Methane Powered Propulsion for Energy Efficient Autonomous Exploration of Titan's Surface

Research Objective

This research project proposes to evaluate the feasibility of a Titan (one of Saturn's moons) rover propelled by compressed methane gas, using resultant thermal energy from a radioisotope thermoelectric generator (RTG). Titan's extremely low temperature (−179.5 °C) and high atmospheric pressure (1.45 atm) produce an environment that allows for pools of liquid methane to exist nominally on the surface [1]. The use of an RTG's excess heat to boil liquid methane and then use the produced gas as a propellant is anticipated to be an energy efficient method of controlled locomotion. The objective of this project is to assess the validity of the proposed propulsion system using physical theorems and computational simulations with a CFD software package (e.g. COMSOL). **The proposed research directly aligns with NASA's mission and falls under the umbrella of the Space Technology Mission Directorate. This research could spur technological advancement and promotes the efficient, low cost technology desired by NASA's Discovery program.**

Introduction

Titan represents a unique balance of environmental conditions and ease of reach that is uncommon in our solar system, which makes it a prime candidate for scientific discovery utilizing autonomous data-collecting probes. One probe already has successfully landed and carried out its mission – the Huygens Lander. Huygens landed on the surface of Titan in January of 2005, recorded and transmitted data for 90 minutes, and to this day remains the only man-made object to have landed in the outer solar system [2]. Since this landing, numerous proposals of probes have been developed ranging in breadth from a submarine to explore the depths of the methane ocean, to a non-propelled balloon that moves with the Titan winds [3]-[9].

Investigation into the Huygens Lander and other probe proposals reveals that the major design challenge is power generation and usage optimization. The Huygens Lander utilized battery power with no system to recharge the batteries once they ran out [2]. All of the previously referenced probes have been designed around the use of RTGs for electrical power generation [3]-[9]. Other power generation devices used on earth, such as photovoltaic panels, gas generators, fuel cells, etc., are not applicable on Titan due to its substantial distance from the sun and atmospheric composition. This limits electrical generation exclusively to RTGs because of their long lifespan, independence from the sun, and minimal dependence upon the operating medium [10].

Hereby, a compressed methane based propulsion system, driven by the thermal energy from the RTG, is proposed to move a vehicle on Titan. This research will focus on such an alternative, non-electric based propulsion method that will allow for control over the locomotion of the probe, with minimal limitation to the potential power able to be devoted to other subsystems.

Investigation Methods

Figure 1 shows a schematic diagram of the proposed propulsion system. This propulsion system takes advantage of the unique environmental conditions present on Titan. Titan's considerable distance from the sun results in a minute solar flux (15 W/m^2) [11], which in combination with the opaque atmosphere, produces cryogenic conditions on the surface [1], [4]. The proposed system collects liquid methane on Titan and vaporizes it using the thermal energy from a RTG. The produced compressed methane is then directly used for propulsion. Figure 2 illustrates that at Titan surface conditions (low temperature and high pressure) methane exists in liquid phase. The lower level atmosphere contains, on average, 5% vaporized methane, which yields methane cycles analogous to water cycles experienced on Earth [1]. Coinciding with the vaporized atmospheric methane is a polar ocean with various protruding deltas and rivers that span down toward the equator [1], [3], [4].

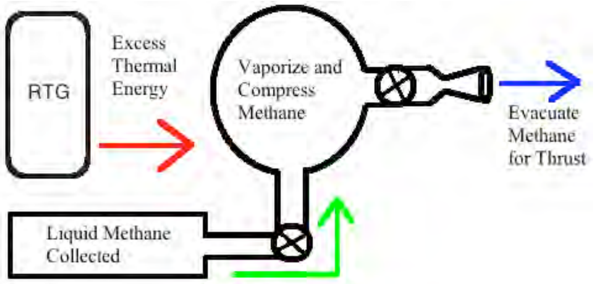

Figure 1: Compressed Methane Propulsion System Overview

The methane propulsion system can be thought of as a whole process consisting of three stages. The first stage is the gathering stage and consists of collecting liquid methane directly out of the liquid methane ocean. A potential mission using this system for a surface probe would land a small station on the shore between the methane ocean and land. This station would gather the liquid methane to be transferred to the probe. The benefit to collecting and pressurizing liquid methane rather than atmospheric gases is the energy density of the liquid. Size and weight are limited commodities on the probe. A very large tank would be needed to collect enough atmospheric gas to produce a

