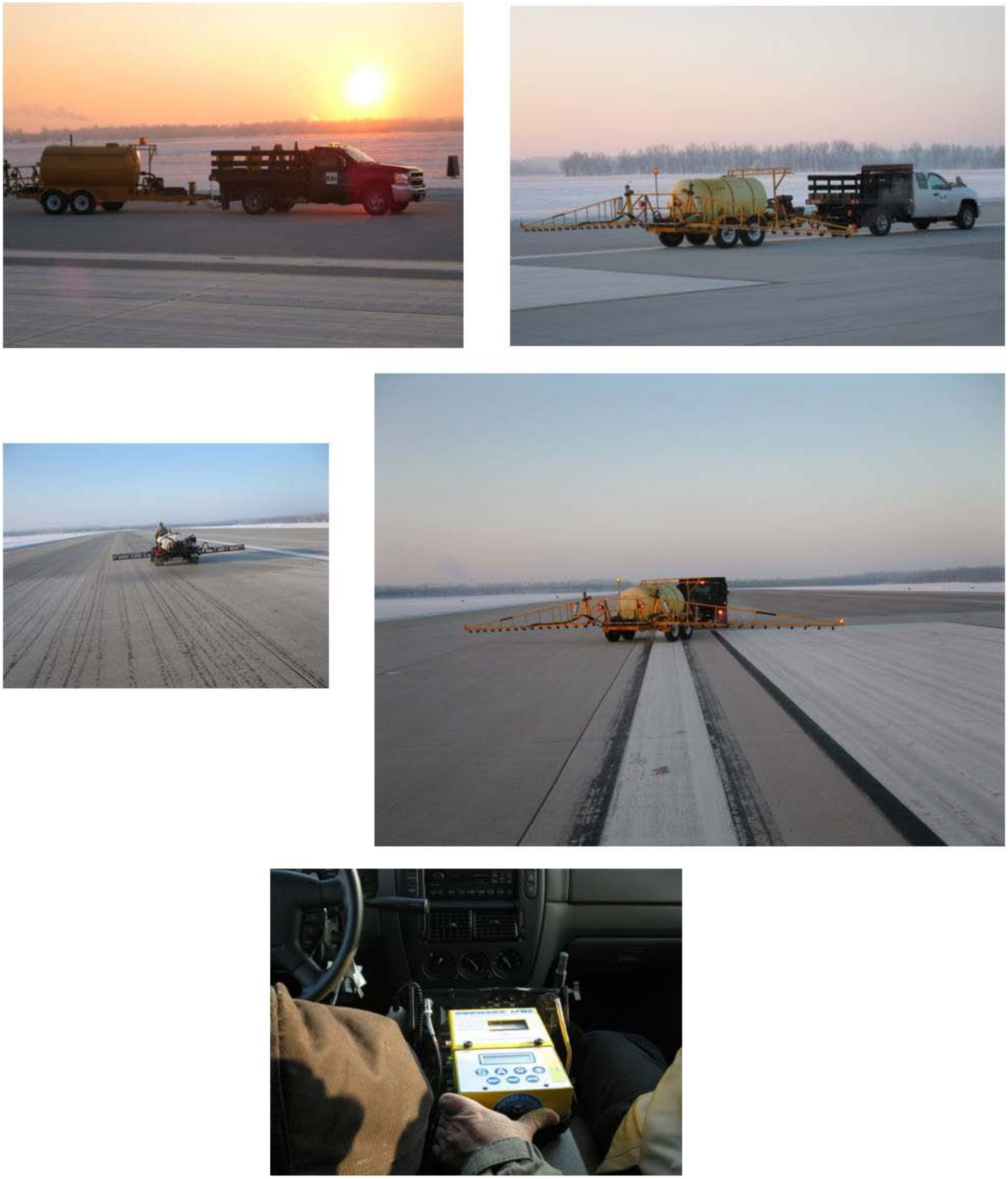


Figure 18. Anti-Icing RCR versus Elapsed Time for KAc RDF and RDF 6-12

Photos of the test site showing fluid being applied, water being sprayed, and RCR data being collected are shown in Figure 19.



Top left: KAc RDF being applied to runway
Middle left: water being applied
Bottom: close up of BOWMONK friction tester

Top right: RDF 6-12 being applied
Middle right: RDF 6-12 being applied

Figure 19. Photos of Test Site During RDF 6-12 Anti-Icing Tests

5.6.8. Deicing Tests

Several snow storms hit WPAFB causing a stop in the RDF testing. This was followed by warm weather and rain, which washed the runway clean but prevented testing.

The first deicing test was conducted on January 29, 2010. Since the Battelle-RDF 6-12 was still in the RDF fluid-application truck, it was tested first. After the test, more storms hit, and the final test with RDF 6-3 was delayed until February 26. The deicing test conditions and data collected are provided below. A discussion of the analysis of the raw data is provided in Section 6.

5.6.5.3 Battelle-RDF 6-12 versus KAc-RDF Deicing Tests

No freezing precipitation was expected, so it was decided to simulate an iced runway by spraying water on the runway the night before the test. The two runway-test sections were sprayed with approximately 12,000 gallons of water. The water was applied by Captain Mike Roberts using the 88th ABW fire department Crash Truck Number 16; see Figure 20.

Left: crash truck
Top right: roof turret-mounted nozzle
Bottom right: bumper-mounted nozzle

Figure 20. Crash Truck Used to Create Ice Sheets for Deicing Tests

The temperature and wind data were collected during the ice making process; see Table 20.

Table 20. Ice-Making Temperature and Wind Log for January 28, 2010

Time	Temperatures, ºF			Wind	
	Air	Surface	Subsurface	Speed, knots	Direction, º
19:34	10		31		
19:45	15	22			
20:45	13	20	35		
22:17	12	16.5	36	7	334

At 20:00 on January 28, the crash truck was driven to the runway and positioned along quadrant Q4; see Figure 21. The air temperature was 15ºF and the surface temperature was 22ºF. Approximately ~¼ of the 3,300-gal load was sprayed using the turret-mounted nozzle adjusted to output a 200-ft spray. The truck was moved about ¼ down runway quadrant Q4 and the process repeated. Four sprays from the roof-mounted turret nozzle covered the right (west) test strip.

The truck was refilled with water and the procedure was repeated at 20:25 on the left (east) strip in quadrant Q1. Ice was formed on the runway, but the discrete sprays did not result in a totally uniform coverage.

For pass number 3, the water was applied from the bumper-mounted spray nozzle directed at a 45º angle from the truck while it rolled at ~5 MPH down the runway. This "bump and roll" procedure was used for the remaining water applications. After the application, the ice was inspected. The water rolled away from the centerline of the runway and froze, leaving a slightly thinner layer near the center (1/32 in.) and a slightly thicker layer (1/8 in.) at the edges; see Figure 22.

Two more truck loads of water were applied in the bump and roll fashion creating a 1/8-in. to ¼-in. thick coating that seemed uniform across the two 50-ft wide by 750-ft long parallel test strips in Q1 and Q4. At the time of the final load, the air temperature had dropped to 12ºF and the surface temperature was 16.5ºF. The wind speed and direction were 7 knots and 334º.

The team met the morning of January 29 to review the conditions. The initial surface temperatures were < 20ºF and almost too cold for assessing relative deicing performance of Battelle-RDF 6-12 and KAc-RDF, but it was decided to proceed as we knew the runway surface would warm up as the sun emerged.

The team was transported to the closed section of the long runway. Meteorological information was obtained from the WPAFB weather station and surface and subsurface temperature data were obtained from probes maintained by the ABW; see Table 21.

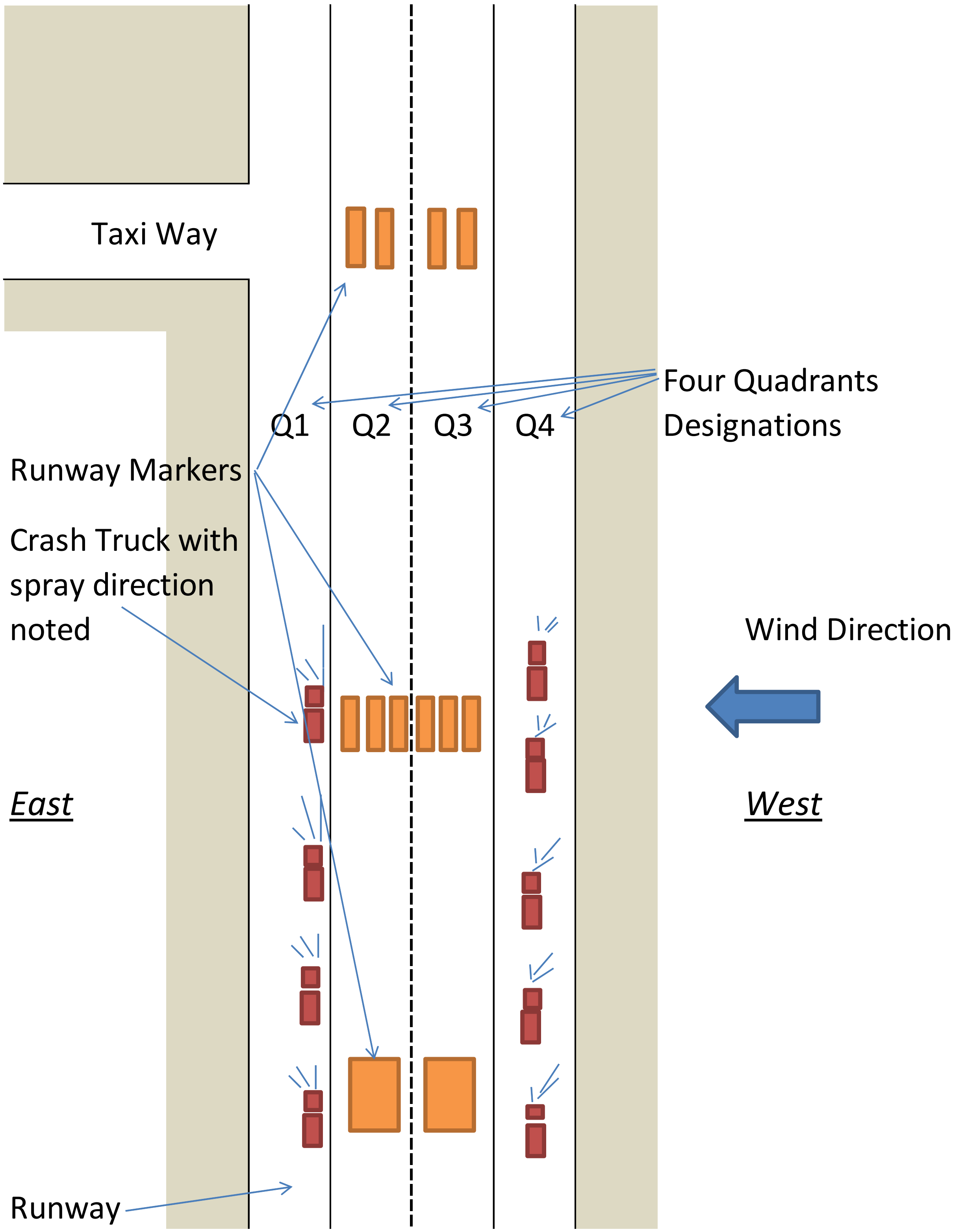
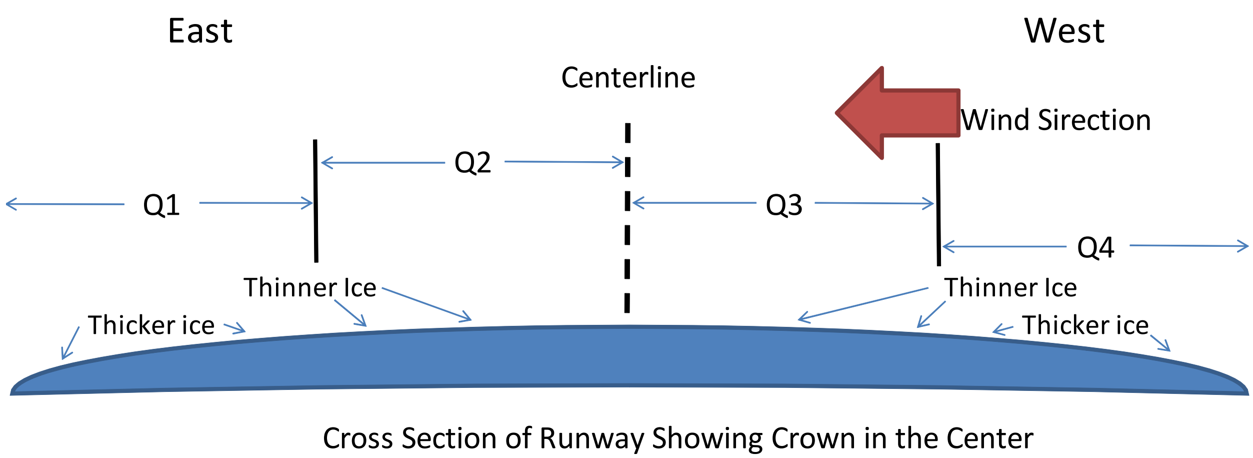


Figure 21. Water Application Prior to RDF 6-12 and KAc RDF Deicing TestS



Note: Each quadrant is 75-ft wide.

Figure 22. Ice Thickness Across Runway

Table 21. First Deicing Test Temperature and Wind Log for January 29, 2010

Time (Clock)	Temperatures, °F			Wind	
	Air	Surface	Subsurface	Speed, knots	Direction, °
07:34	10	17	31		
09:22	12			5	060
10:30	12			5	030
10:42	12.5	24.8	31		
11:33	14	28	32	7	030

The test strips were inspected and the ice thickness was found to be a uniform ~3/16-in. RCR data were collected before any fluid had been applied; see Table 22. The RCR rating of 5 indicated that the test strips were very slippery with a "Nil" friction rating. Also the pre-test RCR indicated that the two sides were equally slippery.

Table 22. RCR Data for Untreated Test Strips

Right (West) Side		Left (East) Side	
Time (Decimal)	RCR	Time (Decimal)	RCR
8.23	5.4	8.18	5.4
8.25	5.0	8.20	5.3
8.27	5.0	8.22	5.2
Average	5.1	Average	5.3

Using the temperature and ice thickness data, the proper liquid RDF dosage was estimated. The tabulated guidance (see Table 6 presented earlier) was converted into a graphical format to assist in interpreting the AFI 32-1002 guidance; see Figure 23.

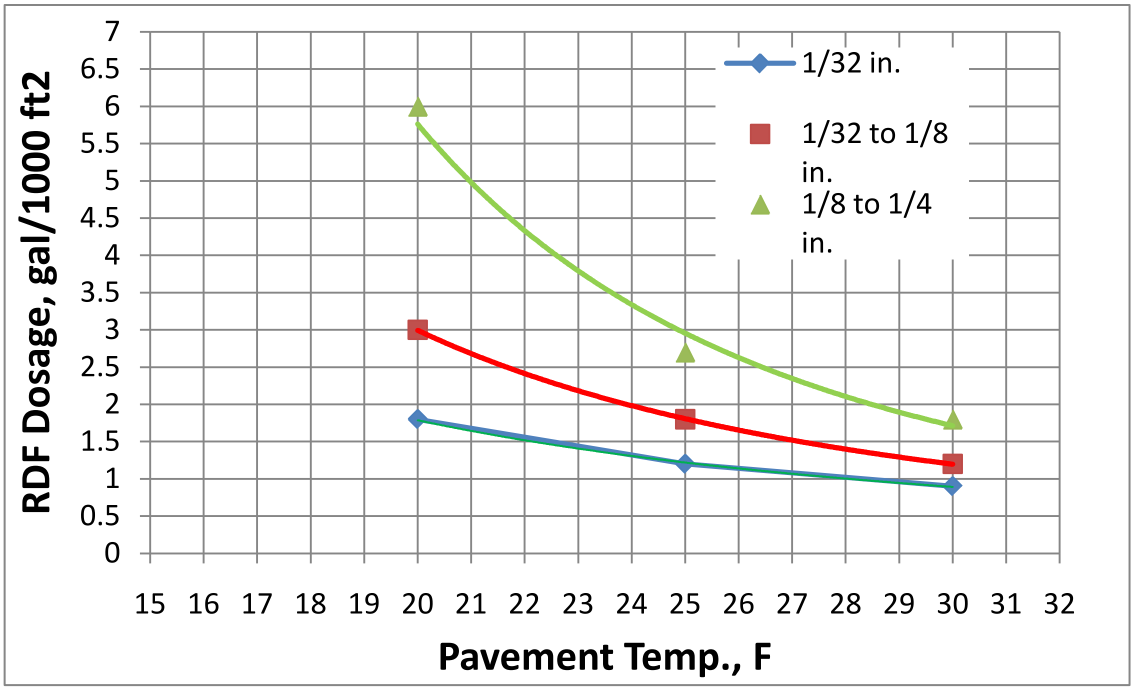


Figure 23. Liquid Dosage Guidance as a Function of Ice Thickness and Pavement Temperature per AFI 32-1002

For a 1/8- to ¼-in. ice thickness (dashed green line in Figure 23) and a temperature of 17ºF, the suggested dosage was >6 gal/thousand ft^2. However, the ABW staff thought that dosage was excessive and recommended an initial 3 gal/thousand ft^2 dose; then, if that was not effective, a second equal dose would be applied.

Other test-condition data are provided in Table 23. Test areas 5 and 6 were used in the first deicing test; see Figure 24.

The first deicing test was conducted after the parallel ice strips were created and the ice thickness was determined; see photos in Figure 25. The procedure included the following steps:

1. Apply Battelle-RDF 6-12 using the Batts T-750 truck over a 44-ft by 750-ft section right (west) of the landing strip centerline at a dosage of 3 gal/thousand ft^2.
2. Apply KAc RDF using the Batts T-1100 truck over a parallel 44-ft by 750-ft section left (east) of the landing strip centerline at a dosage of 3 gal/thousand ft^2.
3. Collect RCR data for both test strips.
4. After approximately 1 hour, the RCR had not risen significantly, and an additional 3 gal/thousand ft^2 dose was applied to each test strip.
5. Collect additional RCR data until the total elapsed time approached 3 hours.

