Research article

Thermal picks for anchoring on icy moons

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ABSTRACT

Europa, Enceladus, and other icy moons are exciting science targets, but our capabilities to adequately explore these planetary bodies needs to be developed. Gripping the surface ice may aid the stability and mobility of surface landers and mobile explorers that are sent to the surface of an icy moon. This paper presents an approach to anchoring into the surface of an icy moon using a heated pick.

The proposed thermodynamic approach contrasts with the traditional mechanical approach to inserting terrestrial ice anchors. This thermodynamic approach maintains the ice structure to provide a reliable hold. The low temperatures and lack of a significant atmosphere on most of the icy moons cause surface conditions to stay below the triple point of water, the primary constituent of the surface ice for both Europa and Enceladus. Under these conditions the surface water ice will sublimate when sufficiently heated. The thermal pick concept presented in this paper is used to study the nature of the sublimation that results from forced insertion of an object into ice, which could then be used as an anchor for stability and mobility.

While the surfaces of the icy moons are composed primarily of water ice at cryogenic and vacuum conditions, the nature of a sublimation process can be more readily examined with frozen CO_2, which sublimates under atmospheric conditions. This paper explores the physical phenomena and thermodynamic design considerations of a heated device that uses a sublimation based insertion into frozen CO_2 under atmospheric conditions. This approach was found to allow for proper insertion of thermal picks with energetic efficiencies of up to 90%.

1. Introduction

Cassini's mission to Enceladus and the planned Europa Clipper mission already have and will continue to provide foundational information on the nature of our solar system's icy moons. Missions aimed at exploring and researching their surfaces will be difficult, but vital to expand our understanding. It is not yet known what surface features will be found, but it is certainly possible that they will include crevasses, cliffs, penitentes, or other extreme terrains. Even without specific information on surface features, the study of mobility schemes for use on a range of possible icy planetary surfaces generally can inform vehicle design or act as a foundation for mobility research once the relevant surface conditions have been determined.

Approaches to human exploration of extreme terrestrial icy terrains traditionally leverage the strength and coordination of the user. In order to climb extreme icy terrains, ice climbers frequently use crampons and ice picks, which require physical force and can damage the ice even when properly used. Visual and tactile assessment of the ice condition and hold quality can be used by the ice climbers, but extending this technique to

sensory-limited robotic applications presents issues. Ice anchors (e.g. ice screws) are also used in the toolkit of ice climbers and provide a static hold that can support a significant load [1, 2]. Terrestrial ice screws require significant force and torque to insert, which may be difficult for a robotic system. However, a thermal approach to inserting an anchor into the ice can bypass the necessary brute force and provide an appealing alternative for mobile robotic systems on the icy moons.

Boring into ice can be accomplished through either mechanical or thermal means, both of which have terrestrial analogs. Mechanical drilling into cryogenic water ice has been studied [3] and has been shown to have a low specific energy cost (60 MJ m^{-3}), but any cutting process has the potential to impart stresses to the adjacent ice structure and cause damage to it. Maintaining the structural integrity of the adjacent ice structure is essential for ensuring its ability to be used as an anchoring point. Thermal drills and coring devices have been developed for terrestrial use and are commercially available. These devices are highly impacted by the ambient ice temperature and have not yet been sufficiently tested in cryogenic water ice but may be able to operate without negatively impacting the adjacent ice structure.

Studies of thermal drills for water ice use have been produced by Kaufmann [4], Kömle [5], Ulamec [6], Davis [7], Biele [8], Weiss [9], and Horne [10]. The water ice found on the surfaces of the icy moons is often below its triple point, preventing the stable existence of its liquid state. Kaufmann et al [4], showed that melting can occur for water ice in a vacuum, although a thermal drill used under these conditions is still expected to result primarily in sublimation, which is the transition of a solid directly into gas, bypassing the liquid phase entirely. The primary thrust of this paper is to gain a better understanding of the sublimation process as it pertains to thermal drills. In order to quickly develop a foundational understanding of sublimation thermal drilling, this study uses frozen carbon dioxide. Under atmospheric test conditions, carbon dioxide will sublimate instead of melting, leading to the nickname "dry ice". Using dry ice allows for quickly adapting and repeating experimental tests, laying the groundwork for future testing of cryogenic water ice in a vacuum chamber.

The primary differences between dry ice and water ice as it pertains to the sublimation process are the density, temperature, and latent heat of sublimation. The dry ice used has a measured average density of approximately 1.35 g/ccm, while the latent heat of sublimation is 0.571 kJ/g. On the other hand, the density of water ice is 0.917 g/ccm, while the latent heat of sublimation is 2.77 kJ/g. The resulting volumetric sublimation energy required for dry ice is 30% relative to water ice. Bulk ice temperatures below the sublimation point will require additional heating energy and cause conductive losses, but these effects are not present in isothermal dry ice which makes up the bulk of the data. Subcooling of the dry ice below its sublimation temperature was achieved in limited cases using liquid nitrogen. While subcooling introduces an additional disparity between water ice and dry ice due to their differing thermal conductivities, the subcooled tests were primarily used to assess the phenomenological differences in the sublimation process. Finally, there are also mechanical differences between dry ice and water ice, but they have not been quantified.

