# Rapid Windshield De-Icing using Solar Thermal Fuels

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## ABSTRACT

The current mechanism for defrosting automobile front windshields is using waste heat from the engine to heat the windshield via convection, an inefficient process taking up 30 minutes. A new de-icing system using a transparent thin film from a templated solar thermal fuel could rapidly de-ice a windshield using stored solar energy. As a step towards assessing the viability of this new system, the amount of energy necessary to form the critical water layer that breaks the bond between the glass and ice and causes the ice on a windshield to slide off was measured to be 4.3 J/cm$^2$. Using these results, Stefan theory, and a surface energy pulse heat transfer model, we predict that the thin film system could de-ice a windshield in less than two minutes, with potential to be even faster depending primarily on the thickness of the windshield.

**Keywords-**De-icing, Windshield, Solar Thermal Fuel, Stefan Theory,

## 1. INTRODUCTION

A windshield that has frosted over, impairing visibility and making driving dangerous is an almost universal experience of automobile owners who live in climates where temperatures can go below freezing. The primary technology available in the vehicle for removing the frost layer is simply to blow warm air onto the windshield; because of visibility issues, front windshields cannot be defrosted using the heating elements that are used to de-ice rear windshields [3].

The use of warm air to defrost a front windshield dates back more than 70 years to the earliest automobiles, and has not really been improved upon, despite the major disadvantages inherent to such an approach: its long length of time and its inefficient transfer—and therefore use—of energy, due to the low heat capacity of the air that carries the heat from the engine to the glass [8]. Current de-icing begins by running a car—burning gasoline—only to use the waste heat the engine generates to warm air, then blowing the air through the defroster nozzles to heat the windshield and the ice. De-icing a front windshield with this approach can take between ten and thirty minutes to reach safe driving conditions [3] [4].

The source of the problems associated with this de-icing system is the use of warm air generated by the waste heat of the engine. The massive energy inefficiency of this approach is the result of the requirement of running the automobile for up to 30 minutes, burning gasoline not to move the car but only to heat up air. Furthermore, as electric cars become more prevalent, there will no longer be the steady supply of “free” waste heat from the engine that is currently used to provide the energy for de-icing.

The other major drawbacks with using warm air to de-ice lie in the slow conductive heat transfer and the inability to rapidly and uniformly heat the windshield, which together are the underlying reasons it can take up to 30 minutes to fully de-ice a car. The temperature distribution of a windshield that has been heated with warm air for nearly 30 minutes, as measured by [2], is shown in Figure 1a, where it is readily apparent that the temperature of the windshield is strongly dependent on the distance from the defroster nozzles. Figure 1b shows the consequence of such an uneven temperature distribution, in terms of the resulting slow and uneven de-icing.

