Mission Incredible: A Titan Sample Return Using In-Situ Propellants

Geoffrey A. Landis,[1] Steven R. Oleson,[2] Elizabeth Turnbull[2], Jeffrey Pekosh, Zach Zoloty
NASA John Glenn Research Center, Cleveland, OH 44017

Ralph D. Lorenz[3]
Johns Hopkins Applied Physics Laboratory, Laurel, Maryland 20723

David Smith, Tom Packard, John Gyekenyesi, Anthony Colozza
HX5, NASA John Glenn Research Center, Cleveland, OH 44017

James Fittje
SAIC, 3000 Aerospace Parkway, Brook Park OH 44142

and the NASA Glenn COMPASS team

An analysis of the use of in-situ volatile propellants for a sample return mission from Titan shows that this mission should be feasible. Such a mission would be invaluable for its science return, and its contribution to our understanding the origins of organic compounds in the solar system and our place in the universe.

I. Nomenclature

GLOM= Gross Lift Off Mass (kg)
Isp = Specific impulse (seconds)
ISRU = In-Situ Resource Utilization
kPa= kilopascals of atmospheric pressure
LOX = Liquid Oxygen
NIAC = NASA Innovative Advanced Concepts program
O2 = Liquid Oxygen
RPS = Radioisotope Power source
ΔV = delta-V (total velocity change), km/s

II. Introduction

Titan is unique in the outer solar system in that it is the only moon with a thick atmosphere, and the only body in the solar system outside the Earth with liquid seas on its surface. The Titanian oceans, however, are seas of liquid

---

[1] Researcher, Photovoltaics and Electrochemical Technology Branch. AIAA Associate Fellow.
[2] Engineer, Mission Architecture and Analysis Branch.
[3] Mission Architect, Space Exploration Sector. Member AIAA.

hydrocarbons, and the rocks on the surface are solid water ice. Like other icy moons of the outer solar system, beneath the ice crust, Titan also has a subsurface ocean. Rodriguez *et al*. refer to it as the “world with two oceans”, an organic-rich body with interior-surface-atmosphere interactions that are comparable in complexity to the Earth [1].

Titan is scientifically fascinating in many ways [2-4]. We will emphasize just one here: Titan is a high priority target for astrobiology [4-11]. It is a world with a surface and atmosphere rich in the complex organic compounds known as tholins. A detailed understanding of the nature of these complex compounds will require an analysis using a full laboratory on Earth. Because of its value to understanding the organic compounds of the outer solar system which may be the primordial building-blocks of life, return of samples from Titan to laboratories on Earth will be the primary goal of this mission.

While this would give unprecedented science return, returning even a small sample from Titan using conventional technology would be tremendously difficult. Saturn is almost a billion miles from the Earth, about thirteen times farther than Mars. A return mission to Saturn requires such a large total-mission ΔV that, with conventional technology, the mass ratios required are prohibitive. Such a sample return would truly be “mission incredible”. But to date, a sample return mission from so distant a target has been assumed to be, not merely incredible, but mission impossible. We have proposed [2, 12] that by manufacturing the propellant for the launch from Titan and the return to Earth using the resources available on Titan, we can make such a mission possible. Our task is to show that it is reasonable with credible space technology.

III. Mission

The mission for Titan sample return consists of launch from Earth, insertion into the interplanetary trajectory and flight from Earth to the Saturn system (possibly incorporating planetary flyby for gravity assist), entry descent and landing on Titan, operations on Titan (including collection of samples, surface science (if any), and, for the ISRU-fueled mission, processing of propellant), launch from the surface of Titan, insertion into the interplanetary trajectory and flight to Earth, entry descent and landing on Earth, and post-mission curation and analysis of samples. This study focused on the elements of the mission which are unique to Titan, and with greatest emphasis on the launch from Titan and the return to Earth.

Two approaches to the return phase of the Titan sample return mission were considered, either a direct launch of the Earth return vehicle from the surface of Titan, or an approach where the vehicle carrying the sample is launched from Titan to a rendezvous with a separate Earth Return vehicle waiting in Titan or Saturn orbit. The orbital rendezvous approach increases the complexity and requires two vehicles, but has the advantage of requiring less mass to be landed on and launched from the surface of Titan. Making the return using a single vehicle with no orbital rendezvous simplifies the system at the cost of somewhat more mass landed on Titan. The comparative merits of each approach is very sensitive to the ΔV required for injection into the trans-Earth trajectory. For the current study, a return trajectory utilizing multiply flybys of Titan and a close approach to Saturn was found which minimized the ΔV for the trans-Earth injection, and hence a direct launch of the Earth return vehicle from Titan was chosen for its reduced complexity as well as its maximizing the use of in situ propellants.

In any case, most of the details of the analysis of launch from the Titan surface into the parking orbit around Titan will be the same, and the analysis here can be used for either approach.

A. Titan Environment

Basic information about the Titan surface and atmosphere has been gathered by the Voyager and Cassini missions, along with surface observations by the Huygens Titan lander [13]. Titan has an average surface temperature of 90.6 K, reaching a maximum temperature of 93.6 K. The atmosphere is primarily nitrogen with about 5.6 percent methane (at the surface), with an atmospheric pressure of 147 kPa (1.45 atm). The atmospheric density is 5.43 kg/m^3, about 4.3 times denser than Earth’s atmosphere.

Titan has an escape velocity of 2.64 km/s. The surface gravity is 1.35 m/s^2 (0.138 times that of Earth). The lower surface gravity results in lower decrease of atmospheric density with altitude, with a density scale height in the lower atmosphere of about 22 km, more than twice that of the Earth. Due to the greater scale height, the altitude of a low orbit above Titan is notably higher than that of a low Earth orbit. For this study, we assumed 1000 km altitude above the surface for the parking orbit, to place the orbit above the drag of residual atmosphere.

Although the lower escape velocity makes launching from the Titan surface slightly easier than launch from Earth, the greater atmospheric pressure and higher scale height combine to make launch more difficult. The high atmospheric pressure also decreased the engine performance. A methane/oxygen engine optimized for the surface atmospheric pressure at an expansion ratio of 20:1, produces about 270 seconds of specific impulse, while the same engine with an expansion ratio of 150:1 optimized for vacuum operation produces about 350 seconds of specific impulse. Our calculations show that roughly 1 km/s of the 3.9 km/s required to launch from the surface into Titan orbit is due to the atmospheric drag (depending on the vehicle area and drag coefficient).

B. System Model

Figure 1 shows the system block diagram showing the key elements of the mission concept.

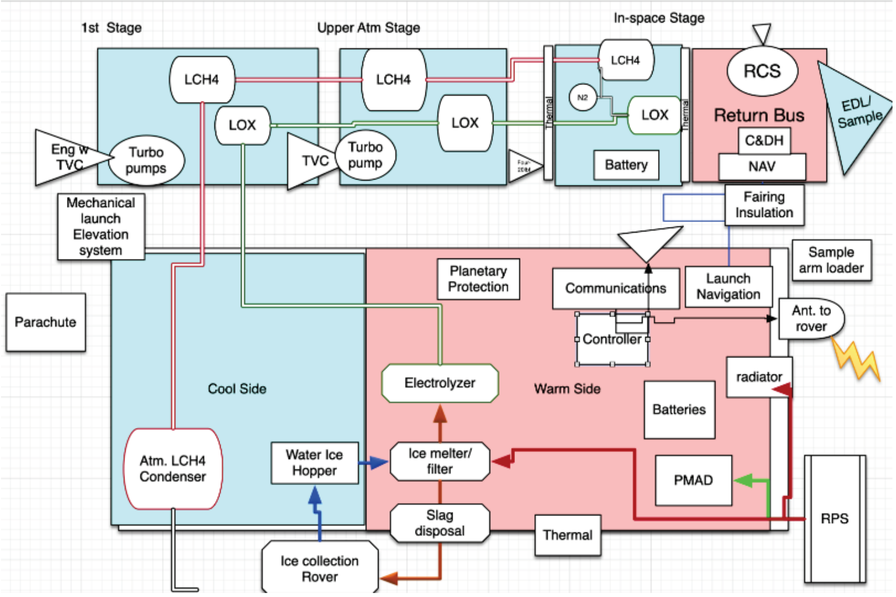


Figure 1: block diagram of major system elements of the Titan Sample Return mission and the propellant processing, showing the vehicle systems at the top, with the propellant processing systems below. Systems shown in blue are "cold" (at ambient Titan temperature, about 91K), while systems coded in red are "warm" (Earth temperature, about 300K).