Table 23. Deicing Tests Log

Pre-Test Data	**Test Area 5 KAc**	**Test Area 6 Battelle 6-12**	**Test Area 7 KAc**	**Test Area 8 Battelle 6-3**
Date	Friday January 29, 2010		Friday February 26, 2010	
Test site	Left (east)	Right (west)	Left (east)	Right (west)
Ground temperature, °F	See Table 22		See Table 29	
Air temperature, °F				
Wind velocity, mph				
Time of day/night	08:33	08:39	06:53	06:36
Sky conditions (clear or cloudy)	cloudy	cloudy	Cloudy	Cloudy
Friction readings prior to deicer application (RCR)	5.3	5.1	6	5
Condition of pavement surface prior to application (dirty or clean, old ice or new)	Fresh ice		Fresh ice	
Deicer fluid temperature, ºF	~60	~60	~60	~60
Test Variables	**Test Area 5 KAc**	**Test Area 6 Battelle 6-12**	**Test Area 7 KAc**	**Test Area 8 Battelle 6-3**
Application method (equipment)	Batts T-1100	Batts T-750	Batts T-1100	Batts T-750
Amount of snow/ice on surface, in.	~3/16 ice	~3/16 ice	~1/8	~1/8
Application rates of deicer fluids, gal/1000 ft^2, FIRST application	3.0	3.0	2.0	2.0
Amount of fluid applied, gal	~100	~100	~88	~88
Application rates of deicer salt, lb NAAC/1000 ft^2	NA		50	50
Amount of NAAC applied, lb			2,200	2,200
Comment	Little change in RCR readings were noted so a second dose was applied			Had to repeat salt application, as salt stopped flowing
Application rates of deicer fluids, gal/1000 ft^2, SECOND application	3.0	3.0	2.0	2.0
Amount of fluid applied, gal	~100	~100	~88	~88

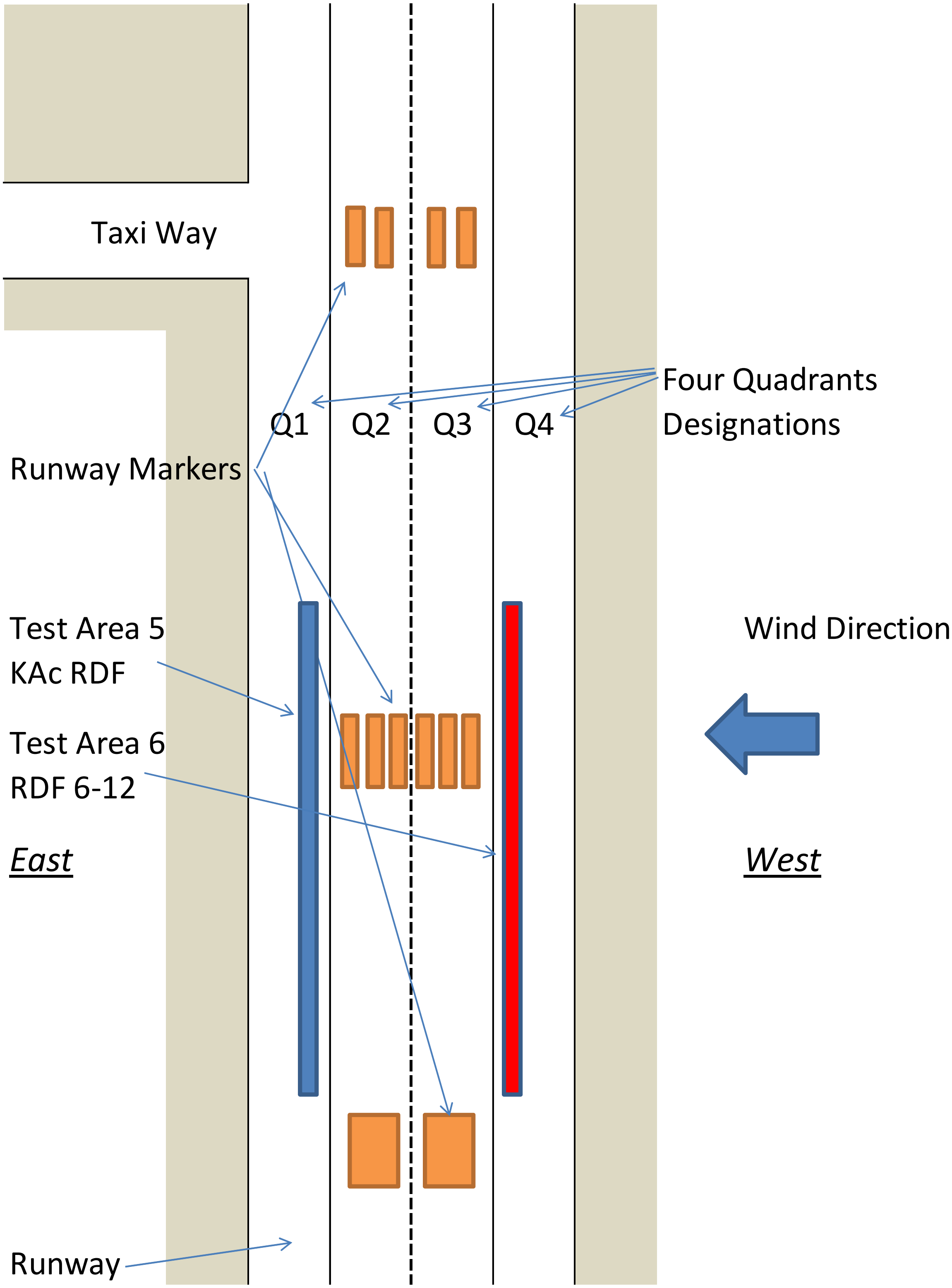


Figure 24. Test Areas 5 and 6 Used in Deicing Tests on 29 January 2010 Test

Top center: ice formed on runway
Top left: preparing to apply RDF 6-12 Top right: preparing to apply KAc RDF
Center: runway with ice after treatment
Bottom left: collecting RCR data Bottom right: deiced runway

Figure 25. Photos of the Parallel Test Strips Being Deiced

The raw RCR data are shown in Table 24 and presented graphically in Figure 26.

Table 24. Battelle-RDF 6-12 versus KAc-RDF Deicing Data

Application No.	RDF 6-12		KAc RDF	
	Elapsed Time, hours[a]	Ruway Condition Rating	Elapsed Time, hours[a]	Ruway Condition Rating
First	0.85	3.8	0.18	4.6
	0.90	4.0	0.23	4.7
	0.91	4.3	0.25	4.1
			0.75	5.9
			0.76	4.5
			0.76	5.3
Second	1.42	5.4	1.37	4.4
	1.43	4.4	1.38	4.5
	1.44	4.7	1.39	4.0
	1.87	4.7	1.75	4.8
	1.87	4.4	1.75	4.1
	1.88	4.3	1.76	3.6
	2.05	5.8	2.00	5.3
	2.06	4.4	2.01	4.8
	2.07	4.9	2.02	5.3
	2.30	7.3	2.25	5.0
	2.32	4.3	2.27	4.5
	2.33	4.3	2.30	4.5
	2.65	7.1	2.62	4.5
	2.68	6.3	2.63	4.4
	2.69	8.2	2.65	4.5
	2.90	7.0	2.78	5.2
	2.92	4.8	2.80	5.1
	2.92	3.7	2.81	4.9
	3.03	7.0		
	3.05	5.4		
	3.07	4.7		

(a) Time after first RDF application.

As noted, the runway suitability (as measured by RCR) of the KAc-RDF treated strip did not increase significantly, even after the second RDF application. The RDF 6-12 data did show an uptick a little after 2.7 hours, but eventually the melted ice froze and the RCR numbers fell again.

Overall, the deicing performance was not impressive. The ABW stated that for conditions with such a heavy ice layer they would normally use a combination of NAAC and RDF; this procedure was included in the second deicing test.

It was planned to estimate ice melting time by a study of the RCR versus time data. It was assumed that the RCR would start in the "Nil" range and rise with time as the ice melted. The time from RDF application until the RCR reached 9 would be the ice melting time. However, the data did not indicate a significant increase in RCR as the demonstration proceeded.

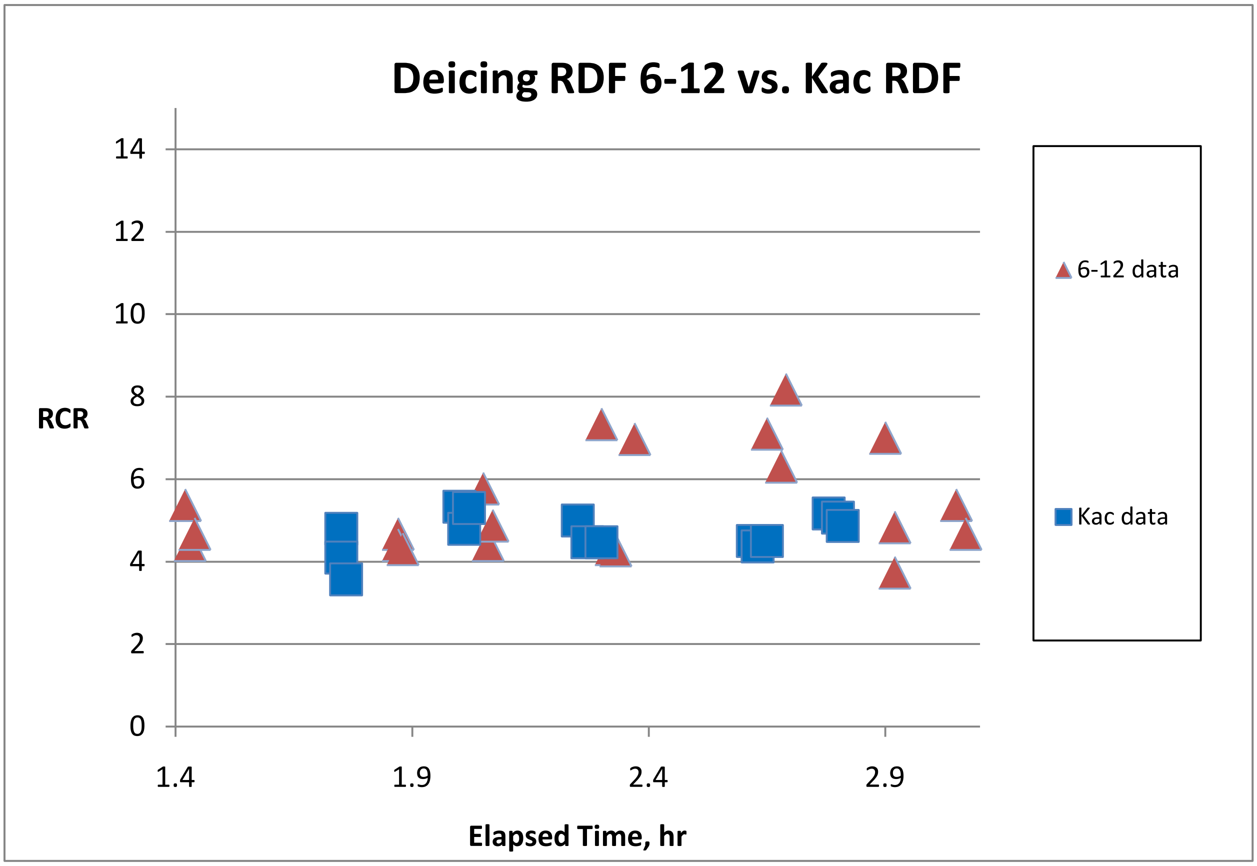


Figure 26. Deicing RCR versus Elapsed Time for KAc RDF and RDF 6-12
Data after second RDF application

A discussion of the analysis of the raw data is provided in Section 6.

5.6.5.4 Battelle-RDF 6-3 versus KAc-RDF Deicing Tests

The final deicing trial was conducted on February 26, 2010. The weather was much warmer than the previous tests with temperatures about 10ºF below the freezing point. In addition, the winds had picked up significantly. No freezing precipitation or snow was expected, so it was decided to again simulate an icing event by spraying water on the test strips. Between the first deicing test and the day of the second test, the weather had warmed and it had rained so the entire runway was washed free of any residual RDF. Since we did not have to worry about contamination from prior tests, water was applied to strips just left and right of the runway centerline.

During the evening of the February 25th, wind speeds of up to 22 knots were recorded. The temperatures were in an acceptable range, but the wind speed was higher than desired. However, as warm weather was predicted in the coming days and weeks, it was recognized that this might be the last suitable day in the 2009/2010 winter deicing season (it turned out that this was correct and conditions suitable for testing did not occur again). For this reason, the team agreed to proceed with the final deicing test.

The two runway test sections were sprayed with approximately three, 3,000 gallon tanker-loads of water. The water was applied by spraying water from the nozzles of the 88th ABW fire department Crash Truck Number 16 (see Figure 20 presented earlier) in a bump and roll fashion.

A diagram of the water application pattern is presented in Figure 27. The ice thickness in the previous test was ~3/16-in. deep with sections over ¼-in. thick which was considered too thick. Therefore three water loads, rather than four, were used in this ice-creating procedure. Data on temperatures and wind were collected during the ice-making process; see Table 25.

Table 25. Final Ice Making Temperature and Wind Log for February 25, 2010

Time	Temperatures, °F			Wind	
	Air	Surface	Subsurface	Speed, Knots	Direction, °
19:58	27	28	36	18/22	318
21:48	27			11	310
22:30	27	28	35	13/19	312

After the final water application was sprayed, the surface was inspected. Two, parallel, 75-ft wide, 1000-ft long, ice tracks were observed. Because of the high wind and relatively mild temperatures, the ice was more spread out and thinner (~1/8-in.) than in the previous test.

The team met the morning of February 26 for the final deicing test. The ABW stated that, with such a thick ice layer, they would normally use NAAC along with RDF using their Epoke salt spreader. Unfortunately, they only had one Epoke truck. If they treated one test section, it would be hours before they could treat the parallel track (because they would have to return the truck to the hanger, empty the liquid RDF, flush, put in fresh RDF, and drive back to the runway). Therefore, it was decided to lay down liquid RDF using the Batts trailers, apply NAAC with a single salt truck, and then apply liquid RDF over the salt to simulate the action of the Epoke truck. To determine the proper dosage, AFI 32-1002 was again consulted. The suggested NAAC dosage table is reproduced as Table 26.

Table 26. Suggested Sodium Acetate Dosage Rates in Kilograms per 100 Square Meters (Pounds per 1,000 Square Feet)

Reference [15]: AFI 32-1002 Table A2.3

Ice Thickness	Pavement Temperature		
	-1.1 °C (30 °F)	-3.9 °C (25 °F)	-6.7 °C (20 °F)
Less than 0.8 mm (1/32")	4.9 (10)	7.3 (15)	18.1 (37)
0.8 mm to 3.2 mm (1/32" to 1/8")	8.8 (18)	18.1 (37)	38.1 (78)
3.2 mm to 6.4 mm (1/8" to 1/4")	38.1 (78)	53.7 (110)	85 (174)

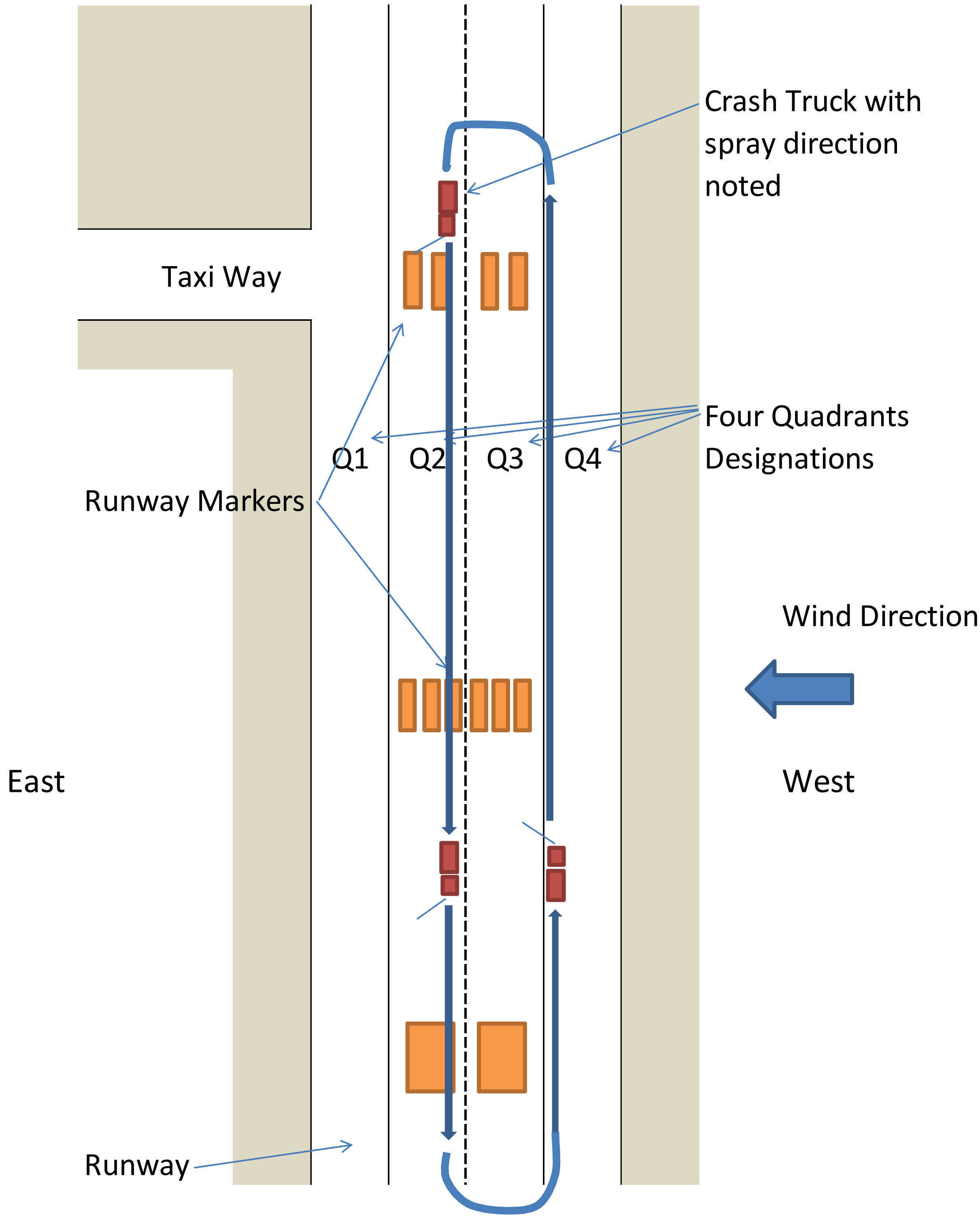


Figure 27. Ice Making Procedure for the Final Deicing Test

For example, if the thickness was 1/32 to 1/8 in. and the temperature was at least 20ºF, the suggested dosage was 38.1 kg/100 m^2 (78 lb/thousand ft^2). So, for a 52-ft wide (the distribution width of the salt truck) and 1,000-ft long ice strip (52,000 ft^2) at a 78 lb/thousand ft^2 dosage, the salt usage would be 4,056 lb or 1.84 metric tonnes of NAAC.

