Nuclear Thermal Propulsion for Robotic and Piloted Titan Missions

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Although, the exploration of Titan has only just begun, the questions of Titan’s origin, history, surface conditions and especially its organic chemistry have increased enormously making it a among the most interesting bodies in the solar system. Sample return and human surface exploration would be able to answer many questions, but the velocity requirements for such missions readily exceed chemical propulsion capabilities. Completing such missions though is possible using bimodal nuclear thermal propulsion and in-situ propellant production. Titan’s atmosphere consists primarily of nitrogen (98.6%) with the rest mostly methane and ethane. There actually is a high probability for hydrocarbon lakes near the poles. The surface also appears to be composed primarily of water ice. These are important to the manufacture of hydrogen as propellant for the return. Methane, and ethane, heated, using a nuclear reactor for power, in the presence of steam readily produces carbon dioxide and hydrogen. The hydrogen can be easily separated and stored for the return. Using the hydrogen produced, a nuclear thermal rocket can efficiently complete robotic sample return, and even piloted, missions.

Nomenclature

- $E$ = Specific energy
- $g_0$ = Standard acceleration of gravity (0.00981 km/s$^2$)
- $I_{sp}$ = Specific impulse
- $M$ = Mass
- $m_i$ = Initial mass
- $m_f$ = Final mass
- $MR$ = Mass ratio
- $R$ = Surface radius
- $r$ = Heliocentric orbit radius
- $V$ = Velocity with respect to planet
- $v$ = Heliocentric velocity
- $v_e$ = Exhaust velocity
- $\Delta v$ = Change in spacecraft speed
- $\Delta v_{opt}$ = Energy for optimum change in spacecraft speed

Subscripts

- $H$ = Hohmann
- $p$ = Periapsis

Acronyms

- GCR = Gas Core Rockets
- IMLEO = Initial Mass in Low Earth Orbit
- LEO = Low Earth Orbit
- NTR = Nuclear Thermal Rocket

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I. Introduction

In a popular book on astrobiology, Peter Ward states that it may be possible to send a piloted mission to the satellite Titan, orbiting Saturn, but the technology does not exist to return the crew\(^1\). Bimodal nuclear thermal propulsion though may just be able to perform the mission. Titan remains a fascinating body because of the pre-biological compounds that apparently are present in large quantities on its surface. The Cassini mission now in orbit about Saturn, has performed several close fly-bys of Titan, and included a lander, Huygens, that returned data from the surface. This single mission has added significantly to our understanding of the Saturn system and, even more importantly, has made Titan one of the most interesting bodies within the solar system\(^2\).

The early flyby missions by the Pioneer and Voyager spacecraft added to our knowledge of the Saturn system, but the Cassini mission has been responsible for the vast majority of the data gained on Titan. Using chemical propulsion the flyby missions of Pioneer and Voyager were considerably easier to perform than the orbital mission performed by Cassini. For a successful orbital Saturn mission, Cassini made extensive use of gravity assists to explore the Saturnian system. We will show that a piloted round-trip mission would be prohibitively expensive if it was limited to chemical propulsion, and gravity assists, as Cassini, Voyager and Pioneer were. However, nuclear thermal propulsion, with a specific impulse that is twice that of chemical propulsion, can complete a roundtrip robotic mission, and maybe even manned Titan surface missions using technology that exists today.

In the next section we estimate the performance requirements using standard astrodynamics calculations. The results of these calculations are then used to complete a rough comparison of propulsion alternatives. The problem for all near term possibilities remains the fuel for the return from the Titan surface. A solution is proposed in the next section, and this is followed by a possible piloted mission scenario.

