Mission to Titan: Komodo

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Anticipating positive results for signs of life found during the Dragonfly mission, we aim to launch a surface rover mission to Titan, Saturn's Moon. The current Dragonfly mission will be launched in the year 2026 and is expected to arrive in 2034; with a 2-year mission planned after its approximately 7-year journey to Titan [1]. Whether or not Dragonfly yields positive results for signs of life the next step is to send a more fully equipped rover (or Komodo). The rover Komodo can be constructed within the 9 years Dragonfly will take to carry out its mission, and be ready for launch in the year 2036.

I. Nomenclature

$\oplus$, ♄, $\odot$	=	Earth, Saturn, Sun
μ	=	Gravitational Parameter of the Sun, Earth, etc.
ΔV	=	Change in Velocity
$v_{\text{helio craft}}$	=	Heliocentric Velocity of Spacecraft
$v_{\text{helio planet}}$	=	Heliocentric Velocity of Planet
$v_{\infty\ \text{dep}}$	=	Hyperbolic Excess Speed at Departure
v_{geo}	=	Geocentric Velocity of Spacecraft at Parking Orbit
$v_{\text{geo dep}}$	=	Geocentric Velocity of Spacecraft at Departure
$r_\oplus$	=	Radius of Earth
$r_{\text{park Alt.}}$	=	Parking Altitude
$R1$ & $R2$	=	Earth & Saturn's Semi-Major Axis of Orbit
a_{Titan}	=	Titan's Semi-Major Axis of Orbit
E_{Craft}	=	Energy of Spacecraft in Orbit

II. Introduction

Dragonfly is cleverly named as it is a rotorcraft utilizing a total of 8 rotors, 4 per side, and is expected to fly across Titan's surface as nibble as a dragonfly in order to probe several selected locations for prebiotic chemical processes [1]. The main disadvantage to this is that the Dragonfly is rather small and can only carry so many onboard labs and analysis equipment for signs of life; such as detecting organic carbons, amino acids, and nucleobases[2]. Komodo will be heavy and crawl slowly over Titan's surface, much like its reptilian counterpart the Komodo dragon, and can be equipped with onboard labs that would make the Dragonfly unable to gain lift in Titan's atmosphere. In order to carry Komodo safely to Titan, on its treacherous orbital course, a spacecraft structure of Titanium, Aluminum, and other materials must be considered. This is especially critical since we plan to perform an atmospheric drag maneuver within Saturn at an altitude with an equivalent pressure of 1 Atmosphere here on Earth. Given our time frame, we hope that more advanced rockets, such as the SLS or SpaceX Starship, are deemed mission-ready in order to deliver the spacecraft [3]. However, we must consider today's market and the options available for our main propulsion system as well. Taking this into account we also must consider that the final spacecraft and rover may have to be reduced in size to accommodate the allocated mission funding, availability of parts on the open market, and rocket capabilities at the time of assembly.

*Orbital Mechanics and Preliminary Mission Trajectoy
†Science and Signs of Life Detection
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III. Mission Orbital Mechanics

This mission to Titan comes with a heavy ΔV price, which is why Cassini needed a once-in-a-lifetime planetary alignment in order to use several flybys to reach Saturn with a minimum ΔV requirement. This allowed the spacecraft to have a dry mass of 2523 kg with 3132 kg of propellant [4]. This means that the Cassini spacecraft had only 55.3846% of its mass as the propellant. This of course is near impossible to recreate given Cassini's flight path. However, Preliminary calculations show that with total fuel-to-mass ratio 88.10% this mission is far from impossible. All preliminary calculations were performed within Python using several programs, and a link to the GitHub repository containing these codes can be found in the appendix.

A. Interplanetary Hohmann Transfer

The initial calculations for the Total ΔV required for the mission were performed using the following relations for an Interplanetary Hohmann transfer; assuming co-planer circular orbits for Earth and Saturn [5]:

$$v_{\text{helio craft}} = \sqrt{\mu_{\odot} \cdot (\frac{2}{R1} - \frac{2}{R1 + R2})} \tag{1}$$

$$v_{\text{helio planet}} = \sqrt{\frac{\mu_{\odot}}{R1}} \tag{2}$$

$$v_{\infty \text{ dep}} = v_{\text{helio craft}} - v_{\text{helio planet}} \tag{3}$$

$$v_{\text{geo}} = \sqrt{\frac{\mu_{\oplus}}{r_{\text{park Alt.}} + r_{\oplus}}} \tag{4}$$

$$v_{\text{geo dep}} = \sqrt{v^2_{\infty \text{ dep}} + \frac{2 \cdot \mu_{\oplus}}{r_{\text{park Alt.}} + r_{\oplus}}} \tag{5}$$