IV. Return Mission Performance

A. Titan Launch

The vehicle designed here used two stages to launch from the surface into Titan orbit, and then a third in-space stage capable of multiple restarts was used to take the vehicle from Titan orbit to the Earth return trajectory. The trajectory was optimized using Optimal Trajectory through Implicit Simulation (OTIS v4.0) software [15], configured with masses that are representative of the return vehicle. Details of the trajectory design will be covered in a second paper.

The optimizer chooses a flight path within the constraints of the problem to minimize drag losses in the lower portion of the atmosphere against gravity losses accumulated through the ascent. The first stage used two 6.2 kN engines delivering a specific impulse of 270 seconds at surface pressure, increasing to 317 s in a vacuum. The second stage, with expansion ratio optimized for higher altitude performance, had a single engine with a maximum vacuum thrust of approximately 7.6 kN. The second stage specific impulse was about 310 s at the initial firing altitude of 33 km above the surface, rising to 342 s I_{sp} in a vacuum. Engine throttle on both stages was optimized during the trajectory between limits of 25% to 100% of maximum.

The resulting trajectory is nearly vertical, with an initial thrust to weight ratio (for weight calculated at Titan gravity) of about 2 to reduce drag loss through the lower atmosphere. Above the thick atmosphere, the engines throttled up and the vehicle pitches over to build up downrange velocity, dropping the launch fairing at 150 km altitude, where the drag is negligible. The resulting trajectory is 72 min ascent, comprising 22.6 minutes of thrust, a 49 minute coast, and then a 0.2 km/s circularization burn to insert into 1000 km circular Titan orbit. The total launch ΔV to Titan orbit was 3.9 km/s, of which the first stage accounted for roughly 25% of the total ΔV and about 45% of the total propellant.

Plots of the implicit solution for altitude, velocity and dynamic pressure are shown in Figure 2. The trajectory is characterized by a slow, vertical ascent to an altitude > 30 km where it begins a slow pitch over. Much of the pitch over occurs at an altitude closer to 40 km. Initial thrust to weight ratio is maintained at or near T/W = 2 by optimal throttling through the majority of the first stage ascent while the vehicle is deep in Titan's atmosphere. The initial ascent is very slow as the OTIS optimization reduces the throttle to minimize drag losses. Typical velocity for the vehicle during the first stage of the ascent is below 100 m/s and, as seen in figure 2, does not increase until the second stage ignites and the launch vehicle is above the densest part of the atmosphere.

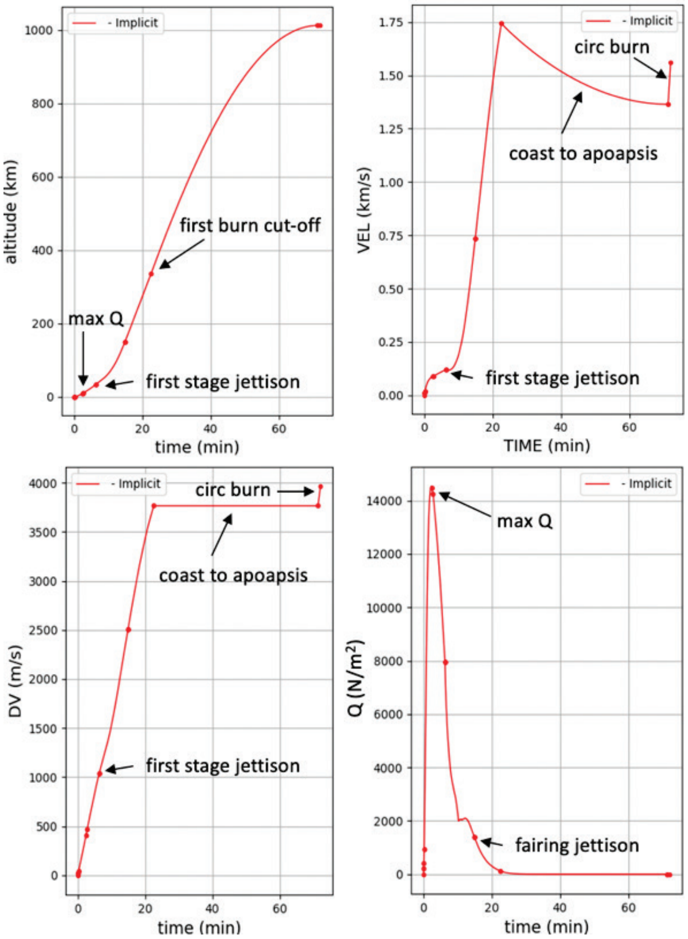
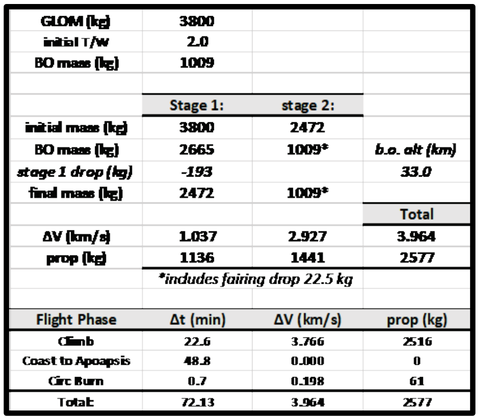


Figure 2: Altitude, velocity, ΔV and dynamic pressure during launch from Titan Surface as a function of time

The launch parameters, ΔV and propellant are summarized in Table 1. The launch ΔV to Titan orbit is somewhat higher than that assumed by a previous analysis of Titan sample return [14], and about 570 m/s higher than assumed in our original proposal [12]. We think that this discrepancy may be due to an unrealistically low estimate of drag losses in the earlier work.



GLOM (kg)	3800		
initial T/W	2.0		
BO mass (kg)	1009		
	Stage 1:	stage 2:	
initial mass (kg)	3800	2472	
BO mass (kg)	2665	1009*	*b.o. alt (km)*
stage 1 drop (kg)	*-193*		*33.0*
final mass (kg)	2472	1009*	
			Total
ΔV (km/s)	1.037	2.927	3.964
prop (kg)	1136	1441	2577
	**includes fairing drop 22.5 kg*		
Flight Phase	Δt (min)	ΔV (km/s)	prop (kg)
Climb	22.6	3.766	2516
Coast to Apoapsis	48.8	0.000	0
Circ Burn	0.7	0.198	61
Total:	72.13	3.964	2577

Table 1: Launch parameters, ΔV, and propellant

B. Return In-Space Trajectory

A direct departure from Titan orbit to Earth requires an impulsive ΔV of 3 km/s, with a flight time of 5.87 years. Use of a Jupiter flyby to decrease the transit ΔV was considered. This can reduce the required ΔV by 0.5 to 0.8 km/s compared to the direct injection, but the required orbital position was not available in the assumed time frame of the mission, and so the Jupiter gravity assist was not considered.

