PROPOSAL FOR A SAMPLE RETURN FROM TITAN

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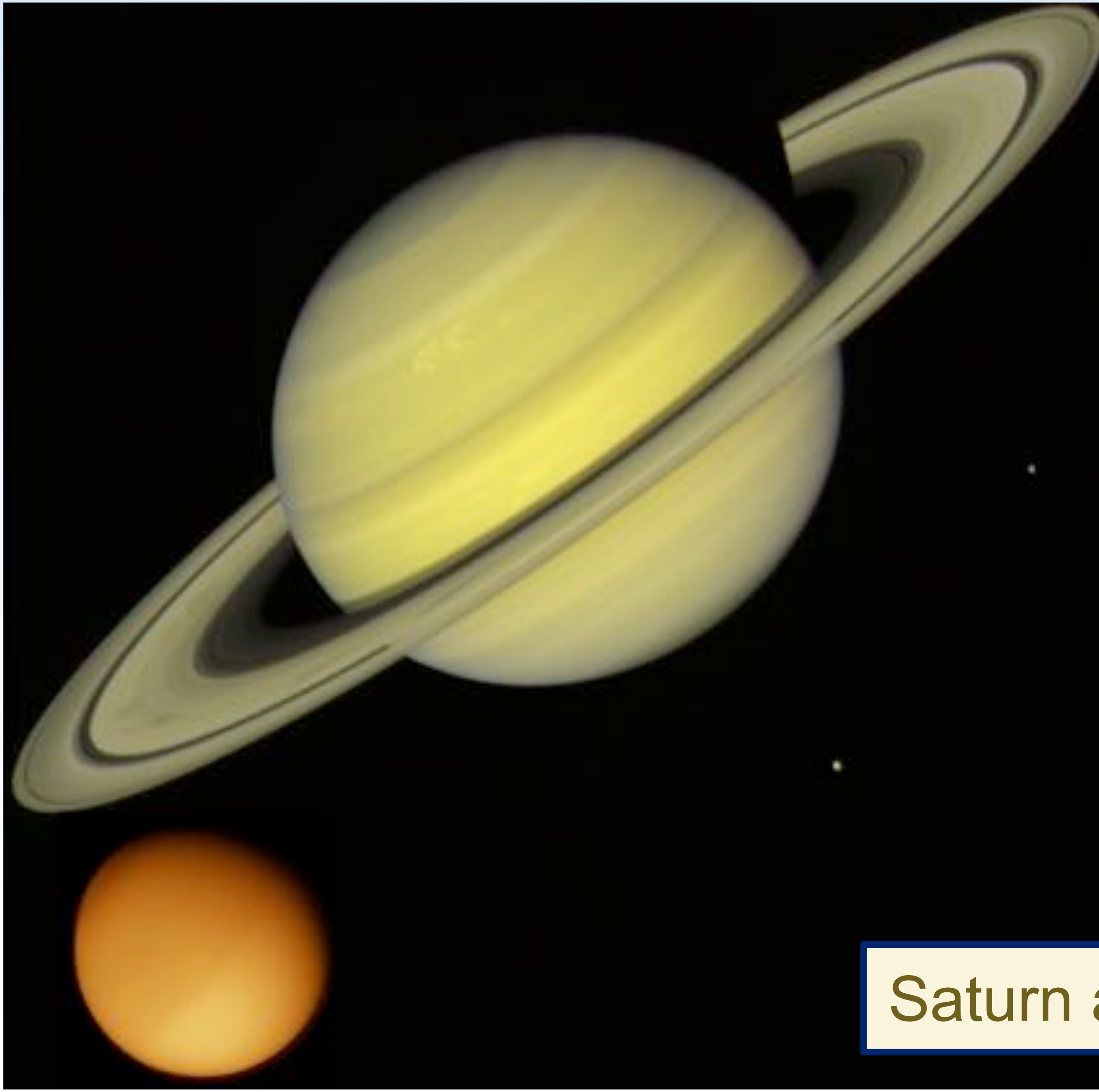


Saturn and Titan

Titan– the *other* world with open liquid bodies on the surface

- Saturn's moon Titan is the second-largest moon in the solar system (after Ganymede).
- It is only moon in the solar system to have a dense atmosphere, and the only body other than the Earth to have bodies of liquid on the surface.

