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Title of Design: LED Runway Lighting for Denver International Airport

Design Challenge addressed: Technical Design Challenge III

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Energy Efficient Engineers

Federal Aviation Administration
Design Competition
Technical Design Challenge III

Airport Environmental Interactions in Non-terminal Areas
Focusing on Energy Efficiency

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1. Executive Summary

Energy consumption is a very important aspect of how an airport functions. Through literature reviews and interviews with technical experts, E-Cubed has worked to formulate possible solutions to help reduce the amount of energy consumed at Denver International Airport (DIA) in non-terminal areas. DIA is a worldwide leader in energy efficiency, and they have already implemented many projects that help to reduce their carbon footprint as well as increase the reliability and productiveness of the facilities. Examples of these projects at DIA include the installation of variable drive motors for walkways and baggage belts, they have changed much of the lighting in the terminals and parking structures from conventional lighting to more efficient LED and compact florescent bulbs, and the implementation of multiple on-site solar arrays to help offset the electrical needs of the facility.

E-Cubed considered multiple options for energy efficiency improvements at DIA including snow melting, geothermal heated runways, and improved lighting efficiency on the runways. Many criteria went into the decision for which project should be proposed including payback period, social impacts, environmental impacts, among others. After a thorough analysis of each design was completed it was determined that the centerline lights with LEDs would be the most effective manner for DIA to reduce their energy consumption. The payback period for LEDs is approximately five years, with a capital investment of a little over $300,000. LEDs need to be considered with and without heaters, and through extensive research E-Cubed has determined that LEDs without heaters will be the best option for DIA given their climate. E-Cubed has analyzed multiple options and is thoroughly convinced that DIA will experience tremendous benefits from this technology. E-Cubed hopes that the findings of this report will help DIA become an innovator in the aviation community.

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2. Introduction

E-Cubed Consulting conducted a feasibility study to determine new and innovative ways to reduce energy consumption in the non-terminal areas at Denver International Airport as part of the Federal Aviation Administration Design Competition. The three areas that are focused on in this report are in-ground snow melting systems, geothermal heating for runways, and runway lighting. The technical aspects, environmental implications, financial analysis, as well as safety and regulations aspects of each alternative are evaluated. Following the analysis of each design option, E-Cubed determined that LED runway centerline lights were the best solution by comparing the three alternatives in a weighted decision matrix. E-Cubed wraps up the report with an in-depth analysis of this design solution and how it can be applied to other airports around the country.

3. Energy Use by Airports in the United States

The United States currently has no national or state level regulations for airports to report their inventory of greenhouse gas (GHG) emissions each year, but some states are reporting their emissions voluntarily. As climate change becomes a more prevalent issue, the FAA is looking at ways that airports can increase energy efficiency and thus reduce their carbon footprint. The greenhouse gases of primary interest include carbon dioxide (CO_2), methane (CH_4), water vapor (H_2O), particulate matter (PM), nitrous oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs). Transportation is the second largest source of greenhouse gas emissions after electricity in the US, with transportation accounting for 33% of the total emissions (Brian Kim, 2009). Aviation accounts for 11% of the total emissions from transportation, with 3% of this due to emissions at airports (Brian Kim, 2009).

Since airports are in continuous operation, it is obvious that managing their energy consumption is crucial. The areas that have the highest potential for lowering energy consumption are lighting, baggage, heating, ventilating, and air-conditioning (HVAC) systems (Lowering Energy Costs at Airports, 2008). Since the FAA Design Competition is only for energy improvements in non-terminal areas, E-Cubed explored other ways to save energy.

4. Energy Use by Denver International Airport

In 2005, Denver Mayor Hickenlooper established the Greenprint Denver initiative, which aimed to reduce Denver's environmental footprint by reducing Denver's per-capita greenhouse gas emissions to 10% below 1990 levels by 2012. DIA plays an important role in Greenprint Denver's 2011 goals, including the following (Greenprint Goals):

- Reducing energy use by 5% from 2006 levels on a per passenger basis at DIA
- Increase the number of alternative fuel vehicles to 70%

Table 1 below is a snapshot of the energy use of DIA in 2010, which gives an idea of just how much energy DIA needs for its operations in a given year.

Table 1: DIA's energy consumption in 2010 (Allee)

	Energy Use	Cost	Greenhouse Gas Emissions	Comments
Electricity Use at DIA in 2010	219 GWh	$16.7 million	4.8 million metric tons of $C0_2$, which is 62% of total emissions in Denver	3% of the electricity goes to powering non-terminal areas

4.1 Denver International Airport's Energy Projects to Date

DIA has completed many energy projects that affect both the interior and exterior of the facility. A summary of its energy efficiency improvements are highlighted in Table 2 below.

Table 2: Energy Projects Already Completed at DIA

Recent Energy Efficiency Measure	Savings	Description
4.4 MW, 2 MW, and 1.6 MW Solar Systems (2011)	4.4 MW system: produces 7,000 MWh/year	• DIA has a total of 8 MW of solar power, which is the most generation for a commercial airport in the US
Terminal efficiency improvements (2010)	4.3 GWh/year, \$300,000/year, and 4,000 tons of CO_2 avoided	• Motor installations, lighting, HVAC • Received rebates from Xcel Energy
Canopy Airport Parking powered by geothermal heating and cooling (2010)	70% cost savings from choosing to build efficiently	• LEED Certified Gold parking lot powered by a 9.6 kW wind turbine farm, geothermal energy, 16.9 kW solar array, charging stations, LED lighting, 1 hybrid bus, 6 CNG buses, and 7 biodiesel buses
LED Taxiway lighting retrofits pilot program (in progress)		• 6.7% of DIA's runway lights are LEDs and they are working on adding more 4
Alternatively fueled bus fleet (2008-present)		• DIA has a fleet of alternatively fuel vehicles including 205 buses, sweepers, and vehicles using compressed natural gas
ISO 14001 certification (2004)	No Cost	• DIA is the first international airport to register its Environmental Management System to the ISO 14001

1 (Olson, 2011), 2 (Xcel Energy, 2010), 3 (Canopy Airport Parking), 4 (Coale, 2012), 5 (Greenprint Goals)

The FAA Competition constrained energy efficiency designs to non-terminal, non-airport building areas. Due to this constraint, E-Cubed focused on snow removal, ground source heat pumps for runways, and runway lighting.

5. Interactions with Airport Operators

E-Cubed interacted with many airport operators and industry experts in order to gain a better understanding of current issues at airports nationwide. Table 3 lists the experts contacted during the project, along with the interactions. Appendix C describes the in depth interactions with DIA personnel.

Table 3: Experts Consulted

Name	Title	Employer	Interactions
Wood Allee	Director of Capital Planning and Special Projects	DIA	- February 10, 2012: Meeting at DIA - March 5, 2012: Tour of airfield
Heather McKee	Critical Systems Administrator	DIA	- February 10, 2012: Meeting at DIA - March 5, 2012: Tour of airfield
Ed Keegan	Facilities Manager, Senior Engineer	DIA	- February 10, 2012: Meeting at DIA - March 5, 2012: Tour of airfield
John S. McCartney, Ph.D., P.E	Assistant Professor and Barry Faculty Fellow	University of Colorado at Boulder	- March 6, 2012: Discuss research with ground source heat pumps
Alex Gertsen	President and Founder	Aviation Fury, LLC	- March 8, 2012: Information on snow removal
Richmond Nettey	Associate Dean	Kent State University College of Technology	- March 8, 2012: Information on snow removal
Matthew Wenham	Managing Engineer	C&S Engineers	- March 8, 2012: Information on snow removal
John K Duval A.A.E.	National Aviation Director	Austin Commercial L.P.	- March 9, 2012: Through Mr. Gertsen for assistance on snow removal structures
Brent Kelley	Principal	Corgan Associates	- March 9, 2012: Through Mr. Duval for assistance on snow removal structures

6. Evaluation of Regulations

Regulations for airport design are primarily found in Advisory Circulars (AC) published by the FAA. The importance of safely transporting passengers means there are extensive guidelines and regulations for anything happening at an airport. The proposed design examines ground source heat pumps, snow removal and runway lighting. The regulations for each sector are discussed in Table 4.

Table 4: FAA Regulations

Sector	Advisory Circular	About
Ground Source Heat Pump (GSHP)	150/5370-17	--Installation of a ground source heat pump using a fluid will fall under the hydraulic heated pavement system regulations. The system must be incorporated in the pavement and must be 2.0 to 4.0 inches from the surface (FAA, 2011). --Every year the system will be inspected for proper operation before winter and after the last winter storm event. --Mandatory maintenance procedures plan for the entire life cycle of the pavement. --Other Regulations for GSHP. These include "Standards for Specifying Construction of Airports", "Measurement, Construction, and Maintenance of Skid Resistant Airport Surfaces," and "Surface Drainage Design (FAA, 2011)." Meeting other standards already in place will provide the most safety for any project that affects runway construction.
Snow Removal	150/5200-30C	--Snow removal regulations mandate that all airports have a Snow and Ice Control Plan (SCIP). --The SICP designates how snow disposal will occur (FAA, 2008). --For snow melters the important factor is to maintain the ability to follow the snow clearing principles. --The snow melters must help or not adversely affect slick ramp surfaces, increased airplane engine thrust, obscured taxi signage, obscured terminal visual aids and snow stockpiles adjacent to airplane operating areas (FAA, 2008).
Runway Lighting	150/5300-13 150/5345-46	--Lighting regulations provide details for all navigation lighting at airports as well as providing more specific details for runway and taxiway lighting. --For an LED design, photometric requirements are important in allowing LEDs to operate safely. This covers light intensity and color and coverage beam. --Other requirements specified by AC include dimensions, structural integrity, drainage, electrical requirements, and maintainability (FAA, 2006).

7. Alternatives

7.1 Snow Removal

7.1.1 Summary

The inevitability of snowfall has always been a matter of concern for airports in snowy regions. This alternatives assessment on snow removal goes through what is currently being done at airports around the country, what DIA has been doing to combat the snow, and our ideas on what DIA, and other airports, could implement to increase snow removal efficiency and decrease the cost associated with these operations.