To minimize the ΔV required for leaving the Saturn system into a trajectory toward Earth, a number of different trajectories were analyzed. The approach taken was to escape from Titan orbit into a Saturn-centric orbit followed by a series of flyby passes of Titan to increase the eccentricity and raise the apoapsis. This is then followed by a burn to lower the periapsis to a close pass over the Saturn cloudtops, and at the periapsis pass, a final burn of about 0.5 km/s injects the vehicle into the trans-Earth trajectory. The trajectory is shown in figure 3 below.

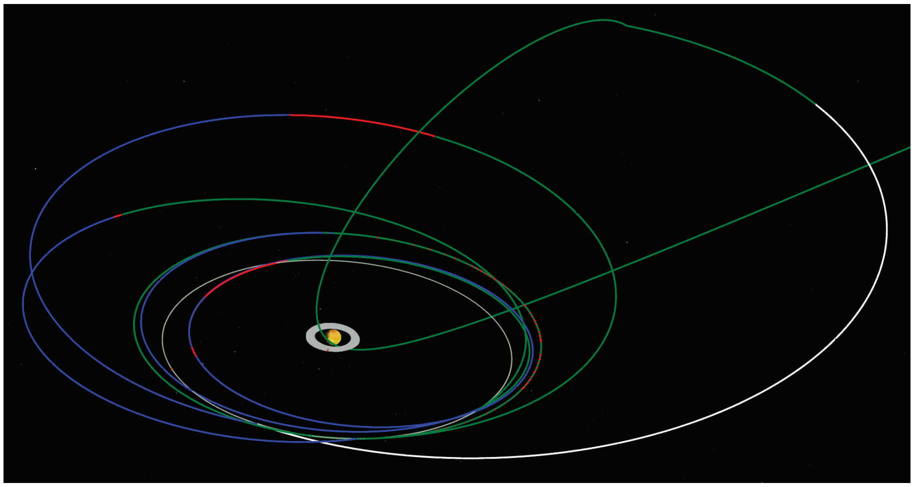
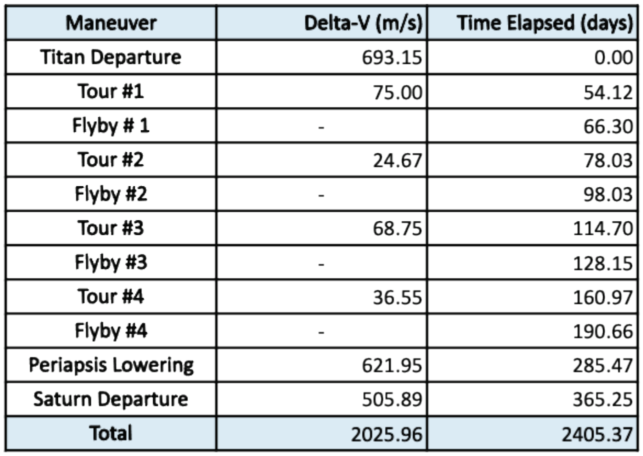


Figure 3. Saturn/Titan Flybys to return sample to Earth

The minimal allowable Saturn periapsis was chosen based on the closest pass by the Cassini orbiter before encountering enough atmosphere for the spacecraft's orientation to be affected by atmospheric torque. This occurred during Cassini orbit 274, during which Cassini passed 2,660 kilometers of Saturn's 1-bar level. Subsequent orbits lowered this periapsis to as low as 2,500 km above Saturn's visible atmosphere, but required Cassini's reaction control thrusters to correct the spacecraft's orientation to offset the torque imparted by atmospheric drag [18].

The lowest ΔV solution found made five Titan flybys before periapsis lowering maneuver and Saturn pass, resulting in a ΔV for the Earth injection of 1.55 km/s. This solution required a duration of 31.5 month sequence for the Saturn system portion of the return. To reduce this time spent in Saturn orbit, a trajectory with four Titan flybys was selected, resulting in a 2 km/s, 12 month sequence. The flyby sequence and ΔVs are summarized in Table 2.



Maneuver	Delta-V (m/s)	Time Elapsed (days)
Titan Departure	693.15	0.00
Tour #1	75.00	54.12
Flyby # 1	-	66.30
Tour #2	24.67	78.03
Flyby #2	-	98.03
Tour #3	68.75	114.70
Flyby #3	-	128.15
Tour #4	36.55	160.97
Flyby #4	-	190.66
Periapsis Lowering	621.95	285.47
Saturn Departure	505.89	365.25
Total	2025.96	2405.37

Table 2. Saturn/Titan Flyby Tour to Minimize Return Vehicle In-Space ΔV.

V. In-Situ Propellants

Many studies of space development have emphasized the use of the in-situ resources to eliminate the requirement to launch propellants from Earth. Titan has surface lakes of liquid methane and ethane, totaling an amount of hydrocarbons larger than the total fossil fuel reserves of the Earth, and surface rocks of water ice, a source of oxygen. With water, liquid methane, and ethane easily available, Titan is a rocket scientist's dream for propellants. In addition, unlike Mars, Titan has a thick atmosphere, allowing us to use a propellantless, direct aerodescent to reduce the entry velocity, and a parachute for soft landing.

In-situ resource utilization (ISRU) for propellant production has been explored for Mars missions, but is little analyzed for missions farther out in the solar system. As will be seen, propellent production from resources on Titan is significantly different than the concepts proposed for Mars, the moon, or asteroids. Demonstration of ISRU for sample return from Titan will be a huge step beyond Mars; the first building block in using the resources of the outer solar system.

A. Choice of Fuel and Oxidizer

Chemical rocket propellant consists of a fuel and oxidizer combination. The obvious choice for fuel is the native Titan hydrocarbon. Methane (and possibly ethane) is abundant, available in liquid form in lakes on the surface, as well as in smaller amounts in the atmosphere. Unlike any other destination in the solar system, producing rocket fuel on Titan needs no processing: it requires only gathering the available fuel from the environment.

The methane/LOX combination is very nearly an ideal rocket propellant. The specific impulse (I_{sp}) of 325 seconds is second only to liquid hydrogen/oxygen among hydrocarbon-based rocket fuels, but methane's much higher density (0.44 kg/m^3, compared to 0.071 for liquid hydrogen), allows for considerably smaller tanks, and eliminates the requirement for cryogenic storage. For these reasons, methane/oxygen engines are being developed for the next generation of launch vehicles, including Starship, New Glenn, and Vulcan. Engine development for these vehicles means that this concept will not require new technology, but can use designed and tested engines.

Alternate possibilities were considered. Liquid ethane, with a slightly higher density of 0.65 kg/m^3, is also likely to be available on Titan. However, ethane has lower I_{sp}, and is difficult to obtain from the atmosphere. Hydrogen, with higher (>430 s) I_{sp} but lower density, could be produced by electrolysis (and is in fact a byproduct of the production of the oxygen from water ice). However, it was eliminated as a desirable fuel due to the difficulty of storage.

On Titan, a more difficult choice is the oxidizer. Nitrogen-based oxidizers such as NTO were considered but rejected in favor of refining liquid oxygen from Titan's water ice resources. The rocks are gathered, melted using the heat from the radioisotope source, and electrolyzed to produce oxygen.