$$\Delta V = v_{\text{geo dep}} - v_{\text{geo}}. \tag{6}$$

These were used for calculating the transfer and departure phases, while the arrival at Saturn was calculated using similar relations. The main differences between the arrival vs. the departure, shown above, is that $(2/R1)$ is changed to $(2/R2)$ within Eq. 1, and similarly $R2$ is used in Eq. 2; the parking radius and planet radius are also replaced within Eq. 4 & 5 to reflect a greater radius of Saturn and a Higher Parking orbit desired. The parking orbit around Saturn was set to an altitude of $591,600.0$ km, which allowed for an optimized transfer to Saturn as well as the Final Hohmann transfer to Titan as seen in Fig. 1. The parking orbit for Earth as can be seen within Fig. 2 was ideally set to 600 km, yet a more realistic 300km parking orbit around earth would not vary the results by much. As the initial calculations were carried out it was found that a flyby gravity assist maneuver was needed to overcome the $\Delta V \approx 7.28358$ km/s required to depart to Saturn from Earth. A Jupiter flyby was then added and the Hohmann transfer to Jupiter was also calculated similar to Saturn's. The following is the calculation output for the Hohmann Transfer using the Mission_to_Titan.py (Assuming an $I_{sp} = 300$ s and a spacecraft mass of 2000 kg):

```
------------------------------------------
| Hohmann Transfer
------------------------------------------
| Initial Calculations Without Maneuvers
------------------------------------------
| Delta_V_To_Saturn: 11.736882879686142 (km/s
| Fuel_Mass_Ratio:
|    0.9814645020471255
| Propellant Mass:
|   105901.06664978174 (kg)
|------------------------------------------
| Earth to Jupiter: 6.283064991537935 (km/s)
|------------------------------------------
| --To Saturn--
| Earth Departure: 7.283581906933882 (km/s)
|
| Saturn Arrival: 4.4533009727522606 (km/s)
------------------------------------------
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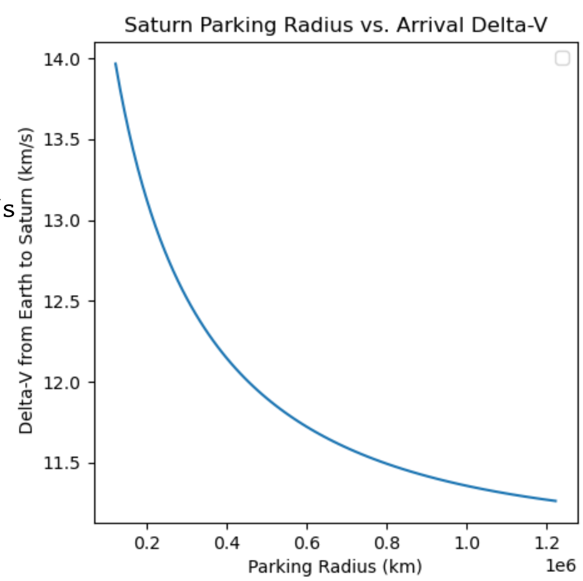

Fig. 1 Optimization of arrival ΔV by change in the desired Saturn parking radius

Figure 1 shows an optimization that was carried out to find an ideal parking orbit while allowing it to remain relatively close to Saturn for an atmosphere drag maneuver. The parking orbit of $591,600$ km is also near the plateau of the decaying curve which reinforced it as an ideal parking orbit. However, it can be seen that without any maneuvers an unrealistic fuel-to-mass ratio of 98.14% is needed in order to reach Saturn, not even including the final transfer to Titan.

The transfer to Titan from a Parking orbit around Saturn was calculated as a Hohmann transfer as Titan's eccentricity is 0.0288 which is under 0.05 and can be approximated as zero in order to assume circular orbits for the Hohmann transfer [6]. The Equations used for the Hohmann transfer calculations are as follows [7]:

$$v_{\text{Craft}} = \sqrt{\frac{\mu_{\saturn}}{r_{\text{Craft}}}} \qquad E_{\text{Craft}} = -\frac{\mu_{\saturn}}{2R_{\text{Craft}}} \qquad v_{\text{Craft Dep.}} = \sqrt{2\frac{\mu_{\saturn}}{R_{\text{Craft}}} + E_{\text{Craft}}}$$

$$v_{\text{Craft Park}} = \sqrt{\frac{\mu_{\saturn}}{a_{\text{Titan}}}} \qquad E_{\text{Craft Park}} = -\frac{\mu_{\saturn}}{2a_{\text{Titan}}} \qquad v_{\text{Craft Ariv.}} = \sqrt{2\frac{\mu_{\saturn}}{a_{\text{Titan}}} + E_{\text{Craft Park}}}$$

$$\Delta V_a = v_{\text{Craft Dep.}} - v_{\text{Craft}} \qquad \Delta V_b = v_{\text{Craft Park}} - v_{\text{Craft Ariv.}} \qquad \Delta V_{total} = |\Delta V_a| + |\Delta V_b|$$

These relations were coded into the "Transfer to Titan" section of Mission_to_Titan.py and calculated that the ΔV requirements to reach Titan was approximately 3.597 km/s from a parking altitude of $591,600$ km. This additional ΔV is a fairly decent approximation of the requirements needed to perform the Transfer to Titan. However given an ideal, highly eccentric, orbit this could be reduced so as to be able to skim the atmosphere of Saturn while remaining in close proximity to Titan or the parking orbit of $591,600$ km at the very least.

B. Maneuvers and Final Calculations for Hohmann Transfer

The flyby for Jupiter was calculated using Mission_to_Titan.py, and it was found that a theoretical maximum of $\Delta V \approx 10.5655$ km/s could be imparted to the spacecraft from Jupiter. To save on ΔV when arriving at Saturn an Atmospheric drag maneuver will be performed. Given that it would still take $\Delta V \approx 6.28306$ km/s to depart to Jupiter, it was found that a total $\Delta V \approx 1.00052$ km/s would need to be imparted to the spacecraft in order to reach Saturn. Using a highly eccentric orbit, our spacecraft will orbit in the outskirts of Saturn and Titan's Atmosphere in order to slow down. Simulations around Saturn were created, and it was found that flying down to an altitude that yielded a pressure of 14.5038 psi would be relatively easy as a pressure-to-altitude calculator showed that 1 Atmosphere (atm) of pressure exceeded its maximum calculation distance of 20,000 meters [8]. The atmospheric density was of $0.19 \times 10^{-}19$ kg/km^3 at 1 Bar was used for the approximations; while the relative velocity was calculated using Saturn's Sidereal Orbit in $radians/seconds$ [9]. Using this Fig. 3 was generated within the Saturn_Atmo_Drag_Delta_V_Calc.py located in the GitHub. Given the flyby and atmosphere drag maneuvers a final ΔV Calculation was conducted within Misson_to_Titan.py which yielded the following outputs:

```
------------------------------------------
| Final Calculations With Maneuvers
|  for a craft with Isp = 300 (seconds)
|  with a mass of:  2000 (kg)
------------------------------------------
| Delta_V_To_Saturn: 6.283064991537935 (km/s)
|
| Delta-V to Titan : 3.5971266032801155 (km/s)
|
| Total Mission Delta-V to Titan:
|    9.88019159481805 (km/s)
|
| Fuel_Mass_Ratio:
|    0.8817457661101025
| Propellant Mass:
|   14912.713686531779 (kg)
|
------------------------------------------
| Delta-V imparted to craft by Jupiter:
|    1.0005169153959468 (km/s)
------------------------------------------
```

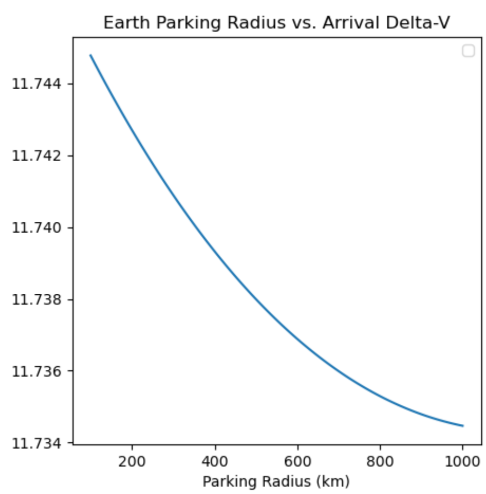

Fig. 2 The optimization of Earth's Parking Orbit for minimizing departure ΔV

Figure 3 shows that given a 24-hour time frame orbiting the outskirts of Saturn can reduce the spacecraft's velocity by 2.0 km/s. Given the length of Titan's period of orbit is approximately 16 days, a total of $\Delta V \approx 4.4533$ km/s can be gained from an atmosphere drag maneuver with Saturn over the course of 1-2 highly eccentric orbits; thus reducing the arrival ΔV to 0 km/s [6]. The final calculations show that a mission from Earth to Titan given a spacecraft weighing 2000 kg which is reasonable given that our rover will be relatively equivalent in size to the Mars rover Curiosity which weighs approximately 899 kg [10]. The preliminary calculations show that a ΔV total of ≈ 9.8623 km/s is needed to perform several Hohmann transfers from Earth to Titan; including all maneuvers. Furthermore, the total fuel-to-mass ratio, including the transfer to Titan, is only 88.10%, which is over a 10% decrease from the initial calculations. This shows that given the proper maneuvers a mission to Titan is more than feasible.

C. Ephemeris Calculations and Non-Hohmann Interplanetary Transfer

Lamberts_Velocity_Claculator_1.0.py, located in the GitHub, was compiled as a .exe and used for calculating the velocity vectors of the spacecraft. These were then used within Mission_to_Titan.py for the ΔV Calculations. An approximate launch date was set for high noon on May 5^{th}, 2036 UT $(12:00:00)$ or in the Julian date format 2464819.0 Days at Launch, and 2467040.734002679 Days upon arrival at Saturn; using the Horizons Systems built-in Julian calculations [6]. Ephemeris data was generated using NASA's Horizons System and used for the ΔV calculations for the main journey to Saturn. This however yielded very poor results with unreal ΔV requirements. An adjustment to the Launch date was made after reading reports made by Dominic Ford on in-the-sky.org. It was found that on February 4^{th}, 2036 that Saturn would 'reach opposition', in that it lies directly opposite the Sun with Earth in between [11]. Using this information and the calculated synodic period between Earth and Saturn:

