

Development of the thermal interface between the Dragonfly Mass Spectrometer and the DrACO Sample Delivery Carousel

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Icy celestial bodies are an exciting new frontier for surface exploration and in-situ sampling and analysis. These destinations are inherently cryogenic in nature, and each body presents unique challenges related to thermal design. The Dragonfly mission to Titan is one such example. One of the most important requirements of a sampling system is to preserve the integrity of the surface material. The interface between the Dragonfly Mass Spectrometer (DraMS) and the Drill for Acquisition of Complex Organics (DrACO) Sample Delivery Carousel (SDC) is complicated by several competing requirements. Development of this interface has required the use of new enabling technologies such as additive manufacturing to achieve a successful design. Additionally, test methodologies were developed to simulate Titan convective conditions with Earth gravity. This overview of the DraMS Cryogenic subsystem will show how the design meets all the requirements of the interface and preserves integrity of Titan surface samples.

I. Nomenclature

<i>A</i>	=	cross-sectional area
<i>CAD</i>	=	computer-aided design
<i>DraMS</i>	=	Dragonfly Mass Spectrometer
<i>DrACO</i>	=	Drill for the Acquisition of Complex Organics
<i>GCMS</i>	=	Gas Chromatography Mass Spectrometry
<i>GSE</i>	=	Ground Support Equipment
<i>ITMS</i>	=	Ion Trap Mass Spectrometer
<i>k</i>	=	thermal conductivity
<i>K</i>	=	Kelvin
<i>L</i>	=	length, characteristic length
<i>PMI</i>	=	<i>polymethacrylimide</i>
<i>LDMS</i>	=	Laser Desorption Mass Spectrometry
<i>PEEK</i>	=	<i>polyetheretherketone</i> thermoplastic
<i>Ra</i>	=	Rayleigh number
<i>SDC</i>	=	Sample Delivery Carousel

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II. Introduction

In our Solar system, ocean worlds with a frozen icy surface have been identified as prime candidates to answer priority science questions related to *insights from terrestrial life, dynamic habitability, and the search for life elsewhere* [1]. Titan, the largest moon of Saturn, is one such planetary target whose icy surface has been only preliminarily explored [2]. Complex organics are known to exist on the surface of Titan, and short of surface sample retrieval, *in-situ* analysis is the preeminent way to look for evidence of biological processes. To preserve the integrity of any surface material collected, a sample acquisition system must be designed to prevent unacceptable warming that could lead to phase transitions, melting, or other chemical reactions [3].

The Dragonfly mission to the surface of Titan is a free-flying rotorcraft that includes the Dragonfly Mass Spectrometer (DraMS) Ion Trap Mass Spectrometer (ITMS) instrument with two operational modes: gas chromatography mass spectrometry (GCMS) and laser desorption mass spectrometry (LDMS) and the Drill for Acquisition of Complex Organics (DrACO) sample acquisition and handling system. Titan's surface is inherently cryogenic at around 94 K. The Sample Delivery Carousel (SDC), part of DrACO where collected samples are stored and transferred to DraMS, has a maximum cup temperature not to exceed 170 K during Titan surface operations to prevent water-ammonia eutectic ice in the sample from melting [4]. Additionally, the internal volume of the SDC is sealed to create a molecularly clean *sample proximate* environment to store a complement of pristine sample cups.

Surface material is collected via a pneumatic system, part of DrACO [5]. The DrACO Sample Acquisition Drill, (SAD), will generate and ingest tailings of the drilled Titan surface regolith. The DrACO Blower immediately entrains the sample particles in a stream of cold Titan atmosphere. The DrACO Pneumatic Transfer System (PTS) transfers the sample directly into a sample cup inserted into the Sample Inlet of the SDC. A full sample cup is then transferred to one of two DraMS instrument inlets for analysis: the Laser Desorption Mass Spectrometry (LDMS) Chamber or the Gas Chromatograph Mass Spectrometry (GCMS) Pyrolysis Oven. The DraMS instrument includes a Laser Desorption Mass Spectrometry (LDMS) mode of operation to analyze larger organic molecules than those capable by the Huygens probe to Titan which had only a GCMS instrument and without a pyrolysis oven [2].

Dragonfly cryogenic thermal design is inside-out from typical cryogenic systems. The Titan surface must be protected from a warm internal lander environment, and the instruments contained within the lander must be insulated from the cryogenic Titan atmosphere to remain operable. The interface between the DrACO SDC and the DraMS instrument is where these opposing thermal environments meet. The relative positions of the DrACO and DraMS instrument subsystems within the Dragonfly lander are shown in Fig. 1. DraMS and the SDC reside within the area of the lander known as the Attic. The Attic is divided into a warm zone that houses DraMS and a cryogenic cold zone that includes the SDC as shown in Fig. 2.