Cryogenic storage is simple because the ambient temperature on Titan is ideally suited for the propellants we have chosen. The maximum measured surface temperature of 93.6 K is just above methane's freezing point at Titan's atmospheric pressure, allowing us to store the methane as a liquid fuel with no refrigeration. The temperature is slightly above the 1-bar boiling point of oxygen, but the high pressure of Titan's atmosphere means by maintaining a tank pressure of 2.5 bar, (about 1 bar above Titan ambient pressure), the oxygen remains liquid up to 100 K, a comfortable margin above the highest temperature measured on Titan. By a fortunate coincidence, the temperature and pressure at the surface of Titan allows cryogenic propellants to be stored in liquid form without refrigeration. Likewise, although not used in this study, ethane is also liquid at Titan temperatures.

B. Propellant Acquisition: Methane

Landing close to one of the Titan lakes would be a straightforward method of methane acquisition; in essence allowing methane to be acquired using little more than a pipe and a pump. However, this acquisition approach would put significant constraints on the landing site; in addition to other constraints of landing site safety, the site must be at the edge of the lake. This will add to the mission a requirement that the landing error ellipse must be precise to within a very tight accuracy, with a risk of a possible mission failure if the landing is out of reach of the methane.

Instead, we propose here to acquire the methane from the atmosphere. On Titan, the methane vapor content of the atmosphere is at or near the saturation point, and hence methane can be condensed out of the atmosphere either by lowering the temperature, or by compressing the atmosphere at constant temperature. We chose the second option. The atmosphere is collected, compressed to 8.8 bar, and then allowed to cool to ambient temperature. Methane from the atmosphere is condensed to liquid, and the liquid methane is transferred to a storage tank to temporarily store it before transferring it to the launch vehicle. The liquification tank is then vented to remove the remaining nitrogen, and the process is repeated until the required amount of liquid methane is collected. Pump and compressor power required for this collection process is about 117 W to produce the required methane production rate of about 700 grams per day.

C. Propellant Acquisition: Oxygen

In the oxygen production system, rocks consisting of water ice are collected by a small rover and transferred to a melting tank, where they are melted using waste heat from the radioisotope power source. The meltwater is then distilled, again using waste heat, to remove impurities. Heat exchangers are used to scavenge the residual heat from the distilled meltwater. The purified water is then piped to the electrolyzer unit, which separates the water into hydrogen and oxygen, and the hydrogen is vented. The electrolyzer design used is a Proton Exchange Membrane (PEM), of a design based on commercial fuel cell technology, similar to electrolyzers considered for other ISRU applications [16]. The oxygen is dried, to remove any residual water, liquified by exposing it to Titan temperatures, and sent to the storage tank, where it is temporarily stored before transfer to the launch vehicle.

The rate-limiting step in propellant processing is the power required for electrolysis of the water to produce the required oxygen, requiring about 3.52 kW-hr per kg of oxygen produced. At an electrolyzer energy efficiency of 0.72, power required for this is 484.5 W.

Power is produced by a Radioisotope Power System (RPS), based on a dynamic radioisotope conversion such as the Dynamic Radioisotope Power System (DRPS). In this case, the efficiency of the power conversion will be increased by the low ambient temperature; the waste heat from the RPS is utilized to melt the water, while electrical power runs the systems and is used to electrolyze the water into hydrogen and oxygen. Three DRPS are assumed to provide roughly 1 kWe of power for all functions of the outbound and surface mission.

VI. Detailed Design

D. Overall Mission Concept of Operations

A brief overview of the 17 year mission to return 3 kg of cryogenic samples is shown in the concept of operations, figure 4. A reasonable launch mass of ~ 3t was possible by producing return propellants on Titan. This enabled the use of a Falcon Heavy expendable launcher with a Star 48 upper stage to a C3 of about 90 km2/s2. Additional velocity is added by a Jupiter flyby. After a seven year trip the vehicle will encounter Titan. Titan's heavy atmosphere allows for a non-propulsive, direct entry like Huygens probe. Since no return stage or spacecraft was needed to be inserted into Titan orbit all that is needed is an entry system. Since the propellant ISRU and return system was the focus of this NIAC concept a representative aerodescent system was chosen based on the X37-C concept [19]. Such a vehicle could allow for entering the Titan atmosphere and then gliding to the desired propellant-rich landing area. The landing could be achieved by skids using a parachute to slow the vehicle. Further work on defining the entry vehicle is needed.

Once on the surface the rover (or alternatively rotor vehicles) will gather both the return cryogenic samples as well as the water ice ore that will be processed into the liquid oxygen propellant by the radioisotope powered ISRU system. The methane is simply distilled from the atmosphere. These propellants are then cooled by exposing them to the Titan ~94 K environment and pumped into the three inflatable return launcher stages. About three years is needed to produce the roughly 3000 kg of LOX and liquid methane propellants. The Titan launcher is elevated and filled slowly with the cryogenic propellants as they are produced over a 3 year period. Once filled the first two stages of the launcher place the upper stage / return vehicle into a 1000 km circular orbit above Titan. Such a high orbit is needed due to the thickness of Titan's heavy atmosphere. While the gravity losses from Titan's low gravity (about one seventh that of Earth) make the launch easier than from Earth, the thicker and denser atmosphere causes significant drag. Further studies will look at ways to utilize the atmosphere to assist in the launch, focusing on replacing the chemical first stage with options such as balloon, rotorcraft, or aircraft launch.

The third (in-space) stage will be used for multiple burns to depart Titan orbit and enter a Saturn orbit that provides Titan and Saturn flybys to minimize the propellant to get on a trajectory to return to Earth. The Titan Samples will be kept cryogenic by continuously exposing them to deep space. Instead of a plutonium power system, an ultralight solar array will be used to power the return vehicle – with power increasing as the vehicle gets closer to Earth and the Sun. A nominal aeroshell/parachute system will return the sample to Earth's surface. Since a science requirement of the mission was that the sample would not be exposed to temperatures high enough to liquify any of the frozen components of the sample, a small amount of liquid oxygen (produced on Titan) will encapsulate the 3 kgs of Titan samples, keeping them cold during the Earth recovery phase during descent and landing.

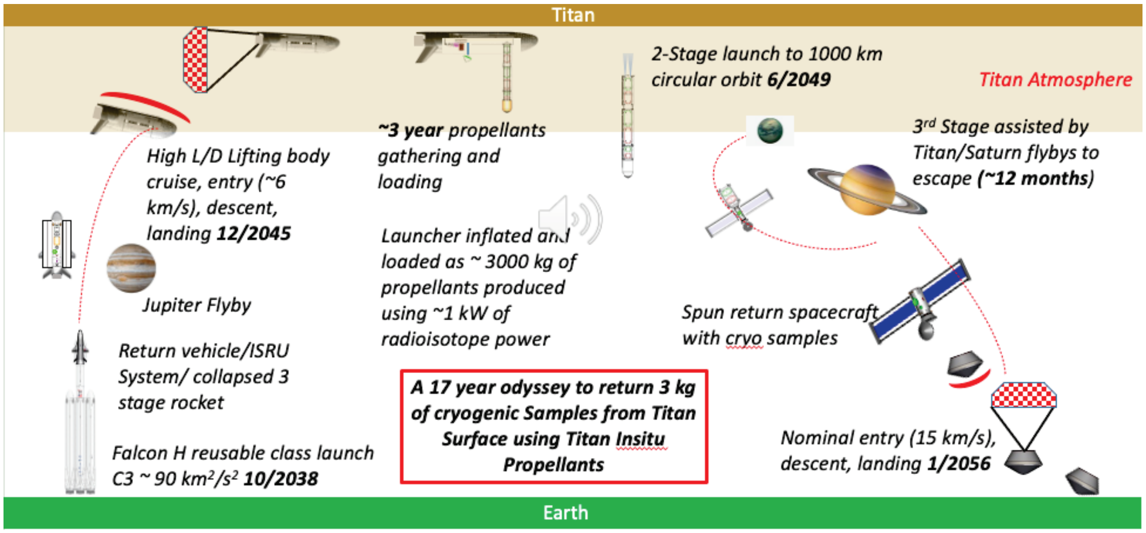


Figure 4: Summary of the Mission Concept of Operations (CONOPS)

E. Mission Elements

The elements of the sample return mission consist of three major elements that will be landed on the Titan surface: the lander element containing the ISRU processing plant; the launch vehicle for ascent off the Titan surface; and the return vehicle located inside a payload fairing atop the launch vehicle, which holds the Titan sample to be returned to Earth.

