COVER PAGE

Title of Design: Improvements to Deicing Environmental Management System at Denver International Airport

Design Challenge addressed: Airport Environmental Interactions

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Note: The team's unofficial cover page has been removed

Table of Contents

List of Acronyms Used

ADF – Aircraft deicing fluid
AOP – Advanced oxidation process
BOD – Biological oxygen demand
CCI - Construction cost index
COD – Chemical oxygen demand
DIA – Denver International Airport
DMWWTP – Denver Metro Wastewater Treatment Plant
FAA – Federal Aviation Administration
H_2O_2 – Hydrogen peroxide
HP – Horsepower
ISO – International Organization for Standardization
kW – Kilowatt
kWh – Kilowatt hours
MeBT – Methyl-benzotriazole
MTBE – Methyl-tert-butyl ether
OH – Hydroxyl
OTE – Oxygen transfer efficiency
PG – Propylene glycol
PSIA – Atmospheric pounds per square inch
RCRA – Resource Conservation and Recovery Act
RO – Reverse osmosis
SCFM – Specific cubic feet per minute
TBE – Tert-butyl alcohol
TKN – Total Kjehldahl Nitrogen
TSS – Total suspended solids
UV – Ultraviolet radiation

Executive Summary: An Anaerobic Digester for Deicing Waste at DIA

Aircraft deicing operations are necessary to ensure safe air travel. However, aircraft deicing fluids (ADF) are a potential contaminant at many airports. ADF containing propylene glycol (PG) has a large biological oxygen demand (BOD) which diminishes the dissolved oxygen in nearby soils and surface waters; thus ecosystems are impacted if ADF is released into the environment. Current best practices involve collection and recycling of PG from the ADF. At low concentrations, the PG cannot be recycled and is typically managed by a wastewater treatment plant (WWTP). Airports, such as Denver International Airport (DIA), must pay for treatment of the ADF. To decrease the environmental footprint and cost of deicing operations, our team of five senior environmental engineering students from the University of Colorado at Boulder (KANDE Consulting) investigated alternative deicing fluid treatment systems.

A state-of-the-art PG recovery system currently operates at DIA. However, there is still a notable amount of PG-contaminated runoff produced from deicing operations, which constitutes an annual cost of more than $600,000. An on-site remedial technology would reduce these costs. Five technologies capable of treating the PG wastewater streams were analyzed in this report: bubble aeration, anaerobic digestion, anaerobic fluidized bed reaction, advanced oxidation processes, and reverse osmosis filtration. KANDE researched each of these systems and selected the anaerobic digester as the option which best suits DIA’s unique needs. A comprehensive cost/benefit analysis for the 20 year design life of the system revealed that the net present value was -$508,100. While this project causes a slight economic loss to DIA over its lifetime, the anaerobic digester system designed in this report could be implemented at other airports with more concentrated deicing waste to generate a net profit.

Problem Statement and Background

Snow and ice on aircraft and runways present a major operational challenge for airports across the United States and in many areas of the world. Ice on the wings of a plane alters the shape, causing the wings to produce more drag and less lift. Icing on runways is a slip hazard for planes both taking off and landing. To prevent these hazards, airports in the colder parts of the world must have deicing systems in place to treat all air traffic. The Federal Aviation Administration (FAA) has established a variety of regulations to ensure that the aircrafts and runways are safely deiced before takeoff (1). Approximately 25 million gallons of ADF are used in the U.S. alone on an annual basis (2). ADF usage is an environmental health and safety hazard and as such, its use is regulated. However, ADF is required for wintertime operations for all airports in the US that are subject to ice, snow, or frost on the runways or on the aircraft. Safe deicing operations require a combination of accurate weather predictions and effective deicing technology. Subsequent sections detail the aircraft deicing system at DIA and ADF chemistry.

Aircraft Deicing Background and Introduction to ADF Chemistry

ADFs are applied to an aircraft or runway whenever any ice, frost, or snow is present on the surface; they are also sprayed to prevent the future buildup of frozen water. These processes are “deicing” and “anti-icing” respectively, but both will be referred to as “deicing” in this proposal. Some of the alternatives to using ADFs for deicing include mechanical removal of snow by compressed air, heat pads on the leading edge of wings, and infrared radiant heating in large hangars. Because of the need for anti-icing to prevent future frosting, most alternative technologies do not completely eliminate the need for these sprays (1).

The most common deicing method is the spray application of ADFs which are usually composed of PG (typically 50%), water (typically 48%), and a mixture of additives (<2%) (3). Propylene glycol ($C_3H_8O_2$) has replaced ethylene glycol ($C_2H_6O_2$) as the preferred freezing point depressant because it is less toxic (4). Propylene glycol, while readily biodegradable, has a sizeable BOD, which deprives aquatic and terrestrial ecosystems of the oxygen they need to live. This BOD is one of the primary concerns with releasing ADFs into the environment. There are four classes of ADFs, differentiated by the percentage of additives. Type I has less than 1% additives while types II, III, and IV have less than 2% additives. ADF additives include surfactants and anticorrosive compounds such as 4(5) methyl-benzotriazole (MeBT). As seen in Figure 1, MeBT has two common isomers, 4(5)-MeBT. 4-MeBT is recalcitrant in the environment and accumulation and persistence are known issues (3). Aerobic biodegradation of 5-MeBT has been explored and an accepted pathway includes degradation to protocatechuate or cathecol which are subsequently degraded (5). The use of triazoles in ADFs presents numerous environmental issues due to their persistence in the environment, solubility in water, and toxicity to biotic organisms (4).

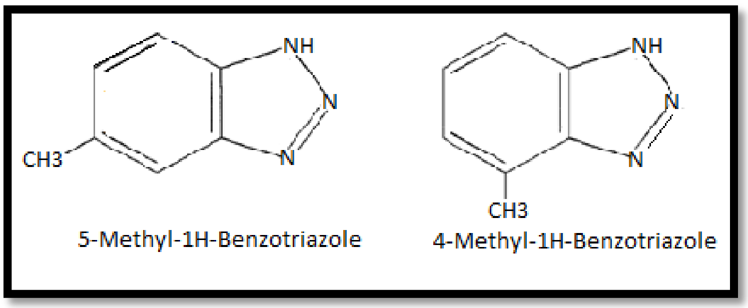

Figure 1. Structure of 4(5)-MeBT (3)

Anti-corrosives like MeBT are a class of compounds that are used in ADFs to decrease the risk of fire caused by corrosion of parts carrying a direct electric current (6). These anti-corrosive compounds may persist in the ground water and soil around airports years after being released (3). Other ADF additives are largely proprietary but generally include surfactants, thickeners, colored dyes, and pH buffers. The environmental and toxicological effects of some of these additives are only just beginning to be explored.

Denver International Airport (DIA) Environmental Management Systems

DIA is a leader in environmental management systems (EMS) and is certified by the International Organization for Standardization (ISO) for their EMS which complies with the ISO 14001:2004 standard (7). The ISO 14001:2004 standard provides general requirements for an EMS including: awareness of the multitude of environmental impacts related to the operation of the business and attempting to limit the impacts that are within control of the business. DIA is the first and only airport in the US to reach this standard and become certified (8), making it the current state-of-the-art model in large scale deicing operations using glycol recovery systems. Smaller and older airports in the US and around the world generally rely heavily upon local wastewater treatment infrastructure for treatment. However, it is becoming more and more common for on-site treatment and recycling of ADF at larger and recently renovated airports (4). The specific flow and cost values for DIA can be seen in Table 1 below.

Table 1. DIA Dilute Deicing Waste Characteristics (9)

DIA Deicing Design Values	
Average Annual Discharge to Denver Metro Wastewater Treatment Plant (DMWWTP)	197 million gallons
Average PG Concentration in DIA Wastewater	2,600 mg/L
Maximum Annual Wastewater Discharge	243 million gallons
Maximum PG Concentration in DIA Wastewater	10,000 mg/L
Average BOD Load to DMWWTP	8.707 tons/million gallons/year
Maximum Historical Year BOD Load to DMWWTP	20,757.55 tons/million gallons/year
Average Annual Cost of BOD Treatment at DMWWTP	$652,000
Average Annual Total Cost of Wastewater Treatment at DMWWTP	$778,600

DIA has four primary deicing pads which can service five to six airplanes at any given time (10). A view of Denver International Airport's facilities can be seen in Figure 3 below. Each of the deicing pads includes an advanced glycol recovery system, which attempts to recover and recycle all of the ADF with greater than 1% propylene glycol that falls onto the pad. The collected PG is separated from the water and then concentrated and distilled into an almost pure glycol. Of the 1,949,230 gallons used at DIA in 2010/2011, 1,376,270 gallons were collected (around 71%). Of this 71%, approximately 72 percent was recycled into pure PG, leaving 28% to be treated by Denver Metro Waste Water Treatment Plant (DMWWTP). The charts in Figure 2 illustrate the overall efficiency of the recovery system.

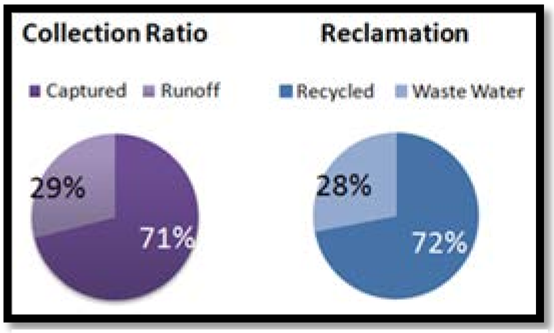

Figure 2. Reclamation and collection ratios of ADF at DIA (10)

DIA's current system recycles glycol from the wastewater stream as long as the glycol concentrations are above 1% (10,000 mg/L). Wastewater with less than 1% glycol is diverted and treated at the DMWWTP (11). According to Keith Pass, a manager of the current EMS at DIA, approximately $650,000 per year is allocated for wastewater treatment at DMWWTP related to deicing operations and more than 80% of this cost is due to the treatment of BOD alone (9). KANDE Consulting has decided to investigate a design alternative to treat the BOD on site to reduce these costs.

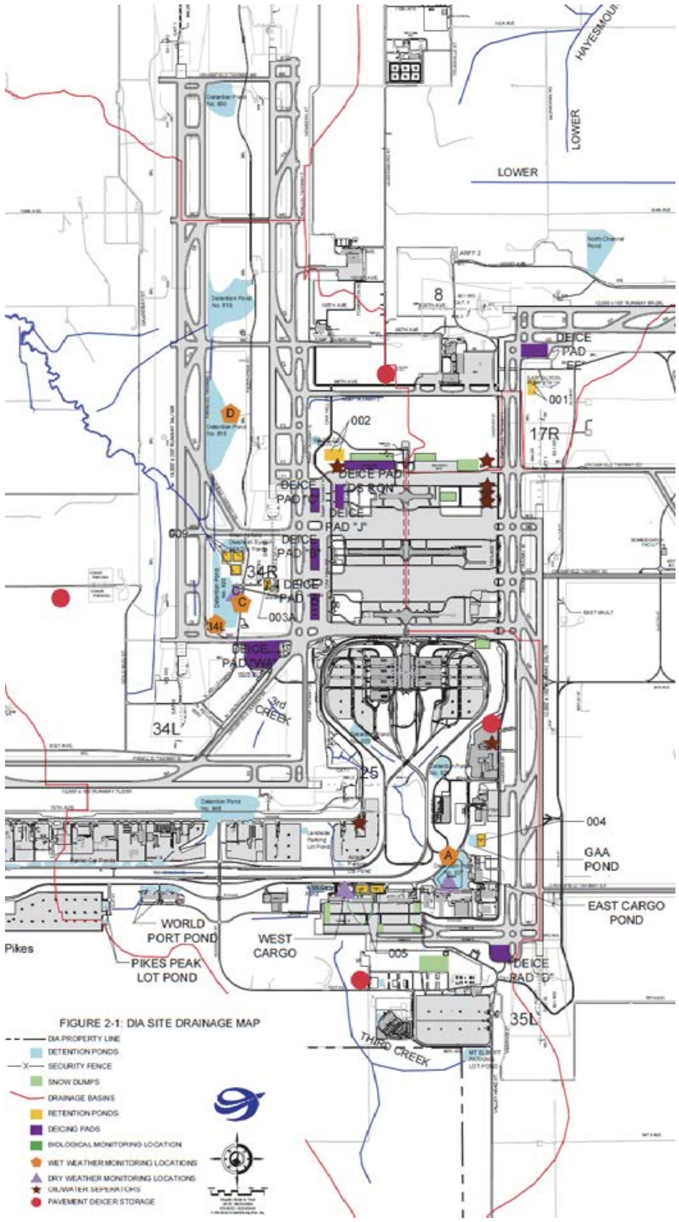

Figure 3. Plan View of Denver International Airport

Summary of Literature and Research Review

This report cites reputable sources including peer reviewed journals, textbooks, FAA and USEPA guidance documents, conference proceedings, PhD theses, technical websites, and direct interaction with experts and professionals. We have attempted to make this document as easily accessible as possible for quick referencing and quality assurance. References to each source are embedded in the design report.

Problem Solving Approach

KANDE Consulting provides a holistic approach to engineering design through interdisciplinary evaluation of design alternatives. Alongside regulatory compliance, technical considerations, and costs estimates, the decision-making process addresses social, political, and environmental concerns. Selection of the appropriate design alternative and the subsequent development of that solution are based on a sustainability analysis of the project. The alternative evaluation provided in this report is based on a twenty year life cycle analysis. Several criteria have been established to select the best alternative for DIA's dilute deicing waste treatment; a preliminary discussion of these criteria is addressed in this section of the report. A more detailed discussion of the criteria is provided in the Decision Matrix section.

