PREDICTION OF SURFACE ICE MELT TIMES FOR A HEATED SPORT FIELD

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Abstract

Students in an independent study project employed a 1-dimensional finite-difference technique to model a football field turf heating system in actual environmental conditions to predict transient temperature distributions in the ground. The model is also applied to predict proactive (i.e., heating system activated in advance of cold weather ice formation on the field) and reactive (activation following ice formation) times required to melt surface ice of varying thicknesses. These results provided stadium personnel with time required for system operation, in lieu of keeping the system activated for arbitrary time periods prior to kick off; substantial cost savings are attainable. Model details are presented, along with plots of required system operation time for varying ice thicknesses.

Nomenclature

A	Cross section area (ft^2)
c	material specific heat (Btu/lbm·°R)
k	thermal conductivity (Btu/hr·ft·°R)
Q	Heat transfer rate (Btu/hr)
R	Thermal resistance (°R·hr/Btu)
v	specific volume (ft^3/lbm)
V	Volume (ft^3)
ρ	material density (lbm/ft^3)

Subscripts

A	Air
FT	Field Turf
PG	Pea Gravel
R	Rubber
S	Soil
P	Peat
G	Geofabric™

Background

Falcon Field at the United States Air Force Academy (USAFA) is equipped with a heating system situated beneath layers of various materials as shown in Figure 1. The intended purpose of the system was to prolong the life of the original grass well into the colder portion of the original football season and to minimize the potential for player injuries; with the current artificial surface, it is used to either prevent the accumulation of ice on the playing field, or to melt ice already formed, with the ultimate objective of removing all ice prior to kickoff.

The physical makeup of the football field can be seen in Figure 1. The surface of the field is composed of Field Turf™, which is synthetic grass, filled in with a 50/50 mixture by volume of sand and rubber. This mixture is kept on the field's surface by a thin layer of Geofabric™ which serves as the base of the field turf. Beneath the Field Turf™ lies 10 inches of the root zone, which is a 90/10 mixture by volume of sand and peat, a remnant of the period in which the field surface consisted of real grass.

Resting directly beneath the root zone, and on top of 4 inches of pea gravel, is the electrical resistance heater. The pea gravel is situated immediately over the indigenous soil.

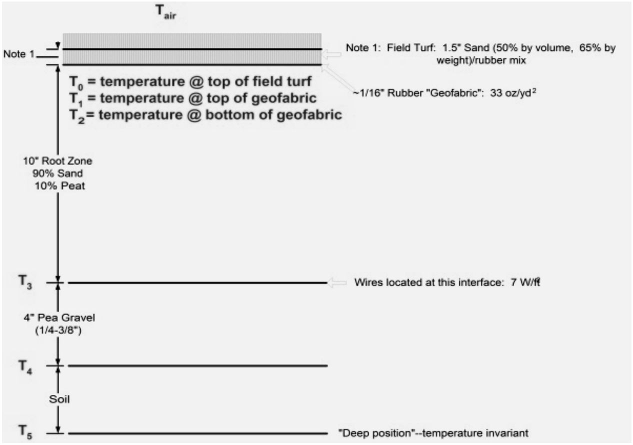

Figure 1: Falcon Field turf layout.

Previous investigations into heat transfer through the near-surface ground have been conducted and shed sufficient light to allow future model development. Parker and Maixner [1] acquired meteorological data (wind speed, ambient temperature, and insolation) in conjunction with analysis of the operation of a thermoelectric device and developed the initial finite-difference model of the Falcon Field heating system. The model described therein was based on a finite-difference derivation of the one-dimensional heat equation.

Each layer in the finite difference model was divided into a number of elements, and material properties such as thermal resistance and capacitance were calculated for each layer. The boundary condition of constant temperature (51°F) at a depth of 8 feet was imposed; an empirical equation provided ambient air temperatures above the field, based on historical data recorded at the Colorado Springs airport in the month of December. Once the model was constructed, Parker and Maixner [1] ran it iteratively to determine exactly how heat was transferred through the layers of the field and ultimately to the surface. The model calculates temperatures at different depths, including at the surface of the field, and can be run with or without the heater activated. Additional details on the system may be found in Reference[1].

Objective

The objective of this research was to provide practical data to the stadium manager to help determine minimum heater activation times that will ensure no ice exists at game time. Due to the nature of the weather in Colorado Springs, snow and ice covering the field is often a concern during the football season. Specifically, the scenario of having a quarter inch layer of ice form on the surface of the field prior to a game was cited by the stadium manager as the scenario of principal concern. A finite difference model, based on the one-dimensional heat equation

$$\frac{\partial}{\partial x}\left(k\frac{\partial}{\partial x}\right)+q=\rho c\frac{\partial T}{\partial t} \qquad (1)$$

which could simulate transient heating in the ground with a layer of ice at the surface was utilized. The model would be used to generate data covering multiple scenarios of ice thickness and game time. Tabular and graphical formats for data presentation were chosen for simplicity and ease of use as a deliverable to the stadium manager. These data sets included both predictive (heating the field in advance based on weather forecasts) heater activation times and reactive (turning on the heater immediately following ice formations) melting times.