While the use of in-situ propellant production reduced the mass to be landed on Titan, a significant challenge of the project was the volume required, which was driven primarily by the size of the fuel tanks needed to hold the three tons of propellant for the launch vehicle, along with the constraint that drag considerations favored a vehicle which minimized the cross-sectional drag area.

This challenge was addressed in two ways. First, rather than using a typical conical-shaped entry body that is typical of most planetary landing missions, we chose to use a lifting body entry vehicle based on the X-37 C vehicle [19]. The X-37 C was originally designed by NASA as a prototype for a Crew Return Vehicle for the International Space Station, and is a flight-proven entry system that is currently being flown by the Air Force missions. The advantage of the X-37 C configuration is that the payload bay had a length considerably longer than the width; well suited for the long but narrow shape of the launch vehicle.

Second, to minimize the required volume, the vehicle was designed with inflatable, rather than rigid, tanks. Various inflatable tank concepts are currently being investigated by NASA [20]. The tank design incorporated here consists of thin polymer-based bladder that is reinforced by longitudinal load carrying tendons which are connected to polar bulkhead assemblies. The inflatable tanks are based on the ultra-high pressure vessel (UHPV) technology, and consist of a flexible bladder sounded by high strength tendons that are attached to bosses located at the tanks poles. Since they are flexible, they can be folded down almost completely flat for packaging. Materials and fabrication techniques that are compatible with cryogenics are currently being tested. Short door-knob style tanks have been built and pressure tested, concepts for equatorial ring mounting systems are being evaluated, and concepts for integral tank internals also exist. The tank mass is anticipated to be less than that of titanium alloy tanks for the same mean operating pressure and volume. Base on this technologies light weight and very low packaged volume it was selected for this design.

The payload bay for the lifting body was based on the size of the X-37C variant, and is 2-meters in diameter and 10-meters long to ensure that the length to diameter ratio is kept at 5:1 or less. All of these surface elements can be seen inside the payload bay envelope in Figure 5 and 6 below.

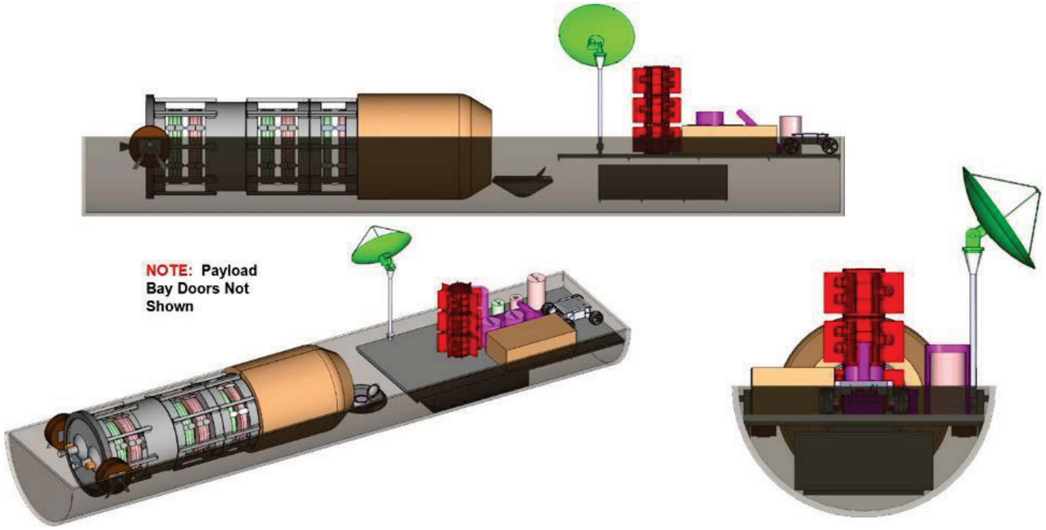


Figure 5 All three major Titan Sample Return elements inside a representative lifting body payload bay.

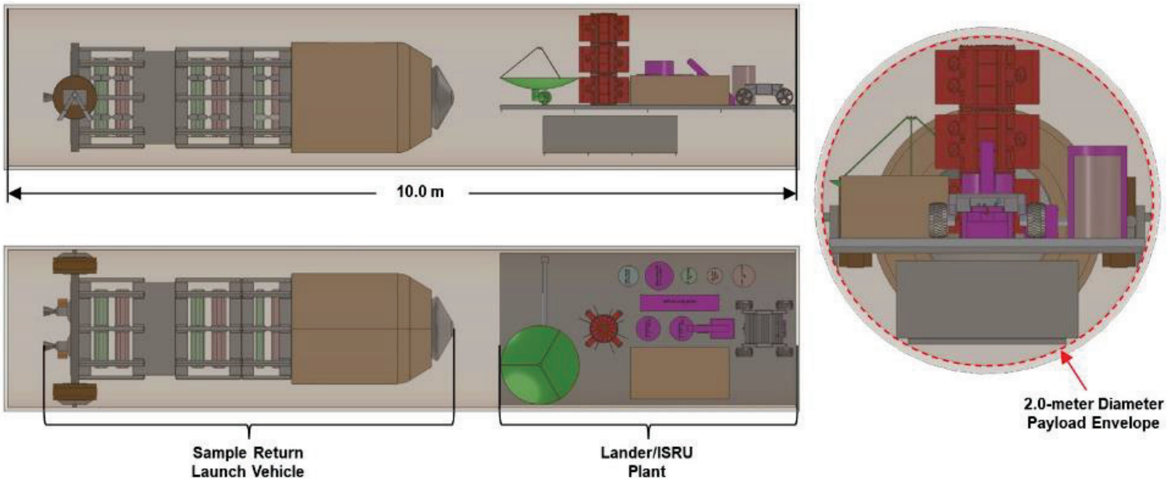


Figure 6. Sample loading configuration on the Titan surface.

Prior to elevating the launch vehicle, the Titan sample to be returned to Earth must be placed inside the sample canister located inside the aeroshell located on top of the return vehicle. While a concept for physically placing the sample inside the canister was not designed during this study, the concept for the sample canister and the aeroshell for which it is contained was conceptually designed. The aeroshell containing the sample canister will open utilizing a hinge mechanism that will separate the heat shield from the backshell, and rotate the heatshield 90 degrees, exposing the sample canister. The canister itself will also utilize a hinge mechanism to open a portion of the canister to allow the sample to be deposited. The open aeroshell and canister can be seen in Figure 6 as it would be during the sample deposit while on the Titan surface. Note in this configuration, the 1-meter diameter X-band dish antenna is deployed to provide communications while on the Titan surface.

The components contained on the top deck of the lander (mounted directly to the inside of the payload bay) include: the three dynamic radioisotope power system (DRPS) units of the electrical power system; all the communications system components; the avionics enclosure of the Command and Data Handling (C&DH) system; the rover/excavator;

and all the components that make up the ISRU processing plant. These components are shown in Figure 7 below.

