DOT/FAA/TC-23/38

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Geothermal System for Airport Pavement Snowmelt and Terminal Cooling

April 2023

Final Report

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

1. Report No. DOT/FAA/TC-23/38	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle GEOTHERMAL SYSTEM FOR AIRPORT PAVEMENT SNOWMELT AND TERMINAL COOLING		5. Report Date April 2023
7. Author(s) William Ziegler and Chad Nixon		8. Performing Organization Report No.
9. Performing Organization Name and Address William Ziegler Executive Director–Binghamton University Scholars Program Associate Professor–T.J. Watson College of Engineering and Applied Science Office of the President Binghamton University–State University of New York Binghamton, NY 13902-6000 Ziegler@binghamton.edu Chad Nixon President McFarland Johnson, Inc. Adjunct Professor–Binghamton University 49 Court Street, P.O. Box 1980 Binghamton, NY 13902 Office: 607-723-9421 cnixon@mjinc.com		10. Work Unit No. (TRAIS) 11. Contract or Grant No. FAA 16-G-013 and addendums FAA 10-G-009 FAA 16-G-017 and addendums
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Airport Engineering Division 800 Independence Ave., SW Washington, DC 20591		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code AAS-110

15. Supplementary Notes

The Federal Aviation Administration Airport Technology Research and Development Contracting Officer Representative (COR) was Jeffrey Gagnon.

16. Abstract

In 2008, a team of undergraduate students from Binghamton University-State University of New York entered the 2008–2009 Federal Aviation Administration (FAA) Design Competition for Universities and were awarded first place in the competition for their proposal, *Geothermal Snowmelt System for Airport Pavements*. The design was so well-received that the FAA, and later the New York State Energy Research and Development Authority (NYSERDA), funded nearly $2 million to construct and study a prototype of the system at the Greater Binghamton Airport (New York). The prototype consists of a geothermal pavement radiant heating system coupled with a terminal cooling system to study the viability of keeping runways and other airport pavements free of ice and snow and to increase efficiencies of terminal building cooling. The research consisted of taking and analyzing measurements 24 hours per day in 15-minute intervals using 40 sensors built throughout the system to measure temperatures of heated pavement surfaces, geothermal well field temperatures, mechanical equipment operations, unheated pavement surfaces (for reference), shallow- and deep-ground temperatures, feeder- and return-line temperatures, in/out flow rates, modes of operation, electricity usage, and more to determine snow and ice melting ability, cooling ability, energy costs, maintenance costs, and cost/benefit. Visual observations and a thorough data analysis show the system operated successfully during even the harshest of conditions. As the system was studied, modifications were made for maximum efficiencies and documented to assist in system design for future installations at other airports, including increased system reliability and actual cost/benefit.

17. Key Words Geothermal, snowmelt, cooling, pavement		18. Distribution Statement This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 60	22. Price

ACKNOWLEDGEMENTS

Federal Aviation Administration (FAA)
Jeffrey Gagnon
Federal Aviation Administration (FAA)
William J. Hughes Technical Center Airport Pavement R&D Section
ANG-E262
Atlantic City International Airport, NJ 08405

Binghamton University
William Ziegler
Executive Director–Binghamton University Scholars Program
Associate Professor–T.J. Watson College of Engineering and Applied Science
Office of the President
Binghamton University-State University of New York
Binghamton, NY 13902-6000
Ziegler@binghamton.edu

McFarland Johnson, Inc.
Chad Nixon
President McFarland Johnson
Adjunct Professor–Binghamton University
49 Court Street, P.O.
Box 1980
Binghamton, NY 13902
Office: 607-723-9421
Fax: 607-723-4979
cnixon@mjinc.com

Greater Binghamton Airport
Mark Heefner
Commissioner of Aviation
Greater Binghamton Airport
mheefner@co.broome.ny.us

TABLE OF CONTENTS

Page

EXECUTIVE SUMMARY ix

1. INTRODUCTION 1

2. OPERATING PARAMETERS 1

3. CONSTRUCTION DETAILS 1

4. GEOTHERMAL SYSTEM ANALYSIS 5

5. COST/BENEFIT FINANCIAL ANALYSIS 8

6. CONCLUSIONS 8

    6.1 Scalability 9

        6.1.1 Design Factors 9

        6.1.2 Design Factors for BGM as Per the Original Design Report, Prepared in November 2011 9

        6.1.3 Design Factors for Comparison of a Similar Installation at a Similarly Sized Airport Facility 10

        6.1.4 Scalability Comparison 10

        6.1.5 Scalability Conclusions 10

    6.2 System Performance 11
    6.3 Electrical Billing 12
    6.4 Electrical Reliability 13
    6.5 Isolated Geothermal System 13
    6.6 Snowmelt Sensor Location 13
    6.7 Snow Slab Tubing Manifold Location 14
    6.8 Snow Slab Controller Location 14
    6.9 System Downtime 14
    6.10 Anticipated Serviceable Life of the System 14

7. REFERENCES 15

APPENDICES

A—Greater Binghamton Airport Geothermal Heated Pavement System: Benefit-Cost Analysis
B—System Utility Usage Per Mode
C—PEGASAS Analysis (Cost/Benefit Model)
D—Photographs of the Snowmelt System in Real Time
E—System Complexity
F—Temperature Plots

LIST OF FIGURES

Figure		Page
1	Control Center Exterior	2
2	Control Center Interior	2
3	Geothermal Tubing	3
4	Pavement Cross Section	3
5	Geothermal Well Drilling	4
6	Heat Exchange Control Facility	4
7	Horizontal Geothermal Trenches and Well Field Control Vault	5
8	System Functioning as Intended—Note Snowmelt Area	11
9	Walkway—Ice and Snow Free	12
10	Walkway and Apron Pavement in Test Area—Ice and Snow Free	12

LIST OF TABLES

Table		Page
1	System Sensors	6
2	Energy Usage	8

LIST OF ACRONYMS

BCA	Benefit-cost analysis
BCR	Benefit/cost ratio
BGM	Greater Binghamton Airport
BLS	U.S. Bureau of Labor Statistics
BOMA	Building Owners and Managers Association
BTS	U.S. Department of Transportation, Bureau of Transportation Statistics
BTU	British thermal units
BTU/hr	British thermal units per hour
COE	Center of Excellence
FAA	Federal Aviation Administration
GPM	Gallons per minute
HPS	Heated Pavement System
kWh	Kilowatt hours
MJ	McFarland Johnson, Inc.
NPV	Net present value
NYSEG	New York State Electric and Gas
NYSERDA	New York State Energy Research and Development Authority
PEGASAS	Partnership to Enhance General Aviation Safety, Accessibility, and Sustainability
SRE	Snow removal equipment
VOT	Value of time
VSL	Value of statistical life

EXECUTIVE SUMMARY

In 2008, a team of Binghamton University-State University of New York undergraduate students in the Thomas J. Watson College of Engineering and Applied Science, under the guidance of Professor William Ziegler entered the 2008–2009 Federal Aviation Administration (FAA) Design Competition for Universities and were awarded first place in the competition for their proposal, *Geothermal Snowmelt System for Airport Pavements*. Subsequently, the FAA, and later the New York State Energy Research and Development Authority (NYSERDA), funded nearly $2 million to construct and study a prototype of the system at the Greater Binghamton Airport located in Binghamton, NY.

The prototype consists of a geothermal pavement radiant heating system coupled with a terminal cooling system to study the viability of keeping runways and other airport pavements free of ice and snow and to increase efficiencies of terminal building cooling.

The snowmelt system harnesses underground heat/energy using geothermal heat-pump technology, which subsequently heats glycol that is pumped through tubing embedded under a portion of concrete pavement to keep water from freezing on its surface. The snowmelt system automatically starts when a pavement sensor detects any type of moisture, and the outdoor temperature falls below 40 °F. Heated pavements in this prototype consist of 3,200 ft^2 of apron pavement and 225 ft^2 of a pedestrian walkway. The well fields, which consist of 20 closed geothermal vertical wells, each 500 feet deep, and four closed geothermal horizontal wells each measuring 150 feet long and 5 feet deep are located several hundred feet away from the heated pavements. Note that closed wells consist of internal tubing carrying a closed system of glycol as opposed to the more common open wells used to extract water in a typical household water system.

During the spring, summer, and fall seasons, the heat pump system is reversed, the pavement heating system is closed, and the cooler temperatures from the geothermal system are used to assist with cooling the terminal building.

Research was conducted to measure the effectiveness of the geothermal terminal cooling and snowmelt system, which consisted of taking and analyzing measurements 24 hours per day in 15-minute intervals using 40 sensors built throughout the system. Measurements included temperatures of heated pavement surfaces, geothermal well field temperatures, mechanical equipment operations, unheated pavement surfaces (for reference), shallow- and deep-ground temperatures, feeder- and return-line temperatures, in/out flow rates, modes of operation, and electricity usage to determine snow and ice melting ability, cooling ability, energy costs, maintenance costs, and cost/benefit. Visual observations and a thorough data analysis show the system operated successfully during all conditions. As the system was studied, modifications were made for maximum efficiencies and documented to assist in system design for future installations at other airports, increased system reliability, and true cost/benefit.

1. INTRODUCTION

This project began as a construction and research project to create a prototype system that would warm airport pavements during snow and ice storms to melt freezing precipitation immediately upon surface contact. As the project progressed, terminal cooling was added as a feature of the system since the primary infrastructure of the system was applicable to both a heating and cooling scenario.

A major hurdle of implementing a snowmelt system is the cost to generate the heat needed to warm the pavement. While the outdoor temperature might be hovering at -20 degrees Fahrenheit (°F), just a few feet below the surface, the ground temperature is typically a constant 50 °F to 55 °F year-round. This underground energy can be harnessed using geothermal heat-pump technology. The FAA funded a proposal to design and construct, at the Greater Binghamton Airport (BGM) located in Binghamton, New York, a prototype geothermal pavement radiant heating system to determine the viability of keeping runways and other airport pavements free of ice and snow. Underground heat/energy is harnessed using geothermal heat-pump technology, which subsequently heats glycol that is pumped through tubing embedded under a portion of concrete pavement to keep precipitation from freezing on its surface. Details of the system including many photographs of the construction are available at http://cs.binghamton.edu/~ziegler/GeothermWeb/.

2. OPERATING PARAMETERS

The snowmelt system automatically starts when a pavement sensor detects any type of moisture, and the outdoor temperature falls below 40 °F. Heated pavements in this prototype consist of 3,200 ft^2 of apron pavement and 225 ft^2 of a pedestrian walkway. The well fields, which consist of 20 closed geothermal vertical wells, each 500 feet deep, and four closed geothermal horizontal wells, each measuring 150 feet long and 5 feet deep, are located several hundred feet away from the heated pavements.

Due to additional grants from the Federal Aviation Administration (FAA) and the New York State Energy Research and Development Authority (NYSERDA), the geothermal system was modified to harness its cooling effects to assist in cooling the terminal building in the spring, summer, and fall. Glycol cooled by geothermal energy, coupled with reversed heat pumps, assists in cooling the terminal building.

3. CONSTRUCTION DETAILS

Construction began in May 2011 and consisted of 3,200 ft^2 of pavement radiant heating and associated controls. An additional 225 ft^2 of radiant-heated pedestrian walkway was also installed. Loops of tubing emit from (and end at) an underground control center (Figures 1 and 2). The system infrastructure was designed to be as unobtrusive as possible so that the system does not impede daily airport operations. The tubing is strategically placed to provide optimal heating of the pavement. The tubing loops span across (underneath) an area of the apron heavily used for arrivals and departures, fueling, luggage handling, jet-bridge maneuvering, and pedestrian traffic. Once installed, the tubing is covered in concrete (Figure 3) and once finished appears just as any unheated portion of the pavement. As shown in Figure 4, the installation consists of six layers of material: stabilization fabric (bottom layer), 10 inches of subbase coarse aggregate, 6 inches of crushed aggregate, 4 inches of bituminous binder course, 2 inches of extruded polystyrene insulation, and 11 inches of concrete pavement (top layer) with steel dowels and geothermal tubing embedded 5.5 inches from the top sitting on metal support chairs.