This body of work aims to quantify the thermal impacts of pick design and operational differences. This is achieved through a set of picks, which are compared to one another to isolate various aspects of the design. The design variables considered were size, tip shape, wall geometry, temperature, heater power, wall insulation, and duty cycling.

2. Experimental setup

2.1. Hardware

Two separate test rigs were developed in order to assess the sublimation characteristics of a range of developed thermal picks. The test rigs differ primarily in their motion types and insertion approach. The first test rig uses linear motion and weights to produce a force-controlled insertion. The second test rig uses "screw" motion (coupled linear and rotation) from a lead screw and a stepper motor to provide a tapping position-controlled insertion.

The linear test rig is composed of two linear sleeve bearings supported by a frame, and a driving rod as seen in Figure 1, above which is a weighted plate to apply the insertion force. The thermal pick is connected to the driving rod by means of the G-10 coupling, which allows for unrestricted linear progression into the ice. The G-10 coupling was used for its low thermal conductivity (0.288 W/m-K) to insulate the thermal pick from the adjacent test rig components. The coupling is a tube that attaches to both the driving rod and thermal pick using set screws. This
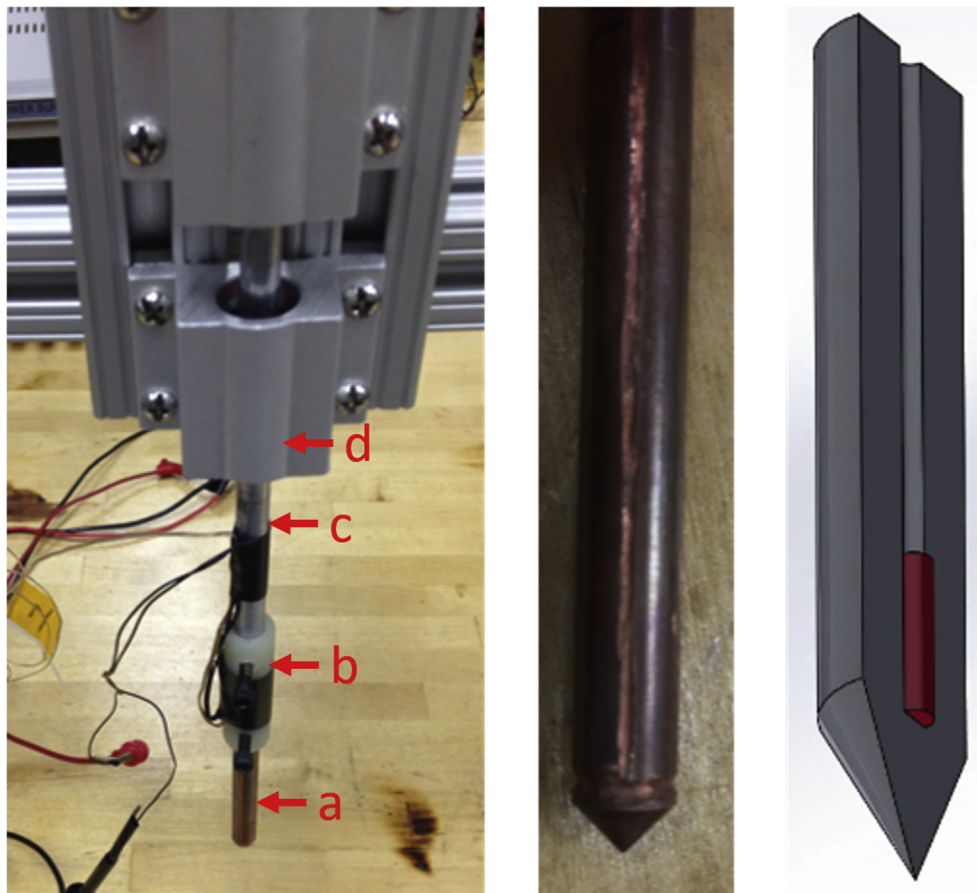
Figure 1. Linear test rig with a) thermal pick, b) G-10 thermally insulating coupling, c) driving rod, and d) sleeve bearings (left). Conical pick with pressure relieving grooves (center). Conical pick model cross-cut showing embedded heater (right).

linear rig allows for a weighted force-controlled insertion into the ice, but can also be manually controlled. The ability to manually control the rig provides useful tactile, visual, and auditory feedback during the sublimation process, allowing for a thorough investigation of the sublimation phenomena. The linear test rig was used to test all cylindrical profile picks (Table 1: a-e), but not the screw-type (rotary) pick (Table 1: f).