```
-----------------------------------------
| Mission TOF: 2221.734002678964 Days
|            : 6.082676267272718 Years
-----------------------------------------
| Mission Start Time: 2464968.0 Days
-----------------------------------------
| Mission End Time: 2467189.734002679 Days
-----------------------------------------
| Window_Titan : 10.161279566723673 Days
| assuming the period of Titan is 16 days
-----------------------------------------
| The synodic Period;  Earth & Saturn:
|    378.0900126493324 Days
-----------------------------------------
-----------------------------------------
|  Jupiter Flyby
-----------------------------------------
| The Delta-V imparted on the spacecraft is:
|         10.565454757638854 (km/s)
-----------------------------------------
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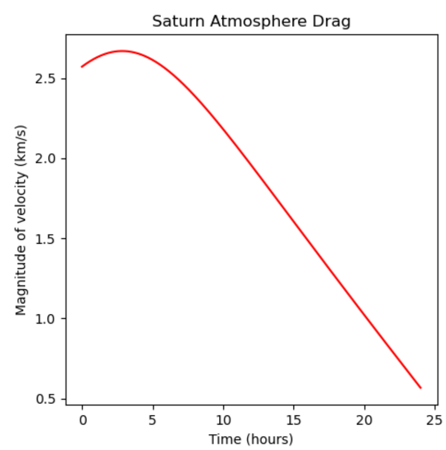

Fig. 3 The Change in ΔV as compared to time spent on the edge of Saturn's atmosphere, approximately 14.5038 psi [8].

A new launch date of October 1^{st}, 2036 was used, as it was found that adding $\frac{SynodicPeriod}{2}$ to the mission time would set a launch date of 2465008.0450063245 or November 10^{th}, 2036. Lamberts_Velocity_Claculator_1.0.py yielded 'nan' results during calculations for Nov. 10^{th}, which led to checking dates near. This is why a launch date of October 1^{st} was chosen, as the velocities calculated for the spacecraft yielded ΔV results that were relatively optimum and similar to that of our Non-Optimized Interplanetary Hohmann transfer. Further analysis showed that the Saturn arrival date, given the October 1^{st} launch date, would be November 1^{st}, 2042 UT $(05:36:57.8315)$; 2467189.734002679 in Julian date. Plotting this orbit, which is seen in Fig. 4 shows that Komodo can make a successful transfer from Earth to Saturn within the calculated Time of Flight (TOF) to be 6.08 years. Below are the calculations made using Misson_to_Titan.py with the velocities calculated with Lamberts_Velocity_Claculator_1.0.py and Ephemeris data collected from NASA's Horizons System[6]:

```
-----------------------------------------
| Ephemeris Calculations
|-----------------------------------------
| October 1st, 2036
|
| Earth Departure: 13.465572194289235 (km/s)
|
| Saturn Arrival: 5.431239884878016 (km/s)
|
| Total Delta-V: 18.89681207916725 (km/s)
-----------------------------------------
| May 5th, 2036
|
| Earth Departure: 26736.19712361714 (km/s)
|
| Saturn Arrival: 569.4028218764182 (km/s)
|
| Total Delta-V: 27305.59994549356 (km/s)
-----------------------------------------
```

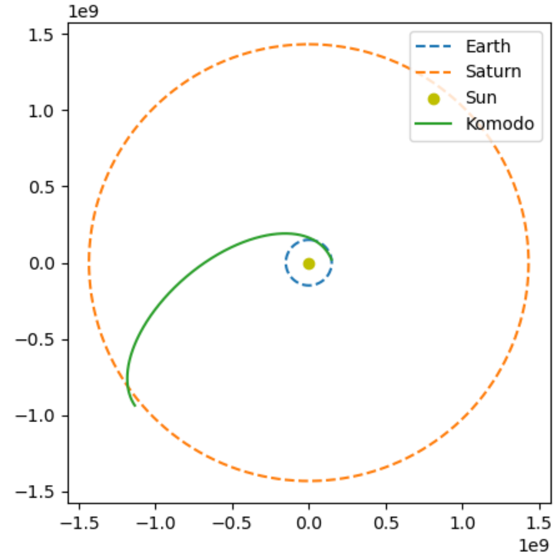

Fig. 4 The ephemeris data Simulated in a 2-Body problem with the sun; chowing the non-Hohmann trajectory.

Further analysis using a more advanced Ephemeris system could yield a launch date with an even greater optimized ΔV Calculation. However, October 1^{st}, 2036 was found to be similar to preliminary Hohmann transfer calculations. The total ΔV requirements for an October 1^{st} launch, as shown, is approximately 18.89681 km/s which is nearly identical to a very early calculation done on the Interplanetary Hohmann transfer to Saturn as shown below. An additional final ΔV calculation was also conducted in case Komodo had to be reduced in size to accommodate the Falcon Heavy currently available on today's market[12]:

```
-----------------------------------------
| Final Calculations With Maneuvers
|  for a craft with Isp = 311 (seconds)
|  with a mass of:  1600 (kg)
-----------------------------------------
| Delta_V_To_Saturn: 6.283064991537935(km/s)
|
| Delta-V to Titan: 3.597126603280115(km/s)
|
| Total Mission Delta-V to Titan:
|    9.88019159481805 (km/s)
|
| Fuel_Mass_Ratio:
|    0.8724704099796787
| Propellant Mass:
|   10946.10792479649 (kg)
|
-----------------------------------------
| Non-Optimized Hohmann Transfer
-----------------------------------------
| Delta_V_To_Saturn: 18.08387217706266 (km/s)
|-----------------------------------------
```

- These Calculations for the Falcon Heavy rocket can be found within Mission_to_Titan_Falcon_Heavy.py, where I_{sp} and $spacecraft\ mass$ was altered to the given specifications.
- we see that the reduced mass and increased I_{sp} yielded a significant loss in propellant mass required by roughly 400 kg given the same optimized Hohmann Transfer.
- This shows that our mission can accommodate the change in funding and availability of propulsion systems, given any untimely change to Komodo and its systems during the following phases of the mission design.