Figure 1. Control Center Exterior

Figure 2. Control Center Interior

Figure 3. Geothermal Tubing

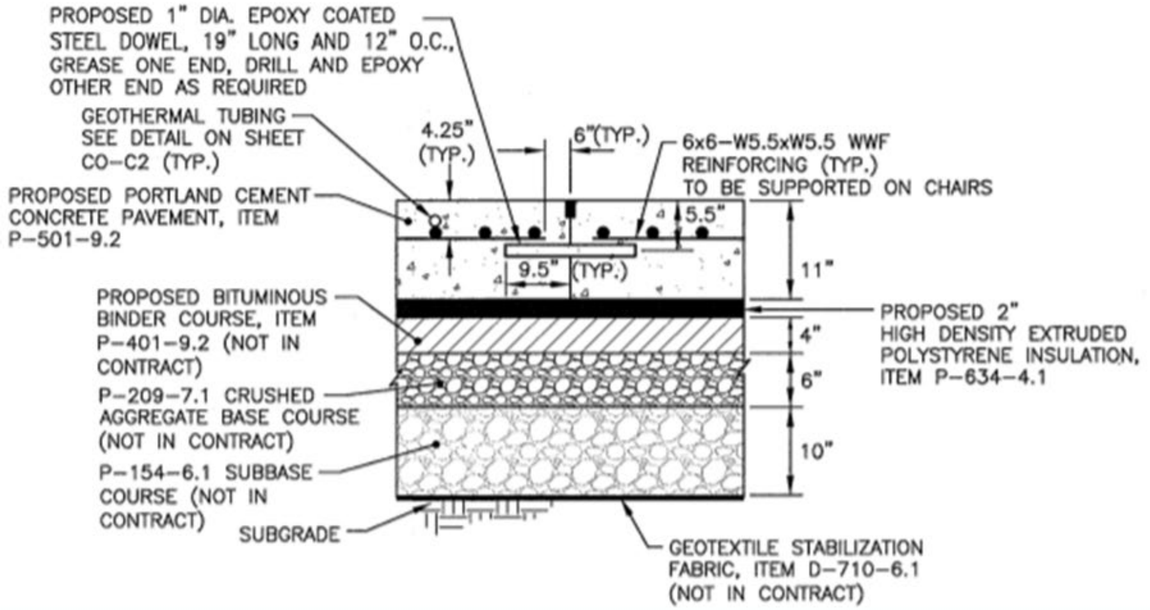

Figure 4. Pavement Cross Section

In December 2013, a building to house the Heat Exchange Control Facility was constructed. In this facility, the heat generated by the geothermal system is utilized to heat the glycol running through the pavement radiant heating system. Before starting the next phase of construction, the geothermal well fields, the FAA asked that preliminary tests be performed on the radiant heating system. Subsequently, a preliminary test of just the radiant heating portion of the system was conducted near the end of the 2011–2012 winter and proved successful in all aspects of the system. At that time, since the geothermal field had not yet been installed, heat to the system was provided by a temporary gas boiler. In April 2014, a groundbreaking ceremony was held for the second phase of the project, the geothermal portion of the system. In August 2014, the Well Field Control

Vault, which controls the geothermal portion of the system, was installed underground in the lawn near the geothermal well field. Drilling rigs drilled 20 500-foot-deep vertical geothermal wells (Figure 5). Four 150-foot horizontal geothermal trenches, 5 feet deep, were also dug (Figure 6). Underground connectors from the well fields were brought to the surface near the Heat Exchange Control Facility (Figure 7) and routed to both the radiant heating system and inside the terminal to assist with terminal building cooling during spring, summer, and fall. Once the system was stabilized, system operations and optimizations were studied (and corrected) to provide direction for possible future similar installations at other airports. Note that further information regarding system complexity is available in Appendix E—System Complexity.

Figure 5. Geothermal Well Drilling

Figure 6. Heat Exchange Control Facility

Figure 7. Horizontal Geothermal Trenches and Well Field Control Vault

4. GEOTHERMAL SYSTEM ANALYSIS

During the start-up and analysis period of this project, the following were the primary system situations that required attention.

A. System Analysis—Data specific

a. Data were collected from 37 sensors (Table 1), most of which record information every 15 minutes, 24 hours per day, 7 days per week, 365 days per year, for a total of approximately 1,296,480 data points per year. The sensors provide temperature readings, valve status readings (open/closed), and pump status readings (on/off).

b. Approximately every 2 weeks, the data collected by the system were categorized, labeled, and archived on a shared drive available to the FAA and the public.

c. Collected data were analyzed regularly to determine correct system operation, and possible system optimizations.

d. Plots of the data collected over a 1-year period are shown in Appendix F—Temperature Plots.

Table 1. System Sensors

Temperature Sensors (TS)	
	OUTDOOR TEMP—(located on walkway wall—Controls Pump 2 (P2) only). This is not a TS sensor.
TS-1	SNOWMELT CONTROL TEMP (outside temp—located on building—NOT located on walkway.) Controls Pump 1 (P1) and Pump 3 (P3) only
TS-2	SLAB TEMP (heated slab temp; 2″ deep, 6′ in from edge)
TS-3	GROUND TEMP (under heated slab; 6″ below insulation)
TS-4	UNHEATED SLAB TEMP (8′ away from heated slab, 2″ deep)
TS-5	GROUND UNDER UN-HEATED SLAB TEMP (6″ below pavement bottom)
TS-6	(not used)
TS-7	(not used)
TS-8	REFERENCE GROUND TEMP SHALLOW (1′) (well field)
TS-9	REFERENCE GROUND TEMP DEEP (4′) (well field)
TS-10	HORIZONTAL FIELD TEMP SHALLOW (1′)
TS-11	HORIZONTAL FIELD TEMP DEEP (4′)
TS-12	VERTICAL FIELD TEMP SHALLOW (1′)
TS-13	VERTICAL FIELD TEMP DEEP (4′)
TS-14	SNOW MELT RETURN TEMP
TS-15	SNOW MELT SUPPLY TEMP
TS-16	TERMINAL COOLING RETURN TEMP
TS-17	TERMINAL COOLING SUPPLY TEMP
TS-18	MECH. BLDG SPACE TEMP (controls Pump 4 [P4]—bldg heater—when bldg temp <45 °F)
TS-19	BUFFER TANK WATER TEMP
TS-20	RETURN WATER TEMP FROM UNIT HEATER
TS-21	TANK WATER SUPPLY TO CHILLERS TEMP
TS-22	TANK WATER RETURN FROM CHILLERS TEMP
TS-23	CHILLERS SUPPLY TEMP TO WELLS
TS-24	CHILLERS RETURN TEMP FROM WELLS
TS-25	TERMINAL CHILLED WATER RETURN TO (heat exchanger) HX-1 TEMP
TS-26	TERMINAL CHILLED WATER RETURN AFTER (heat exch.) HX-1 TEMP
TS-27	HORIZONTAL FIELD RETURN WATER TEMP
TS-28	VERTICAL FIELD RETURN WATER TEMP
Control Valves (CV)	
CV-1	SIDEWALK SNOWMELT VALVE OPEN/CLOSE (buffer/sidewalk loop)
CV-2	SNOWMELT SUPPLY VALVE (buffer/snowmelt loop)
CV-3	TERMINAL COOLING SUPPLY VALVE (buffer/terminal chiller loop)
CV-4	TERMINAL SUPPLY VALVE (heat exchanger/terminal chiller loop)
Pumps (P)	
P-1 a/b	CHILLER/BUFFER LOOP PUMP *STATUS*
P-2 a/b	BUFFER/SIDEWALK, SNOWMELT, TERMINAL LOOP PUMP *STATUS*
P-3 a/b	CHILLER/WELLFIELD LOOP PUMP *STATUS*
P-4 a/b	MECHANICAL BUILDING HEATER PUMP *STATUS* (buffer to heater loop)

B. Upgrades

a. Electrical submeters were installed on electric service to the Mechanical Building housing the geothermal equipment. Submeters were used to determine energy use in real time related to heating, cooling, idle, and off modes. Previous to the submeter installation, the energy usage was only obtained by the primary service meter, read once per month.

b. Electrical submeters were installed on multiple components within the existing terminal cooling system to track when the chiller system was in operation, compared to the geothermal system.

C. Maintenance/Operation

a. The snowmelt sensor in the apron slab was faulty. The sensor was relocated to a position adjacent to the mechanical building. The snowmelt sensor failed in a manner that had not been previously experienced by the manufacturer. The controller failed in the "ON" position, rather than the "OFF" position. This resulted in the system remaining in "snowmelt mode" for weeks.

b. The snowmelt controller software was outdated. A new controller was installed. Replacement was pursued rather than modifying a 6-year-old unit that had already been relocated once.

c. The temperature controls contractor added an automated alarm to alert project and airport personnel when the system has been operating in "snowmelt mode" for 8 hours or longer.

d. It was discovered that manual overrides had been applied to settings controlling the supplemental terminal cooling operations. Rather than being the first source of cooling within the terminal, the geothermal cooling is energized when the chiller system cannot maintain return water temperature. As part of the original installation, the system was commissioned in 2015 with the sequence operations working as designed.

D. Optimization

a. During an August 2018 meeting with BGM Airport personnel, and the controls contractor, it was discovered that the cooling side of the geothermal system was no longer operating correctly. McFarland Johnson, Inc. (MJ) then worked with the controls contractor to return the system to its intended operational status to gain the cooling-side savings anticipated during September and October 2018. It was discovered that valves had been manipulated by hand and locked into the closed position, preventing the cooling function to operate as intended. The valves were reset into the automated position, allowing the system to return to proper function.

b. With MJ's help, the airport is investigating options to incorporate the geothermal system into additional heating and cooling functions within the terminal building. Due to the age of the existing cooling tower and chiller system (currently 19 years old), any potential modifications will be incorporated into a comprehensive heating and cooling system modification project.

5. COST/BENEFIT FINANCIAL ANALYSIS

Three distinct analyses were conducted on the system's cost vs benefit.

1. MJ conducted an analysis of BGM's annual operating expenses for clearing pavements during snowfall events and showed that there is much benefit to be gained in terms of cost savings. Findings from the Net Present Value (NPV) analysis indicate that with all benefits included, those to the airport, airlines, and passengers, benefits of the geothermal pavement heating system at BGM outweigh costs. The full analysis is available in Appendix A—Greater Binghamton Airport Geothermal Heated Pavement System (HPS): Benefit-Cost Analysis.

2. Binghamton University performed a study that consisted of data collection and analysis over an approximately 1-year period totaling around 8,236 clock-hours, to determine the energy usage in terms of clock-hours and kilowatt-hours (kWh) as shown in Table 1.

Table 2. Energy Usage

Energy Usage in Clock-hours and kWh for Approximately 1 Year		
Mode	Time in Mode (%)	kWh Usage (%)
Heating	19.60	42.30
Cooling	5.40	38.50
Idle	88.30	12.10
Tank Cooling*	0.12	0.35
Tank Heating*	1.20	6.77

*Note that there are times when Tank Cooling occurs simultaneously with Cooling Mode and times when Tank Heating occurs simultaneously with Heating Mode. In 11 of these situations, the time and kWh were recorded in Cooling or Heating Modes since those modes consume more energy than Tank Heating or Tank Cooling. Total usage for the year in this particular study was approximately 57,000 kWh in an 8,236-hour period (about 1 year). The full analysis is available in Appendix B—System Utility Usage Per Mode.

3. An additional analysis was conducted by Binghamton University using the software , Partnership to Enhance General Aviation Safety, Accessibility, and Sustainability (PEGASAS) Cost/Benefit Model, provided by the FAA. On January 17, 2017, the PEGASAS spreadsheet, populated with information directly related to BGM, was emailed to the FAA. The FAA then requested a review of the PEGASAS tool to consider the potential for broad use by airports. This review found the PEGASAS tool to be comprehensive in several areas but also recommended changes to improve accuracy. An analysis of the PEGASAS software is available in Appendix C— PEGASAS Analysis (Cost/Benefit Model).

6. CONCLUSIONS

During the period of this grant, the following represent "lessons learned" for moving forward with possible similar installations at other airports.

6.1 SCALABILITY

The scalability of the Greater Binghamtom Airport (BGM) system was considered for its applicability for use on future installations. System design is dependent on a variety of factors, which include the following:

6.1.1 Design Factors (in General)

1. Design outside air temperature (From ASHRAE Handbook of Fundamentals, 2022)
2. Design wind speed (From ASCE 7-05, 2006)
3. Maximum snowfall (determined by coordination with National Weather Service Data)
4. Thickness of the slab (determines the mass that needs to be heated)
5. Soil conductivity of the well field and the soil's ability to conduct heat
6. Thermal diffusivity of the well field and the soil's rate of heat transfer. Diffusivity is calculated by dividing the soil conductivity by the product of the density and specific heat of the soil at a constant pressure.
    i. Density and specific heat are factors of the soil composition.
    ii. Soils are rarely homogeneous and weighted averages of the soil's compositions are used to determine density and specific heat.
    iii. Soil characteristics can vary across a site. The larger the well field, the greater the possibility of geological variations.
7. Depth of wells
8. Separation of wells

6.1.2 Design Factors for BGM as Per the Original Design Report, Prepared in November 2011

1. Design load of the slab was 556,700 British thermal units (BTU)/hr (45.5 tons).

2. Each chiller can flow 80 gallons per minute (GPM) (160 GPM combined) resulting in 53.3 tons of heating/cooling capacity.

3. Each well was anticipated to produce 48,000 BTU/hr (4.0 tons) of cooling or heating. This determination was based on the equipment manufacturer's design materials and experience of other installations performed in Broome County, which is where the BGM Airport is located. No thermal conductivity test was performed. With a 500-foot well, 0.8 tons of heating or cooling was anticipated per 100 feet of well depth.

4. Each chiller can produce 1 ton of heating/cooling for every 3 GPM of fluid flow.

5. Result—12 GPM/loop, 13.3 loops required.

6. Fifteen wells were included in the base design to account for a factor of safety. Wells were spaced 20 feet apart.

7. An additional five vertical wells were added in case of a failure of a single five-well loop.

8. Four 140-foot-long horizontal loops were also installed to determine the heat absorption/rejection in shallow wells and the resulting impact on soil temperatures.
9. Therefore, not including the horizontal wells, the vertical well field could produce 80 tons of heating or cooling, which is greater than the 53.3-ton design load. This would result in the system operating less often.