Titan as viewed by the Cassini orbiter, showing the orange haze of the atmosphere, as well as the forward-scattering of blue light. Image courtesy NASA/JPL

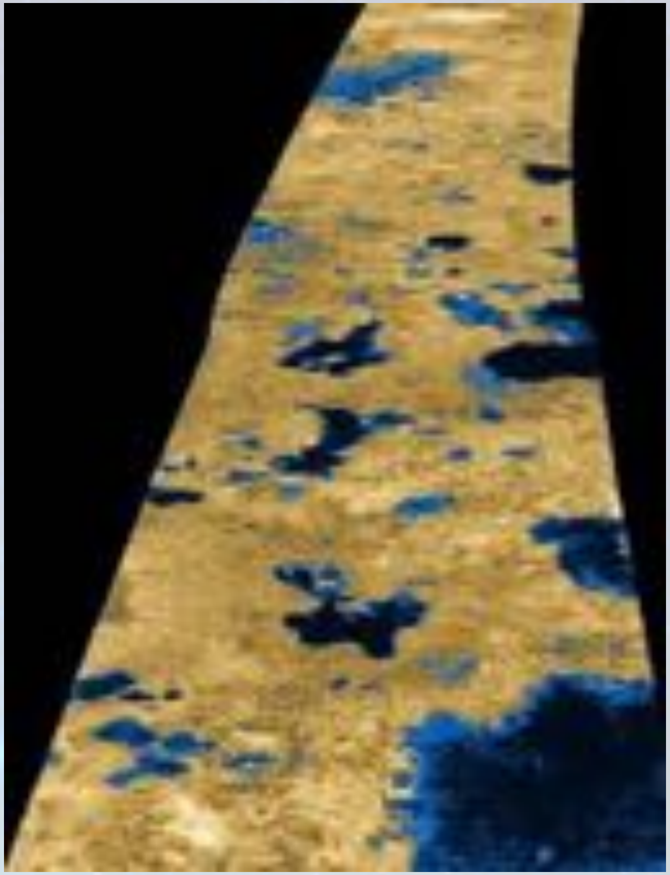
Titan science

- Titan is a high priority target for astrobiology. 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.
- To date, a sample return mission from so distant a target has been assumed to be impossible. Our task is to show that it is credible with credible space technology.
- Our approach is to use *in situ resources* of Titan to produce the propellant for the return to Earth

Surface of Titan viewed from the Huygens probe. The orange color is due to organic tholins. Image courtesy ESA/NASA

Titan– the *other* world with open liquid bodies on the surface

- Saturn's moon Titan is the only moon in the solar system to have a dense atmosphere, and the only body other than the Earth to have bodies of liquid on the surface.
- The Titanian oceans, however, are not composed of water, like Earth's oceans, but are in the form of a series of hydrocarbon (methane and ethane) lakes, covering a surface area of over 500,000 km^2.



Titan's hydrocarbon lakes shown in false color, as viewed by the Cassini radar.

Potential In-Situ Propellants.