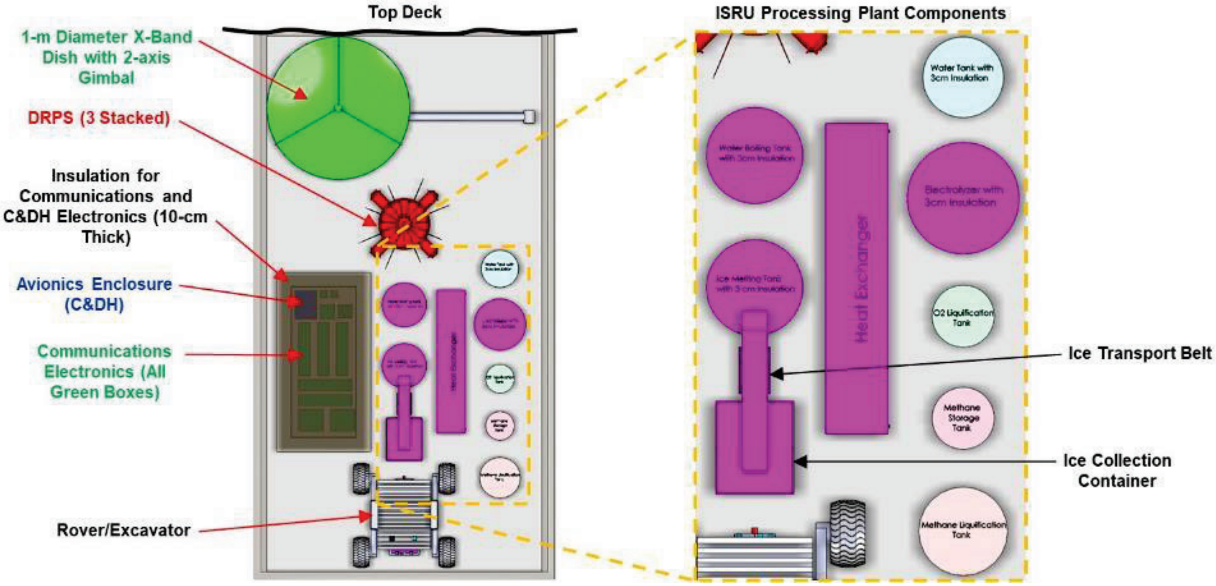


Figure 7 Components located on the top deck of the lander.

The three RPS units are stacked one on top of another with the bottom one being integrated to the deck. This configuration allows the top two units and about half of the bottom unit to be above the hinge line of the payload doors, exposing the units to either deep space or the Titan atmosphere, thus providing a better cooling environment for the RPS units.

The rover/excavator sits on the deck at the very back of the payload bay. It was not designed during this study, but rather a representative rover/excavator was used from a past Compass design in to obtain good mass, power, and size estimates. The rover/excavator shown in the images is just representative and used to show approximate size and location within the lander system. The rover/excavator is used to excavate the Titan surface and deposit the soil containing ice to the ice collection container of the ISRU processing plant. It may also be used for collecting the sample for Earth return, though that phase of the mission was not designed during this study. Another option for sample collection could be a robotic arm. A ramp would be deployed out of the back of the lifting body to allow the rover to exit to the Titan surface and return to deliver the excavated soil. Design of the ramp system was not performed during this study as it would be part of the lifting body.

Those components that make up the liquid oxygen portion of the ISRU processing plant include: the ice collection container; an ice transport belt; an ice melting tank; a water boiling tank; a heat exchanger; a water tank; an electrolyzer; and an O2 liquification tank. The liquid methane used as the fuel for the launch vehicle is produced from the methane contained in the Titan atmosphere. This system includes a methane liquification tank and a methane storage tank. It should be noted that all of the tanks are covered in 3-cm of foam insulation with the exception of the O2 liquification tank, methane liquification tank, and the methane storage tank which utilize the cold Titan environment to keep them at their desired temperatures. All these components are shown in the magnified image at the right in Figure 7.

The launch vehicle is comprised of three stages: the first stage; the upper atmosphere stage (second stage); and the in-space stage (third stage). Atop the in-space stage encapsulated is a payload fairing is the return vehicle, which will be discussed in more detail in a later paper.

Inflatable liquid methane and liquid oxygen tanks allow the launch vehicle stages to stowed at a much shorter length than when deployed. This is key to allowing the launch vehicle to fit in the 10-meter long payload bay with all the other components that make up the lander and propellant processing plant. Deployment of the stages is done through a set of eight rails evenly distributed around each stage. Each rail is comprised of a set of five square tubes that are nested inside one another when stowed and telescope out upon deployment using a screw drive. This allows for a 5:1 ratio of deployed to stowed rail length. The overall length of the stowed launch vehicle is 520.6 cm while the deployed length reaches 1173.9 cm. Figure 8 shows the stowed launch vehicle along with the overall dimensions and some of the major components for each stage.

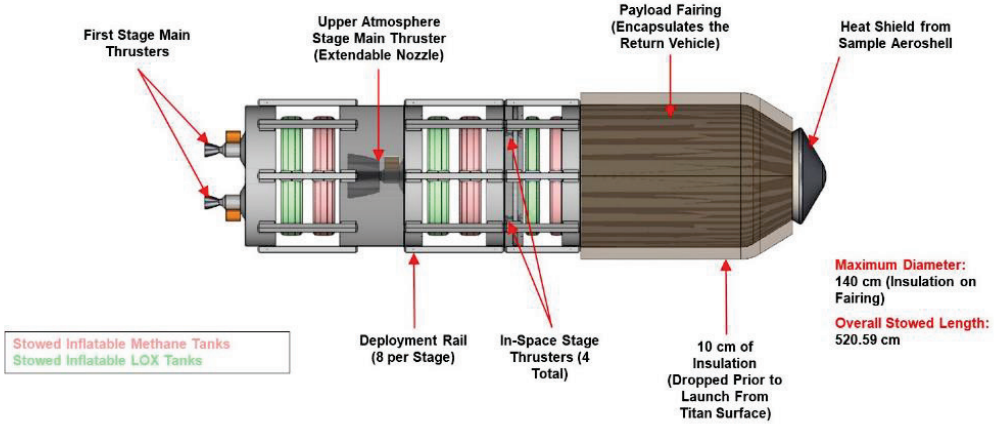


Figure 8 The Titan Launch Vehicle in its stowed configuration.

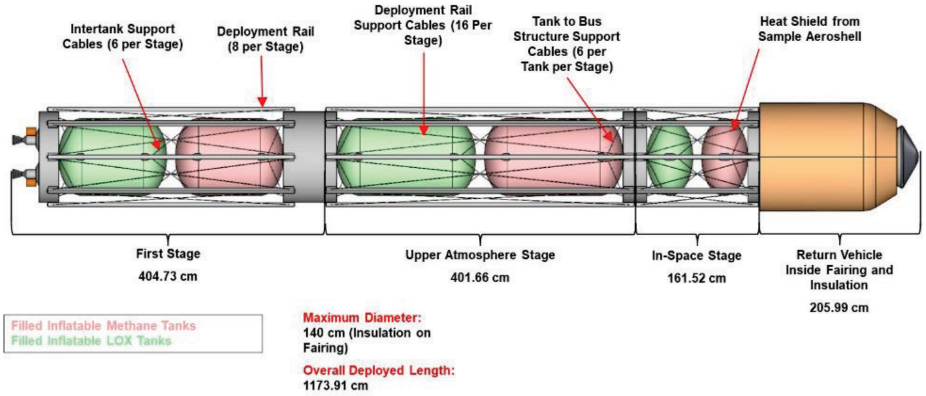


Figure 9: Titan Launch Vehicle in deployed configuration

A series of cables are used to stiffen the overall deployed structure of the launch vehicle. These cables run between each end of a rail to the opposite end of the adjacent rail producing an "X" pattern between two adjacent rails. Cables are also used to hold the deployed tanks firmly in place once deployed. Each tank has a set of six cables that run from the tabs around the base of one of the tank domes to the cylindrical bus structure of the stage, and another set of six cables that run from tabs around the base of the other tank dome to the other tank in that stage. With this cable layout, the oxidizer and propellant tank for each stage are each attached to the stage bus structure at one end, and to the other tank at the other end. Figure 9 shows the fully deployed launch vehicle along with its primary dimensions, components, and provides a good look at the cable layout for each stage.