In addition to the thermal isolation between the cryogenic SDC and the warm DraMS instrument, there is another requirement to ensure that the ultraviolet laser will strike its target on the inserted LDMS sample cup. This alignment is done during integration of the DraMS instrument where both subsystems are at ambient temperature. The change in temperature of the SDC upon arrival at Titan, from 293 K to <170 K, will cause the SDC to change dimension from thermal contractions. This effect limits the material choices available for primary structures, which complicates thermal management strategies.

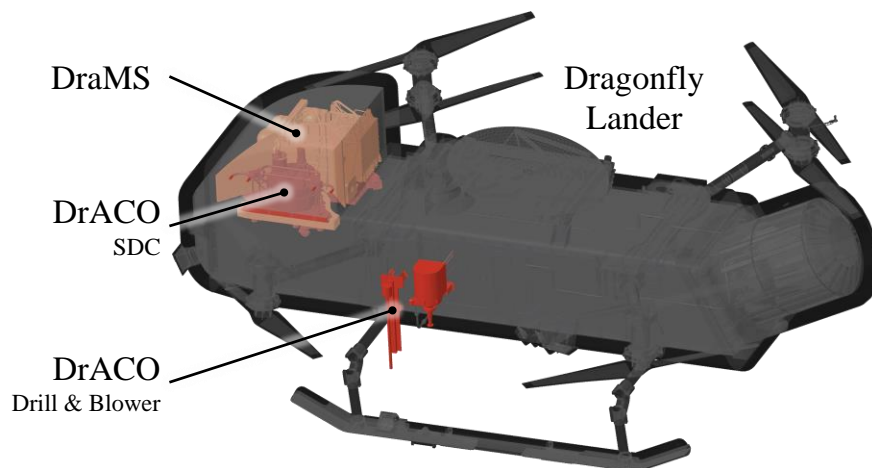


Fig. 1 DraMS and DrACO instruments shown in context of the Dragonfly lander in this computer aided design (CAD) rendering.

The SDC is kept cold on the surface of Titan by coupling to the nearly infinite cold sink of Titan’s atmosphere. The SDC itself is composed of warm actuators on its underside and cryogenic sample delivery and sample cups above. This steep temperature gradient requires thermal isolation to be built into the primary structure of the SDC. Parasitic heat flow from the lander internal volume is managed by minimizing the cross-sectional area (A) to length (L) ratio (A/L) of SDC structures and by choosing materials with poor thermal conductivity (k), such as titanium alloys. The SDC Isolator design was iterated further using generative design to maximize efficiency.

Since Titan has an atmosphere, parasitic heat is also transferred convectively. The SDC Cover is made from titanium to achieve acceptable dimensional stability across a wide temperature range for LDMS laser alignment. The SDC Cover creates a sealed volume that easily traps heat within, like a cover on a cooking pot. The parasitic heat that is conducted and convected through the SDC must be efficiently transferred to the Titan atmosphere. Mounted to the Carousel Cover of the SDC, double-sided aluminum fin heatsinks transfer heat from within the SDC to a buoyancy-driven chimney of Titan air that flows through the cryogenic Attic. The fins were optimized for Titan gravity and pressure conditions and were best suited for additive manufacturing.

The process to design and test the interface between DraMS and DrACO that meets requirements for temperature, alignment, mass, contamination, and manufacturability, is summarized in this work.