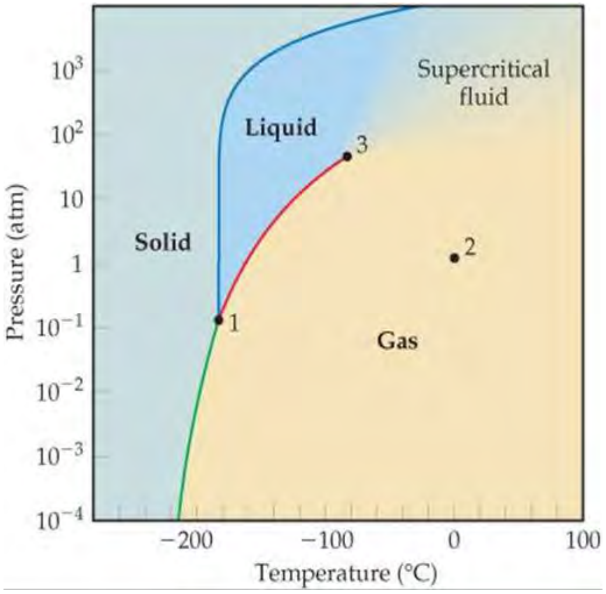

Figure 2: Methane Phase Diagram

reasonable volume of high-pressure gas. The energy density of liquids is much higher than the energy density of gases, and much in the same way liquid propellants reduce the volume of launch vehicles, liquid methane will conserve volume on a probe. The second stage would be to vaporize the liquid methane. Excess thermal energy from the probe's onboard RTG would be harnessed to heat the liquid methane into a compressed gas. The RTG as a power generator is generally inefficient and a lot of potentially valuable thermal energy is wasted [10]. The RTG utilized by the Mars Science Laboratory has a beginning of life electrical output of 108W and a beginning of life thermal energy waste of 1892W – an efficiency of only 5.4% [10]. The key feature of the proposed propulsion system is to utilize the wasted heat from the RTG to boil methane and produce compressed gas. The final stage is to eject the compressed methane through a variable-flow nozzle to produce thrust and, in turn, locomotion of the probe.

The theoretical analysis will be carried out in two steps. First, theoretical calculations will be conducted using thermodynamics and fluid dynamics to provide a guideline to design the proposed propulsion system based on Titan's environmental conditions. Second, a model will be constructed and simulated using a CFD software package, COMSOL. COMSOL will be used to simulate the mass and heat transfer of the boiling and compression of methane. It will also be used to simulate propulsion driven by pressurized methane propellant. Based on all the simulation results, the reasonable performance characteristics of a hypothetical probe will be identified, and potential ways this propulsion system could be effectively implemented will be discussed.

Research Timeline

Project Tasks		**Month**											
		5	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**1**	**2**	**3**	**4**
1	Literature Review	■	■										
2	Learn COMSOL		■	■	■								
3	Theoretical Analysis of CH4 Vaporization				■	■	■						
4	Simulation of CH4 Propulsion System							■	■	■	■		
5	Produce Report											■	■

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Implications of Long-term Resilience of Delmarva Peninsula Marshes on Barrier Island Stability

Question: Are the marshes behind the Delmarva Peninsula barrier islands able to keep pace with accelerated sea-level rise, and therefore able to continue to provide for stability of the fronting barrier islands?

Significance: Among the most heavily used and the most threatened by climate change, estuarine and coastal ecosystems provide numerous ecological services to some of the most vulnerable populated places in the United States (Barbier et al. 2011). This study focuses on coastal saltmarshes, critical habitats and stabilizing forces for fronting barrier islands. It will investigate the ability of these marshes to keep pace with relative sea-level rise (RSLR), and thus continue to serve to provide ecosystem services and stabilize fronting barrier islands. It will incorporate marshes from behind barrier islands with a range of characteristics, most notably different migration rates (and thus different rates of sediment input via barrier overwash), past management practices, and marsh/bay sizes. As these diverse barrier-island systems all provide substantial ecological and economic benefits (*e.g.*, carbon sequestration, fishery habitat, storm surge protection, etc.), understanding how they will respond to RSLR is extremely important in-of-itself, beyond their attendant impacts on barrier island stability. This study aligns with NASA's Science Mission Directorate, as it seeks to answer a question about how and why Earth's climate and environment are changing.