II. Astrodynamics

Hohmann transfers will be used to estimate the performance requirements. The missions will start from low earth orbit (LEO) and proceed directly to an atmospheric entry and landing on Titan. The return will again be directly from the surface of Titan to an atmospheric entry at Earth. The planetary parameters that were used are from the References \([3]\) and \([4]\) and are summarized in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Saturn</th>
<th>Earth</th>
<th>Titan</th>
</tr>
</thead>
<tbody>
<tr>
<td>(GM - \text{km}^3/\text{s}^2)</td>
<td>3.7931E+07</td>
<td>3.9860E+05</td>
<td>9.0400E+03</td>
</tr>
<tr>
<td>Radius of planet - km</td>
<td>6.0268E+04</td>
<td>6.3568E+03</td>
<td>2.5750E+03</td>
</tr>
<tr>
<td>Orbital radius* - km</td>
<td>1.4242E+09</td>
<td>1.4960E+08</td>
<td>1.2220E+06</td>
</tr>
</tbody>
</table>

*Saturn and Earth about Sun, Titan about Saturn

For the Hohmann transfer ellipse, the excess hyperbolic velocity after launch from low earth orbit can be readily calculated. Take the Earth and Saturn to orbit the Sun in circular orbits with the radii in Table 1. The specific energy of the Hohmann transfer orbit, \(E_H\), is

\[
E_H = -\frac{GM_{\text{Sun}}}{r_{\text{Earth}} + r_{\text{Saturn}}} - \frac{1}{2}v^2 - \frac{GM_{\text{Sun}}}{r}
\]

where \(GM_{\text{Sun}}\) is 1.327E-11 \(\text{km}^3/\text{s}^2\), \(r_{\text{Earth}}\) and \(r_{\text{Saturn}}\) are the orbital radii of Earth and Saturn about the Sun and are given in Table 1, \(v\) is the velocity with respect to the Sun, and \(r\) is the distance to the Sun. From equation (1), at the orbit of the Earth the velocity becomes 40.1 km/s. The velocity of the Earth about the Sun \(\sqrt{GM_{\text{Sun}}/r_{\text{Earth}}}\) is 29.8 km/s leaving a velocity with respect to Earth of 10.3 km/s. We will take this as the speed of the spacecraft at an infinite distance from the Earth. We can use this to find the speed from required in low earth orbit to achieve 10.3 km/s by considering the specific energy, \(E\), for orbits about the Earth.
where \( V_p \) is the velocity at perigee with respect to the Earth of the hyperbolic escape orbit, \( V_\infty \) is the speed with respect to the Earth at an infinite distance from the Earth (10.3 km/s), and \( GM_{Earth} \) and \( R_{Earth} \) are the gravitational constant \((G)\) times the mass of the Earth and the surface radius of the Earth respectively and are given in Table 1. Using equation (2) launch from LEO will require a total speed equal to 15.2 km/s. The velocity change from LEO is just the difference between the total speed (15.2 km/s) and LEO speed \( \sqrt{GM_{Earth}/R_{Earth}} \) or 7.3 km/s.

Since we will only look at missions that use atmosphere entry to directly land on Titan there will be no need to perform a propulsive maneuver to rendezvous with Saturn. The speed with respect to Titan is important for the design of the atmosphere entry system. To find this, the entry speed into the Saturnian system must be found. We can use the conservation of angular momentum for the Hohmann transfer ellipse to get the speed at Saturn with respect to the Sun since

\[
r_{Saturn}v_{Saturn} = r_{Earth}v_{Earth} \tag{3}
\]

where \( r_{Earth} \) is Earth’s orbital radius about the Sun, \( v_{Earth} \) is the spacecraft heliocentric speed of the spacecraft at the Earth (40.1 km/s), \( r_{Saturn} \) is Saturn’s orbital radius about the Sun, and \( v_{Saturn} \) is the spacecraft heliocentric velocity at Saturn. We can now readily find the spacecraft heliocentric speed at Saturn as 5.5 km/s. Saturn has an orbital speed of 9.7 km/s about the Sun. Since the spacecraft is moving in the same direction as Saturn, the speed relative to Saturn is 4.2 km/s. The distance from Saturn when the spacecraft enters the sphere of influence of Saturn, \( R_\infty \), is given by

\[
R_\infty = r_{Saturn} \left( \frac{M_{Saturn}}{M_{Sun}} \right)^{2/5} \tag{4}
\]