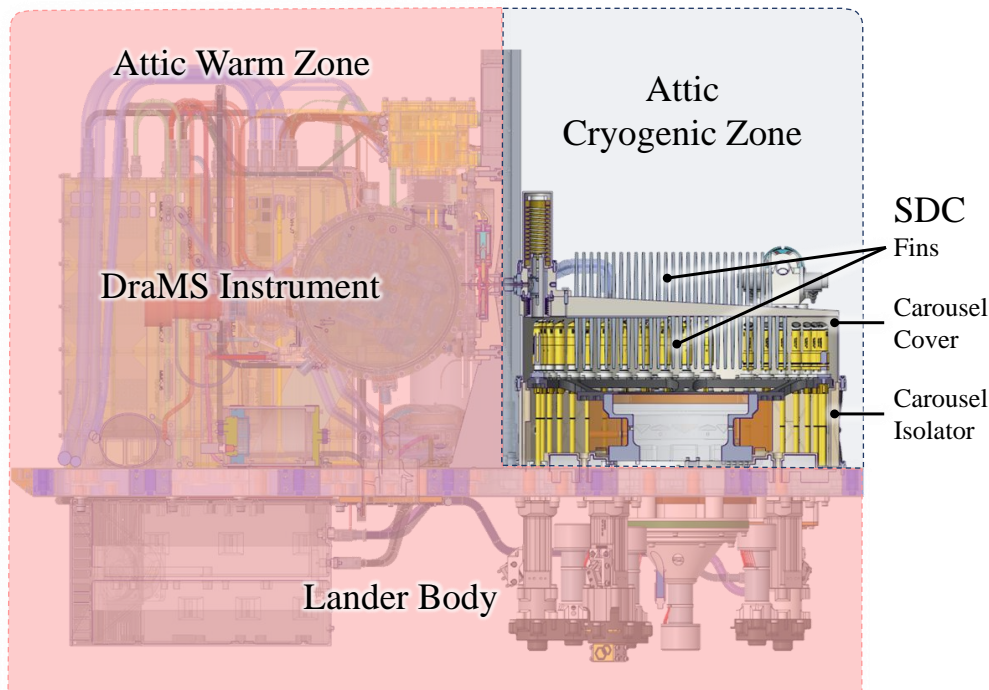


Fig. 2 Schematic of the Sample Delivery Carousel (SDC) and the Dragonfly Attic. The view is looking back at DraMS from the nose of Dragonfly.

III. System Design

A. Design Space & Requirements

The DraMS Cryogenic Zone is the intersection of two subsystems with very different operating environments. Thermal, Structure, Alignment, and Contamination all constrain the design space as shown notionally in Fig. 3. Thermal design is the first discipline that comes to mind with such a steep gradient from the warm DraMS instrument and the cold SDC. Structural design is the next discipline with driving requirements that directly compete with thermal performance. Additionally, the Dragonfly instrument will experience long-term fatigue loading from repeated flights, which adds complexity to the structural design. The intersection of DraMS and the SDC must be done with very precise alignment, performed at room temperature during the DraMS Suite integration. The alignment must also tolerate an extreme temperature change upon entry to Titan. This requirement enables performance tests to be carried out both on the lab bench and during Titan-relevant environmental tests without realignment. The last major discipline is contamination control. The interior of the SDC is a *sample proximate* region. Pristine sample cups may be

contaminated with molecular residue during the long cruise from Earth to Titan. Careful restriction of the materials used in the construction of the SDC, specifically insulation materials, will ensure sample cups remain pristine.

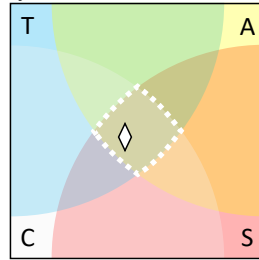


Fig. 3 Conceptual design space with “A” for Alignment, “T” for Thermal, “C” for Contamination, and “S” for Structure. The final design, \diamond , must reside within the dashed region in the center.

B. Thermal Design

Temperature control for the Cryogenic Zone and the SDC is achieved through passive coupling to Titan’s atmosphere. A heat flow diagram is shown in Fig. 4. The cups contained within the SDC shall remain below 170 K, or even better, as close to Titan ambient temperature as possible. DraMS is provided temperature control from the Dragonfly Lander. Thermal isolation from Titan is used to minimize what is termed *heat-leak* or energy lost to Titan. The SDC too has “warm” components that must be thermally isolated from the Titan atmosphere to operate. The warm components are mounted to the bottom surface of the carousel baseplate, which serves as the boundary between warm and cryogenic regions of the SDC. A steep temperature gradient, greater than 100 K, across the baseplate leads to an inevitable heat-leak from within the lander. Structural components that are mounted to the baseplate cryogenic side must be designed to limit the flow of heat to protect both the Lander and the samples contained within the SDC.

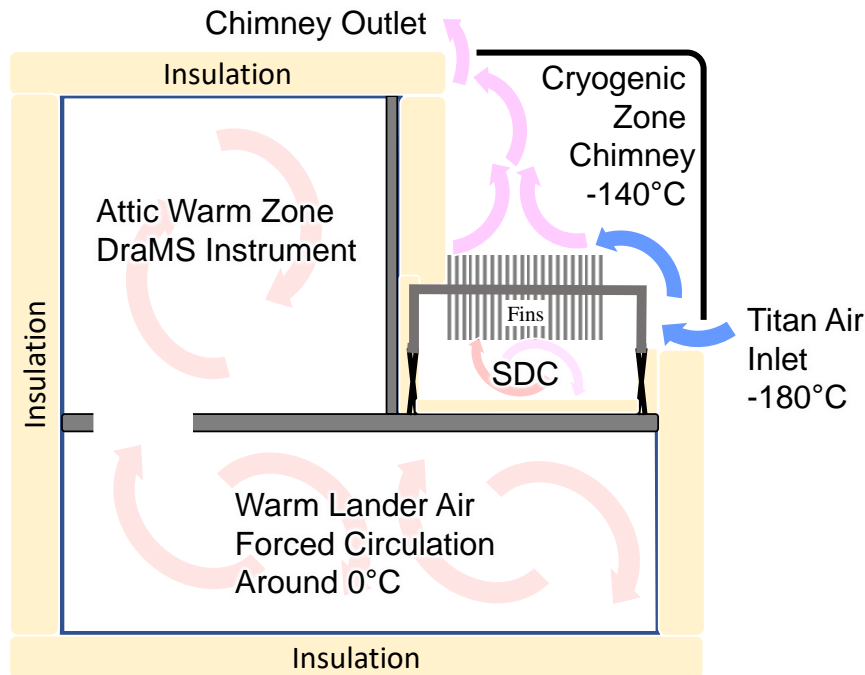


Fig. 4 DraMS Suite Cryogenic Zone heat flow diagram.