6.1.3 Design Factors for Comparison of a Similar Installation at a Similarly Sized Airport Facility

The Elmira Corning Regional Airport used a geothermal system to provide full cooling and supplemental heating to the terminal. Design factors for that system were determined by in situ testing of the soils.

1. A test well was drilled, and tests were conducted to determine the thermal conductivity and diffusivity of the soil.
2. The design result was an 80-well field, with wells spaced at 15-foot intervals (some at 25 feet to avoid an existing electrical conduit) and drilled to a depth of 450 feet.
3. The field resulted in 1,442,000 BTU/hr of cooling and 1,400,000 BTU/hr of heating.

6.1.4 Scalability Comparison

1. Elmira's soil consisted of gravel (0–30 feet), gray clay (30–40 feet), cemented gravel (40–66 feet), gravel with water (66–68 feet), blue shale (68–440 feet), and black shale with methane (440–450 feet).
2. Binghamton's soil consisted of topsoil (0–6 inches), glacial till (6 inches–18 feet), and gray siltstone (18,500 feet). The siltstone is hard rock in comparison to the shale of medium hardness. Specific gravity and density are similar.
3. Elmira Corning Regional Airport created two and a half times the heat of BGM but needed four times the number of wells to generate/transfer that heat.

6.1.5 Scalability Conclusions

1. Because geothermal systems are dependent on a variety of factors, directly correlating the number of wells to the size of the pad is not a suggested method for sizing the well field. Soil characteristics are a critical component to the field design and because soil characteristics can differ greatly from location to location (even within a singular airport), there are risks in designing without proper testing.
2. Rules of thumb may be used for programming and preliminary design, but advanced design should be based on field-collected soil data.

6.2 SYSTEM PERFORMANCE

The system operated as designed and intended. Observations during this particular snow event showed that, while snow on the apron pad was being removed by machinery (as well as being melted), snow on the walking ramp was removed solely by the heating tubes within the slab. Further observations showed the ramp surface accumulated up to 14 inches of snow, the snow turned to slush, then the slush turned to water. Finally, the ramp surface became completely dry, while 32 inches of snow was stacked adjacent to the dry surface. Figures 9, 10, and 11 show photographs of varying snow events. Note that additional photographs regarding system performance are included in Appendix D—Photographs of the Snowmelt System in Real-Time.

Figure 8. System Functioning as Intended—Note Snowmelt Area

Figure 9. Walkway—Ice and Snow Free

Figure 10. Walkway and Apron Pavement in Test Area—Ice and Snow Free

6.3 ELECTRICAL BILLING

The existing terminal did not have a suitable location to house the geothermal equipment. Also, added electric load would have overextended the electrical service of the terminal. Consequently, the geothermal equipment was housed in a remote building with a separate electric service. The billing of demand charges to the new electric service was an unintended consequence of this design aspect. The monthly electric bill is divided between distribution charges and demand charges. The distribution charge is based on the kWh of electricity used, while the demand charge is based on the peak demand, in kilowatts, during the peak activity on the service at any moment in time during the billing period. Because the equipment building is isolated from the terminal, the highest peak demands of the geothermal equipment (e.g., heat pump, circulation pumps) are applied against the monthly charge. If the geothermal equipment was incorporated into the terminal, then the demand load would be diversified with the multitude of equipment in the terminal (e.g., multiple air handlers, pumps, baggage equipment, monitors). While it is conceivable that the demand charge could have increased for the 15 terminals, the reduced usage of the terminal during overnight hours would have corresponded with lower temperatures and activation of the geothermal system.

6.4 ELECTRICAL RELIABILITY

BGM is susceptible to lightning strikes, but the equipment building design did not account for this during the planning stage. After the equipment was damaged in the terminal due to a lightning strike, a protection and surge suppression system was installed on the equipment building to protect the equipment. Subsequent strikes have damaged additional terminal equipment with no impact on the geothermal system.

6.5 ISOLATED GEOTHERMAL SYSTEM

As part of the program's intent, the geothermal system was designed only to heat the apron pad and not to be incorporated into the heating system of the terminal. In a comprehensive geothermal heating and cooling system, the geothermal system would circulate fluid to heat or cool throughout the terminal. The geothermal system could be the sole source of heating and cooling or supplement a boiler/chiller system (as was done in the Elmira Corning project). In a whole-building scenario, the heated pad would be a zone on the heating system. When the apron called for heat, valves would open, and a pump would energize to circulate fluid through the pad. The pad would be pulling heat from the building heating water loop, thereby requiring either the boilers to increase their firing rates or the geothermal heat pumps to modulate on. In this project, the pad is the solitary zone on the geothermal heating system. Consequently, the building energy usage did not reap the efficiency benefits of a geothermal system.

6.6 SNOWMELT SENSOR LOCATION

The snowmelt sensor was originally located within the airport apron pad. The concept was that the sensor needed to be in the area of the snow-melting process to properly regulate the activity. There are multiple issues with this location. Sensor replacement costs $1,500 each time.

a. The sensor requires drainage through a hole in the bottom of the housing. Due to the highly compacted nature of an airfield apron subbase, the housing would not drain properly. Consequently, the device would fail after being exposed to extended periods of moisture. After two devices failed, the sensor was installed in an alternate location adjacent to the equipment building, with a thermistor installed in the pad to track pad temperature only. Moisture (snow) was tracked at the equipment building.

b. Even with the sensor installed within the apron, the slab heating system did not prevent airport operations staff from plowing and brushing the heated apron during snow events. It was not practical to repeatedly raise and lower blades and brushes to avoid the heated area.

6.7 SNOW SLAB TUBING MANIFOLD LOCATION

Due to the staged implementation of the geothermal system, the tubing manifold was installed in an underground vault as part of an apron replacement project. Installing within the vault minimized disruption within the terminal and kept the construction work area isolated to the exterior of the building, but this resulted in the manifold being installed in a harsh environment that is difficult to service. In a system integrated with a building heating and cooling system, the tubing manifold would likely be located in a recessed box on an exterior wall, accessible from the interior of the building.

6.8 SNOW SLAB CONTROLLER LOCATION

Also due to the staged implementation of the geothermal system, the snowmelt controller was installed in an underground vault as part of an apron replacement project. The damp environment posed a risk to the electrical components and also required personnel to enter the vault to modify settings and/or reset the system into operation. The controller was relocated into the equipment building to prevent damage and to increase serviceability. The relocation cost was approximately $5,000. The exact cost was included within invoices covering multiple component issues/repairs.

6.9 SYSTEM DOWNTIME

The system experienced multiple short instances of downtime. This is the inherent danger of any mechanical automated system. Implementation of a mechanically heated pavement system requires vigilant maintenance and monitoring and would not be considered a fail-safe system of slab heating, nor would it eliminate the need for manual clearing (when necessary) by airfield operations personnel.

6.10 ANTICIPATED SERVICEABLE LIFE OF THE SYSTEM

An apron is designed for a 20-year life. Based on information from the Building Owners and Managers Association (Schoen, 2010), the following is a list of relevant system components and their respective anticipated useful lives:

a. Base-mounted pumps: 25 years
b. Scroll chillers (heat pumps): 15 years
c. Motors: 18–25 years
d. Starters: 25 years
e. Valve actuators (electric): 18 years
f. Underground piping: 20 years
g. Power distribution panels: 30 years
h. Switchgear and electrical service: 40 years
i. Circuit breakers: 30 years
j. Wiring (600 volts and fewer): 40 years
k. Lightning protection: 40 years

While some equipment has a longer life, the pumps and chillers are the most crucial components of the system. Per the list above, the 20-year useful life of the apron aligns well with the useful life of the geothermal system.

7. REFERENCES

American Society of Heating, Refrigerating and Air-Conditioning Engineers. (ASHRAE) (2022). *ASHRAE handbook of fundamentals—Refrigeration*. https://www.ashrae.org/technical-resources/ashrae-handbook/ashrae-handbook-online

American Society of Civil Engineers (ASCE). (2006). *Minimum design loads for buildings and other structures* (ASCE/SEI 7-05). https://doi.org/10.1061/9780784408094.fm

Schoen, L. (2010). *Preventative maintenance guidebook: Best practices to maintain efficient and sustainable buildings, Appendix 7: Building systems useful life*, Third Edition, Building Owners and Managers Association. https://icap.sustainability.illinois.edu/files/projectupdate/2289/Project%20Lifespan%20Estimates.pdf

APPENDIX A—GREATER BINGHAMTON AIRPORT GEOTHERMAL HEATED PAVEMENT SYSTEM: BENEFIT-COST ANALYSIS

A benefit-cost analysis (BCA) was performed for the geothermal heated pavement system (HPS) at Greater Binghamton Airport (BGM). The following sections describe components of benefits, costs, data, and assumptions utilized to conduct the analysis.

Components of Cost

The following components of costs for the HPS at BGM included in the analysis is as follows:

- Capital Expense: Costs associated with up-front/initial design, purchase of equipment, and the construction and installation of HPS.
- Annual Operating Expense: Operating expenses for the HPS are comprised of monthly and annual charges for electrical service provided by New York State Electric and Gas (NYSEG) for operation by kilowatt hour.
- Annual Maintenance & Repair Expense: Maintenance and repair expenses are anticipated over time associated with any of the component parts of the HPS, including the concrete slab, heat exchange parts, heat pumps, controls, etc.

As documented, the capital cost associated with the HPS at BGM, including construction, construction administration, and inspection, was $1,145,216. Table A-1 presents usage by kilowatt hour (kWh) for each month for the period January 2016–December 2019. The average annual operating usage for the HPS is about 77,700 kWh and costs $12,550. Note that the values for September 2019 – December 2019 were not available when constructing this table and therefore have been estimated based on previous usage.

Table A-1. Annual Usage and Cost Performance Data by Month, 2016-2019 (McFarland Johnson, 2019a)

	2016		**2017**		**2018**		**2019**		**Average**	
MONTH	**kWh**	**Charge**	**kWh**	**Charge**	**kWh**	**Charge**	**kWh**	**Charge**	**kWh**	**Charge**
Jan	2,023	$626	14,585	$1,593	44,213	$4,712	3,497	$952	16,080	$1,971
Feb	1,109	$587	13,367	$1,504	31,756	$2,529	8,916	$1,393	13,787	$1,503
Mar	935	$755	14,244	$1,476	2,082	$867	3,461	$951	5,181	$1,012
Apr	893	$413	6,662	$1,216	1,254	$741	1,238	$798	2,512	$792
May	642	$314	4,178	$1,083	3,667	$1,013	1,238	$798	2,431	$802
Jun	794	$447	7,280	$962	5,266	$943	1,229	$607	3,642	$740
Jul	881	$396	2,425	$758	4,161	$906	2,296	$732	2,441	$698
Aug	620	$94	3,445	$816	1,796	$735	2,600	$807	2,115	$613
Sep	2,298	$746	8,968	$1,050	4,303	$929	6,636	908	5,551	$908
Oct	4,344	$869	6,759	$1,006	8,107	$1,159	6,403	1,012	6,403	$1,012
Nov	3,210	$772	9,322	$1,372	1,366	$884	4,633	1,009	4,633	$1,009
Dec	10,036	$1,399	25,405	$2,031	3,264	$995	12,902	1,475	12,902	$1,475
Total	**27,785**	**$7,418**	**116,640**	**$14,867**	**111,235**	**$16,412**	**55,048**	**$11,441**		

Operations and maintenance staff at BGM reported minimal costs related to maintenance and/or repair of the HPS at BGM from January 2016–December 2019. Most expenses to date have been related to data collection for FAA monitoring, public information (kiosk). A sample of maintenance costs that might be related to a typical installation are presented in Table A-2.

Table A-2. Sample Maintenance Costs (McFarland Johnson, 2019a)

Description of Maintenance and/or Repair Item	**Amount**
Year 1	
Snowmelt Sensor and Controller Replacement/relocation	$7,100
Lighting Protection for the Building	$6,300
Year 2	
Controls Changes due to Snowmelt Sensor Failure	$3,000
Year 3	
No Maintenance and/or Repair Recorded	$0
Total	**$16,400**
Average Annual	**$5,467**

As shown, a total of about $16,400 in maintenance and repair expenses was incurred over the 3-year period; an average of about $5,500 per year. To account for aging of equipment that might occur the useful life of the system, the benefit-cost analysis incorporates an annual estimate at a rate of one percent of capital cost. This amounts to approximately $11,500, annually.

Components of Benefit

Considering BGM's annual operating expenses for clearing pavements during snowfall events, there is much benefit to be gained in terms of cost savings. Table A-3 shows the components of conventional costs for clearing the area of the HPS at BGM.

Table A-3. Estimate of Conventional Costs (McFarland Johnson, 2019a)

Conventional Cost Components	**Total**
Snow Removal Equipment	
Multi-Function Chassis, Plows, Brooms, Blowers, Loaders, Sprayers, Deicer – Capital	$8,748,560
Annual Equipment Depreciation Expense[1/]	**$675,000**
Annual SRE Maintenance Cost	**$21,821**
Annual SRE Fuel Cost	**$18,000**
Deicing Agents Cost	
Annual Budget Potassium Acetate	$12,600
Annual Budget Sodium Acetate	$6,800
Total	**$19,400**
Labor/Personnel Cost[2/]	
Annual Estimated Labor/Personnel Expense	**$40,800**
Annual Conventional Clearing Costs	**$775,000**

[1/] *Labor/Personnel Estimate is based upon six staff x $20 x 340 hours.*

[2/] *Annual Depreciation Expense estimated using straight line method, assuming a salvage value of $2million over a useful life of 10 years.*

Considering that the HPS system at BGM covers a modest 3,200 square feet of ramp area and one aircraft parking position, it is not likely that the system will have a significant reduction on existing expenses. However, some reduced amount of deicing agent usage and labor time and expense for clearing could be reasonably anticipated.