Refining Material Properties

Most of Parker and Maixner's work [1] concentrated on the development of the finite difference model for use as a student project in a heat transfer course; they also determined baseline values for the material properties at each layer of the field. Of the five separate layers in the field, two were homogeneous: the rubber Geofabric™ and the indigenous soil. Of the remaining three layers, the field turf and the root zone were mixtures of sand with rubber and peat, respectively, while the pea gravel was a mixture of rock and air pockets. Since published material properties for these mixtures were unavailable, an electrical analog model was employed to determine the hybrid values for each layer, as seen in Figure 2 below, shown for the field turf layer.

Figure 2a represents the composite material, and depicts a nominal downward heat flow, Q. The composite material can be broken down into the two basic materials contained within the composite (Figure 2b). Since heat flows through each material, it may be considered to flow through the thermal resistances in parallel (Figure 2c). Once the individual properties are ascertained, they combine according to the same equations used in electrical engineering for parallel resistors and conductors. As seen in Figure 2d, the goal is to determine the heat transfer properties of the composite material. Using this analogy, all of the thermal properties for the composite materials were determined using

$$k_{FT} = \frac{v_R k_R + v_S k_S}{v_R + v_S}$$
$$\rho_{FT} = \frac{v_R \rho_R + v_S \rho_S}{v_R + v_S} \qquad (2)$$
$$c_{FT} = \frac{v_R c_R + v_S c_S}{v_R + v_S}$$

Many of the material property values employed by Parker and Maixner [1] were rough estimates, rather than precise values needed to conduct detailed analysis of the heating system capabilities. It was discovered that the Air Force Academy had no records from the construction of the stadium which pertained to the material properties of the soil and rock beneath the field. Additionally, the original equipment manufacturer of the heating system

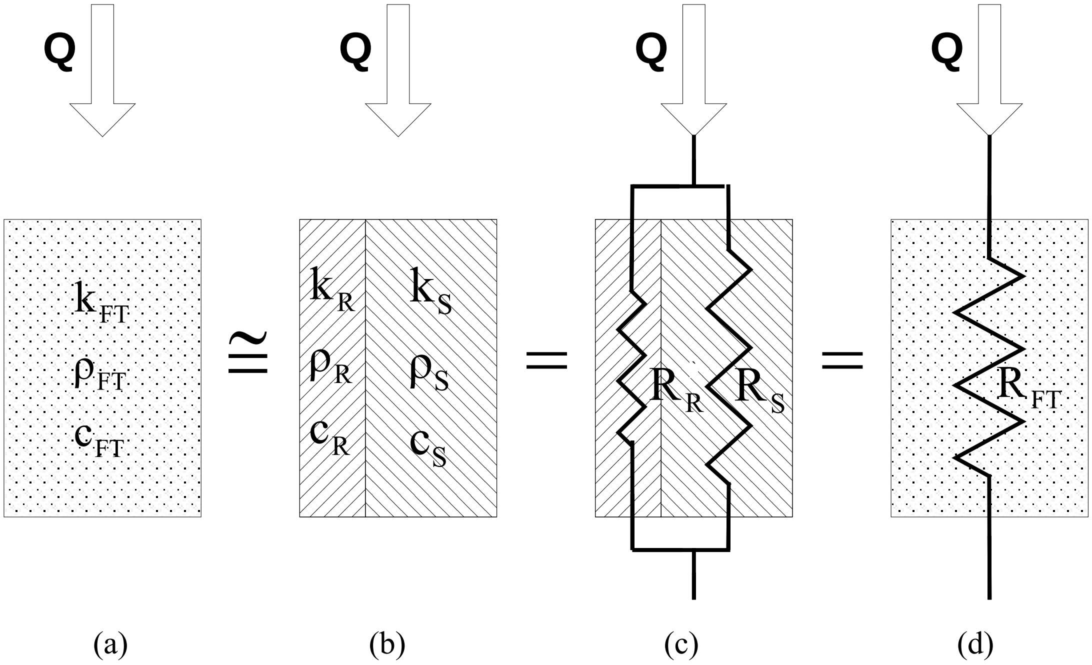

Figure 1: Electrical analog of heat transfer (Q) through FieldTurf™ (subscript FT) layer, comprised of sand (subscript S) and rubber (subscript R); thermal conductivity (k), density (ρ), and specific heat (c) are shown for each material, along with thermal resistance (R).