Titan’s atmosphere provides cooling for the SDC passively through a buoyancy-driven chimney effect. Atmosphere flows in through the side of the Lander and up through the top. Although Titan’s surface temperature is around 94 K, the buoyancy effect is limited by Titan’s weak gravity. The sample cups would benefit from direct contact with the Titan atmosphere to keep them cold. However, contamination control requires the SDC to be a sealed volume to prevent contamination of the sample cups from Lander molecular or particulate sources. Simply exposing

the outside surface of the SDC to Titan air was insufficient to provide enough cooling. Surface enhancement was necessary on both sides of the Carousel Cover. Thus, double-sided aluminum fins are used to increase surface area available for free convection. The size and spacing of the fins were optimized using computational fluid dynamics software.

C. Structural Design

The temperature gradient in the SDC is through the primary mechanical structure². A mechanical block diagram is shown in Fig. 5. The Carousel Isolator provides mechanical support and thermal isolation for the Carousel Cover. The Carousel Cover supports the GCMS Pyrolysis Oven, the LDMS Chamber, and the pneumatic lines that deliver sample to the Sample Collection Port. The Carousel Isolator was identified as one of the major contributors to heat leak through the SDC.

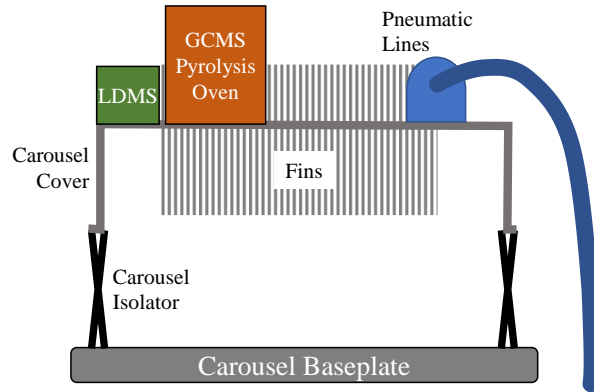


Fig. 5 Mechanical block diagram of the SDC enclosure.

Generative design approach addressed three concerns with the Carousel Isolator design: manufacturability, heat leak, and fatigue tolerance. A side-by-side comparison between the output from NASA’s *Evolved Structures* initiative [6] to implement generative design into engineering design and the final Engineering Model (EM) design is shown in Fig. 6. Manufacturability and the necessity to create a sealed internal volume of the Carousel Isolator led to a traditional machined part. The truss density was increased following hints from the generative output. The part was originally designed and prototyped as a machined part from a 3D-printed titanium precursor. The final EM version is machined directly from a billet of titanium.

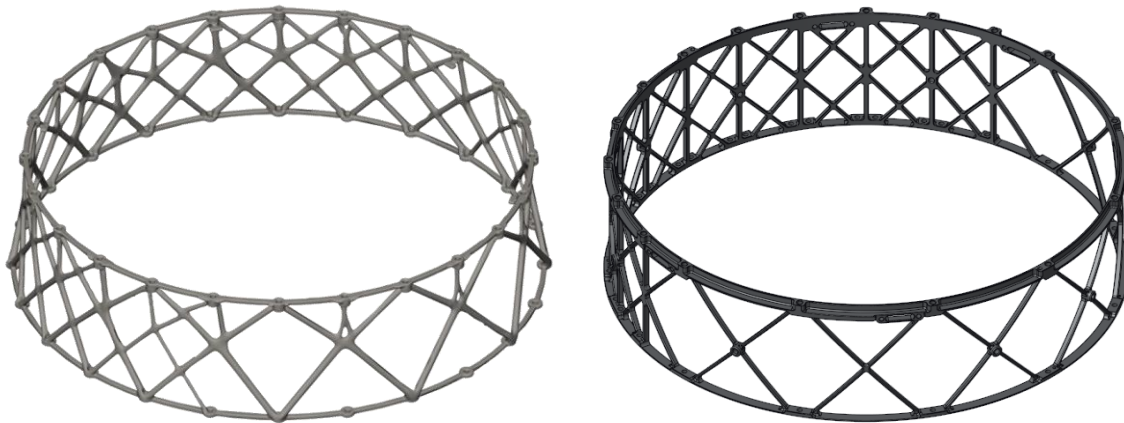


Fig. 6 Side-by-side comparison of the Evolved Structure (left) and the final EM design (right) of the Carousel Isolator.

² In early design concepts, the LDMS and GCMS ports were supported elsewhere. However, the eventual alignment strategy between the SDC and DraMS prevented de-coupling mechanical support from the carousel baseplate.