Context: The majority of barrier islands formed *ca.* 6000 to 4000 years ago during a period of decelerating RSLR. Since then, depending on local conditions (*i.e.*, sediment supply, storm frequencies, RSLR rates, etc.) they have either migrated landward and/or stabilized and prograded (Timmons et al. 2010; Hein et al. 2012). That initial period of decelerating RSLR allowed for the growth of marshes behind barriers. Contemporary RSLR now threatens these marshes and their associated barriers. If marsh accretion rates are less than RSLR, the marsh will likely not be able to grow vertically at a rate commiserate with RSLR. Relative sea-level rise is

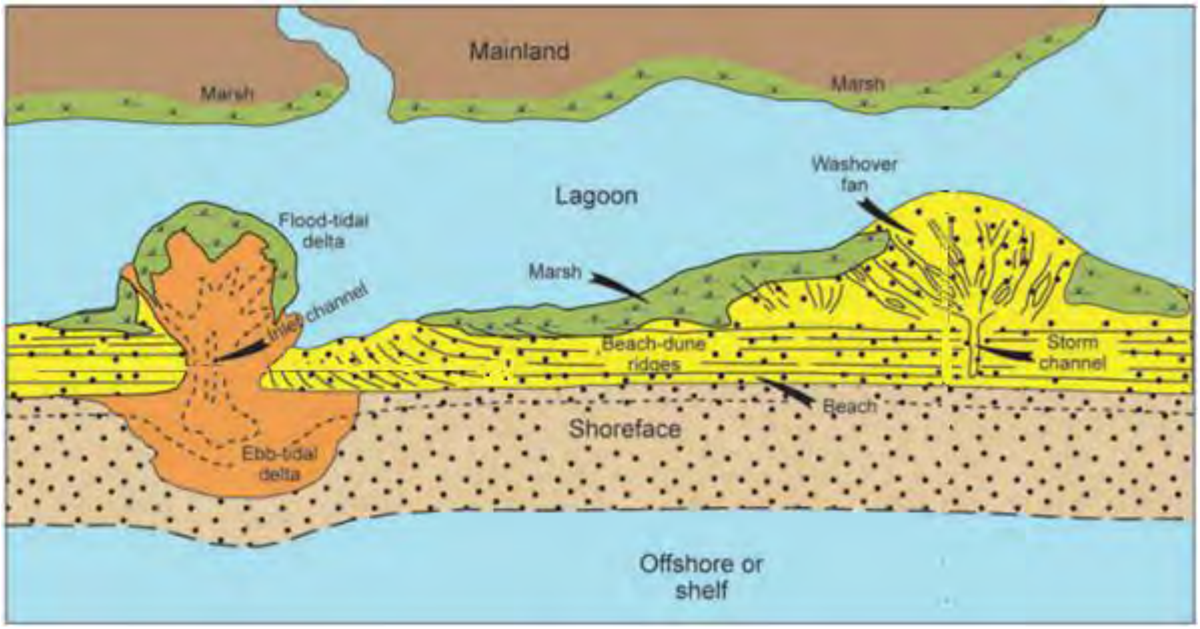

Figure 1: A generalized barrier island system. The washover fan will nourish the backbarrier marsh. The ebb- and flood-tidal deltas are sand reservoirs. Above surface sediment and sand is shown in yellow, marsh is in green, and subaqueous sand deposition in light brown (within the inlet channel including flood and ebb tidal deltas). *Figure from FitzGerald et al. 2008*

predicted to have a variety of interrelated, often detrimental, effects on barrier-island systems. These include inundation of population centers, flooding due to storm surges and extreme tides, increased storm magnitudes and greater recurrence intervals of intense storms, and potential drowning of backbarrier marshes; these latter two may contribute to near-term barrier-island disintegration (FitzGerald et al. 2008). In particular, the loss of backbarrier marshes will lead to increased backbarrier tidal prisms, requiring more and larger tidal inlets to transfer this water between the backbarrier and coastal ocean, and the attendant trapping of barrier sands on enlarging ebb- and flood- tidal deltas, through a processes referred to as "runaway transgression" (FitzGerald et al., 2008).