Weather-related delays are events that cause increased expenses for passengers, airlines, and BGM. An estimate of typical costs associated with annual slips and falls to airport staff at BGM is shown in Table A-4. Please note, data for categorizing injuries at this level of detail is not available from the U.S. Bureau of Labor Statistics (BLS); therefore, some data is used, and certain assumptions have been made.

Table A-4. Estimate of Typical Cost Due to Slip & Fall Injuries
(McFarland Johnson, 2019b)

Input	**Description**	**Factor**	**Fraction of VSL**[3/]
Incident Rate [1/]	Slips/Falls per 10,000 Workers	6.4	
Injury Classification	Minor	60%	0.003 VSL
Injury Classification	Moderate	25%	0.0470 VSL
Injury Classification	Serious	15%	0.1050 VSL
Value of Statistical Life (VSL)[2/]		$9,600,000	
Estimate of Typical Annual Cost			
Number of Cases Annually			0.05
Minor			$829
Moderate			$5,414
Serious			$7,258
Estimated Annual Cost of Slip & Fall Injuries to Airport Staff			**$13,501**

[1/] *U.S. Bureau of Labor Statistics*
[2/] *U.S. Department of Transportation, Office of Transportation Policy*
[3/] *Fraction of injury classification fractional value to VSL is estimated.*

The analysis assumes that slips and fall will not result in critical and unsurvivable injuries and hence are not taken into consideration. Therefore, only three classes of injuries were assumed minor, moderate, and serious, as shown in Table A-4. Other factors affecting the ultimate savings due to a reduction in slip and fall injuries at BGM include:

- Ground Support Staff Employer: The ground staff may be employed by the airport or the airlines, and they are financially responsible for any injuries.
- Incidence Rates: Rates available from BLS do not relate directly to slips and falls due to snowy conditions.
- Limited to Airport Staff: Notably, the cost born by BGM for slips and falls could be higher due to airline staff or passenger incidents.

Other components of benefit are not directly appreciated by the Airport, but over time can have a marked impact on passenger satisfaction with service at BGM include reductions in lost passenger time**.** Table A-5 presents inputs and descriptions of data factors used to estimate the annual value of time lost by passengers due to weather-related delays.

Table A-5. Estimate of Typical Passenger Cost for Weather-Related Delays
(McFarland Johnson, 2019b)

Input	**Description**	**Factor**
Annual Passenger Growth Rate	Current Draft from Existing MPU Process	1.30%
Weather-Related Delays[1/]	Percentage of All Delays	1.33%
Aircraft Load Factor[1/]	All Domestic Carriers - 2018	79.2%
Leisure Passengers[2/]	Leisure Passengers Percentage of Total	35%
Business Passengers[2/]	Business Passengers Percentage of Total	65%
Leisure Passenger Value of Time (VOT)	Leisure Passenger VOT/Hour	$35
Business Passenger Value of Time (VOT)	Business Passenger VOT/Hour	$63
Airline Operations per Day	Current Draft from Existing MPU Process	16
Duration of Delays	Hours	1.64
Number of Enplaned Passengers	Per Aircraft	47.5
Estimate of Typical Annual Passenger Delay Cost		
Operations During Four-Month Winter Period		1,920
Number of Delays During Winter Period		32
Total Delay Hours		42
Estimated Annual Value of Lost Time to Leisure & Business Travelers		**$105,806**

Source: Pegasus Analysis.
[1/] *U.S. Department of Transportation, Bureau of Transportation Statistics*
[2/] *Airport Management*

Lost passenger time is calculated using the recorded percentage of delays that are weather-related from U.S. Department of Transportation, Bureau of Transportation Statistics (BTS). November through February are considered the peak winter months, and delays were calculated for this period. Monthly operations were calculated by multiplying the daily number of operations by 30. That value was multiplied by 4 to get the number of operations during the winter period, and the duration of delays to estimate total hours of lost passenger time.

Another component of benefit not accrued by the airport is a reduction in airline crew time and fuel usage due to weather-related delays. Table A-6 presents data factors used to estimate annual value of time and fuel wasted due to weather-related delays. The estimate utilizes total delay hours calculated for lost passenger time (Table 5) and applies that annual delay time to variable direct operating cost of an aircraft, which were estimated for regional jet aircraft commonly in use at BGM.

Table A-6. Estimate of Typical Airline Crew & Fuel Costs for Weather-Related Delays (McFarland Johnson, 2019b)

Input	Factor
Estimate of Typical Airline Crew and Fuel Delay Cost	
Aircraft In-Flight Operation Cost/Hour	$4,960
Aircraft Ground Operation Cost/Hour	$2,148
Aircraft Terminal Area/Gate Operation Cost/Hour	$1,443
Average Operational Cost/Hour	$2,850
Estimated Annual Value of Airline Crew & Fuel Usage	**$119,364**

Source: Pegasus Analysis

BCA Analysis Findings & Summary

Using the various components of cost and benefits associated with the HPS at BGM described in this section and removing the initial capital expense of the system, a discounted cash flow and net present value (NPV) analyses was conducted. The analyses were used to determine if Benefit-Cost Ratio (BCR) is above or below 1. A BCR above 1 means that the benefits of the HPS outweigh the costs, and a BCR less than 1 means that the project's costs outweigh the benefits. A summary of the discounted cash flow and net present value analysis is presented in Table A-7.

Table A-7. Net Present Value & Benefit-Cost Ratio (McFarland Johnson, 2019b)

Analysis Inputs	Factor	
Period (Years)	20	
Discount Factor	7%	
Capital Cost	$1,145,200	
Benefits	**Year 1**	**Year 20**
Reduced Lost Passenger Time	$105,806	$135,235
Reduced Airline Crew & Fuel Cost	$119,364	$152,564
Reduced Slip & Fall Incidents	$13,501	$13,501
Annual Summation of Benefit	$238,671	$301,301
Present Value of Benefit	$223,057	$77,862
Net Present Value of Benefit		**$2,771,633**
Costs	**Year 1**	**Year 20**
Operations & Maintenance	($24,409)	**($34,050)**
Equivalent Annual Capital Cost	($108,100)	($108,100)
Annual Summation of Cost	($132,510)	($142,151)
Present Value of Cost	($123,841)	($36,734)
Net Present Value of Cost		**($1,440,518)**
Benefit -Cost Ratio		
BCR—Airport, Airlines, and Passengers		**1.92**

As indicated in Table A-7, findings from the NPV analysis indicate that with all benefits included, those to the Airport, Airlines, and Passengers, benefits of the geothermal pavement heating system at Greater Binghamton Airport outweigh costs.

Additional Considerations

Importantly, as described in this section, tangible benefits to the Airport in terms of savings from use of the HPS are difficult to quantify at this time. This is primarily due to the small size of the heated apron area (3,200 square feet), which is not enough to reduce the number, type, or standard operation of snow removal equipment at the Airport. However, the system provides substantial benefits. As more data becomes available, installing such a system could demonstrate benefits not only to the airport, but also to airlines, and subsequently maintenance facilities and personnel.

With respect to airfield operation benefits, the annual cost of snow removal equipment (SRE) and continual maintenance can range from the low thousands to millions of dollars, especially for large airports. In addition to the operational cost of SRE, the activation and utilization of personnel can be high due to the long hours and overtime associated. Most airports will budget for winter operations, and this can be often a 50 percent increase of man-hours. Additionally, some airports will contract out snow removal operations. Regardless, both are opportunities to increase a return on investment with geothermal pavement.

At airports where airlines control snow removal on the airfield due to proximity and legal issues, airlines spend a significant amount of money to contract out those services. If the airport had a geothermal pavement installed, the airlines .could eliminate the need, and thereby the cost, to contract snow removal services. For example, at Kansas City International Airport, American Airlines contracts out snow removal to Commercial Aviation Maintenance (CAM) during winter operations and the per-hour charge can be over $100 an hour during winter operations. The labor hours needed for snow removal could be mitigated through geothermal pavement investment by an airline.

Furthermore, the use of geothermal pavement can mitigate accidents or incidents, such as collisions between aircraft and tractors or SRE. The cost of accidents or incidents have both direct costs (repair) and indirect costs (medical and worker’s compensation) that can easily reach into the millions of dollars.

References—Appendix A

McFarland Johnson, Inc. (2019a). *Airport Meter Usage & Accounting Records*

McFarland Johnson, Inc. (2019b) *PEGASAS Analysis*.

APPENDIX B—SYSTEM UTILITY USAGE PER MODE

To provide a summary overview of utility usage required by the heated pavement system (HPS) during idle, cooling, and snowmelt modes (Table B-1),three samples (out of thousands available) of each mode were analyzed. It was discovered that the amount of snow or ice received during a weather event is not necessarily directly tied to the cost of the system to operate during that event. The duration of the period during which snow/ice fell, rather than the amount of accumulation was a more important factor. For example, if snow flurries are falling for a period of 10 hours, then the system will run constantly for 10 hours. If it snows 2 inches per hour, and 20 inches of snow accumulates, the system will still run about 10 hours. Even though it would be logical to assume the cost to run the system was contingent on snowfall accumulations, that assertion, for the most part, has been proven incorrect.

Tables B-2, B-3, and B-4 show the results of data collection and analysis over an approximate 1-year period (totaling around 8,236 clock-hours) to determine the energy usage in terms of clock-hours and kilowatt-hours (kWh).

Table B-4 shows the year in summary by mode. The system spent a significant amount of time in Idle Mode, followed by Cooling and Snowmelt. In terms of cost (kWh), Snowmelt was slightly more expensive than Cooling, followed by Idle, Tank Heating, and Tank Cooling.

Table B-1. Data Samples of Each Mode

MODE	Start Date	Start Time	kWh Start	End Date	End Time	kWh End	Difference	Hours	kWh/hr
Idle	8/20/18	11:45 AM	47,980.97	8/23/18	7:00 AM	48,029.54	48.57	67.25	0.722
Idle	4/24/18	9:30 AM	32,538.11	4/27/18	3:30 PM	32,601.56	63.45	78	0.813
Idle	5/10/18	9:45 PM	35,275.9	5/14/18	9:00 AM	35,344.13	68.23	83.25	0.819
Cooling	6/27/18	7:30 AM	43,385.84	6/27/18	8:30 AM	43,439.3	53.46	1	53.46
Cooling	4/28/18	8:30 AM	32,681.69	4/28/18	2:00 PM	32,968.14	259.16	5.5	52.08
Cooling	8/23/18	8:30 AM	48,090.84	8/23/18	1:15 PM	48,347.22	256.38	4.75	53.97
Snowmelt	2/1/18	8:45 PM	13,560.63	2/8/18	8:45 AM	23,795.53	10,234.9	156	65.61
Snowmelt	2/11/18	10:30 PM	26,831.9	2/12/18	8:15 AM	27,508.46	676.56	9.75	69.39
Snowmelt	2/10/18	9:15 PM	26,198.43	2/11/18	5:00 AM	26,742.19	543.76	7.75	70.16

SUMMARY: AVERAGE UTILTY USAGE PER MODE:

Idle:	0.785 kWh (per hour)
Snowmelt:	69.387 kWh (per hour)
Cooling:	53.170 kWh (per hour)

Table B-2. Year in Summary by Percentages

Mode (over a 1-year period)	% Time in Mode in Clock-hours	% kWh Usage
Heating	19.6%	42.3%
Cooling	5.4%	38.5%
Idle	88.3%	12.1%
Tank Cooling *	0.12%	0.35%
Tank Heating *	1.2%	6.77%

Total usage for the year in this particular study was approximately 57,000 kWh in an 8,236-hour period (about 1 year).

*Note that there are times when Tank Cooling is occurring simultaneously with Cooling Mode and times when Tank Heating is occurring simultaneously with Heating Mode. In those situations, the time and kWh were recorded in Cooling Mode or Heating Mode since those modes consume much more energy than tank heating or tank cooling.