The 88th ABW representative stated that the Epoke spreader distributes NAAC in a pre-set range creating a 19- to 52-ft wide salt layer. From their experience, 2200 lb (1 metric tonne, 1000 kg) of NAAC required about 50 gal of KAc RDF to be effective. The NAAC rate was set and the KAc RDF rate was automatically adjusted to maintain this ratio.

In this calculation above, 1.8 metric tonnes were required to treat an ice strip. At 50 gal KAc RDF per metric tonne, this is 92 gal of KAc RDF for 52,000 ft^2, which translates into ~2 gal/thousand ft^2. The suggested RDF dosage for this ice thickness and pavement temperature, per Table 7 (presented earlier), would be 3 gal/thousand ft^2. Therefore, we elected to apply a pre-RDF dosage at 2 gal/thousand ft^2, then NAAC, and then a final RDF dosage at 2 gal/thousand ft^2.

We also learned that the ABW does not adjust the NAAC dosage per the weather conditions. Instead, they use a constant 25 g/m^2 (equivalent to 25 kg/100 m^2 or 51 lb/thousand ft^2) rate and apply multiple doses if necessary. Therefore we used this NAAC rate for the final deicing test.

The test strips were inspected after the water was applied; the ice depth was uniform with depths ranging from 1/8 to 3/16 inch. However, because of the relatively warm air temperatures and high winds, much of the ice had sublimed over the evening leaving parallel 30-ft wide, 1000-ft long, by 1/8 to 1/16-inch thick ice sheets on the runway. Because of the wind effects, the ice depth on the east side of the runway was slightly thinner, and had small patches of dry (no ice) surface at the beginning of the final deicing test.

Initial RCR data were collected before any fluid was applied to measure the friction properties of the two ice strips; see Table 27. The RCR rating of 5 to 6 indicated that the test strips were very slippery with a "Nil" friction rating. Also the pre-test RCR indicated that the west side (the one to be treated with RDF 6-3) was slightly more slippery. It was also noted the east side had patches of bare pavement, which could result in higher RCR readings.

Table 27. Initial RCR Data for Untreated Test Strips of February 26, 2010

Right (West) Side		Left (East) Side	
Time (Decimal)[(a)]	RCR	Time (Decimal)	RCR
05.82	5.1	5.93	5.6
05.83	4.6	5.95	5.7
05.84	4.2	5.96	5.5
Average	4.7	Average	5.6

(a) 05.82 decimal is equivalent to 05:49 AM. Decimal time was used to facilitate data plotting.

The team moved to the closed runway. Temperature and wind data are noted in Table 28, and the other test-condition data were collected, see Table 23 presented earlier. Figure 28 shows test strips 7 and 8 using in this final deicing test.

Table 28. Final Deicing Test Temperature and Wind Log for February 26, 2010

Time (Decimal))	Temperatures, °F			Wind	
	Air	Surface	Subsurface	Speed, knots	Direction,°
7.20	27	28	32	14/23	320
8.13	25	30	33	15/21	300

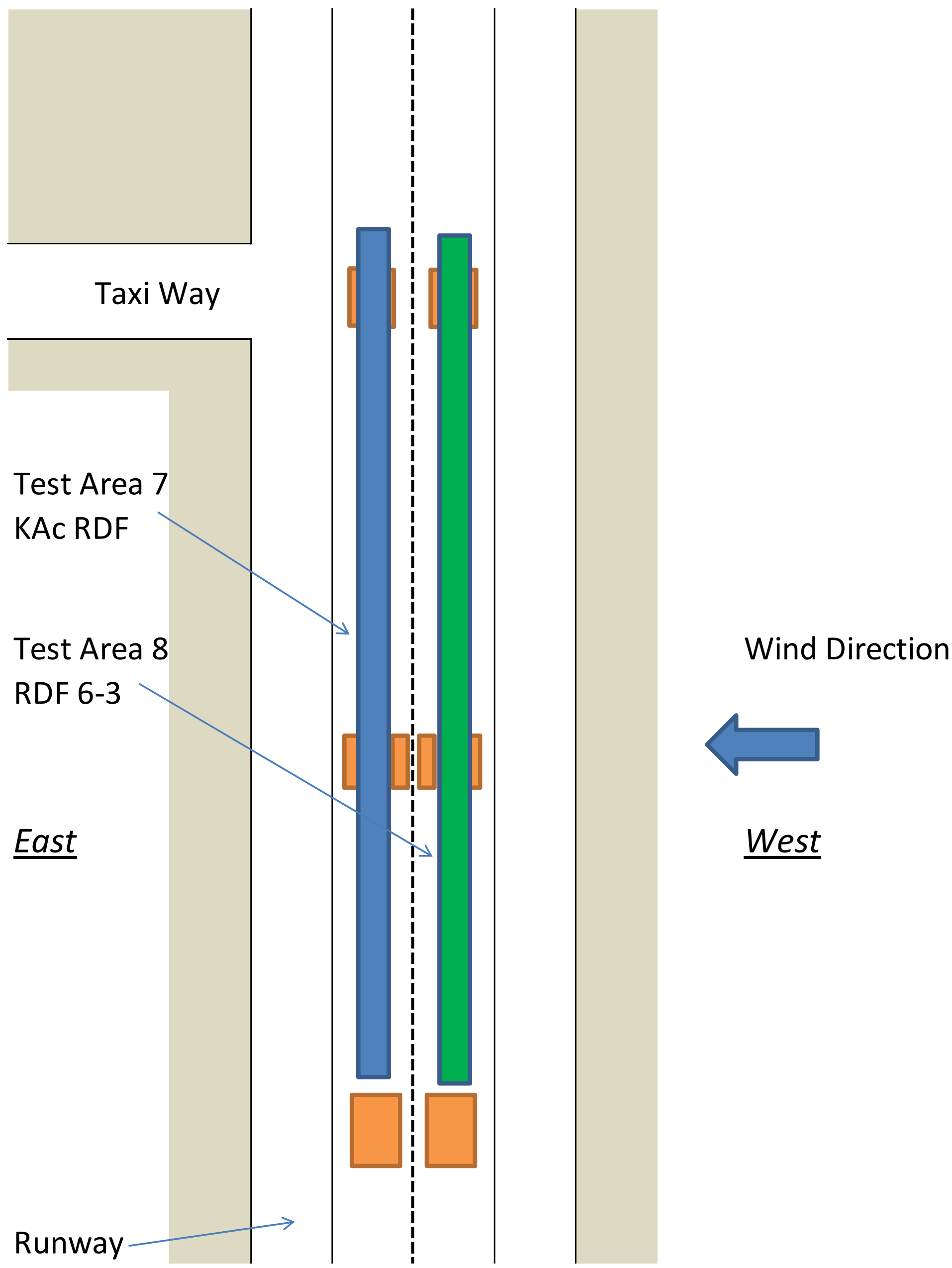


Figure 28. Test Areas 7 and 8 Used in Deicing Tests on 26 February 2010 with RDF 6-3 and KAc RDF

The tests were conducted as follows:

1. RCR data were collected on test strips 7 and 8 before the application of RDF.
2. A 44-ft by 1,000-ft section right of the landing strip centerline (the west side) was sprayed with Battelle-RDF 6-3 using the Batts T-750 truck; the RDF was applied at a rate of 2 gal/thousand ft^2.
3. A 44-ft by 1000-ft section left of the landing strip centerline (the east side) was sprayed with KAc RDF using the Batts T-1100 truck; the RDF was applied at a rate of 2 gal/thousand ft^2.
4. NAAC was applied immediately at 50 lb/thousand ft^2.
5. A second dose of RDF was applied immediately after the NAAC at a rate of 2 gal/thousand ft^2.
6. RCR data were collected for both test strips until the total elapsed time approached 1 hour.

Photos of the test site showing the NAAC and RDF 6-3 trailer and the NAAC being applied are shown in Figure 29. Much of testing was conducted before sunrise, limiting the number of pictures taken.

Figure 29. Second Deicing Test with RDF 6-3 and KAc RDF

The raw RCR data are shown in Table 29 and presented graphically in Figure 30.

Table 29. KAc-RDF versus Battelle-RDF 6-3 Deicing Data

RDF 6-3		KAc RDF	
Elapsed Time (Decimal), hours[(a)]	Ruway Condition Rating	Elapsed Time (Decimal), hours[(a)]	Ruway Condition Rating
0.22	5.27	0.28	7.63
0.23	6.00	0.30	8.57
0.25	5.50	0.32	11.90
0.53	6.33	0.57	9.37
0.55	4.97	0.57	6.63
0.57	5.53	0.57	13.73
0.80	6.90	0.67	9.27
0.81	6.17	0.67	13.30
0.80	5.43	0.67	5.53
0.88	6.77	0.73	10.87
0.89	5.87	0.75	12.00
0.90	4.50	0.76	9.07
0.97	5.97	0.83	4.80
0.98	5.67	0.85	8.83
0.99	6.10	0.86	7.57
1.07	4.97	0.97	5.10
1.08	4.57	0.97	12.47
1.10	6.23	0.97	9.77
1.20	5.17	1.07	10.87
1.21	6.10	1.09	10.83
1.22	5.60	1.07	6.93

(a) Time after application of all deicing fluids and salts.

In contrast to the other demonstration tests, the Battelle fluid did not generate higher RCR numbers. This may have been due to the high wind conditions and lower ice coverage on the iced strip treated with KAc RDF. More consistent results might be achieved if this test could be repeated under more controlled conditions. If feasible, a short test in December 2010 under more suitable conditions may be scheduled at a DoD or commercial airport.

It was planned to estimate ice melting time by a study of the RCR versus time data. It was assumed that the RCR would start in the Nil range and rise with time as the ice melted. The time from RDF application until the RCR reached 9 would be the ice melting time. However, the data did not indicate a significant increase in RCR as the demonstration proceeded.

A discussion of the analysis of the raw data is provided in Section 6.

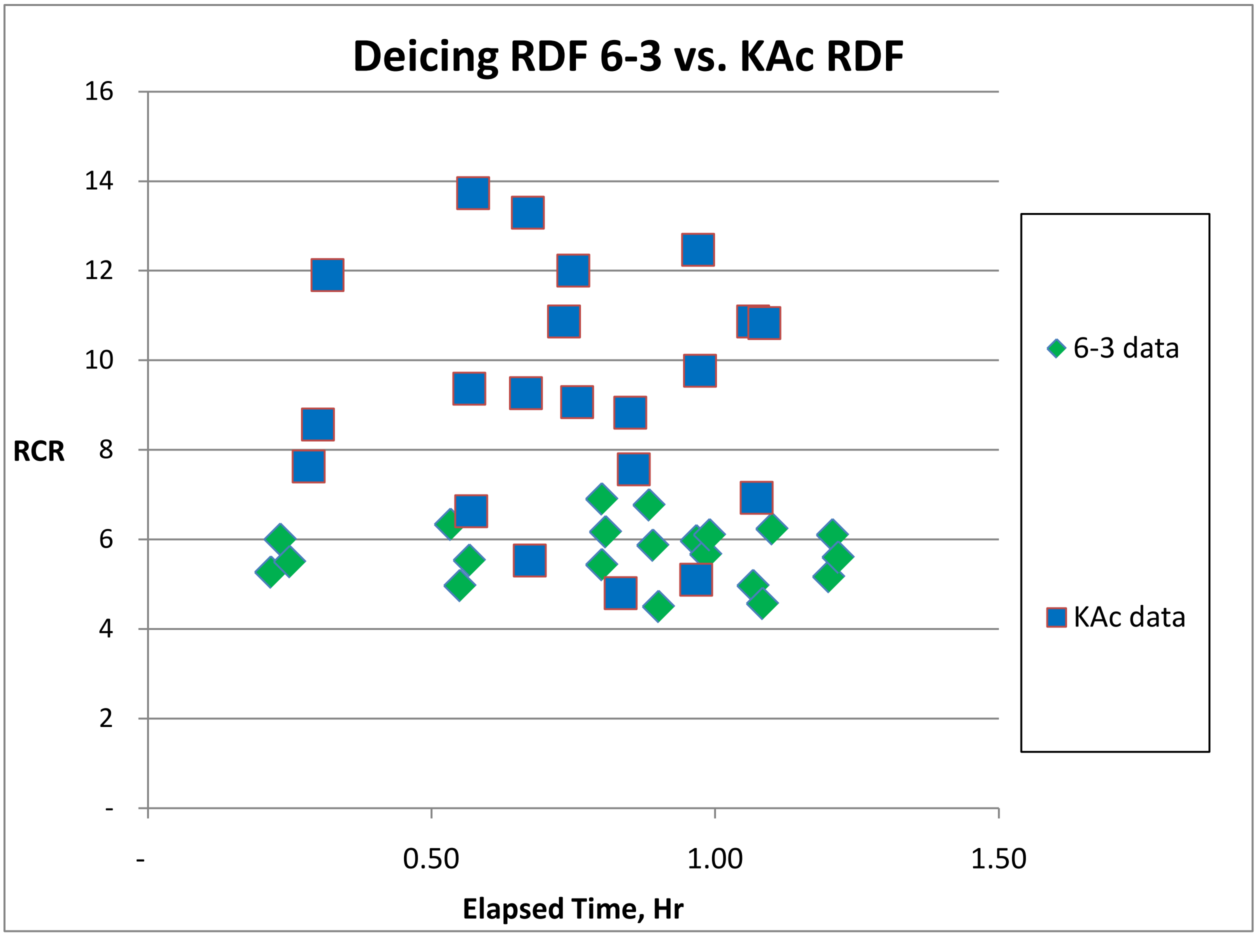


Figure 30. RCR versus Elapsed Time for RDF 6-3 Deicing Tests

5.6.6 Qualitative Data

Qualitative data covering ease of use and maintenance were gathered using a survey form completed by staff who participated in the survey. A blank form is displayed in Table 30.

A total of 10 forms were received; all 10 rated ease-of-use, but only 7 rated ease-of-maintenance. In some cases observers did not feel qualified to rate a specific attribute and put “NA” rather than a numeric rating; these responses were ignored. In other cases they said “same as KAc RDF;” in those cases a 10 was assigned to all three fluids.

The numbers were totaled and averaged. The results are noted in Table 31. The standard deviation of the full survey was 1.5 rating points for ease-of-use and 1.7 points for ease-of-maintenance.

Table 30. Qualitative Data Collection Form

Qualitative Ease of Use and Maintenance Rating
Demonstration of an Environmentally Benign and Reduced
Corrosion Runway Deicing Fluid

Name ________________	**Date __/__/2010**
Duty/Expertise _______________	

Please rank how you view the fluid listed above in qualitative rating system for use of ease and ease of maintenance.

(Rating system is 1 to 10, with 10 being the highest ranking/best/easiest to use/ maintain)

	Rating (1 to 10; 10 is best)		
	RDF 6-12	RDF 6-3	KAc RDF
Criteria (Ease of Use)			
Filling			
Fluid application			
Odor/Smell			
Corrosion/deterioration of pumps/valves/seals/fittings			
Equipment modifications			
Overall Ease of Use rating			
Criteria (Ease of Maintenance)			
Other fluid comments			
Overall Maintenance Rating			

Table 31. Results of Qualitative Evaluation Survey

Parameter	**Mean Rating (1 to 10; 10 is best)**		
	RDF 6-12	RDF 6-3	KAc RDF
Ease of Use	8.3	8.3	8.2
Ease of Maintenance	8.6	8.4	8.7

A discussion of the analysis of the raw qualitative data is provided in Section 6.

6.0 PERFORMANCE ASSESSMENT

6.1 QUANTITATIVE DATA ANALYSIS

The results of the data analysis procedures for the quantitative data identified in Table 3 (presented earlier) are described below.

6.1.1 Acute Aquatic Toxicity

1. Metric description: LC_{50} for water fleas (*Daphnia magna*, 48 hr test period) and LC_{50} for fathead minnows (*Pimephales promelas*, 96 hr test period) in mg/L.
2. Data description: LC_{50} for the two noted species were obtained from AMS 1435A for Battelle-RDFs, and from the open literature for KAc RDF. The results were presented earlier in Table 14 and Figure 8.
3. Data analysis: The LC_{50} values were compared.
4. Success criteria: the Battelle-RDFs shall be considered acute-toxicity successes if their LC_{50} values for *Daphnia magna* and *Pimephales promelas* are higher than the corresponding LC_{50} values for KAc RDF.
5. Status: Success criteria were met because the LC_{50} values for *Daphnia magna* and *Pimephales promelas* for both Battelle-RDFs were higher than the LC_{50} for KAc RDF.

6.1.2 Chronic Toxicity

1. Metric description: IC_{25} for *Ceriodaphnia magna* and *Pimephales promelas*.
2. Data description: IC_{25} for the two noted species were obtained from the Wisconsin State Laboratory of Hygiene. The results were presented earlier in Table 15 and Figure 9.
3. Data analysis: The IC_{25} values were compared.
4. Success criteria: The Battelle-RDFs shall be considered chronic-toxicity successes if their IC_{25} values for Ceriodaphnia magna and Pimephales promelas are higher than the corresponding IC_{25} values for KAc RDF.
5. Status: Success criteria were met because the IC_{25} values for *Ceriodaphnia magna* and *Pimephales promelas* for both Battelle-RDFs were higher than the IC_{25} for KAc RDF.

6.1.3 Chemical Oxygen Demand and Biochemical Oxygen Demand

1. Metric description: COD and BOD_5 in kg O_2/kg fluid.

2. Data description: COD and BOD_5 were obtained from AMS 1435A for Battelle-RDFs, and from the open literature for KAc and KAc+PG RDFs. The results were presented earlier in Table 16 and Figure 10.

3. Data analysis: The COD and BOD_5 values were compared.

4. Success criteria: If the COD and BOD_5 values (for Battelle-RDF 6-12 and 6-3) are between the respective COD and BOD_5 levels for KAc RDF and KAc-PG RDFs, the fluid shall be considered a success.

5. Status: The success criteria were met as the COD and BOD_5 values for both Battelle-RDFs were between the values for KAc RDF and KAc+PG RDF.

6.1.4 Cadmium Corrosion

1. Metric description: Corrosion of cadmium-plated parts, in weight change $mg/cm^2/24$ hours.

2. Data description: Each Battelle-RDF and the KAc RDF were subjected to the AMS 1435A cadmium corrosion test. The weight losses for each fluid were compared to the established limit and to each other. The results were presented earlier in Figures 11 and 12.

3. Data analysis: Lower Cd corrosion is related to reduced aircraft-corrosion rates and reduced airfield-maintenance requirements. They were reflected in the cost-benefit analysis figures.

4. Success criteria: If the weight loss of either Battelle-RDF is more than 50% lower than the KAc RDF weight loss, it was considered superior. If it is no more corrosive, then it was considered acceptable; both cases would constitute a success.