The rotary test rig (Figures 2 and 3) is composed of a stepper motor, a lead screw, a slip ring, and a stabilizing sheet. The stepper motor rotates the lead screw, which follows a prescribed path set by the lead screw nut, resulting in a coupled linear-rotational motion. The discrete steps taken by the stepper motor result in a stepped linear progression of the thermal pick. The lead screw and nut are not back-drivable, which causes all forward progress made by the thermal pick to be permanent, unless the motor is run in reverse. The G-10 stabilizing sheet serves to restrict the pick's lateral motion at the insertion point, which was added due to excessive lateral play in the test rig.
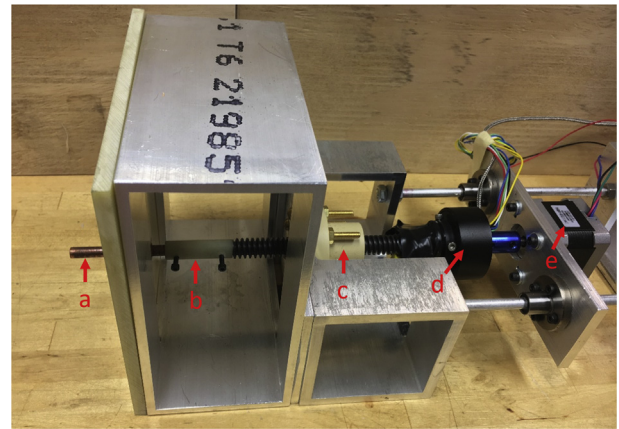
When the rotary test rig is used with a screw-type thermal pick that has a pitch matching that of the test rig's lead screw, the thermal pick will only contact the dry ice surface at the leading edge of the pick and not on the threads. As a result, insertion into the ice produces a threaded borehole such that the thermal pick cannot be pulled linearly out of the ice. When thermal picks with a cylindrical profile are used with the rotary rig, the pick will rotate as it progresses linearly into the ice. The rotation of these cylindrically symmetrical picks does not have any observed impact on the sublimation process relative to their use on the linear test rig. The entire set (Table 1: a-f) of thermal picks was tested on the rotary rig, which is both position-controlled and fully automated.

Controlling the motor and heater as well as taking readings from the thermocouple are accomplished through the use of an Arduino MEGA and associated electronic components. A relay, motor micro-controller board, thermocouple amplifier, heater power supply, and motor power supply, are all controlled by the Arduino board. The slip ring allows the power and the thermocouple signal to pass down to and up from the thermal pick, which is necessary given the ~17 rotations made for a 50.8 mm insertion.
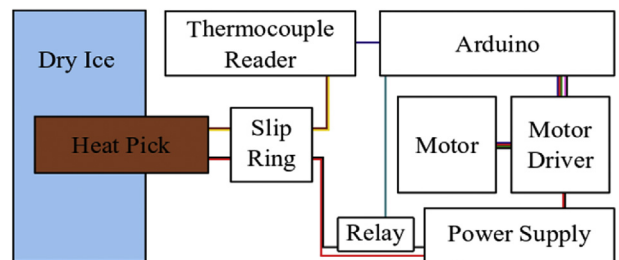
The set of thermal picks used vary by tip shape, wall material, core material, size, and threading. Each thermal pick is outfitted with an embedded 30 Watt, 24V-DC cryogenic cartridge heater (3.18 mm diameter x 25.4 mm length), and a K-type thermocouple embedded at the tip. While the embedded cartridge heater has a heating profile that is not characterized, it is assumed to output heat evenly across its surface for the purposes of this study. The thermal picks are mounted to the test rigs using a Garolite G-10 coupling chosen for its low thermal conductivity (0.5 W/m-K). The capabilities of these picks to be used as load bearing anchors were not considered. Instead, the thermal picks used in this study were designed to examine the characteristics of the sublimation process. All picks are built to a 63.5 mm total length with a 50.8 mm insertion depth. The six picks that were tested are shown in Figure 4. While an individual screw-type thermal pick (f) can be used for anchoring, multiple cylindrical picks (a-e) must be used in a non-

Figure 2. Rotary test rig with a) thermal pick, b) G-10 thermal insulation, c) lead screw nut, d) slip ring, and e) motor.

Figure 3. Rotary test rig schematic showing the system's major electronic components.