Table B-3. Results of Data Collection and Analysis Over an Approximate 1-year Period

February 1, 2018–February 21, 2018						Feb 21–Mar 19		June 2, 2018–June 30, 2018						Jun 30–Jul 1
Mode	Snowmelt	Idle	Cooling	Tank H	Tank C	Idle		Mode	Snowmelt	Idle	Cooling	Tank H	Tank C	Idle
Total Hours	259.25	209.75	0.5	0	0.5	620		Total Hours	0	545	114.5	0.5	0.25	27.75
kWh	14,173	336	13	0	19	1,019		kWh	0	559	61.48	0	6	71
March 19, 2018–March 30, 2018						Mar 30–Apr 1		July 1, 2018–July 31, 2018						Jul 31–Aug 1
Mode	Snowmelt	Idle	Cooling	Tank H	Tank C	Idle		Mode	Snowmelt	Idle	Cooling	Tank H	Tank C	Idle
Total Hours	1.25	174.75	0	4	0	34.75		Total Hours	0	669.5	22.5	3.75	0.5	256.75
kWh	87	377	0	151	0	36		kWh	0	641	1,173	76	22	236
April 1, 2018–April 28, 2018						Apr 28–May 1		August 1, 2018–August 31, 2018						Aug 31–Sep 1
Mode	Snowmelt	Idle	Cooling	Tank H	Tank C	Idle		Mode	Snowmelt	Idle	Cooling	Tank H	Tank C	Cooling
Total Hours	3	552	7.75	9	1.5	65.5		Total Hours	0	454.25	28.5	0.5	1.75	26
kWh	160	599	374	300	55	59		kWh	0	400	1,552	7	32	1,549
May 1, 2018–May 20, 2018						May 28–Jun 2		September 1, 2018–September 30, 2018						Sep 30–Oct 1
Mode	Snowmelt	Idle	Cooling	Tank H	Tank C	Idle		Mode	Snowmelt	Idle	Cooling	Tank H	Tank C	Idle
Total Hours	0	392.75	85.65	0.5	0.5	120.25		Total Hours	0	619.25	80	0	2.5	17
kWh	0	595	4,338	4	8	104		kWh	0	504	4,209	0	23	20

October 1, 2018–October 31, 2018						Oct 31–Nov 2		November 1, 2018–November 30, 2018						Nov 30–Dec 1
Mode	Snowmelt	Idle	Cooling	Tank H	Tank C	Idle		Mode	Snowmelt	Idle	Cooling	Tank H	Tank C	Idle
Total Hours	0	548.5	76	2	1.25	38.25		Total Hours	13	641.75	4.5	12	0	16.75
kWh	0	505	4,186	77	13	28		kWh	314*	309*	228	264*	0	13
December 1, 2018–December 31, 2018						Dec 31–Jan1		January 1, 2019–January 31, 2019						Jan 31–Feb 1
Mode	Snowmelt	Idle	Cooling	Tank H	Tank C	Idle		Mode	Snowmelt	Idle	Cooling	Tank H	Tank C	Snowmelt
Total Hours	17.25	682.35	0	18.5	0.5	34.75		Total Hours	111.5	582.5	0	31	0	0.75
kWh	1,024	754	0	709	21	27		kWh	7,240	847	0	1,483	0	30
February 1, 2019–February 28, 2019						Feb 28-								
Mode	Snowmelt	Idle	Cooling	Tank H	Tank C	Idle								
Total Hours	26.5	608	0	26.5	0									
kWh	1,465	762	0	1,067	0									

*The yellow-shaded boxes indicate only those values that were attainable. From November 10–November 24, no energy data could be recorded due to construction. However, it is assumed that the same amount of energy was consumed each day, i.e., (62364-60742)/14= 115.8571 kWh per day. The month of November is excluded from the summary table calculations.

Table B-4. Year in Summary by Mode

	Year in Summary				
Mode	Snowmelt	Idle	Cooling	Tank H	Tank C
Total Hours in Year	419.5	7270.35	441.4	96.25	8.75
kWh/hr	57.5662	0.94617	49.8256	40.2494	22.7429
Total kWh	24162.2	6906.9	21981.7	3869.3	198.6

The summary table excludes data from November 2018.

APPENDIX C—PEGASAS ANALYSIS (COST/BENEFIT MODEL)

Review of Partnership to Enhance General Aviation Safety, Accessibility, and Sustainability (PEGASAS) Cost/Benefit Model (FAA, 2021)—Greater Binghamton Airport (BGM) Geothermal Pavement Heating and Terminal Cooling System

INTRODUCTION

On January 17, 2017, the PEGASAS spreadsheet was emailed to Benjamin Mahaffay (FAA), populated with information directly related to BGM. Tables C-1 through C-9 show the input/output of each spreadsheet. The comments that follow are intended as observations/suggestions to make the PEGASAS tool even more useful.

REVIEW COMMENTARY AND OBSERVATIONS

1. **Useful input that would be of benefit to the PEGASAS template, but is not currently used**

    a. The costs related to the buildings that house snow removal equipment (SRE) are not addressed. If less SRE is needed, then the space to house them is reduced as well, with significant savings.

    b. Associated with the actual buildings to house SRE is the cost of utilities to heat and power the buildings. Again, this does not seem to be addressed and could result in substantial savings.

    c. The cost of utilities to run the geothermal system is not addressed. The geothermal system relies on very large pumps that require a good deal of electricity to keep running. BGM's small system accumulated an electric bill approaching $2,000 per month for December 2016, which will be a significant cost when multiplied out to much larger surfaces.

    d. BGM's geothermal system is reversed in the spring and fall to assist with cooling the terminal building during non-peak periods. While running the system in heating mode during the winter will result in direct costs (and future savings), using the system in cooling mode provides immediate savings and no negative direct costs. Therefore, the true positive cost/benefit is more substantial on the cooling side than the heating side. This is not addressed in the PEGASAS template.

2. **Basic Input Parameters—Comments and Observations**

    a. The common input values section was fairly straightforward and begins with values for the analysis year and discount factor.

    b. The years observed were left at 20 as many of the other calculations relied on data predicted for a 20-year period.

    c. The discount factor was left at 7 percent because the report stated that this is the value used in federally funded airport projects. However, further proof of this number would be beneficial in the future, as now this value is only stated in the report as true without a citation.

d. The area of aprons and area of paved surfaces parameters could be better labeled as "area of aprons," which actually refers to the area of heated pavement. This caused confusion for the BGM system as only a small section of the apron is heated and, therefore, only this smaller heated section was included in this value.

3. Conventional Methods Section—Comments and Observations

a. The first group of parameters asking for the quantity of SRE was easily inputted with assistance from the airport. The price for each piece of equipment was left the same as the template examples. However, the annual maintenance cost was brought into question by officials at the airport. They had listed the maintenance, oil, and grease costs for the SRE, but also gave costs for the building space that houses the SRE, the utilities cost for those buildings, and the maintenance costs for the buildings themselves. This is a much higher cost and should likely be included in the conventional methods cost in some way for future analysis.

b. For the deicing agents listed in the Conventional Methods Cost section, splitting the quantity and the unit price was not very helpful as it was simpler for the airport to just give their annual budget for both types of deicer. It was also not explicitly stated in the spreadsheet or in the user's manual that these were annual costs, but they were taken as such when it was filled out with the BGM data.

c. Regarding the labor section, estimates had to be made as BGM brings in a different number of personnel based on the amount of snow falling and for different amounts of time. Therefore, the quantity and labor hours are estimated, as they are not constant from year to year. If possible, this parameter should accommodate different snow-clearing methods at different airports.

d. Regarding the SRE fuel cost, again it was easier for the airport to simply provide its annual budget rather than on a unit basis. However, it does not appear that fuel cost is included, or that the calculation is incomplete. Using the ratio of ramp/apron area (3,200 ft^2) to total airport paved surfaces (~4.393 million ft^2) to calculate the portion of the total fuel budget ($18,000) to clear the area results in a very minimal level of annual costs ($13.11) associated with SRE fuel.

e. One question to consider is whether the initial capital cost and maintenance of all SRE used at the airport are the correct equipment cost metrics to use. Rather, might a more limited number and specific type of SRE be used to clear the area vs runway plows? Additionally, perhaps those specific types of SRE are used more frequently to clear the area vs other areas of the airport. If these conditions are true, this would result in a higher percentage of use for certain equipment to clear the ramp/apron area being considered.

4. Heated Pavement System (HPS) Indirect Benefit Section—Comments and Observations

a. The percentage of weather-related delays is estimated at 2 percent as stated in (Anand et al., 2017). It states that this was used as a conservative value. However, if you look at the numbers given by the Bureau of Transportation Statistics for on-time arrival performance for 2016, it states that the actual percent of weather-related delays was 0.51 percent (around one-half percent) (U.S. Department of Transportation, 2016). This value increases slightly for airports in more snow-prone areas, although not by much. When the spreadsheet values were entered specific to BGM, the actual 1-year period delay percentage was entered, which was 0.24 percent.

b. For the passenger growth rate, a national value of 2.3 percent was used, as the 2.8 percent value given in the report was outdated (FAA, 2018).

c. The number of seats per aircraft, load factor, duration of delays, and operations per day were provided by BGM airport personnel. In the template, these amounts are listed as fixed values. However, BGM gave different percentages of leisure vs business travelers. It would be more thorough to have these as changeable values as every airport is different.

d. Regarding passenger value of time ($63 for business travelers and $35 for leisure travelers, per hour), the model uses 2014 data, which were not risen over the 20-year period to align with an annual rate of passenger growth that is included. There was an error in the formula that calculated the value of lost passenger time per year. The change affects the net present value calculated in Economic Analysis Tab and changes the end result benefit/cost Ratio from 1.208 to 1.564.

e. For the incidence rate of injuries, the model notes an incidence rate of 20.9 for falls, slips, and trips per 10,000 workers. But then calculates for an incidence rate of one. It was assumed that this was an annual value. However, it was not clear if this value was intended to be for workers only or also for passengers. For a small airport like BGM, some airplanes must be boarded from the apron pavement and, passenger injuries can occur. HPS could prevent these injuries.

f. For the number of full-time workers, questions were also raised as to whether this was meant to be a full-time equivalent or purely full-time employees since about half of BGM's employees are part-time.

5. Heated Pavement System (HPS) Cost Section—Comments and Observations

a. The initial construction cost was found based on the price of the system per square foot. The value for BGM was extremely high as it included the entire geothermal system, not just the pavement heating portion.

b. The maintenance cost was hard to predict as the BGM system has not been functional for long enough to get true values for the annual maintenance budget. Maintenance costs of 1 percent of initial HPS costs may be appropriate; whatever costs are, they should likely be escalated over time in the Economic Analysis Tab to account for the system aging.

6. **Snowmelt Calculations Section—Comments and Observations**

   a. Calculating average snowfall in inches per hour is not a commonly measured value. The NOAA office in Binghamton was contacted and stated that this is not a recorded measurement. It is easy to find the average overall snowfall and the number of snow events but is not feasible on an hourly basis.

   b. Ambient temperature is a vague parameter. Is this the average yearly temperature at the airport or the average winter temperature when the system would be functioning? The documentation does not go into detail about what this value is and could be clearer.

7. **Economic Analysis Section—Comments and Observations:**

   a. The model did not include the initial capital cost of HPS in the net present value calculation of investment, which skews the benefit-cost ratio.

8. **Miscellaneous Comments and Observations:**

   a. The names of parameters on the summary sheet could be made more descriptive or intuitive and it would be of great benefit to add the time period over which they are wanted.

   b. The user's manual also could be improved. A step-by-step guide that defines and details the expectations of each parameter would be extremely helpful in the future when trying to input data from different airports.

   c. As the system installed at BGM is geothermal-powered, much of the cost savings come from using the system during warmer months for cooling the terminal building. There is nowhere in the spreadsheet to account for these types of savings which greatly offset costs and could make a large difference in the economic viability.

   d. Although this tool is for any boiler (or other such heating system)-driven HPS, there is no parameter for the operating costs of these, including electricity, gas, or oil, unless these are meant to be included in maintenance. However, this is not clear from the spreadsheet or from the user manual.

Financial Analysis Utilizing PEGASAS Center of Excellence Software with Data Specific to BGM

As shown in Tables C-1 through C-9, all variables in the PEGASAS Center of Excellence **(**COE) software have been populated with data specific to BGM.

Tables C-1 through C-4 represent **HPS Indirect Costs**:
C-1 and C-2: Reduced Lost Passenger Time
C-3: Reduced Crew Time and Fuel Waste
C-4: Enhanced Safety—Reduced Costs Due to Injuries:

Table C-1. Indirect Costs—Reduced Lost Passenger Time

Affected Shareholder	
Passengers—Taxpayers	
Airlines	
Airlines or Airports	
REDUCED LOST PASSENGER TIME	
Item	
Pasenger Growth Rate (%)	1.90
Weather-related Delays (%)	0.24
Load Factor (%)	76.14
Passengers traveling for leisure (%)	35.00
Passengers traveling for business (%)	65.00
VOT for business (2014 USD values)	63
VOT for leisure (2014 USD values)	35
Operations in a day	45
Duration of delays (hours)	1.64
No. of seats in aircraft	124
No. of occupied seats	94.4136

Table C-2. Indirect Costs—Reduced Lost Passenger Time Continued

Year	Operations in 4-Month Period	Delays in 4-Month Period	Total Delay Hours	Value of Lost Time (P+B)
1	5,400	13	21	106,757
2	5,503	13	22	66,332
3	5,607	13	22	67,593
4	5,714	14	22	68,877
5	5,822	14	23	70,186
6	5,933	14	23	71,519

Year	Operations in 4-Month Period	Delays in 4-Month Period	Total Delay Hours	Value of Lost Time (P+B)
7	6,046	15	24	72,878
8	6,160	15	24	74,263
9	6,278	15	25	75,674
10	6,397	15	25	77,111
11	6,518	16	26	78,577
12	6,642	16	26	80,070
13	6,768	16	27	81,591
14	6,897	17	27	83,141
15	7,028	17	28	84,721
16	7,162	17	28	86,330
17	7,298	18	29	87,971
18	7,436	18	29	89,642
19	7,578	18	30	91,345
20	7,722	19	30	93,081

Explanation of Calculations for Tables C-1 and C-2

The reduced lost passenger time is calculated by first determining the seasonal percentage of delays. A value of 2% of the total number of operations is adopted as the percentage of weather-related delays. November through February are considered peak winter months, and delays were calculated for this time period. By multiplying the daily number of operations by 30, monthly operations were calculated. Then is value was multiplied by 4 to get the number of operations in 4 months. This was calculated as 144,000, 2% of this i.e., 2,880 were the number of delays in 4 months. Each of these delays was assumed to last 1 hour.