7.1.2 Literature Review

The majority of inefficiencies coming from the snow removal fleet at airports are the implementation of single-function machinery instead of more efficient multi-function equipment. Multi-functional equipment incorporate plowing and sweeping of snow, air-blasting ice and residue, and spreading sand or deicing salts – all while going 45 miles per hour – into a single truck - as shown in Figure 1 (M-B companies, 2011). One of these trucks can replace up to 6 engines and can be used year round. New equipment means higher functional efficiency, overall less equipment needed for the same task, and a faster, more efficient way to clean the same amount of area (Gerber, 2009). All of these benefits lead to a decrease in fuel consumption and an increase in total savings. Not only does the implementation of these devices lead to a decrease in operation and fuel costs, but also a decrease in costs associated with airport delays.

Figure 1: Multifunction Snow Removal Vehicle MB2 by M-B Companies, INC. (M-B Companies, INC.,

As the airport is left inoperable during snow removal processes, thousands of dollars a minute are spent, directly and indirectly. A study conducted by the Joint Economic Committee (JEC) Majority Staff estimates the total U.S. annual cost of domestic air traffic delays to be $41 billion while extreme whether contributed 5.7% of this total. (The Joint Economic Committee Majority Staff, 2008). Other categories for costs associated with delays are: direct operational costs to airlines (47% of total delay costs at $60.46/min), indirect cost to the economy ($37.60/passenger/delayed hour), and the value of traveler's time; also, for every dollar of direct costs, $0.50 indirectly affected the GDP due to decreased tourism, mail delays, decreased business etc. (The Joint Economic Committee Majority Staff, 2008).

The JEC also estimated the environmental ramifications of jet fuel wasted as a result of delay; 740 million additional gallons of jet fuel were consumed due to the delayed flights. Referencing Figure 2, jet fuel prices are significantly higher in November and December when snowfall is prevalent. Therefore, it is crucial that snow be removed quickly and safely from airports to avoid the high costs associated with seasonal fuel costs. It is important to note that the report excludes costs associated with freight, military, international and general aviation flights, and costs due to cancelled or missed connecting flights. JEC also estimated a 2.7% increase in air traffic through 2025, which will result in a total of 1.1 billion passengers by 2025. Airports must be improving their snow management systems to prepare for the drastic increase in passengers. In 2007 Denver International Airport experienced an estimated 9,364,240 ground-based passenger delay hours and at 24,909,795 domestic departing passengers the average delayed passenger experienced 13.72 minutes of delay.

Month	Jet Fuel US Wholesale Price Per Gallon
January	$1.73
February	$1.77
March	$1.85
April	$2.02
May	$2.08
June	$2.11
July	$2.17
August	$2.15
September	$2.26
October	$2.35
November	$2.66
December	$2.66

Figure 2: Joint Economic Committee (JEC) estimated 2007 seasonal jet fuel prices (The Joint Economic Committee Majority Staff, 2008).

There is no event more notorious to DIA for snow delays than the blizzard in 2006; which left 22 inches of snow within a 24-hour period, resulting in over 60 million dollars of losses to the airlines alone (Gerber, 2009). DIA battled back after this storm by implementing a new snow removal fleet, comprised mostly of new mulit-function equiptment. This lead to a decrease in runway removal time from 45 minutes to 13 minutes and cutting ramp and taxiway clearing time in half; which accordingly cut associated costs in half. (Gerber, 2009). DIA also cut costs through implementing 12 portable snow melters – like the Aero snow melter show in Figure 3.

Figure 3: Aero 600 tph Snow Melter (Dejana Industries, 2011)

Excess snow in terminal areas is removed via snow-melters, which are contracted out through the company Aero, eliminating high costs associated with offsite removal.

This report highlights a few new ideas and designs to increase the energy efficiency of DIA's snow removal operations and decrease all of the costs associated with snow. The solutions presented below are focused on DIA, but the ideas inherently can be applied to any airport dealing with snow removal.

7.1.3 Preliminary Analysis

After reviewing the snow problems DIA and airports across the U.S. face, two main types of solutions were reviewed: snow prevention and snow control. Preventing snow from accumulating on areas used by aircraft can significantly reduce flight delays and the fiscal/energy costs associated with these delays. One design solution is erecting a "roof-like" structure over one of the most problematic areas – the ramps. A roof-like structure would not only decrease the amount of delays at the gates, but would also potentially extend the lifetime of the aircraft and decrease deicing time pre-take off. After discussing erecting such a structure with several FAA experts, this design was not pursued for multiple reasons; an increase to ground-collision probability, the actual size the structure needs to be able to hold a variety of planes - Boeing 747 dimensions seen in Figure 4, cost of effective ventilation of exhaust gases, new lighting costs, and natural day lighting for the passengers waiting in the terminal could be blocked.

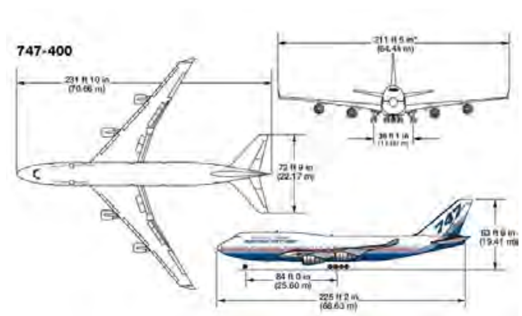


Figure 4: Overall aircraft dimensions of Boeing 747-400 showing the height limitations for snow prevention structures (Boeing).

The second snow removal strategy is snow control through the implementation of in-ground snow melters instead of the portable snow melters DIA currently uses; a comparison analysis is demonstrated within this section.

7.1.3.1 Technical Aspect of Design

For this analysis two different types of snow melters are compared; an in-ground model made by Snow Removal Systems and a portable snow melter made by Trecan. The Trecan model, 500-PD (as seen in Figure 6), has a rated capacity of melting 500 tons per hour (tph) of snow, a representative model for DIA's current melting systems. Snow Removal System's, SRS-IG300 (as seen in Figure 7), model has a rated capacity of 300+ tph of snow, and was chosen as the in-ground counterpart to the portable model. The SRS-IG300 was chosen as the in-ground melter of study due to its natural gas fuel source and high rated capacity. Technical specifications for each model, compared side by side, can be found in Figure 5. The method for melting snow in both of these snow melting systems is basically the same for each. A fuel source is used through combustion in a burner, the burner heats up a gas, the gas flows through a heat exchanging device to heat up water as the working fluid, and this now warmed water is sprayed over the top of the supplied snow. Particulates from dirty snow are caught in a cleanout screening area and the melted water is drained. A basic diagram of this process can be found as Figure 5.

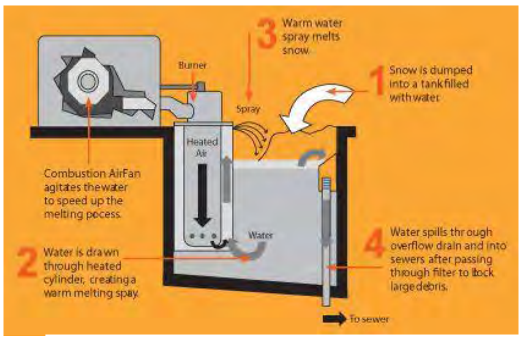


Figure 5: Basic snow melting process

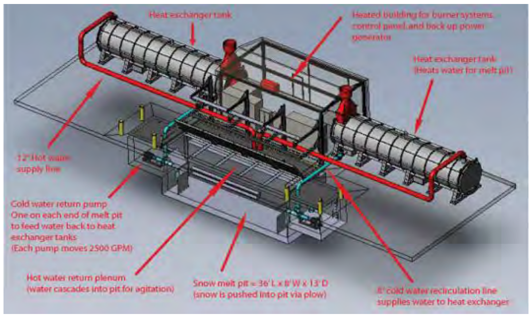


Figure 7: SRS-IG300 In-Ground Snow melter schematic (Trecan Combustion, 2012)

Figure 6: Trecan Portable Snow Melters (Trecan Combustion, 2012)

This study shows that there are more benefits to using in-ground snow melters over the current portable snow melters at DIA. The combustion of natural gas leads to a lower amount of CO_2 emissions per unit fuel than that of diesel; natural gas emits 2.8 kg of CO_2 per kg fuel, and diesel emits 3.0 kg of CO_2 per kg of fuel (The Engineering Toolbox, 2011). Running off of natural gas also means that there is a constant supply of fuel from the fuel supply line. Extra equipment, fuel, time, employees, and logistics are all required for loading portable snow melters.

Table 5: Specifications of Trecan's Portable Snow melter and SRS' In-Ground Snow melter (Trecan Combustion, 2012)

	SRS-IG300 In-ground	Trecan 500-PD Portable
Rated Capacity	300+ tph	500 tph
Burner Output	56,000,000 BTU/hr	84,000,000 BTU/hr
Water Outflow	1250 US GPM	2000 US GPM
Water Exit Temperature	39-40 °F	38 °F
Fuel Type	Natural Gas	No. 1 Fuel Oil, Stove Oil or Diesel
Fuel Flow (to burner)	54.37 MCF/hr	571 US GPH

7.1.3.2 Financial Analysis

The major benefits from switching to in-ground natural gas powered snow melters is the cost saving annually and the relative short payback period for making such a substantial investment. The Trecan-500PD portable melter and the SRS-IG300 are compared on a 25-year design lifetime, the average operation lifetime of the snow melters, with a discount rate of 1.85%

(The White House, 2011). The cost summary for each investment is presented in Table 8 outlining capital and annual costs. Due to the nature of snow removal operations at airports, fuel costs can be the largest annual operating cost. It is important to count for the fluctuations in the market price of each fuel over the course of the design lifetime. Determining a "fair" price for a MBTU of natural gas was determined by averaging the price over the last snow season (Oct '11-Feb '12) as the price fluctuates seasonally as well as monthly. The "fair" price used in this analysis is $3.16/MBTU (Wolfram Alpha, 2012). The average "fair" price for diesel was calculated in a similar fashion resulting in the "fair" average cost as $4.07/ US gallon (Energy Information Agency, 2012) In order to compare the two types of melters accurately, two SRS-IG300 in-ground melters are considered at a total capacity of 600 tph. Industry accepted annual operation and maintenance costs for portable snow melters are roughly 1% of capital costs and for stationary melters 0.1% of capital costs (Dwyer, 2012). A total estimated mass of snow (at 30 lbs/ft^3) of 1.15 million tons at DIA per year was assumed in this comparison.