was unable to provide details on their system beyond a heating capacity of 7 W/m^2. Since it was impractical to dig up the field to measure these properties, a computer simulation was employed, using the electrical resistance modeling technique. Properties of two materials were left unchanged: those of the Geofabric™ and of the indigenous soil. Unlike the makeup of the other layers, these were homogeneous, and the determination of their exact material properties was straightforward. On the other hand, the composition of the Field Turf™, root zone, and pea gravel required further refinement. The literature revealed that the thermal conductivity of sand may vary from 0.2 to 3 Btu/hr·ft·°R a difference of more than an order of magnitude depending on the moisture content. A thermal conductivity value of 2.2 Btu/hr·ft·°R was selected for sand, representing a 70% level of saturation[2].

Looking at other materials in the model, the values for the indigenous soil were found to be acceptable. However, the thermal properties of the pea gravel originally used by Parker and Maixner [1] were based on solid granite; without taking into account the air pockets in between the stones, the thermal properties were likely inaccurate. Solid granite would conduct heat much more readily than would granite with air pockets, while the density and specific heat of the pocketed stones would change accordingly. Once the volumetric ratio of air to pea gravel was ascertained from Reference[3], the parallel resistance theory was employed to determine the correct properties.

Modeling the Ice Layer

It was necessary to augment the original finite difference model with a layer of ice above the Field Turf™. This layer changed the interaction of the surface with the atmosphere, which proved to be an important detail in the proper functioning of the model.

Since the model was based on individual nodes and their interactions, it was first thought necessary to separate the ice into layers of equal size. As the ice melted, the thickness of each layer changed, until no ice remained. After numerous trials, it was found that this method was impractical since the maximum allowable time step to ensure numerical stability for the model became far too small for run times of reasonable duration. Ultimately, the ice was modeled in a simple, more appropriate manner as a single isothermal element, subject to conduction, convection and radiation. This surface ice layer was situated above the surface element in the model described by Parker and Maixner [1]. Knowing the heat of fusion for water, it was possible to determine the melting rate for the ice as a function of heat flow into the ice layer.

Several simplifying assumptions regarding the ice on the field were made. The ice was modeled as a non-reflective solid, opaque sheet, with any heat entering the ice absorbed by it rather than flowing through it. Assumptions were also made regarding exactly how the ice formed and melted. The first was that during a storm, a layer of ice would form instantaneously. During an ice storm, precipitation falls as a super-cooled liquid and upon impacting the ground, it freezes almost instantaneously[4]. It was also assumed that water from any melted ice drained off the field immediately. This assumption was important to the model for reasons concerning heat conduction to the ice, and the idea that no water could re-freeze after it had been melted. In fact, the field is actually sloped, being six inches higher in the middle than at the sidelines, thereby facilitating drainage. The ice layer was also assumed to be of uniform temperature.

The model was run without an ice layer until the temperature profile through the ground was essentially identical at the same times from day to day. Once this quasi-steady state situation was achieved, the model was paused and a layer of surface ice whose temperature was at 32 °F was added. Ice will only melt (i.e., undergo a phase change) if at 32 °F, but it may assume temperatures *less than* 32 °F. Consequently, it was necessary to develop a method to track the heat flow into (or out of) the ice layer. When the temperature of the ice remains at 32 °F and the net heat flow is into the ice, the ice will melt. However, if the temperature of the ice is below 32 °F, and the heat flow is into the ice, the temperature of the ice would increase up to the melting temperature without the ice melting. Finally, if the net heat flow is out of the ice, the temperature of the ice would decrease. A Visual Basic for Applications (VBA) algorithm was created which incorporated the above logic.

Results

With the model parameters and the ice layer complete, the simulation was used to develop data that could be provided to the stadium manager. Two major types of tests were conducted, the first of which was to generate reactive data. The results of this test could be used by the stadium manager to determine how long an ice layer would take to melt if the heater were switched on at the time of ice formation (i.e. reacting *after* ice formation). The other type of test was designed to allow the stadium manager to be more proactive in preventing ice accumulation on the field at kickoff time. For this test, the model returned the amount of time of heater operation required prior to ice formation to ensure that the ice is completely melted not later than two hours prior to kickoff, in order to allow for warm up and practice before the game.