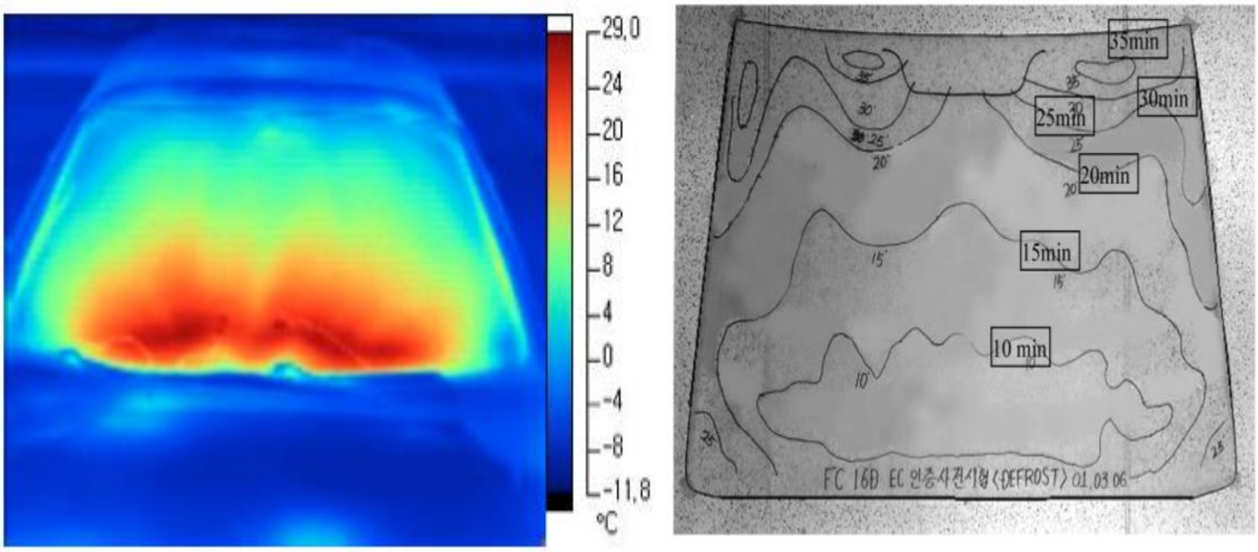


Figure 1 (Left) Measured temperature contours for a windshield, reproduced from [2], and (Right) Experimental windshield defrosting pattern from [4].

In order to overcome the intrinsic limitations of the conventional warm-air de-icing approach, we examine here the potential advantages of a new type of de-icing system, one based on uniform, rapid windshield heating from a transparent thin film made from a solar thermal fuel. A solar thermal fuel is a material that uses light absorbing molecules to capture and store solar energy at the molecular level [7], and when triggered, releases this stored energy in the form of heat. Solar thermal fuels store emission-free sunlight energy and are closed-cycle: they can in principle be recharged up to tens of thousands of times, and the release of the stored energy can be triggered thermally, optically, with a catalyst, or even passively by tuning the storage lifetime. The material can be liquid or can be deposited into thin films for solid-state applications, as would be the case for the proposed de-icing system. This new concept for de-icing has the potential to address the largest problems with the warm air system: namely, its time-consuming nature and reliance on waste heat. A transparent, solid-state solar thermal fuel windshield de-icing system could provide a way to heat uniformly over an entire windshield to a controllable temperature. The system would be completely rechargeable assuming the presence of sunlight. Because a thin film of a solar thermal fuel would uniformly heat the entire windshield, it would result in a thin layer of water melting between the ice and glass, breaking the bond between the two surfaces and causing the entire sheet of ice or frost to slide off the windshield.

In order to assess the potential advantages of a solar thermal fuel de-icing system, we must first address the following crucial question: can a thin film made from a solar thermal fuel store enough energy to de-ice a windshield but remain transparent in the visible part of the spectrum? Obtaining an answer to this question is the focus of this work.

## 2. BACKGROUND

Previous research on windshield defrosters concluded that although the systems do meet the federal guidelines for deicing, the airflow the nozzles provide is highly uniform and results in an uneven temperature heating pattern [1]. As figure 1 shows, the defroster nozzle systems result in slow deicing due to the large temperature gradient across the windshield [4]. In addition, these types of systems melt almost no ice during the first five minutes of use [1].

Research into alternative methods for de-icing has focused on two other areas: conducting thin films and heat storage devices [3]. Heat storage devices use latent heat, rather than waste heat from the engine, to heat the air used in the defroster. While this method addresses the issue of wasting gasoline to warm the car, it still relies on warm air blown through a defroster nozzle, which cannot overcome the problems of uneven windshield heating and long de-icing times [6]. Any de-icing system that relies on waste heat will have the same shortcomings as today's nozzle systems. The concept of electrically heating transparent conducting thin films [5] could overcome this drawback although cost remains a challenge.

A transparent thin film made from a solar thermal fuel represents a combination of these previous ideas based on transparent thin films and latent heat storage, in a new approach that has the potential to rapidly de-ice a windshield using energy from the sun. The film would be integrated directly into the windshield like a transparent conducting thin film, and would store solar energy chemically that it could later be triggered as a heat source to de-ice a windshield. Table 1 compares the key features of different de-icing systems, including the proposed solar thermal fuel transparent thin film.

Table 1 Comparison of De-icing Systems

| Type of System | Defroster Nozzle | Thin Conducting Wires | Transparent Conducting Thin Films | Latent Heat Storage | Solar Thermal Fuel Thin Film |
|---|---|---|---|---|---|
| Power Source | Waste Heat from gasoline | Electricity from Car Battery | Electricity from Car Battery | Stored latent heat | Stored Solar Energy |
| Transparent | Yes | No | Yes | Yes | Yes |
| De-icing Time Range (minutes) | 20-30 | < 5 | < 5 | 20-30 | < 2 |
| Direct Contact | No | Yes | Yes | No | Yes |

Solar thermal fuels are not new, although they have had little technological impact due to low energy densities, short storage lifespans, and degradation [7]. Recently it was shown [7] that templating photoswitchable molecules can lead to solar thermal fuels with improved energy density (on the order of that of Li-ion batteries), thermal and mechanical stability, and high cyclability. This new type of solar thermal fuel opens new opportunities for applications based on such materials.