5. Status: Success criteria were met because the weight losses were more than 50% lower than the KAc RDF weight loss.

6.1.5 Carbon-carbon Brake Pad Corrosion

1. Metric description: Corrosion of carbon-carbon brake pad coupons, in weight loss percent.

2. Data description: Each Battelle-RDF and the KAc RDF were subjected to the Honeywell carbon-carbon brake oxidation test. The weight losses for each fluid were compared to each other. The results were presented earlier in Figure 13.

3. Data analysis: Lower carbon-carbon brake pad corrosion is related to lower aircraft-brake-system maintenance requirements. They were reflected in the cost-benefit analysis figures.

4. Success criteria: If the weight loss of either Battelle-RDF was more than 50% lower than the KAc RDF weight loss, it was considered superior. If it is no more corrosive, then it was considered acceptable; both cases would constitute a success.

5. Status: Success criteria were met because the weight losses from the Battelle-RDFs were more than 50% lower than the KAc RDF weight loss.

6.1.6 Anti-icing Friction Values

1. Metric description: RCR.

2. Data description: Battelle-RDF and KAc RDF were applied to the runway. Water was sprayed on the pavement to simulate an ice storm. Data on runway friction, or slipperiness, were determined (using a BOWMONK AFM2 decelerator mounted in a truck and operated by the 88th ABW) as a function of time. The truck was driven along the airfield and the decelerator used to generate an RCR number. The process was repeated as water was added to the anti-iced runway to generate several measures of the surface slipperiness during each test. An average RCR value of >17 is categorized as “good,” 12-17 as “fair,” and < 11 as “poor.” (The RCR range was established for civilian passenger and cargo aircraft but don’t necessarily translate exactly to all Air Force aircraft.) The data for anti-icing friction values were presented earlier for RDF 6-3 in Table 19 and Figure 15, and for RDF 6-12 in Table 19 and Figure 18.

3. Data analysis: Lines were fitted to the RCR data to establish the mean for the Battelle-RDF and the KAc RDF fluid. Using a 95% confidence interval, an upper and a lower bound was calculated (see Appendix B for details). The results were plotted on the figure. The confidence interval (RCR at the lower bound to the RCR at the upper bound) was determined for the RDF 6-3 versus KAc RDF test series after 23 minutes of elapsed test time after the start of simulated freezing precipitation; see Table 32 and Figure 31. The process was repeated for the RDF 6-12 versus KAc RDF anti-icing series; see Figure 32. The Battelle-RDFs intervals were compared to the KAc intervals.

4. Success criteria: If the Battelle-RDF interval was higher than the KAc interval with no overlap, it was considered superior, or if the two intervals overlapped (so that one was not statistically better than the other) then the Battelle-RDF was considered acceptable and the test a success.

5. Status: Success criteria were met for both Battelle-RDFs because their intervals overlapped the KAc RDF intervals. This is shown graphically on Figure 33.

Table 32. Comparison of Anti-Icing Friction Values

	RCR: Anti-Icing Series No. 1 (Confidence interval at 36 min elapsed time)			RCR: Anti-Icing Series No. 2 (Confidence interval at 23 min elapsed time)		
Parameter	**RDF 6-3**	**KAc RDF**	**Assessment**	**RDF 6-12**	**KAc RDF**	**Assessment**
Lower bound	9	6	RDF 6-3 interval overlapped the KAc RDF interval and was therefore equivalent	9	8	RDF 6-12 interval overlapped the KAc RDF interval and was therefore equivalent
Mean	11	8		10	9	
Upper bound	12	10		11	10	

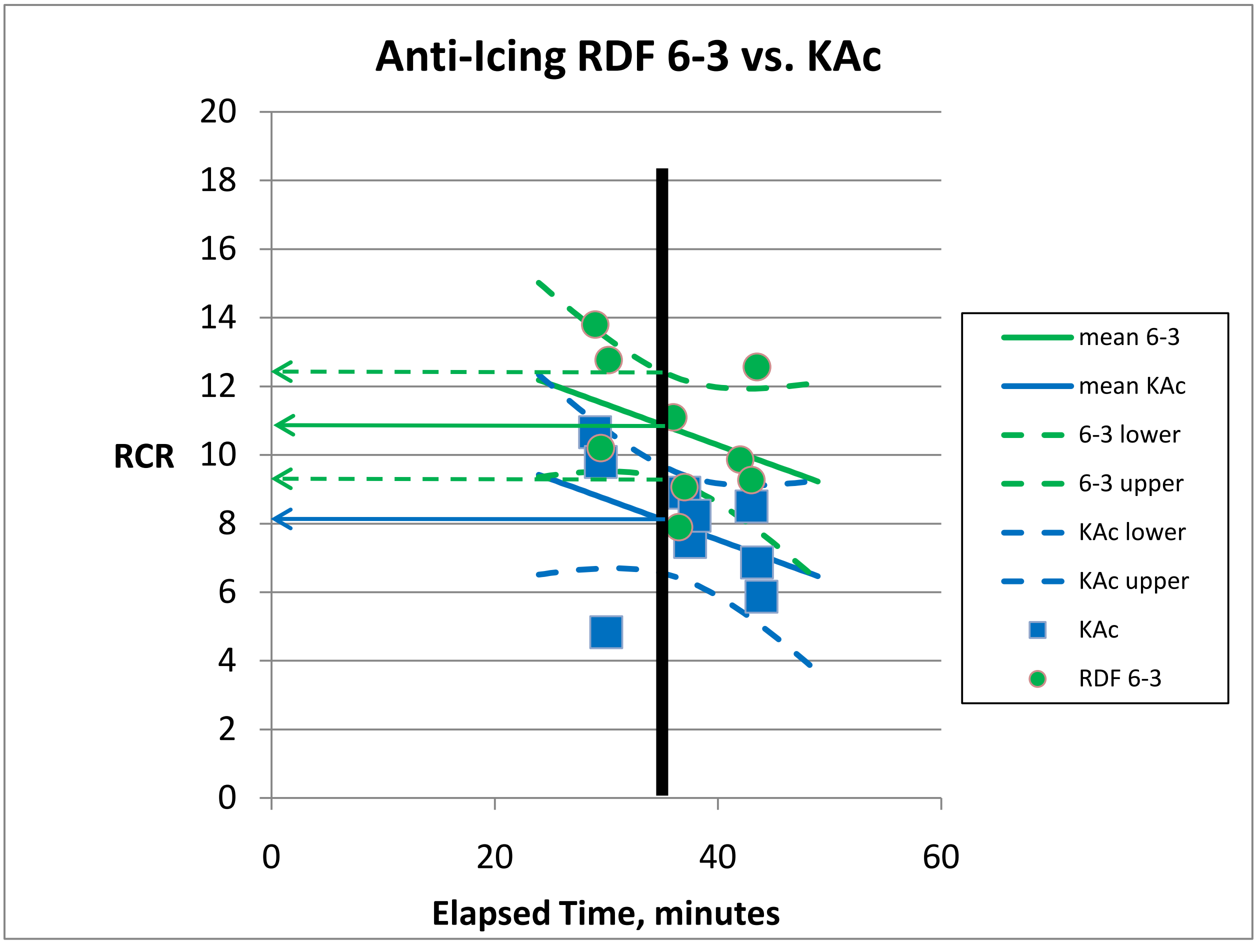


Figure 31. Anti-Icing Friction Test with RDF 6-3 and KAc RDF, Showing Range and Mean Friction Values

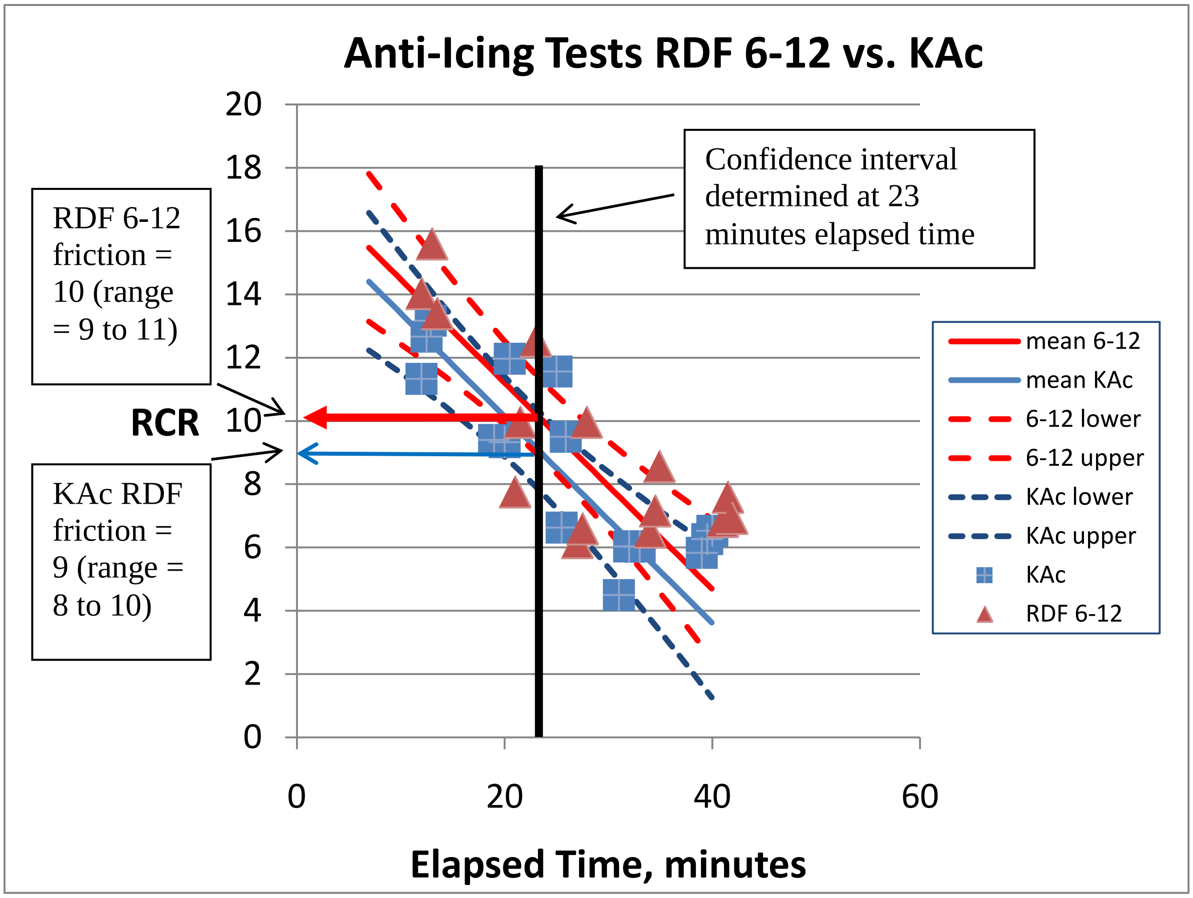


Figure 32. Anti-Icing Friction Test with RDF 6-12 and KAc RDF, Showing Mean Friction Values

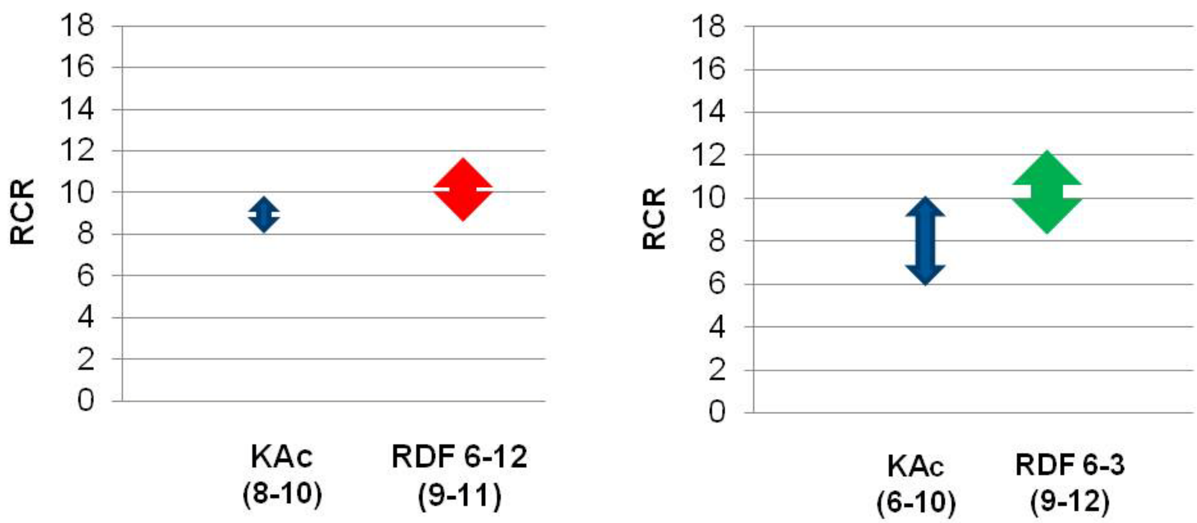


Figure 33. Comparison of Anti-Icing Friction Test Confidence Intervals for RDF 6-12 and RDF 6-3 versus KAc RDF

6.1.7 Anti-icing HOT

1. Metric description: HOT in minutes.

2. Data description: The Battelle-RDF was applied by one truck on the test surface. Simultaneously KAc RDF was applied by a second truck onto a similar section of the runway. Water was sprayed on the pavement to simulate an ice storm. Data on runway friction, or slipperiness, were determined as a function of time. The minutes the surfaces remained suitable for aircraft traffic was estimated based on the RCR readings.

3. Data analysis: The RCR values were plotted versus elapsed time. Vertical lines were dropped down from the point where a RCR= 9 horizontal line crossed the upper and lower bounds for each fluid. The corresponding elapsed times represented the HOT interval. The HOT confidence intervals for RDF 6-3 versus KAc RDF are summarized in Table 33 and Figure 34. The process was repeated for the RDF 6-12 versus KAc RDF anti-icing series; see Figure 35.

4. Success criteria: If the Battelle-RDF HOT interval represented a longer runway protection time interval than the KAc RDF protection interval with no overlap, it was considered superior or if the two intervals overlapped (so that neither fluid was statistically better than the other), then the Battelle-RDF was considered acceptable and the test a success.

6. Status: Success criteria were met because the HOT intervals for both Battelle-RDF fluids operated overlapped the corresponding KAc RDF interval. This is shown graphically on Figure 36.

Table 33. Comparison of Anti-Icing Hold Over Times

Parameter	HOT: Anti-Icing Series No. 1 (Confidence interval at RCR=9), minutes			HOT: Anti-Icing Series No. 2 (Confidence interval at RCR = 9), minutes		
	RDF 6-3	KAc RDF	Assessment	RDF 6-12	KAc RDF	Assessment
Lower bound	24	8	RDF 6-3 HOT interval overlapped the KAc RDF interval and was therefore equivalent	23	20	RDF 6-12 HOT interval overlapped the KAc RDF interval and was therefore equivalent
Mean	51	28		27	24	
Upper bound	78	47		31	27	