For each test category, simulation runs were conducted at a variety of ice thicknesses and ice formation times. Even though the stadium manager suggested that the most likely scenario involved an ice layer thickness of ¼ inch, in order to provide comprehensive data, thicknesses of 1/8, 1/4, 3/8, 1/2 and 1 inch were all tested. Ice formation times were also varied, with runs begun at four hour intervals, starting at midnight. A final test parameter that was adjusted for the proactive test runs was the kickoff time of the game. In order to provide a range of kickoff times throughout the day, 8:00 A.M., 12:00 P.M. and 4:30 P.M. were used. While tests were being conducted, it was also determined that wind speed was a significant factor in the speed at which ice melts. Therefore tests were run with wind speeds of 1 mile per hour and 7.5 miles per hour. This gave convection coefficients of 1 and 3 $\text{Btu/hr}\cdot\text{ft}^2\cdot{}^\circ\text{R}$ respectively[5].

Figure 3 through Figure 8 show the results of the proactive tests (data for all figures are tabulated in Appendix A). The most obvious result seen in these figures is the difference between heater activation times due to wind speed. The model was designed to allow the heater to be run for a maximum of seven days before terminating the run. For the tests with wind speeds of 1 mph, it was only for ice thicknesses above 3/8 inches that the model ran for seven days, and this was only in cases of ice formation times just before kickoff times. However, for the tests conducted with wind speeds of 7.5 mph, even tests with only 1/8 inch of ice required more than seven days of heater operation to obtain adequate melting. This indicates that the model is extremely sensitive to changes in wind speed.

When the model was run with 7.5 mph wind speeds, the amount of heat transfer out of the ice due to convection was often roughly equal to the amount of heat transfer into the ice from the heater. While the heater provides some benefit, it is not powerful enough to make a difference in melting times. For the 1 mph tests, however, the heat in from the heater was greater than the heat lost due to convection, allowing the heater to greatly reduce ice melting times.

It was noted in all tests that for ice formation times within four hours of kickoff times, there was a strong possibility that at least a week of heater operation prior to ice formation would be required to achieve melting; this effect is particularly apparent in Figure 3 and Figure 4. If ice is predicted to form within four hours of kickoff time, the stadium manager is most likely going to be unable to achieve melting prior to game time.

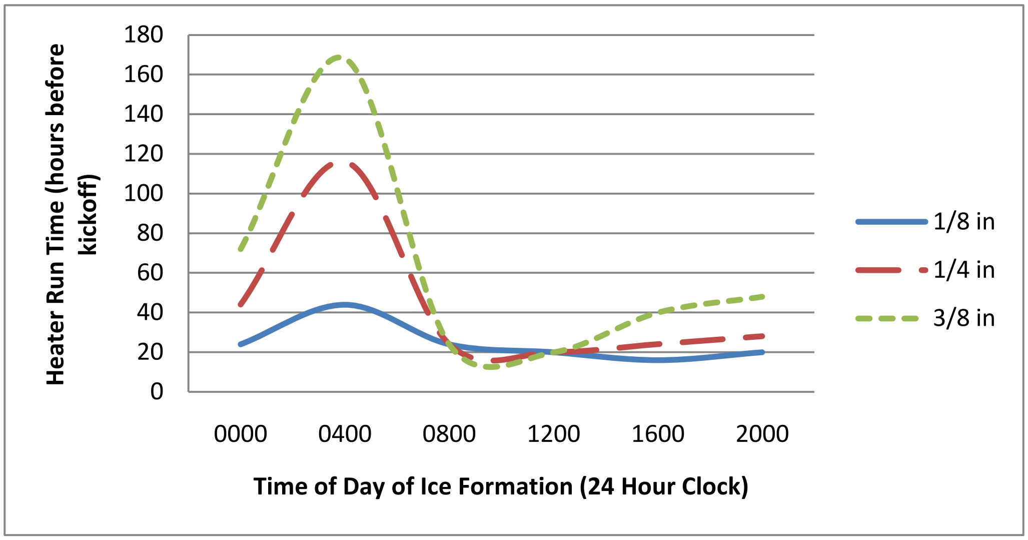

Figure 3: 0800 Kickoff with 1 mph winds.