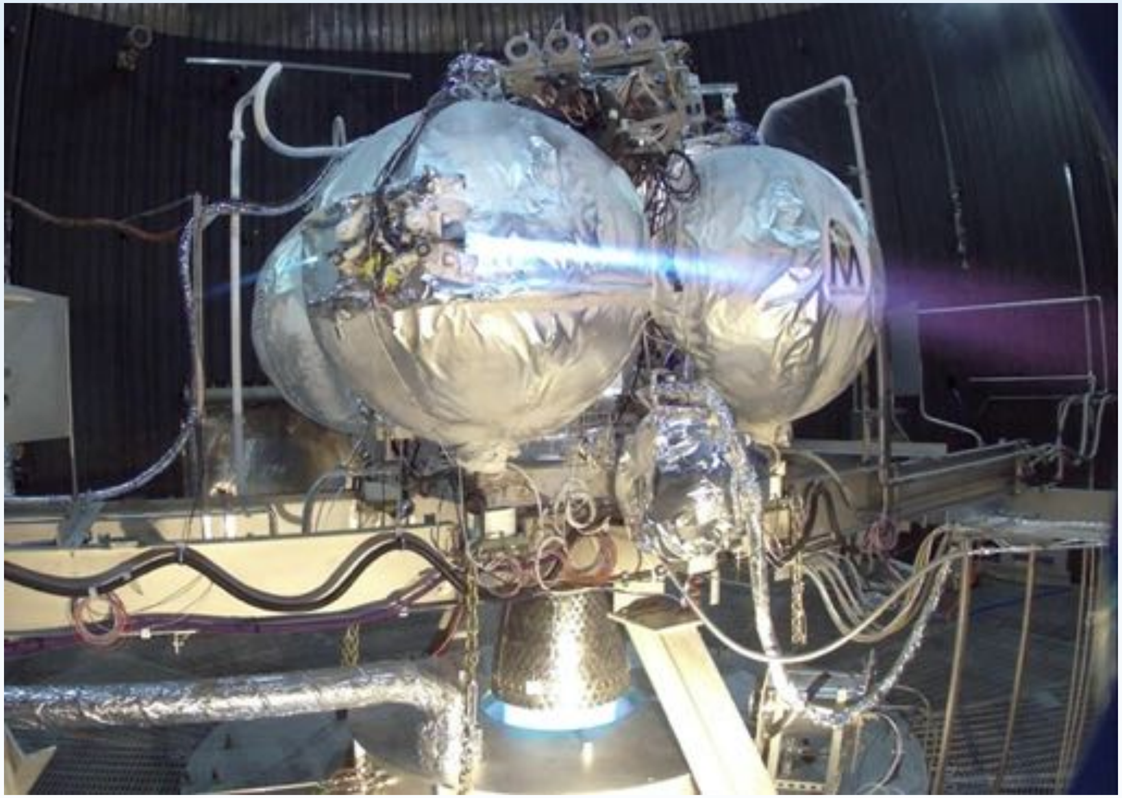
- In-situ resource utilization (ISRU) for propellant production has been explored for Mars missions, but is little analyzed for missions farther out in the solar system.
- Chemical propellants requires producing both fuel and oxidizer.
- The obvious choice for fuel is the native Titan hydrocarbon. Methane and ethane are abundantly available in liquid form in lakes on the surface.
  - Unlike any other destination in the solar system, producing rocket fuel on Titan needs no processing: it requires little more than a pipe and a pump.
- The more difficult choice on Titan is the oxidizer.
- Our baseline choice is refining oxygen from Titan's water-ice rocks.
- Methane/Oxygen engines optimize at Oxygen:Fuel ratio of about O:F=3:1, so we need three times as much oxygen as methane.
- To generate oxygen, we gather water-ice rocks, melted using heat from the radioisotope source, and electrolyze the H_2O to produce oxygen.

Methane/LOX Propellants.

Methane/LOX combination is very nearly the ideal rocket propellant.

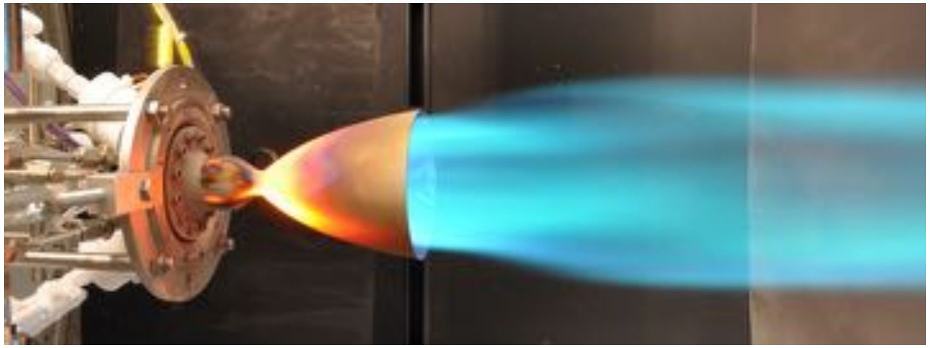
- Specific impulse (Isp) of 325 seconds.
  - second only to liquid hydrogen among hydrocarbon-based rocket fuels
- Density of 0.44 kg/m^3. This is dense compared to hydrogen (0.071 kg/m^3), allowing for considerably smaller tanks
- The higher boiling point (111 K) eliminates need for cryogenic storage.
  - For these reasons, methane/oxygen engines are being developed for the next generation of launch vehicles, and the concept will be able to use designed and tested engines.
- Alternate possibilities are liquid ethane; with a slightly higher density (0.65 kg/m^3), but lower Isp, or hydrogen, with higher (>430 s) I_{sp}, but lower density and more difficult storage.
  - While methane/LOX is proposed as the baseline choice for all three stages, all possibilities will be compared during the study.