Table 6: Cost estimate of Trecan-500PD and two SRS-IG300s for snow removal at DIA

Cost	Unit	SRS-IG300 (x2) In-ground	Trecan-500PD Portable
Capital Purchase	$	2000000	1500000
Installation	$	6000000	N/A
Operation/Maintenance	$ per year	8000	15000
Fuel Costs	$ per hour of operation	1062	2324
Annual Fuel Cost	$ per year	2035040	5345131
Price per Ton of snow	$ per ton	3.54	4.56
Payback Period	years	2.45	-

With a payback of less than two and a half years, and saving considerable amounts of money on fuel, switching to an in-ground snow melter like the SRS-IG300 is economically and environmentally the right choice. If the location of the airport and the site-specific characteristics require portable snow melters or trucking the snow at least 1 mile away, it is beneficial to choose the snow melters over the grossly expensive trucking method. Overall, in-ground snow melters are more efficient at removing snow from airport aprons, ramps and gates area than portable melters.

7.2 Geothermal Runway Heating

7.2.1 Summary

One of the potential ways that DIA can improve the energy efficiency of their non-terminal areas is to use the Earth's natural energy to melt snow on the runways through the use of geothermal energy. The technology for geothermal energy has been used in residential applications since the late 1940s (IGSHPA, 2011). However, the use of the geothermal energy for pavement heating applications is a relatively new area of development and has only been used at nine sites in the US, three sites in Japan, one site in Argentina, and one site in Poland (Lund, 2000).

DIA indicated interest in using geothermal runway heating on their new runway 16R-34L, which will be built over the next few years and will be 3.2 miles long and 150 feet wide. In order to determine how much heat must be supplied to the runway to raise the temperature of the surface to above freezing (0°C) so that the snow can melt, E-Cubed is using the design suggestion from the FAA to use an energy density of 300 BTU/hr●ft^2 (FAA, 2006). Since the area of the new runway will be 2,500,000 ft^2, this means that the geothermal runway heating system will have a total heating load of 760 million BTU/hr, or 63,000 tons.

There are many ways that snow can be removed from a surface, one of which is a pavement heating snow melting system, as shown in Figure 8 below. The green boxes in the figure represent the natural energy alternative that E-Cubed will evaluate and the red boxes represent the fossil fuel sources that DIA currently relies on to remove snow from their runway.

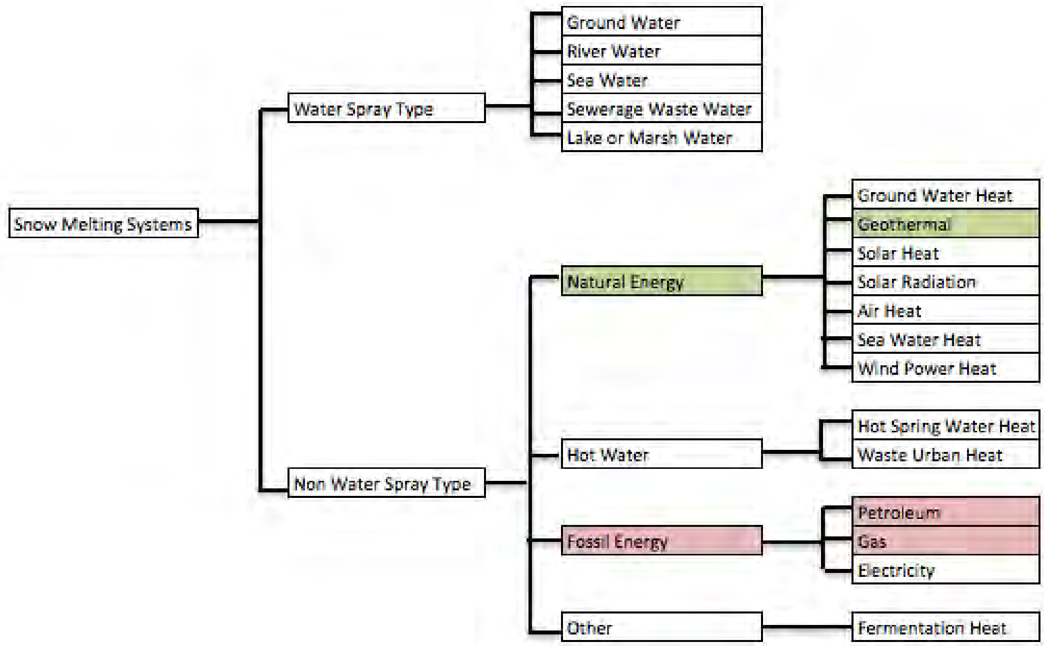


Figure 8: Snow melting options (Lund, 2000)

In order to design a snow melting system that uses natural energy there are a few important design components to take into consideration. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) have established a set of design criteria for these unique types of heating systems. The basic concept of this type of heating system is that it melts the snow through a continuous supply of hot fluid circulating through the runway, this creates a water film which becomes runoff or evaporates, making room for more snow to be melted. The rate of snowfall and ambient air temperature determine the amount of heat needed to raise the temperature of snow to 32°F in order for it to melt so that it can then be replaced. The heat supply can be determined from the snowfall rate, air temperature, relative humidity, and wind velocity (Lund, 2000).

7.2.2 Literature Review

There are a variety of different types of geothermal systems, including heat sink, hot water, and ground source heat pumps, but due to design constraints it became clear that ground source heat pumps are the most feasible option for airports. This system uses groundwater or air to heat the antifreeze solution that is then circulated in a closed loop system. It is imperative that an antifreeze solution is used to prevent the pipes from freezing and rupturing. If the groundwater is not warm enough to heat the solution inside of the pipes a heat exchanger must be placed at the top of each wellhead to ensure that the solution is heated to a proper temperature. The price for these systems can range between \$20/ft^2 and \$35/ft^2, in addition to expensive excavation costs (Lund, 2000). A trial system in Japan was able to melt a maximum snowfall of 4 cm/hr with an exterior air temperature of -1.9°C (CTC & Associates, 2007).

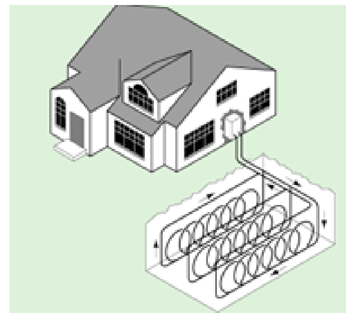


Figure 9: Horizontal slinky configuration used in a residential application

An example of a horizontal configuration is the slinky. This is typically used in areas where space is not an issue, such as DIA. As shown in Figure 9, the slinky configuration consists of multiple loops that are typically buried approximately 6-10 feet below the ground. The rule of thumb is that there needs to be one loop per ton of heating load. The typical diameters for each loop range between 2-4 feet. This amounts to roughly 12 ft of piping per loop, assuming a loop diameter of 4 feet.

This type of system is being used in Trenton, NJ where they use an ethylene glycol-water solution through pipes buried two inches below the pavement connected to five layers of horizontal pipes that are buried two feet apart between 3-13 feet below the surface (Lund, 2000).

One of the most important components of ground source heat pumps is the pipe material, which can either be plastic or metal. Steel and iron typically corrode more easily due to the high temperature fluid running through the heat pipes and the corrosive nature of salt. A cross-link polyethylene pipe is most commonly used instead of iron in order to prevent corrosion from happening. The lifetime of this type of material is usually 50 years and it can handle water temperatures up to 200°F and pressures up to 80 psi (Lund, 2000).

7.2.3 Preliminary Analysis

Upon conducting the literature review of various snow melting systems using geothermal energy, the slinky configuration was determined to be the most economically viable option.

Table 7: Pros and cons for various geothermal heating pump systems

	Pros	Cons
Horizontal Configuration		
Open System	Cheap—Not as much piping needed	Violates Colorado Water Rights
Closed System	Less excavations costs Easier to maintain and repair Cheaper	Large space requirements More piping required
Vertical Configuration		
Open System	Cheap—Not as much piping needed	Violates Colorado Water Rights
Closed System	Less space needed Less piping needed	Much greater excavation costs Difficult to maintain

7.2.3.1 Horizontal Slinky Loop Configuration

The University of Oklahoma first developed slinky piping systems, which are the most popular application of ground source heat pumps other than vertical boreholes. They are