Relevance to NASA: An important NASA asset, the Wallops Flight Facility (WFF), is located on a Virginia barrier island that has been eroding throughout all six decades that it has been occupied. Efforts have been taken to mitigate the continual loss of beach, including installation of a wooden seawall and a stone rubble-mound seawall, and recurring beach nourishment (Morang et al., 2006). These have been expensive, short-term measures which have attempted to combat erosion that averages 5 m/yr on the south end of Wallops Island. Infrastructure investment on Wallops Island alone is valued at over $800 million (in 2006) (Morang et al., 2006). Studies conducted by the US Army Corps of Engineers have shown that erosion due to sea-level rise and increased storm activity poses a long term threat to the island. Moreover, these can likely not counter the wholesale destabilization of the island if its backbarrier marshes drown. The proposed study will investigate the responses of backbarrier marshes to sea level rise through quantification of the long-term (*ca.* 100 years) vertical accretion rates of those marshes. Rather than targeting Wallops Island, where development, infrastructure and shoreline stabilization all likely have shifted marsh growth out of natural balance, this study will focus on nearby marshes behind two proximal barriers, Parramore and Cedar islands, which are different in both morphology and sediment supply. Parramore Island is rapidly eroding, but is wide and high; as such, it does not overwash during storms and no barrier sand is fed to backbarrier marshes. By contrast, Cedar Island continuously rolls over and feeds its backbarrier marshes with sand and nutrients. However, this landward migration also serves to bury and destroy proximal marshes. While neither contains substantial infrastructure, study and comparison of the marshes behind these two islands will help elucidate backbarrier marsh responses to RSLR in this broader Virginia barrier island system. For example, if marshes behind Cedar, which are fed sand through regular storm overwash, are able to better keep pace with RSLR, that will better inform best management practices (*e.g.*, nourishing marshes with sediment to help them grow faster) along stabilized islands (such as Wallops), where overwash and barrier migration are artificially prevented. It is thus imperative that NASA understand the role of barrier dynamics on backbarrier marshes, and the return role that loss of those marshes could have in the barrier island's long-term stability.

Methods: We will collect marsh sediment cores from diverse locations behind both Parramore and Cedar islands. These locations will span the width of the marshes perpendicular to the shore, ensuring they cross both the proximal marsh, distal marsh, and mainland marsh. All cores will be analyzed for inorganic/organic content using loss-on-ignition (LOI). Accretion rates over the last *ca.* 100 years will be determined from four marsh sediment cores per island (two high marsh, two low marsh) using the ^{210}Pb and ^{137}Cs radioisotopes, capturing ~100- and ~60- year timeframes, respectively.