LOX/Methane engine



Top: Integrated hot-fire test of 12.5 kN (2800 lbf) LOX/methane engine at the Plum Brook ISP Thermal Vacuum Chamber

NASA Image



Bottom: uncooled small LOX/methane rocket engine being tested at NASA Glenn Altitude combustion stand

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Citation: Robert L. Morehead, *et al.* "Vehicle-Level Oxygen/Methane Propulsion System Hotfire Demonstration at Thermal Vacuum Conditions." *53rd AIAA/SAE/ASEE Joint Propulsion Conference*. 2017.

Calculated ΔV and mass ratios for Titan to Earth trajectory

Titan launch vehicle	ΔV (m/s)	M_o (kg)	Stage mass (kg)	Propellant (kg)	Burnout mass (kg)	Injected mass (kg)
Ascent stage 1	3300	4500	576	2881	1619	1042
Return stage 1	1380	1042	73	363	680	607
Return stage 2	3220	607	77	383	224	147
Total	7900	6149	873	3627		147

Return Vehicle	Mass (kg)
Sample return capsule	60
Return cruise vehicle	80
Sample	7
Total mass	147

By coincidence, 7.9 km/sec is the minimum velocity of an Earth orbit: thus, the Titan surface to Earth flyby launch is similar (but slightly less) in ΔV to launching from the Earth to LEO

Assumptions:

Isp: 329 s at Oxygen:Fuel (O:F) ratio=3:1
Ascent ΔV: 3300 m/s
Trans-Earth injection ΔV: 4600 m/s
Does not include Saturn or Jupiter swing-by for the Earth return

ISRU-fueled Titan Launch Vehicle

Propellant

- While the three-stage vehicle's mass is 4.5 tons, only around 1000 kg needs to be landed. The mission acquires 3.5 tons of propellants from Titan.

Propellant mass:

- **875 kg** of Methane
- **2,625 kg** of Oxygen
  - Assuming we run the engine at near the optimum O:F ratio of 3:1

Volume:

- **2 m^3** of Liquid Methane
  - density 440 kg/m^3 at Titan temperature
- **2.3 m^3** of of Liquid Oxygen
  - density 1140 kg/m^3 at Titan temperature

Propellant Production

875 kg CH_4
2,625 kg LOX

- Landing close to a Titan sea would make methane acquisition simple.
- The bottleneck to propellant production will be the oxygen
- The rate-limiting step in processing is likely to be be electrolysis of water to produce the required oxygen.
- Power in the baseline calculation is assumed to be the Advanced Stirling radioisotope generator (ASRG).
  - the efficiency of the power conversion will be increased by the low ambient temperature.
- The waste heat from the ASRG is used to melt the water, while electrical power is used to electrolyze the water into hydrogen (assumed to be discarded) and oxygen.
- An alternate, power from a reactor power system, will be considered in a trade study.

Oxygen Production: Energy analysis

875 kg CH_4
2,625 kg LOX

Energy to melt Titan ice

- Heat ice from 90K to 273K:
  - Heat capacity of ice varies with temperature
  - Average over temperature range = 1.5 kJ/kgK
  - Total energy needed 270 kJ/kg
- Melt ice
  - Heat of fusion 334 kJ/kg
- Total to heat and melt ice: 600 kJ/kg
- Total to produce 3000 kg of water: **1800 MJ (500 kW-hr)**
  - we are assuming that this can be done using waste heat from the power system

Energy to electrolyze water to produce oxygen

- Theoretical energy for electrolysis of water requires 18 kJ per gram of O2 produced (5 kW-hr per kg)
- 2,625 kg LOX will thus require **47 GJ (13,000 kW-hr)**
  - This is theoretical value for 100% efficient electrolysis with no losses: real world power will be higher
- Assuming two 150-watt ASRGs, this will take 5 years
- Assuming a 1 kW next-generation power supply, this will take 1.5 years