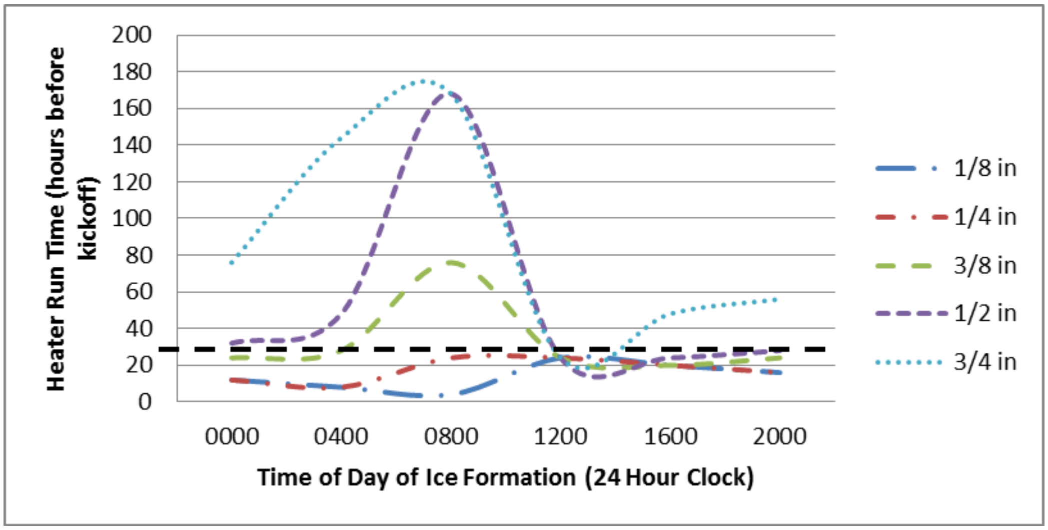

Figure 4: 1200 Kickoff with 1 mph winds.

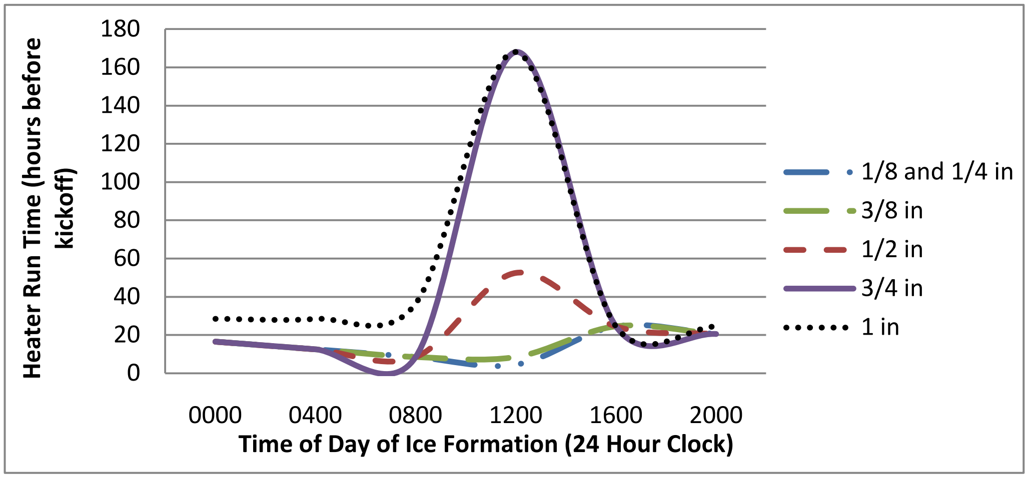

Figure 5: 1630 Kickoff with 1 mph winds.

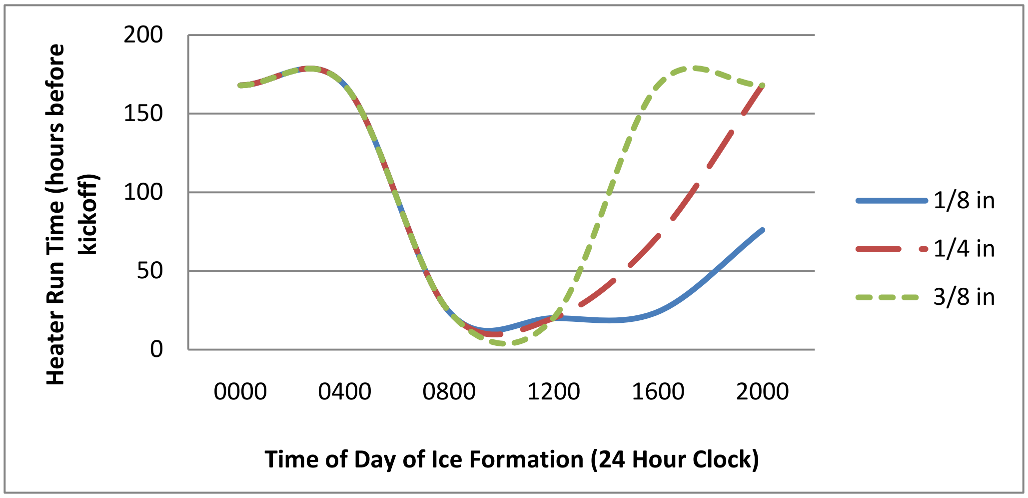

Figure 6: 0800 Kickoff with 7.5 mph winds.