In this paper, we combine Stefan theory with experimental measurements in order to answer the question posed above, to determine the amount of energy necessary to de-ice a sheet of glass. Previous work used Stefan theory to model the process of defrosting and other phase change problems using the enthalpy method [4]. Stefan theory separates the de-icing process into two time segments, heating time and melting time [5].

Using the framework of Stefan theory, in the de-icing process a layer of water is formed at the glass-ice interface and the thickness of the water layer and its time rate of change are used to characterize the process. When the water layer reaches a critical thickness, the remaining ice will slip off of the glass, which can then be considered de-iced. Given this framework, determining the potential of using a solar thermal fuel approach to de-icing means measuring the energy necessary to melt this critical distance of water.

## 3. MATERIALS & METHODS

The purpose of the experiment was to measure the amount of energy a block of ice absorbs before slipping off a sheet of glass by using a resistive heater to model the uniform conductive heating provided by the solar thermal fuel thin film. This corresponds to the amount of energy necessary to melt the critical water layer that causes the ice to slip. From this measurement, the required thickness of the solar thermal fuel thin film can be estimated.

The procedure for the experiment was to first freeze a block of ice onto a sheet of glass equipped with K-type thermocouples to measure its temperature. The glass was then heated until a critical layer of water formed and the block of ice slipped. The heater was then turned off and the system was allowed to cool until it returned to its initial cold temperature. The glass was then reheated for the same amount of time, but without the block of ice. When glass is heated with ice on it, the temperature is lower because of the energy absorbed by the ice as it melts.

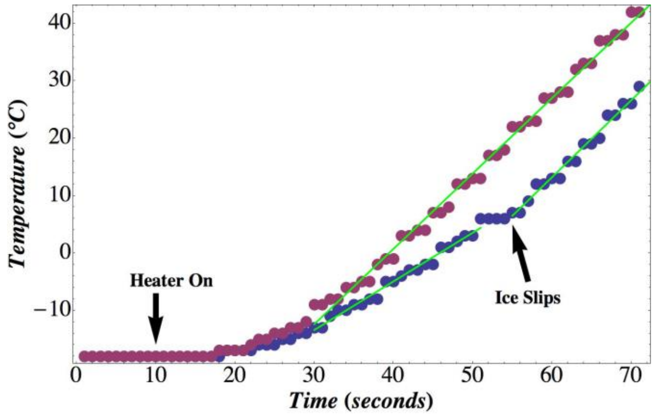


Figure 2 Glass temperature with (red) and without (blue) the ice frozen onto the surface of the glass. The discontinuity in the temperature with the block of ice marks the point in time when the block slips. The temperature difference between the two sets of data at the point is used to calculate the energy the block absorbed to slip.

Without the block of ice to absorb heat, the glass temperature is higher. Taking the difference between the two temperatures allows for the measurement of the amount of heat the block of ice absorbed, as shown in Figure 2 for one particular measurement.

Although this method does not directly reflect the much more rapid heating of a solar thermal fuel thin film, it still allowed us to measure the amount of energy required to form the critical water layer, which should be the same regardless of the method of heating.

In order to obtain an accurate measurement of the surface temperature of the glass (McMaster Carr Heat Resistant Borosilicate Glass, 3'' by 3'' by 1/8'') with the K-type thermocouples thin slits were etched into the glass surface using a sandblaster and polyurethane adhesive-backed rubber (McMaster Carr Medium Hard Adhesive Back Rubber; Polyurethane 6'' by 6'' by 1/8'') to protect the glass surface. The thermocouples were then embedded into the slips and covered with heat resistant Kapton tape. The block of ice was then frozen on the other side of glass directly opposite the thermocouples. This allowed for the measurement of the temperature of the glass directly below the block of ice.

Once the etched glass was prepared, it was placed in contact with the silicon heater (MacMaster 12'' by 12'' 10 W/in^2 Silicon Heater). Figure 3 shows a schematic of the experimental set up. In order to confirm that this setup was uniformly heating the surface of the glass, IR images were taken. Temperature isosurfaces from those images are shown in figure 4, confirming the uniform glass temperature.