- Below we see an early Calculation performed with 150 km parking orbit for Earth and Saturn.
- This Non-Optimized Interplanetary Hohmann Transfer is relatively similar to that of a Non-Hohmann Interplanetary Transfer.
- This also shows that the optimization of the Hohmann transfer, including maneuvers, could also be applied to that of the Non-Hohmann calculations performed with ephemeris data.

As can be seen, the Ephemeris calculation for a Non-Hohmann Interplanetary transfer is only greater by approximately 0.81294 km/s as compared to a non-optimized Interplanetary Hohmann transfer. There is also a significant amount of ΔV that can be imparted to the spacecraft from Saturn's flyby, reducing the needed 13.466 km/s by up to a theoretical 10.57 km/s. Upon arrival at Saturn, the 5.431 km/s can also be reduced by up to roughly 2.0 km/s for every 24 hours spent within Saturn's upper atmosphere. With this in mind, the ΔV requirements can be approximated as equal for the Hohmann and non-Hohmann interplanetary transfer to be ≈ 9.8623 km/s; assuming optimum maneuvers and a launch date of October 1^{st}, 2036.

Furthermore; additional flybys can be added to account for extra fuel needs when dealing with perturbations of our flight trajectory such as solar radiation pressure, and perturbations from interacting with Saturn and Titan in a highly eccentric orbit. The latter especially as if the spacecraft exceeds $e = 1$. the trajectory we will use to slow the craft will turn into a parabolic and then Hyperbolic escape trajectory. We must account for these and add additional propellant in order to maintain a highly eccentric $e \approx 0.98$ orbit. This will require a more advanced ephemeris system that can scan dates for optimum planetary alignment, allowing us to plot additional maneuvers to be plotted while keeping our mission TOF close to the projected 6.08 years.

IV. Science and Signs of Life Detection

Titan is the largest moon orbiting around Saturn, one of approximately 83 moons which have been noted to orbit Saturn. This moon is very similar in size to Mercury at $5,149.4$ km in diameter [13]. For many years not much was known about Titan besides that it had a thick predominately nitrogen atmosphere. It wasn't until the Cassini mission and the data collected from the Huygens probe. The probe collected a variety of data which is still used by scientists today as we attempt to better understand the environment on and within the surface of Titan.

A. Huygens Probe: Discovery's on Titan

The first task of the Huygens probe was to take pictures during its descent and after landing to allow for a clear visual of the surface under the atmosphere. This provided us with the understanding of a nonuniform surface, where smooth rocks and what appears to be rivers exist on Titan. Continuing its orbit above the moon, Cassini also took pictures of Titan. These pictures were able to get a visual of the terrain of the moon on a larger scale than the probe. It is these images that we first begin to see signs that Titan is a more active celestial body than originally suspected. In these images there appear stripes across the surface. This phenomenon is very similar to the formation of sand dunes on earth. These are so similar that there can be seen a shallow slope and a steep slope all indicting a steady wind direction as seen in the Mojave Desert [14].

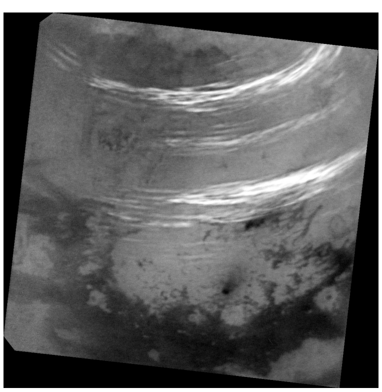

Fig. 5 Enhanced View of Cloud Bands on Titan taken in 2017 [15]

Along with the potential of winds strong enough to move particles on the surface into dune-like formations, there were also many recorded areas which appear to be oceans or lakes on the surface of Titan. This is further suggested by the smooth rocks found by the probe which follow a smoothing pattern like rocks tumbled through water. However, Titan has a temperature of about -179° Celsius [13]. This is significantly lower than the freezing point of water. The temperature is instead the perfect range to find liquid methane. We know there is a higher concentration of methane as you get closer to the surface, courtesy to the Huygens probe measuring methane concentrations as it descended through the atmosphere. Liquid methane in high concentrations would act similarly to water on earth. Even given the fact that the solid surface of Titan is more likely to be regular ice, studies mimicking methane rain show once the methane is absorbed into the ice, the remainder will rest on the surface and form a pool of liquid [14]. Another similarity between Titan and Earth found through the Cassini mission is the ability to for clouds. This is aided by the fact that Titan has a tilted axis very similar to Earth, creating its own version of seasons [14]. The change in temperatures from the North pole to the South pole helps with the convection of the atmosphere around Titan. This in turn helps create the rainfall which in turn