Figure 10 shows the changes in the configuration of the launch vehicle from the initial stowed phase to the final in-space operations phase around Titan. In addition to the thermal insulation fairing insulation being dropped prior to liftoff, it should be noted that a protective fairing is jettisoned during the upper atmosphere stage (second stage) burn and the return vehicle solar arrays are deployed and aeroshell heatshield opened prior to jettisoning the in-space stage (third stage). Deployment of the return vehicle arrays allows the return vehicle to provide the power to the in-space stage during its operations and the heatshield is opened to allow the sample inside to be exposed to deep space to keep it cooled.

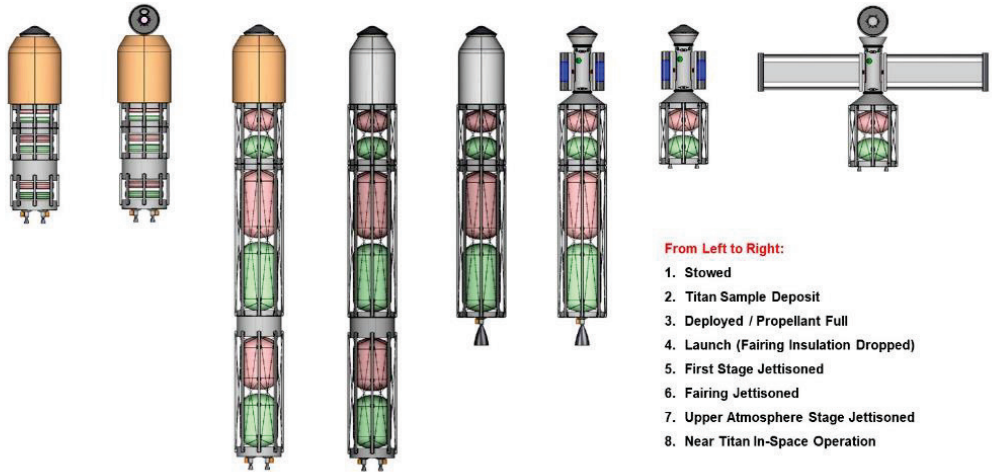


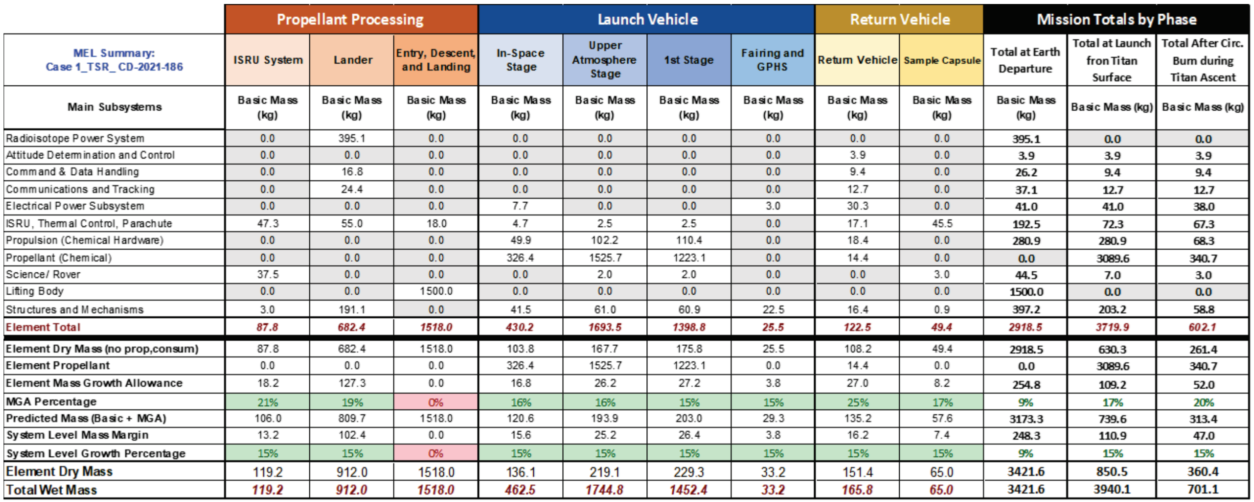
Figure 10 Various launch vehicle configurations during its various mission phases.

VIII. System Masses

Not surprisingly, returning a 3 kg cryogenic sample from Titan has huge mass requirements. A previous study [14] found that, even with optimistic assumptions, returning a sample from Titan without using in situ propellants required over 10 tons of mass and an SLS launcher, plus on-orbit rendezvous and an aerocapture system for the return stage. By using in-situ propellants, the launcher requirement is reduced to around 3.4 tons and only needs a heavy class launcher (Falcon H expendable as representative). The in-situ approach will need ISRU propellant technologies and unfoldable cryogenic tanks.

The 3.4 tons of mass is divided between the delivery lifting body, ISRU plant and rover, the three stage rocket, the return spacecraft and the return aeroshell. Table 3 shows the masses by each element. Note that both subsystem growth and system level margins are carried using the ANSI/AIAA mass estimation guidelines [21]. Per the guidelines, each system has a total growth/margin mass of 30% or more, except for the Titan entry/descent/landing system which was allotted a mass of 1500 kg.

As table 3 shows, the ISRU and support systems tally to around a metric ton while the propellants produced are over three times that mass. Indeed, it is interesting to note that the mass of the system sent to Titan (without the return propellants) is actually less that the fully fueled launcher/return vehicle on Titan.