FAA Design Competition Requirements

The FAA provides the framework for a safe, secure, and efficient aviation system. Innovative research on the potential benefit of the long-term growth of civil aviation is vocally encouraged by the FAA. The pursuit of basic and applied research in scientific and engineering disciplines in aviation is crucial to the realization of this goal. KANDE Consulting is proud to deliver this caliber of research for the FAA Airport Environmental Interactions design competition. An important goal of the FAA design competition is that each student team interacts with airport operators and industry experts. See Appendix C for a complete description of these interactions. Other important FAA goals which pertain to this design are provided in the

Flight Plan 2009-2013 charter (12). These goals include the ability of future projects to "address environmental issues associated with capacity enhancements" and this design report aims to do just that with regard to PG use. The main goal of our team for our client is to provide a solution to the adverse effects of deicing while providing DIA with both economic and social benefits.

Preliminary Design Criteria

KANDE Consulting has identified criteria and constraints which are applicable to DIA, our partner airport. These criteria and constraints are discussed fully in the "Decision Process" section of this report. However, a basic review of the most important constraints is pertinent to the preliminary selection of alternatives. The following three constraints for the design were developed in cooperation with airport operators at DIA and were used in the "Preliminary Screening of Alternatives" section below.

1) The alternative has the ability to treat less than 1% propylene glycol waste stream.

2) The alternative has the ability to adapt to variable wastewater flow rates throughout the year.

3) The alternative minimizes the cost of implementation and maintenance over design life.

Preliminary Screening of Alternatives

To identify the best possible solution for treatment of DIA's dilute deicing waste, KANDE Consulting has researched thirteen preliminary design alternatives. A literature review of the preliminary alternatives elucidated the main design and operational considerations of each. The relevant design, construction, and operational characteristics of each preliminary alternative were evaluated based on the three constraints described in the previous section. The process of elimination used to select the five best alternatives is presented in Table 2. Description of Preliminary Alternatives In this table, the preliminary alternatives are categorized according to their mechanism of operation—physical, chemical, or biological. The advantages and disadvantages of each preliminary alternative are discussed. References that apply to the preliminary screening process are provided along with the indication of whether the alternative is likely to meet the preliminary criteria. Out of the thirteen preliminary alternatives, eight were eliminated by the preliminary screening process because they did not effectively meet the preliminary criteria.

The preliminary elimination of alternatives based on the above criteria resulted in five feasible solutions: fine bubble aeration, anaerobic biogas digestion, anaerobic fluidized bed reaction, advanced oxidation processes, and reverse osmosis membrane filtration. Each of these was explored in more detail in this report. Final elimination of these five alternatives resulted in a single, best alternative for DIA.

Future Deicing Considerations

KANDE Consulting understands that no engineering challenge stays constant over time. As each alternative was evaluated, increases in wastewater flow rates and changes in BOD concentration were considered. DIA has informed KANDE Consulting that there are plans to build another concourse in the near future. This expansion will inevitably require additional ADF use and thus more wastewater as air traffic increases. This increased load on the selected technology will be evaluated in more detail during the final design process in order to ensure that the design will be flexible enough to fit the client’s future needs. The selected technology will also be evaluated for its ability to conform to future regulations.

Table 2. Description of Preliminary Alternatives

Alternative Type	Alternative Name	Advantages	Disadvantages	References / Examples	Meets Preliminary Criteria
Physical	Reverse Osmosis	‣ Can recover PG ‣ No seasonality issues	‣ Storage tanks are needed to regulate flow ‣ May be too costly to remove the lowest concentrations of PG ‣ Costly	‣ (13) ‣ Installed at Pittsburgh International Airport	‣ Yes: Effectively removes propylene glycol and MeBT, along with other contaminants
	Mechanical Vapor Recompression and Vacuum Distillation	‣ Modification to existing system at DIA ‣ Allows for recovery of PG ‣ Can operate seasonally	‣ Large vacuum pump and heater power requirements	‣ (Inland Technologies, 2011) ‣ Installed at DIA	No: Power requirements are prohibitive
Chemical	Fine Bubble Aeration	‣ Can use existing infrastructure ‣ Low capital costs ‣ Can operate seasonally	‣ Large pump power requirement ‣ Potential wildlife hazard	‣ (13) ‣ Installed at Greater Rockford Airport, NY	Yes: Low cost option
	Plug Flow Trench Aeration	‣ More efficient than pond aeration ‣ Modular (for future expansion) ‣ Can operate seasonally	‣ Large pump power requirement	‣ (Siemens, 2011) ‣ Installed at Red Gold tomato processing plant, IN	No: Similar to Pond Aeration but more costly
	UV with Oxidizer	‣ Can be easily turned off and on ‣ UV lighting has long lifetime and system has low maintenance ‣ Relatively short treatment time needed	‣ Must either buy or make oxidizer (peroxide or ozone) onsite ‣ Turbidity of the influent could occlude the UV's penetration	Clark County, Nevada has employed a 30 MGD wastewater treatment plant	Yes: Thoroughly removes propylene glycol and MeBT, along with other contaminants

Alternative Type	Alternative Name	Advantages	Disadvantages	References / Examples	Meets Preliminary Criteria
Biological	Anaerobic Fluidized Bed Reactor (FBR)	‣ Less energy required over aerobic processes ‣ No odors ‣ Methane generated	‣ Needs to be heated for maximum efficiency ‣ Seasonal concentration fluctuations are bad for microbes	‣ (13) (14) ‣ Installed in both the Albany, New York and Akron/Canton, Ohio airports	Yes, when compared to the other options, this option has the least amount of technical complications due to sizing and cost.
	Batch-loaded FBR	‣ Effectively biodegrades propylene glycol ‣ Can be aerobic or anaerobic	‣ Clogging ‣ Batch process causes it to require more storage space for wastewater	‣ (13) ‣ No current implementation found but studies assert feasibility	No: Complications due to sizing
	Membrane Bioreactor	‣ Up and coming technology ‣ Would help reduce propylene glycol in two steps	‣ Similar to RO but requires more space and is more costly	‣ (15) ‣ Pilot study performed for general municipal waste water.	No: Reverse Osmosis is cheaper and allows for recovery
	Trickling Filter	‣ Proven system for lower loading rates ‣ Fairly simple design	‣ Clogging and pooling of water on the surface ‣ Unproven at these loading rates	‣ (16) ‣ Utilized in many WWTP, but none for these loading rates	No: Complications due to sizing
	Constructed Wetlands	‣ Lower maintenance compared to other methods of treatment	‣ Wildlife issues - birds ‣ Highest concentrations of PG will be present during less active times for bacteria	‣ (13) ‣ Installed at Buffalo Niagra International Airport in New York	No: Need for dilution, complications due to sizing
	Anaerobic Mobilized Film	‣ Generates methane ‣ Proven to work with organic high loading rates	‣ EcoLab discontinued producing these systems	‣ (17) ‣ Installed at Maker's Mark Distillery	No: Lack of accessibility to technology
	Anaerobic biogas digester	‣ Generates methane ‣ Proven system for high loading rates ‣ Possible to use current Infrastructure ‣ Low maintenance costs	‣ Seasonal startup issues ‣ Needs to be heated for maximum efficiency ‣ Batch reaction; need extended period of time to fully treat	‣ (18) ‣ Lemvig Biogas Digester in Denmark ‣ (Global Methane Initiative)	Yes: Currently used at high loading rates
	Activated Sludge	‣ Currently used to treat DIA's ADF at DMWWTP	‣ Seasonal startup issues ‣ Very large system	‣ Common practice in Wastewater Treatment Plants	No: Prohibitive cost

Evaluation of Alternatives

The five proposed alternatives were evaluated in detail in the context of the design criteria, described in the Decision Process section below. For each alternative, a cost analysis was performed involving both the initial capital cost of the system and the operations and maintenance costs over a 20 year lifespan. The costs were based off the current market price for materials and labor. Every project was also analyzed for effectiveness under the unique needs of deicing operations such as BOD loading rate, seasonal considerations, and sizing limitations dictated by airfield regulations. In the case of DIA, the BOD loading sent to DMWWTP was 8.707 tons per million gallons per year. This average BOD loading rate was used because detention ponds on the premises allow for flow equalization and dilution, resulting in a consistent PG concentration throughout the year.

One of DIA's main concerns is to minimize the cost associated with deicing waste treatment, which averages $652,000 annually. Each technology was designed to remove approximately 90% of the BOD associated with PG (except for the advanced oxidation process which would eliminate ~80% of the total PG).

Fine Bubble Aeration

Technical Description and Literature Review

In the context of wastewater treatment processes, aeration systems introduce air into wastewater to support aerobic microbial degradation of organic material. Aeration provides the oxygen that aerobic bacteria need to metabolize the organic matter, and mixes the water so that these microbes contact the full volume of water. Aeration systems may be used to reduce the oxygen demand imposed by waste from deicing operations, and can be adapted to that specific waste stream.

In a bubble aeration system, an air compressor forces air into a system of pipes laid across the bottom of the pond. Diffusers are strategically spaced along the pipe system to effectively bubble air into the entire body of water (19). Oxygen in the air stream partitions into the water to fuel the growth of aerobic bacteria, which consume the oxygen demand associated with deicing fluids. An aeration system could be implemented at DIA by retrofitting some of the detention ponds have already been built for the purpose of storing deicing fluid before transport to Metro WWTP. This would reduce the waste disposal fees that DIA pays to Metro WWTP, which is the goal of this design evaluation (9). Based on the kinetics of aerobic degradation of PG, the required residence time for ADF in the aeration ponds is five days. Figure 4 displays a basic schematic of the aeration process.

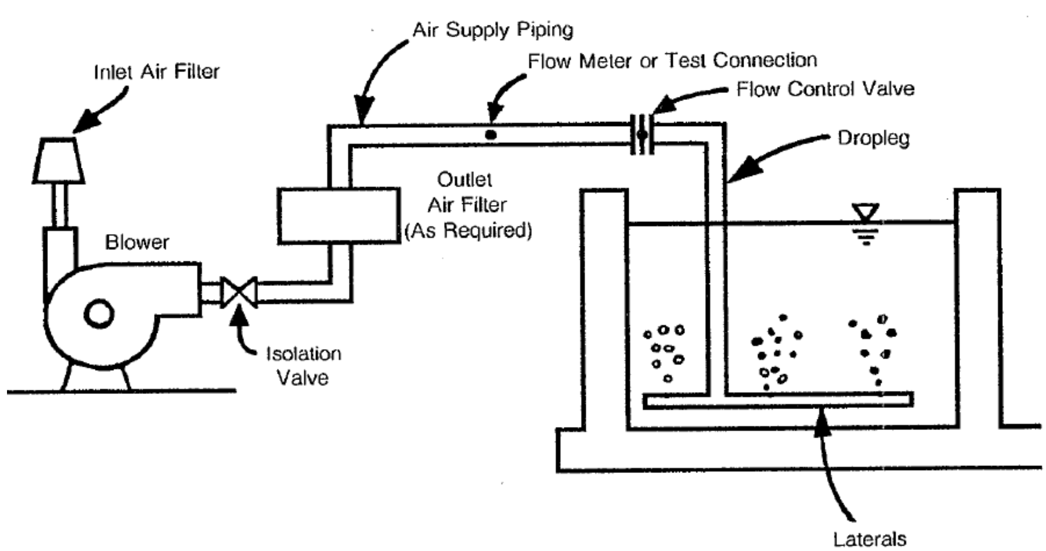

Figure 4. Aeration Process Schematic (20)

Design Summary

Table 3. Design Summary for Fine Bubble Aeration

Design Parameter	Value	References
Oxygen required to consume BOD	13,200 lbs. O_2 per day	(20); (21); (22); (9)
Air demand from blower	5300 SCFM	
Blower discharge pressure	19.7 psia	
Blower power requirement	76 hp	
Diffuser Heads	3500	
Diffuser and Distribution Piping	5,200 feet	

Cost Summary

Table 4. Cost Summary for Fine Bubble Aeration

Cost Item	Present Value Cost (2012)	References
	Capital Cost	
System Component Initial Cost	$197,780	(20); (9)
Other Construction Initial Cost	$71,340	(20)
Total Initial Cost	$269,100	
	O&M Cost	
Annual Energy Cost	$34,790 per year	(20)
20 year projection Energy Cost (PV)	$477,100	
Total Annual O&M Cost	$8,042 per year	(20)
20 year projection O&M Cost (PV)	$110,300	
Total Present Value Cost	$865,400	

Anaerobic Biogas Reactor

Technical Description and Literature Review

Anaerobic digestion is a naturally occurring process, which is driven by the decomposition of organic matter by bacteria in environments that contain little to no oxygen. For a biogas digester, the process is monitored under ideal conditions, resulting in the production of methane gas. Organic material in the influent stream (PG) contains COD, which can be digested by microorganisms to produce methane gas and treat the wastewater. DIA could use the methane gas as an energy source to provide heating for the system.

The biogas produced from the reaction above generally contains approximately 65% methane and 35% carbon dioxide. The production of methane gas will almost completely remove the COD from the wastewater propylene glycol stream. Under this assumption, at 35°C and 1 atmosphere, 1 gram of COD removed is equivalent to 395 mL of methane gas produced (23). Figure 5 below depicts the basic design for an anaerobic biogas digester (24).