Energy conservation using Saturn, Titan and the spacecraft can now be used to estimate the entry speed into Titan’s atmosphere. The specific energy is now given by

\[
\frac{1}{2}V_\infty^2 - \frac{GM_{Saturn}}{R_\infty} - \frac{GM_{Titan}}{R_{Titan}} = \frac{1}{2}V_p^2 - \frac{GM_{Saturn}}{r_{Titan}} - \frac{GM_{Titan}}{R_{Titan}} \tag{5}
\]

where \( V_\infty \) is the entry speed to the sphere of influence at Saturn (4.2 km/s), \( r_{Titan} \) is the orbital radius of Titan about Saturn, \( R_{Titan} \) is the surface radius of Titan and \( V_p \) is the entry speed, with respect to Saturn, into Titan’s atmosphere. From equation (5) \( V_p \) is 10.3 km/s. More accurate calculations using the restricted three body problem (Saturn, Titan and the spacecraft)\(^6\) gives the same result. The orbital speed of Titan about Saturn is 5.6 km/s. If the entry into Titan’s atmosphere occurs while the velocity vectors of Titan and the spacecraft are aligned then this leaves 5.7 km/s for the entry speed.

The atmosphere of Titan is similar in pressure (1.5 bars) and molecular mass (27.9 g/mole) to the Earth\(^7\), and, hence, the design of a direct atmosphere entry system should be about as difficult as re-entry from LEO. Of course, the size will be significantly larger. Note that the since the absolute temperature is lower on Titan the atmospheric surface density on Titan is higher than the Earth’s.

The return from Titan must include the speed changes from the surface of Titan, and not from an orbit about Titan and hence is equivalent to the entry speed of 10.3 km/s with respect to Saturn.\(^4\). For the launch from Titan while Titan is moving in the same direction that the spacecraft must head, then we again require a speed change of 5.7 km/s. The total speed change over the entire mission then is about 13.0 km/s (7.3 km/s for Earth departure from LEO and 5.7 km/s for Titan departure from its surface).
Hohmann transfers provide a good estimate for the minimum speed changes required for impulsive maneuvers but also result in near maximum travel times. The Hohmann transfer ellipse to Saturn has a period of about 12.06 years and the stay time on Titan for proper alignment for the return is about 0.97 years. Hence the total trip time will be almost exactly 13 years. This has important implications for piloted missions but is not a serious design problem for sample return missions.

III. Propulsion Options

The choice for the propulsion system is critical. Higher performance systems can greatly reduce the initial mass in low earth orbit (IMLEO) but have a higher technological risk. There is over forty years of experience with high performance chemical propulsion systems and they are considerably more reliable than in the 1960s. The best performance, to date, is that of liquid oxygen, liquid hydrogen systems which, in the Space Shuttle, can achieve a specific impulse of 455 seconds. In the early 1970s endurance ground testing of the NERVA nuclear thermal rocket (NTR) engine had been successfully completed. These rockets had a specific impulse a little less than 900 seconds. Today we estimate that the specific impulse could be increased to 950 seconds through the use of new high temperature fuels and materials. In our comparison we will also use gas core nuclear rockets as an advanced high thrust propulsion system. The specific impulse of a gas core rocket (GCR) will be taken as 1900 seconds.

We are now in a position to estimate mass ratios for the each leg and the round-trip. Recall that the mass ratio, $MR$, is given by

$$MR = \frac{m_i}{m_f} = e^{\Delta v / v_e}$$

(6)

where $m_i$ is the initial mass, $m_f$ is the final mass, $v_e$ is the exhaust velocity, and $\Delta v$ is the change in speed. The exhaust velocity can be estimated from the specific impulse, $I_{sp}$, using

$$v_e = I_{sp} g_0$$

(7)

where $g_0$ is the standard acceleration of gravity at the surface of the Earth 0.00981 km/s$^2$. Three possibilities are considered: 1) Earth departure (the outbound leg where $\Delta v = 7.3$ km/s), 2) Titan departure (the return leg where $\Delta v = 5.7$ km/s), and the round-trip (where $\Delta v = 13.0$ km/s). Table 2 presents the resulting mass ratios. In Table 2 the optimum velocity change, $\Delta v_{opt}$, is the energy optimum for a constant exhaust velocity rocket and is given by

$$\Delta v_{opt} = 1.6 v_e$$

(8)

Using a mass ratio of 5.0 for a single stage rocket (again this it approximately the value for an energy optimum), Table 2 shows that a gas core rocket can readily perform the entire mission, while a nuclear thermal rocket will need one stage and a chemical rocket would require one stage out and one stage back.