Once the glass-heater system was prepared, a round block of ice, frozen in a 3.35 ± 0.01 cm diameter round plastic mould was allowed to freeze on the middle of the glass, directly over the thermocouples in a 1.8 Cu Ft display freezer. The system was then left overnight to ensure that the block of ice had fully solidified.

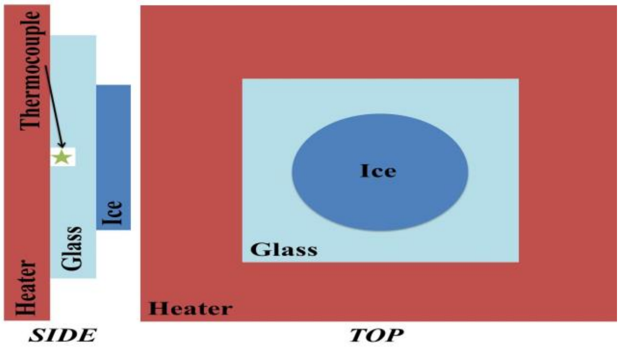


Figure 3 Conceptual schematic of the experimental system.

The sheet of glass with the frozen block of ice was suspended inside the freezer using binder clips. The heater was then turned on and the temperature of the glass was recorded wirelessly from thermocouples as the ice and glass slowly heated and the ice melted. After the block slipped, the heater was left on and data was recorded for 75.

The heater was then turned off and the glass was cooled to its initial temperature, undisturbed. Once returned to its initial state, the glass was reheated for 75 seconds and its temperature was once again recorded. During this second run, the glass reached a much higher temperature because there was no block of ice to absorb heat.

## 4. RESULTS

Using the above procedure, data was collected for seven different runs. Figure 5 shows the average of the results over the seven runs along with linear fits that show the effect of the ice melting and thus changing the rate of change in the glass temperature. The difference between the surface temperature of the glass with ice and without ice is evident, and suggests that the experimental setup used allows for enough accuracy to measure the amount of energy required to melt the interfacial layer. The point at which the block slips is represented by the discontinuity in the temperature and slope of the glass surface temperature with ice. This discontinuity is then used to calculate the energy absorbed by the block of ice, which is equal to:

$$E = \frac{\Delta T * m * c_p}{A} \quad (1)$$

where E (J/cm$^2$) is the critical energy required for the ice block to absorb in order to slip, ΔT (C) is the temperature difference between the glass surface with and without ice, m (kg) is the mass of the glass directly under the ice, $c_p$ (J/kg C) is the heat capacity of the glass, and A is the area of the ice block in cm$^2$. The materials parameters are given in Table 2. The mass of the entire sheet of glass was measured as 40.384 ± 0.001 grams. The area of the block of ice was set by the diameter of the mould at 8.81 ± 0.05 cm$^2$, and the area of the entire sheet of glass was 56.08 cm$^2$ (9 in$^2$). Taking the ratio of the two areas and multiplying by the mass, the mass of the area of glass directly below the sheet of ice is 6.34 g.