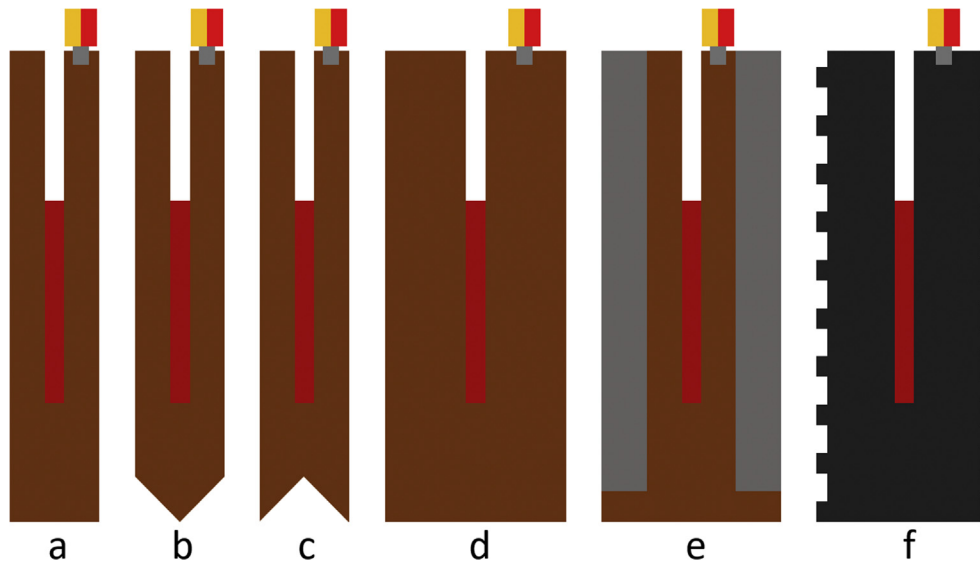colinear orientation to provide an anchor that can support axially directed loads.

2.2. Test procedure

The test procedure was developed to determine the thermal efficiency and the time spent sublimating. Due to its variability, the density of each dry ice block was calculated prior to testing. A cylindrical "plug" of ice was cut and its diameter, length, and weight were measured. The dry ice densities were found to be consistent throughout a given block, but between blocks the densities ranged between 1.2 g/ccm and 1.45 g/ccm. Due to dry ice storage time of over a day between its formation and testing, it was assumed to be approximately isothermal by the time of testing.

Completing a full thermal cycle allows for the accounting of the total sum of energy used in the sublimation process. The test procedure involves starting the sublimation process at a target temperature as read by the embedded thermocouple, performing the sublimation action, and then returning to the target temperature. This full cycle allows for differences in temperature and the corresponding thermal energy storage to be neglected. The four thermodynamic processes of the test procedure are as follows.

(1–2) Heating up to the target temperature
(2–3) Insertion into ice and maintaining the target temperature
(3–4) Removing from ice and settling of the thermal gradient
(4–5) Heating back up to the target temperature

The target temperature is a chosen value and is maintained by a thermostat-based control, which cycles the heater. If the embedded thermocouple reads a temperature of 1 °C above or below the target temperature, the heater is turned off or on, respectively. The temperature measurements and thermostat control are performed by the Arduino

Table 1. Thermal pick variants prototyped and tested.

	Diam.	Tip Shape	Material	Misc.
a	6.35mm	Flat	Tellurium Copper (Cu 145)	
b	6.35mm	45° Conical	Cu 145	
c	6.35mm	45° Inverse Conical	Cu 145	
d	12.7mm	Flat	Cu 145	
e	12.7mm	Flat	Cu 145 and Titanium (Al6V4)	3.18 mm thick titanium walls
f	12mm	Flat	Aluminum (EN-AW6060)	Threaded 3mm pitch 2mm depth

Figure 4. Sketched cross-sectional cut showing the geometry of each thermal pick variant and thermocouple location. Colors represent copper (light brown), titanium (gray), aluminum (dark gray), cartridge heater (red), and thermocouple (red/yellow/gray).

microcontroller, which also tracks the timing of events. The lower bound of the target temperature is 0 °C, below which sublimation occurs slowly enough such that heat exchange with the ambient environment becomes significant, while the upper bound of 90 °C is a physical limitation of the thermal paste used.

The total time that the heater is on between state 2 and state 5 is recorded by the Arduino microcontroller as τ_h and is used to determine the total input energy. The insertion time between state 2 and state 3 is when sublimation occurs and is recorded as τ_i.

The efficiency of the process is calculated as the comparison between the ideal energy required for the sublimation of a perfect borehole (E_i) and the actual energy output by the heater (E_o).

$$\eta = E_i / E_o \tag{1}$$

The calculation of the ideal energy requires the minimum borehole volume (V), the density of the ice (ρ), and the latent heat of sublimation (Δh).

$$E_i = V \rho \Delta h \tag{2}$$

Assuming an average measured dry ice density of 1.35 g/ccm, the ideal energy costs for sublimation are approximately 5.05 kJ for the 12.7 mm diameter picks, 1.13–1.26 kJ for the 6.35 mm diameter picks, and 3.15 kJ for the screw-type pick.

The last phase of heating back up to the target temperature is only required due to the relatively large thermal mass in the thermal pick. The pick starts at a temperature of up to 90 °C and ends the test as low as -30 °C. Given that the pick mass is 14.5 g for the 6.35 mm diameter picks and 58 g for the 12.7mm diameter picks, this corresponds to 0.67 kJ and 2.7 kJ of thermal reserves used for the small and large picks respectively. Thermal reserves are a measure of how much of the energy of the sublimation process comes purely from the thermal pick body changing temperature and assumes the thermal pick is isothermal. This means that without any active heating, the thermal pick will progress approximately 25mm into the ice before slowing dramatically, which matches the experimental findings.