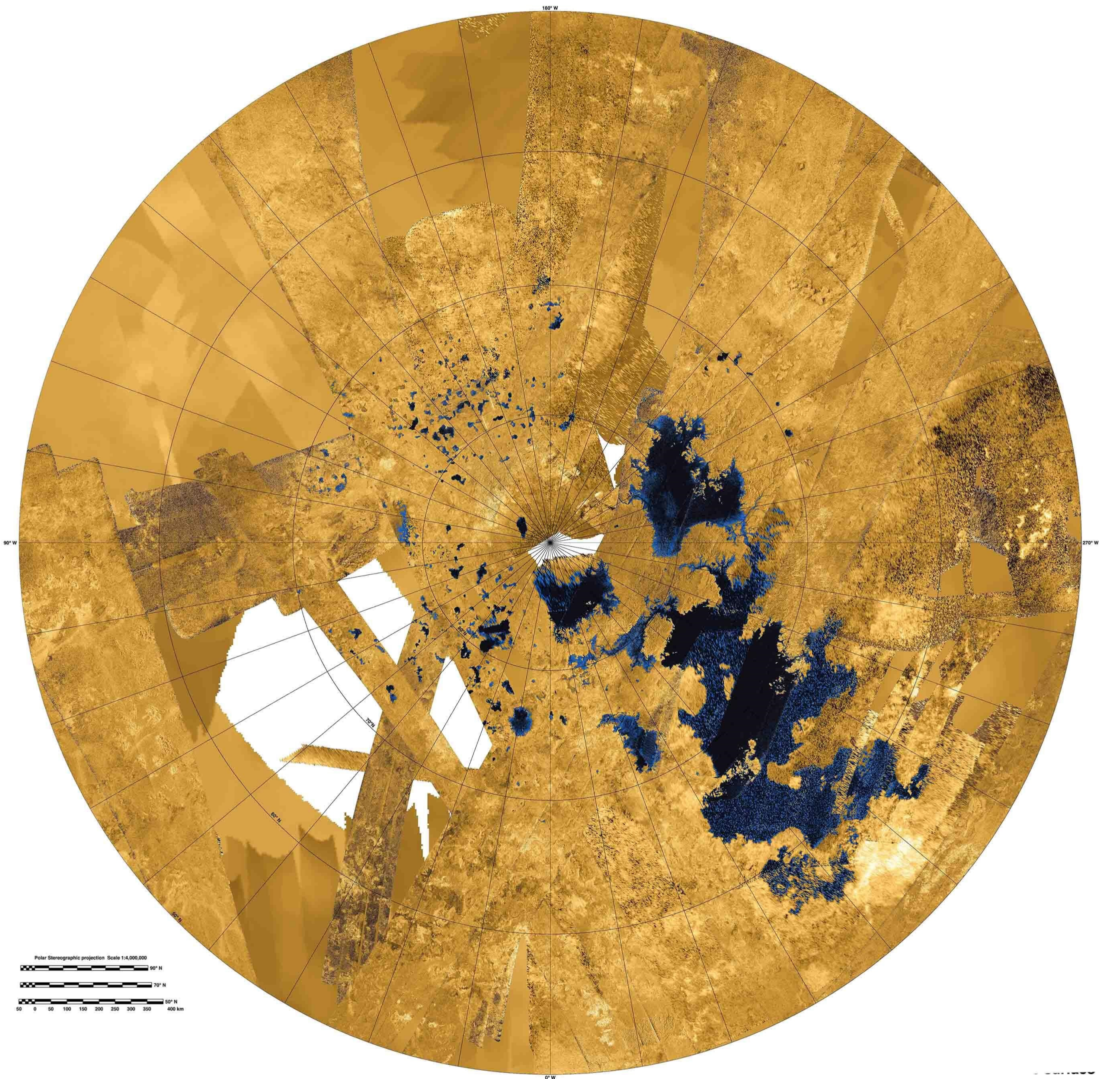

Fig. 6 Titan's Lakes

creates the lakes found on the surface near the poles. These discoveries make Titan the only other body in our solar system to have liquid activity on the surface besides Earth [13].

Another compelling discovery is the evidence of tidal forces on Titan as it orbits Saturn. Between the perigee and apogee, the radius of Titan changes by 10 km [14]. This combined with visual evidence of what appears to be volcanoes could mean that Titan has a liquid mantle or core under the ice. A liquid under the surface would allow for a wide fluctuation of the radius without causing too much destruction to the top layer. It would also create friction as the radius expands and contracts leading to potential volcanic eruptions. Currently, if there is volcanic activity on Titan, the temperature would be too low for the lava flow experienced on Earth. Instead, it is most likely liquid water, meaning that under the surface of Titan is an entire undiscovered ocean [14].

B. Titan's Atmosphere & Signs of Life

One of the most intriguing aspects of Titan is the high presence of methane gas. As one of the simplest hydrocarbons, it can be one of the many signifiers of life. Experiments done to mimic the creation of life have shown similarities to the atmospheric haze surrounding Titan. Bishun Khare successfully created organic molecules found in lifeforms by electrifying a nitrogen and methane mixture [14]. This experiment, like the Miller experiment [16], simulates lightening or other electrical charges which exist in nature charging the molecules and causing them to separate and reform into the building blocks of life. On the Cassini mission, a device called the Ion and Neutral Mass Spectrometer (INMS) was able to determine the concentrations of Titan's atmosphere to compare it to the hypothesis presented by Khare. Organic compounds were discovered to exist in Titan's atmosphere ranging from a single carbon atom to seven carbon atoms, and they were all discovered in the upper atmosphere [14]. Further experiments on Earth have shown the composition of Titan's atmosphere can create the molecular form of various amino acids and nucleobases, and physical experiments have produced all molecules necessary for the formation of DNA [14]. Life as we know it is based upon amino acids and nucleobases. To be able to find them present on the surface, water, or atmosphere would be a clue for the potential of life on Titan.

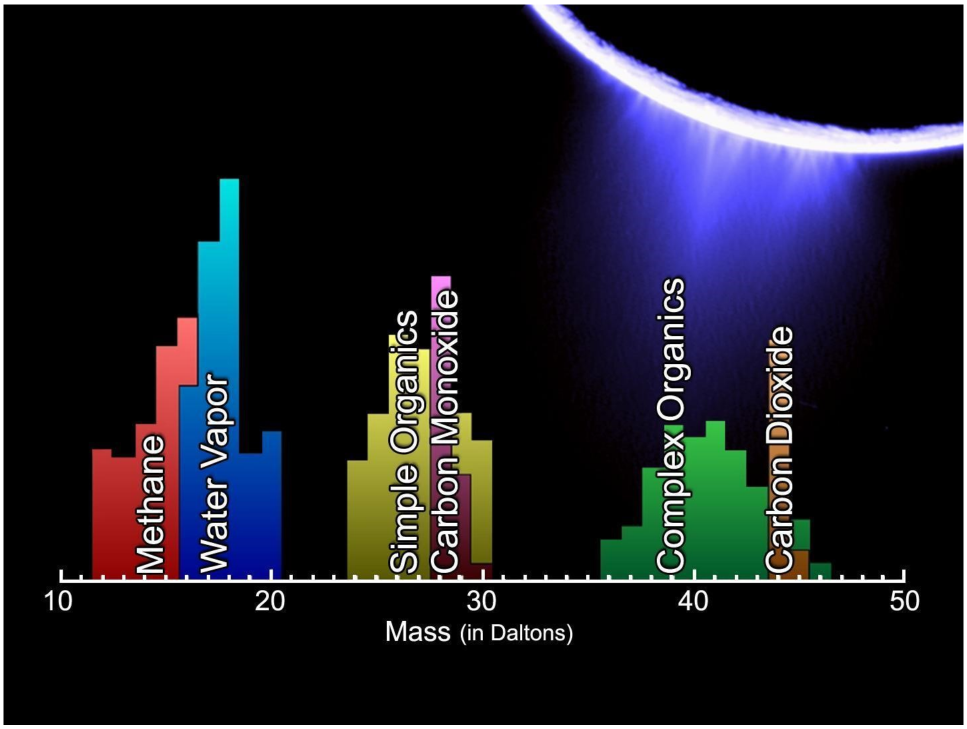

Fig. 7 Chemical Constituents in Enceladus's Plume, Similar Compounds Were Found On Titan

Due to the high level of methane on Titan and the extreme temperatures, life will most likely be different from what we are familiar with. The atmospheric pressure of Titan is about 60% more than Earth but the gravity is less as the size of Titan is much smaller than Earth. Any life found would more closely resemble the life found in the ocean. It could appear as microscopic organisms like single-celled heterotrophs and autotrophs around hydrothermal vents on the ocean floor on Earth. These organisms use chemosynthesis to survive and are mostly types of bacteria and archaea [17]. If any of these are found on Titan, it can signify the beginning of life in the way very early life on Earth began. Being able to detect organic carbons, amino acids, and nucleobases is a vital part of space missions in the search for worlds capable of supporting life [2].