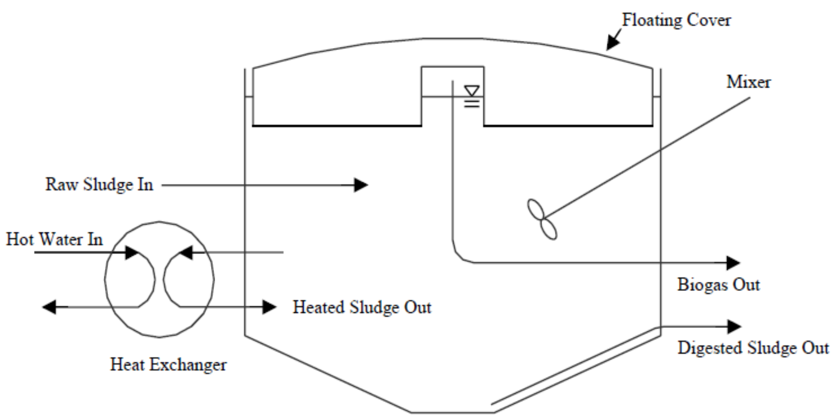

Figure 5. Anaerobic Biogas Reactor

Design Summary

Table 5. Design Summary for Anaerobic Biogas Reactor

Design Parameter	Value	References
Temperature	35° Celsius	(25)
Methane Produced	18.9 ft^3/min	(25)
Retention Time	20 days	(25)
Volume of Tank	20,430 m^3	(25)
Heating Requirements	144,350 kWh per year	(25)

Cost Summary

Table 6. Cost Summary for Anaerobic Biogas Reactor

Cost Item	Present Value Cost (2011)	References
Annual O&M Cost	$12,990	(25)
Initial Capital Cost	$1,705,000	(26)
Initial Labor Cost	$12,000	(27)
Total Capital Cost	$1,717,000	(26), (27), (28)
Annual Savings	$165,500	(29)
Present Value Benefit	$403,350	

Anaerobic Fluidized Bed Reactor (AFBR)

Technical Description and Literature Review

The anaerobic fluidized bed reactor is a type of anaerobic biological treatment for different types of wastewater. Similar to the anaerobic biogas reactor, the treatment of wastewater occurs when bacteria metabolize the organic material in the water without the presence of oxygen. The general design of the anaerobic fluidized bed reactor consists of a vertical cylindrical tank filled with granulated activated carbon, a fluidization pump, a separator tank, and piping to transport the fluid (30). Contaminated water is pumped up through the bed of media, usually activated carbon or sand, at a velocity high enough to suspend the solids in a uniform manner. In the tank, microorganisms form a biofilm on the suspended media (31). The suspended media provides a much larger surface area for the attachment of microbial consortia, making a more effective system for treating contaminated water compared to fixed film reactors (31). The microorganisms that occur in the in the anaerobic fluidized bed reactors are naturally occurring in locations such as peat bogs, sediment, and cattle intestines (30). Microorganisms of this type are then able to biodegrade the organic matter in the wastewater and produce methane gas. AFBR technology is effective at removing BOD which could reduce our client’s fees to DMWWTP.

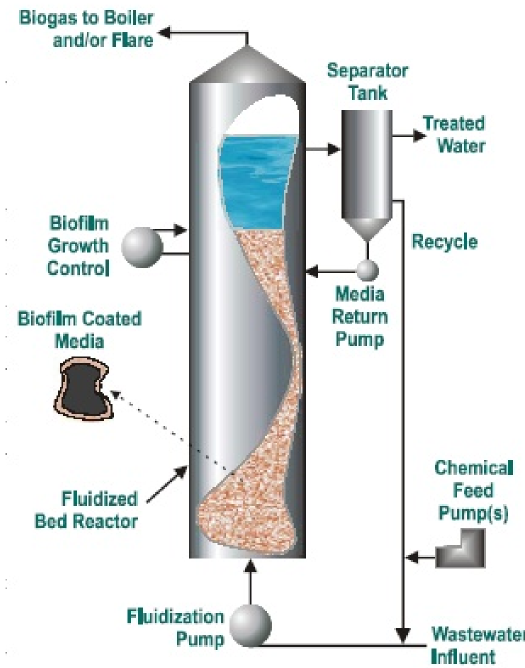

Figure 6. Anaerobic Fluidized Bed Reactor

Design Summary

Table 7. Design Summary for Anaerobic Fluidized Bed Reactor

Design Parameter	Value	References
Approximate Tank Height and Radius	Height = 23 meters Diameter = 24 meters	(32)
COD Loading Rate	Up to 100 $\frac{kgCOD}{m^3 day}$	(33)
Successful Operation Flow Rate Ranges	Between 5 and 6,000 gallons per minute	(34)
Acceptable Temperature Range for Operations	Between 20 and 42 degrees Celsius	(33)

Cost Summary

Table 8. Cost Summary for Anaerobic Fluidized Bed Reactor

Cost Item	Present Value Cost (2012)	References
Capital Cost (including storage for spent fluid and mixing)	$16.2 million	(35); (9)
Operations and Maintenance Costs (normalized)	$92.80/year/lbs COD/day	(35)
Operations and Maintenance Costs	$759,000 per year	(35); (9)
Savings from Methane Production	$165,533	(29)
Present Value Costs over a 20 year lifetime	$24.3 million	

Advanced Oxidation Process: Ultraviolet Degradation with Ozone

Technical Description and Literature Review

The use of advance oxidation processes is a relatively new technology in the realm of wastewater treatment. While ultraviolet radiation (UV) is utilized as a disinfection treatment, its use with oxidizers such as ozone and hydrogen peroxide is still not widely employed. Some chemicals absorb UV directly, resulting in degradation of chemical bonds and removal of the contaminant. However, not all organics react in this way, presenting the need for an oxidizer such as hydrogen peroxide or ozone. The ultraviolet rays form hydroxyl radicals with the oxidizer that catalyze the oxidation process. Due to the high reactivity of the radical, a wide range of biologically toxic and non-biodegradable organic compounds can be destroyed. This is a particularly desirable characteristic since advanced oxidation can remove both the PG and the MeBT, along with other contaminants contained in the ADF (2). Oxidation is capable of complete mineralization. In this process toxic, organic compounds react with the oxidizer yielding carbon dioxide, water and salts (36). However, complete mineralization requires a high dose of UV and oxidant; resulting in elevated operating costs. Therefore, for the purposes of this project, the system will only administer the dose necessary to treat the water to meet the standards put forth by the EPA and Federal regulations. Another beneficial quality of the advanced oxidation process is the speed at which it is able to treat the water. Due to the high reaction constant in free radical processes, a short exposure time would yield a completely treated effluent stream. After applying the DIA effluent flow data, the specifications shown in

Table 9 were calculated assuming that a 2 minute retention time is necessary for sufficient (>80%) degradation.

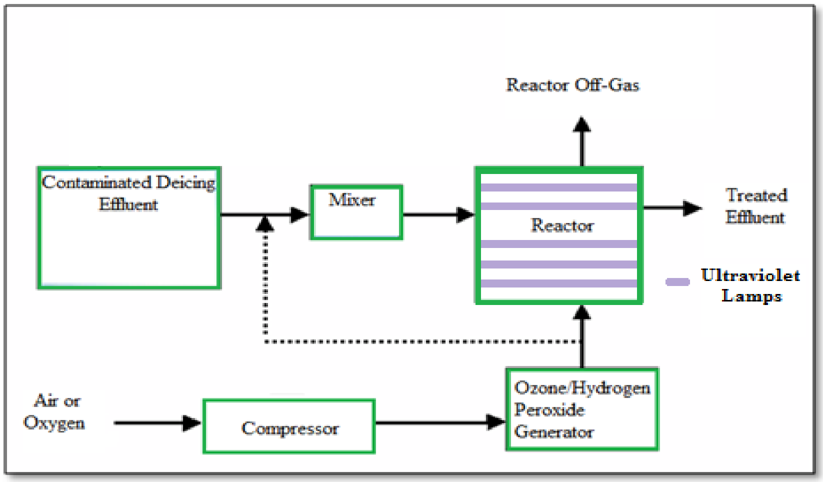

Figure 7. Illustration of Ultraviolet Degradation Coupled with Oxidizing Compound

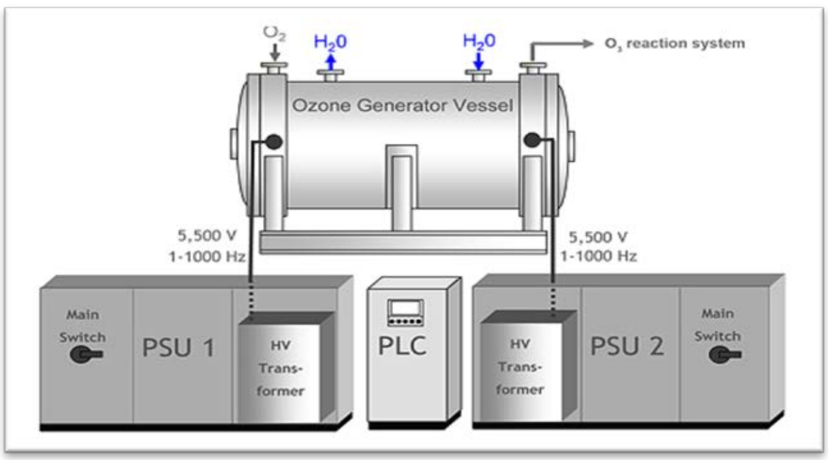

Figure 8. Wedeco Technologies (36)

Design Summary

Table 9. Design Summary for Ultraviolet Degradation Coupled with Oxidizing Compound

Design Parameter	Value	References
Flow rate	380. gal/min	(37)
Required UV lamps	23 lamps	
Power/lamp	kW	
Annual Power Consumption	10,080 kWh/year	
Required Ozone	345.47 kg/hr	
Ozone Produced per Generator	200 kg/hr	
Required Ozone Generators	4 units	

Cost Summary

Table 10. Cost Summary for Ultraviolet Degredation Coupled with Oxidizing Compound

Ozone Generation		UV System	
O & M Cost			
Annual cost of power	$15,380	**Annual lamp replacement**	$1,100
Maintenance	Lifetime Warranty	**Annual power cost**	$705
		Cleaning/maintenance /yr.	$1,440
Total Cost per year:	$15,380	**Total Cost per year:**	$3,250
Overall O&M Cost: $18,630 per year			
Overall O&M Cost for 20 year Lifespan: $255,400			
Capital Cost			
Cost per Generator	$549,000	**Cost per Lamp**	$48
Capital Cost for 4 generators	$2,196,000	**Total Lamp Cost**	$1,100
		Installation Cost	$20,000
		Capital Cost:	$21,150
Overall Capital Cost: = $2,214,630			
Total Present Value Cost: $2,470,050			

Physical Separation Process: Membrane Filtration (Reverse Osmosis)

Technical Description

Reverse osmosis (RO) is a membrane based water treatment technology that is normally associated with desalination of seawater. RO involves high-pressure forcing of contaminated water through membranes with very small pores. Water, a small molecule, is forced through the pores and the larger contaminants, including salts such as propylene glycol and other ADF additives, are not allowed to pass through the membranes due to their size relative to the pore size of the membrane. The wastewater is separated into the permeate stream (through the membrane) and the concentrate stream (the rejected water and contamination). The permeate stream will have greatly reduced BOD (generally 99%+ removal rates (38)). The concentrate stream will have enhanced concentrations of PG. If the concentrations are high enough, the PG from the concentrate stream may be recycled by Inland.

Reverse osmosis systems are beginning to be used for this purpose in the US. At Pittsburgh International Airport a 1-4% PG by volume stream is fed to a reverse osmosis system to concentrate the water to 8-12% PG by volume. This concentrated stream is then recycled by the airport. The permeate is discharged to the local treatment plant (39). The USEPA conducted a feasibility pilot study to clean glycols from airport wastewater using heated ceramic membranes (40). The results of this investigation were promising and further large-scale pilot scale experiments were recommended. A similar system was proposed by New Logic for the Minneapolis / St. Paul International Airport in Minnesota (41). The New Logic system could be adapted for implementation at DIA. New Logic's process diagram is displayed in Figure 9.

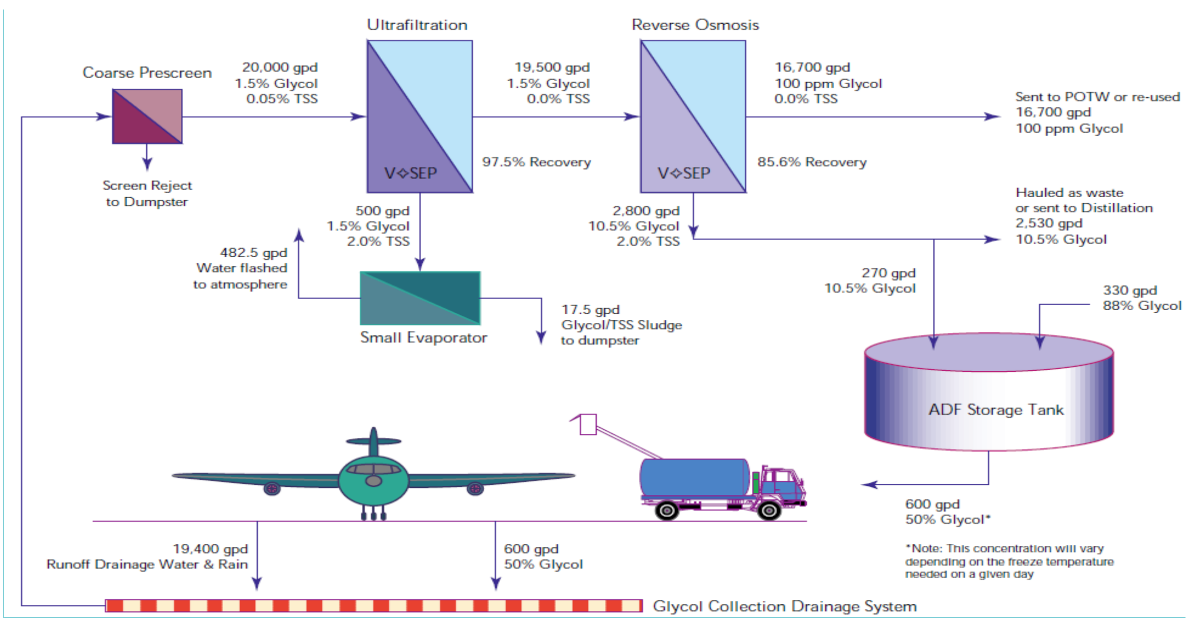

Figure 9. Membrane Filtration Implementation at DIA (41)

Design Summary

Table 11. Design Summary for Reverse Osmosis Sysem

Design Parameter	Value	References
Area of Membrane Required	600 m^2	(38)
Area per Membrane	32 m^2	(38)
Number of Thin-film Composite Spiral Wound Membranes	197	
Total Volume of Membranes	6.2 m^3	

Cost Summary

Table 12. Cost Summary for Reverse Osmosis System (42)

Construction Costs	Value
Concrete	$1,178,640
Labor	$259,700
Electrical and Instrumentation	$239,720
Housing	$319,630
Total	**$1,997,700**
Annual Operations and Maintenance Costs	
Electricity (3.56E6 kWh/yr.)	$249,700
Labor	$177,400
Maintenance Material, Membrane Replacement, and Cleaning Chemicals	$230,000
Total Cost per Year	**$657,100**
Total 20 Year Net Present Cost	**$9,049,000**

Decision Process

To select the best possible alternative for DIA, a variety of decision factors were considered. They key factors which have influenced our decision are client-specific criteria and constraints and FAA design competition guidelines. A preliminary discussion of the criteria was discussed in the Problem Solving Approach section at the beginning of this report. These criteria are fully developed in the section below.