The energy output by the heater uses the tracked heater time, the applied voltage (V_h), and the measured heater resistance (R_h).

$$E_o = \tau_h V_h^2 / R_h \tag{3}$$

The thermal losses are considered as the difference between the output energy and the ideal energy.

$$E_l = E_o - E_i \tag{4}$$

The quantities measured in testing are the thermal pick temperature, total test time (from first contact with ice to returning to the target temperature), insertion time (from first contact with ice to maximum depth reached), heater time (total time the heater relay is on), commanded insertion rate of the stepper motor (rotary test rig only), and insertion force (linear test rig only).

3. Observed phenomena

The following phenomena were observed during the sublimation process.

3.1. Pushback force

The most immediately observable effects of the sublimation process are the normally directed "pushback" force and low surface friction that results from the rapid creation of gaseous CO_2. This effect has been identified in boiling liquids [11] as an inversion of the Leidenfrost effect. The thin-film boiling, first noticed by Leidenfrost [12] in 1756, is known to levitate liquid droplets above a heated surface. The inverted Leidenfrost effect is found to suspend small objects over a low temperature boiling liquid or sublimating solid, if there is a sufficient temperature differential. This has been observed between a hot surface and sublimating CO_2 and the power released by the rapid production of gas has even led to the study of sublimation engines [13].

Within the context of a thermal pick, the normal force that often causes levitation has the effect of impeding progress and reducing the rate of sublimation. When allowed to freely descend into the ice under its own weight, a thermal pick of sufficient temperature was found to have poor heat transfer rates into the ice. Lowering only under the pick's weight, the heat transfer rates into the ice were found to be far lower than the 30W heater power and this resulted in a slow sublimation process. If the critical force needed to counter this effect (similar to reaching the Leidenfrost point found in fluids) was exceeded, then heat transfer rates were consistently found to exceed the power output of the heaters used, with the additional heat being drawn from the stored heat of the pick. For the thermal picks and conditions examined on the linear test rig, this critical force was found to be between 2.5 and 5 N, which came from using either one or two 250 g weights and corresponds between 20 and 160 kPa tip pressure. This critical force required has a strong dependence

on the tip shape and the ice-to-pick temperature differential (which varies with time) making the critical force difficult to quantify, although the 250 g weight was found to be insufficient in all cases, while the 500 g weight was found to be sufficient in the majority of cases.

3.2. Surface friction

Unless actively prevented, the low surface friction would cause the thermal pick to slip laterally down a sloped ice surface. When combined with the required critical applied force to counter the Leidenfrost lift, this was found to bend the driving rod on the linear test rig and result in a deviated insertion angle. This shift would result in poor pick-to-ice contact quality and cause an oblong bore volume as the thermal pick would eventually sublimate a path back to its natural vertical position as seen in Figure 5.

3.3. Escaping sublimated gas heat transfer

Another effect of the rapid production of CO_2 gas is the high rate of heat transfer that can occur as a result. Most of the sublimation occurs at the leading edge of the thermal pick and the created gas will then escape through the most expedient path. A thin channel quickly forms around the thermal pick that both deepens (as the pick progresses into the ice) and thickens (as the ice wall erodes) throughout the sublimation process. Within the thin channel, the escaping gas is exposed both to the hot wall of the pick and the cold ice, which causes convective heat transfer to occur. Heat lost from the pick wall increases the temperature of the

Figure 5. Oblong bore caused by lateral slipping of the pick. Visual aid with desired (green) and undesired (red) bore area.

escaping gas, which in turn loses heat to the surrounding ice. Because dry ice thermally equilibrates to its sublimation point, all heat transferred to the ice wall results in unintended sublimation, which erodes the ice surface and thickens the channel. The rate of this heat loss mechanism increases with insertion depth as the exposed surface areas increase.

The borehole gap was found to vary dramatically depending on the insertion stability and depth. Stable insertions with high rates of sublimation were found to have borehole gaps thin enough to restrict outflow of gas such that pressured-based fracturing and expulsion of dry ice at the borehole lip was observed. The thermal ablation of the borehole was found to produce consistent expansion of the borehole throughout the course of a test. For insertions depths of 50mm the 12.7mm diameter thermal pick's borehole measured at the lip varied between 13.6 to 14.2mm, corresponding to a maximum gap size of 0.45–0.75mm.

3.4. Ambient losses

Heat transfer to and from the ambient environment occurs in two forms. Natural convective losses/gains occur when thermal pick surfaces are exposed to the ambient air. Conductive losses (or gains) occur through the G-10 sheet and coupling, which are directly in contact with the thermal pick. These convective and conductive losses were experimentally measured by tracking the temperature drop of a heated thermal pick over time and calculating the corresponding energy loss. The rate of loss is included in the energy accounting section.

4. Results

4.1. Stability and insertion angle

The most dramatic reductions in the efficiency of a thermal pick were found to be a function of path stability. Small cyclic path deviations and misalignments were both found in the test rigs. These were difficult to discern by eye, but they resulted in significantly increased bore volumes and expended energy. Misalignment can be caused both by issues in the test rig or by a sloped ice surface if the pick is not laterally constrained.