The values assigned to passengers traveling for business is $63/h and for passengers traveling on leisure is $35/h. The total percentage of passengers who fly for business purposes is 40.40%, and 59.60% are leisure travelers. The total number of seats in a mid-sized aircraft is about 150. The average overall load factor for domestic flights in the U.S. for 2014 was 83.38%. This translates to 83.38% of 150 seats being occupied which gives a value of 125.07 seats. By multiplying the total number of passengers (each case) by the value of time and the number of delays in four months, the value of lost time can be found. The combined value of lost time for the two categories of travelers was found to be approximately 16.7 million USD annually. As the number of passengers continues to grow every year, a value of 2.8% annual passenger growth rate is considered in the value of time calculation for subsequent years.

Table C-3. Indirect Costs—Reduced Crew Time and Fuel Waste

REDUCED CREW TIME AND FUEL WASTE	
Item:	
Variable aircraft direct operating costs:	
Mid-air ($/h)	4,960
Ground ($/h)	2,148
Gate ($/h)	1,443
Assuming equal no of all 3 delays; combined value	2,850

YEAR	TOTAL COST TO AIRLINES (USD)
1	60,579
2	61,730
3	62,903
4	64,098
5	65,316
6	66,557
7	67,822
8	69,110
9	70,424
10	71,762
11	73,125
12	74,514
13	75,930
14	77,373
15	78,843
16	80,341
17	81,867
18	83,423
19	85,008
20	86,623

Explanation of Calculations for Table C-3

The number of delayed flights was calculated in the same way as lost passenger time. Aircraft can have delays in three possible ways, midair, gate, and ground delays. The mid-air delays will have the most amount of fuel wastage, while the others will draw only idling fuel wastages. According to the Airport Cooperative Research Program (ACRP) Report 123 (McGormley et al., 2015), Mid-air delays are assigned a value of $4,960/h, ground delays as $2,148/h and gate delays as $1,442/h. It is undeniable that each category of delay would contribute in different percentages to the total delays and hence incur different costs. However, for ease in computations, it was assumed that all delays were in equal proportion. This gave an average value of $2,850/h suffered by airlines in weather delays. The annual (four concerned months) cost to airlines due to weather-related delays can then be computed by multiplying this value by the total number of operations in four months. This value comes out to be $8,208,576. The annual growth rate of operations is also accounted for in this case for subsequent years.

Table C-4: Indirect Costs—Enhanced Safety—Reduced Costs Due to Injuries:

COST DUE TO INJURIES			
	Percentage	Fraction of VSL	
Classified bruises, sprains, and tears as MINOR	60%	0.0030	Assumed percentages out of the total for each type of injury
Classified fractures as MODERATE	25%	0.0470	
Classified multiple traumatic injuries as SERIOUS	15%	0.1050	
Value of statistical life (2014)	9,200,000		
Incidence rate of injuries		1	
No. of full-time workers in the airport		75	
No. of cases (per year)		0.0075	
Minor		124.20	
Moderate		810.75	
Serious		1,086.75	
Total		2,021.70	

Incidence rate is 20.9 for falls, slips, and trips.
Incidence rates are calculated per 10,000 workers.

Explanation of Calculations for Table C-4

Data for categorizing injuries for this level of detail is not available at the U.S. Bureau of Labor Statistics (BLS). The available data, per the BLS report on occupational injuries, was used, and certain assumptions were established to quantify cost due to injuries. The ground staff may be employed by the airport or the airlines, and they will be financially responsible for any injuries. It is assumed that slips and falls will not result in critical and nonsurvivable injuries and are not taken into consideration. Hence, only three classes of injuries were assumed minor, moderate, and serious. Bruises and strains were classified as minor, fractures as moderate, and multiple traumatic injuries as serious. Minor injuries were assumed to have maximum cases and were assumed as 60% of total injuries. Moderate was assumed as 25% and serious as 15%.

BLS incidence rates did not relate directly to the slips and falls due to snowy conditions, and the available incidence rate of 20.9 seemed too high. Therefore, a value of 5 was adopted and sensitivity analyses were also done at 7.5 and 10. Incidence rates are calculated per 10,000 full-time workers. The number of cases with an incidence rate of 5 was 9.603. Based on the above data, the injury cost was calculated by multiplying the percentage of each injury by its contributing fraction of the value of statistical life (VSL). The summed value of all the injury cases for BGM for the concerned four months was calculated as $2,022.

Table C-5 shows the cost of the hydronic HPS at BGM including initial costs, maintenance, and operations.

Table C-5. Cost of the Hydronic Heated Pavement System (HPS) at BGM

Item	Unit Price ($\$/ft^2$)	Area (ft^2)	Total Cost ($)
Initial Cost (C)	357.88	3,200	1,145,216
Maintenance Cost	1%		11,452
Operation Cost			5,205
Total Maintenance and Operation Cost (A)			16,657

Explanation of calculations for Table C-5

The capital costs consist of installation of the HPS. The costs per unit feet are multiplied by the total area to be heated to get the capital cost. Based on the literature (Minsk, 1999) and consulting with companies dealing with heated pavements a base value of $\$25/ft^2$ was adopted. To make the analysis more adequate, sensitivity analyses were performed at different unit cost values such as $\$15/ft^2$, $\$35/ft^2$, and $\$45/ft^2$.

Annual or recurring costs are comprised of the operation and maintenance costs to run the HPS. Operation costs include the cost of natural gas needed to heat anti-freeze circulating in the pipes and electricity needed to power the control system. The amount of natural gas required was calculated depending upon the annual heat energy required to melt snow or the design heat load of the system. The heat load was calculated using Equation 1 in the report. The amount of the cost of commercial natural gas in Minnesota was $9.33 per 1,000 cubic feet (April 2014, monthly average). The cost for natural gas was calculated to be $5,610,656 for a season. Maintenance cost was taken as 1% of the capital cost, and the total O&M costs were calculated to be approximately 6.8 million USD.

Table C-6 shows the cost of conventional methods for SRE, deicing agents, labor, and fuel costs as a function of area.

Table C-6. Cost of Conventional Methods for Snow and Ice Remediation at BGM

COST OF CONVENTIONAL METHODS				
SNOW REMOVAL EQUIPMENT				
Item	**Quantity**	**Unit Price ($)**		**Total cost ($)**
Multifunctional vehicle	1	910,000		910,000
Runway plows	6	485,000		2,910,000
Rotary brooms	4	650,000		2,600,000
Blowers	2	875,000		1,750,000
Front-end loaders	2	250,000		500,000
Sprayer	1	34,560		34,560
Deicer truck	1	44,000		44,000
TOTAL	**17**			**8,748,560**
Annual SRE Maintenance Cost				21,821
Note: cost of SRE is a function of area.				
AREA				
Ramp and apron area (ft^2)				3,200
Total paved surface (ft^2)				4,392,658
Ratio				0.001
DEICING AGENTS				
potassium acetate (gallons)	1	12,600		12,600
sodium acetate (lb)	1	6800		6,800
Note: cost of deicing agents is a function of area.				
LABOR				
	No.	**Unit Price ($)**	**Labor hours**	**Total price ($)**
Personnel	6	20	340	40,800
Note: cost of labor is a function of area.				
FUEL COST FOR SRE				
	17	18000		-
Capital investment = purchasing cost of SRE @ YEAR 0 (for concerned area)				
C=				**6,373.22**
Annual recurring cost in terms of AREA considered				
Maintenance costs for SRE				15.90
deicing agents				14
labor				29.72
fuel				-
A=				**59.75**

Table C-7 shows the energy usage and associated costs required to melt snow and ice at BGM. Note that for a total of 64 snow events, the cost was $5,205 per hour per square foot of pavement.

Table C-7. Energy Usage and Associated Costs Required to Melt Snow at BGM

SNOW MELT CALCULATIONS—ENERGY AND COST REQUIRED TO MELT SNOW	
Snowfall events (days)	64
Average snowfall (in./h)	1
Snow water equivalent(s) in./h	0.1
Ambient temperature (Ta) (°F)	24.7
Dew point temperature (°F)	9
Wind speed (V) (mph)	16
Specific heat of snow(Cp) (Btu/lb/°F)	0.5
Density of water equivalent of snow (D) (lb/ft^3)	62.4
conversion factor (c1) (in./ft)	12
Sensible heat transferred to the snow (qs) (Btu/h.ft^2)	1.898
hf (Btu/lb)	143.5
heat of fusion (qm) (Btu/h.ft^2)	74.62
Pdry air (lb/ft^3)	0.074887
hm (ft/h)	1.7
hfg (Btu/lb)	1074.64
Wf (lbv/lba)	0.003947
Wa (lbv/lba)	0.0021531
heat of evaporation (qe) (Btu/h.ft^2)	0.245423749
tf	33
hc	4.4
heat transfer by convection and radiation (qh) (Btu/h.ft^2)	36.52
ratio of snow-free area to total area (Ar) (qe + qh) (Btu/h.ft^2)	36.76
Pavement heat output (qo) (qs + qm + qe + qh) (Btu/hr/ft^2)	113.2834237
After taking 20% back and edge losses	135.9401085
Area (ft^2)	3,200
Energy requirement (Btu/hr)	435,008.35
Cubic ft/hr	423.57
Dollars/h for natural gas	3.389
Amount per season for NG($) per hour per sq ft	5,204.85

Tables C-8 and C-9 show a full 20-year economic analysis (only years 0, 1, 5, 10, and 20 are displayed) specific to BGM, summarized as a benefit-cost ratio.

Table C-8. 20-Year Economic Analysis Specific to BGM (part 1 of 2)

ECONOMIC ANALYSIS							
YEAR	20	0	1	5	10	15	20
		2014	2015	2019	2024	2029	2034
Discount factor	7%	1	0.934579439	0.7129862	0.50834929	0.362446	0.258419
HPS—Benefits							
1. Reduced lost passenger time			106,757	70,186	77,111	84,721	93,081
2. Reduced crew time & fuel waste			60,579	65,316	71,762	78,843	86,623
3. Enhanced safety			2,022	2,022	2,022	2,022	2,022
Annual summation of benefits			169,358	137,523	150,895	165,585	181,726
Present value of benefits			158,278.19	98,052.35	76,707.21	60,015.76	46,961.38
Net present value of HPS benefits	**1,596,698**						
HPS—Costs							
Operation & maint. cost (O&M)			(16,657)	(16,657)	(16,657)	(16,657)	(16,657)
Capital cost		(1,145,216)	–	–	–	–	–
Equivalent annual capital cost*			(108,100)	(108,100)	(108,100)	(108,100)	(108,100)
Total cost			(124,757)	(124,757)	(124,757)	(124,757)	(124,757)
Present value of cost			(116,595.61)	(88,950)	(63,420)	(45,218)	(32,240)
Net present value of HPS costs	**(1,321,681)**						
Net Cash Flows			44,600	12,766	26,137	40,828	56,968
Present Value (by year)			41,683	9,102	13,287	14,798	14,722
NPV of investment	**275,017**						

Values in parenthesis () indicate negative values.

Table C-9. 20-Year Economic Analysis Specific to BGM Continued (Part 2 of 2)

NPV of HPS benefits	440,015						
NPV of HPS costs	(346,424)						
Benefit Cost Ratio	**1.270**						
NPV of conv. methods costs	(1,836)						
Cost of HPS/Cost of conv	189						
Incremental Benefit Cost Ratio	**1.277**						
Chart data							
Year		0	1	5	10	15	20
PV of HPS Benefits ($million)			0.16	0.10	0.08	0.06	0.05
PV of HPS Costs ($million)			0.12)	(0.09)	(0.06)	(0.05)	(0.03)
PV of conventional Costs ($million)			(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Year		0	1	5	10	15	20
PV of reduced lost passenger time			0.099773	0.050041	0.0392	0.030707	0.024054
PV of reduced crew time and fuel waste			0.056616	0.04657	0.03648	0.028576	0.022385
PV of enhanced safety			0.001889	0.001441	0.001028	0.000733	0.000522
Year		0	1	5	10	15	20
PV of HPS capital cost			-0.10103	-0.07707	-0.05495	-0.03918	-0.02794
PV of HPS recurring cost			-0.01557	-0.01188	-0.00847	-0.00604	-0.0043

NPV = Net present value
PV= Present value

References—Appendix C

Anand, P., Nahvi, A., Ceylan, H., Pyrialakou, V.D., Gkritza, K., Gopalakrishnan, K., Kim, S., & Taylor, P.C. (2017). *Energy and financial viability of hydronic heated pavement systems*. (DOT/FAA/TC-17/47). Department of Transportation, FAA. https://www.airporttech.tc.faa.gov/Products/Airport-Safety-Papers-Publications/Airport-Safety-Detail/ArtMID/3682/ArticleID/154/Energy-and-Financial-Viability-of-Hydronic-Heated-Pavement-Systems

Federal Aviation Administration (FAA). (2018, March 15). *FAA releases aerospace forecast* [Press release]. https://www.faa.gov/newsroom/faa-releases-aerospace-forecast

FAA (2021). Partnership to Enhance General Aviation Safety, Accessibility, and Sustainability (PEGASAS) https://www.pegasas.aero/

McGormley, R., Arendt, T., Seal, D., & Fisher, E. (2015). *A guidebook for airport winter operations* (Airport Cooperative Research Program Report 123). The National Academies Press. https://doi.org/10.17226/22221

Minsk, L.D. (1999). *Heated bridge deck technology—Report on ISTEA sec. 6005 program* (Report No. FHWA-RD-99-158). Federal Highway Administration. https://www.fhwa.dot.gov/publications/research/infrastructure/bridge/99158/index.cfm

U.S Department of Transportation. (2016). *Airline on-time statistics and delay causes.* Bureau of Transportation Statistics. https://www.transtats.bts.gov/OT_Delay/OT_DelayCause1.asp?pn=1

APPENDIX D—PHOTOGRAPHS OF THE SNOWMELT SYSTEM IN REAL TIME

In this section, photographs of the Snowmelt System show proof of the system's operation and performance.