<table>
<thead>
<tr>
<th>Type</th>
<th>$I_{sp}$ s</th>
<th>$v_e$ km/s</th>
<th>$\Delta v_{opt}$ km/s</th>
<th>Mass Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Outbound</td>
</tr>
<tr>
<td>Chemical</td>
<td>475</td>
<td>4.66</td>
<td>7.45</td>
<td>4.80</td>
</tr>
<tr>
<td>NTR</td>
<td>950</td>
<td>9.31</td>
<td>14.90</td>
<td>2.19</td>
</tr>
<tr>
<td>GCR</td>
<td>1900</td>
<td>18.62</td>
<td>29.79</td>
<td>1.48</td>
</tr>
</tbody>
</table>

Table 2. Mass Ratio and Optimum $\Delta v$ for High Thrust Propulsion Systems
These results indicate that chemical rockets would be expensive to use for sample return missions, and since gas core rockets have never been tested their technological risk and development costs are still prohibitive. (Gas core nuclear rockets are also low thrust rockets.) The choice of nuclear electric remains, but, of course, an additional high thrust rocket must be provided for departure from the surface of Titan. This would mean the development of two completely separate propulsion systems and, hence, cannot compete with bimodal nuclear thermal propulsion which, of course, can provide all of the propulsion and power needs. Note also that the energy optimum speed change, $\Delta v_{opt}$, is closest to the performance of the nuclear thermal rocket.

**IV. Hydrogen Generation**

The return from Titan adds a significant speed change, but the propellant for the return does not need to be carried to Titan. The Titan atmosphere can maintain a significant fraction of methane which is typically about 1.4% but can range up to about 5-6% at the surface\(^7\), with the remainder nitrogen. Also the surface contains a significant amount of ice.

Methane conversion into hydrogen has been the subject of considerable research as a part of a possible source of a hydrogen in a hydrogen fuel economy\(^{12,13}\).

Three choices will be considered: 1) electrolysis of water to make hydrogen and oxygen, 2) heating methane to a temperature of 1500 K where it will decompose into carbon and hydrogen\(^{15}\), and 3) heating methane and water to produce a mixture of hydrogen and carbon dioxide\(^{16,17}\). We can see that if we optimize the total mission energy that bimodal NTR appears to be ideal. The reactors used in the nuclear thermal rockets can readily produce temperatures of 1500 K\(^{14}\). Hence, both ice and methane can provide the hydrogen fuel needed for the return.

For piloted missions hydrogen production will be critical to its success. In order to increase the probability for mission success a factory, with a surface habitat, could be sent about fifty weeks ahead of the piloted mission (i.e., the previous Hohmann launch opportunity). Upon its arrival at Titan it could be set into operation and its status used to decide if the crew should land on Titan, or use gravity assists, with Saturn and its satellites, for a fast free return to Earth.

All manufacturing techniques considered will have to include a refrigeration and storage system. Titan has a relatively low surface temperature (95 K\(^{18}\) and liquid hydrogen needs to be stored below about 20 K. Hence, the system will not have to reject as much heat as on the surface of the earth and the system will have a lower temperature sink to reject the heat into. Since the factory will be autonomous an effective storage system will be required. Recently Plachta, et al\(^{19}\), have proposed a zero boil-off cryogenic system for space missions that appears to be ideal for the return leg.

**A. Production of Hydrogen from Water Ice**

The surface of Titan appears to consist of “dirty” water ice\(^{20}\). The ice can be used as a source for hydrogen by using the reactor to electrolyze the water. The oxygen can be collected for supplies, but most would be rejected. Unfortunately, contaminants would have to be removed, possibly by distillation, but the solid material remaining would have to be removed automatically. This is a significant but not insurmountable complication.