Criteria and Constraint Analysis

To objectively compare the alternatives, each was assessed based on the criterion descriptions shown in Table 13. Explanation of Decision Matrix Categories and Alternative

Scoring Economic, socio-political, environmental, and technical aspects were taken into consideration. Each of these categories was broken down into subcategories, with the exception of economic constraints which were grouped together to best evaluate the total economic value for all present and future operations. The economic value of each alternative is based on a standard process explained in the Financial Analysis section below. These specific factors were developed in collaboration with DIA (9). The alternatives were scored in the decision matrix according to the specific factors explained in the right-most column of Table 13.

Explanation of Decision Matrix Weights

The relative importance of each criterion was determined through careful consideration of the opinions of the client Denver International Airport, University of Colorado Professors and Teaching Assistants, and the KANDE Consulting team. Because DIA is at the forefront of environmentally responsible deicing practices, their main concern is that the new design will improve upon the current costs they face when treating the non-recyclable deicing wastewater. Therefore, the Economic portion of our decision matrix was weighted at 0.5. Environmental and technical considerations were weighted at 0.2 each because it is understood that the client is currently leading in environmental responsibility and has implemented technically challenging projects already. These categories, therefore, are less important for this particular design because any improvement on current technology will go above and beyond technical and environmental standards. The social and political section of the decision matrix was weighted at a 0.1 because we feel that the client currently possesses a great reputation for environmental stewardship and that any additions to their current system would only be an improvement from this currently good standing.

Financial Analysis

Financial analysis was the most important criteria in the alternatives assessment. Capital costs include all of the building material, labor costs, and extra costs associated with initial implementation of the technology. Annual operations and maintenance costs include labor, replaceable material costs, and upkeep. In this equation, annual savings refers to the technologies that will be producing a form of energy that the client may either use or sell and is only applicable for the anaerobic technologies as well as the savings associated with the BOD reduction sent to DMWWTP. All alternatives except the AOP system were designed to reduce BOD concentrations to 2.2mg/L, which is the current DMWWTP BOD effluent (43). The AOP system was designed for 80% BOD reduction due to elevated costs associated with the amount on UV radiation and ozone necessary for complete mineralization, and will therefore not produce as much savings as the other alternatives. It is also important to note that the anaerobic biogas digester produces a valuable product: methane. This gas can be sold for auxiliary revenue, making this alternative especially attractive. The equation used to determine the present value cost of the technology over a twenty year lifetime is shown below. Each alternative assessment will undergo analysis to normalize the costs of the different alternatives in a uniform manner.

Equation 1. Net present cost

$$Net\ Present\ Cost\ = Capital\ Cost + Annual\ O\&M\ Costs * \left(\frac{1-(1+i)^{-n}}{i}\right)$$

In this equation, ”i” is the inflation rate (44) and “n” is the design lifetime of 20 years. The outcome of the above analysis can be seen in the individual alternatives decision matrices which can be found in the Decision Matrix section below. Each alternative has been scored accordingly to facilitate in the design decision process.

Table 13. Explanation of Decision Matrix Categories and Alternative Scoring

Categories	Subcategories	Subcategory Explanation	Explanation of Relative Scoring
Economic	Cost	·Based on net present value ($) in 2012 for a 20-year lifespan ·Includes capital costs: construction, equipment, labor, operations and maintenance costs: electricity, labor, replacement parts ·Includes income associated with operation (if applicable)	Cost ratings based on differences in present value costs for each technology; exponential distribution of prices but differences are significant enough to warrant different ratings on a score of 1 to 5
Social and Political	Reputation	·The alternative improves DIA's reputation as a leader in environmental management systems ·It demonstrates state-of-the-art use and application ·DIA is pioneering a system that could be applied elsewhere	RO, anaerobic biogas digester, and anaerobic fluidized bed reactor technologies received a 5 because they allow for recovery of PG or the recovery of methane gas; other technologies received a 3 because they remove COD from airport waste but do not recover desirable products
	Public Perception	·The public will view the alternative as an improvement to the current system ·The alternative won't negatively impact public livelihood	Alternatives are situated far from local residents but smell and visual distractions could still be an issue for the anaerobic technologies therefore they scored lower than other options. RO scored the highest because it allows for recovery of PG
	Government Perception	·DIA is setting new standards for controlling airport environmental footprints ·The alternative will meet potential future regulatory requirements ·The alternative will reduce loading to DMWWTP	Waste to energy options are rated higher because of the general push for renewable energy; other options scored neutral
Environmental	Ethics and Responsibilities	·Environmental stewardship · Shows proactive responsibility for actions ·Full life-cycle analysis with regard to sustainability of the system	It is ethical to completely treat deicing wastewater; technologies that treat the water so that it is closest to appropriate for direct discharge rated highest
	Resource Use	·The alternative uses minimal non-renewable resources ·The alternative promotes renewable resources	RO has the highest resource use (the majority being electricity) therefore scored lowest; AFBR has energy demands but it also produces energy so it rated neutrally; other options do not use many resources and scored highly
	Pollution Control	·The alternative contributes minimal greenhouse gases (directly or indirectly) ·The alternative has small waste streams ·The alternative requires minimal use of hazardous materials	RO requires cleaning with RCRA classified hazardous materials so it scored low; UV with ozone has no solid waste and oxidizes all contaminants so this technology scored highly; other technologies scored neutrally because they have small waste streams or do not treat all contaminants
Technical	Design Complexity	· Historically relevant case studies for the design and operation of the alternative ·Geography and geometry are not inhibitory ·The construction and operation of the alternative do not interfere with the day to day operations of DIA	Large construction, the anaerobic technologies score lowly in this category; fine bubble aeration scores highly because it utilizes current infrastructure; other technologies score neutrally
	Operation Complexity	·The operation of the alternative is highly automated ·The alternative requires a low amount of labor for day to day operation ·The alternative does not require extremely skilled or specialized operators	Anaerobic technologies require nutrients and temperature regulation and fine bubble aeration requires some nutrient input and monitoring, these technologies receive neutral ratings; other technologies are difficult to operate and require more hands on monitoring so they will score lower than the rest

Decision Matrix Development

Each of the five alternatives was evaluated according to the criteria explained previously in Table 13. Explanation of Decision Matrix Categories and Alternative Scoring The alternatives were scored on a scale of one to five, where one represents non-attainment of the criteria and five represents full attainment of the criteria. The scores for each alternative were compared to decision matrix scores for the "do nothing/no change" option, which constitutes continued deicing waste shipments to DMWWTP. Comparison to the 'no change' option is critical to evaluating the relative benefit of each alternative to the current practices. The scores for all options are condensed into a single decision matrix table, which was used for the selection of an alternative. The decision matrix is displayed in Figure 10.

Decision Matrix

Criteria				Alternatives					
Categories	**Weight**	**Subcategories**	**Weight**	**AFBR**	**RO**	**Advanced Oxidation**	**Pond Aeration**	**Biogas Reactor**	**No Change**
Economic	0.5	Total Cost	1.0	1	2	3	4	5	2
Social and Political	0.1	Reputation	0.4	5	5	3	3	5	3
		Public Perception	0.3	4	5	4	4	4	3
		Government Perception	0.3	4	3	3	3	4	3
Environ-mental	0.2	Ethics and Responsibility	0.3	4	5	4	3	3	3
		Resource Use	0.3	3	2	5	4	5	3
		Pollution Control	0.4	2	2	4	3	3	3
Technical	0.2	Design Complexity	0.4	2	4	4	5	2	5
		Operation Complexity	0.6	2	5	3	4	2	5
Total Scores				**1.7**	**2.7**	**3.2**	**3.7**	**3.8**	**2.7**

Figure 10. Decision Matrix

Anaerobic Biogas Reactor Design

Based on the results of the decision matrix, an anaerobic reactor has been selected as the technology of choice for the client, DIA. This system includes several principal process components. The anaerobic reactor receives dilute deicing waste from an existing detention pond at DIA called Pond 009. After removing most of the BOD in the deicing waste stream, the treated water is discharged to DMWWTP via an existing pipeline at a constant flow rate of 0.33 MGD. In steady state conditions, the digester will produce a constant flow rate of biogas. The gas will be used for mixing the reactors and powering the boiler, which heats the incoming deicing waste. The purpose of this design is to reduce the fees paid by DIA to DMWWTP for BOD and TKN loads through the anaerobic degradation of PG. Below is a flowchart depicting the necessary components of the biogas digester system.

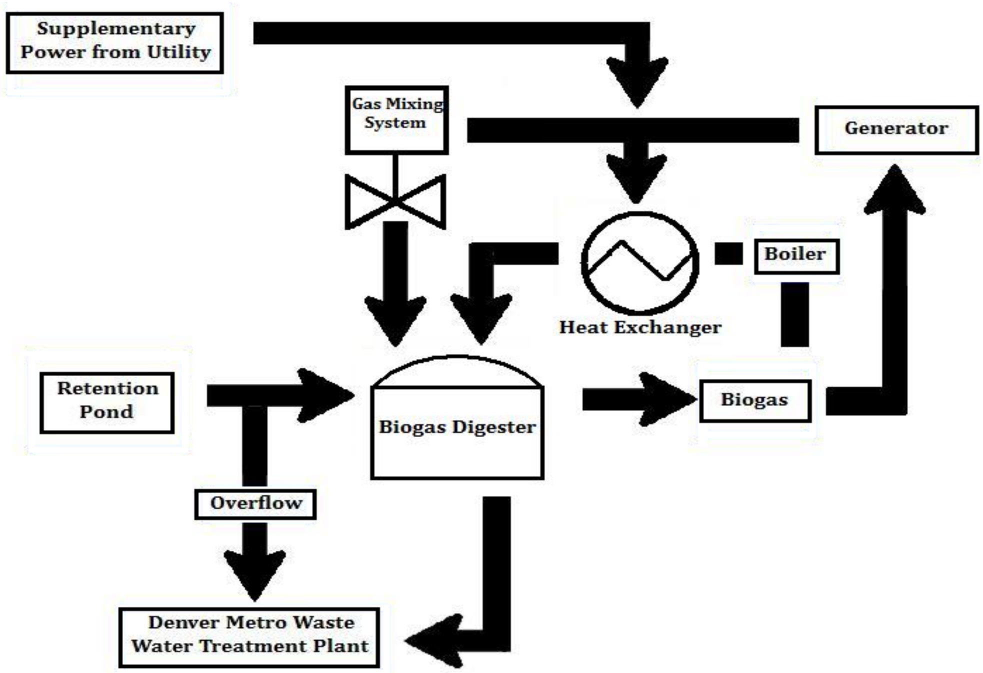

Figure 11. Flowchart Depicting Biogas Digester System

The placement of the digesters, as seen below, accounts for proximity to the settling ponds, amount of excavateable land area, FAA regulations regarding on-site construction, and proximity to other existing airport infrastructure.

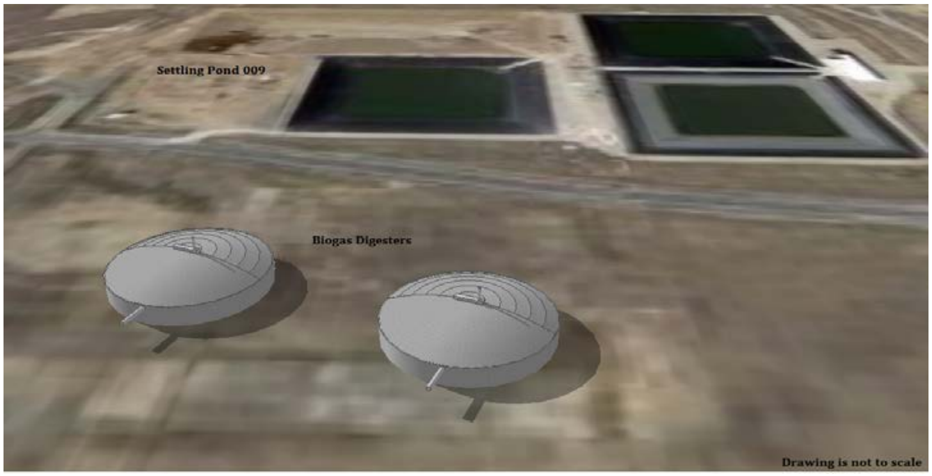

Figure 12. Arial view of the digesters near the existing settling ponds at DIA

The sections that follow present a more detailed design of this system, including the rationale for selecting individual process components.