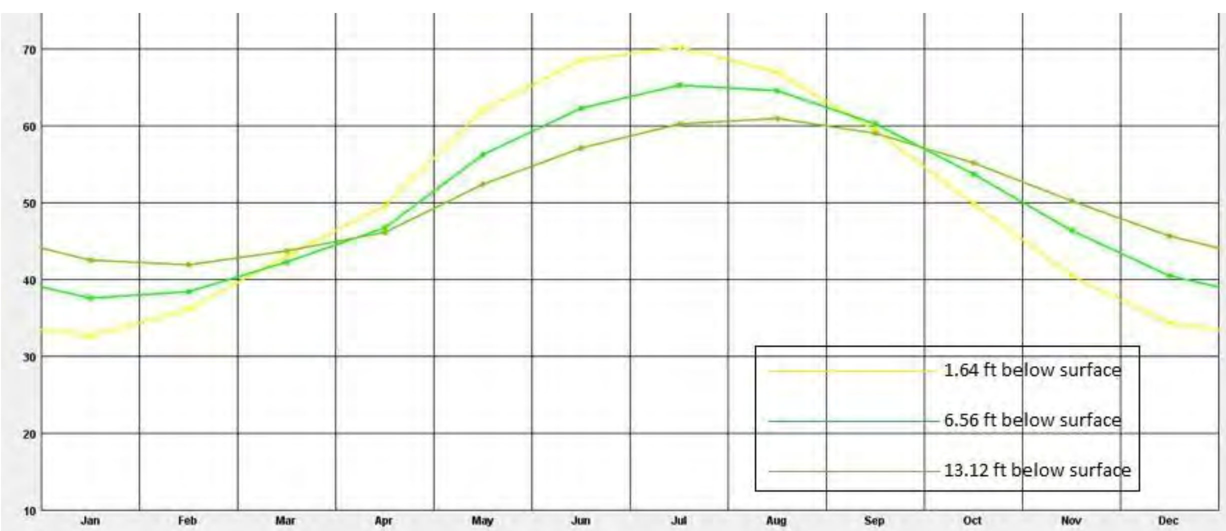


Figure 10: Average ground temperatures at DIA at depth of 1.64 ft (yellow), 6.56 ft (light green), and 13.12 ft (dark green). The y-axis goes from 10°F-70°F and the x-axis goes from January to July (US Dept of Energy, 2011)

typically placed into the ground by a digger at depths between 6-10 feet below the ground surface. The slinkies consist of coiled plastic pipe, usually high-density polyethylene, buried 6-10 ft into the ground. They can be installed using a horizontal or vertical configuration, but since DIA has so much land available E-Cubed has decided to use a horizontal slinky configuration. E-Cubed also used the design recommendation from the FAA to deliver 300 BTU/hr●ft^2 for the runway heating system (US Dept. of Transportation FAA, 2011). Climate Consultant was used to determine ground temperature 6-10 ft below the surface at DIA (US Dept of Energy, 2011). The annual trends can be seen in Figure 10. For all of these depths the average annual ground temperature is 51°F. It is important to note from this graph that there is a lower fluctuation in ground temperatures the further away from the ground surface the system is placed.

Technical Aspect of Design

E-Cubed has chosen to do an analysis of the slinky configuration buried 10 feet below the ground with a loop diameter of 4 ft. The reason why the loops will be placed at 10 feet below is due to the lower fluctuation in temperature at the lower depth. As mentioned in the literature review, the rule of thumb in the design of slinky systems is one loop per ton. Since DIA needs 63,000 tons of heat to keep the runway above freezing (0°C), this means that this ground source heat pump system

Figure 12: Horizontal slinky configuration

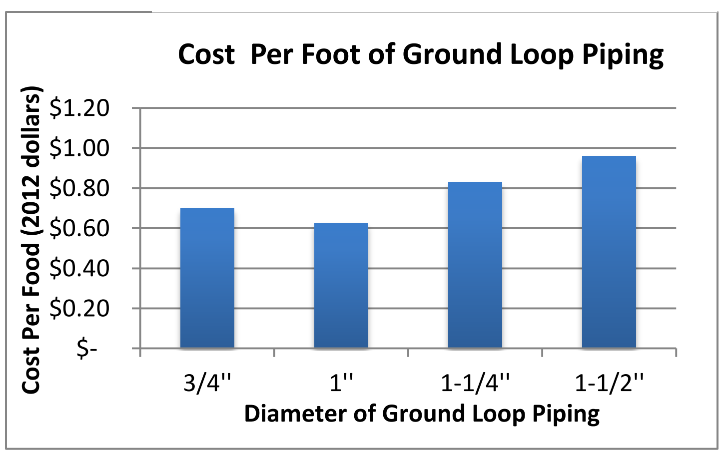


Figure 11: Cost per foot of ground looping piping

would need 63,000 loops. Figure 12 shows what a typical horizontal configuration looks like.

E-Cubed has decided to use ¾ inch high density polyethylene (HDPE), 160 psig water piping. The plastic piping chosen will avoid the corrosion inherent in the metal pipes. A pipe diameter of ¾ in. was chosen because it is a cheaper option as compared to larger diameters.

Figure 11 shows the cost of HDPE water piping ranges between \$0.38/ft for ¾'' piping to \$0.52/ft for 1-1/2'' piping (Note: these are 2012 dollars).

It is also important to note that in addition to the horizontal configuration that lies out in the field next to the runway, there are also heat pipes needed underneath the runway to circulate the warm glycol water solution to melt the snow on the surface of the runway. Keeping in mind that the runway is 3.2 miles long and 150 ft wide, E-Cubed looked at the design used by the Virginia Department of Transportation to heat a bridge (Lund, 2000). A visual representation of the design in Virginia can be seen in Figure 13.

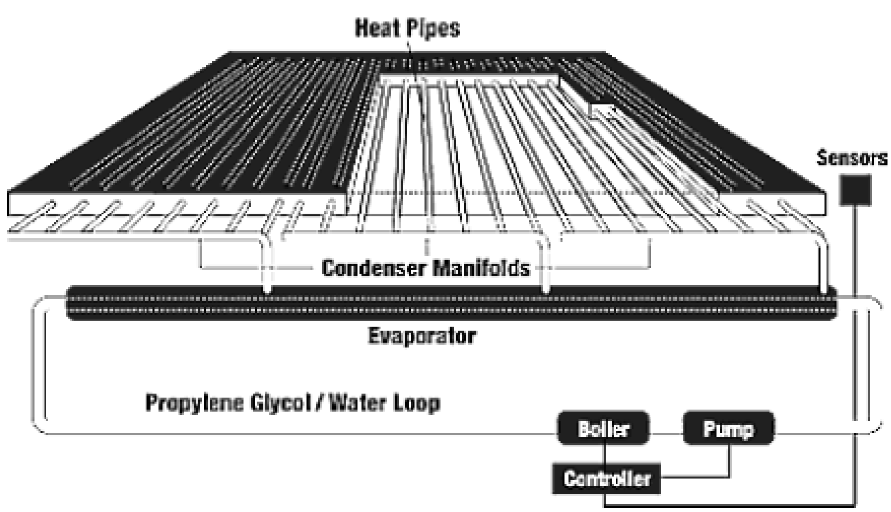


Figure 13: Heating system used in West Virginia (Lund, 2000)

Finally, the last component of the design is the antifreeze solution that runs through the pipes. E-Cubed will be using a 15% ethylene glycol, 85% water mixture running through the heat pipes. Ammonia and Freon have been used in the past but Ammonia is toxic when released into the environment and Freon can no longer be used due to restrictions on chlorofluorocarbons (Lund, 2000). A summary of the design for ground source heat pumps is shown in Table 8.

Table 8: Design summary for ground source heat pumps

	Pipes	Pumps	Antifreeze Solution
Heat pipes under runway	590 miles of ¾'' HDPE piping that are spaced in 150' lengths spaced 9'' apart	6 units of York International Titan heat pumps (6,167 tons each)	72,000 liters of 15% ethylene glycol, 85% water mixture
Heat pipes out in the field	150 miles of ¾'' HDPE piping that are 10' below the surface comprising 63,000 loops of 4' diameter	5 units of York International Titan heat pumps (6,167 tons each)	18,000 liters of 15% ethylene glycol, 85% water mixture

Financial Analysis

The payback period was calculated by comparing the capital cost of the new ground source heat pump system to the estimated savings to remove snow from runway 16R034L each year. It is assumed that DIA will build this system when they are constructing the new runway. Table 9 below shows the cost of the preliminary design that E-Cubed is proposing to DIA. The net capital cost takes into account the rebates mentioned in Table 10. Without these rebates the net capital cost would be $112 million, instead of $77 million. After considering the savings between the current system and the system the payback period would be 77 years.

Table 9: Cost of preliminary design

Material	Description of Material	Amount of Material	Cost/Unit	Total Cost
Capital Costs				
Heat pipes in field[1]	HDPE 3/4" diameter	793,800 ft	$3.25/ft pipe	$2,579,850
Heat pipes in runway[1]	HDPE 3/4" diameter	3,133,558 ft	$3.25/ft pipe	$10,184,903
Heat pumps[2]	York Titan (6167 tons each)	11 units	$9,044,933/ heat pump	$994,494,263
Ethylene glycol antifreeze[3]	Ethylene glycol	55,666 kg	$1.50/kg	$83,499
Net Capital Cost				**$77,924,907**
Electricity for heat pumps[2]	12.5 kW/pump	11 units	$10,950/pump	$120,450
Net Annual Cost				**$120,450**

[1] (Kavanaugh, 1995), [2] (York Titan, 2012), [3] (Science Stuff Inc, 2010)

Table 10: Rebates available for ground source heat pumps in Colorado

Organization/Company	Program	Incentive	Total Incentive
Xcel Energy[4]	Ground Source Heat Pump Rebate	$300/ton	$ 18,900,000.00
Federal Government[4]	Business Energy Investment Tax Credit	10% of project cost	$ 11,234,167.40
Federal Government[4]	Renewable Electricity Production Tax Credit	$0.0202/kWh	$ 4,239,840.00
Total Incentives			**$ 34,416,767.89**

[4] (DSIRE USA, 2012)

Environmental and Social Benefits

The proposed system will reduce DIAs dependence on snow plows and chemical deicing agents, which will reduce maintenance costs as well as reduce the needed fleet size. The decreased need for trucks will reduce the amount of greenhouse gases that DIA emits from their diesel-powered vehicles. The decreased need for snow trucks will allow for DIA to have closer scheduled and more consistent arrivals and departures. In addition, the system will maintain a more constant temperature for the runway, meaning that less fracturing will occur due to temperature change. The decrease in temperature change related fracturing across the runway will greatly extend the life of the pavement.