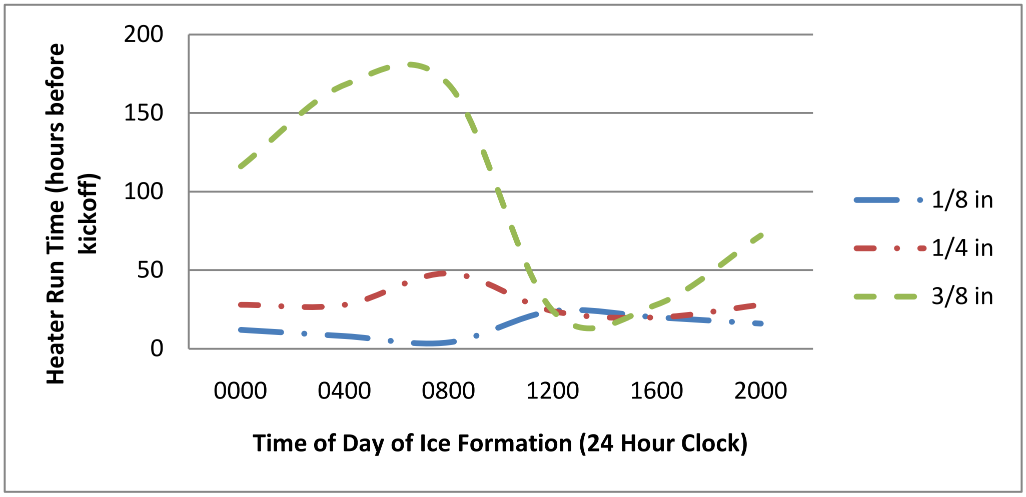

Figure 7: 1200 Kickoff with 7.5 mph winds.

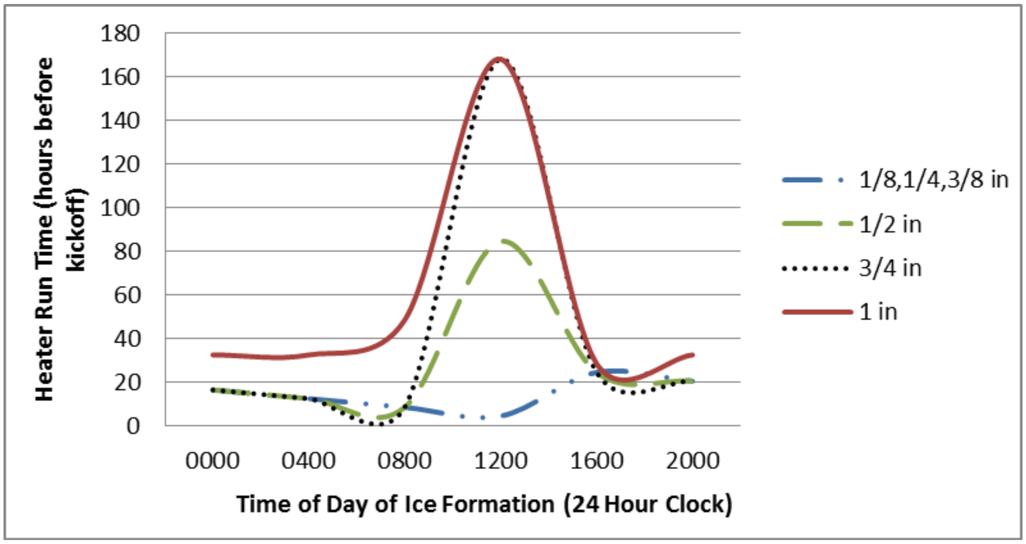

Figure 8: 1630 Kickoff with 7.5 mph winds.

The stadium manager predicted that any ice formed would most likely be on the order of 1/4 inch thick. Figure 3 through Figure 5 show that for 1/4 inch ice and 1 mph wind speeds, melting can be achieved in a very reasonable amount of time (less than 24 hours of heater operation in most cases). For 7.5 mph wind, results are not as promising, but in about half the tests with 1/4 inch ice, melting could be achieved with less than 24 hours of heater operation. What this means for the stadium manager is that even in the case of short notice ice formation, the heater may still be activated with a good chance for melting all ice prior to two hours before game time.

Figure 9 shows the melting times for the reactive testing, where the heater was activated at the time of ice formation. The kickoff time is irrelevant here because the reactive data are only concerned with the time required to melt the ice based on heater activation at ice formation time.