The Carousel Isolator is part of the barrier that creates the sample proximate clean region within the SDC. A preliminary version of the isolator (not shown) was to leave a thin web between the ribs or to simplify the geometry to a simple cylinder. The *Evolved Structures* version was so mass-efficient that the equivalent cylinder of titanium would be only 0.015 inches thick. This would have complicated manufacturing and caused a secondary issue with fatigue. A single flaw in a continuous cylinder could rapidly grow in a fatigue environment and cause the part to fail. The final EM design concentrates mass into truss members that are “fail-safe” meaning that the loss of one or more to fatigue crack growth would not cause the entire part to fail.

D. Alignment

The DraMS LDMS mode depends on an ultraviolet laser to ionize and mobilize large molecules for analysis. The laser spot on the sample cup is very small compared to the overall size of the DraMS instrument. Additionally, the laser strikes the sample cup mesh at an angle which means misalignment of the cup in the port-starboard Lander direction creates a further laser misalignment in the fore-aft Lander direction. The most significant alignment challenge is the dimensional stability of the SDC structures as they cool and contract upon entry to Titan. The effect of this is shown schematically in Fig. 7.

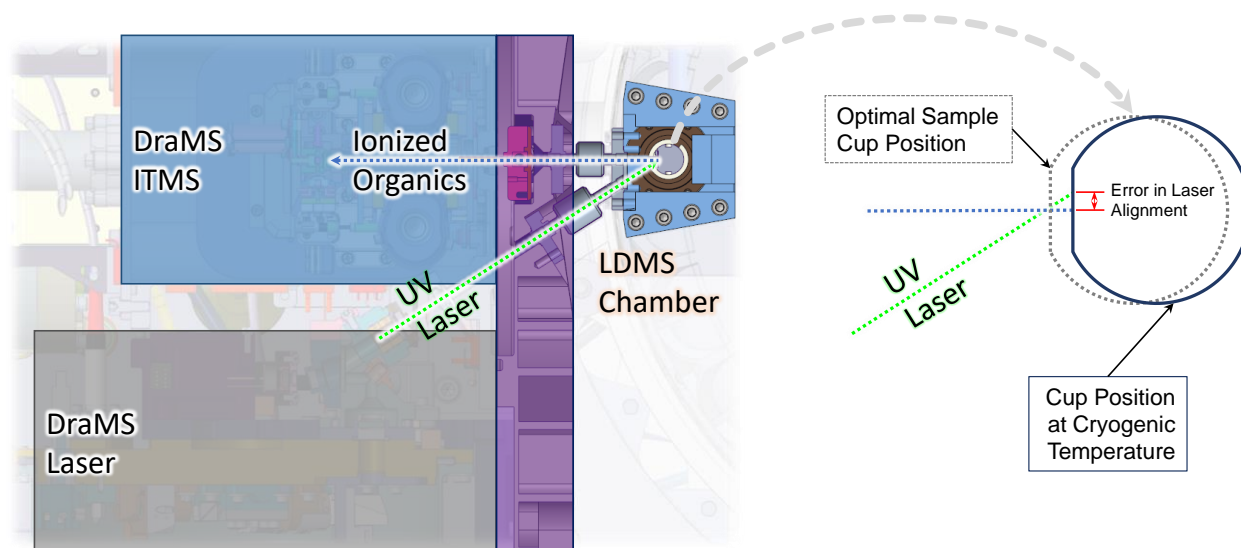


Fig. 7 Misalignment caused by thermal contraction on Titan's surface.

The Carousel Cover and Carousel Isolator are made from titanium to improve dimensional stability over a wide range of temperatures. The LDMS Chamber and GCMS Pyrolysis Oven are mounted directly to the Carousel Cover to maintain alignment with the SDC internal mechanisms.

Alternate material choices for the Carousel Cover included invar and beryllium. Invar was prohibitively dense, and beryllium prohibitively complex for manufacture. Titanium is the optimal choice for the Carousel Isolator, but the Carousel Cover could have benefitted from a more thermally conductive material like beryllium. The compromise was to add the double-sided fins inserted into the Carousel Cover to provide enough surface area to effectively couple with the Titan atmosphere.

E. Contamination

The SDC is a *sample proximate* region meaning that materials contained within have direct access to pristine sample cups. Any molecular outgassing or foreign object debris generated within this volume could migrate to the sample cups and skew or completely overwhelm the mass spectrometer during analysis.