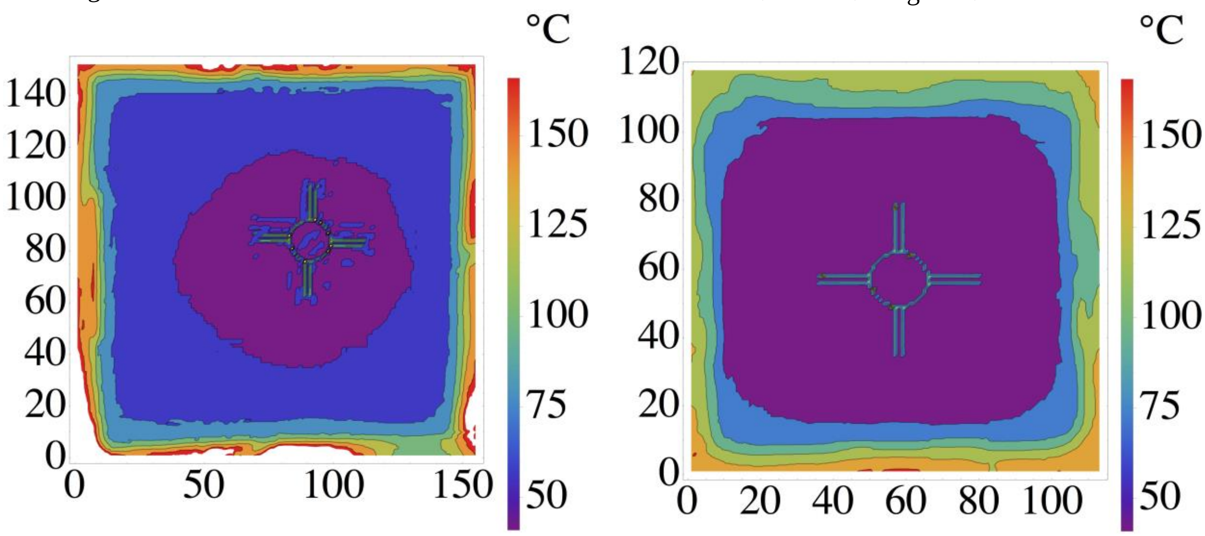


Figure 4 Visualizations of temperature isosurfaces from IR Camera images. The glass is the darker square and the heater lighter colored area directly behind it. On the left is the glass with the block of ice frozen as it heats up. On the right is the ss heating without the ice with a uniform surface temperature.

Using the temperature difference, mass, and heat capacity, the normalized energy the block of ice absorbed to create the critical water layer was calculated to be 4.3±1.5

J/cm^2. In order to find the critical water layer distance, we use the following equation,

$$d = \frac{E}{H*\rho} \quad (2)$$

where d is the critical distance, E is the energy calculated in equation 1, H is the enthalpy of melting, and ρ is the density. We find that our measured value of the energy density results in a critical water layer distance of 0.14 mm. Using an energy density range of 100-500 Watt-hours per liter [7], according to this result the solar fuel thin film would have to be between 24-120 microns in order to store enough energy to deice a windshield.

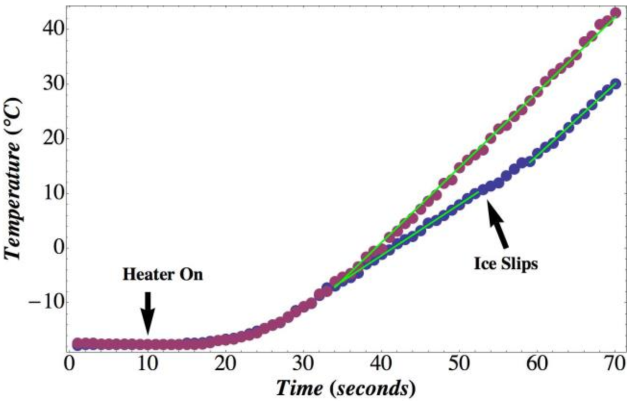


Figure 5 Average glass temperature for all seven runs

Table 2 Material Properties

| *Material* | Car Glass | Ice |
|---|---|---|
| *Density (kg/m^3)* | 2190 | 920 |
| *$C_p$ (J/kg K)* | 740 | 2040 |
| *K (W/m K)* | 1.38 | 1.88 |
| *Latent Heat (kJ/kg)* | - | 334.96 |

Using our measurement of the energy required to form the critical water distance, we then tried to model the heat transfer from the solar thermal fuel thin film system in order to predict the de-icing time. Our model was focused on understanding the heat transfer through the glass into the ice, the rate-limiting step in our system. Our model neglected the energy to raise the ice temperature to 0°C, and instead assumed a fixed temperature boundary condition at the glass ice interface. Because the enthalpy of melting is ten times greater than the energy needed to raise the ice temperature for temperatures above -20 °C, neglecting that energy is a reasonable assumption. Furthermore, using a fixed temperature boundary condition allowed us to model the glass as a semi-infinite body and use an analytical solution to the heat equation.

Our model was based on a surface energy pulse solution to the heat equation, with the temperature of the glass as a function of position and time equal to Equation 3,

$$T = T0 + \frac{E}{\rho * c * (\pi * \alpha * t)^{1/2}} * e^{-x^2/(4*\alpha*t)} \quad (3)$$

where T0 is the initial temperature of the glass, 0°C for our case, ρ is the density of the glass, α is the thermal diffusivity, t is time, x is position, and E is the surface energy of the solar thermal fuel.

Using this model, the temperature of the glass as a function of time was calculated for several different conditions and used to calculate the heat flux into the glass by equating the flux out of the glass at the glass-ice interface to the flux into the ice. Integrating this flux over time gives total energy absorbed by the ice and can be used to calculate the time when the ice as absorbed enough energy to melt the critical thickness. Figure 6 shows the de-icing melt time as a function thickness of the glass for several different thicknesses of thin film made from a solar thermal fuel with an energy density of 300 Wh/L. The results show that the melt time is most sensitive to thickness of the windshield, and that the solar thermal fuel thin film has the potential to de-ice a car in less than 30 seconds.