Safety and Risk Assessment

A review of the FAA Safety Management Systems Manual (2011) provided guidance for our team to perform a thorough safety risk assessment of this project. The five steps set forth by the document allow for possible hazards to be identified, analyzed, and mitigated by utilizing the necessary safety mechanisms.

The deicing waste, which is less than 1% by volume PG, is hazardous to both human and ecological health. Although PG is less toxic than ethylene glycol, adverse health effects can be caused by exposure. If ingested in relatively large quantities PG can cause nausea, cognitive problems, heart and kidney complications and even death. Skin and eye contact with undiluted liquid PG rarely causes irritation; however, airborne concentrations have been known to cause eye and upper respiratory inflammation (44). In order to avoid all of the above health hazards, human contact with the waste must be minimized. Operators of the digester must take preventative precautions not to inhale or touch the influent waste. Proper safety gear such as respirators and gloves should be worn when operating machinery in or around the digester system.

Once introduced into the environment, PG depletes its surroundings of oxygen due to a large BOD necessary for complete biodegradation. Ecosystems need a certain dissolved oxygen concentration in order to sustain life. If this value drops below a critical value species will emigrate or die, drastically affecting the biodiversity of the area. As with any system, prolonged use could result in corrosion of piping, releasing contents into the environment. The correct materials must be chosen to ensure endurance and compatibility of the PG with the piping. Regular and thorough inspection of the system should safeguard against leaks or malfunctions. This measure will minimize the amount of fugitive PG introduced both into the air and water, preventing accidental exposure of humans and the environment.

In order to foster optimal microbial growth, the digester must be heated to 35 degrees Celsius. The boiler will be heated by a methane powered generator presenting the need for technicians to regularly inspect the gas storage pressure and piping to protect against leaks. Similarly, the digester's mixing system is powered by the same methane gas and requires safety measures to be exercised. For both processes the use of pressurized fuel gas can cause an explosive environment if not maintained properly.

The effluent from the digester will be pumped straight to DMWWTP, eliminating safety concerns on the tail end in terms of water treatment; however, the digester will produce a sizeable amount of solid waste. Microbial metabolism and death will cause accumulation of sediment in the bottom of the tank. General cleaning and maintenance of the digester and examinations of associated systems must happen regularly. Due to the possibility of residual deicing chemicals, operators must employ the same precautions as stated above when handling influent deicing runoff.

To ensure proper operation, only properly trained personnel should be allowed to work on the system. The training should include not only technical material but also safety and risk information associated with the toxicology of compounds as well as the proper medical measures that must be taken with each. If any health concern is encountered, employees should be encouraged to seek immediate medical attention.

Technical Design Considerations

The design of the anaerobic reactor system is comprised of several components that work together to treat the dilute dicing waste. These sections focus on the key components of the system, from the reactor kinetics to the design of a reactor tank and heating and mixing systems.

Reactor Kinetics and Microbial Considerations

A hydraulic residence time of 20 days was selected for the anaerobic reactor based on kinetic parameters for anaerobic of PG (45) (46) (47) (48) (49) and published references for anaerobic reactor design (50). To verify this as appropriate, first-order Monod kinetics were used to model the degradation of 2600 mg/L of PG to 0 mg/L in approximately 16 days with an initial biomass concentration of 150 mg VSS/L and a mean of 0.01 per day for the endogenous decay coefficient. This affirms that the selection of a residence time of 20 days is appropriate and the majority of the PG will be degraded in the reactor.

A concern with using an anaerobic digester is the startup time to handle the full BOD loading rate. This becomes an issue when considering the initial startup time, startup after cleaning the digester, and seasonal fluctuations. Using the kinetic parameters for anaerobic digestion of PG, kinetic rates were calculated for the growth of biomass in the reactor. If the reactor is seeded with 1500 kg of anaerobic reactor sludge (12 mg/L as biomass) from the nearby DMWWTP, the reactor will take between 90 and 110 days to reach operation conditions. The microbial population doubles in roughly 20 to 25 days which is sufficient since the concentration of PG will likely not double in this timeframe due to DIA's large flow equalization pond. However, more sludge may be added to reduce this startup time if necessary.

The reactor will require nitrogen and phosphorous additions of 28 and 6 mg/L respectively to prevent micronutrient limitation effects on the microbial population. Calcium carbonate will also need to be added at 2750 mg/L to buffer the pH in the reactor. Other micronutrients (sodium, chloride, potassium, calcium, and sulfate) may need to be added in low concentrations if pilot scale studies show deficiencies in the DIA wastewater.

Using Figure 13, the yield of the biomass (45), the concentration of methane in the biogas (50), and the average yearly wastewater conditions at DIA, the calculated production of methane is 1615.8 kilograms per day. BioWin WWTP modeling software was used to verify reactor parameters, nutrient additions, and kinetic calculations.

Table 1. Propylene Glycol Bioconversion Reactions[a]

Reaction		$\Delta G^{\circ\prime}$ (kJoules/mol)
1	$CH_3CH(OH)CH_2OH \rightarrow 0.5\ CH_3CH_2COO^- + 0.5\ H^+ + 0.5\ CH_3CH_2CH_2OH + 0.5\ H_2O$	−24.4
2	$0.5\ CH_3CH_2CH_2OH + H_2O \rightarrow 0.5\ CH_3CH_2COO^- + 0.5\ H^+ + H_2$	+1.5
3	$CH_3CH_2COO^- + 3\ H_2O \rightarrow CH_3COO^- + H^+ + HCO_3^- + 3\ H_2$	+18.3
4	$4\ H_2 + H^+ + HCO_3^- \rightarrow CH_4 + 3\ H_2O$	−32.4
5	$CH_3COO^- + H_2O \rightarrow HCO_3^- + CH_4$	−7.4
Overall Reaction:		
6	$CH_3CH(OH)CH_2OH + H_2O \rightarrow H^+ + HCO_3^- + 2\ CH_4$	−44.4

[a]Adapted from Veltman et al. (1998b).

Figure 13. Propylene gycol biodegradation pathway (45)

Toxic effects on the microbial populations from the ADF additives are anticipated to be low. The most toxic ADF component is tolyltriazole (MeBT). However, the concentration of MeBT will be approximately 25 mg/L in the influent and 5.7 mg/L in the biomass. Both of these concentrations are below significantly toxic effect levels (6).

Design and Sizing of Reactor

A cylindrical reactor shape has been selected for this design because of advantages such as low vertical profile and significant gas storage capacity. These advantages outweigh the disadvantages, which include accumulation of grit in the bottom of the reactor. The volume of the reactors is based on the average flow rate of deicing waste into the system. To ensure complete mixing of the reactors, a maximum diameter of 125 feet is recommended (51). At the specified steady-state flow rate, two reactors are needed to satisfy this maximum diameter constraint. The mixing system used in these reactors will be an unconfined gas-injection system; providing the optimum combination of complete mixing and low operational expense (51). The reactor cover will be fixed, which allows for sufficient gas storage while minimizing capital and operational costs (52). The sludge generated by this anaerobic reactor design is less than that of comparable municipal wastewater systems (43), and the concentration of total suspended solids exiting the reactor will not be a significant burden on DMWWTP. For this reason, the sludge will be transported along with the treated deicing waste to DMWWTP without further sludge processing. A summary of the reactor design parameters is provided in the table below. This design will be able to handle anticipated future increases in loading rates due to expansion at DIA.

Table 14. Anaerobic Biogas Digester Design Parameters

Parameter	Description	Source
Hydraulic Retention Time	20 days	(50)
Reactor Shape	Cylindrical	(50)
Total Volume of One Reactor	579,960 ft^3	
Total Surface Area of One Reactor	33,750 ft^2	
Cover style	Fixed dome	(51)
Mixing system	Unconfined gas-injection via floor mounted, 12" diameter fine bubble diffusers	(51)
Sludge Disposal	Discharge to DMWWTP	

Heating Requirements

In order for Anaerobic Biogas Digesters to operate properly and efficiently, constant temperature must be maintained inside the digester tank to ensure an optimal microbial environment. The energy that is required to provide sufficient heat in order to maintain a constant, elevated temperature is considerable, however. There are three major heat requirements for anaerobic digesters:

- The amount of heat required to raise the temperature of the incoming feedstock to the temperature of the sludge within the digester (typically 35^{o}C for mesophilic organisms).
- The amount of heat required to compensate for heat losses through the floor (conical), roof (dome), and walls (cylindrical) of the digester.
- The amount of heat required to compensate for any heat losses that occur between the piping to the heating source and the digester tank. For typical digesters, however, the heating required for the piping is considered negligible due to a small surface area subjected to heat loss.

The table below summarizes the monthly heating requirements for both anaerobic digester tanks. The total heat requirement incorporates the amount of heat required to raise the temperature of the incoming feedstock and the amount heat required to compensate for the heat loss to surroundings

Table 15. Montly Heating Requirements

Month	Total Heat Requirement (KJ/day)	Source
January	1.69E+08	(50), (51), (52)
February	1.64E+08	
March	1.54E+08	
April	1.44E+08	
May	1.09E+08	
June	9.30E+07	
July	7.74E+07	
August	7.78E+07	
September	1.22E+08	
October	1.38E+08	
November	1.54E+08	
December	1.84E+08	

The influent wastewater to the reactor will need to be heated to 35 degrees Celsius and the reactor will need to be maintained at this temperature during operation in order to achieve maximum efficiency. These heating requirements will be met by implementing a gas burning boiler which will be designed to run on the biogas produced by the reactor and supplemental natural gas. This boiler will feed steam to three shell and tube heat exchangers (53). The equipment displayed in Table 16 will be used to meet the heating requirements.

Table 16. Heat Exchanger Description

Heat Exchanger Purpose	Heat Exchanger Type	Heat Transfer Surface Area per Unit	Heating Duty per Unit	Cost per Unit	Flow Rate of Steam per Unit	Flow Rate of Reactor Water per Unit
Heating influent waste water	Shell and Tube	11.80 square meters	8,481,400 kJ per hour	$13,000	4,160 kg per hour	0.33 million gallons per day
Maintaining reactor temperature	Shell and Tube – 2 units required	.31 meters s0quared	201,500 kJ per hour	$2,000	100 kg per hour	5000 kg per hour

Heat exchangers were sized using a chemical engineering program called SuperPro Designer. Input parameters were influent water temperature, exit temperature, heat exchanger type, influent flow rate, heat transfer efficiency (53), heating agent, and fluid composition.

To have sufficient steam for these heating requirements, a 3.5 MW boiler is required. This boiler will have an efficiency of about 75% when close to a full load (54) and will operate around 90% capacity on average throughout the year.

Biogas Production and Usage/Electricity Generation

KANDE has calculated that the reactors will produce 1615.8 kg of methane per day. It is recommended to the client that the gas be used in the boiler to offset the costs of natural gas. However, should the client choose to produce electricity with the biogas, three different gas turbine generators were evaluated and are shown in Table 17.

Table 17. Cogeneration Considerations (55)

Biogas Production (MMBTU/hr)	Capstone Turbine (55)	Turbine Efficiency	Energy Input Requirements for one unit (MMBTU/hr)	Energy Input Requirements for one unit (kW)	Number of Units	Net Electrical Output (Running at % load)
1.56	C30 HP	26%	.393	115	4	119 kW at 99% load
1.56	C65 ICHP	29%	.765	224	3	133 kW at 68% load
1.56	C200 HP	33%	2.068	606	1	151 kW at 76% load

KANDE recommends that if the client chooses to cogenerate electricity, 4 30 kW gas turbines should be installed. This will ensure that the turbines operate as close to maximum load as possible to maintain the highest efficiency.

Cost Estimation

The cost of the system is dependent on both the capital and operations and maintenance costs associated with implementation. The two tables below show the calculated values for both cost types.

Table 18. Summary of Operations and Maintenance Costs for Biogas Digester

Annual Cost Item	Annual Cost (in 2012)	Net Present Cost	Source
Operator salary	$40,770	$559,000	(56)
Boiler, heat exchanger, pump, and compressor maintenance	$1,130	$15,500	(57)
Grit cleaning and mixing system maintenance	$1,360	$18,650	(57)
Natural gas	$303,570	$4,162,250	(58)
Pump power	$7,600	$104,200	(58)
Compressor power	$2,760	$37,800	(58)
Nutrients	$160,900	$2,206,100	(59), (60)
Total annual costs	$518,090	$7,103,500	

Table 19. Estimated Capital Cost for Biogas Digester

System Component	Specifications	Useful Life (years)	Amount Needed	Total Capital Cost	Source
Reactor	12" thick concrete walls, 4" thick concrete cover. Stainless Steel Reinforcing wire. Water Curing. (Equipment/Operations)	20	2	$737,000	(57) (61)
Excavation	3 C.Y excavator, deep excavation	N/A	27,270 yd^3	$105,000	(57)
Boiler	3.5 MW, cast iron with controls and insulated jacket	10	1	$181,200	(57) (62)
Heat Exchanger	12.1 meters squared heat transfer area, shell and tube	10	3	$17,000	SuperPro Designer
Mixing System	12" ceramic disc diffuser system	10	2	$32,450	(57) (62)
Gas Compressors	Compression ratio ≈2	10	2	$25,000	(63)
Pumps	Centrifugal, single stage, 30HP, end suction	10	4	$33,400	(57) (62)
Housing	500 ft^2 control room for operation and control systems	20	1	$153,000	(57) (62)
Electrical	10% of total cost including everything except piping and supplemental nutrients	10	N/A	$37,000	(57)
Piping	PVC, 50 mm diameter, includes joints and valves	20	0.5 miles	$69,550	(57) (64)
Supplemental Nutrients for First Year of Operation	28 mg/L Nitrogen 6 mg/L Phosphorous 1,711 mg/L Calcium Carbonate	1 1 1	- 29.7 tons N/year - 8.3 tons P/year - 2,658 metric tons $CaCO_3$/year	$22,220 $5,810 $132,900 Total $160,900	(59) (60)
Total Capital Cost				$1,551,500	

The total net present cost of the anaerobic reactor system includes the capital cost and the net present costs from operations, maintenance, and replacement. The total net present cost of this system, in 2012 dollars, is $8,803,100.