The linear force-controlled test rig was found to have significant issues when inserting into slanted ice surfaces due to the slipping that could occur. The oblong bores, as seen in Figure 5, would result from pick path deviation. These issues caused unpredictable efficiency reductions (often over 20%) proportional to the path deviation and resulted in overheating of the pick when the misalignment lowered the pick-to-ice contact area.

The rotary position-controlled test rig was found to have a periodic misalignment corresponding to the pitch of the screw and nut in the test rig. This was observed as a repeated sweeping lateral deviation of the thermal pick and caused a significant increase in the bored ice volume. This cyclic deviation resulted in efficiency losses of over 50% but was resolved by the addition of the stabilizing G-10 sheet into the test rig. The addition of the stabilizing G-10 sheet constrained lateral play of the thermal pick, which improved the thermal efficiency up to 90%, matching the maximum that was found in corresponding tests on the linear test rig.

4.2. Temperature and size

The impact of temperature on thermal pick efficiency is a consequence of convective and conductive heat losses. Convective losses occur at the walls of the thermal pick to sublimated and ambient gas, while conductive losses occur at the G-10 attachment points. These loss mechanisms are all dependent upon the differentials of the pick temperature relative to the ice and ambient temperatures. Lowering the thermal pick temperature was found to increase the thermal efficiency of the sublimation process, but also resulted in longer overall process times, which can be seen in Figure 6.
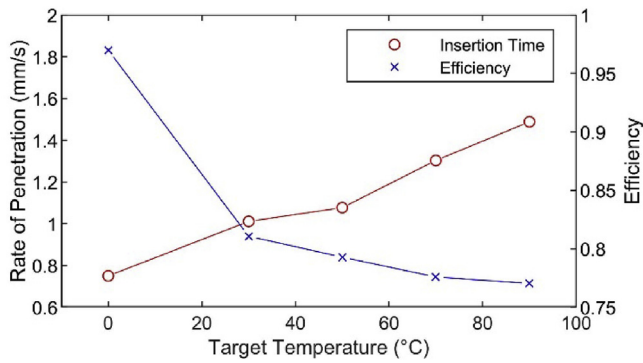
Figure 6. Inverse conical tip pick with cylindrical profile tested with varying target temperature.

The temperature of the thermal pick is determined by the power output of the heater and the specified target temperature. Adjusting the heater power alone was not found to directly impact efficiency, but could have indirect effects by influencing the temperature of the pick. A test using a constant uninterrupted heater power of 15, 22.5, and 30 W resulted in average thermal efficiencies within 1% of one another. In cases where the heater power output was too low relative to the thermal pick's size and target temperature, the 30W heater was found to be incapable of sustaining the target temperature despite remaining on throughout the test. High pick temperatures lead to pick-to-ice heat transfer rates greater than 30W, which results in cooling of the pick despite the heater remaining on.

The overall size of the thermal pick was only found to impact the efficiency of the device when it affected the temperature of the pick during the sublimation process. The smaller 6.35 mm diameter thermal picks have the same 30W heater as the larger 12.7 mm diameter thermal pick, but have a smaller pick-to-ice contact surface. As a result, the smaller picks can maintain higher temperatures throughout the sublimation process. Under low temperature conditions when both the large and small picks will sustain the target temperature, the efficiencies are closely matched regardless of pick size. However, as the target temperatures rise, the larger thermal picks quickly become unable to sustain the target temperature and have higher relative efficiencies as a result.

4.3. Wall insulation

In order to examine the possibility of reducing the thermal losses from the thermal pick walls, an insulated thermal pick was compared to an uninsulated thermal pick of the same size. The large diameter thermal pick designs (d and e) shown in Figure 7 were examined side by side.

Given the end goal of using the thermal pick as an anchor that is subject to loading, titanium was chosen for its combination of high yield strength (880 MPa) and low thermal conductivity (6.7 W/m-K). Altering the wall material was not found to significantly change the sublimation process efficiency and resulted in an 2% efficiency gain, which is within the 2.6% standard deviation of the test data. The lack of improvement is believed to be a result of the low rates of wall heat loss, the relatively large surface areas from which the losses occur, and the timescale of the sublimation process. If the energy losses from the walls were larger, it might be possible for a temperature gradient to build up in an insulated wall, but this was not found to be the case. By using a better thermal insulator, it may be possible to reduce the wall losses, but low strength materials will have an impact on the ability to reliably support an anchoring load.

4.4. Wall geometry

The development of the rotary test rig made it possible to test a threaded thermal pick. The threaded thermal pick was found to have

Figure 7. Titanium insulated pick (left) and uninsulated copper walled pick (right).

slightly lower efficiencies than the cylindrical profile thermal picks under similar testing conditions. As seen in Figure 8 the threaded thermal pick efficiency varies with the target temperature. The conductive losses are determined by the G-10 thermal isolators and are solely a function of temperature. The threading on the walls of the thermal pick is thought to increase the convective losses from the escaping gas. This increase in convective losses is believed to be the cause for the difference in efficiency between the screw-type and cylindrical profile picks. The physical consequence of these high convective losses are shown in Figure 9, where significant degradation of the threads in the threaded borehole occurs for the high temperature tests.