**B. Direct Hydrogen Production from Methane**

Hydrogen can be generated by heating methane to produce carbon and hydrogen or acetylene and hydrogen, that is

\[
CH_4 \rightarrow C + 2H_2 \quad (9a)
\]

or

\[
2CH_4 \rightarrow C_2H_2 + 3H_2. \quad (9b)
\]

Reaction (9a) can be completed using microwave and will produce copious amounts of hydrogen\(^{21}\), but will also produce many other ingredients including carbon soot\(^{21}\). A similar conclusion should hold for reaction (9b), and again for both reactions the manufacturing unit would have automatically remove solid products (i.e., the carbon soot) produced.
C. Hydrogen Production without Carbon from Methane

The soot produced in reactions (9a) or (9b) can be removed by heating the methane in the presence of water (i.e., steam produced from surface ice) by reactions (10) below

\[ CH_4 + H_2O \rightarrow CO + 3H_2 \]  
(10a)

and

\[ CO + H_2O \rightarrow CO_2 + H_2. \]  
(10b)

Hydrogen would have to be separated from the other gases. Diffusion through a palladium membrane\textsuperscript{17} could be used to separate the hydrogen. The reactions would again produce other species including some carbon soot and residue from the water ice, but the efficiency should be high\textsuperscript{18}.

V. Mission Scenario

A mission scenario can consist of three launches from LEO. The first would be the launch of the factory and the return supplies one synodic period (about 378 days) before the launch of the crew. The operation of the factory could then be monitored on the surface of Titan for about one year before the crew would attempt a landing. The launch of the crew with a duplicate factory and the outbound supplies would then proceed after a successful launch of the factory. The crew would launch with a duplicate unpiloted spacecraft containing a factory and return supplies. If the original factory fails to produce fuel, then the crew would have the option of using a free return trajectory after a transfer of the supplies from the second robotic spacecraft. The duplicate factory would then land on Titan to be used in the next mission attempt. The crew could decide to land if the first factory fails and if there is high confidence one of the two other factories will produce the return fuel. After the crew lands they can choose between the various factories and supply depots set up. Hence even after launch there would be many choices to help insure mission success, including a duplicate vehicle for the return. The first launch would require the two extra vehicles, but after the first mission only one extra vehicle would be required since an operational factory would always be present on the surface, with a new one or two left behind after each mission.

It should also be noted that the factories will be able to produce excess fuel that could be used to rendezvous with, and even land on, other moons of Saturn if suitable extra equipment is provided.

Using reference 9 as a guide we can get a very rough estimate for the dry initial mass in LEO (IMLEO) of about 250 metric tons for a crew of four to Titan. Using a NTR this means a total mass including propellant of 550 tons per vehicle. The International Space Station is about 300 metric tons. Recall that there are three vehicles on the first mission and two on each succeeding mission. Obviously piloted missions would be very expensive, but feasible while robotic sample return missions are readily achievable.

VI. Conclusion

Titan’s unique surface characteristics make it of immense scientific interest, and it is these surface characteristics that also make it possible to complete robotic and piloted round-trip missions efficiently from low earth orbit. Bimodal nuclear thermal rockets are clearly the best choice for the propulsion system. Nuclear thermal rockets have already been tested and they more closely match the energy optimum for round-trip missions than other propulsion systems. Bimodal nuclear thermal propulsion can not only provide the power required for the entire mission but it can also be used to process the surface constituents to produce propellant for the return trip. Nuclear thermal rockets also have a sufficient thrust to mass ratio to lift off from the surface of Titan which electric propulsion systems cannot provide.

The organic compounds on the surface are not only of scientific importance (for determining the first steps in the origin of life on Earth), but they also provide the necessary constituents for the propellant for a return trip. The production of propellant on the surface will provide a considerable reduction in the total mission mass, but this gain will be countered by a significant increase the mission risk. The risk can be decreased by increasing the launch mass in low earth orbit through the use of three identical spacecraft, on the first mission, and two on each succeeding mission. This increase in mass is still much less than the increase in mass required if the return propellant is carried from LEO.

Much work still needs to be done. There is an immediate need for accurate mass estimates and the examination of alternate faster trajectory options. Cosmic radiation exposure for a piloted mission will require a significant development program and adequate artificial gravity should be provided for multi-year missions.
Acknowledgment

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References

20. http://www.esa.int/SPECIALS/Cassini-Huygens/SEMHB881Y3E_0.html