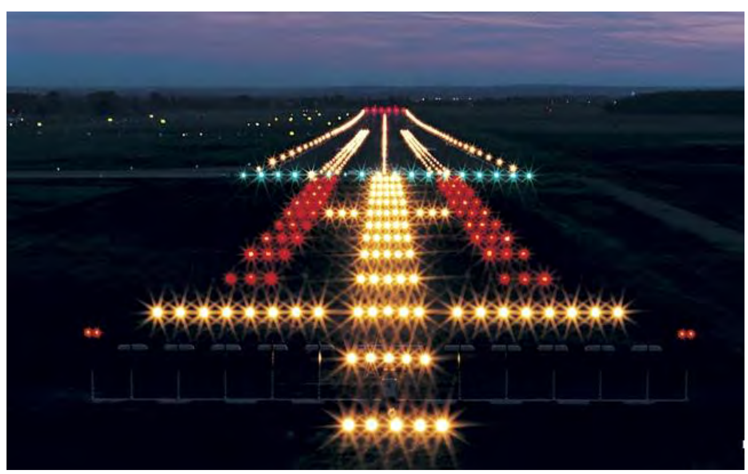


Figure 14: Airfield ground lighting at night (Airfield Ground Lighting)

7.3 Runway Lighting

7.3.1 Summary

The lighting of airfields is essential to an airport's operation at nighttime. There are nine different areas in which lights are necessary – they include runway edge, threshold, end, exit, and centerline lights, as well as taxiway lights (SKYbrary, 2011). Currently, DIA uses quartz incandescent lights with the exception of roughly 2,000 light-emitting diode (LED) lights. With a total of 30,000 lights on the airfield at DIA, only 6.7% of the lights are LEDs. E-Cubed has determined that designing two solutions to obtain higher energy efficiency within the runway lighting system that will be beneficial to DIA as well as other airports nationwide.

7.3.2 Literature Review

In an effort to improve lighting efficiency, LED lighting began to be implemented at airports starting in 2002. LED lighting can provide the same lighting with 50% less energy consumption and a running lifetime that is 35 times longer than traditional lighting. LEDs can reduce energy costs as well as maintenance costs. LEDs are able to provide these benefits because they do not operate like other lighting sources. These lights are semiconductors that emit photons instead of using a filament in glass like incandescent lights (Taylor, 2010).

LED lighting can be used in almost all aspects of runway lighting such as elevated applications as well as in-ground on both runways and taxiways (Runyun & Chapman, 2009). LEDs also can produce a variety of colors that are already used in runway lighting. LEDs are able to produce similar colors, but they are not always compliant with FAA standards. This is partly because standards were originally based off of incandescent lighting designs. A study conducted by the Lighting Research Center (LRC) found that LEDs may produce acceptable colors, but more testing needs to be done to set new standards (Taylor, 2010). The brightness is another important factor in changing the lighting on runways. LEDs produce a brighter, harsher light that some pilots have said is too bright. To account for this, LEDs can reduce their brightness by balancing the brightness to luminous intensity. A study conducted by the LRC examined ways for LEDs to match the brightness of incandescent runway lights (Taylor, 2010).

Other alternative lighting technology is available, but do not provide as many benefits as LED lighting does.

An important consideration for switching to LED lights is their performance in cold weather. LED lights do not produce as much heat as incandescent bulbs because they are more efficient. The heat that incandescent provides also allows the light to melt frost or snow that may accumulate on the light in low temperatures and snowstorms. In cold weather climates, an additional heater is attached to LED lights to have them act like the old style of lighting. The heater works in cycles once the temperature reaches below 40° F to keep the glass of the lighting fixture above freezing. This greatly reduces any energy savings gained from switching to LED lighting (Gu, 2007). Currently in the aviation industry there is active discussion on whether LED lights need to contain heaters or not. Some colder climate airports in Alaska and Canada have switched to using LED lights L-850A Light (ADB Airfield Solutions) without heaters and have not reported any problems. Other industry experts say that the heaters are absolutely necessary for proper operation of the lights. In a further assessment of LED lighting, E-Cubed would examine how necessary heaters are with LED lights. This would include an evaluation specific to DIA for the large temperature fluctuations the airport sees during night and day.

Figure 15: L-852C and L-852D Light (ADB Airfield Solutions, 2010)

Figure 16: L-850A Light (ADB Airfield Solutions, 2010)

Airports that have installed LED lighting have experienced success in terms of energy and cost savings. The Monterey Peninsula Airport in California installed LED lights on taxiways and pilot controlled lighting on runways in 2004. The airport saw a yearly drop of energy use from

193,600 kilowatt-hours (kWh) to 102,960 kWh. This was a 47% reduction in energy consumption (Monterey Airport, 2011). These LED lights did not contain heaters as they were unnecessary in California.

7.3.3 Preliminary Analysis

After assessing the research above, E-Cubed has chosen to focus on in-pavement runway centerline lighting. Our contacts at DIA have observed that runway edge lights are knocked down often, which facilitated the team's decision in selecting runway centerline lighting. DIA currently uses ADB Airfield Solution L-852C and L-852D taxiway centerline inset lights, both of which are Category III F-Series taxiway lighting, as well as L-850A incandescent runway centerline lights. E-Cubed has decided to work with ADB Airfield Solutions on the runway centerline lighting because of DIA's previous experience with the company. ADB Airfield Solutions manufactures Category III LED runway centerline lights, known as L-850A LED. These lights are made with heaters as well as without heaters. DIA has plans to construct a new 16,000 foot runway and E-Cubed has been asked to design this runway in two ways; one with L-850A lights with heaters and one with L-850A lights without heaters. These two designs, as detailed in the next two sections, will be compared with the construction of a new runway using the current in-pavement incandescent runway centerline lighting.

7.3.3.1 Solution

Changing the lighting to L-850A LED lights with or without a heater for a new runway will require the installation of approximately 320 lights on a 16,000 ft runway spaced 50 ft apart. The current average cost of commercial electricity is 10.3¢ per kWh which will be used in various energy calculations (Wolfram Alpha, 2012). The Environmental Protection Agency provides a tool to calculate

Figure 17: L-850A LED light (igureADB Airfield Solutions)

greenhouse gas (GHG) emissions that will be used to help assess environmental impact (EPA, 2011). DIA current and alternative lighting options will be assessed for technical, economic, and environmental factors

Technical Aspect of Design

The current L-850A F-series incandescent bulbs being used at DIA for centerline lights are made by ADB Airfield Solutions. The LED version of the L-850A lighting could be installed with a heater that will not reduce the energy savings by a large amount. To be able to operate the heater the light fixture has to have a larger transformer which consumes more power even when the heater is not running. The energy consumption for this model light is difficult to calculate because of the additional energy consumption of the heater. We used a return on investment tool provided by ADB to calculate the energy savings of this model light. (ADB Airfield Solutions,

Table 11: Technical Data for Lighting Options

	Incandescent	LED with Heater	LED without Heater
Number of Lights	320	320	320
Power Rating (W)[1]	48	30	65
Amperage (A)[1]	6.6	6.6	6.6
Fixture Load (VA)[1]	48	14.5	24.84
Lifetime hours[1]	1,500	56,000	56,000
Average Operating Hours	4380	4380	4380
Power consumed (kWh)[2]	77,788	34,815	24,528
Fixture cost ($)[3]	550	975	975

[1] (ADB Airfield Solutions) [2] (ADB Airfield Solutions, 2011) [3] (Runway Centerline Lighting Costs, 2012)

2011) This tool accounts for how many days the heater will be active when the temperature drops below 5°C which was 156 days for DIA (NOAA). It also account for the constant current regulator (CCR) which supplies the power to both LED and Incandescent lighting. Below are the specifications for each type of light and the energy consumption. Unfortunately these are not the energy savings reported by DIA with their current LED lighting. This is because operationally they are affected by having to have a larger transformer for the heater that increases energy consumption even without the heater in use.

Financial Analysis

A finical assessment of all lighting alternatives is the most important part of deciding whether any of the alternative lighting options are a good idea. When comparing the options we are looking at installation in a new runway. This will make new installations cost equal. Other capital investments like CCRs will also be equal given that new ones will have to be installed under any circumstance.

A payback period will be calculated by comparing the two LED option to the incandescent lighting. Table 12 shows the capital and annual costs of each design. It is clear that LEDs have a higher capital cost but much lower annual cost. The payback period for both LED designs is about five years, which can be seen in Table 13. The option without the heater is a more cost effective option, but not by much.

Table 12: Costs of Lighting Designs

		LED		
		With heater	**Without Heater**	**Quartz-Incandescent**
Capital cost	Installation	$ 312,000	$ 312,000	$ 176,000
Annual Cost	Energy Cost	$ 3,592	$ 2,529	$ 8,016
	Maintenance	$ 6,400	$ 6,400	$ 22,400
	Total	$ 9,992	$ 8,929	$ 30,416

Table 13: Savings and Payback Period

		With Heater	**Without Heater**
Yearly Savings	Energy Cost	$ 4,424	$ 5,487
	Maintenance	$ 16,000	$ 16,000
	Total	$ 20,424	$ 21,487
Payback	Capital Cost difference	$ 136,000	$ 136,000
	Payback Period (years)	5.10	4.90

8. Decisions and Design Criteria

In order for the best possible designs to be chosen, a comparative decision matrix is implemented. A decision matrix allows the client to provide multiple evaluation criteria to the consulting company, and apply these criteria to the alternatives being assessed. Each criterion is weighted and placed into a matrix. Finally, the weighted scores for each criterion and alternative are summed together, and the alternative with the highest scores will be deemed the best solution. The criteria for this project are broken into four main categories: technical, economic, social and environmental. The individual criteria along with an explanation of each are included in Table 15.

The four main criteria categories of technical, economic, social, and environmental were each givens weights of 20%, 50%, 20%, and 10%, respectively, after discussing the priorities of DIA, the advice from industry experts and E-Cubed's experience. DIA expressed a considerable desire for a design that had a relatively short payback period and overall large cost savings. This input motivated the 50% significance of the economic category.