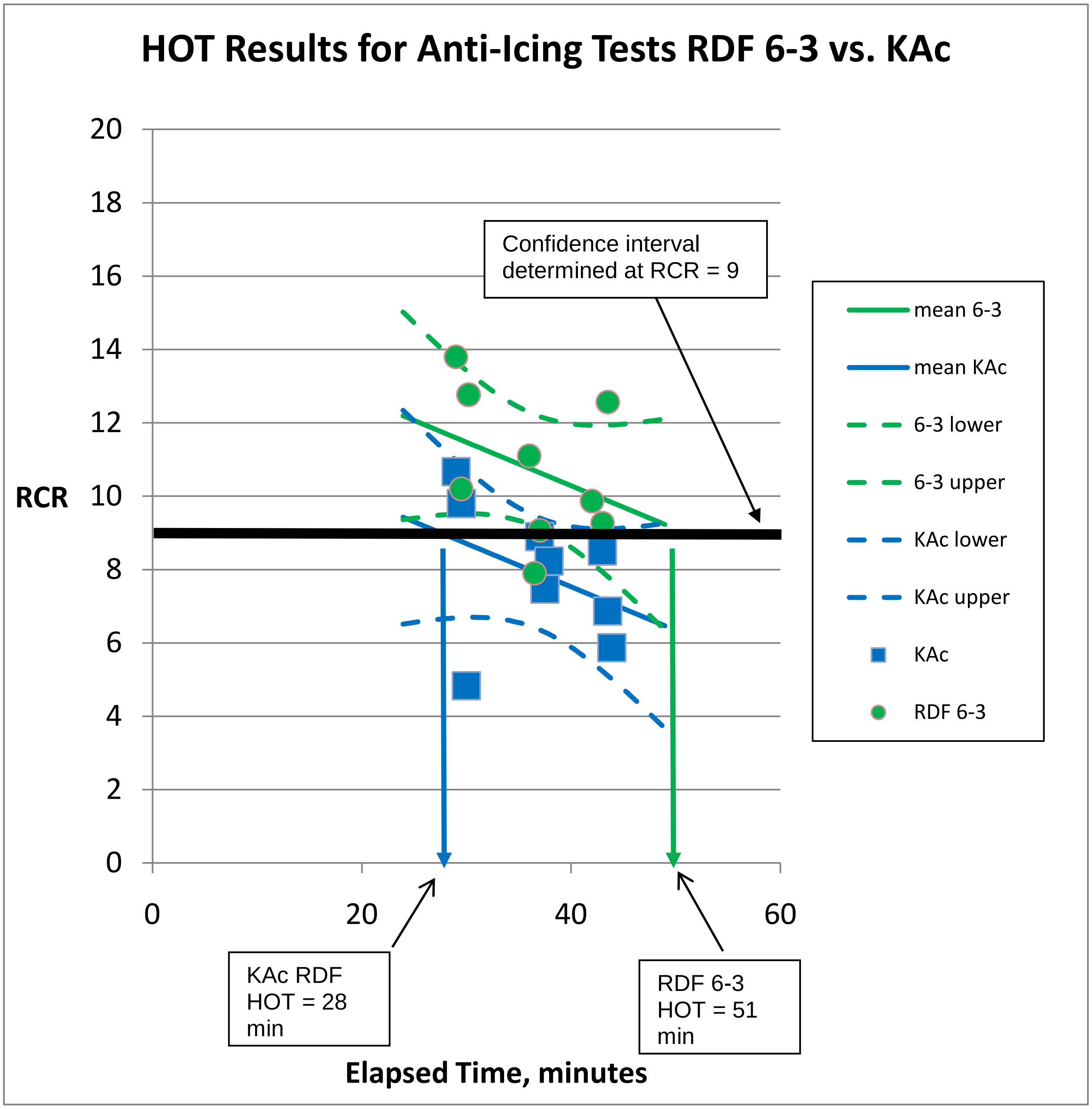


Figure 34. Anti-Icing Tests with RDF 6-3 and KAc RDF Showing Predicted HOTs

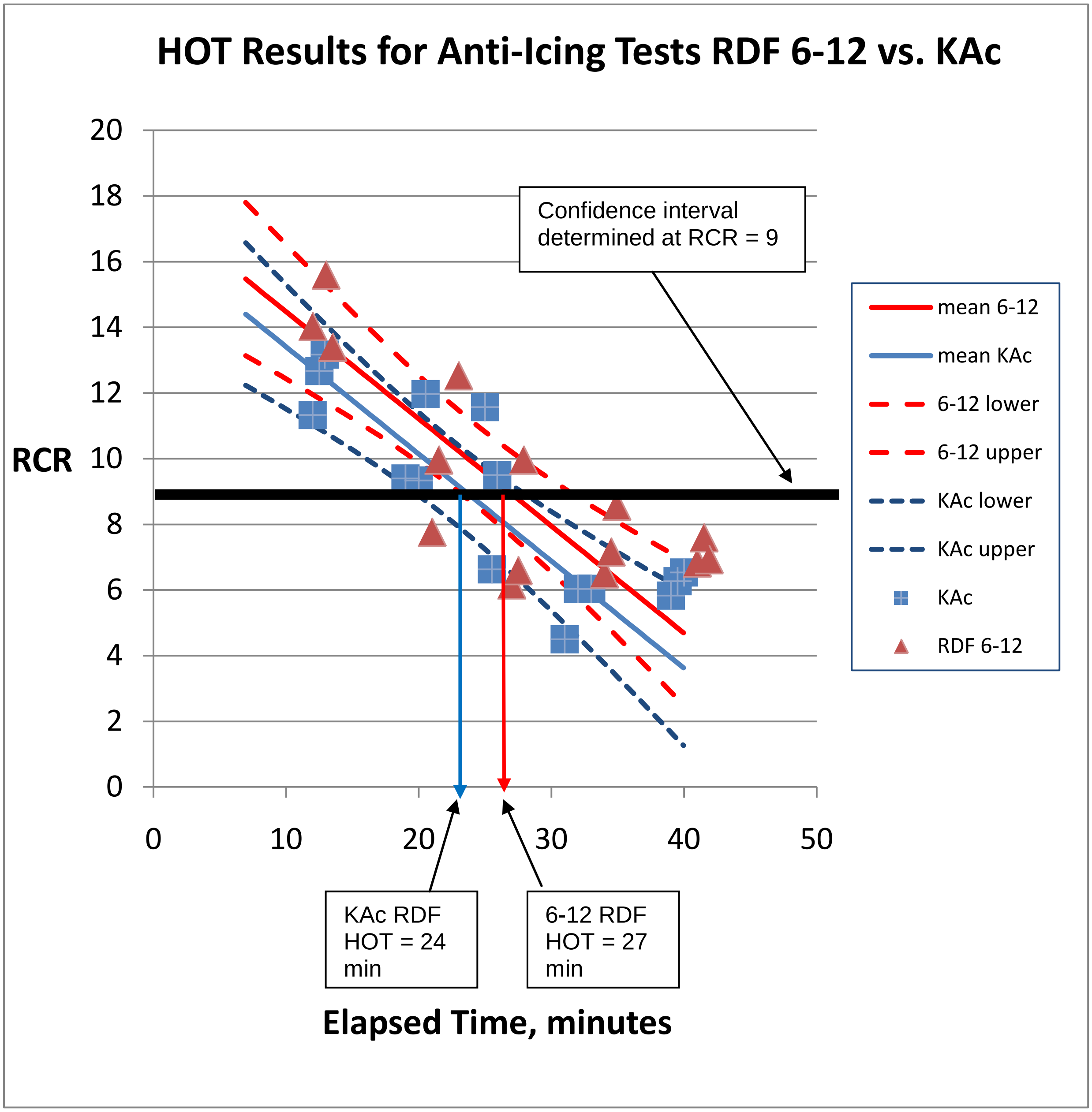


Figure 35. Anti-Icing Test with RDF 6-12 and KAc RDF Showing Predicted HOTs

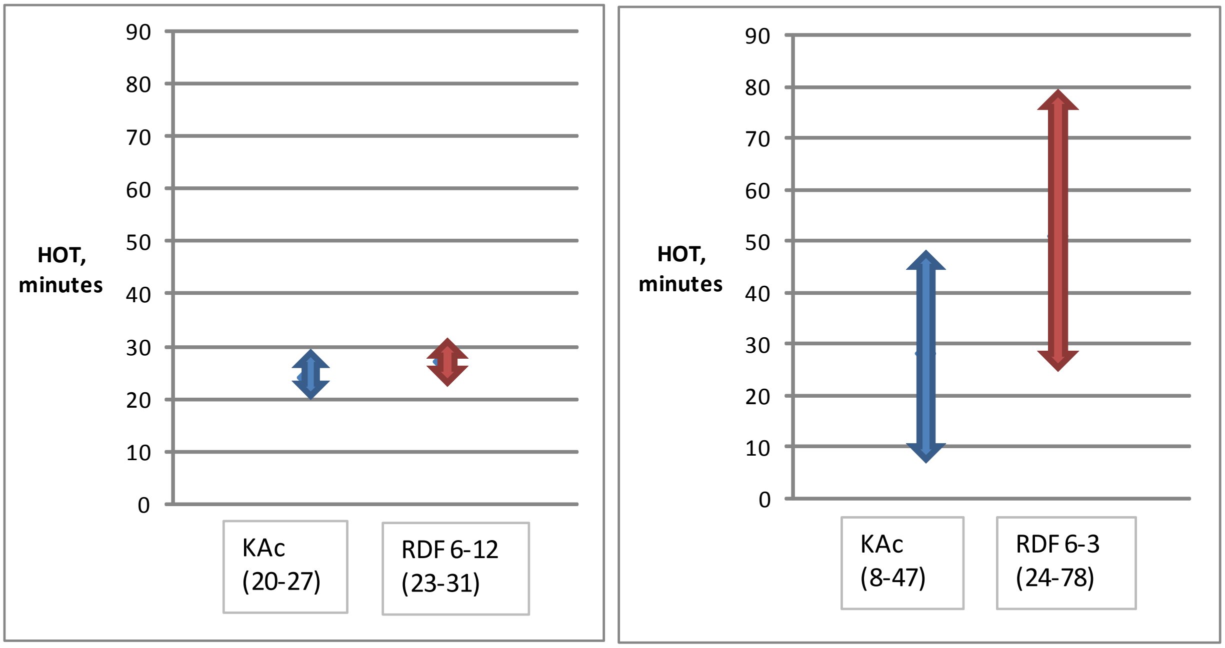


Figure 36. Comparison of Anti-Icing HOT Intervals for RDF 6-12 and RDF 6-3 versus KAc RDF

6.1.8 Deicing Friction Values

1. Metric description: RCR.
2. Data description: The runway was iced with water and then the following day data on runway friction, or slipperiness, were collected. The process was repeated to generate several measures of the surface slipperiness during each test.
3. Data analysis: Lines were fitted to the RCR data to establish the mean for the Battelle-RDF and the KAc RDF fluid. Using a 95% confidence interval, an upper and a lower bound were calculated for the period after the second RDF application; see Appendix B for details. The results were plotted on the figure. The confidence interval (RCR at the lower bound to the RCR at the upper bound) was determined for the RDF 6-12 versus KAc RDF test series at 2.72 hours (point of highest RCR) after the application of the RDFs; see Table 34 and Figure 37. The process was repeated for the RDF 6-3 versus KAc RDF deicing series; see Figure 38. The Battelle-RDFs intervals were compared to the KAc intervals.
4. Success criteria: If the Battelle-RDF interval was higher than the KAc interval with no overlap, it was considered superior or, if the two intervals overlapped, (so that one was not statistically better than the other), then the Battelle-RDF was considered acceptable and the test a success.

5. Status: Success criteria were met for both Battelle-RDFs because their intervals overlapped the KAc RDF intervals. This is shown graphically on Figure 39.

For the first deicing test, the period after the second deicing was analyzed and exponential trend lines were fitted to the data. They are shown along with 95% confidence lower and upper bounds. As noted, the RDF 6-12 trend line is always slightly higher than the one for KAc RDF.

Table 34. Comparison of Deicing Friction Values

Parameter	RCR: Deicing Series No. 1 (Confidence interval at 2.7 hours elapsed time)			RCR: Deicing Series No. 2 (Confidence interval results were found to be independent of elapsed time)		
	RDF 6-12	KAc RDF	Assessment	RDF 6-3	KAc RDF	Assessment
Lower bound	5	4	RDF 6-12 interval overlapped the KAc RDF interval and was therefore equivalent	4	3	RDF 6-3 interval overlapped the KAc RDF interval and was therefore equivalent
Mean	5.4	4.8		6	9	
Upper bound	6	5		7	16	

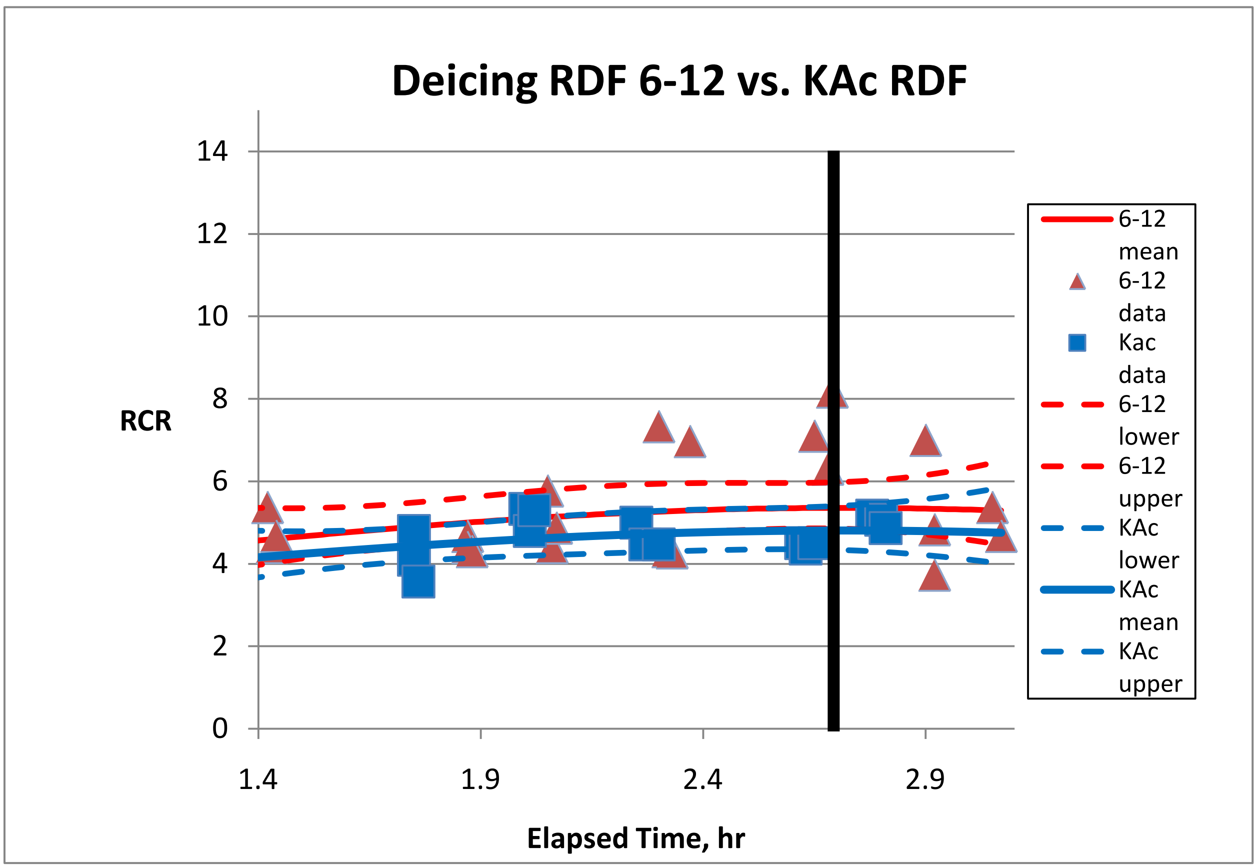


Figure 37. Deicing RCR versus Elapsed Time for KAc RDF and RDF 6-12 Showing Range and Mean Friction Values

For the second deicing test, most of the KAc RDF friction values were higher than for RDF 6-3; but the KAc RDF also showed a greater variability. Results were expected to be similar to those found in Figure 37 (for RDF 6-12). We suspect the high winds provided an uneven ice surface which may have affected the results.

A generalized least squares model with only a fixed treatment effect produced 95% simultaneous confidence intervals of 5 to 6 for the RDF 6-3 and 8 to 11 for the KAc RDF, which would indicate the RDF 6-3 was inferior. However, by calculating a prediction interval, we can be 95% confident that an airport that uses RDF 6-3 can expect RCR values between 4 and 7, and KAc RDF values between 3 and 16. These latter figures were included in Figure 39 in recognition of the large variability in the data.

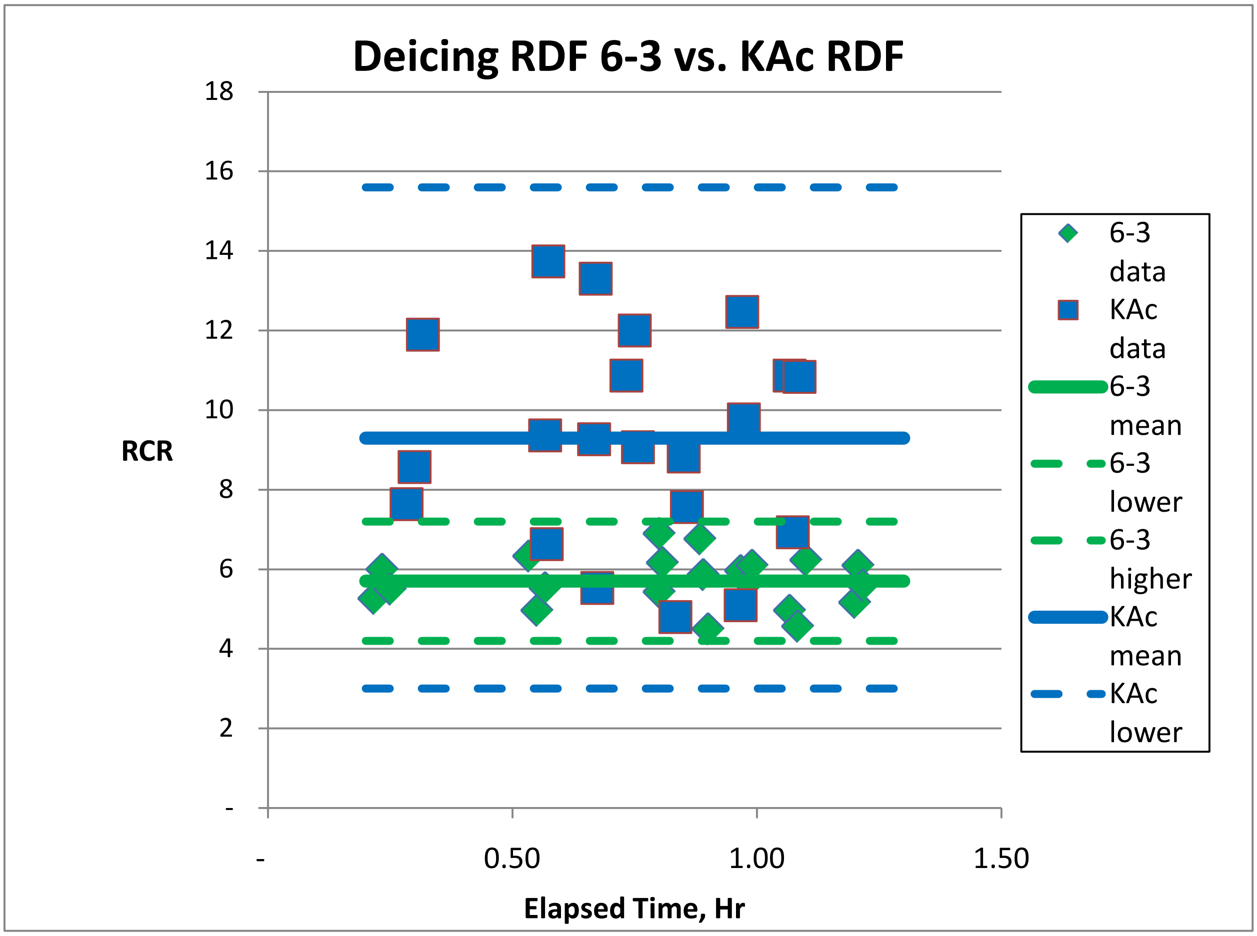


Figure 38. Deicing RCR versus Elapsed Time for KAc RDF and RDF 6-3 Showing Range and Mean Friction Values

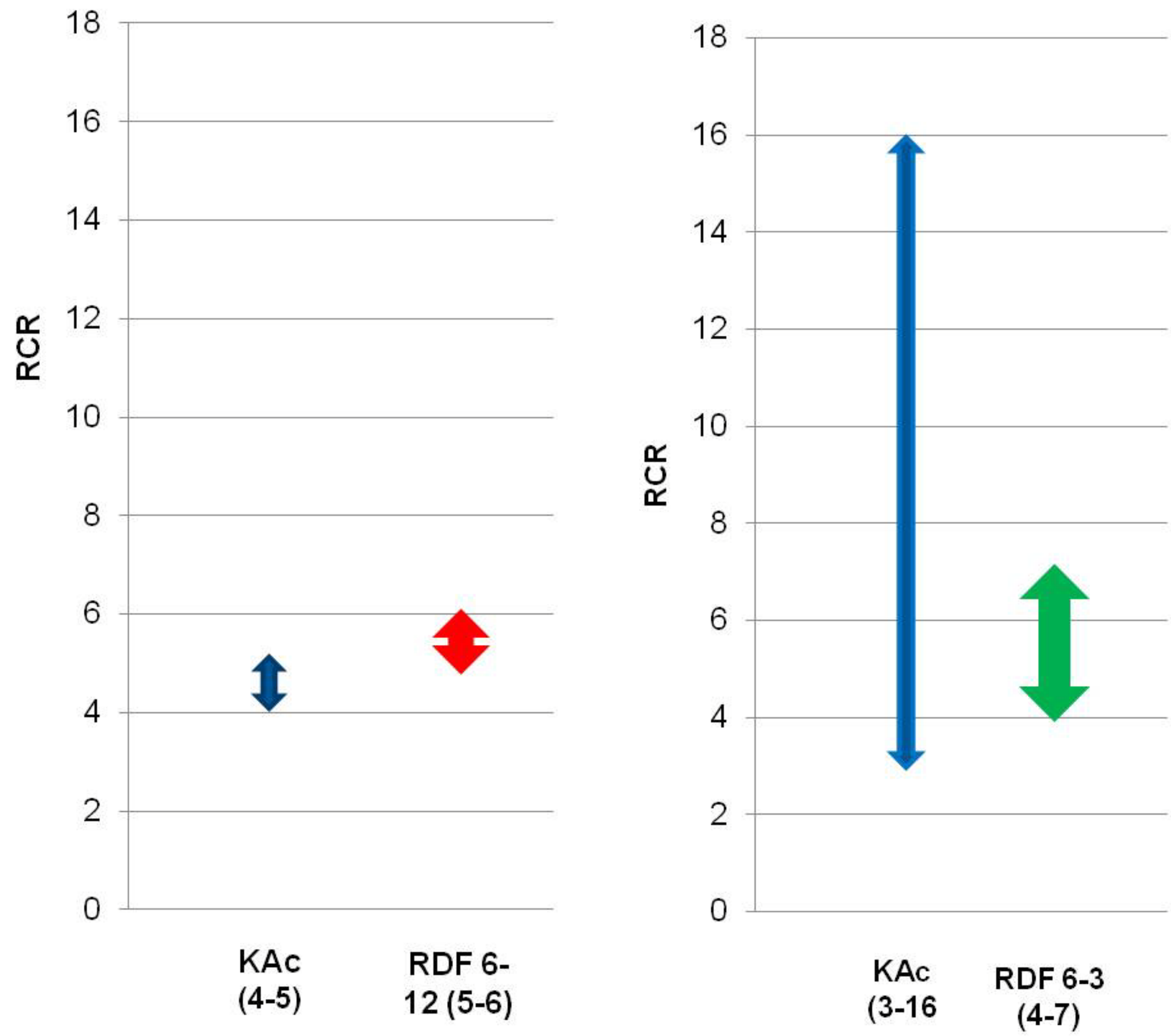


Figure 39. Comparison of Deicing Friction Test Confidence Intervals for RDF 6-12 and RDF 6-3 versus KAc RDF

6.1.9 Deicing Melting Time

1. Metric description: The melt efficiency in minutes.
2. Data description: The plan was to apply the Battelle-RDFs with one truck on the test surface. Simultaneously KAc RDF would be applied by a second truck onto a similar section of the runway, under similar meteorological (e.g., ice and snow thickness, temperature, wind) conditions, using similar dosage levels. The times to melt through to the surfaces would then be measured.