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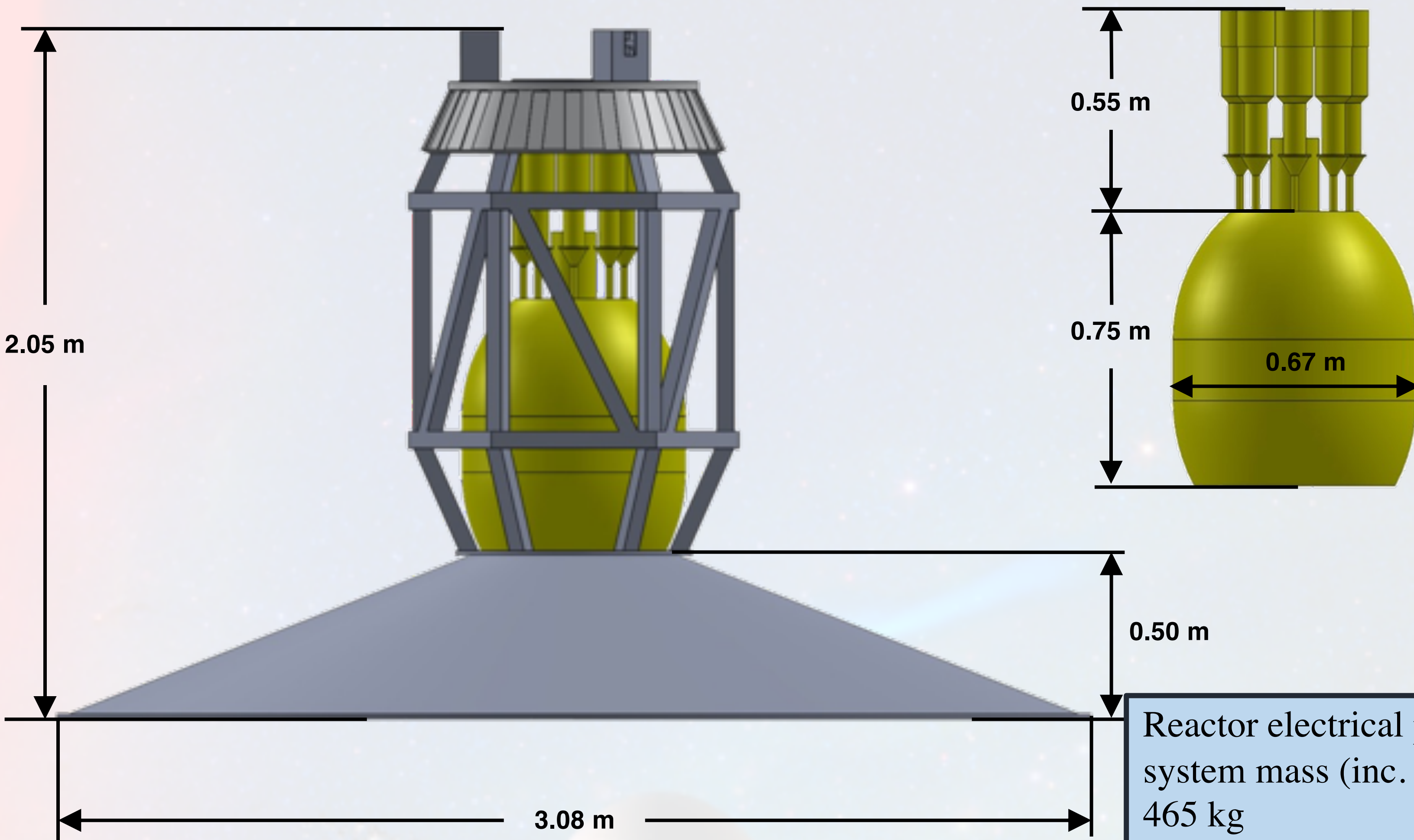
- An alternate, power from a reactor power system, will be considered in a trade study.

Possible power system trade-off: Titan Lander Reactor



Reactor electrical power system mass (inc. structure) 465 kg
Growth 91 kg
Total 556 kg

COMPASS design study of nuclear reactor for Titan surface mission, based on NASA Kilopower design (2017).