The carousel thermal design requires insulation wherever possible and especially within the SDC clean volume. Closed-cell *polymethacrylimide* (PMI) foam was the baseline insulation of choice due to its low density and low thermal conductivity. However, PMI foam tends to easily shed particles and outgasses water and other organics. To find an alternative material to replace the PMI foam, a survey of candidate polymers was conducted. Thermoplastic *polyetheretherketone* (PEEK) was found to be one of the most chemically stable options. A development effort to use PEEK as an effective insulator led to a 3D-printed material with cubic infill to cause the air trapped inside the insulation to stagnate. A study of the effect of cell size and pressure on thermal conductivity was conducted [7]. The

effective thermal conductivity of the 3D-printed PEEK was around 2.5 times greater than PMI foam. To close the thermal design, PMI foam was ultimately reintroduced as a single thin layer covering the Carousel Baseplate upper surface. A compromise was to cover the PMI foam with a 3D-printed PEEK shell to encapsulate the foam.

Careful consideration was taken to control the air venting direction during launch and back-fill of the SDC during entry to Titan. The SDC internal volume is sealed, and vent paths for the PMI insulation and internal air volume were provided down through the SDC mechanism. Venting is ultimately controlled by a reed-valve that opens automatically during launch and seals closed during entry to Titan. A filter screen mounted to the Carousel Cover and filled with molecular adsorbent will allow the SDC to repressurize with clean air upon entry to Titan. The venting schematic is shown in Fig. 8.

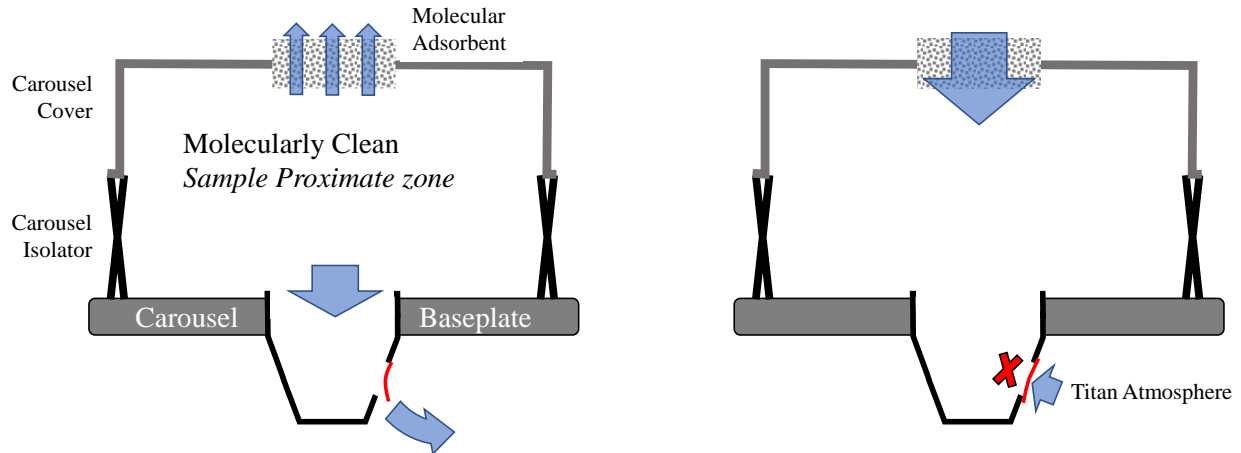


Fig. 8 Controlled venting scheme for launch (left) and entry to Titan (right)

IV. Subcomponent Tests and Model Validation

A. Fin Optimization Study

The Carousel Fins are the key components to make the thermal design of the SDC close. Several prototype iterations were printed with fins protruding from one side from a flat plate. The prototypes were then tested in open air and at Titan-relevant conditions. The configuration that showed the best performance overall was the dense array of thin pyramid fins, the EM baseline design (3.) in Fig. 9. The fin prototypes were compared by measuring the power required to maintain a given differential temperature (ΔT) between the fins (T_{fin}) and the ambient air (T_{∞}). The heater power was compared to a flat aluminum plate with the same dimensions as the base of the fin samples. The fin effectiveness factor was calculated as the ratio of the heater power for fin prototypes to heater power for the flat plate for a given ΔT . Early CFD predictions for minimum fin effectiveness for thermal model closure was approximately 10. Data collected during the final prototype run at Titan relevant pressure and temperature is shown in Fig. 10.

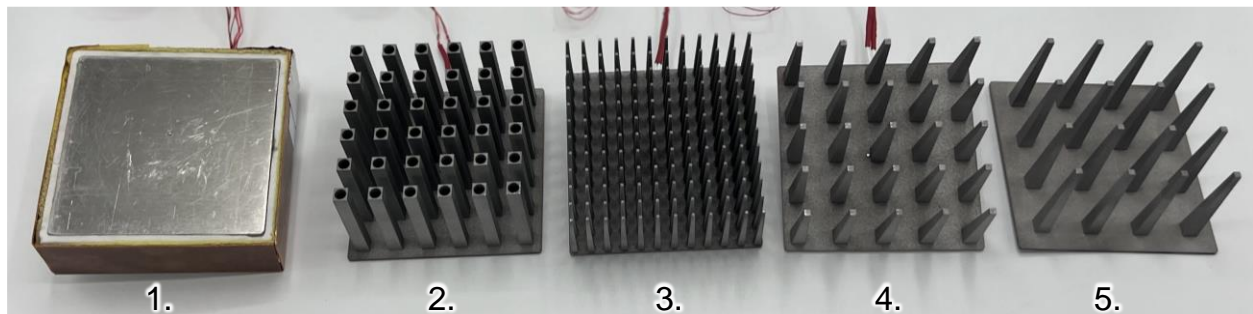


Fig. 9 Fin prototypes showing the flat plate reference inserted into a thermal guard to prevent conduction losses (1.), hollow square pins (2.), small dense pyramids: EM baseline (3.), medium pyramid fins (4.), and sparse pyramid fins (5.).