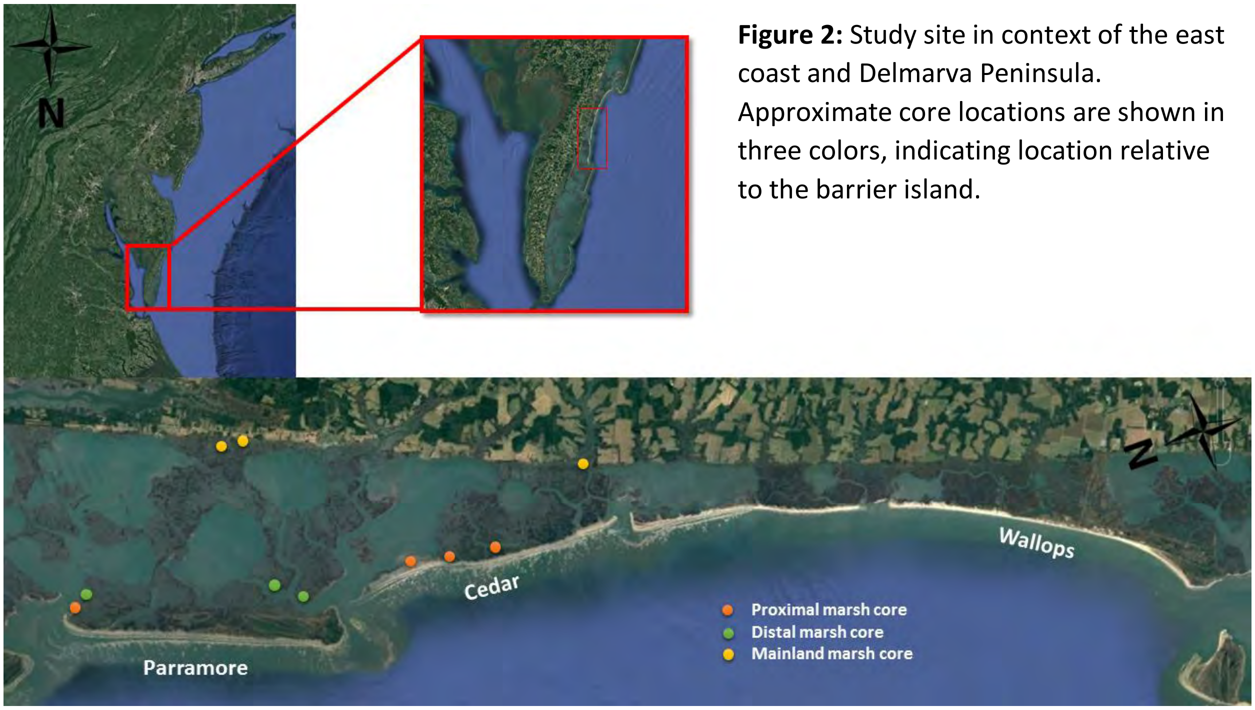

Figure 2: Study site in context of the east coast and Delmarva Peninsula. Approximate core locations are shown in three colors, indicating location relative to the barrier island.

Implications: At the conclusion of the study we will have quantified average marsh accretion rates behind Cedar and Parramore islands and compared them to RSLR rates during those same periods. Using Parramore as a proxy for Wallops (neither contribute sand to their backbarrier marshes), and Cedar as a proxy for Wallops in its natural, migrational, state, we will be able to inform best management practices for marsh resilience given artificial barrier stabilization. The ability or inability of marshes behind these two representative islands to keep pace with RSLR will help us relate the importance of backbarrier marshes to the long-term stability of barrier islands within the Delmarva Peninsula system and beyond. This work will not only affect policy related to NASA's WFF, but also to residential and tourist areas located on barrier islands, boating channels, and the developed coastlines these barriers protect.

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Research Proposal

With increased oil drilling in the artic, oil leaks and spills become more of a threat to the environment[1]. Oil spills pollute water and land, threaten the habitats and lives of marine mammals, and can spread for kilometers on ice in the right conditions[2]. Any oil spilled has the potential to interact with water and ice, both above and below the surface, as shown in Figure 1. With this increased risk comes the need to understand fundamentally how oil interacts with ice, specifically the frost layer on top of the ice. Past studies have attempted to quantify this interaction; however, none have controlled the experiments to understand the fundamentals of how the oil spreads. One study modeled the spreading as wetting, assuming that the frost layer was a smooth surface[3]. This study completely disregarded the fact that dendritic frost is always present on the outer surface of ice, such that oil wicks along the porous frost layer by capillarity. The proposed research will obtain a more accurate estimation of the spread of oil spills by measuring and analyzing the fundamental interactions between oil and frost for the first time. This correlates to NASA's science directorate, as it seeks to analyze and understand the Earth's reaction to hazardous oil spills in an attempt to improve the prediction of propagation.

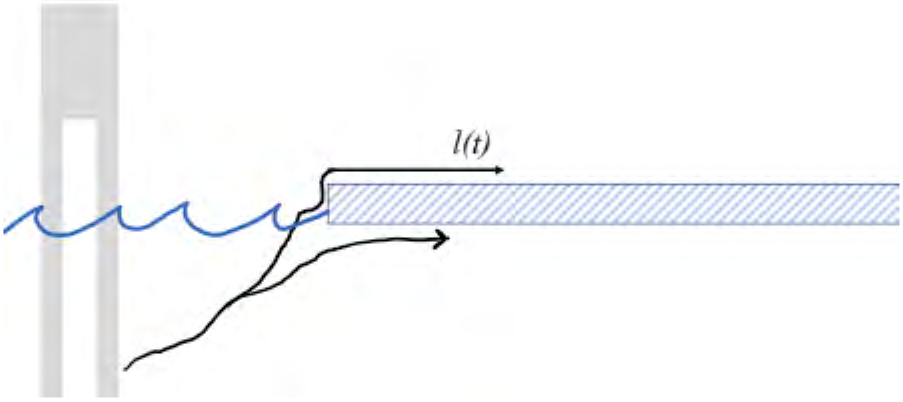

Figure 1: Oil leaked from a rig in the artic interacts with sea ice.

To obtain a proof of concept, untreated aluminum was held at a constant temperature using a cold plate attached to a chiller circulating water and ethylene glycol. Once the aluminum reached the desired temperature, a tray of 10 cSt silicone oil was raised below it until the bottom of the aluminum met the oil. The oil contained a 0.1% concentration of a fluorescent tracer that increased the visibility of the oil under a UV light. Pictures were taken at time intervals to track the vertical distance traveled by the oil.