## 5. DISCUSSION

When considering the results of both the experiments and the simulations, it is important to consider the limitations and sources of error. One limitation is the precision of the thermocouples, which only resolve the temperature to the nearest degree. Furthermore, our receiver could only transmit data at a rate of one point per second. We believe this is the reason for the large standard deviation in our measurement of the melting energy. Differences in the position of the block of ice on the glass mean that the thermocouples are not measuring the temperature of the same region of the ice and could be a source of error.

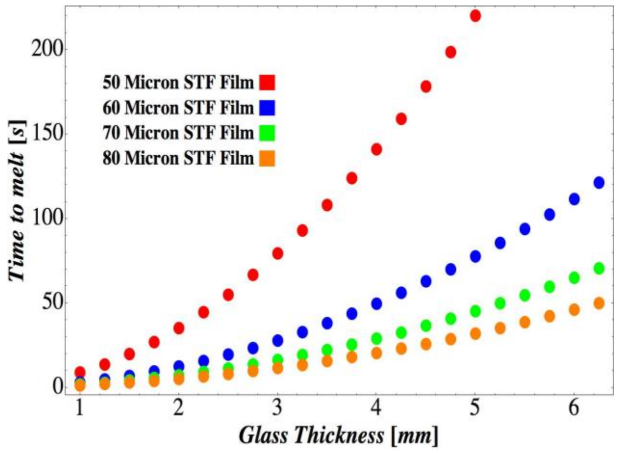


Figure 6 De-icing time as a function of windshield glass thickness for several thickness thin films as calculated from the surface energy pulse model. The curvature of the lines indicates that melt time is super-linear with glass thickness: reducing that glass thickness by a factor of two reduces the melt time bv more than two.

Another source of variation in the experiment lies in the mass and area of ice. Although the same mould was used to form all the blocks of ice, it is possible that the mass of water poured into the mould varied slightly from one run to another. Because the only variable that changed between runs was whether or not the glass had ice on its surface, all other losses should be the same between runs and should cancel when the two temperatures are subtracted. Therefore, we believe that the measured temperature difference was in fact due to the energy used to form the critical water distance.

The main assumptions in our surface energy pulse model were that there is no energy lost at the surface and that the glass is a semi-infinite solid. Because the last is fixed to the ice, we believe modelling it as a semi-infinite body with the temperature fixed at 0 degrees C is a valid assumption. Because the thin film will be embed in the windshield, it is also reasonable to assume that there will be no surface losses, especially considering the rate of heat transfer via conduction through the glass is far greater than convective transfer.

In addition to the thickness, the optical properties of the thin film also play an important role in de-icing performance. Both the spectral range of absorbed light and the penetration depth are relevant parameters. The templated solar thermal fuels can be engineered to absorb in the UV part of the spectrum and to avoid the visible range, resulting in an optically transparent film. This will allow for optical transparency and the use of thicker films. A film absorbing in the UV range would have the additional benefit of blocking (because of absorption) the transmission of UV light to the vehicle interior. Under these conditions, the use of UV blocking layers in windshields may not even be necessary.

Finally, it is important to note that the glass used in our experiments does not reflect the complexity of windshield glass, which may add additional constraints to the thin film. Windshield glass contains additional materials including polymer films for adhesion, as well as certain optical and mechanical requirements. Determining how these constraints will affect the viability of the system is an important next step in this work. The other logical next step is to design a new experimental setup not only with more precise temperature measurements but also with heat source closer to the surface energy pulse the solar thermal fuel thin film will provide.

## 6. CONCLUSION

In this work, we have taken the first step towards assessing the viability of a transparent thin film windshield de-icing system made from a template solar thermal fuel. The advantage of such a system is its ability to rapidly de-ice a windshield without the use of waste heat. Our measurement of the energy needed to create the critical water layer predicted by Stefan theory shows that the thin film needs to between 24-120 microns. Using a surface energy pulse solution to the heat equation, we modelled heat transfer into from the film, through the glass, and into the ice in such a system, showing that that it has the potential to de-ice a windshield in less than 30 seconds, depending on the thickness and position of the thin film.

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