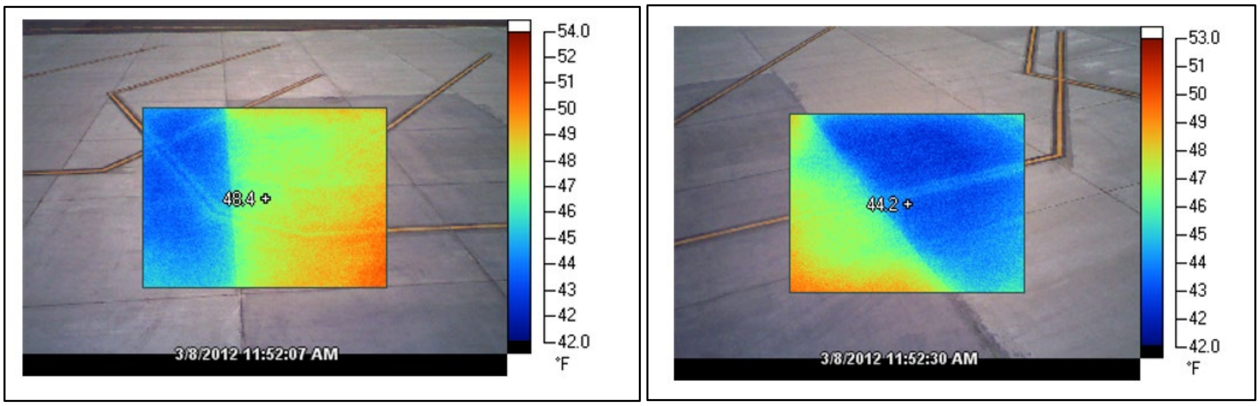

Figure D-1. Thermal Imaging of the Left Side (left photo) and Right Side (right photo) of the Heated Slab and Adjacent Section of the Apron (Note the heated slab is reaching the 50-degree range and the unheated slab is in the low 40-degree range, as expected.)

Figure D-2. A preliminary test of just the radiant heating portion of the system was conducted near the end of the winter of 2011–12 and proved successful in all aspects of the system. (Note the cleared area of the tarmac). At that time, since the geothermal field had not yet been installed, heat to the system was provided by a temporary gas boiler.

Figure D-3. System in operation following a snow event:
Heated pedestrian walkway in the foreground; heated slab to the right; unheated area in the background (left photo); Heated slab under and to the right of the aircraft; unheated apron is in the foreground (right photo)

Figure D-4. System in Operation Following a Snow Event 12/29/2016 (Heated slab can be seen under and to the left of the aircraft. Unheated apron is in the foreground.)

Significant Snow Event:

During a 24-hour period, BGM received 32 inches of total storm accumulation. Snow began falling around 3:30 a.m. on Monday, March 14, 2017. Accumulations reached up to 4 to 6 inches per hour. Snow continued until late in the day on Tuesday, March 15, 2017. The weather turned to partly sunny/cloudy early on Wednesday, March 16, 2017, and continued throughout the day. Transportation experts typically agree on a rule of thumb: up to 1 inch per hour is manageable, 1 to 2inches per hour is moderately manageable, and greater than 2 inches per hour is unmanageable.

Figure D-5. System in Operation During a Snow Event Falling at the Unusually High Rate of 4–6 inches per hour (Note the system is slightly behind, as expected in such a rare event. However, the slush as seen by the footprints shows the system is operating and will, in fact, clear the area as soon as the downfall lets up.)

Figure D-6. Snow Events During the 2017 Winter Season (Snowmelt system working as designed/expected on apron and on pedestrian walkway.)

APPENDIX E—SYSTEM COMPLEXITY

In the simplest terms, a geothermal energy system is simply tubing laid in trenches and connected to a heat pump. That scenario could be adequate to describe a residential system for a small home with a well-insulated roof, thermal windows, and insulated walls. However, designing a system for an airport creates a scenario that does not resemble a residential system. Some of these differences are listed below anddescribe what a more complex system.

1. The tarmac/pavement/concrete is typically at least 11–12 inches thick at an airport. Heating that much mass requires a robust system capable of handling that much heat transfer in a reasonable amount of time. A homeowner might come home to a house measuring 50 degrees Fahrenheit (°F), turn on the system, and in 2 hours the house would be a comfortable 70 °F. Unlike a home with adequate insulation, a runway is outdoors in all the elements. The system must handle significant snowfall and ice storms, accompanied by high winds. At BGM, which sits on top of a mountain, wind chills can reach minus 20 °F with ice and snow typically falling in excess of 2 inches per hour during a snow event.

2. If the system is going to be used in a manner that eliminates the use of plows and brushes, then it must be designed with complete redundancy to avoid a runway shutdown in the case of a failure of the system. This particular system has two heat pumps, two pumps for well field circulation, and two pumps for snowmelt/air cooling circulation. These devices have been designed to operate in a manner such that the system alternates between the redundant systems and a backup is always available.

3. This particular system has both vertical wells and horizontal trenching to capture the geothermal energy. This was done for research purposes only and no significant differences were found except for cost. If an airport has considerable land available, then trenching is the most cost-effective route. However, if land is at a premium, then vertical wells would be an alternative, although significantly more expensive.

4. This particular system was built with dozens of sensors for research purposes. While the sensors are useful, they might not all be necessary, thereby further reducing system complexity.

APPENDIX F—TEMPERATURE PLOTS

The following plots show various temperature sensors during a year of data collection of all sensors every 15 minutes, 24 hours per day, 365 days per year. The data in the plots were minimized to provide readable graphs consisting of only pertinent data. The plots cover the dates January through May followed by the following January and February. Note that blank areas represent sensor failures that were later corrected.

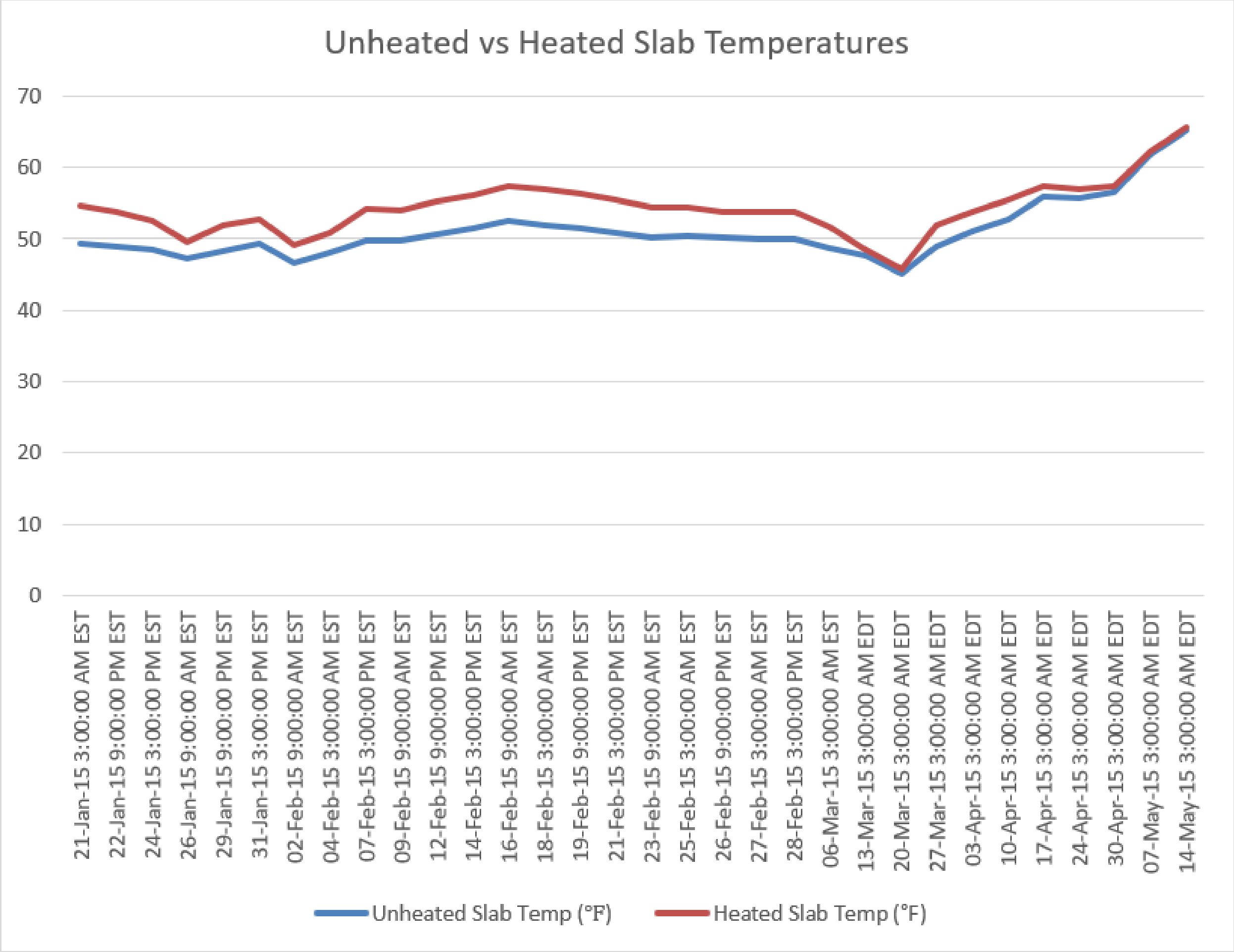

Figure F-1. Temperatures of Unheated Slab vs Heated Slab (Note heated slab is always slightly warmer than unheated slab as expected.)