As expected, the melting time increases greatly as the thickness of the ice increases, but the interesting result here is the comparison of the melting times for 1/4 inch of ice both with the heater activated and the heater turned off. The heater has almost no effect in aiding in melting the ice until the time of ice formation occurs in the afternoon. The heater has the chance to operate overnight, while the test with no heater has to wait until the next morning for insolation to aid in melting. These data are also useful for the stadium manager because they provide an estimate of how long ice will take to melt in the event of a surprise storm, an occurrence not uncommon on the front range of the Rockies.

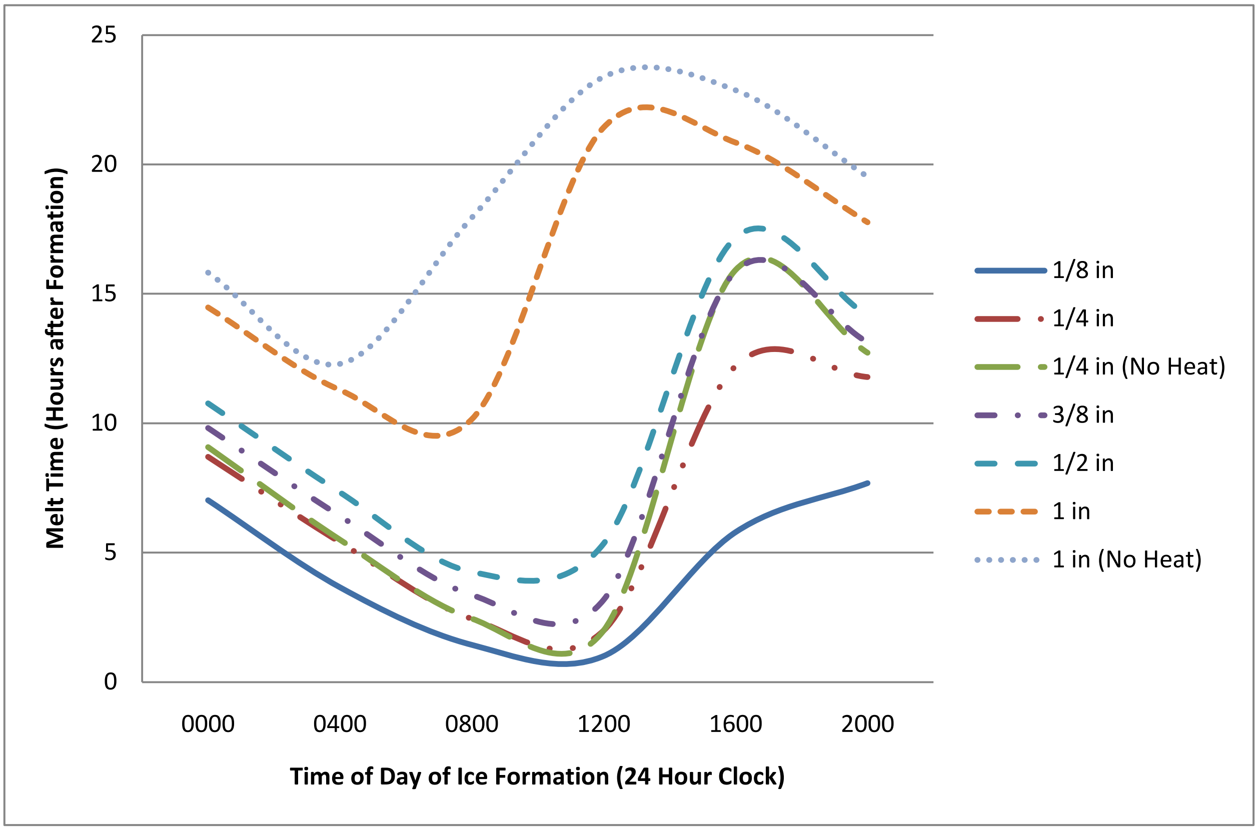

Figure 9: Reactive Ice Melting Times.

Conclusions

The data obtained from this simulation can be put to practical use by the stadium manager in limiting the impact of ice formation on football games. Although sensitive to wind speed, the data still provide a general guide for how long the heater needs to be operated or how long ice will take to melt. Currently, the field heater is rarely operated, and when it is, it is generally run for a period of seven days prior to a home football game. For FY2009 average electrical costs at USAFA ($0.04855/kW-hr), this would come out to a cost of $3080, with the heater running at 7 W/ft^2 over an area of 54000 ft^2 for seven days, using 63504 kW-hr. Given the data from this simulation, for ice thicknesses less than 3/8 inches, the heater can generally be run for 24 hours, which would give an electrical cost of $440, resulting in a savings of $2640 each time the heater is utilized. Prior to using this heating approach before an actual game, it is recommended that the stadium manager use the heater in accordance with results from the model when icing is predicted during a week when there is no home game. This empirical test can provide validation of the results predicted by the model.