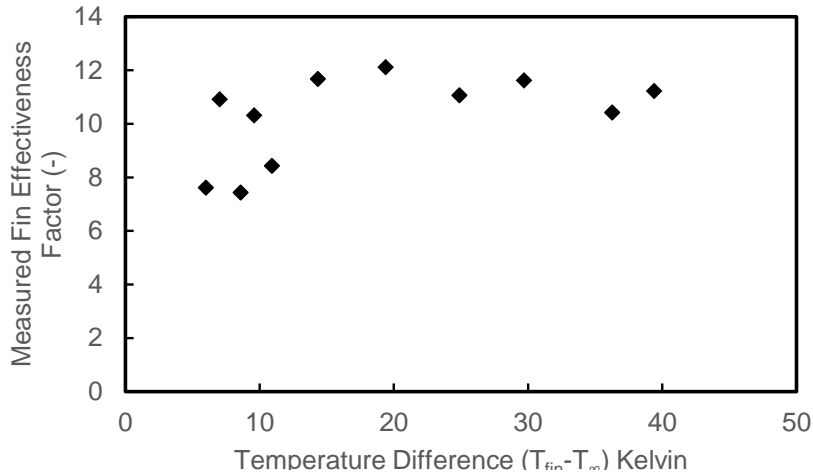


Fig. 10 Fin effectiveness factor for fin Design 3 with a dense array of thin pyramid fins.

For low ΔT representing SDC temperature well below its requirement, the fin effectiveness is diminished but without negative consequence. As heater power is increased, the fins begin fully participating in the heat transfer. With further increase in heater power, the fin effectiveness continues to exceed the target. Thermal model predictions show the temperature of the SDC Carousel Cover to remain around 130 K for most situations. The one case where the GCMS Pyrolysis Oven is operational tends to drive the fins about 10 degrees warmer than what was tested. Mass flowrate of Titan atmosphere through the Cryogenic Zone Chimney is expected to increase by about 15% during GCMS mode which should enhance cooling effectiveness. The interdependent relationship between the SDC and the Cryogenic Zone Chimney will be evaluated at the full-scale DraMS EM test campaign.

B. DraMS Foam Mockup

Insulation effectiveness is one of the most important aspects of the Dragonfly mission. The insulation surrounding the entire Dragonfly Lander is a complicated 3-dimensional puzzle. DraMS is preparing a mockup that will serve several purposes. First, the Attic volume must be air sealed to prevent excessive convective mass transfer resulting in an intolerable heat leak to Titan. The mockup will be pressure tested to ensure that all mechanical interfaces, penetrations, and potential gaps are sealed adequately. Second, the mockup will be used as a template to build insulation sections piece-by-piece to ensure that the insulation fits together as shown in Fig. 11. Additionally, the Attic Cryogenic Zone Chimney will be constructed primarily from foam insulation. The mockup will provide hands-on practice to secure foam to itself to form the Chimney. Third, the mockup will provide early heat-leak measurements for the DraMS instrument. The mockup will stand in for the DraMS EM assembly during a shake-down Titan thermal test. Ground support equipment (GSE) that will be used to test the DraMS EM unit will be “qualified” by the mockup initial thermal test.

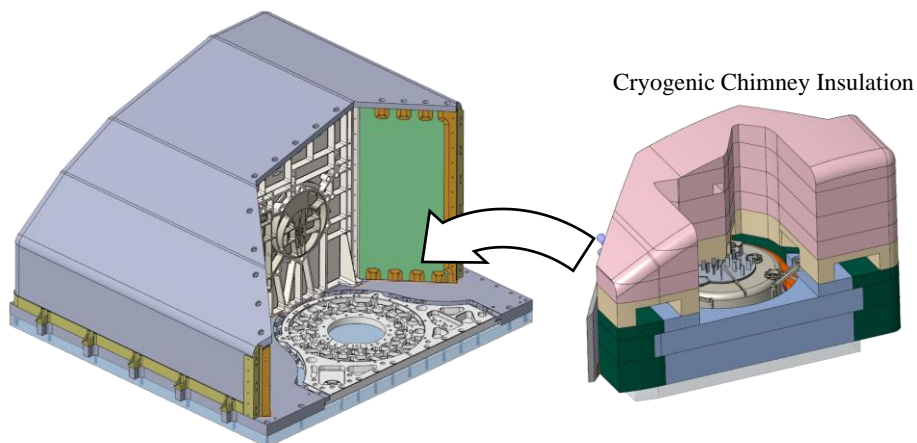


Fig. 11 DraMS EM Foam Mockup will be used to build the cryogenic attic Chimney shown as a preliminary CAD rendering.