As seen in Figure 2, the vertical distance traveled cannot simply be due to wettability. Therefore, the oil wicked through the porous frost and traveled up by capillarity, and it can be modeled using the Washburn equation. The Washburn equation is given by:

$$l(t) = \sqrt{\frac{\gamma\, r \cos(\theta)\, t}{2\, \mu}}$$

Where *l(t)* is the vertical distance traveled with time, γ is the surface tension of the silicone oil, *r* is the effective pore radius of the frost, θ is the contact angle, and μ is the viscosity of the silicone oil.

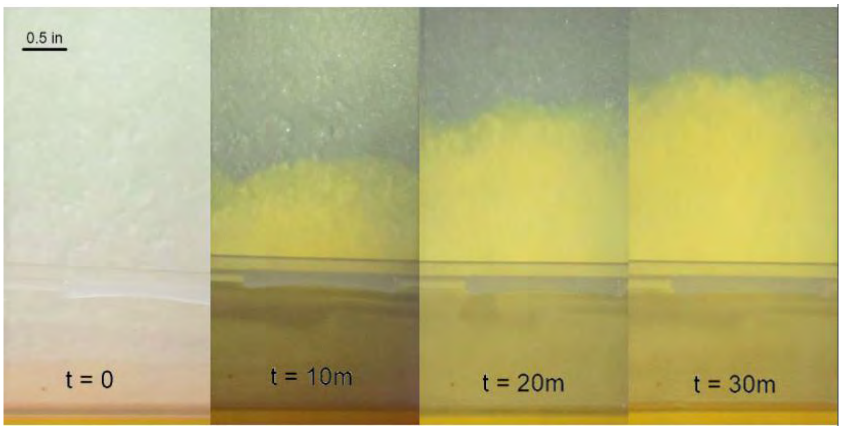

Figure 2:Time lapse of florescent dyed oil wicking up aluminum.

The proposed research will obtain a fundamental, non-dimensional understanding of the mechanism of frost wicking across ice. Previous research has shown that the structure of frost varies depending on the substrate[4]; therefore, superhydrophilic, hydrophilic, hydrophobic, and superhydrophobic aluminum surfaces will be tested. It is expected that the frost forming on the superhydrophilic surface will most resemble frost and sea ice interface found in the artic. The experiments will be conducted inside a humidity chamber to ensure consistency across trials. The temperature will be held constant at 20°C. The aluminum surface will be an 8" x 3" x 1/2" bar bolted to a cold plate that is attached to a chiller, circulating water and ethylene glycol to keep the surface temperature constant at -5°C. In order to rapidly grow the layer of frost, the humidity chamber will be set to 54% to maintain a saturation pressure ratio of 3, and water vapor will condense onto the surface. Once the frost is grown to the desired thickness, the growth of the frost will be stopped. This will be achieved by lowering the humidity to 18% to maintain a saturation pressure ratio of 1, to ensure that no water vapor is condensing or evaporating.

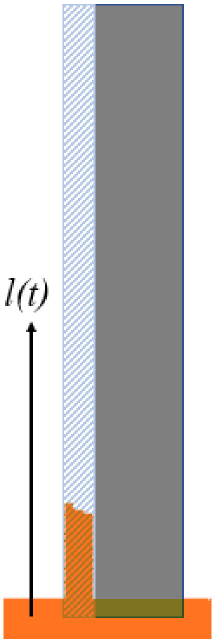

Figure 3: Depiction of fluorescent dyed oil wicking up frost on aluminum plate.

Once the frost is grown to the desired thickness, a tray containing silicone oil underneath the bar will be raised so that the bottom of the bar is just coming in contact with the oil, as shown in Figure 3. The oil will contain a fluorescent UV tracer at a concentration of 0.1% to improve visibility, and a UV lamp will be directed at the surface. A picture will be taken every 30 seconds. These pictures will be analyzed to correlate the distance traveled by the oil to the time. The data points will be plotted on a distance vs time graph, and will ideally fit the Washburn equation. The data can then be nondimensionalized for each surface to determine the effective pore radius of frost formed on superhydrophilic, hydrophilic, hydrophobic, and superhydrophobic surfaces.