Storage of Cryogenic propellants

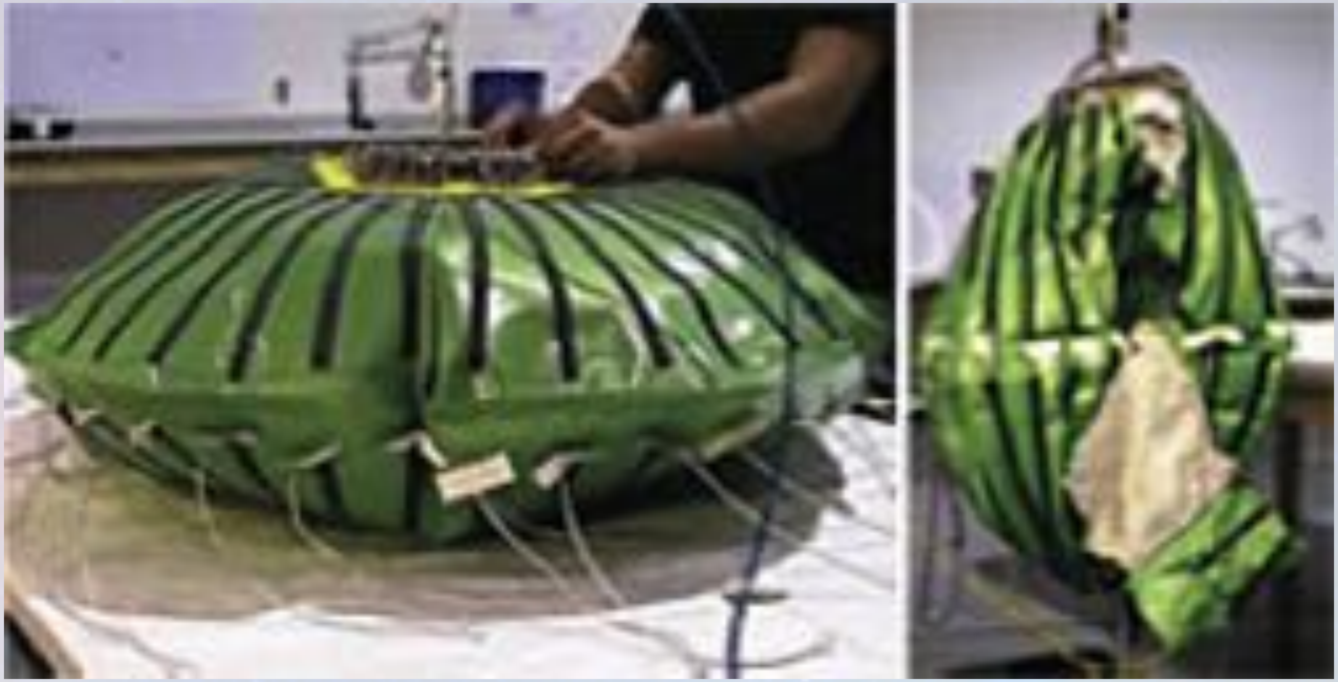
Titan environment:
Average surface temperature: 90.6 K
Maximum temperature: 93.6 K
Atmospheric pressure: 146.7 kPa (1.45 atm)
Gravity: 1.35 m/s^2 (0.138 g_{Earth})

Cryogenic storage is simple for both methane and oxygen:

- The maximum measured surface temperature 93.6 K is well below methane's boiling point of 111.5 K, allowing us to store the methane as a liquid fuel with no refrigeration.
- While the temperature of Titan is above the boiling point of oxygen, the high pressure of Titan's atmosphere means that by maintaining about 1-bar above ambient pressure in the tank, 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 is ideally suited to allow cryogenic propellants to be stored in liquid form without refrigeration.

Possible Inflatable tank



Lightweight Inflatable Cryogenic Tank (image courtesy NASA/KSC).

- Use of inflatable tanks for cryogenic propellants have been investigated at NASA KSC
- Could allow smaller volume for the entry vehicle
- Possibly a lower mass option
- Will be considered as a trade-study

Conclusions

- A sample-return mission from Titan would be invaluable for science and for its contribution to our understanding the origins of organic compounds in the solar system and our place in the universe.
- A top-level analysis of the production and use of in-situ volatile propellants for a sample return mission from Titan shows that such a mission should be feasible.
- The concept has been selected by the NASA Innovative Advanced Concepts (NIAC) for a detailed phase-1 study.

Acknowledgement

This work has been selected as a Phase 1 Study by the NASA Innovative Advanced Concepts program