This system eliminates 90% of the BOD fees paid to DMWWTP annually. The following equation was used to calculate the net present savings, in 2012 dollars.

$$Net\ present\ savings = Annual\ fee\ paid\ to\ DMWWTP\ * \left(\frac{1-(1+0.039)^{-20}}{0.039}\right)$$

This formula yields a net present savings of $8,223,000 assuming that the annual BOD fees are reduced by 90%, or approximately $600,000 per year.

The net present value of this system is the net present savings minus the net present cost. Note that the net present cost is greater than the net present savings; therefore the net present value is negative meaning there is an overall loss in capital investment. The net present value of this design is -$580,100 over 20 years.

Although the system costs more money than it saves over a twenty year lifespan, the cost of the system must be considered next to other factors. For example, the cost of wastewater treatment at DMWWTP could rise in the future, causing greater expenses for deicing waste discharge from DIA. These costs may also rise when DIA expands in the future. These considerations could make the system more economically feasible. Furthermore, if future regulations mandate that a greater amount of deicing waste must be recovered and treated, the system may become necessary to meet these regulations. Finally, implementing this anaerobic reactor would enhance DIA’s reputation as a preeminent leader in airport environmental interactions. Each of these possibilities suggests that proactive steps toward reducing the environmental footprint of DIA deicing operations are worth the expense.

Projected Impacts

At DIA, any deicing waste containing greater than 1% by volume PG is recycled by Inland Technologies. The design presented in the preceding sections operates on the dilute deicing waste which cannot be economically recycled. DIA has one of the most progressive PG recycling systems in the nation, which is able to recycle about 50% of the deicing waste generated at the airport for reuse. The concentration of PG available at DIA for the anaerobic reactor is significantly less than that at other airports, meaning the reactor produces less biogas than might be possible elsewhere. Because of this restriction, the implementation of an anaerobic digester at an airport that lacks such a high PG recycling capability could prove more profitable.

If the digester at DIA were able to produce 233.1 kilograms of methane per hour (kg/hr.), as opposed to the current capacity of 67.3 kg/hr., the system would be able to completely offset the power requirements necessary for operation. To achieve this methane flow rate, the concentration of PG in DIA's wastewater would need to be approximately 9,000 mg/L on average throughout the year, corresponding to a 0.9% concentration in the wastewater. This is within the design parameter range for the DIA reactor; however, the current average PG concentration in storm water is about 0.25% PG by volume. This is promising since most airports in the US have higher concentrations of PG in their runoff due to lower recycling capabilities. In general, PG concentrations for storm water runoff vary greatly depending on geographic location. A reasonable average can be assumed to be 16,000 milligrams PG per liter or 1.5% PG by volume (65). This percentage is almost twice as much as that necessary to completely power DIA's system. Therefore, it can be reasonably assumed that anaerobic digestion will be viable in other airports along with the capability of producing enough methane to offset the energy requirements of the reactor. Also, it is a possibility that with this increased concentration, excess methane could produce an auxiliary income by producing electricity via gas turbine generators (53). The applicability of a biogas digester is highly dependent on the unique characteristics of each airport. However, after analyzing the implementation at DIA, KANDE Consulting is optimistic in its robustness for widespread use. As seen from the cost analysis, the cost of implementation may be offset by conversion of PG to methane. This economic benefit supplements a biogas digester's ability to significantly reduce the environmental footprint of the airport deicing operations.

Designing a system that meets the goals of the FAA was held at the forefront of KANDE Consulting's considerations during the design process. The FAA's mission states that all operations must "comply with regulations protecting the environment." Specifically, the FAA "has chosen to focus on making snow and ice removal more environmentally friendly" (66). KANDE Consulting's design meets this goal because implementation of a biogas digester not only reduces the amount of contaminated water that must be sent to the local wastewater treatment plant but it also produces a biogas that can be used in a number of different energy applications. This design is applicable for many airports that produce consistent amounts of deicing runoff. Overall, a biogas reactor can reduce environmental impacts of aircraft deicing and be a source of energy for many airports. This will lead to a more sustainable future for aircraft deicing, which ultimately complies with FAA goals.

Description of Interaction with Airport Operation and Industry Experts

KANDE Consulting interacted with airport operators and industry experts throughout the design process. A meeting on February 10th consisted of disclosure of the desires of DIA's

Airport Environmental Interactions staff for the project. As a result of the first meeting, we were introduced to several people who could help us with our design, namely Mr. Keith Pass. Subsequently the team toured the ADF treatment facilities on March 2nd. During the tour of the deicing facilities at DIA, the team had the opportunity to see the process of deicing in action and gained a better understanding of DIA deicing procedures. The information and experiences from this tour became especially important during the design of the anaerobic reactor system.

Correspondence with Mr. Keith Pass through email and phone was helpful to the design process. On February 5th, Mr. Pass sent an email to the team clarifying the scope of the design and explaining the duties of DIA and the airlines involved in deicing operation. This helped to provide useful a perspective on the business of deicing at DIA. On Feb. 23rd, a phone call with Mr. Pass elucidated the ADF control infrastructure at DIA. This was instrumental in understanding the flow of ADF around the airport and how our design might fit in to existing infrastructure. On Feb. 24th, Mr. Pass provided feedback on the decision matrix that we had sent to him for approval. His comments were used in part for the alternative selection process.

Additional industry contacts were helpful throughout the design process. John Lengel, a P.E. for Gresham, Smith and Partners aided our team with useful industry advice. Phone correspondence allowed for explanations of the current systems used for propylene glycol wastewater. Moreover, John Lengel was able to provide KANDE Consulting with other industry contacts, specifically Mark Ervin, who has a more specialized knowledge and experience with anaerobic digesters. Mark Ervin, also a P.E. at Gresham, Smith and Partners was able answer questions which provided relevant technical information concerning anaerobic biogas digesters via email.

Appendix A: Contact Information

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Appendix B: Description of University

The University of Colorado at Boulder was founded in 1876; the first graduating class was comprised of only forty four students. Now, 136 years later, the college has expanded to include the Boulder, Colorado Springs and Denver campuses. The Boulder campus is comprised of four separate schools with an overall enrollment of over 30,000 students.

The University of Colorado at Boulder is one of thirty four public schools invited to join the Association of American Universities. Entry into this organization is "based on the high quality of programs of academic research and scholarship and undergraduate, graduate, and professional education in a number of fields, as well as general recognition that a university is outstanding by reason of the excellence of its research and education programs (67)." Additionally, the National Science Foundation ranked CU in the top ten percent of Universities in the United States. This excellence has been made possible by the renowned faculty, four of which are Nobel Laureates.

The University of Colorado offers degrees in 80 majors at the bachelor's level, 70 at the master's level and 52 and the doctoral level. The broad spectrum of majors offered has caused an influx of students from around the nation and the world. One of seven enrolled students is from minority or under-represented backgrounds. In order to perpetuate its prestigious reputation, the University has developed Flagship 2030 Strategic Plan. Some core values of this initiative include fostering research excellent, enhancing graduate education and enhancing education and scholarship. This initiative will "set new standards in education, research, scholarship, and creative work that will benefit Colorado and the world (68)."

Appendix C: Description of Non-University Partners

Interaction with Airport and Industry Experts

Communications with airport and industry experts have been instrumental throughout the design process. The majority of correspondence has been with Mr. Keith Pass, the Storm Water Discharge Permit Manager for DIA. Mr. Pass has generously volunteered to be the liaison between DIA and the University of Colorado for this design project. The KANDE Consulting team has met with Mr. Pass at DIA twice, and interacted numerous times via phone and email correspondence. One of the meetings included a tour of the deicing recovery and recycling facilities on the airfield. KANDE Consulting has also corresponded with project engineers John Lengel and Mark Ervin from Gresham, Smith, and Partners. These professional engineers provided insight and answered specific questions regarding the implementation of an anaerobic biogas reactor for treatment of propylene glycol at airports. Each of the airport and industry professionals contacted by the design team is expert in their field, and their advice provided practical insight into the design experience. The most important interactions with airport and industry experts are summarized in the Meeting and Consultation Summary Reports on the following pages.

Meeting and Consultation Summary Report

Date and Location:
02/03/2012
Denver International Airport
8500 Pena Boulevard
Denver, Co 80249
Consultant(s) / Advisor(s):

Keith Pass, Manager of the Industrial Permit and Colorado Discharge Permit System

Norm Higley, Director of Environmental Services at DIA

Agenda:

• Discuss current technology

• Understand DIA’s desires for project

• Set up contact for future interactions

Comments:

This was the first interaction our team had with Denver International Airport; therefore the main goal was to get acquainted with the project and the client. From this meeting we learned the basics of the current Environmental Management System infrastructure as well as specific ways in which the system could be improved to improve DIA’s reputation, decrease their environmental footprint and reduce the cost of the current processes.

Meeting and Consultation Summary Report

Date and Location:
03/02/2012
Denver International Airport
8500 Pena Boulevard
Denver, Co 80249

Consultant(s) / Advisor(s):

Keith Pass, Manager of the Industrial Permit and Colorado Discharge Permit System

Agenda:

• Tour the current PG recycling system implemented at DIA

• Gain better understanding of technology

Comments:

Three of the five members of our team were given a tour of the Inland Technologies propylene glycol recycling facility. During this time, the main components of the ADF collection and recycling processes were clarified. This was a particularly valuable experience that shed light upon current cutting edge technologies. The team was granted special airfield visitation clearances that would have been impossible were it not for the FAA design competition.

Meeting and Consultation Summary Report

Date and Location:
04/11/2012
University of Colorado
Engineering Drive
Boulder, CO 80302

Consultant(s) / Advisor(s):

Mark Ervin, Project Engineer at Gresham, Smith and Partners

Agenda:

- Discussion of specific questions concerning technical aspects of anaerobic digestion

Comments:

Mark Ervin contacted our design team following a referral from John Lengel. Mr. Ervin has worked specifically on anaerobic biogas digesters and fluidized bed reactors at airports. Both processes were able to generate significant methane production from propylene glycol waste streams. Most importantly, Mr. Ervin was able to answer questions concerning variable flow rates, co-generation processes and heating requirements.

Meeting and Consultation Summary Report

Date and Location:
04/10/2012
University of Colorado
Engineering Drive
Boulder, CO 80302

Consultant(s) / Advisor(s):

John Lengel, Project Engineer at Gresham, Smith and Partners

Agenda:

• Discussion of current systems in place for propylene glycol management.

Comments:

Over the phone, John Lengel was able to provide our team with insights on current projects which are managing deicing wastes at airports around the U.S. Mr. Lengel emailed the team relevant documents describing deicing waste management systems, and was able to put our team in contact with other industry contacts working specifically on anaerobic biogas digestion projects.

Appendix D: Mentor Signoff Forms

Note: Signoff forms for the Faculty Advisor and Department Chair are provided in the hard copy of this design report submission.

Appendix E: Evaluation of Educational Experience

For Students:

1. Did the FAA Design Competition provide a meaningful learning experience for you? Why or why not?

Involvement in the FAA Design Competition has provided an ideal situation in which to further our understanding of the engineering industry. Partaking in an in depth technical analysis illuminated the complexity of designing a full scale system. Few members possessed previous knowledge specific to deicing technologies forcing all members of the team to hone their research skills. Also, our team was able to interact with professionals involved in the industry. Regular correspondence with Mr. Keith Pass, the Storm Water Discharge Permit Manager for Denver International Airport, allowed for insight into the airport industry as well as contemporary design technologies. Equally, professional correspondence rendered professionalism. When interacting with both faculty and industry representatives, it is important to exude respect and enthusiasm for the project. Intra group interactions allowed for members to practice the qualities important for functional team work such as communication and give and receive criticism. The skills learned from this experience will prove useful in the future when members go forth as professional engineers.

2. What challenges did you and/or your team encounter in undertaking the Competition? How did you overcome them?

Such a high level design project presented several obstacles for our team. Most notably, a large amount of research was necessary to ensure a reliable design was produced. Research starting *from scratch presents a limitless amount of data that must be sifted through. Discriminating between sources proved very difficult. Multiple sources provided conflicting information, forcing teammates to judge each to the best of their ability. In order to choose the best information, the team consulted both the faculty and industry correspondents.*

3. Describe the process you or your team used for developing your hypothesis.

In order to develop a high quality hypothesis for the proposed problem the team first conducted in depth research on deicing fluid in general as well as the current technologies employed by DIA. This required regular correspondence with both Keith Pass and faculty sponsors. After the team gathered sufficient background information, we conducted further research on viable alternatives that could be employed to treat the propylene glycol in the runoff stream. This research yielded 13 alternatives. In order to narrow the possibilities each alternative went through a preliminary screening process. The constraints required that the alternative has been previously installed successfully for similar flow rates and BOD loading values, can function with a seasonal startup and has a reasonable size requirement. After the initial constraints were applied, only five alternatives remained for in depth analyses. These alternatives were thoroughly researched. A decision matrix with economic, technical, social and environmental categories was applied to each. Each alternative was ranked according to its specific characteristics. The decision matrix scores ultimately produced our final hypothesis for the most suitable technology to treat the deicing problem: implementation of a biogas digester.