C. DraMS Engineering Model End-to-End Test

The end-to-end test will simulate Titan conditions on Earth. Although surface pressure on Titan is around 1.5 atmospheres, the test will be run at sub-atmospheric conditions to account for the difference in gravity. A Lander Simulator will simulate the warm convective boundary conditions inside the Dragonfly Lander. The Cooler Canopy is an enclosure made from liquid nitrogen cooling plates and is covered with insulation. The Cooler Canopy simulates Titan surface conditions. DraMS or the DraMS Mockup is installed on top of the Lander simulator and is exposed to Titan conditions on the external surfaces. The entire GSE assembly is placed within a thermal vacuum chamber with room temperature dry nitrogen. The pressure will be held somewhere between 0.3 to 1.0 atm to simulate various convective conditions.

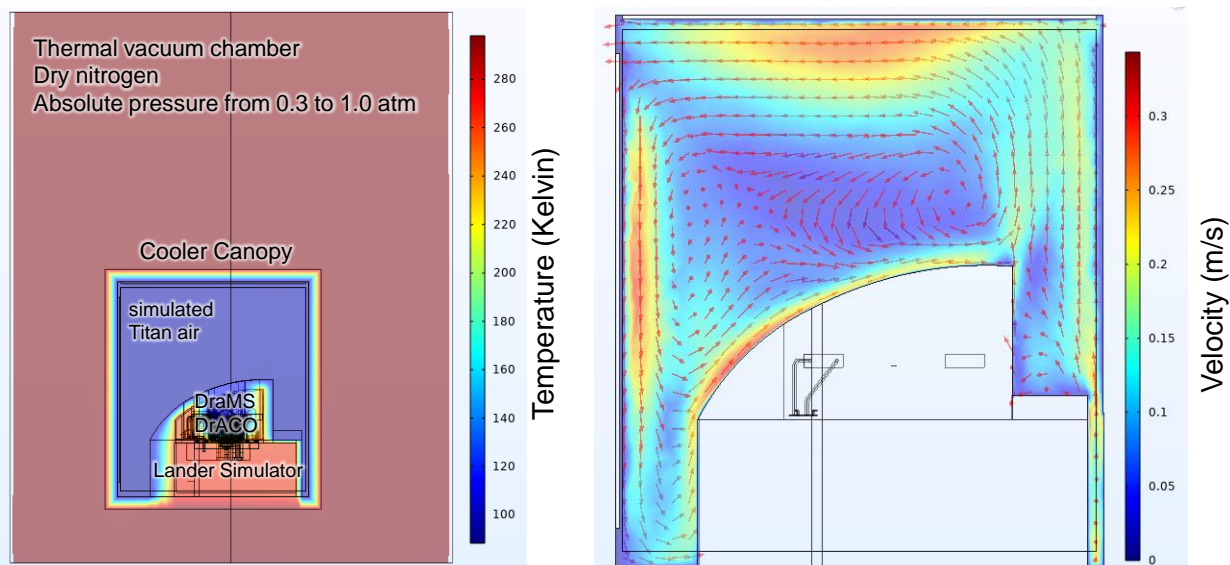


Fig. 12 Temperature contour plot (left) and convection velocity, shown enlarged (right) of the DraMS EM T-Titan test.

Natural convection can be described [8] by the dimensionless Rayleigh number (Ra) shown in Equation (1). The density of the air ρ , thermal expansion coefficient β , differential temperature ΔT , characteristic length L , and gravitational acceleration g , are balanced by dynamic viscosity η and thermal diffusivity α . To calculate the appropriate test parameters on Earth, the Rayleigh number is calculated for what is expected on Titan, and the test pressure on Earth is adjusted to change the air density such that $Ra_{Earth} = Ra_{Titan}$. For forced convection cases such as the numerous fans being used within Dragonfly, the pressure in the chamber is increased to 1 atm, which is the pressure limit of the facility. Natural convection will tend to be enhanced for those cases, and the Cryogenic Attic will tend to run slightly colder as a result.

$$Ra = \frac{\rho \beta \Delta T L^3 g}{\eta \alpha} \quad (1)$$

V. Conclusion

The intersection between DraMS and DrACO has proven to be a conjunction of many competing requirements. The design process has followed some unexpected paths along the way to lead to the current Engineering Model baseline design. Preliminary tests to validate the design have shown promise that the design will be successful. The complexity of the interface will be fully characterized with the upcoming full-scale DraMS EM test campaign.

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