3. Data analysis: The first test series was conducted on the melting of packed snow. The melting time was nearly instantaneous, making collection of comparative data difficult. The next melting series attempted was on RDF applied to the ice-coated runway. We planned to determine the time for the RCR to rise from a "Nil" initial rating to an acceptable level (RCR = 9). The observed RCR values did not significantly increase with time. While the planned test methodology could not be followed, it could be concluded that the Battelle-RDFs melted the ice as fast as the KAc RDF.

4. Success criteria: If the Battelle-RDF melt time interval was shorter than the KAc RDF interval with no overlap, it was considered superior or, if the two intervals overlapped, (so that one was not statistically better than the other), then the Battelle-RDF would be considered acceptable and the test a success.

5. Status: The observed RCR values did not significantly increase with time. While the planned ice-melting time methodology could not be followed, it could be concluded that the Battelle-RDFs melted the ice as fast as the KAc RDF and was, therefore, a success.

6.2 QUALITATIVE DATA ANALYSIS

The data analysis procedures for the qualitative data are described below.

6.2.1 Ease of Use

1. Metric description: Qualitative 1 through 10 ease-of-use rating.

2. Data description: The 88th ABW operators plus other knowledgeable observers rated KAc RDF and each Battelle-RDF for ease of use. Areas of interest included filling, fluid application, and smell.

3. Data analysis: The average ease-of-use rating for KAc RDF and each Battelle-RDF was determined; see Table 31 (presented earlier) and Figure 40. Because the viscosity of RDF 6-3 is slightly higher than the other fluids, it received a slightly lower rating.

4. Success criteria: If the mean of each Battelle-RDF was higher or fell within 2 digits of the KAc RDF rating, the fluid was deemed a success.

5. Status: The success criteria were met because the means were nearly identical and within the 2 digit success criteria.

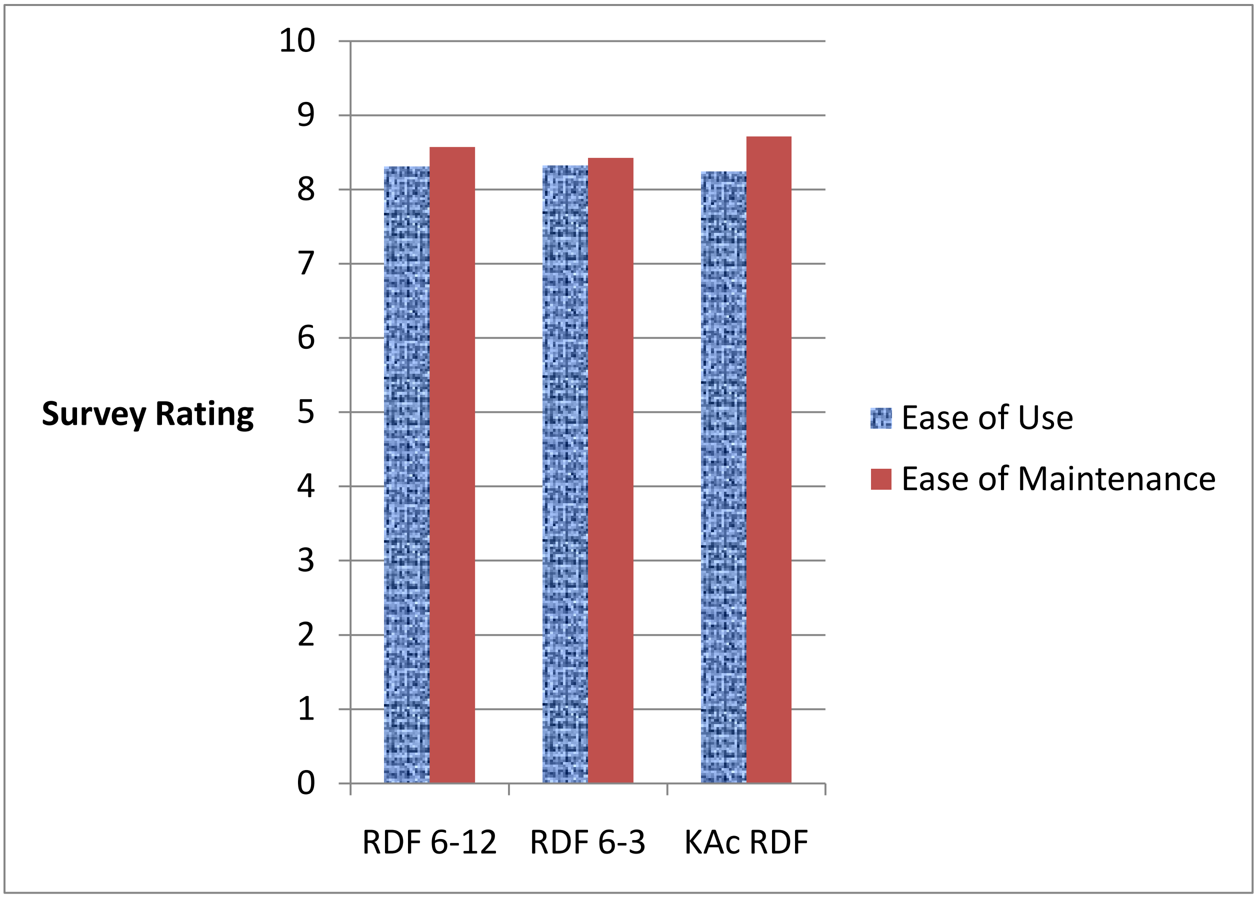


Figure 40. Relative Results from Ease of Use and Ease of Maintenance Surveys

6.2.2 Maintenance

1. Metric description: Qualitative 1 through 10 ease-of-maintenance rating.
2. Data description: The 88th ABW operators, as well as other knowledgeable observers, rated the KAc RDF and each Battelle-RDF for ease of maintenance. Areas of interest included obvious corrosion/deterioration of pumps, valves, seals, or fittings and the need for equipment modifications to facilitate use.
3. Data analysis: The average ease-of-maintenance ratings for KAc RDF and each Battelle-RDF were determined; see Table 31 and Figure 40 presented earlier.
4. Success criteria: If the mean of each Battelle-RDF was higher or fell within 2 digits of the KAc RDF rating, the fluid was deemed a success.
5. Status: The success criteria were met because the intervals were nearly identical and within the 2 digit success criteria.

7.0 COST ASSESSMENT

The development of a cost-effective RDF with superior environmental and material compatibility properties is critical to its acceptance at DoD and commercial airports. While the impact of excessive corrosion and degradation of aircraft materials on aircraft owners is substantial, the airport/runway operators (not the aircraft owners) pay for the fluids and, therefore, seek the lowest cost RDFs. An environmentally superior and less corrosive RDF at a higher cost may not be acceptable. Using the data gathered in this demonstration, a life-cycle analysis was conducted to determine if there was a benefit to using Battelle-RDFs.

Good numbers on RDF consumption data are difficult to obtain. As noted on Figure 41, there are 80 USAF sites, located in the northern half of the U. S. (including Alaska) where RDF would likely be used. This includes 31 active USAF bases, 45 Air National Guard bases, and 4 Air Force Reserve Command bases [26]. A survey was conducted by AFCESA [27]. They solicited usage information and received the following responses for the 2009/2010 deicing season as noted in Table 35.

Table 35. Runway Deicing Fluid Usage Data Collected by Survey

Installation	RDF Usage, gal	Installation	RDF Usage, gal
Minot AFB, ND	3,300	WPAFB, OH[(a)]	14,200
Ellsworth AFB, SD	3,000	Eielson AFB, AK	4,035
Mountain Home AFB	3,450	Misawa, Japan	81,996
Hill AFB, UT	56,013	Osan, S. Korea	12,000
Elmendorf AFB, AK	105,000	Kunsan, S. Korea	24,000

(a) Obtained separately from personnel at WPAFB based on the 2008/2009 deicing season.

The total is ~307k gallons and represents only about 10% of the possible respondents. The average is ~31k gallons. No data were collected from the Air Force Reserve (AFR) or Air National Guard (ANG) bases, but presumably their usage would be lower. Assuming each of the 31 Air Force Bases located in the northern half of the US consumed the average per base usage (31k gallons), the annual usage would be 961k gallons per year (gpy). Assuming the AFR and ANG bases use ~1k gallons/year, the US Air Force usage in North America would be ~1 million gpy.

For the purposes of this cost assessment, it was assumed that the average RDF usage for the entire DoD is ~1 million gallons/year. This is consistent with the estimate of the commercial sector consuming ~8 million gallons/year of liquid RDF [28] in the U. S.
Cost figures for the transition from KAc RDF to Battelle-RDF were estimated for the following three levels of changeover:

1. A single “typical” Air Force base: 31k gpy.
2. All North American DoD airfields: 1 million gpy.
3. All (military and civilian) in the U. S.: 9 million gpy.

This page intentionally left blank.

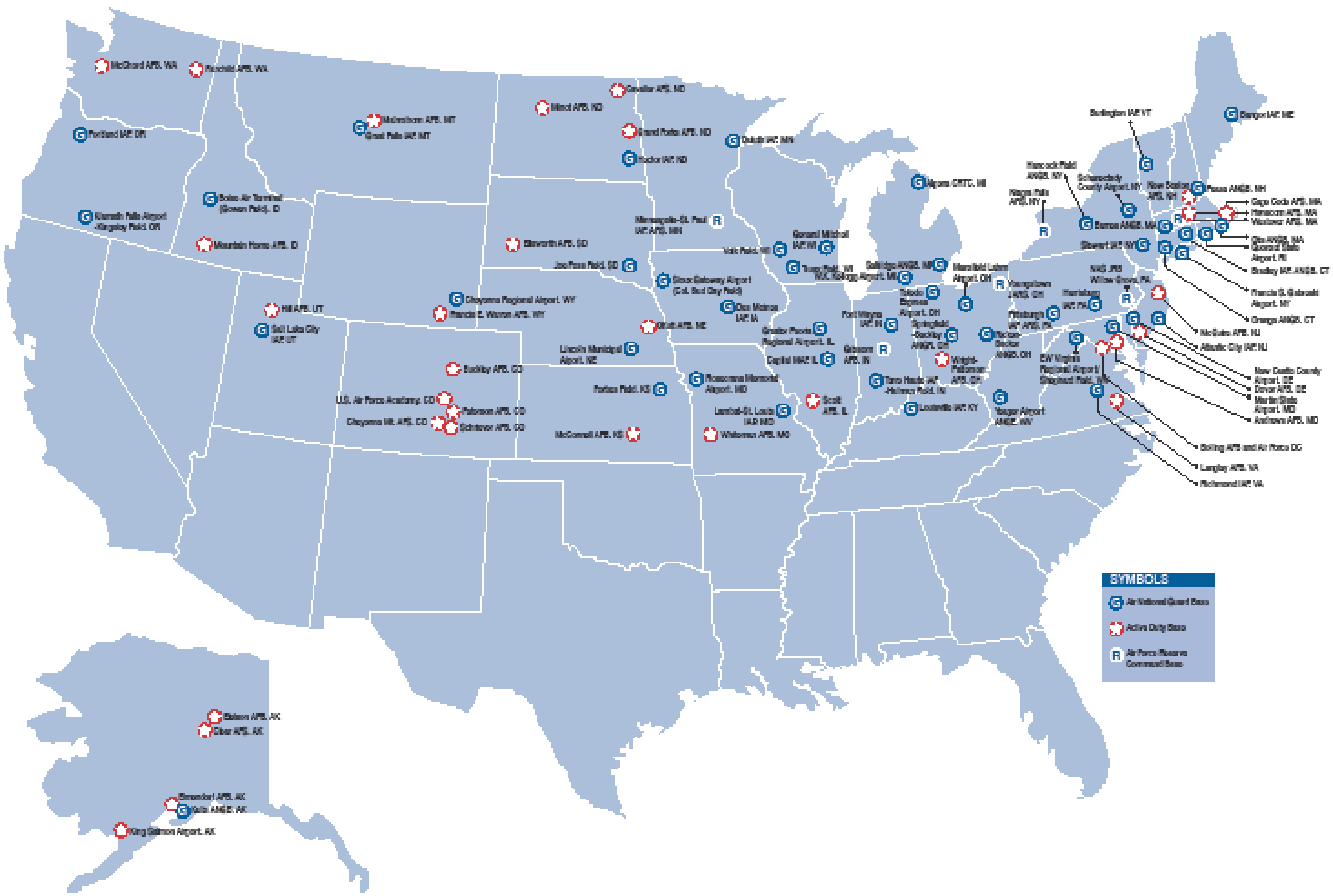


Figure 41. Potential RDF Use Site in North America

This page intentionally left blank.

7.1 COST MODEL

A description of the cost elements in the cost model is provided in Table 36.

Table 36. Cost Model for RDF Replacement

Cost Element	Data Collected During the Demonstration
Capital Costs	
Hardware capital costs	Estimates made based on the need to modify the RDF storage tank or spray truck (pumps, seal, nozzles, etc.)
Installation costs	Labor and materials to make any necessary modifications to the RDF fluid equipment
Operating Costs	
Consumables	Estimate based on the cost to procure raw material, formulate, and distribute the RDFs to the base, plus profit
Facility operating costs	Charge for the number of operators, fuel or equipment needed to deice the airfield, and wastewater treatment charges
Operator training	Estimate of operator training
Maintenance	Charge for required maintenance and the labor and materials for the maintenance actions

Provided on the next pages is more information on each cost element, including:

1. A brief description of the cost element.
2. A list of the data collected and the basis for the cost estimate.
3. An explanation of how the data was interpreted and how other important issues were addressed.

7.1.1 Hardware Capital Costs

7.1.1.1 Description of Cost Element

This cost element covers hardware costs for fluid storage and spraying equipment modification.

7.1.1.2 Data to Be Collected and Basis for Estimate

The right to manufacture and distribute Battelle-RDFs was licensed to Basic Solutions North America Corp, a major supplier of KAc RDFs in North America and Europe. Basic Solutions began selling Battelle-RDF 6-4 under the trade name **GEN3 64™** for the 2009/2010 deicing season. (Formulation 6-4 is similar to the 6-12 and 6-3 formulations except that it has a higher bio-based content.) Fifteen Canadian commercial airports and four USA commercial concerns are using or testing **GEN3**. In all these commercial airport trials, **GEN3 64™** was used without modification to the storage tanks, transfer pumps, deicing fluid trailers, spray nozzles, or fluid delivery pumps. This supports the conclusion that Battelle-RDFs can be used as a drop in replacement.

7.1.1.3 Data Interpretation

No capital costs need be included for conversion from KAc RDF to Battelle-RDF 6-12 or 6-3. Thus, this cost element is zero.

7.1.2 Installation Costs

7.1.2.1 Description of Cost Element

This cost element includes required labor and materials to make necessary modifications to the RDF fluid equipment.

7.1.2.2 Data to Be Collected and Basis for Estimate

Because it was concluded the Battelle-RDF can be used as a drop in replacement, no data needed to be collected.

7.1.2.3 Data Interpretation

Because no equipment installation or modification will be needed, this cost element is zero.

7.1.3 Consumables

7.1.3.1 Description of Cost Element

The costs include the RDF raw-material costs, formulation charges, profit, and transportation charges associated with delivering the RDF to the Air Force bases.

7.1.3.2 Data Collected and Basis for Estimate

The following unit cost data were collected for KAc, bio-based FPDs (crude and pure), PG, and additives through telephone contact with material suppliers in May 2010:

- KAc (50% solution): $0.33/lb (or > $0.66 on a 100% basis).
- Bio-based FPD (pure, 99.7% solution): $0.32/lb.
- Bio-based FPD (crude, 69% solution): $0.11/lb (after purification for FFA and color removal).
- PG: $0.85/lb.
- Additives: $2 to 4/lb depending on the process.

We assumed that the RDF would be manufactured in a toll facility. Based on an estimate from the toll producer, we used a formulation charge of $0.86/gal. Adding in profit at $1.00/gal and transportation charges of $0.17/gal (based on $0.16/ton-mile and a fixed distance of 200 miles from the formulation site to the user), the selling price was estimated as follows:

- Battelle-RDF 6-12: $4.96/gal.
- Battelle-RDF 6-3: $5.51/gal.
- KAc RDF: $5.82/gal.
- KAc + PG RDF: $6.97/gal.

The consumables costs for the three scenarios are presented in Table 37.