Beyond the results of this study, the sensitivity of the model to wind speed provides a fertile area for further research. Another area for further research would be in continuing to refine the material properties of the model, perhaps supplemented by empirical testing. Finally, more work needs to be conducted in terms of developing a more realistic model for the ice formation and melting. Many assumptions were made to simplify the analysis, but further research will provide more realistic results from the model.

References

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Biographical Information

Benjamin Saunders, a distinguished graduate from the U.S. Air Force Academy, completed his undergraduate degree in mechanical engineering in 2010. He is currently an S.M. candidate in the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology and a Draper Laboratory Fellow.

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Michael Maixner graduated with distinction from the U.S. Naval Academy, and served as an officer in the USN for 25 years; his first 12 years were spent as a shipboard officer, while his remaining service was in strictly engineering assignments. He received his Ocean Engineer and SMME degrees from MIT, and his PhD in mechanical engineering from the Naval Postgraduate School. He served as an instructor at the Naval Postgraduate School, as a Professor of Engineering at Maine Maritime Academy, and in his current capacity as Professor of Engineering Mechanics at the United States Air Force Academy. He is a registered professional engineer (mechanical) in the state of California.

Appendix A

Table 1: Melt times required for 1 mph wind speed.

	0800 Kickoff					
Ice Thickness (inches)	1/8	1/4	3/8	1/2	3/4	1
Time of Ice Formation						
0000	24	44	72	8	8	8
0400	44	116	168	8	8	8
0800	24	24	24	8	8	8
1200	20	20	20	8	8	8
1600	16	24	40	8	8	8
2000	20	28	48	8	8	8

	1200 Kickoff					
Ice Thickness (inches)	1/8	1/4	3/8	1/2	3/4	1
Time of Ice Formation						
0000	12	12	24	32	76	168
0400	8	8	28	48	144	168
0800	4	24	76	168	168	168
1200	24	24	24	24	24	28
1600	20	20	20	24	48	76
2000	16	16	24	28	56	112

	1630 Kickoff					
Ice Thickness (inches)	1/8	1/4	3/8	1/2	3/4	1
Time of Ice Formation						
0000	16.5	16.5	16.5	16.5	16.5	28.5
0400	12.5	12.5	12.5	12.5	12.5	28.5
0800	8.5	8.5	8.5	8.5	8.5	36.5
1200	4.5	4.5	8.5	52.5	168	168
1600	24.5	24.5	24.5	24.5	24.5	24.5
2000	20.5	20.5	20.5	20.5	20.5	24.5

Ice Forms On Same Day as Game

Ice Forms on Day Prior to Game

Table 2: Melt times required for 7.5 mph wind speed.

	0800 Kickoff					
Ice Thickness (inches)	1/8	1/4	3/8			
Time of Ice Formation						
🟩 0000	168	168	168			
🟩 0400	168	168	168			
🟦 0800	24	24	24			
🟦 1200	20	20	20			
🟦 1600	24	72	168			
🟦 2000	76	168	168			
	1200 Kickoff					
Ice Thickness (inches)	1/8	1/4	3/8			
Time of Ice Formation						
🟩 0000	12	28	116			
🟩 0400	8	28	168			
🟩 0800	4	48	168			
🟦 1200	24	24	24			
🟦 1600	20	20	28			
🟦 2000	16	28	72			
	1630 Kickoff					
Ice Thickness (inches)	1/8	1/4	3/8	1/2	3/4	1
Time of Ice Formation						
🟩 0000	16.5	16.5	16.5	16.5	16.5	32.5
🟩 0400	12.5	12.5	12.5	12.5	12.5	32.5
🟩 0800	8.5	8.5	8.5	8.5	8.5	48.5
🟩 1200	4.5	4.5	4.5	84.5	168	168
🟦 1600	24.5	24.5	24.5	24.5	24.5	28.5
🟦 2000	20.5	20.5	20.5	20.5	20.5	32.5

🟩 Ice Forms On Same Day as Game

🟦 Ice Forms on Day Prior to Game

Table 3: Results of reactive runs.

Ice Thickness (inches)	1/8	1/4	1/4 (no heat)	3/8	1/2	1	1 (no heat)
Time of Ice Formation							
0000	7.020	8.706	9.077	9.818	10.768	14.470	15.815
0400	3.660	5.405	5.500	6.413	7.327	11.280	12.289
0800	1.440	2.446	2.452	3.363	4.251	10.152	17.941
1200	1.010	1.997	2.000	3.182	5.352	21.429	23.379
1600	5.790	12.216	15.924	15.871	17.175	20.839	22.861
2000	7.680	11.790	12.723	13.133	14.161	17.760	19.521