The second wall geometry alteration that was considered was cutting pressure relief grooves to ease the escape of sublimated gasses. Grooves were cut into the walls of one of the cylindrical profile thermal picks in order to explore their possible impacts on the normal force and efficiency. Grooves of approximately 0.6 mm depth, which can be seen in Figure 1 were found to have no noticeable impact on either the efficiency or normal force of the thermal pick. This result suggests that leading edge pressure and not drag on the escaping gas is the primary component of the normal force. More complex pick geometries may be capable of reducing the normal force, but were not explored in this study.
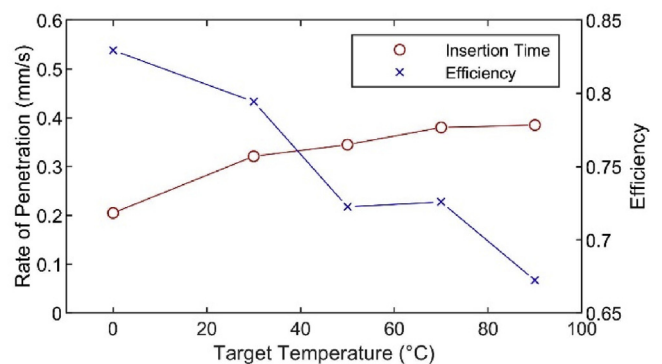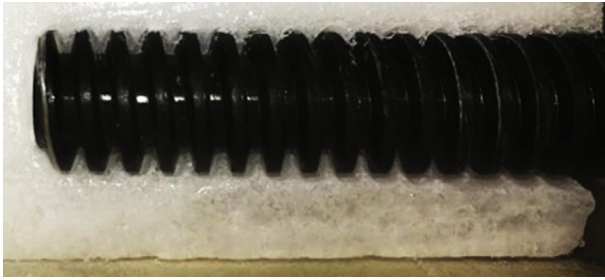

Figure 8. Screw-type pick tested with varying target temperature.

Figure 9. Cross cut of screw type pick in ice. Thread quality degrades towards the surface of the ice due to thermal erosion.

Table 2. Uncertainty in electrical components.

Quantity	Variable	Uncertainty	Effect on Efficiency	Description
R_h	Heater resistance	$\pm 0.2\ \Omega$	$\pm 1\%$	Cartridge heater (30W, 24V-DC)
V_h	Supply voltage	± 0.1 V	$\pm 0.8\%$	DC Power Supply
T	Temperature	$\pm 0.1\ ^\circ$C	-	Omega HH309 Thermocouple Reader (K-Type)
τ	Total insertion and heater timing	± 1 ms	-	Arduino MEGA
l	Distances	± 0.1 mm	$\pm 2\%$	Digital micrometer

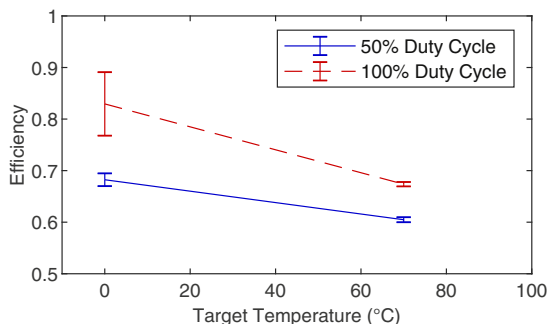**Figure 10.** Flat, conical, and inverse conical tips shown left to right.

4.5. Tip shape

In order to determine the impact of tip shape, three different thermal picks were compared. The tip shapes used were flat, 45° conical, and 45° inverse conical, shown in Figure 10. Under the conditions tested, the only difference was in the normal force. The inverse conical tip shape resulted in noticeably higher normal forces and would not overcome the Leidenfrost lift under the same applied load as the flat and conical tipped picks. However, given the normal force's strong dependence on the thermal pick leading edge temperature (which in turn depends on time and other factors), this effect was not quantified.

4.6. Duty cycling

The bulk ice temperature based conductive losses that are expected with cryogenic ice introduces a time dependent loss mechanism. Conductive losses in cryogenic water ice have been analytically modeled for a thermal drill under steady state conditions by Biele et al. [8] using the theory developed by Aamot [14] and observed by Ulamec [6]. This analysis shows that the impact of conductive losses on thermal efficiency is heavily time dependent, incentivizing the use of high instantaneous power outputs.

Reducing these conductive losses can be accomplished through shortening the time during which contact occurs, but this requires

speeding up the insertion rates. This can be achieved through higher heater powers or by duty cycling, both of which increase the pick temperature.