Table 37. Estimated Consumable Costs by Scenario

Fluids (fluid price, $/gal)	Scenarios, $k/year		
	Single Base (31k gal RDF /year)	All DoD (1 million gal RDF /year)	All U.S. Airports (9 million gal RDF/year)
Consumables			
Battelle-RDF 6-12 (4.96)	154	4,956	44,602
Battelle-RDF 6-3 (5.51)	171	5,509	49,584
KAc RDF (5.82)	181	5,823	52,405
KAc + PG RDF (6.97)	216	6,965	62,688

7.1.3.3 Data Interpretation

The interpretation of the data shows that consumable costs can be significantly lowered by switching to Battelle-RDFs. For example, if the DoD were to switch from KAc RDF to Battelle-RDF 6-12, there would be a savings of approximately ~$0.9 million/year.

7.1.4 Facility Operating Costs

7.1.4.1 Description of Cost Element

Facility operating costs include the labor cost for the operators, fuel for equipment needed to deice the airfield, maintenance of fluid application equipment, upkeep of the runway surfaces, plus wastewater disposal charges.

7.1.4.2 Data Collected and Basis for Estimate

No additional labor, fuel, or equipment and runway maintenance needs were identified based on the findings from the ease-of-use and maintenance surveys and commercial experience with GEN3. Therefore, the only difference in operating costs will be the BOD surcharge. This surcharge was based on the BOD content of the various RDFs. An oxidative load surcharge of ~$0.05/lb BOD is typical based on the experience at commercial airports. The wastewater-treatment cost calculations for the three scenarios are presented in Table 38.

Table 38. Wastewater Treatment Costs by Scenario

Fluids (lb BOD/lb fluid)	Wastewater Treatment Costs by Scenario, $k/year [(a)]		
	Single Base (31k gal RDF/year)	All DoD (1 million gal RDF/year)	All U.S. Airports (9 million gal RDF/year)
Battelle-RDF 6-12 (0.26) [10.43]	4	136	1,221
Battelle-RDF 6-3 (0.3) [10.48]	5	157	1,415
KAc RDF (0.15) [10.71]	2	80	723
KAc + PG RDF (0.37) [9.66]	6	179	1,608

(a) Basis: BOD surcharge = $0.05/lb BOD.

In the example above, the BOD surcharge for a single AFB was compared for Battelle-RDF 6-12 versus KAc RDF:

(31,000 gal RDF 6-12/year) * (10.43 lb/gal RDF of Battelle-RDF 6-12) * (0.26 lb BOD/lb RDF 6-12) * ($0.05/lb BOD) = $4k/year.

(31,000 gal KAc RDF/year) * (10.71 lb/gal RDF of KAc RDF) * (0.15 lb BOD/lb KAc RDF) * ($0.05/lb BOD) = $2k/year.

The difference is about $2k/year per base, or ~1% of the annual RDF-purchase expense per base.

7.1.4.3 Data Interpretation

The estimated charge to facility operating costs due to the slightly higher BOD of the Battelle-RDFs (compared to the KAc RDF) has a very minor impact on total costs.

7.1.5 Training Costs

7.1.5.1 Description of Cost Element

This cost element includes required training to instruct operators in the differences in utilizing Battelle-RDF versus the standard KAc RDF.

7.1.5.2 Data to Be Collected and Basis for Estimate

Because it was concluded the Battelle-RDF can be used as a drop in replacement, there would be little or no training required.

7.1.5.3 Data Interpretation

Because no training or operational modification will be needed, this cost element is zero.

7.1.6 Maintenance of Aircraft

7.1.6.1 Description of Cost Element

For this evaluation, maintenance costs will be limited to the deterioration of carbon-carbon brake pad assemblies in aircraft and Cd-plated electrical connectors and airfield lighting.

7.1.6.2 Data Collected and Basis for Estimate

The most significant factor, in terms of costs, is the aggressive attack of KAc-RDF on carbon brakes (due to catalytic oxidation). According to a briefing at the SAE G-12 “Carbon Pad Corrosion Working Group,” [29], RDF-related carbon-carbon corrosion costs are around $3 to 5 million per year per major civilian airline. No cost figures are available for the USAF but costs are significant. For instance, the cost to replace the carbon-carbon brake system for a single C-17 is estimated at $400k per set (not including labor) [30]. For cost estimating purposes it was assumed that the entire USAF fleet had brake corrosion costs similar to a major airline (i.e., $3 to 5 million/year). The carbon-pad corrosion costs for a single base were estimated at 1/31 of the full-fleet cost (since there are 31 USAF bases in the northern half of the U. S.), or ~$100k/year. To estimate the annual carbon corrosion costs for all U. S. airports ($30 million), the number of U. S. airlines was multiplied times the per-airline RDF-induced brake corrosion costs. It was assumed there were 10 major airlines including the USAF; i.e., American Airlines, Cargo (DHL, FedEx, UPS), Continental Airlines, Delta Airlines, Northwest Airlines, Southwest Airlines, United Airlines, US Airlines, and minor carriers (Jet Blue, Frontier, Alaska Airlines). Therefore, the annual costs was $3 million/airline times 10 airlines, or $30 million/year.

Based on the corrosion rates in Table 12 (presented earlier), the following corrosion-level multiplier was established for the Battelle-RDFs and KAc RDF:

- KAc RDF: standard, 100% of carbon-carbon corrosion costs
- Battelle-RDF 6-12: 61% reduction [base on (18% weight loss – 7%)/18%]
- Battelle-RDF 6-3: 78% reduction [(18% - 4%)/18%].

The calculated cost for carbon-carbon corrosion is noted in Table 39.

Table 39. Estimated RDF-Induced Carbon-Carbon Brake Corrosion Costs by Scenario

Fluids (Corrosion Reduction Compared to KAc RDF)	Carbon-Carbon Corrosion Costs, $k/year $k/year		
	Single Base (1/31 of Airline)	All DoD (1 airline)	All U.S. Airports (10 airlines)
Battelle-RDF 6-12 (61 percent)	38	1,170	11,700
Battelle-RDF 6-3 (78 percent)	21	660	6,600
KAc RDF (0 percent)	97	3,000	30,000

The second key maintenance concern is the RDF-induced corrosion of Cd-plated electrical connectors and airport lighting systems. While many have indicated the costs represent a significant maintenance cost, there are no published estimates of the dollar amount associated with the damage. Therefore, it was assumed to be 10% of the annual carbon-carbon brake pad cost; i.e., 10% * $3 million/year/airline = $0.3 million/year/airline.

Based on the corrosion rates in Table 11 (presented earlier), the following corrosion-level multiplier was established for the Battelle-RDFs and KAc RDF:

- KAc RDF: standard, 100% of Cd corrosion costs
- Battelle-RDF 6-12: 81% reduction [81% calculated as: (0.16 mg/cm^2/24 hours – 0.03 mg/cm^2/24 hours)/0.16 mg/cm^2/24 hours]
- Battelle-RDF 6-3: 75% reduction [(0.16-0.04)/0.16]

The calculated cost for Cd corrosion is noted in Table 40.

Table 40. Estimated RDF-Induced Cadmium Corrosion Costs by Scenario

Fluids (Corrosion Reduction Compared to KAc RDF)	Cadmium Corrosion Costs, $k/year $k/year		
	Single Base (1/31 of Airline)	All DoD (1 airline)	All U.S. Airports (10 airlines)
Battelle-RDF 6-12 (81 percent)	2	57	570
Battelle-RDF 6-3 (75 percent)	2	75	750
KAc RDF (0 percent)	10	300	3,000

7.1.6.3 Data Interpretation

The potential savings from reduced carbon-carbon brake and Cd corrosion are significant. For example, combining Battelle-RDF 6-12 versus KAc RDF costs in Table 39 and 40 (presented earlier), the annual savings for a single base, the DoD, and all U. S. airports, are $67,000, $2.1 million, and $21 million, respectively.

7.2 COST DRIVERS

Based on the analysis covered in Section 7.1, the major cost drivers are fluid cost and carbon-carbon corrosion costs. The cost impact of the higher oxygen demand of the Battelle-RDFs and Cd-corrosion costs is so low that it is insignificant.

7.3 COST ANALYSIS AND COMPARISON

To assess the relative attractiveness of switching away from conventional KAc RDF, three scenarios were considered. Capital costs for the switch were essentially zero, so the cost analysis focused on the impact on annual costs.

7.3.1 Base Case Description

The base case was for a "typical" USAF base located in the mid-to-northern section of the U. S. Two alternative cases were also considered, where the entire USAF and the rest of the DoD switched to a Battelle-RDF, and where all U. S. airports (military and civilian) switched to this bio-based, low-corrosion alternative RDF.

7.3.2 List of Assumptions

The following four assumptions were made to support the cost analysis and comparison of the Battelle-RDFs versus conventional KAc RDF:

1. Based on the RDF usage of WPAFB, it was assumed that a typical installation would consume ~31 K gallons of RDF each year.
2. Based on the estimate that the DoD consumes approximately 1 million gallons of RDF a year, there are ~31 "typical" North American U. S. military users of RDF.
3. Since RDF-induced corrosion cost estimates are only available on a "per airline" basis, it was assumed that the USAF/DoD together would represent one airline.

4. Recognizing that the relative costs of RDF components change with time, it was assumed that the price movement would be relatively small and that PG would always be more expensive than KAc, which would always be more expensive than purified bio-based materials, which would be more expensive than crude bio-based materials (even after upgrading to remove FFA and color and odor bodies).

7.3.3 Approach to Developing the Estimated Life-Cycle Cost

Life-cycle costs (LCC) are the sum of the costs to acquire RDF components, formulate and distribute the RDF to the users; the cost to apply; and the cost to remediate any adverse environmental effect from cradle to grave. If modifications to the standard equipment or procedures need to be instituted, then the capital cost to make the modifications and to re-train the users should be included on an amortized basis.

The demonstration at WPAFB, and full-scale implementation of similar bio-based RDFs at over 19 commercial airports in Canada and the U. S., indicated that the Battelle-RDF can serve as a drop in replacement with similar ease of use, ease of maintenance, and anti-icing and deicing performance. Therefore, there are no capital costs or training cost impacts.

Therefore, the estimated operating cost for the Battelle-RDFs and commercial KAc RDF can serve as a valid LCC cost estimate of these fluids.

7.3.4 Cost Comparison

The cost components for the various fluids, described in Section 7.1, were combined to provide an estimate of the operating costs of each fluid for each of the three scenarios; see Table 41.

7.3.5 Cost Analysis Findings

Analysis of the projected non-labor operating costs indicates that the most significant cost factor is the cost of the RDF fluid. Carbon-carbon brake pad corrosion is also a significant contributor, while Cd corrosion and wastewater treatment costs are minor contributors.

As expected, savings increase as the scale of operations increase. But even on a single base level, the potential savings of $92K/year for switching to Battelle-RDF 6-12 (and $90K/year for switching to Battelle-RDF 6-3) from KAc RDF are noticeable.

The annual savings, by scenario and Battelle-RDF type, are shown in Figure 42. Note: The numbers above the blue bars in the figure indicate the annual savings for switching to RDF 6-12 from KAc RDF. As noted by the numbers above the red bars, the projected savings by switching from KAc RDF to RDF 6-3 are very similar.

Table 41. Estimate of Changes in the Non-Labor Operating Costs, by Scenario

Cost Components	Operating Costs, by Scenario $k/year		
	Single Base	**All DoD**	**All U.S. Airports**
Battelle-RDF 6-12			
Consumables	154	4,956	44,602
Wastewater treatment	4	136	1,221
Cd corrosion	2	57	570
Carbon-carbon brake corrosion	38	1,170	11,700
Total	197	6,318	58,092
Battelle-RDF 6-3			
Consumables	171	5,509	49,584
Wastewater treatment	5	157	1,415
Cd corrosion	2	75	750
Carbon-carbon brake corrosion	21	660	6,600
Total	199	6,402	58,349
KAc RDF			
Consumables	181	5,823	52,405
Wastewater treatment	2	80	723
Cd corrosion	10	300	3,000
Carbon-carbon brake corrosion	97	3,000	30,000
Total	289	9,203	86,128

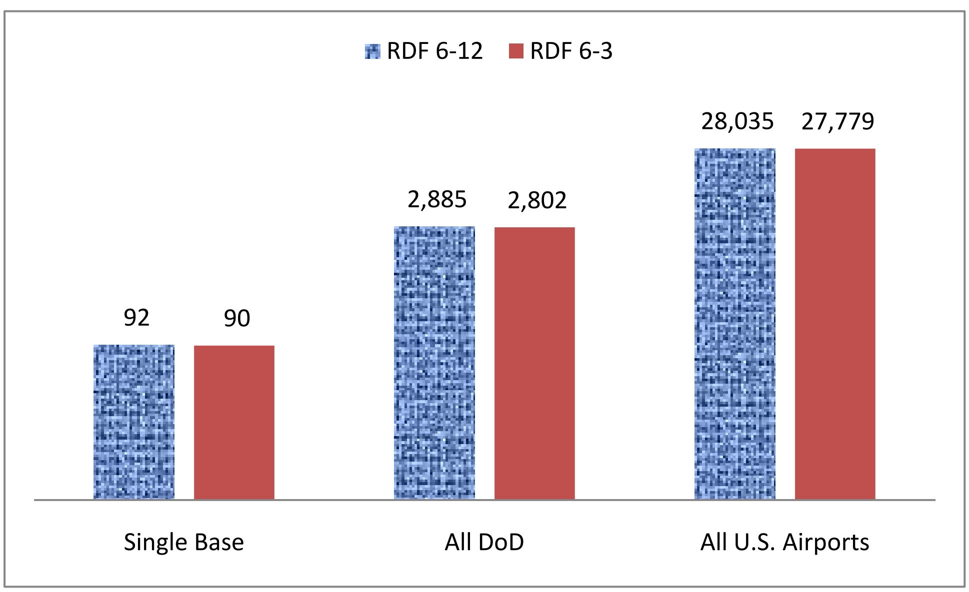


Figure 42. Comparison of Projected Life-Cycle Savings by Scenario and RDF Type
(in $k/year)

8.0 IMPLEMENTATION ISSUES

8.1 POTENTIAL REGULATIONS AFFECTING IMPLEMENTATION

Currently, KAc RDFs can meet the CWA requirements. While the EPA has proposed new airport discharge requirements, they include only a ban on the use of urea for runway deicing (which the USAF had adopted years ago). Current regulations do not require the use of bio-based RDFs to meet discharge requirements. However, there likely will be pressure on the airport authorities in the future to control the toxicity of RDFs and such pressure could encourage the use of bio-based RDFs or KAc+PG RDFs.

Three Presidential EOs promote increased use of bio-based materials. So far, these orders have not had a significant impact on bio-based materials demand, and alone will not ensure the implementation of Battelle-RDFs.

8.2 END USER CONCERNS, RESERVATIONS, AND DECISION-MAKING FACTORS

Users may express concern because the fluid is new and they may have reservations because of its potential damage to aircraft or weapon system components. Reservations should be allayed once the range of tests performed and the consistent equal-or-better corrosion properties of Battelle-RDF are disseminated.

8.3 RELEVANT PROCUREMENT ISSUES

On 18 January 2011, we received an email from Dr. Craig A Rutland of AFCESA indicating that the fluid had been reviewed and approved for use on Air Force airfields, as required for Air Force use. A copy of his email is provided in Figure 43.

The implementation path for new deicing materials in the USAF (and DoD) is evolving. The path is outlined in AFI 32-1002; see relevant excerpts for the AFI in Figure 44.

From: Rutland, Craig A Civ USAF AFCESA AFCESA/CEOA
[mailto:Craig.Rutland@tyndall.af.mil]
Sent: Tuesday, January 18, 2011 5:48 PM
To: Wyderski, Mary T Civ USAF AFMC ASC/WWME
Cc: Benedyk, Preston J Civ USAF AFCESA AFCESA/CEOO; ISAACS, LARRY K GS-14 USAF DoD AFCEE/TDNQ; Fetter, Clifford C Civ USAF AFCESA AFCESA/CEOA; Benedyk, Preston J Civ USAF AFCESA AFCESA/CEOO
Subject: RE: Battelle Runway Decing Fluid

Ma'am

I apologize for the delay. I just spoke with Dr Isaacs and I believe we are in agreement.

We believe the Battelle deicing fluids 6-4, 6-3, and 6-12 formulations will not harm the runway surfaces, asphalt or concrete. The BOD of these formulations is slightly higher than the currently used products. Therefore, the use of the product on specific airfields may be limited by existing permits and storm water quality laws and regulations.

Our analysis did not consider the effects of these fluids on the aircraft. Prior to general use of this product it is recommended that AFMC and the individual aircraft SPOs examine the effect of these fluid on corrosion, brake operation, sensors, coatings, connectors and weapon systems.

Please let me know if you require additional information

V/R
CRAIG A. RUTLAND, PhD, PE, DAF
USAF Pavement Engineer
Engineering Support Branch
Operations and Program Support Division
Air Force Civil Engineering Support Agency

DSN: 523-6439 FAX: 523-6488
COM: (850) 283-6439 FAX: 283-6488

Figure 43. Approval Email from AFCESA

2.1.8 Weapon System Single Managers (WSSMs) including Aircraft Single Managers (ASMs) Responsibilities

2.1.8.1. Evaluate impact of desired/requested airfield deicing/anti-icing agents on systems' performance for which they are responsible.

2.1.8.2. Identify to MAJCOMs the funding needs associated with the analysis and testing required to evaluate the impact of desired/requested airfield deicing/anti-icing agents.

2.1.9 Aircraft Single Manager (ASM) Responsibilities

2.1.9.1. Upon receipt of a MAJCOM request for approval to use an airfield deicing/anti-icing agent, the ASMs will become the focal point for coordination. They will act as single interface to the MAJCOM and coordinate the approval and/or requirements for all other weapon system components used on the aircraft to include those components managed by different Single Managers (e.g., landing gear, electronic countermeasure pods, navigational pods, weapons).

2.1.9.2. Upon notification from a MAJCOM of airfield deicing/anti-icing agents being used at a non-Air Force owned installation, ASMs will:

2.1.9.2.1. Advise any Weapon System Single Managers whose components are used on their aircraft of the airfield deicing/anti-icing agents being used.

2.1.9.2.2. Work with the respective Weapon System Single Managers to adjust maintenance activities and/or inspection intervals, or impose operational restrictions to mitigate if possible, any impact of the airfield deicing anti-icing agents.