4. Was participation by industry in the project appropriate, meaningful and useful? Why or why not?

Correspondence with Keith Pass proved very useful in the design process. Without help from Mr. Pass, the team would have very limited knowledge on the current deicing situation at DIA. Mr. Pass organized a meeting with our team that presented all the necessary data and dimensions for the effluent stream in question. Mr. Pass played a key role in ensuring the applicability of our alternative. He proofread our decision matrix and weighed the categories according to DIA's needs. His input on each alternative allowed us to better understand each one's realistic implementation. Also, the tour of the deicing facility was made possible by Mr. Pass. Witnessing firsthand how the technology functions was an experience that would otherwise be impossible.

5. What did you learn? Did this project help you with skills and knowledge you need to be successful for entry in the workforce or to pursue further study? Why or why not?

Competing in the FAA Design Competition provided each member with valuable skills and knowledge that can be employed in the future. Each member was able to improve upon their professionalism. Regular correspondence with both faculty and industry sponsors was conducted both formally, through e-mails, and informally, through meetings and telephone conversations. The mix of communication modes allowed for written and oral skills to be practiced. In the professional world, the ability to communicate is paramount.

Intra team communication allowed for important teamwork skilled to be built. Each member was encouraged to both give and receive constructive criticism, contribute valuable work to the project and assess the progress of the team. Practicing these responsibilities will prove useful for *future interactions. Possessing the ability to function as a valuable team member, especially in the engineering industry, is essential for producing an exceptional product.*

Along with the interpersonal skills gained from the experience, our team was exposed to technical skills that will carry forth into our professional lives. The in depth design required implementation of technical writing skills. Such writing presents the need for not only technical knowledge but also the ability to portray such information in a way that is easily understood. Each team mate was responsible for a portion of the design, requiring that everyone practice these skills. Engineering professionals often lack the ability to write effectively. This experience has certainly allowed for improvement in this area.

For Faculty Members:

1. Describe the value of the educational experience for your student(s) participating in this Competition submission.

The context of environmental issues at airports was novel for all of the students. The opportunity to meet with the folks at Denver International Airport (DIA) provided excellent real-world context and an understanding of cutting edge needs in the industry. The students were able to compare a wide array of options to explore the issues around aircraft deicing wastes. This enabled the students to teach themselves new information and learn how to apply skills that they had learned in other contexts to the needs at DIA.

2. Was the learning experience appropriate to the course level or context in which the competition was undertaken?

The students were all participating in the 4-credit Environmental Engineering Design course, which is the required capstone design course for all students earning a bachelor's degree in Environmental Engineering from the University of Colorado Boulder. The learning experience was unique compared to the other projects in the course, which were defined more tightly from the very beginning of the semester. For example, the AECOM Academic Design Competition defines a specific problem and site conditions for a drinking water or wastewater treatment problem and then asked the students to propose a solution. The nature of the FAA competition gave the students more choice on the direction of their project, but this same flexibility made it more difficult to start the process.

3. What challenges did the students face and overcome?

The first challenge was starting the spring semester activities in January prior to meeting with DIA representatives. This made it difficult for the students to get started on their project, particularly since it was difficult to acquire specifics on DIA from traditional references and sources. Therefore, some of the work that the students had completed at the beginning of the semester was not used in the overall project and was not useful to DIA. The students also faced challenges getting detailed information that allowed them to confidently design on-site de-icing waste treatment. But some research that had been conducted at the University of Colorado ended up being pertinent to their project, and it was nice for the students to see that CU research was pertinent to their real-world design challenge.

4. Would you use this Competition as an educational vehicle in the future? Why or why not?

I hope to use the competition again. However, we would likely try to find a different local airport partner, since we already worked on key environmental issues with DIA this semester. A site visit was critical to helping the students appreciate the challenges and opportunities at airports, so we would hope to continue to interface with experts at DIA. But since DIA is very advanced in all of its environmental systems, it was difficult to find environmental elements to improve upon. My attempts to find interested partners at other local airports were less successful, so I would likely need more lead time to cultivate these partnerships in advance of spring semester next year. Using the student design reports as examples of the student work might help entice partners for future years.

A challenge for me as the course instructor was to merge the learning objectives for the design course and the project requirements for the competition. Specifically, the course requires students to complete designs, with detailed supporting calculations, AutoCAD drawings, etc. The FAA competition guidelines were restrictive in terms of length and not allowing supporting appendices, so this required the students to do "extra" work beyond the FAA competition for the course (but did not allow them to present this information to the FAA), and extra formatting challenges for the competition that were not required for the other students in the design course.

5. Are there changes to the Competition that you would suggest for future years?

The primary recommendation that I would make relates to changes in the formatting and length requirements. Allowing students to submit appendices of supporting calculations would be helpful. The double-spaced text also seemed odd – a shorter page limit with single spaced text might be more effective. Further, environmental engineering designs are typically site-specific, *but it is unclear the degree to which the FAA desires general ideas versus more detailed designs for specific sites.*

Appendix F: Works Cited

1. U.S. Deptartment of Transportation. *AC135 - 16.* Washington, DC : Federal Aviation Administration, 1994.

2. Kommineni, Sunil. Advanced Oxidation Processes. [Online] [Cited: 03 09, 2012.] http://www.nwri-usa.org/pdfs/TTChapter3AOPs.pdf.

3. Cornell, Jeffrey. *The environmental impact of 4(5)-methylbenzotriazole from aircraft deicing operations.* Boulder : s.n., 2001.

4. FAA. *Indoor Snow Testing of Aircraft Ground Anti-Icing Fluids.* Virginia : Federal Aviation Administration, 2006.

5. O'brien, Ivette. Biotransformation potential and uncoupling behavior of common benzotriazole-based corrosion inhibitors. [Online] May 22, 2003. http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA414450.

6. *Comparative measures of the toxicity of component chemicals in aircraft deicing fluids.* Cornell, J.S, Pillard, D.A, Hernandez, M.T. 2000, Environ. Toxicol. and Chem. , pp. 1465-1472.

7. Internation Organization for Standardization. ISO 14000 essentials. [Online] 2011. [Cited: January 30, 2012.] http://www.iso.org/iso/iso_14000_essentials.

8. Metro Denver. City/County of Denver departments earn ISO 14001. *Metro Denver News Center*. [Online] 2012. [Cited: January 30, 2012.] http://www.metrodenver.org/news-center/metro-denver-news/Denver-ISO-14001.html.

9. Pass, Keith. *DIA Stormwater Permit Manager.* [interv.] KANDE. March 2, 2012.

10. City & County of Denver, Department of Aviation. Aviation Facilities: Research Center. *Business Center: Denver International Airport.* [Online] [Cited: January 30, 2012.] http://business.flydenver.com/info/research/aviation.asp.

11. Inland Technologies. Denver International Airport Turnkey Aircraft Deicing Fluid Recycing Program. [Online] [Cited: January 30, 2012.] http://www.inlandgroup.ca/glycol/pdf/denver.pdf.

12. FAA. *Flight Plan 2009 - 2013.* Washington, D.C. : FAA, 2009.

13. US EPA. [Online] 02 10, 2012. http://www.epa.gov/region1/npdes/stormwater/.

14. Obayashi, Alan W. US EPA. [Online] 02 1982. http://nepis.epa.gov/Exe/ZyNET.exe/30000FCO.TXT?ZyActionD=ZyDocument&Client=EPA&Index=1981+Thru+1985&Docs=&Query=FNAME%3D30000FCO.TXT%20or%20%28%20anaerobic%20or%20fluidized%20or%20bed%20or%20reactor%29&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&Toc.

15. *Membrane Bioreactor on Domestic Wastewater Treatment Sludge Production and Modeling Approach.* Chaize, S. and Huyard, A. 1991, Water Science Technology.

16. Silverstein, Joann. History of Waste Water Treatment in the US. *University of Colorado at Boulder Civil Engineering.* [Online] http://civil.colorado.edu/~silverst/cven5534/History%20of%20Wastewater%20Treatment%20in%20the%20US.pdf.

17. Jeffries, Adrian. Is It Green? Maker's MArk Whiskey. *Inhabitat.* [Online] 01 15, 09. http://inhabitat.com/is-it-green-makers-mark/.

18. Lemvig Biogas. [Online] http://www.lemvigbiogas.com/GB.htm.

19. *Oxygen Transfer and Aeration Efficiency-- Influence of Diffuser Submergence, Diffuser Density, and Blower Type.* Wagner, Martin R., Johannes Popel. s.l. : Elsevier, 1998. Water Science and Technology. pp. 1-6.

20. USEPA. *Design Manual: Fine Pore Aeration Systems.* Cincinnati, OH : U.S. EPA, 1989.

21. Stamford Scientific Inc. Diffuser Membrane Materials. *Stamford Scientific Inc.* [Online] 2012. [Cited: March 9, 2012.] http://www.stamfordscientific.com/aboutus.html.

22. USEPA. *Summary Report: Fine Pore (Fine Bubble) Aeration Systems.* Cincinnati, OH : USEPA, 1985.

23. Ferguson, Linda Noelle. *Anaerobic Co-Digestion of Aircraft Deicing Fluid and Microaerobic Studies.* Milwaukee, WI : s.n., 1999.

24. Igoni, A. Hilkiah, Ayotamuno, M.J. and Eze, C.L. . Designs of anaerobic digesters for producing biogas from municipal solid waste. *Applied Energy.* s.l. : Elsevier, 2007, pp. 430-438.

25. USEPA. *Opportunities for Combined Heat and Power at Wastewater Treatment Facilities: Market Analysis and Lesson from the Field.* s.l. : USEPA Combined Heat and Power Partnership, 2011.

26. *Construction Costs for Municipal Wastewater Treatment Plants.* Washington, D.C. : USEPA Facility Requirements Division, 1973-1978.

27. McDonald, Norma. Anaerobic Digester Case Study. *Michigan Department of Agriculture.* [Online] 2006. [Cited: March 8, 2012.] http://www.michigan.gov/documents/mda/AD_CaseStudy_221950_7.pdf.

28. RSMeans. *RSMeans City Cost Index.* s.l. : RSMeans, Division of Reed Construction Data, Inc, 2011.

29. Zitomer, Daniel H. *Waste Aircraft Deicing Fluid: Management and Conversion to Methane.* Madison, WI : Marquette University, 2001.

30. *Integrated Modeling of Anaerobic Fluidized Bed Bioreactor for Deicing Waste Treatment. II: Simulation and Experimental Studies.* Komisar, Jonghyuk Seok and Simeon J. 2003, Journal of Environmental Engineering.

31. Seok, Jonghyuk and Komisar, Simeon J. 2003, Journal of Environmental Engineering.

32. *24 Fixed Film Stationary Bed and Fluidized Bed Reactors.* Jordening, Hans-Joachim and Buchholz, Klaus.

33. *State-of-the-art of anaerobic digestion technology for industrial wastewater treatment.* Rajeshwari, K. V., et al. 1999, Renewable and Sustainable Energy Reviews.

34. Envirogen Technologies. Technologies. *Envirogen Technologies.* [Online] [Cited: March 9, 2012.] http://www.envirogen.com/pages/technologies/bioreactors/.

35. USEPA. *Technical Developement Document for Proposed Effluent Limitation Guidelines and Standards for the Airport Deicing Category.* Washington D.C. : U.S. Environmental Protection Agency, 2009.

36. Federal Remediation Technologies. *Advanced Oxidation Processes.* [Online] [Cited: 03 08, 2012.] http://www.frtr.gov/matrix2/section4/4-45.html.

37. Chapman, Michelle. Water Treatment Estimation Routine. s.l. : Department of the Interior, 12 18, 2006.

38. Summers, R. Scott. Class Handouts: Membranes. *University of Colorado at Boulder: CVEN 3424 Water and Wastewater Treatment.* Boulder, Colorado : s.n., 2011.

39. The Environmental Quality Company. Airport Services Solutions - Pittsburgh International Airport. [Online] 2012. http://www.eqonline.com/services/airport_services_solutions/pittsburgh.asp.

40. Liu, Paul K.T., Ciora, Richard J. Final Report: on-Site Recovery of Glycols from Airport Deicing Fluid Using Polymeric / Ceramic Composite Membranes. *United States Environmental Protection Agency.* [Online] 1998. http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/1352/report/F.

41. New Logic Research Inc. V*SEP Filtration of Glycol Recovery. *New Logic Research.* [Online] http://www.vsep.com/pdf/GlycolRecovery.pdf.

42. Sharma, J. R. Development of a preliminary cost estimation mehod for water treatment plans. [Online] May 2010. http://dspace.uta.edu/bitstream/handle/10106/4924/Sharma_uta_2502M_10652.pdf?sequence=1.

43. Bielefeldt, A. CVEN 5514 Bioremedation Notes. *University of Colorado at Boulder.* Boulder, Colorado : s.n., 2012.

44. Proplene Glycol. *Agency fo Toxic Substances and Disease Registry.* [Online] 09 1997. http://health-report.co.uk/ethylene_glycol_propylene_glycol.html.

45. *Propylene Glycol Deicer Biodegradation Kinetics: Anaerobic Complete-Mixed Stirred Tank Reactors, Filter, and Fluidized Bed.* Zitomer, Daniel Harris and Tonuk, Gulseven Ubay. 2003, Journal of Environmental Engineering, pp. 123-129.

46. Bielefeldt, Angela R., et al. Biodegradation of Propylene Glycol and Associated Hydrodynamic Effects in Sand. *Water Research.* August 1, 2001.