Varying oil viscosity, surface wettability, and frost thickness will yield a comprehensive understanding of the mechanism of oil spreading across a porous frost surface. This model can then be applied to any situation for any given oil viscosity, surface, and frost thickness. Thus, more accurate estimations of the rate at which oil will propagate along sea ice, and the extent to which it will spread can be provided. Future work would include analyzing the interaction between oil and ice underwater. Additionally, there are other applications of this study. There has been increased interest and research in anti-frosting surfaces, particularly using lubricant-impregnated surfaces where oil is locked into a fine surface structure. Experiments also observed that when droplets freeze on this surface, the oil wicks onto the frozen droplets which degrades the surface.[5] However, like the aforementioned studies with arctic ice, the capillarity of the oil onto the porous ice is not characterized or modeled. The proposed research will supplement this finding by explaining and modeling how the oil leaves the surface.

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Integrating carbon nanotube enhancers into the porous, cell wall of ultra-high temperature ceramics for extreme temperature applications

I. Introduction

Advancing space technology demands materials that can survive extreme conditions and be easily manipulated to support different applications. Ultra-high temperature ceramics have been selected as potential candidates to develop components to withstand high thermal loads and stresses during hypersonic flight and/or reentry conditions. Porous ultra-high temperature ceramics are being developed to be easily integrated as insulation packages integrated with leading edges or combustor linings. Highly porous ceramic materials offer high surface area, low density, and thermal insulation. These properties can be tailored to individual applications by controlling the microstructure of the porous ceramic. Unfortunately, these highly-porous structures lend to friability and loss of strength. At the same time, other challenges such as oxidation and achieving the right thermal conductivity have to be considered. I plan to combat these material demands by attempting to integrate uniformly dispersed and disentangled multi-walled carbon nanotubes into the porous cell-wall structure.

Ideally, implementing such nanomaterial enhancer will increase the material's thermal conductivity and offer additional flexural strength. The extreme thermal conditions may combat this prediction by seizing the oxidative properties of the carbon nanotubes. Under extreme thermal conditions, like those experienced by hypersonic vehicles, the carbon nanotubes may function as ablatives. Upon burning out the carbon nanotubes may imprint their high-aspect into the macroporous structure and offer a unique structure benefit to the material.

Whether the nanomaterial remains existent or is ablated, it is believed that the porous matrix will gain flexural strength and increase thermal conductivity properties. These direct benefits will lead to low density materials that can withstand extreme thermally induced stresses.

II. Background and Motivation

Current research, identifies the success and promise of increasing the thermal conductivity, hardness, and flexural strength of ultra-high temperature ceramics. Although there is some literature about development of porous materials for high temperature insulation applications, there is a lack of research in examining the possibility that carbon nanotubes may act as an ablative under extreme conditions and protect the porous structures, while enhancing the thermal conductivity and mechanical performance. I plan to combat their weaknesses by effective integration of uniformly dispersed carbon nanotubes into the porous cell-wall structure.

A common method used to disperse CNTs, which naturally exist in entangled bundles, is horn sonication. A literature source[1] observed that longer carbon nanotubes required greater ultra-horn sonication times to deagglomerate the nanotubes. The longer the carbon nanotubes the greater the number of possible contact points, and therefore the greater possibility for cross-linking and entanglement between neighboring carbon nanotubes.[1] The energy density imparted to the carbon nanotubes must be great enough to detangle the nanotube bundles, but gentle enough to avoid fracturing the individual nanotubes.

Literature shows that integrating carbon nanotubes with ultra-high temperature ceramic materials, such as zirconium diboride, leads to an increase in fracture toughness, maintained thermal conductivity, and unchanged microstructures.[2,3,4] Porous structures can directly benefit space applications through their low density and high surface area. An observation of zirconium diboride-silicon carbide ceramics, toughened with carbon nanotubes, showed the activation of some toughening mechanisms, such as carbon nanotube 'pull-out' and crack deflections.[3] In addition, the porous matrix can be tailored based on application specifications by changing the porosity and average pore size via processing techniques. The adaptability of the material makes it ideal for varying missions and objectives.

Additionally, if the carbon nanotubes act as ablatives the structure of the material may be modified in-situ when in service. For example, the material could lose weight upon re-entry if high enough temperatures were reached to exhaust the nanomaterial from the ceramic. Likewise, burning out the carbon nanotubes could imprint their high-aspect into the macroporous structure. Increasing their insulation properties.