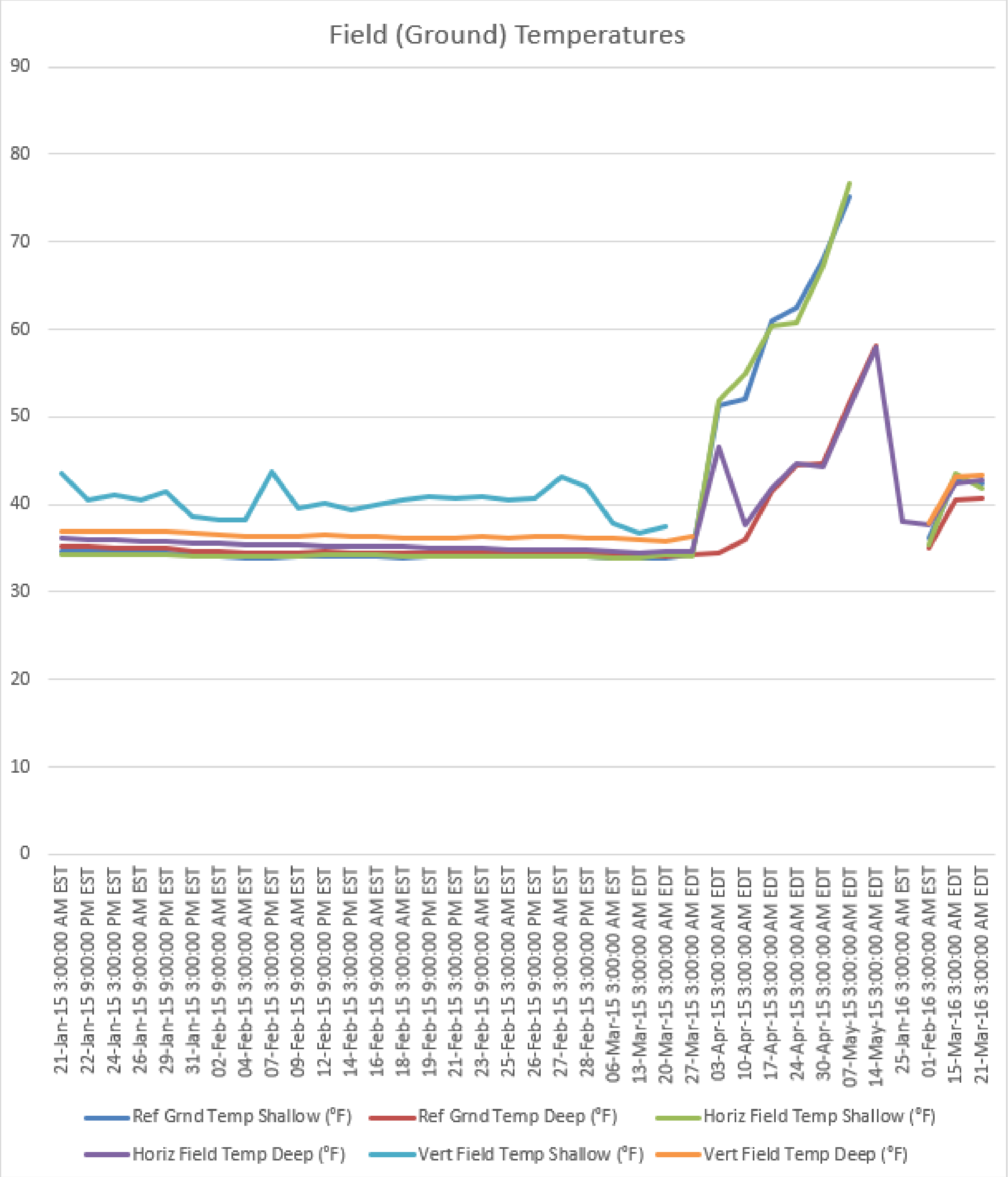

Figure F-2. Temperatures of Various Ground Temperatures

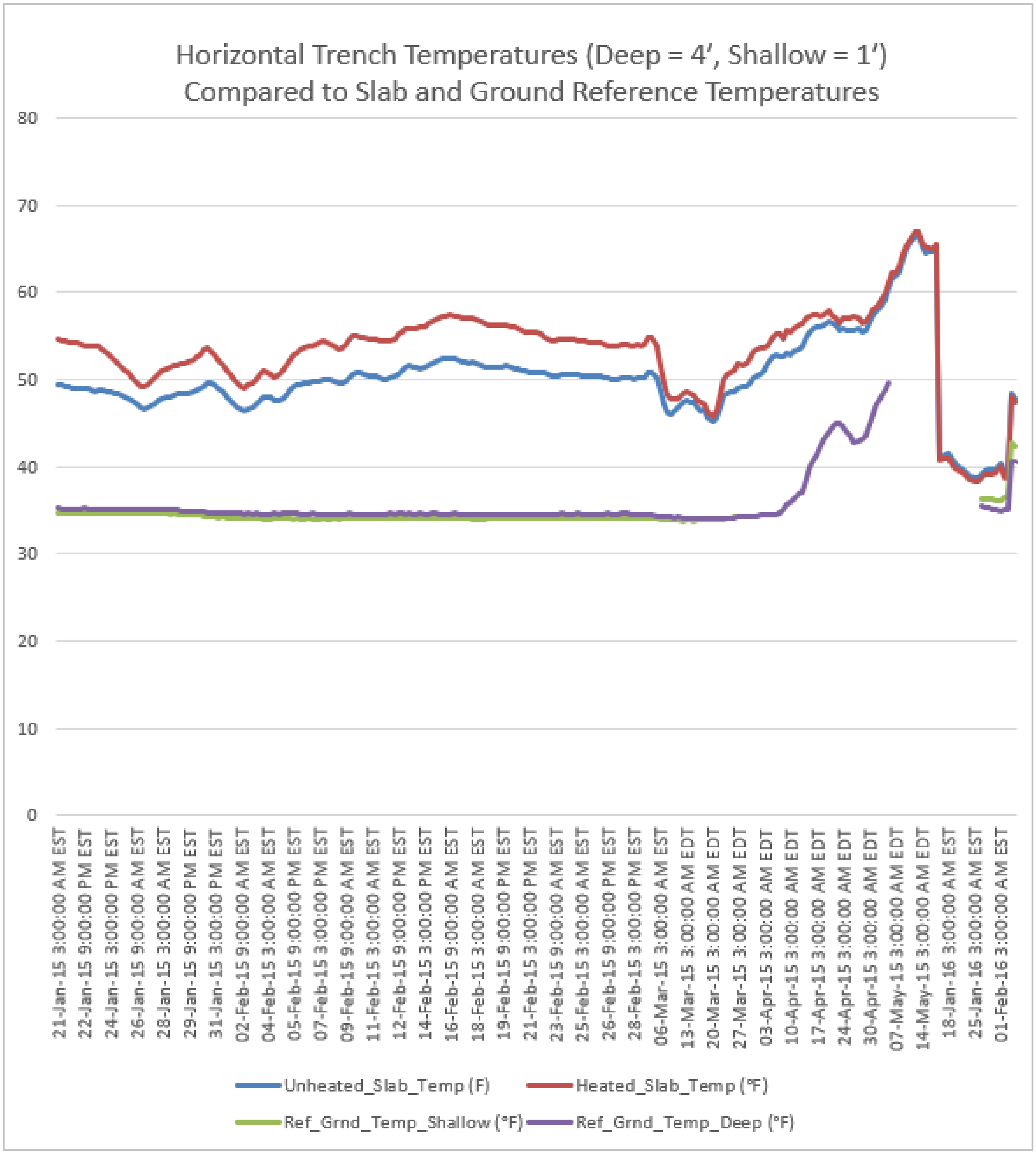

Figure F-3. Horizontal (shallow and deep) Trench Temperatures in Comparison to Reference Ground Temperatures (located away from the horizontal trenches and vertical wells), Heated and Unheated Slab, and Vertical Wells (shallow and deep) (Note temperatures seem to follow a logical pattern of being colder in the coldest months and warmer in the warmer months.)

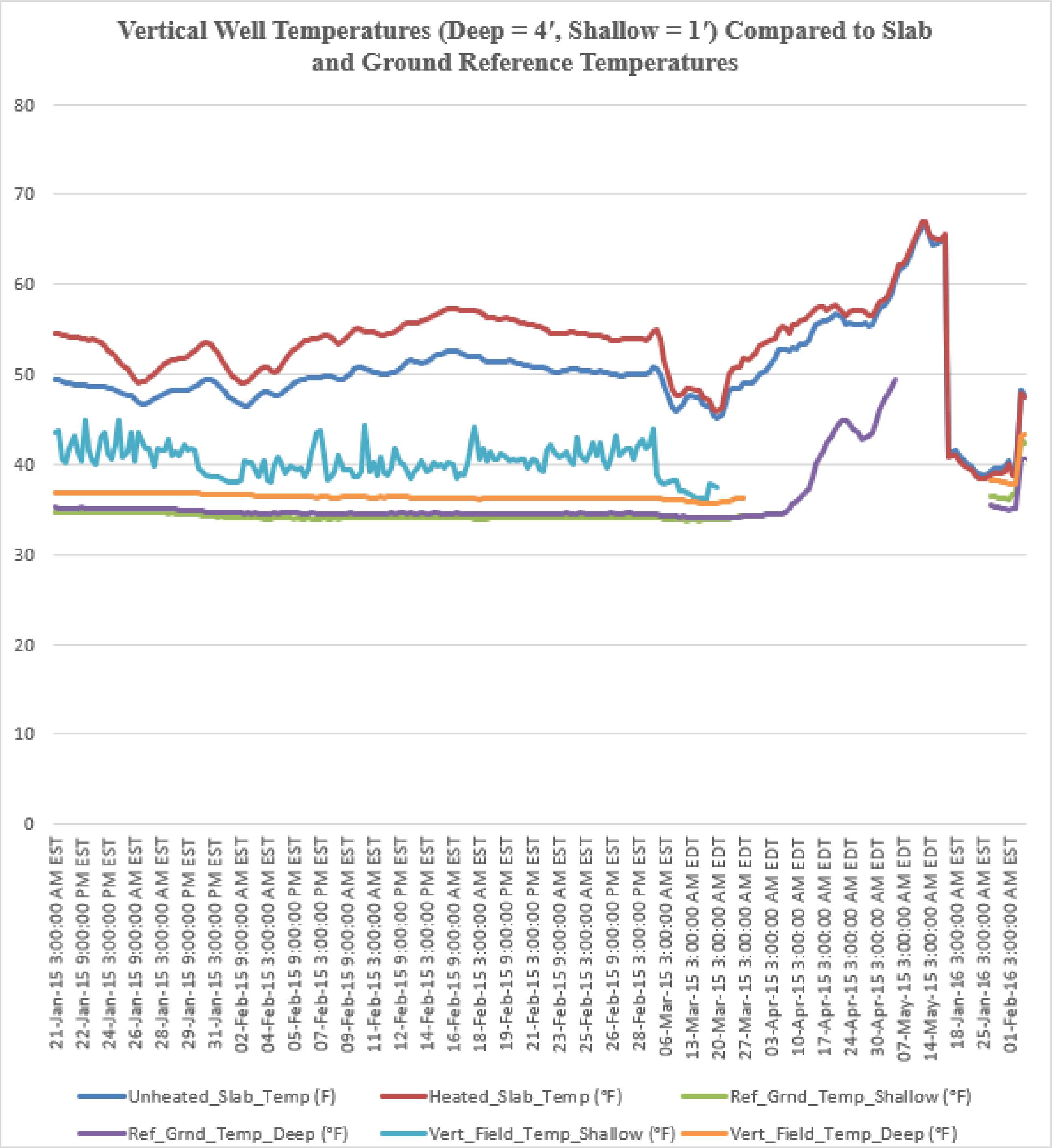

Figure F-4. Vertical (shallow and deep) Well Temperatures in Comparison to Reference Ground Temperatures (shallow and deep)—Located Away from the Horizontal Trenches and Vertical Wells, and Heated and Unheated Slab Temperatures (Note temperatures seem to follow a logical pattern of being colder in the coldest months and warmer in the warmer months.)

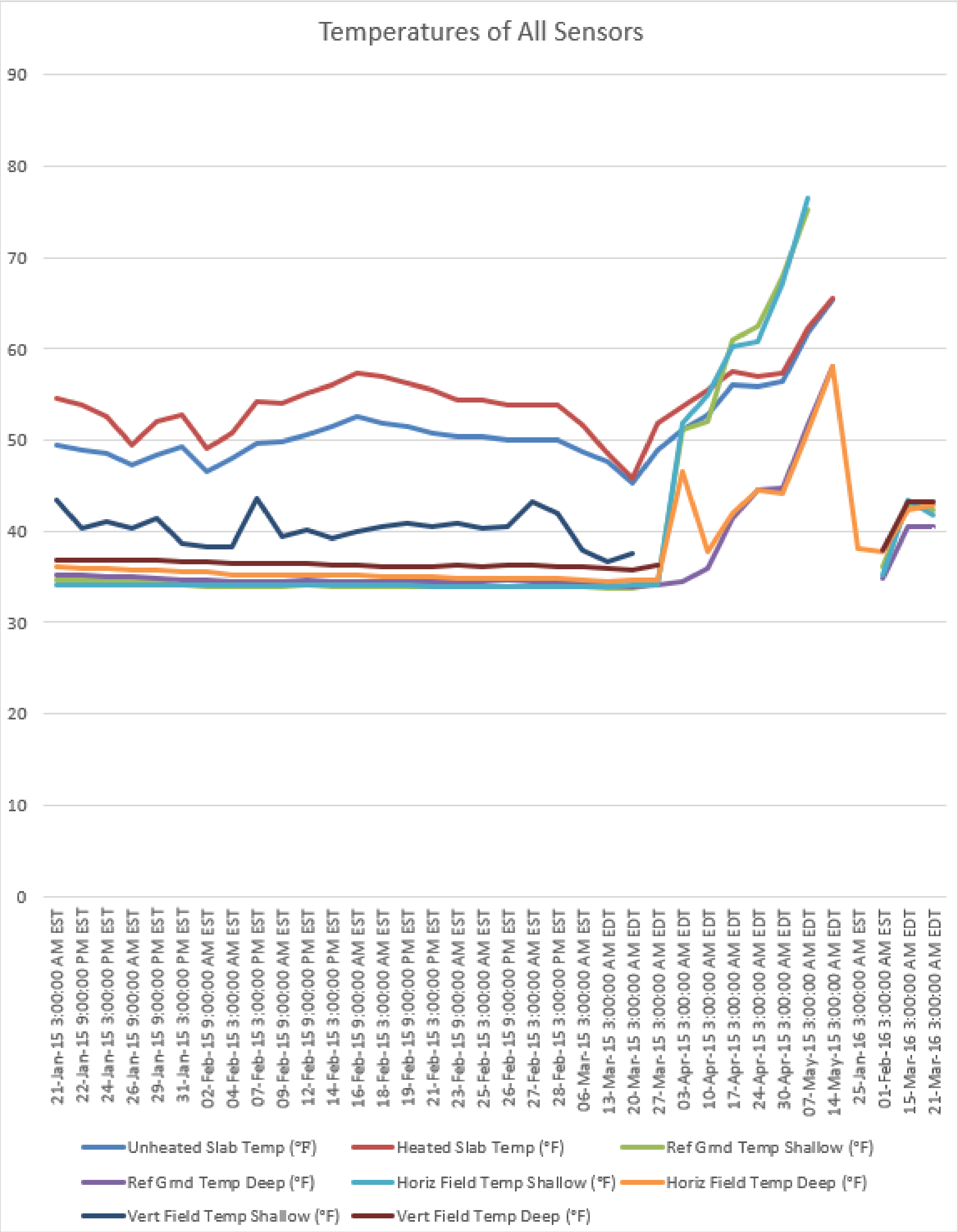

Figure F-5. All Temperatures—Unheated Slab and Heated Slab; Horizontal Trenches Shallow and Deep; Vertical Wells Shallow and Deep; and Ground Reference Shallow and Deep