8.1 Decision Matrix and Weighting Process

The complete design matrix presented in Table 14 shows the weights allotted to each criteria subcategory and the ratings for each design solution. The designs were rated for each criteria from 1 to 5, 5 being the most desirable score. The greatest weighted criterion in the decision matrix was the payback period, as requested by DIA, at 35% significance. An example of the rating processes is as follows. For payback period, any design solution that had a payback period between 0 and 2 years received a 5, between 2 and 5 years received a 4, between 5 and 10 received a 3 and so on. This resulted in the in-ground snow melter and LED without heaters receiving a score of 4 while LEDs with heaters scored a 3 and lastly geothermal heated runways with a payback period of 77 years a 1. Ultimately, with high rankings in most criteria, runway centerline LED lighting without heaters surpassed the other options. After completing the decision matrix, it was determined that LEDs without heaters was the most desirable option mainly due, but not limited to, its reasonable payback period of less than five years.

Table 14: Decision Matrix for Alternatives

Criteria Category	Criteria	Comments	Weight %	Geothermal heated runway	In-ground snow melters	LEDs with heaters	LEDs without heaters
Technical	Commercial Potential	Applicability to airports nationwide.	8	3	3	4	5
	Increased Utility	Acceptance and applicability nationwide.	8	4	4	4	4
	Feasibility	Practicality – how realistic.	4	3	4	5	5
Economic	Payback Period	Time taken for cost savings to match investment.	35	1	4	3	4
	Annual Costs	Operation, maintenance, miscellaneous, fuel.	5	4	2	3	4
	Capital Costs	Purchase price, installation, material and labor.	5	1	2	2	2
	Increased Affordability	Fiscal effect on airports' ability to provide services.	5	3	3	3	3
Social	Safety	Low hazards and health risks.	9	5	3	4	3
	Public Acceptance	Aesthetics, attractive, Green Print Denver Plan.	8	5	4	5	5
	Innovation	Leading edge technology, model for others.	3	5	2	3	4
Environmental	Energy Saved	Annual energy savings potential	5	3	5	3	4
	GHG Offset	Annual GHG offset potential	3	3	2	5	5
	Local Resources	Materials and labor from local companies/suppliers.	2	4	3	2	2
Totals			**100**	**275**	**349**	**348**	**364**

9. Safety Risk Assessment

A safety risk assessment is important to all of our design alternatives. Lighting is the most critical for the FAA because it will have the most impact on day-to-day operations, and has the highest importance for airport safety. Before any changes are implemented at an airport it must be assessed for hazards using the Safety Management System (SMS). The SMS provides policies and practice guidelines for safety throughout all its operations. Safety is ensured using

Safety Rick Management (SRM) that provides five phases to identify and document risk. The formal process as laid out by the Introduction to Safety Management Systems is to describe the system, identify the hazards, determine the risk, assess and analyze the risk, and finally treat the risk (Federal Aviation Administration, 2007).

The proposed installation of LEDs would be on new runways to be constructed at DIA which reduces any risk from the initial installation. The main risk for the proposed design is the LED lights operation in adverse weather conditions. DIA receives snowfall every winter and always experiences large changes in temperature over the course of a day. Installing LEDs that do not have heaters may not be able to operate correctly by removing any snow accumulation on the light. Snow obstructing runway lighting could be extremely hazardous and to airport safety. A full safety assessment would have to be done to ensure that LEDs without heaters do not present any more risk than current lighting systems.

Ground source heat pumps underneath the runway do not have many obvious safety risks but still need to be assessed. The proposed system would be a closed loop system reducing the risks even further. One possible hazard is if the system fails or breaks and releases the ethylene glycol mixture. However, because this is already used in the airports deicing fluid and is treated on site at DIA it should not be a large risk because it can be cleaned up readily. The larger risk is from the failure of the runway due to the piping system underneath it. Ensuring that the runway still has structural integrity is imperative to airport safety. Ground source heat pumps are a reliable technology that should improve the lifetime of the runways and their overall safety.

Snow removal is a very important safety aspect of any airport that annually receives snowfall. With the proposed snow melters there is very little risk changing to the in-ground model, but under the Safety Management System Manual, "All proposed changes to the National Airspace System (NAS) require evaluation (Federal Aviation Administration, 2008). In-ground models are already use at other airports very effectively. The main risks will be locating them in areas away from airplane traffic. Snow melters will also need to be easily accessible by snow removal equipment that will not interfere with the operations of planes. Snow melters help reduce the risk of snow between the concourses because it increases the capacity of snowfall that the airport can handle, improving the safety of the airport. Possible failure of these devices will result in difficult snow removal because of the complexities in the area between the concourses.

10. Final Design

After analyzing the decision matrix results, E-Cubed selected runway centerline LED lighting without heaters as the most energy efficient solution. The FAA competition goals incorporate commercial potential, increased affordability and increased utility of designs. In the decision matrix, runway centerline LED lighting without heaters scored the highest for the FAA goals above, which is why E-Cubed has chosen this option as the final design.

10.1 Fixture Options

DIA currently uses a combination of quartz incandescent lights and LEDs to light their runways, with only 6.7% of their lights being LEDs. The manufacturer that DIA purchases their incandescent lights and L-850A LED runway centerline lights from is ADB Airfield Solutions. A few other LED options that ADB offers include runway edge lights (L-850C LED), touchdown zone lights (L-850B LED), and runway guard lights (L-852G LED). ADB also has solar powered LED options, but these are only for directional signs on the runway and obstruction lights (ADB Airfield Solutions). Unfortunately, there aren't any solar powered runway centerline lights on the market and the only ones out there have an electrical input requirement.

A few other manufacturers of LED runway lights include Allen Enterprises, Multi Electric, Hella, and Cooper Crouse-Hinds. It is important to note that LED runway centerlines run on one of the Constant Current Regulator's (CCR) lower intensity step setting, typically either 3-step or 5-step. Another important component to consider is whether or not an airport needs to have a heater to melt snow and ice at low temperatures. This is only applicable for climate regions with large variations in temperature throughout the course of the day.

10.2 Design for Using LEDs on Future Runways at DIA

Implementing LED centerline runway lights for a new runway is the simplest way to receive the energy and cost savings that LED lighting provides. With a new installation, the most efficient CCRs can be used to help reduce energy consumption (ADB). Below shows a map of DIA with tentative plans for future runways. The new runway 16R-34L is going to be 16,000 ft long. The LEDs with heaters will be placed in 50-foot intervals, which will amount to 320 lights on the runway.

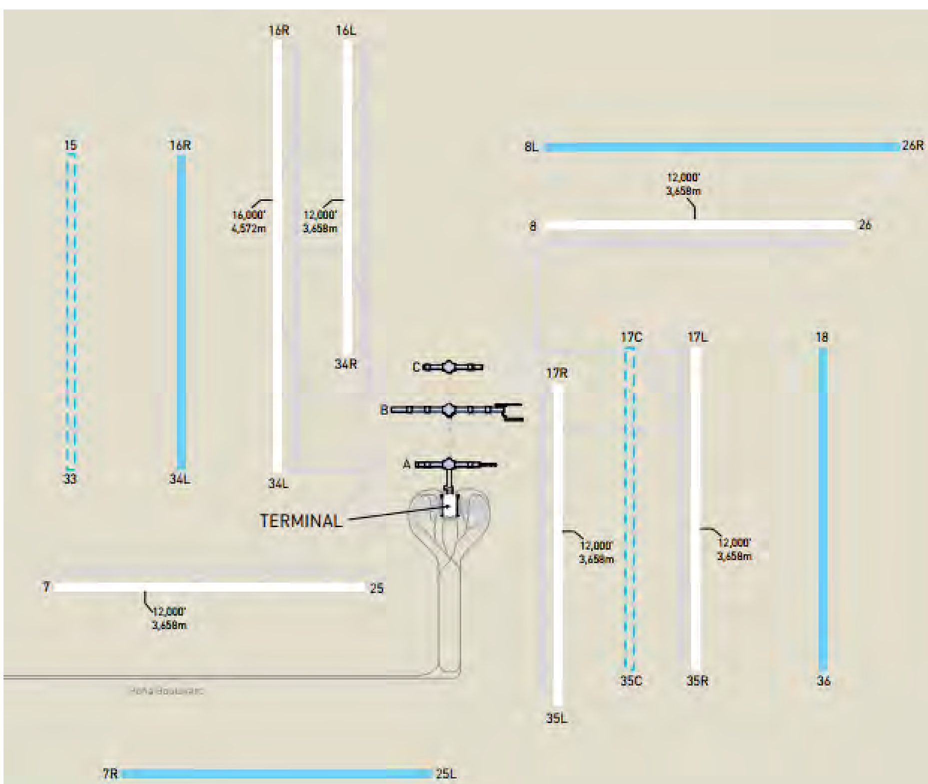


Figure 19: Map of DIA runways. The white lines represent current runways and both the solid blue lines and dotted blue lines represent future runways. (DIA, 2008)

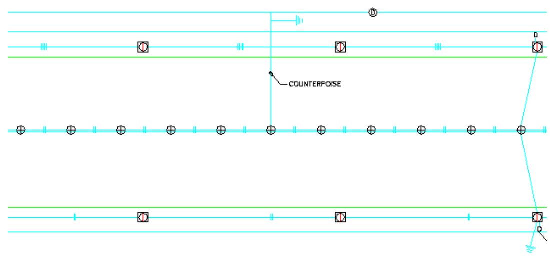


Figure 20: Sample section of a new runway at DIA. (DIA, 1991)

10.3 Retrofitting Existing Runways to Use LEDs

The installation of centerline lighting should in no way stop an airport from switching their current system to the one proposed here. The act of changing out the current lights with the new LED centerline lights is almost as easy as changing out an ordinary household incandescent bulb with a CFL bulb. The lights are incorporated in one system and have the same attachments as the current lights. Uninstalling the old lights is a matter of unbolting an average of 6 bolts, taking out the unit, unplugging it, plugging in the new LED unit, and bolting it back down. The new LED centerline lights installation can be worked into the regular lighting maintenance schedule where newly burnt out incandescent lights are replaced with the LED lights. This way of integrating the new technology will allow use of the current system until it is completely inoperable without involving any excess maintenance costs.