Literature shows promise that the reinforced ceramics will maintain high thermal conductivity and increase fracture toughness due to either the physical presence or imprinted remains of the carbon nanotubes. My research will explore the effect of CNT on the properties of macroporous UHTC materials.

IV. Experimental Method

During the Fall of 2016, I worked to determine the optimum parameters for uniform dispersion of multi-walled carbon nanotubes. The parameters studied in order to optimize their dispersion were solvent, dispersant amount and sonication time. Dynamic light scattering testing demonstrated successful dispersion of the CNT, reaching particle size compatible with supplier data and scanning electron microscopy (SEM) images. In addition, scanning electron microscopy imaging highlighted the impact of adding a dispersant and the repercussions of horn-sonication.

This project will now focus on integrating the CNTs with the Zirconium Diboride (ZrB2). The solvent and dispersant selected for the best conditions of CNT dispersion are known to be compatible with the preparation of concentrated suspensions of ZrB2 suspensions.[5] The ceramic and carbon nanotube suspensions will be sonicated for different lengths of time to detangle the carbon nanotube bundles, without fracturing the individual nanotubes. The desired amount of imparted energy will debundle the nanotubes without damaging their high aspect ratio or thermal properties.

The suspensions will be rolled on a mechanical roller to ensure uniformity throughout. After being rolled, porous structures will be created using the replica technique using polyurethane sponges. The polyurethane sponge will be dipped into the ceramic-CNT-suspension and allowed to dry, creating a CNT-ceramic replica of the macroporous structure of the polymeric sponge. After the CNT-ceramic replica, has air-dried, the samples will be calcined to remove the polymeric sponge and sintered to densify the particles in the struts.

My research will create a macroporous structure of zirconium diboride, reinforced with carbon nanotubes, via a replica technique and sintering. Placing the samples under extreme thermal and stress conditions will test the mechanical, flexural, and thermal strengths of the CNT modified ultra-high temperature material. In addition, scanning electron microscopy imaging will demonstrate the effects of the macrostructure.

V. Expected Outcomes

The key results will depend on the uniformity of the carbon nanotubes dispersion and integration into the cell-wall of the porous structures, and therefore, how well protected the carbon nanotubes are by the ceramic from the environment. My initial suspicion is that if the CNT are not properly dispersed into the ZrB_2 powders in the macroporous structure I am attempting to create, the carbon nanotubes may be destroyed when placed under extreme temperatures. Both the ceramic material and carbon nanotubes are susceptible to oxidation under extreme thermal conditions. I anticipate that the carbon nanotubes may increase the ceramics susceptibility to oxidation and be themselves deteriorated. Even if the CNTs are exposed and were ablated during application, I can see the benefits of their destruction, specifically in re-entry vehicles. Upon being ablated the carbon nanotubes may imprint their tubular shape into the porous structure and offer benefits to material applications. If the carbon nanotubes oxidize and 'burn-out' this feature could be manipulated to offer additional features to applications, such as re-entry vehicles where the material could be altered due to the extreme conditions of atmospheric re-entry. If ablated the porous structure of the ceramic would change during use and would not only lighten the material, but may also introduce microstructure toughening agents such as crack deflections.

The alternative scenario expectation is that the carbon nanotubes will retain their shape and presence therefore offering mechanical reinforcements due to their high-aspect ratio, if they are well integrated within the ceramic particles. Additionally, the strong thermal capabilities of the carbon nanotubes should contribute to the thermal conductivity of the ceramics.

Both benefits will allow advancing space technology to produce lighter weight vehicles, engines, and machine parts that can withstand more extreme conditions.

VI. Conclusion

The promise of uniformly integrating dispersed carbon nanotubes with porous ultra-high temperature ceramics opens the door to innovation in space technology, specifically for hypersonic vehicles, high temperature materials, and re-entry equipment. Carbon nanotubes, with strong thermal capabilities and a high-aspect ratio, are the optimum nanomaterial enhancement for extreme applications. Once the carbon nanotubes are disentangled they have the opportunity to uniformly integrate with the porous ceramic cell-wall. After integration, the carbon nanotubes may burn out and leave a structural imprint or remain present to offer direct mechanical strength benefits. By observing patterns, imaging macroporous structures, and testing results I will determine the impacts of extreme temperatures and the overall benefits of integrating nanomaterial reinforcements with ceramics. This study presents the opportunity to advance space technology by offering a tailored material that has the possibility to withstand the extreme conditions of mission re-entry vehicles, parts, and equipment.

VII. Citations

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