Figure 44. Implementation Procedures Outlined in AFI 32-1002

While the AFI describes the roles of the WSSM and the ASM, it does not supply a set of clear step-by-step procedures to follow for new fluid implementation. Based on discussion with AF user, procurement experts, deicing experts, and the AFCESA, the following three steps must be completed before any new deicing fluid can be procured and utilized by DoD airfields:

1. **Data collection.** An advocate in the Weapon System organization in a MAJCOM (e.g., Mary Wyderski acting for the Weapon System) must:
    a. Collect data to ensure the fluid is suitable for USAF and DoD needs. [Completed] For RDF, this includes documentation to show the fluid complies with:
        i. AMS 1435A
        ii. Joint Test Protocol (in our case, the MTMS)
        iii. Performance requirements (in our case, the data in the SERDP report and the ESTCP demo)
    b. Present the data to AFCESA for review [Completed]

c. Obtain approved by the AFCESA, that he fluid will be approved for use general use. [Completed]
   i. As the AFI is not updated annually (it was last updated October 1999), it is unlikely the AFI would be modified to include the use of a single additional RDF.
   ii. Instead, AFCESA would issue a memo to the MAJCOMs informing them of the inclusion of the new approved RDF.
   iii. It would be the responsibility of the MAJCOMs to convey the information to the ASM/WSSM for approval on their specific aircraft of weapon system.

d. Present the data package to the ASMs/WSSMs and obtain their approval for the bio-based RDFs use on their aircraft/weapon system. [Not Completed at this Time]

2. **Obtain a National Stock Number (NSN)**. The new fluid may be assigned a NSN to facilitate the procurement of **GEN3** (this is not required, but may prove useful). These NSNs are managed and assigned by the Defense Logistics Information Service in Battle Creek, Michigan [24]. Manufacturers and suppliers do not have the authority to request a NSN. This is usually accomplished once a requirement/need for that manufacturer's/supplier's item has been identified by a military service, NATO country or federal/civil agency (e.g., Mary Wyderski acting for the Air Force). Information collected during the assignment of the NSNs includes qualified vendors, unit pricing information, and quality requirements (such as compliance with AMS 1435A).

3. **Disseminate information/AFI changes to other WSSMs and ASMs.** The ASM designee (such as Mary Wyderski), may present the RDF suitability findings and changes in the AFI to other WSSMs and ASMs. This could be one on one or at a national logistics meeting/conference. The WSSMs and ASMs can then accept the changes and allow this new fluid to be used on their weapon system or aircraft. In some cases, special material-compatibility concerns may delay acceptance; or additional material-specific testing may be required by a weapon system before acceptance.

9.0 REFERENCES

1. Joutti, Anneli, et. al., "Ecotoxoicity of Alternative De-icers," *Journal of Soils and Sediments*, **3** (4) 269 – 272, 2003.
2. Testing Alternative Aircraft and Runway/Taxiway Deicers – Phase II Test Report, a report submitted to the Air Force Research Laboratory by Concurrent Technologies Corporation, Task Order 5TS570D035P, Contract Number GS-23F-0061L, June 21, 2004.
3. Chauhan, S. P., Roshon, M. S., Conkle, H. N., Samuels, W. D., Berman, E., and Wyderski, M., Final Report, SERDP Project SI-1535, Development Of Environmentally Benign And Reduced Corrosion Runway Deicing Fluid, 14 August 2009.
4. US EPA proposed rule, entitled *Effluent Guidelines for the Airport Deicing Category*, Federal Register, http://epa.gov/guide/airport, August 28, 2009.
5. Conkle, H. N., Wyderski, M, Kuczek, S. F., Chauhan, S. P., and Samuels, W. D., *D^3: Degradable by Design Deicer*, presentation at the SAE G-12 Subcommittee Meeting, Vancouver, British Columbia, May 19, 2003.
6. Conkle, H. N., Wyderski, M, Chauhan, S. P., Kuczek, S. F., Chauhan, S. P., Samuels, W. D., and Simmons, K. L., *Environmentally Friendly, Non-Glycol Type I Aircraft Deicing Fluid*, paper presented at the 2003 FAA In-Flight Icing and Ground Deicing International Conference, Chicago, IL, August 16-20, 2003.
7. Chauhan, S.P Simmons, K.L., Frye, J.G., Werpy, T.A., Samuels, W.D., Conkle, H.N., Monzyk, B.F., Kuczek, S.E., "Deicing/Anti-Icing Fluids," US Patent No. 7,105,105, September 12, 2006.
8. Chauhan, S.P., Simmons, K.L., Frye, J.G., Werpy, T.A., Samuels, W.D., Conkle, H.N., Monzyk, B.F., Kuczek, S.E., "Biobased Deicing/Anti-icing Fluid", US Patent NO. 7,169,321, January 30, 2007.
9. Chauhan, S.P., Samuels, W.D., Kuczek, S.F., Conkle, H.N., "Process for Producing a Deicing/Anti-Icing Fluid", U.S. Patent No 7,048,871, May 23, 2006.
10. *European Union Promotes Increased Biodiesel*, Chemical Market Reporter, February 7, 2005.
11. Walker, T., *Carbon Pad Corrosion Working Group*, briefing paper presented at SAE G-12 Subcommittee meeting in Frankfurt, Germany, May 2004.
12. Chappelow, Cecil C., A. Dean McElroy, Robert R. Blackburn, et al., Handbook of Test Methods for Evaluating Chemical Deicers (SHRP-H-332), Strategic Highway Research Program, 1992.
13. Wright-Patterson Air Force Base, http://en.wikipedia.org/wiki/WPAFB, search results for 10 September 2009.
14. *2008 Base Economic Impact Analysis*, reported in WPAFB Skywrighter, http:///www.wpafb.af.mil/shared/media/document/AFD-090824-008.pdf, 28 August, 2009.
15. Air Force Instruction 32-1002, *Snow and Ice Control*, Secretary of the Air Force, www.wbdg.org/ccb/AF/AFI/afi_32_1002.pdf, 1 October 1999.

16. Dayton weather. Ref: http://www.climate-harts.com/Locations/u/US72429003320751. php, search results 10 September 2009.
17. *WPAFB Snow and Ice Control Plan*, September 2009.
18. Conkle, H. N., Roshon, M. S., and Chauhan, S. P., Fluid Qualification Report, a report by Battelle to the SAIC, 25 August 2009.
19. Wyderski, M. T., Conkle, H.N., Chauhan, S.P., and Roshon, M.S., Demonstration Plan for an Environmentally Benign And Reduced Corrosion Runway Deicing Fluid, 16 December 2009.
20. Wyderski, M. T., Chauhan, S.P., and Conkle, H.N., Draft Cost and Performance Report for Environmentally Benign and Reduced Corrosion Runway Deicing Fluid, a report by Battelle to the ESTCP, 7 July 2010.
21. Conkle, H.N., Roshon, M.S., and Chauhan, S.P., *Environmentally Benign And Reduced Corrosion Runway Deicing Fluid*, a presentation at the Air Force Material Command Deicing Workshop, Dayton, OH, 18 November 2009.
22. Chauhan, S.P. and Conkle, H.N., *Environmentally Benign and Reduced Corrosion Runway Deicing Fluid*, a poster presented at the Partners in Environmental Excellence conference, December 2010.
23. Chauhan, S.P., *Demonstration of Battelle-RDFs/ Basic Solutions Gen3 RDFs*, paper presented at SAE G-12 Subcommittee meeting in Berlin, German, May 2010
24. Williamson, K., *Gen 3– Airport Results 2009/2010*, paper presented at SAE G-12 Subcommittee meeting in Berlin German, May 2010.
25. Technical specification for Octamelt (a KAc+PG RDF), http://www.octagonprocess.com/pdfs/technical/Octamelt.pdf
26. http://upload.wikimedia.org/wikipedia/commons/a/ad/Air_Force_Facilities.jpg
27. Reference for RDF usage by AFB: private Communication between base staff at individual AFBs and Preston Benedyk (AFCESA/CEOO), May 2010.
28. Reference to 8 million gallon of RDF usage in civilian U. S. airports: letter from the FAA, Office of the Associate Administrator of Airports to "Industry Representatives," 10 October 2008.
29. Walker, T., *Carbon Pad Corrosion Working Group*, briefing paper presented at SAE G-12 Subcommittee meeting in Frankfurt, Germany, May 2004.
30. Reference for C-17 brake replacement costs: private communication with Mary Wyderski, June 2010.
31. Procedure to obtain a National Stock Number: http://www.dlis.dla.mil/PDFs/NSN.pdf.

APPENDIX A: POINTS OF CONTACT

The points of contact are noted in Table A-1.

Table A-1. Points of Contact

Point of Contact Name	Organization Name Address	Phone E-mail	Role in Project
Mary Wyderski	AF/ASC WPAFB OH	937-656-5570 office 937-304-3833 cell Mary.Wyderski@wpafb.af.mil	Overall Program Manager and base POC
William Kassinos	AF/88 Air Base Wing WPAFB OH	(937) 257-6207 William.Kassinos@WPAFB.AF.MIL	Airfield supervisor
Michael Patterson	AF/88 Air Base Wing WPAFB OH	(937) 904-2390 Michael.Patterson3@WPAFB.AF.MIL	Fluid applications
James Tufano	AF/88 Air Base Wing WPAFB OH	(937) 904-2056 James.Tufano@WPAFB.AF.MIL	Fluid application manager
Romulo Alcantara	AF/88 OSS/OSAM WPAFB OH	(937) 257-2131 Romulo.Alcantara@WPAFB.AF.MIL	Airfield operations
Brian Robinson	AFMC 88 ABW/CEMEP WPAFB OH	(937) 257-7360 Brian.Robinson@WPAFB.AF.MIL	Fluid applications
Elizabeth Berman	AF/AFRL/RXSC WPAFB OH	937-656-5700 office Elizabeth.Berman@wpafb.af.mil	Review impact on specialized DoD material
Michael Sanders	HQ AFPET/AFTT	(937) 255-8107 Michael.Sanders@wpafb.af.mil	Observe airfield testing
Benet Curtis	HQ AFPET/AFTT	(937) 255-8039 Benet.Curtis@WPAFB.AF.MIL	Observe airfield testing
Charles Ryerson	Army/ CRREL Hanover, NH	603-646-4487 office Charles.C.Ryerson@usace.army.mil	Provide insight in applicability of the fluid to Army applications
Don Tarazano	SAIC Dayton, OH	937-431-2242 office donald.tarazano@wpafb.af.mil	Support airfield test
James Davila	SAIC Dayton, OH	937-431-2272 office JAMES.A.DAVILA@saic.com	SAIC Program Manager
Preston Benedyk	AFCESA/CEOO	(850) 283-6582 Preston.benedyk@tyndall.af.mil	Support assessment of impact on the runway
Karen Beason	AF/88 Air Base Wing/CEVO WPAFB OH	937-257-5899 Karen.Beason@wpafb.af.mil	Review and approve of AF Form 813
Nick Conkle	Battelle Columbus, OH	614-937-4171 cell 614-424-5616 office conkle@battelle.org	Direct airfield testing
Melissa Roshon	Battelle Columbus, OH	614-562-2810 cell 614-424-4837 office roshonm@battelle.org	Support airfield testing

Point of Contact Name	Organization Name Address	Phone E-mail	Role in Project
Satya Chauhan	Battelle Columbus, OH	614-937-0851 cell 614-424-4812 office chauhan@battelle.org	Provide insight in RDF use and application
Kelvin Williamson	Basic Solutions Toronto, Canada	905-562-0770 Kelvin@basic-solutions.ca	Provide support in conducting tests based on prior experience as RDF vendor

APPENDIX B: STATISTICAL ANALYSIS

The appendix describes the analysis methodology used to analyze the RCR versus time data for the four test series.

B.1 SERIES NO. 1 – ANTI-ICING WITH RDF 6-3

The following mixed model was fit to the RCR anti-icing measurements (y_{ijk}):

$$y_{ijk} = \mu + \tau_i + \alpha_{ij} + \beta_i time_k + \varepsilon_{ijk} \tag{1}$$

$$\varepsilon_{ijk} \sim iid\ N\left(0, \sigma_\varepsilon^2\right)$$

$$\alpha_{ij} \sim iid\ N\left(0, \sigma_\alpha^2\right)$$

$$\alpha_{ij} \text{ and } \varepsilon_{ijk} \text{ are independent}$$

where, anti-icing measurements from the ith anti-icing fluid (i=1,2 for RDF 6-3 and RDF KAc, respectively) at the jth location sampled at the kth time point ($time_k$); τ_i is the fixed treatment (anti-icing brand) effect, β_i is the fixed slope for the ith anti-icing brand (interaction of anti-icing brand and time), α_{ij} is the random time effect for jth location (interaction of time and location) and ε_{ijk} is the residual variation (analytical variation plus departure from the model).

Initial analysis indicated that there was no significant location effect. This was accomplished by testing the null hypothesis $H_0 : \sigma_\alpha^2 = 0$ (p-value=0.5538). Further tests of the interaction between anti-icing fluid and time ($H_0 : \beta_1 = \beta_2$) (p-value=0.8935) indicates that the different anti-icing brands share a common slope.

Ninety-five percent simultaneous confidence intervals were obtained for the mean RCR at 36 minute elapsed time for Battelle-RDF 6-3 ($\mu + \tau_1 + 36\beta_1$) and for RDF KAc ($\mu + \tau_2 + 36\beta_2$). The 36-minute elapsed time selection was chosen as it was approximately the midpoint of the elapsed times in which observations were made for this study. The formula for the 95% simultaneous confidence intervals were $\hat{\mu} + \hat{\tau}_i + 36\hat{\beta}_i \pm t_{\frac{o.o5}{2*2},df} SE(\mu + \tau_i + 36\beta_i)$ for i=1,2 where

$\hat{\mu}, \hat{\tau}_i$ and $\hat{\beta}_i$ are the maximum likelihood estimates obtained from fitting model (1), $SE(\mu + \tau_i + 36\beta_i)$ is the estimate of the standard error of the mean RCR for the ith anti-icing brand and $t_{\frac{o.o5}{2*2},df}$ is a Student's t-quantile adjusted for the simultaneously obtaining the confidence intervals for the various anti-icing brands.

To estimate the HOT corresponding to an RCR of 9, the expected value of equation (1) is set equal to 9, which corresponds to $time_{HOT_i} = \frac{9 - \mu - \tau_i}{\beta_i}$ where $time_{HOT_i}$ is the expected HOT corresponding to an RCR of 9 for the ith anti-icing brand. Thus, to obtain a confidence interval for the HOT corresponding to an RCR of 9 for ith anti-icing brand, the formula is $\frac{9 - \hat{\mu} - \hat{\tau}_i}{\hat{\beta}_i} \pm t_{\frac{o.o5}{2*2},df} SE\left(\frac{9 - \mu - \tau_i}{\beta_i}\right)$ and the Delta Method is used to approximate the standard error**.**

B.2 SERIES NO. 2 – ANTI-ICING WITH RDF 6-12

Equation (1) is again used for anti-icing measurements from the ith anti-icing fluid (i=1,2 for RDF 6-12 and RDF KAc, respectively) at the jth location sampled at the kth time point ($time_k$). Initial analysis again indicated that there was no significant location effect (p-value=0.5422) and that the different anti-icing brands share a common slope (p-value=0.9561).

Both 95% simultaneous confidence intervals for the mean RCR at 23 minute elapsed time for Battelle-RDF 6-12 ($\mu + \tau_1 + 23\beta_1$) and for RDF KAc ($\mu + \tau_2 + 23\beta_2$) and HOT corresponding to an RCR of 9 were obtained using the same approach as B.1 Series No. 1. The 23-minute elapsed time selection was chosen as it was approximately the midpoint of the elapsed times in which observations were made for this study.

B.3 SERIES NO. 3 – DEICING WITH RDF 6-12

The following mixed model was fit to the inverse transformations of the RCR data for the deicing fluids

$$y_{ijk} = \mu + \tau_i + \alpha_{ij} + \beta_{1i} time_k + \beta_{2i} time_k^2 + \varepsilon_{ijk} \quad (2)$$

$$\varepsilon_{ijk} \sim iid\ N\left(0, \sigma_\varepsilon^2\right)$$

$$\alpha_{ij} \sim iid\ N\left(0, \sigma_\alpha^2\right)$$

$$\alpha_{ij} \text{ and } \varepsilon_{ijk} \text{ are independent}$$

where, deicing measurements from the ith deicing fluid (i=1,2 for RDF 6-12 and RDF KAc, respectively) at the jth location sampled at the kth time point ($time_k$); τ_i is the fixed treatment (deicing brand) effect, β_{1i} and β_{2i} are the fixed terms for the quadratic model for the ith deicing brand (interaction of deicing brand and time), α_{ij} is the random time effect for jth location (interaction of time and location) and ε_{ijk} is the residual variation (analytical variation plus departure from the model). The model was fit to the inverse of the RCR data to stabilize the variance and required a quadratic model rather than a linear model as used for the anti-icing analysis.

Initial analysis indicated that there was no significant location effect $H_0 : \sigma_\alpha^2 = 0$ and testing the interaction between deicing fluid and time ($H_0 : \beta_{11} = \beta_{12}$ and $H_0 : \beta_{21} = \beta_{22}$) indicates that the different deicing brands share the same quadratic terms.

The time at which the expected RCR value is maximized is equal to $\frac{-\beta_{1i}}{2\beta_{2i}}$, which is the same for both treatments as $\beta_{11} = \beta_{12}$ and $\beta_{21} = \beta_{22}$. This is obtained by taking the partial derivative of the expected value of equation (2) and setting that equal to 0 and solving for time. Thus, using the maximum likelihood estimates from model (2), we find the time at which the expected RCR value is maximized is 2.7 hours elapsed time. Then our 95% simultaneous confidence intervals for the mean RCR at 2.7 hours elapsed time for Battelle-RDF 6-12 ($\mu + \tau_1 + 2.7\beta_{11} + 2.7^2 \beta_{21}$) and for RDF KAc ($\mu + \tau_2 + 2.7\beta_{12} + 2.7^2 \beta_{22}$) in the same fashion as the anti-icing confidence intervals.

B.4 SERIES NO. 4 – DEICING WITH RDF 6-3

The final model fit to the RCR data for the RDF 6-3 and RDF KAc deicing fluids was

$$y_{ijk} = \mu + \tau_i + \varepsilon_{ijk} \qquad (3)$$

$$\varepsilon_{1jk} \sim iid\ N\left(0, \sigma_{1\varepsilon}^2\right)$$

$$\varepsilon_{2jk} \sim iid\ N\left(0, \sigma_{2\varepsilon}^2\right)$$

$$\varepsilon_{1jk} \text{ and } \varepsilon_{2jk} \text{ are independent}$$

where, deicing measurements from the i^{th} deicing fluid (i=1,2 for RDF 6-3 and RDF KAc, respectively) at the j^{th} location sampled at the k^{th} time point ($time_k$); τ_i is the fixed treatment (deicing brand) effect, and ε_{ijk} is the residual variation (analytical variation plus departure from the model). Unlike the previous models, this data required a model that allowed for different variance between the two deicing fluids.