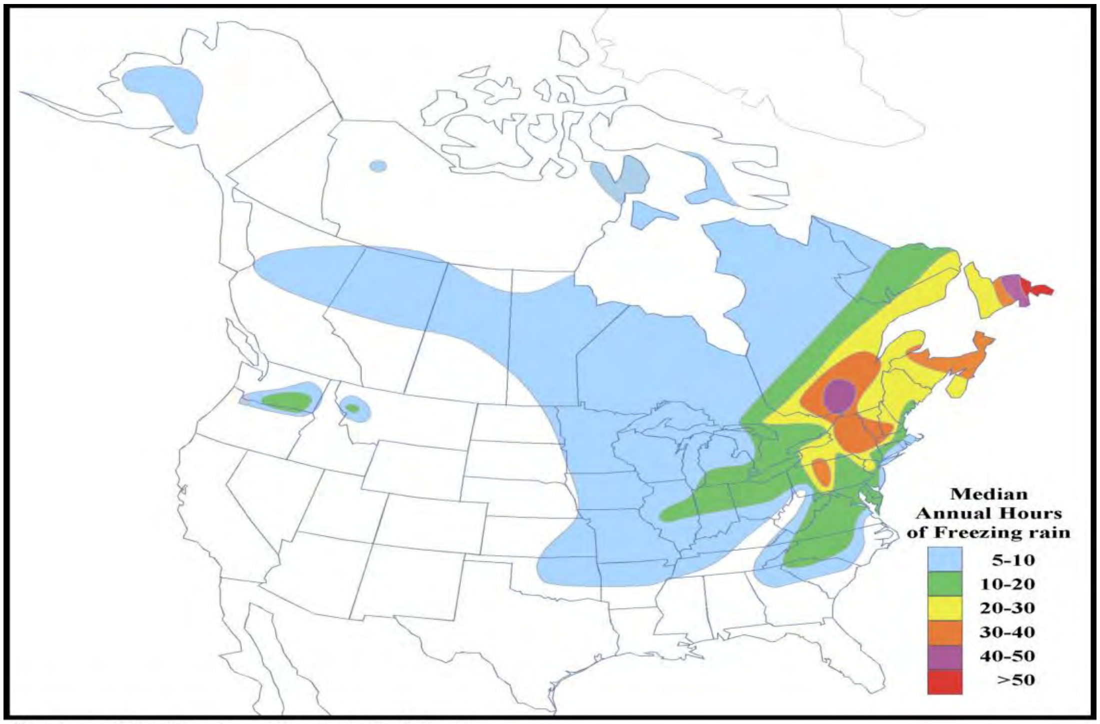
10.4 National Applicability

The Energy Independence and Security Act of 2007 requires that incandescent and halogen incandescent lamps be phased out beginning in 2012 (Gallagher & Williams, 2009). With this mandate, E-Cubed determined that looking at the need for LEDs with and without heaters across the United States was necessary. The use of heaters in combination with LEDs should be used in areas that are prone to freezing rain and ice accumulation (Inc., 2003). These conditions are very rare in the western U.S. but frequent in the northeastern U.S (Rauber, Charlevoix, & Walsh, 2008). To date, there have been no field tests that prove what the threshold in terms of weather conditions is for the need of heaters. The FAA, however, does require that for medium intensity approach lights, the “energized LED light source shall prevent the accumulation of ice on the face of the light source when exposed to an ambient air temperature of -10°C ± 2°C and water droplet temperature of 0°C to 3°C” (Federal Aviation Administration). Eight airports have been selected as models as shown in Table 15, each from a different part of the continental U.S. with different climates. Other airports can be modeled off of these eight airports depending on similar climate conditions as well as Figure 21 and Figure 22, but E-Cubed recommends that further studies be conducted.

Table 15: Model Airports and Probability of Freezing Rain and/or Ice Accumulation

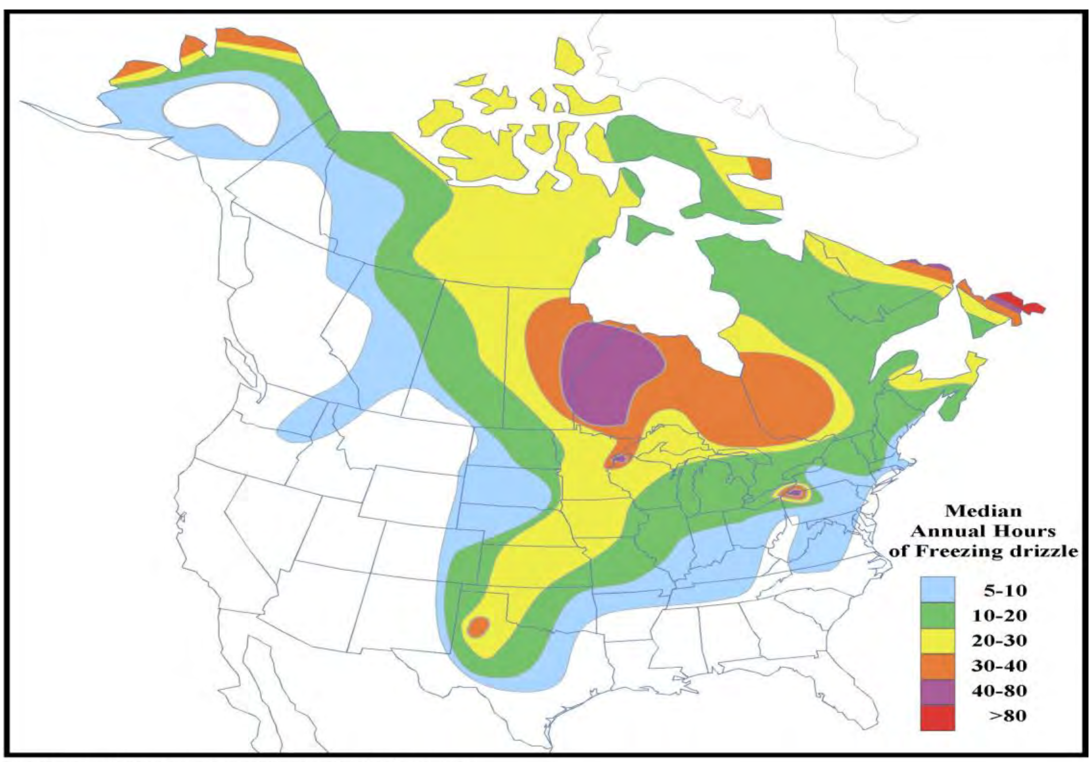
Airport	Location	Probability of Freezing Rain and/or Ice Accumulation[1]
Los Angeles International Airport (LAX)	Los Angeles, California	Not probable
Lambert-St. Louis International Airport (STL)	St. Louis, Missouri	Probable
George Bush Intercontinental Airport (IAH)	Houston, Texas	Not probable
John F. Kennedy International Airport (JFK)	New York, New York	Probable
Hartsfield Jackson Atlanta International Airport (ATL)	Atlanta, Georgia	Not probable
Seattle-Tacoma International Airport (SEA)	Seattle, Washington	Probable
Washington Dulles International Airport (IAD)	Washington, D.C.	Probable
Denver International Airport (DIA)	Denver, Colorado	Probable

[1] (Rauber, Charlevoix, & Walsh, 2008)



Courtesy of the American Meteorological Society

Figure 21: Map of the United States showing areas that are prone to freezing rain (Rauber, Charlevoix, & Walsh, 2008)



Courtesy of the American Meteorological Society

Figure 22: Map of the United States showing areas that are prone to freezing drizzle (Rauber, Charlevoix, & Walsh, 2008)

10.5 Life Cycle Analysis

E-Cubed has performed a life cycle analysis (LCA) on the proposed LED runway lights which is detailed below. The LCA was performed on the five main phases of LED life cycle which include: primary resource acquisition, raw material processing, manufacturing and assembly, use, and disposal. Multiple sources were referenced for the desired information, leading to in which incandescent bulbs are compared to compact florescent bulbs (CFLs), and LEDs.

Table 16: Total Life-Cycle Primary Energy Use (MJ/20 million lumen-hours) (Navigant Consulting, Inc, 2012)

	Incandescent			CFL			LED (2011)		
	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
Bulk Lamp Material Manufacturing	10.1	42.2	106	11.3	170	521	38	87.3	154
LED Package Manufacturing	N/A	N/A	N/A	N/A	N/A	N/A	1.88	256	1340
Total Manufaturing	10.1	42.2	106	11.3	170	521	39.9	343	1490
Transport	0.26	0.27	0.27	1.42	1.57	1.71	1.23	2.71	4.19
Use	15100	15100	15100	3780	3780	3780	3540	3540	3540
Total	15100	15100	15200	3790	3950	4300	3580	3890	5030

By combing the above data, with known lifecycles of the various lighting devices, E-Cubed has been able to determine that LEDs are not only cost effective, but reduce energy required for the entirety of the life of the light.

10.6 Benefits

10.6.1 Energy Savings

Energy savings associated with LEDs versus quartz-incandescents stem from the inefficiencies associated with incandescents. Both LEDs and incandescents emit heat and light, but LEDs emit less heat than incandescents for an equal amount of luminous intensity. In addition, incandescent fixtures result in larger energy losses at the transformers due to larger power requirements. In order to determine a national average for the projected energy savings from switching from incandescent fixtures to LEDs an average value of energy saved per fixture (ESF) is determined. This value incorporates the average annual operating time (hours), average fixture load measured in volt amps (VA), and average isolation transformer load (VA). Annual ESF values are summarized for the various switches in Table 17.

10.6.2 Cost Savings

In order to quantify the projected cost savings for airports a nationwide average of costs saved per fixture (CSF) is determined. This value incorporates the average US commercial electricity price, ESFs for the various replacements, and annual operating costs for maintenance, replacements, labor costs etc. The sum of the saved annual energy costs and saved annual maintenance costs generate the annual CSF found in Table 17.