Ideally tests for all the compounds mentioned previously would be conducted on the surface of the moon. Due to the layer of ice on the surface, the methods used for sample collection on Mars will not work. Instead, a drilling method would be preferred for analysis. The drill would be held inside the rover and extend through hydraulics to pierce through the ice. These samples can either be a solid ice core like the ice cores drilled in Antarctica or the shavings can be gathered for the next phase of testing [18]. A device similar to the INMS would be preferred to find the spectrometry of the samples taken. This data would then be sent back to scientists and engineers on Earth to analyze the concentration of the different molecules. This method can be used to find the overall mass of different chemicals as on the original Huygens probe. A more refined version of the INMS could narrow down the analysis range to detect amino acids within the organic compounds.

Despite the importance of amino acids and organic compounds when it comes to life, D-sugars are even more significant to life but in a very specific way. These sugars are found in spaces that contain life as they are vital to living organisms as a source of energy. D-sugars are also the more common form of the molecules verses L-sugars. The most common way of checking the level of these sugars on Earth is with glucose monitors. On its own a glucose monitor provides the mission with a basic overview of the quantity of sugar found in a sample. A monitor could potentially be combined with another device such as a spectrometer to further analyze the samples taken on Titan to discover the types of sugars present.

To aid in the process of analyzing the surface of Titan, a similar set of monitors from the Cassini mission can be added to the rover. The primary set is called the Surface-Science Package and was used to determine the physical properties of the moon. This will help confirm data collected from the Cassini mission as well as create a baseline for the data before and after collection [15].

[12]

V. Propulsion Systems

A. SpaceX Falcon Heavy

As the Komodo mission is designed to be a continuation of research collected by the Dragonfly mission, the initial launch vehicle selected for consideration was the SpaceX Falcon Heavy which is to be used in the Dragonfly mission. The Falcon Heavy is the 2^{nd} most powerful rocket in active use with over 5 million pounds ($22,000$ kN) of thrust. [12] The Space Launch System is the only active system with more power, however it has higher operating costs, lower availability, and fewer launches compared to the Falcon Heavy. The vehicle weighs over 3 million pounds (1,400,000 kg) and is separated into 2 stages, the 1st of which is reusable which would help significantly save on costs and reduce complexities of disposal planning later in the mission. [12] The fuel used by the Merlin rocket engines within the Falcon Heavy is a liquid oxygen and RP-1 mixture which has a specific impulse value of 311s, similar to other hydrocarbon fuels typically used in rocket design. [19] As mission length increases the available mass for payloads are reduced considerably with only around 3,600 lbs available for a trip to Titan.

Table 1 Comparison of Falcon Heavy Specifications to Estimated Trip Requirements

Propulsion System Specs.	Specific Thrust	Propellant Mass Ratio	ΔV	Payload Weight
Theoretical Trip Calculations	300 seconds	88.17458%	9.88 km/s	2000 kg
Falcon Heavy Specifications	311 seconds	95%	9.51 km/s	1600 kg

As seen in Table 1, to determine if the vehicle would also work for the scaled-up size of the Komodo mission the values from the Falcon Heavy were compared with the initial astrodynamics calculations to ensure the launch vehicle would still be a good fit for the larger mission and payload. Notably, the Falcon Heavy exceeds many parameters set by the travel requirements with a higher specific thrust of 311s to 300s and a higher propellant mass ratio of almost 95% gathered by comparing fuel vs empty masses of the stages compared to the required 88%. [12] [19] Despite this the estimated delta-v performance of the Falcon Heavy is still slightly lower than the necessary 9.88 km/s at only around a theoretical value of around 9.13 km/s and a listed value of 9.51 km/s. [19] Additionally, following the results determined for the structural integrity of the payload the weight would be insufficient at only $3,600$ lbs ($1,600$ kg) of the estimated 2000 kg spacecraft. Given these results, we decided that using the same launch vehicle was not recommended unless other more powerful launch vehicles are not available by 2036.

B. Space Launch System (SLS)

Since the main issues with attempting to use the Falcon Heavy for the Komodo mission is the limited delta-v and payload the next logical option is to look at the most powerful launch vehicle in active use, the Space Launch System otherwise known as SLS. The difference in power between the Falcon Heavy and SLS is immense with the current Block 1 configuration of the SLS able to produce over 8.5 million pounds (37,800 kN) of thrust to the Falcon Heavy's 5 million (22,000 kN), and the planned Block 2 configuration is expected to raise that thrust to over 9.5 million pounds (42,000 kN) in the near future. [3] Additionally, the payload capacity for the weaker Block 1 is around 59,500 lbs (26,900 kg) for a Trans Lunar Injection Orbit (TLI) whereas the Falcon Heavy is only able to carry roughly 80% of that amount assuming its TLI value is somewhere between its 58,860 lbs (26,700 kg) Geosynchronous Transfer Orbit (GTO) capacity and its 37,040 lbs (16,800 kg) Mars capacity. Block 1B and Block 2 especially would make the payload issue mostly a non-factor as a result of their estimated 92,500 lbs (41,900 kg) and 101,400 lbs TLI (45,900 kg) capacities respectively. [12][3] Among other improvements in performance the SLS core stages use RS-25 engines which use a liquid oxygen and liquid hydrogen mixture as fuel improving vacuum-specific impulse to 452s which is significantly higher than hydrocarbon fuels. [20]

Table 2 Comparison of SLS Specifications to Estimated Trip Requirements

Propulsion System Specs.	Specific Thrust	Propellant Mass Ratio	ΔV	Payload Weight
Theoretical Trip Calculations	300 seconds	88.17458%	9.88 km/s	2000 kg
Space Launch System (SLS)	452 seconds	Block 1/1B-95% Block 2-90%	Block 1/1B-13.3 km/s Block 2-10.0 km/s	Block 1-2049 kg Block 1B-3192kg Block 2-3497kg

Similar to the determination of the Falcon Heavy's suitability for the mission, all of the SLS variants were compared to the expected requirements of the travel to Titan as seen in Table 2. As can be seen, every SLS configuration would be able to meet the requirements given by the astrodynamics estimations, many with room for error in the estimation. The specific impulse, propellant mass ratio, and delta-v provided are markedly higher than the required values with the only concerns possibly being the payload capacity for the Block 1 configuration due to its limited thrust in comparison to the others. Given these results, the SLS in any of the variations should be adequate for the Komodo mission though the extremely high price and limited testing of 1 successful launch to date makes the selection less desirable if another similarly powerful and reusable alternative came into active use.

C. SpaceX Starship

In order to try to solve the issue of the immense cost of the SLS another possible alternative not yet in active use could be the SpaceX Starship. Though currently still in development the Starship is believed to be capable of producing a maximum thrust of over 16.7 million pounds (74,000 kN) most of which is to be used to leave the atmosphere, however even the second stage retains over 3.3 million pounds (14,600 kN) of thrust. [21] The payload capacity as one might expect with the massive gain in thrust is also claimed to be much higher at over 200,000 lbs (90,700 kg) to Mars which is almost doubles the strongest of the SLS variants in their Moon capacity. [21] The Raptor engines used with the Starship burn a liquid oxygen and methane mixture which has a middle specific impulse in vacuum of 363s in comparison to the other launch vehicles' core engines. In addition to the large gain in power the cost is also claimed to be only around \$2 million a launch due to reusability versus the \$4 billion cost of the SLS, though this like much of the Starship performance is still only and estimate and could change significantly with further testing and implementation.