Thermal pick duty cycling was tested and is achieved by intermittent insertion of the pick. Between insertion steps the pick will naturally break its conduction path into the ice through sublimation, allowing the pick to warm back up. This enables higher pick temperatures and increases insertion rates during the active insertion phase. A 50% duty cycle was achieved by repeating a cycle of inserting for 5 seconds then holding steady for 5 seconds. A 100% duty cycle was achieved by constantly applying pressure to insert the thermal pick into the ice until the final depth was reached.

The reduction in efficiency observed in Figure 11 is a consequence of a higher operating temperature during the insertion phase and convective losses in that holding phase that would not be present under vacuum. While duty cycling represents a net reduction in efficiency when conductive losses are not observed, these small efficiency reductions can potentially result in a net efficiency gain when applied to a cryogenic water ice test where conductive losses are substantial. Duty cycling represents a promising approach to improving the energy efficiency of cryogenic water ice thermal drilling systems by mitigating a primary loss mechanism.

4.7. Subcooled dry ice

Subcooling of the dry ice was achieved by placing the ice on a liquid nitrogen cooled aluminum block. This approach allowed for controlled cooling of the dry ice through the medium of the aluminum block, which was found to avoid thermal shock based degradation of the dry ice. Testing using the 12.7mm copper thermal pick (d) showed no new phenomenon when penetrating a dry ice block with a measured internal temperature of -146 °C. A limited data set did not show a significant change in heat expenditures when compared to previous tests, but requires additional testing to confirm.

4.8. Energy accounting

In all cases, the bulk of the energy transfer was found to result in the desired sublimation. The remaining energy is split between convective losses to the escaping gas, convective losses to the ambient air, and conductive losses to the test rig. The convective losses due to the escaping gas were not able to be isolated from the other loss mechanisms and experimentally measured.

The convective losses to the ambient air and conductive losses to the test rig were quantified by holding the thermal picks at an elevated temperature and measuring the losses. The power loss was found to be a function of temperature differential from the environment and was measured to be 19 mW/K, resulting in estimated losses as high as 1.24 W for the 90 °C tests. These forms of heat transfer cause the 0 °C tests to overestimate efficiency, where up to 0.47 W of ambient convective and conductive heat gain may occur.

Figure 11. Duty cycling of the screw-type pick across two target temperatures.

The uncertainty in the electrical components and their impact was also evaluated (see Table 2).

5. Conclusions

The study of thermal picks using dry ice in the laboratory environment provides an understanding of basic sublimation processes that can be used to inform cryogenic vacuum testing of sublimating devices. The lateral pick stability, wall geometry, and temperature were established to be the primary factors that determine the efficiency of the process.

The stability of the thermal pick had the largest impact on efficiency, resulting in significant unnecessary sublimation. A support structure that laterally constrains the thermal pick at the surface of the ice was found to be sufficient to produce stable insertion. Increasing the complexity of wall geometry results in increased heat loss due to the larger surface area and impeding the outflow of sublimated gas. Higher operating temperatures result in increased convective losses to the sublimated gas and increased conductive losses to the test rig.

The axial force required to overcome the Leidenfrost effect and allow heat conduction into the ice surface was found to be a function of tip geometry and heat transfer rate. Tip geometries that impede the escape of sublimated gas (such as the studied inverse conical shape) will incur higher normal forces. Relieving tip pressure by introducing channels in the thermal pick wall was not found to be an effective approach to reducing the normal force, although limited designs were considered. Reducing sublimation rates will increase the overall process time, but was found to result in lower normal forces. For applications where the ability to apply axial force is limited, more complex tip geometries may be studied.

Thermal efficiencies as high as 90% were achieved. The loss mechanisms were convective heat transfer to the escaping sublimated gas and conductive losses to the test rig.

This study provides a base of information to work from before moving into the more time consuming and technically challenging hardware testing environment of a thermal vacuum chamber. Learning these lessons quickly in the laboratory environment has obviated the need to learn them slowly in a vacuum chamber.

Some of the studied characteristics yielded clear results that can be implemented in future designs. For example:

- Tips should provide an easy gas escape path.
- Wall insulation provides minimal benefit within the bounds of the materials tested.
- The applied axial force is correlated with heat transfer into the ice.
- Complex thermal pick wall geometries impede gas flow and increase convective losses.
- Size directly increases energy costs but does not appear to have an impact on efficiency.
- Stability of the pick throughout insertion is essential for good energy efficiency.

Other results yielded benefits that trade off against deficits that must be considered, such as:

- Higher temperatures speed up the sublimation process but incur larger energy losses. Thermal and operational time dependencies must inform the temperature choice.
- Duty cycling incurs additional losses but may be a net benefit if bulk ice conductive loss rates are significant.

6. Future work

Testing of sublimation devices under more representative conditions is essential to improving our understanding of how sublimating devices might function on an icy moon. Testing cryogenic water ice under vacuum is still a better representation of the expected icy moon conditions. Creating cryogenic and vacuum conditions in a thermal vacuum chamber

is a planned extension of this work and the results of this study will be disseminated in a future publication.

Declarations

Author contribution statement

Adam H. Halperin: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Raymond Sedwick: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Arjun Agarwal: Performed the experiments.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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