47. *Comprehensive model of anaerobic digestion of swine manure slurry in a sequencing batch reactor.* Masse, D.I., Droste, R.L. 2000, Wat. Res., pp. 3087-3106.

48. *Mesophilic digestion kinetics of manure slurry.* Karim, K., Klasson, K.T., Drescher, S.R., Ridenour, W. 2007, Appl. Biochem. Biotechnol., pp. 231-242.

49. *Anaerobic digestion of vinasse for the production of methane in the sugar cane distillery.* Baez-Smith, C. 2006. SPRI Conference on Sugar Processing.

50. Metcalf and Eddy. *Wastewater Engineering.* Boston, MA : McGraw Hill, 2003.

51. WEF. *Design of Municipal Wastewater Treatment Plants, Volume 3.* Alexandria, VA : Water Environment Federation Publications, 1998.

52. National Weather Service. Surface Weather Observation Stations. *Federal Aviation Adminisration.* [Online] [Cited: April 15, 2012.] http://www.faa.gov/air_traffic/weather/asos/?state=CO.

53. Cengel, Yunus and Turner, Robert. *Fundamentals of Thermal-Fluid Sciences.* s.l. : McGraw-Hill Professional.

54. Council of Industrial Boilder Owners. Energy Efficiency & Industrial Boiler Efficiency, An Industry Perspective. *Council of Industrial Boiler Owners.* [Online] March 2003. [Cited: April 19, 2012.] http://cibo.org/pubs/whitepaper1.pdf.

55. Capstone. Capstone Turbine. *Capstone Turbines.* [Online] http://www.capstoneturbine.com/_docs/Product%20Catalog_ENGLISH_LR.pdf.

56. Bureau of Labor Statistics. *Water and Wastewater Treatment Plant Operators.* [Online] 03 29, 2012. [Cited: 04 21, 2012.] http://www.bls.gov/ooh/Production/Water-and-wastewater-treatment-plant-and-system-operators.htm.

57. RS Means. *CostWorks.* [Online] 2012. [Cited: 04 20, 2012.]
http://meanscostworks.com/MyEstimate/MyEstimate.aspx?InvokedFrom=LandingPage&EstimateID=275298.

58. US Energy Information Administration. Natural Gas. *EIA.* [Online] April 12, 2012.
http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm.

59. Economic Research Service. *United States Department of Agriculture.* [Online] 01 05, 2012. [Cited: 04 20, 2012.] http://www.ers.usda.gov/Data/FertilizerUse/.

60. Global Trade. [Online] [Cited: 04 20, 2012.] http://www.alibaba.com/showroom/calcium-carbonate-price.html.

61. American Concrete Institute 318. *ACI 318-08 Building Requirements for Structural Concrete and Cemmentary.* Farmington Hill, MI : American Concrete Institute, 2008.

62. Northwestern University. *Equipment Inventory Useful Lives.* [Online]
http://www.northwestern.edu/equipment-inventory/propertycodes.html.

63. RIX Industries. Compressor Finder and Calculator. *RIX Industries.* [Online] April 22, 2012.
http://www.rixindustries.com/compressor-finder.html.

64. PVC Sustainability. [Online] [Cited: 04 21, 2012.] http://www.pvc.org/en/p/sustainability.

65. *Analysis of Airport Runoff Waters.* Anna Maria Sulej, Zaneta Polkowska, Jacek Namiesnik. 2011, Critical Reviews in Analytical Chemistry, pp. 190-213.

66. Federal Aviation Administration. FAA Design Competition for Universities. *FAA Design Competition.* [Online] 2011-2012.
http://emerald.ts.odu.edu/apps/faaudca.nsf/Designcomp_booklet.pdf?OpenFileResource.

67. Association of American Universities. [Online] [Cited: 03 09, 2012.]
http://www.aau.edu/about/default.aspx?id=4020.

68. Flagship 2030 Strategic Plan. [Online] [Cited: 03 09, 2012.] http://www.colorado.edu/flagship2030/.

69. *Propylene Glycol Deicer Biodegradation Kinetics: Anaerobic Complete-Mix Stirred Tank Reactors, Filter, and Fluidized Bed.* Tonuk, Daniel Harris Zitomer and Gulseven Ubay. 2003, Journal of Environmental Engineering.

70. Rashed, I.G. *Overview of Chemical Oxidation Technology in Wastewater Treatment.* Mansoura, Egypt : Mansoura University, 2005.

71. Quick, Darren. New reverse-osmosis membrane to improve desalination. *gizmag.* [Online] April 6, 2010. [Cited: March 10, 2012.] http://www.gizmag.com/reverse-osmosis-desalination-membrane/14741/.

72. Sagle A., Freeman B. Fundamentals of Membranes for Water Treatment. *Texas A&M: Texas Water.* [Online] http://texaswater.tamu.edu/readings/desal/membranetechnology.pdf.

73. Kawamura, S. *Integrated Design and Operation of Water Treatment Facilities.* New York : John Wiley & Sons, Inc., 2000.

74. Beery, M., Wozny, G., Repke, J. Sustainable Design of Different Seawater Reverse Osmosis Desalination Pretreatment Processes. *20th European Symposium on Computer Aided Process Engineering.* [Online] 2010. http://www.aidic.it/escape20/webpapers/84Beery.pdf.

75. Good Water Company. Green Options: Eco-Friendly Purification Options. *Good Water Company.* [Online] November 2008. http://goodwatercompany.com/Products/Green_Options/index.html.

76. E.S.P. Water Products. About Reverse Osmosis. *E.S.P water products.* [Online] 2009. http://espwaterproducts.com/about-reverse-osmosis.htm.

77. PB Water. *Project Cost Estimate Peer Review of Microfiltration Supplemental Technology Demonstration Project.* 2001.

78. *Basic cost equations to estimate unit production costs for RO desalination and long-dstance piping to supply water to tourism-dominated arid coastal regions of Egypt.* Lamei, A., van der Zaag, P., von Munch, E. 2008, Desalination, Vol. 225, pp. 1-12.

79. Rosenfeldt, Linden, Canonica, van Gnuten. *Comparison of the Efficiency of OH Radical Formation During Ozonation and the Advanced Oxidation Processes O3/H2O2 and UV/H2O2.* s.l. : Water Research 40, 2006.

80. Aquifer Solutions, Inc. *In Situ Chemical Oxidation.* [Online] [Cited: 03 11, 2012.] http://www.dtsc.ca.gov/hazardouswaste/upload/clayton_remsymp_presentation.pdf.

81. Spartan Environmental Technologies. *Determining Amount of Ozone Required for Ozone Water Treatment.* [Online] [Cited: 03 11, 2012.] http://www.spartanwatertreatment.com/how-much-ozone-do-i-need-to-treat-water.html.

82. *Treatment of Textile Wastewater by Advanced Oxidation Processes.* Al-Kdasi, Adel. 2005, Global Nest, pp. 222-230.

83. ATG UV Technology. *UV Dose and System Sizing.* [Online] [Cited: 03 11, 2012.] http://www.atguv.com/uv_dose_sizing/.

84. Mar Cor Purification. Minnclean AC & Minnclean TF: Reverse Osmosis Membrane Cleaners. [Online] 2009.

http://www.mcpur.com/main/library/08_brochures/3025090A_(Minnclean_AC_TF).pdf.

85. Maloney, Stephen W. and Heine, Robert L. *Demonstration of the Anaerobic Fluidized Bed Reactor for Pinkwater Treatment at McAlester Army Ammunition Plant.* s.l. : US Army Corps of Engineers, 2005.

86. USEPA. *Wastewater Technology Fact Sheet: Fine Bubble Aeration.* Washington, D.C. : USEPA, 1999.

87. Mena Water FZC. Fine Bubble Aeration. *Mena Water FZC.* [Online] 2008. [Cited: March 12, 2012.] http://www.google.com/imgres?start=91&um=1&hl=en&client=firefox-a&rls=org.mozilla:en-US:official&biw=1920&bih=1107&tbm=isch&tbnid=aIFmEAf191j_PM:&imgrefurl=http://www.mena-water.com/6-3fineaeration.htm&docid=00W7QrwSvytqPM&imgurl=http://www.mena-water.com.

88. Biogas (Anaerobic Digestion). *Ontario Ministry of Agriculture, Food and Rural Affairs.* [Online] June 2011, 2011. [Cited: March 8, 2012.] http://www.omafra.gov.on.ca/english/engineer/ge_bib/biogas.htm.

89. Horton, Vince. Tank Connection. *Tank Connection Affiliate Group.* [Online] [Cited: March 10, 2012.] http://www.tankconnection.com/docs/anaerobic-digesters.pdf.

90. Water Treatment Estimation Routine. s.l. : US Bureau of Reclamation, 12 18, 2006.

91. Wedeco Technologies. *PDA/PDO Ozone Systems.* [Online] [Cited: 03 09, 2012.] http://www.wedeco.com/us/products/wedeco-ozone-systems/pdopda-series.html.

92. HiPOx. *HiPOx Case Study, South Lake Tahoe, CA.* Long Beach, CA : apt water.

93. Environmental Protection Agency. *National Pollutant Discharge Elimination System.* [Online] [Cited: 03 03, 2012.] http://cfpub.epa.gov/npdes/home.cfm?program_id=3.

94. Jensen, Michael E. Colorado Department of Health and the Environment. *Technical Review Document for Operating Permit 950PEP147.* [Online] 12 10, 1997. [Cited: 02 12, 2012.] http://www.cdphe.state.co.us/ap/downop/ep147trd.pdf.

95. Denver International Airport. *DIA Annual Report 2010.* Denver : Denver International Airport, 2010.

96. USEPA. Radionuclides in Drinking Water: Reverse Osmosis. [Online] 2012. http://cfpub.epa.gov/safewater/radionuclides/radionuclides.cfm?action=Rad_Reverse%20Osmosis.

97. University of Colorado CVEN 5514. Bioremediation. *Course Notes.* Boulder, Colorado, United States of America : s.n., Spring 2012.

98. State of Washington. Fact Sheet for NPDES General Permit Water Treatment Plants - Wastewater Discharge. [Online] June 16, 2004. http://www.ecy.wa.gov/programs/wq/wtp/wtpfs.pdf.

99. *Several Engineering Equations in the Design of Reverse Osmosis Plants.* Zhou, J., Ohya, H., Matsumoto, K. 80, 1991, Desalination, pp. 15-30.

100. *Environmental life cycle assessment of reverse osmosis desalination: The influence of different lice cycle impact assessment methods on the characterization results.* Zhou, J., Chang, V., Fane, A. 283, 2011, Desalination, pp. 227-236.

101. CDPHE. [Online] 02 10, 2012. http://www.cdphe.state.co.us/.

102. Global Methane Initiative. *Network of Biodigesters for Latin America and the Carribean.* [Online] 2012. http://www.globalmethane.org/projects/projectDetail.aspx?ID=1191.

103. Federal Aviation Administration. *Safe, Efficient Use and Preservation of Navigable Airspace.* [Online] 04 12, 2012. http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=f7780e4d527cd2a76a520fe6606ebc9d&rgn=div5&view=text&node=14:2.0.1.2.9&idno=14#14:2.0.1.2.9.2.1.3.

104. Federal Aviation Administration. *Notification Requirements for Construction in Vicinity of Airports.* [Online] http://www.dot.state.oh.us/Divisions/Operations/Aviation/Pages/FAAandStateNotificationRequirements.aspx.

105. Heibeck, Wayne T. Federal Aviation Administration. *DEsign of Aircraft Facilities.* [Online] October 10, 2005. http://www.faa.gov/documentLibrary/media/advisory_circular/150-5300-14B/150_5300_14b.pdf.

106. BP Cherry Point Cogeneration Project. [Online] 04 2003. http://www.efsec.wa.gov/bpcogen/bpasc/asc/3.16HealthSafety4-28-03.pdf.

107. Wolfram. Spherical Cap. *Wolfram MathWorld.* [Online] April 12, 2012. http://mathworld.wolfram.com/SphericalCap.html.

108. The Engineering Toolbox. The Engineering Toolbox. *Fuel Gases - Heating Values.* [Online] [Cited: April 15, 2012.] http://www.engineeringtoolbox.com/heating-values-fuel-gases-d_823.html.

109. Felder, Richard M and Rousseau, Ronald W. *Elementary Principles of Chemical Processes, Updated 3rd Edition.* s.l. : John Wiley & Sons, Inc., 2005.

110. Cooper, C. David and Alley, F. C. *Air Pollution Control, A Design Approach.* Long Grove : Waveland Press, Inc., 2011.

111. Useful Lives Table. *Accounting Manual.* [Online] 04 02, 2012. [Cited: 04 21, 2012.] http://legislativeaudit.sd.gov/Counties/Accounting_Manual/County_Section_4/County_Section%204_Useful_Life_Table.pdf.

112. FAA. Airport Construction Standards (AC 150/5370-10). *FAA: Engineering, Design, and Construction.* [Online] April 22, 2012. http://www.faa.gov/airports/engineering/construction_standards/.

113. Blackmer. *CB-207: Compressors.* s.l. : Blackmer, 1999.

114. Toolbox, The Engineering. Pump Power Calculator. *The Engineering Toolbox.* [Online] April 22, 2012. http://www.engineeringtoolbox.com/pumps-power-d_505.html.

115. Bartok, John W. Approximate Heating Values of Common Fuels. [Online] December 2004. http://www.hrt.msu.edu/energy/pdf/heating%20value%20of%20common%20fuels.pdf.

116. US Office of Management and Budget. Circular A-94 Appendix C. *The White House Government Website.* [Online] 2012. http://www.whitehouse.gov/omb/circulars_a094/a94_appx-c.

117. *Membrane replacement: Permasep reverse osmosis desalination.* Sackinger, C.T. 1983, Desalination, pp. 41-55.