Table 3 Comparison of Starship to Estimated Trip Requirements

Propulsion System Specs.	Specific Thrust	Propellant Mass Ratio	ΔV	Payload Weight
Estimated Trip Requirements	300 seconds	88.17458%	9.88 km/s	2000 kg
Starship Specifications	363 seconds	92%	9.11 km/s	8,638 kg

As with the other determinations of suitability, the performance specifications of the SpaceX Starship were compared with the estimated requirements of the trip to Titan as seen in Table 3. As expected with the massive increase in power the Starship well exceeds many of the necessary criteria, especially the payload weight which is one of the more important factors in designing a larger scale successor mission such as the Komodo mission. That said the estimated delta-v performed using the propellant mass ratio and specific thrust produced the lowest value of all of the launch vehicles though this seems to be the result of limited availability of information on the vehicle or an outsized impact of the reduced specific thrust more than anything else as the massive power disparity would lead to the assumption that the vehicle should outperform the SLS. Given all of these results the SpaceX Starship would be more than adequate for the Komodo mission potentially even allowing additional objectives while also potentially being one of the more affordable options for the launch vehicle.

D. Selection for the Komodo Mission

Following the comparisons of the various potential launch vehicles for the Komodo mission the SpaceX Starship would seem to be the most suitable assuming testing and implementation confirm the estimated performance and cost specifications available at this time. However, if the Starship is not in active use by 2036 as expected and/or if the costs become much higher than anticipated and surpass the SLS then the SLS as the more proven candidate and/or cost-effective vehicle should be selected for the mission as it would also meet all mission requirements.

VI. Structures

The structure of the spacecraft is one of the most integral parts of any space mission, providing necessary support and protection for the payload and the instrumentation in the interior of the spacecraft. For a mission to Titan, the spacecraft structures are of utmost importance in completing a successful mission. The structures must be designed to withstand the harsh condition of deep space, including extreme temperatures, radiation and space debris. In addition, the structures must be optimized for mass, volume and cost, while meeting the requirements for stiffness, strength and stability. In this section, we will discuss the design and analysis of the spacecraft structures for our mission to Titan, including the materials selection, structural capabilities, and integration with other spacecraft subsystems.

A. Requirements

The requirements for the spacecraft structures for the mission to Titan are critical to ensure the success of the mission. These requirements are driven by the mission objectives, as well as the environment and operational constraints of the mission. The following are the key requirements for the spacecraft structure:

1) Mass: the spacecraft structure must be designed to minimize weight of the spacecraft while maintaining strength and stiffness needed to complete the mission. The total mass of the structures will be a significant driver of the launch casts and the overall mission cost.
2) Volume: the spacecraft structure must be designed to fit within the launch vehicle payload fairing and to accommodate the payload and subsystems. The volume requirement will be influenced by the mission's payload and power requirements.
3) Stiffness: the spacecraft structure must be designed to maintain their shape and structural integrity under various loading conditions, including launch and landing, as well as extreme temperature and radiation environment of deep space.
4) Strength: the spacecraft structure must be designed to withstand the loads and stresses during the mission, including acceleration, vibration, and thermal stresses. The strength requirement will be influenced by the mission's trajectory, launch and landing profiles, and the spacecraft's size and shape.
5) Stability: the spacecraft structure must be designed to maintain their stability and orientation during the mission, including the cruise phase of the mission to Titan. The stability requirement will be influences by the mission's propulsion and guidance systems, as well as the atmospheric conditions of Titan.
6) Integration: the spacecraft structures must be designed to integrate with the rest of the spacecraft subsystems, including the payload, propulsion, and thermal control systems. The integration requirement will be influenced by the mission's design and operational constraints, as well as the compatibility and performance of the subsystems.

These requirements will drive the design and analysis of the spacecraft structure and will be critical to achieving the mission objective for a successful mission to Titan.

B. Materials

The selections of materials for the spacecraft structure is also critical to meeting the requirements of the mission to Titan. The materials must be strong, lightweight, and able to withstand the harsh environment of deep space, including extreme temperatures, radiation, and debris. Several materials were evaluated, and a trade-off analysis was performed to select the most appropriate materials for spacecraft structures. The following are the materials that were considered:

- Aluminum: Aluminum is a material with a high strength to weight ratio that is commonly used in spacecraft structures. It is easy to fabricate, has good mechanical properties, and is resistant to corrosion. However, aluminum has low temperature resistance, which can be problematic for a mission to Titan where temperatures can reach as low as $-290°$ Fahrenheit.

- Titanium: Titanium is a strong and lightweight material that is widely used in aerospace applications. It has good mechanical properties, is corrosion-resistant, and has good temperature resistance. However, titanium is more expensive than aluminum and can be much more difficult to fabricate.
- Carbon fiber reinforced polymer (CFRP): CFRP is a composite material that consists of carbon fibers embedded in a polymer matrix. It is strong, lightweight, and has good thermal stability. However, CFRP is more expensive than aluminum and titanium and can be more difficult to fabricate.

Table 4 Evaluation criterion of potential materials

Materials	Fabrication Difficulty	Cost per pound	Maximum Stress
6061 Aluminum	Easy	$ 0.65	125 MPa
Titanium Alloy	Difficult	$ 1.40	1400 MPa
CFRP	Difficult	$ 80	3.5 GPa

After analyzing the advantages and disadvantages of each material, titanium was selected as the primary material for the spacecraft structures. Titanium has excellent strength and stiffness properties, as well as good temperature corrosion resistance and cost per pound. It is also widely used in aerospace application and is proven to have success in various in space missions. In addition to titanium, aluminum was also considered for some of the less critical structural components, where weight was a more significant factor. Aluminum is less expensive than titanium and is easier to fabricate, making it a good choice for some of the secondary structures. The selection of materials for the spacecraft structures was a critical decision and will be essential to meeting the mission requirements for a successful mission to Titan.

C. Design

The design of the spacecraft for the Komodo mission is based on the successful Mars Science Laboratory (MSL) spacecraft, which was designed to explore the surface of Mars. However, modifications and improvements have been made to the design to meet the specific requirements of the Titan mission. The spacecraft will also have the structural capabilities to travel into deep space like the Dragonfly spacecraft.