10.6.3 GHG Benefits

Greenhouse gas emissions from power plants can be reduced when the demand for energy is reduced. By switching to a lighting source that requires less energy per year, GHG emissions can be cut back at power plants. Similar to other savings calculations, the amount of GHG emissions that can be reduced by making a particular lighting switch will be determined for a given fixture. This value will be referred to as the GHG emission reduction per fixture (GERF). The annual ESF value for each switch can be converted to an annual GERF value using the EPA's Clean Energy Greenhouse Gas Equivalencies Calculator. This calculator uses an equivalency factor of 6.8956×10^{-4} metric tons CO_2 per kWh. The GERFs are shown in Table 17.

Table 17: Annual Energy, Cost and GHG Benefits of Switching to LEDs with and without Heaters (ADB Airfield Solutions, 2011)

Benefits	Quartz-incandescents to LEDs without Heaters	Quartz-incandescents to LEDs with Heaters	LEDs with Heaters to LEDs without Heaters
Energy Saved per Fixture	166 kWh	144 kWh	22 kWh
For single 320 fixture runway	53,120 kWh	46,080 kWh	,7,40 kWh
CSF	$65.60	$63.05	$2.27
For single 320 fixture runway	$20,992	$20,176	$726
GERF	0.115 tons CO_2	0.093 tons CO_2	0.015 tons CO_2
For single 320 fixture runway	37 tons CO_2	30 tons CO_2	5 tons CO_2

10.7 Non-Centerline LED Applications

There are a variety of different airport applications for LED lights other than centerline runway lighting, including runway edge, threshold, runway end, stopway, touchdown zone, caution zone, and taxiway lighting (SKYbrary, 2011). Table 18: **Different LED fixture options** below summarizes these different options and gives examples of airports that have already applied this technology.

Table 18: Different LED fixture options

Application	Description	Example
Runway edge	Located along or just beyond the edges of the runway (white light)	-Hollis Municipal Airport[1] -Raleigh Durham International Airport[2]
Threshold	Green lights that define the landing distances	
Runway end	Red lights in a line at the end of the runway	
Runway exit taxiways	Blue lights that replace the white runway edge lights to signify the end of the runway	
Stopway	Red unidirectional edge lights that can be used in varying intervals at the end of the runway	
Centerline Runway	White lights until 900 meters from the end of the runway, alternating white and red lights until 300 meters, and just red lights until the end	-Punta Cana International Airport[4]
Touchdown zone	Used in times of low visibility to direct planes to the touchdown areas	-Dallas/Fort Worth International Airport[4]
Taxiway	Used to direct flight crew to follow their assigned route on the taxiway	-Dallas/Fort Worth International Airport[4] -Punta Cana International Airport[4]
Taxiway edge	Define the edge of the taxiway	-Tulsa International Airport[3]

[1] (The Engineering ToolBox, 2011), [2] (RDU International Airport goes green, 2009), [3] (LED lighting on runways to save Tulsa airpot money, 2011), [4] (ADB)

11. Conclusion

E-Cubed Consulting conducted an analysis of energy efficiency opportunities in the non-terminal areas of DIA through the Federal Aviation Administration Design Competition to determine the most feasible energy efficient option for DIA and other airports across the country. The primary alternatives evaluated were in-ground snow melters, geothermal runway heating, and LED center lighting (with or without heaters) for the runways. Based on a preliminary financial, technical, and environmental impact analysis for each design solution, using LEDs without heaters is the most economically viable option. Not only can the implementation of LED lights into runways save the airport money, but it is also great for the environment for cutting down greenhouse gas emissions. Consideration and implementation of this design will not only lead to a more efficient airport, but a more efficient way of life for all of those that are involved.

12. Appendix A

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13. Appendix B

The University of Colorado at Boulder (CU-Boulder) was founded in 1876, and doors officially opened on September 5th, 1877. Being the flagship university in Colorado, CU-Boulder is known for being a public research university, producing the highest quality scholars, athletes and citizens. There have been 18 astronauts, ten Nobel Laureates, and eight MacArthur Fellows associated with CU-Boulder (Wikipedia, 2012). A proud tradition of academic excellence is always at the forefront of this university – being one of only 34 U.S. public institutions to belong to the prestigious Association of American Universities (University of Colorado Boulder, 2012). Attracting students to fields of engineering, science, business, law, arts, humanities, education, and many more disciplines, this university has a strong program for almost any scholar.

The College of Engineering and Applied Science at the University of Colorado at Boulder was founded in 1893 and has been reaching higher excellence every year since (University of Colorado Boulder, 2012). Being one of the top-ranked undergraduate and graduate engineering programs in the country, CU-Boulder offers a wide range of high quality engineering degrees. Departments include Aerospace, Chemical, Biological, Civil, Environmental, Architectural, Computer Science, Electrical, Computer, Energy, and Mechanical Engineering; all with an ABET accredited curriculum. The undergraduate Environmental Engineering program (EVEN) was ranked 18th in public universities specially programs in U.S. News and World Report's 2010 America's Best Colleges Issue (Wikipedia, 2012). A wide range of disciplines can be found within the EVEN program including emphases on energy, air pollution control, remediation, and more.

The E-Cubed Team is proud to be a part of such a prestigious and noble community the University of Colorado at Boulder produces. More about the university can be found on the university's website at, www.colorado.edu.

14. Appendix C

Denver International Airport (DIA) is E-Cubed's primary airport partner for the FAA design competition. It opened on February 28, 1995 twenty three miles northeast of downtown Denver, Colorado and covers 53 square miles. DIA has six runways; five of which are 12,000 feet long and one that is 16,000 feet long. The current facilities at DIA can accommodate 50 million passengers a year (Denver International Airport). In 2011, DIA was the eleventh busiest airport in the world in terms of passenger traffic, and the fifth busiest airport in the world by aircraft movements in 2010.

Figure 23: Denver Int'l Airport (Jaskol, 2009)

Woods Allee, Ed Keegan and Heather McKee are current employees at DIA. They have provided E-Cubed with detailed information about current systems at the airport, as well as assisting in identifying areas in need of improvement. Mr. Keegan and Ms. McKee have taken E-Cubed on a tour of the airfield to give the team a first-hand look at systems operation. E-Cubed first met with the three contacts at DIA on February 10, 2012. The team then took a tour of the airfield on March 5, 2012 to look at lighting and other areas.

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16. Appendix E

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

This competition provided our student team many beneficial learning experiences. We all developed a very in-depth understanding of the technical details that surround United States airports. We also gained significant insight into the production of a professional, full-scale design proposal and feasibility study. This competition allowed our team to focus on our problem solving and consulting skills both of which are difficult to get in a classroom alone. From proper document formatting to official client (DIA) meetings and on-site experience, this design competition has allowed our team to develop real-world, professional engineering and business skills we will be able to take to our next endeavors.

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

One of the major obstacles in undertaking this competition was generating, as a team, unique design solutions, which had not been attempted by previous teams. We reviewed past competition submissions and wanted to pursue new design solutions to new and old problems. Knowing what had been attempted before, our team heavily brainstormed novel, innovative ideas for US airports. Our team also had difficulty orchestrating meetings with and gathering information from our local airport, DIA. We overcame this problem early on by designating a team liaison and a DIA contact that we could reach easily. Another challenge that we encountered during the design competition is that our key contact at DIA passed away. We overcame this by developing other contacts that we could rely on as resources.

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

Our team came to our final hypothesis by first analyzing the energy use at DIA and what areas could be improved upon. We also factored in what possible improvements could be implemented at other airports in the US aside from DIA. Next, we consulted with DIA to refine the options that we had come up with and compared them with the options that DIA was considering in the near future. A thorough literature review was conducted on the three areas of interest and through process of elimination we determined the most feasible option based on economics, technical feasibility, social acceptance, and environmental impact. DIA specified to our team that having a reasonable payback period was the most important factor in determining the most feasible energy efficiency improvement, which is why our team ended up choosing runways with LED lighting without heaters.

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

The industry experts were very helpful in providing information that was difficult to acquire. They provided insight that comes with experience that could not be obtained by undergraduate students. We contacted many experts provided by the FAA Design Competition in all fields that we researched and the responses were quick, accurate and detailed. Outside of the provided expert list by the FAA, John McCartney, a professor at the University of Colorado at Boulder, offered his expertise in relation to ground source heat pumps. His guidance prevented our team from going down the wrong path and recommended the most feasible design given our constraints.

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?

Our team learned countless engineering, social, political, economical and logistical lessons during this project. Our research skills drastically improved as we each delved into new information databases and found abundant literature on many of the topics. In addition, our team had the chance to meet formally with DIA contacts and conduct business meetings (some of us had never been to one) and informal tours of the airfield. Industry experts at the University of Colorado at Boulder also aided in guiding us with several of our potential solutions. Our overall problem solving approach developed drastically as we learned we need to step back and look at the large picture as well as the individual consequences of our solutions. Performing a detailed feasibility study with economic, social, technical and environmental factors offered our team the opportunity to perform real-world calculations and analyses. Many of the mentioned lessons will benefit each team member in the workforce or graduate school, as essentially all of these skills are necessary to be successful in the industry.

For faculty members:

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

The open-ended nature of the design competition allowed the students to explore a diverse array of potential energy-related issues for airports. 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 context of energy and greenhouse gas impacts from airports was a useful perspective on energy issues.

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 are 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. In addition, it turned out that the selected option that was most appropriate for DIA had less rigorous design components than typical course projects.

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 they had completed at the very beginning of the semester ended up as not being used in the overall project and was not useful to DIA. The students also faced challenges getting detailed information from vendors and industry folks. In particular, it was difficult to find lab or field studies than would support or refute the need for lens heaters for the in-pavement LED runway lights. The DIA contact indicated that the industry disagreed on this question, but it was difficult to find data to support either side of the argument.

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 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.

17.Appendix F

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