	Propellant Processing			Launch Vehicle				Return Vehicle		Mission Totals by Phase		
MEL Summary: Case 1_TSR_ CD-2021-186	ISRU System	Lander	Entry, Descent, and Landing	In-Space Stage	Upper Atmosphere Stage	1st Stage	Fairing and GPHS	Return Vehicle	Sample Capsule	Total at Earth Departure	Total at Launch fron Titan Surface	Total After Circ. Burn during Titan Ascent
Main Subsystems	Basic Mass (kg)	Basic Mass (kg)	Basic Mass (kg)	Basic Mass (kg)	Basic Mass (kg)	Basic Mass (kg)	Basic Mass (kg)	Basic Mass (kg)	Basic Mass (kg)	Basic Mass (kg)	Basic Mass (kg)	Basic Mass (kg)
Radioisotope Power System	0.0	395.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	395.1	0.0	0.0
Attitude Determination and Control	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.9	0.0	3.9	3.9	3.9
Command & Data Handling	0.0	16.8	0.0	0.0	0.0	0.0	0.0	9.4	0.0	26.2	9.4	9.4
Communications and Tracking	0.0	24.4	0.0	0.0	0.0	0.0	0.0	12.7	0.0	37.1	12.7	12.7
Electrical Power Subsystem	0.0	0.0	0.0	7.7	0.0	0.0	3.0	30.3	0.0	41.0	41.0	38.0
ISRU, Thermal Control, Parachute	47.3	55.0	18.0	4.7	2.5	2.5	0.0	17.1	45.5	192.5	72.3	67.3
Propulsion (Chemical Hardware)	0.0	0.0	0.0	49.9	102.2	110.4	0.0	18.4	0.0	280.9	280.9	68.3
Propellant (Chemical)	0.0	0.0	0.0	326.4	1525.7	1223.1	0.0	14.4	0.0	0.0	3089.6	340.7
Science/ Rover	37.5	0.0	0.0	0.0	2.0	2.0	0.0	0.0	3.0	44.5	7.0	3.0
Lifting Body	0.0	0.0	1500.0	0.0	0.0	0.0	0.0	0.0	0.0	1500.0	0.0	0.0
Structures and Mechanisms	3.0	191.1	0.0	41.5	61.0	60.9	22.5	16.4	0.9	397.2	203.2	58.8
Element Total	***87.8***	***682.4***	***1518.0***	***430.2***	***1693.5***	***1398.8***	***25.5***	***122.5***	***49.4***	***2918.5***	***3719.9***	***602.1***
Element Dry Mass (no prop,consum)	87.8	682.4	1518.0	103.8	167.7	175.8	25.5	108.2	49.4	2918.5	630.3	261.4
Element Propellant	0.0	0.0	0.0	326.4	1525.7	1223.1	0.0	14.4	0.0	0.0	3089.6	340.7
Element Mass Growth Allowance	18.2	127.3	0.0	16.8	26.2	27.2	3.8	27.0	8.2	254.8	109.2	52.0
MGA Percentage	21%	19%	0%	16%	16%	15%	15%	25%	17%	9%	17%	20%
Predicted Mass (Basic + MGA)	106.0	809.7	1518.0	120.6	193.9	203.0	29.3	135.2	57.6	3173.3	739.6	313.4
System Level Mass Margin	13.2	102.4	0.0	15.6	25.2	26.4	3.8	16.2	7.4	248.3	110.9	47.0
System Level Growth Percentage	15%	15%	0%	15%	15%	15%	15%	15%	15%	9%	15%	15%
Element Dry Mass	119.2	912.0	1518.0	136.1	219.1	229.3	33.2	151.4	65.0	3421.6	850.5	360.4
Total Wet Mass	***119.2***	***912.0***	***1518.0***	***462.5***	***1744.8***	***1452.4***	***33.2***	***165.8***	***65.0***	3421.6	3940.1	701.1

*Note this does not explicitly include any propellant for outbound leg

Table 3: Table of mass elements broken out by subsystem, including growth.

VII. Conclusions

Return of a sample from the surface of Titan sample return would have great science value, but is very difficult mission to accomplish with conventional technology. This conceptual design study showed that using in situ propellants provides a mass and volume feasible solution for returning a cryogenic sample from Titan. Various propellants were considered but the use of methane distilled from the atmosphere along with oxygen generated from water ice from the surface allowed for all the needed propellants to be produced in under 3 years with a relatively low power (1 kWe) radioisotope power system. The use of these cryogenic propellants was greatly simplified by the Titan environment; the methane was easily collected and both were stored as propellants in the launcher tanks without insulation due to the 94 K environment. A 3-stage launcher incorporating inflatable propellant tanks was developed which both saved mass and volume, and could deliver the sample back to Earth without the need for a rendezvous with a return stage in Titan orbit. This mission would be invaluable for its science return, and its contribution to our understanding the origins of organic compounds in the solar system and our place in the universe.

Acknowledgments

This work was supported by the NASA Innovative Advanced Concepts Program.

References

1. S. Rodriguez, S. Vinatier, D. Cordier, G. Tobie, R.K. Achterberg, C.M. Anderson, S.V. Badman *et al.,* "Science goals and new mission concepts for future exploration of Titan's atmosphere geology and habitability: Titan POlar Scout/orbitEr and In situ lake lander and DrONe explorer (POSEIDON)." arXiv preprint arXiv:2110.10466 (2021).
2. G. Landis and S. Oleson, "Sample Return from Titan," Planetary Science and Astrobiology Decadal Survey 2023-2032; *Bulletin of the American Astronomical Society, Vol. 53,* No. 4, e-id. 309 (2021).
3. S. MacKenzie, *et al.,* "Titan: Earthlike on the Outside, Ocean World on the Inside," white paper submitted to the Planetary Science Decadal Survey, July 2020. *The Planetary Science Journal*, *2* No. 3 (June 15 2021) p. 112.
4. R.D. Lorenz, J. Lunine, W. Zimmerman, "Post-Cassini Exploration of Titan," *Adv. Space Research, 36,* 2 (2005) pp. 281-285.
5. F. Raulin, "Astrobiology and Habitability of Titan," Space Sci. Rev. 135, pp. 37-48 (2008)
6. R. Shapiro and D. Schulze-Makuch, "The Search for Alien Life in Our Solar System: Strategies and Priorities," *Astrobiology, 9,* No. 4 (11 Jun 2009).
7. F. Raulin, C. McKay, J. Lunine, and T. Owen, "Titan's Astrobiology", *Titan from Cassini-Huygens,* Springer Verlag, Dordrecht. (2009).
8. N. Sarker, *et al.*, "Titan Aerosol Analogues: Analysis of the Nonvolatile Tholins," *Astrobiology, 3*, No. 4 (July 5, 2004) pp. 719-726.
9. C.D. Neish, Á. Somogyi, and M.A. Smith, "Titan's Primordial Soup: Formation of Amino Acids via Low-Temperature Hydrolysis of Tholins," *Astrobiology, 10*, No. 3 (April 2010) pp. 337-347.
10. S.M. Hörst, *et al.*, "Formation of Amino Acids and Nucleotide Bases in a Titan Atmosphere Simulation Experiment," *Astrobiology, 12,* No. 9 (Sept. 2012) pp. 809-817.
11. H.J. Cleaves II, *et al.*, "Amino acids generated from hydrated Titan tholins: Comparison with Miller–Urey electric discharge products", *Icarus, 237* (July 15, 2014) pp. 182-189.
12. G. Landis and S. Oleson, "Proposal for a Sample Return from Titan," *18th International Planetary Probe Workshop*, June 17, 2021.
13. R.D. Lorenz, *Saturn's Moon Titan,* Haynes 2021.
14. B. Donahue, "Titan Sample Return Mission Concept", *57th JANNAF Propulsion Meeting*, Colorado Springs, CO (May 2010).
15. S.W. Paris, *et al.*, Optimal Trajectories by Implicit Simulation: OTIS. Version OTIS 4, Vols. I to IV, Export Controlled International Traffic in Arms Regulations document (2008).
16. C.S. Iacomini and K.R. Sridhar, "Electrolyzer Power Requirements for Oxidizer Production on Mars", *J. Propulsion and Power, 21*, No. 6 (Nov.–Dec. 2005).
17. H.H. Waite, J. Bell, R. Lorenz, R. Achterberg, R. and F.M. Flasar, "A model of variability in Titan's atmospheric structure," *Planetary and Space Science, 86*, pp. 45 (2013)
18. NASA Cassini mission, "Grand Finale Overview: Orbit Guide," https://solarsystem.nasa.gov/missions/cassini/mission/grand-finale/grand-finale-orbit-guide/
19. A.C. Grantz, "X-37B Orbital Test Vehicle and Derivatives," paper AIAA 2011-7315, *AIAA Space 2011 Conference & Exposition,* Long Beach, California (Sept. 27-29 2011).
20. See: https://sbir.nasa.gov/SBIR/abstracts/10/sbir/phase1/SBIR-10-1-X5.03-8613.html; https://techport.nasa.gov/view/102657; https://www.sbir.gov/sbirsearch/detail/372215
21. "Mass Properties Control for Space Systems," AIAA standard S-120A-2015 (2019). https://doi.org/10.2514/4.103858