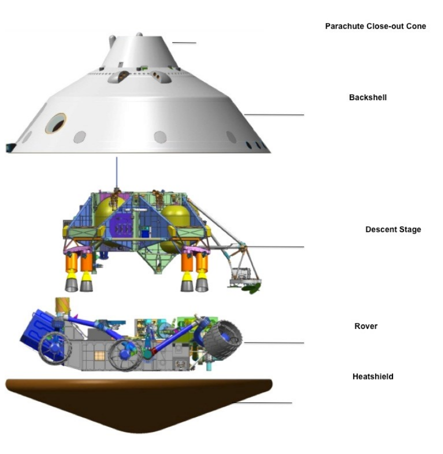

Fig. 8 MSL Spacecraft [22]

The spacecraft will have a total mass of approximately 2,000 kg, with a payload of the Komodo rover, scientific instruments, sensors, and communication equipment. The primary structure of the spacecraft will be made of titanium, which will provide the necessary strength and stiffness while minimizing the overall mass of the spacecraft.

The spacecraft will be equipped with a propulsion system that will enable it to adjust its trajectory and velocity when needed in its flight to Titan. It will also have a communications system, including a high-gain antenna and a low-gain antenna, which will enable communication with Earth and other spacecraft in the Saturn system.

The spacecraft and rover will be designed to operate autonomously, with a pre-programmed flight plan that can be updated based on real-time data received from scientific instruments and sensors. The spacecraft and rover will also have the capability to be remotely controlled from Earth as needed.

Another important consideration in the design of the spacecraft for a mission to Titan is power. Because the moon is located so far from the Sun, it receives only a small amount of solar energy. This means that traditional solar panels, which are commonly used on spacecraft to generate electricity, may not be sufficient for a mission to Titan. To address this challenge, the Komodo spacecraft will use a radioisotope thermoelectric generator (RTG) to generate electricity. An RTG works by using the heat generated from the decay of radioactive isotopes to produce electricity. This allows the spacecraft to generate power even in the low-light conditions on Titan [23]. The use of an RTG also has other benefits for a mission to Titan. Because the generator produces heat as a byproduct, it can be used to keep the spacecraft's instruments and systems warm, even in the frigid temperatures on the moon's surface. This is important for ensuring that the scientific instruments continue to operate effectively throughout the mission.

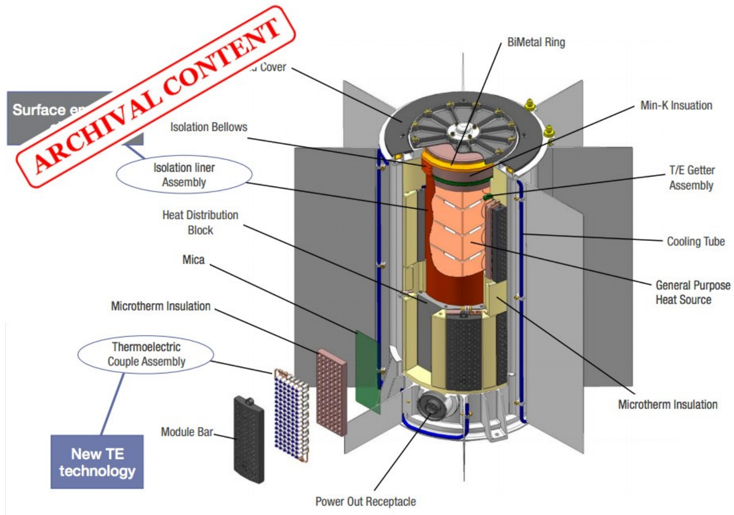

Fig. 9 Radioisotope thermoelectric generator [24]

Finally, the design of the spacecraft needs to take into account the challenges of landing on Titan's surface. Because of the moon's dense atmosphere, a spacecraft landing on Titan needs to be able to slow down quickly in order to avoid crashing. The Komodo spacecraft will use a combination of aerobraking and a rocket-powered descent stage to land safely on the moon's surface. Once on the surface, the spacecraft will deploy the Komodo rover to explore the moon's terrain and collect scientific data. The rover will be equipped with a range of scientific instruments, including cameras, spectrometers, and drill samplers, to study the composition and geology of the moon's surface for signs of life. The rover will be designed to withstand the harsh conditions on Titan, including extreme temperatures and rough terrain. The rover will have six wheels, similar to the Curiosity rover, which will provide mobility on the surface of Titan. The scientific instruments and sensors on the rover will include a mass spectrometer, gamma ray spectrometer, meteorological sensors, cameras, and a laser spectrometer. These instruments and sensors will enable the rover to study the geology, chemistry, and climate of Titan.

Overall, the design of the spacecraft and rover for a mission to Titan is a complex and challenging task that requires careful consideration of a range of technical and scientific factors. The Dragonfly mission provides a great example of how these challenges can be addressed through innovative design and engineering, while the MSL spacecraft provides examples on spacecraft with the ability to transport rovers for scientific research.

D. Conclusion

In conclusion, the design of the spacecraft structures for a mission to Titan is a crucial aspect of ensuring the success of the mission. The spacecraft must be able to maintain structural integrity while encountering harsh conditions of deep space travel and the challenging landing on Titan's surface, while also carrying a payload of scientific instruments and equipment. The Dragonfly mission serves as an excellent example of how innovative design and engineering can overcome these challenges and pave the way for future exploration of this fascinating moon.

The use of high-strength, lightweight materials such as titanium coupled with advanced manufacturing techniques, allows for the creation of a spacecraft that is both strong and efficient. The incorporation of an RTG for power generation ensures that the spacecraft can operate even in the low-light conditions on Titan, while also providing the necessary heat to keep the instruments and systems functioning properly.

Overall, the design of the spacecraft structures for a mission to Titan requires a careful balance between strength, weight, and functionality, all while ensuring that the scientific objectives of the mission can be achieved. The Dragonfly mission provides a model for how these factors can be integrated into a successful mission design, and the future of exploration on Titan looks promising as we continue to develop new and innovative technologies for space exploration.

VII. Conclusion

Komodo's goal is to follow the Dragonfly to Titan in search of life on Saturn's moon. Sampling ice cores and relaying INMS spectrometry data to scientists on Earth with the aid of onboard communications and RTG power generation. Our hope is to equip Komodo with as many onboard science modules as possible, in order to scan for any traces of amino acids or even D-sugars. However, we must also consider the availability of propulsion systems during the construction of Komodo. The Starship and SLS both exceed what our mission requires and could even allow the mission to be expanded upon in terms of onboard science equipment. While the use of the Falcon Heavy would lead to a loss in payload mass and a significant decrease in the size of Komodo, we still believe the 400 kg can be stripped away from various parts and integrated into a smaller scientific rover. This would also lead us to design a more disposable craft made of Aluminum and less Titanium and CFRP. Even though we would see a lifetime decrease on Komodo as Titan's corrosive atmosphere could hinder the Aluminum over time, this would decrease the cost of production significantly; and if designed properly could be made to be disposable in order to leave little to no trace of our presence on Titan which would aid our disposal phase at the end of the mission. Furthermore, we noted that this change in mass has little effect on the mission trajectory itself allowing for a flexible design of Komodo that can change with current market costs and availability.

Appendix

All codes used for this project can be found at: https://github.com/Galactikhan/Misson_To_Titan

Acknowledgments

Special Thanks to Dr. Diogo M. Sanchez for being an amazing teacher; as well as our colleagues, friends, and family for being there for us.

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