# TITAN EXPLORER MISSION TRADES FROM THE PERSPECTIVE OF AEROCAPTURE

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**A detailed Titan aerocapture systems analysis and spacecraft design study was performed as part of NASA's In-Space Propulsion Program. The primary objective was to engineer a point design based on blunt body aeroshell technology and quantitatively assess feasibility and performance. This paper reviews the launch vehicle, propulsion, and trajectory options to reach Titan in the 2010-2015 time frame using aerocapture and all-propulsive vehicles. It establishes the range of entry conditions that would be consistent with delivering a 360 kg entry vehicle plus a 580 kg orbiter to Titan. Results show that inertial entry velocities in the range of 5.3 to 6.6 km/s are to be expected for chemical and solar electric propulsion options with Venus and/or Earth gravity assists. Trip times range from approximately 6 years for aerocapture orbiters to 8-11 years for all-propulsive vehicles. In addition to trip time reduction, the use of aerocapture enables the mission with a Delta 4450 class launch vehicle as opposed to an all-propulsive orbit insertion approach, which requires a Delta IV heavy or Titan IV class launch vehicle.**

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## INTRODUCTION

As part of the NASA In-Space Propulsion Program, aerocapture was investigated as an option for orbit insertion around Titan, the largest Moon of Saturn. This study involved several NASA centers and had for objective to conceptually design an aerocapture system for a generic orbiter/lander mission. This paper provides an overview of the mission trades performed during this study. The main objectives of the mission trades were to:

1. Identify potential mission architecture and trajectories for a launch circa 2010-2015, which meant to identify launch vehicle options, launch opportunities and sensitivities, and potential trajectories using chemical ballistic propulsion and solar electric propulsion (SEP);
2. Understand the sensitivities in flight time and Titan atmosphere's inertial entry velocities;
3. Provide a baseline trajectory and mission timeline.

The level of analysis for the mission trades varied from relatively very detailed, in the case of the aerocapture system and SEP trajectory optimization, to more parametric in the case of the chemical system. The approach was to survey as much as possible the trajectory trade space, both for chemical with multiple gravity assists and for SEP with a wide range of flight times and various gravity assist options. Once the trajectories were compiled, the delivered mass at Titan was calculated given the maximum performances of representative launch vehicles. This delivered mass was then compared to the actual mass needed for Titan orbiter and lander design, thus highlighting the benefits of aerocapture.

This paper first briefly describes the Titan Explorer lander and orbiter and then summarizes the transportation architectures considered. It then describes the findings for chemical and SEP transit to Saturn options, system and trajectories. It also describes briefly the aerocapture system and the baseline trajectory. Finally, it shows the overall architecture trade results.

## SPACECRAFT DESCRIPTION

The science objectives and basic spacecraft concept of this Titan Explorer mission were based on previous studies performed internally at the Jet Propulsion Laboratory.[1] The mission includes a landed module and an orbiter.[2] The lander was considered here as a black box, and only the navigation aspects of carrying this lander were taken into account. The lander performs a direct entry, independently of the orbiter. The orbiter was designed to perform aerocapture and modified in the trades when a chemical insertion was performed instead. The baseline concept uses Solar Electric Propulsion (SEP) to reach Saturn/Titan. Figure 1 shows the launch configuration of the overall spacecraft.

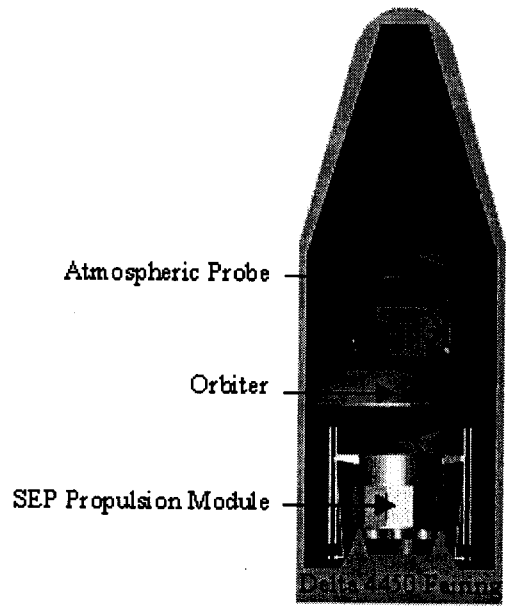


**Figure 1: Titan Explorer spacecraft launch configuration.**

## TRANSPORTATION ARCHITECTURES

To understand the sensitivities in aerocapture entry conditions into Titan's atmosphere, it was necessary to perform a trade study of the various and most probable transportation options to Titan's orbit in the 2010-15 launch time frame. The transportation options for **launch and transit** from Earth to Titan were the following:

- Option 1: Ballistic with or without a chemical stage, launch to a high positive C3, with gravity assists.

- Option 2: Solar Electric Propulsion, launch to a low positive C3, with gravity assists.

The final science orbit around Titan was a 1700-km altitude circular orbit. Thus the **orbit insertion** options considered were:

- Option 1: Chemical insertion.

- Option 2: Aerocapture with a chemical burn for periapsis raise.

All four combinations of transportation were evaluated and will be described.

Aerobraking, which consists of low orbit insertion via several passes in a planetary atmosphere, was not considered at the time of the study. A more recent study on the possibility of performing aerobraking in Titan's atmosphere[3] has shown that aerobraking at Titan is limited by the gravitational perturbations of Saturn. The apoapsis of the aerobraking orbit would have to be quite low (below the 10000 km altitude range) to be in a gravitationally stable orbit around Titan. Higher apoapsis altitudes feature large spread in periapsis altitude (800 km spread in periapsis at an apoapsis altitude of 16000 km), making it very difficult to plan for and maintain aerobraking orbits. With this restriction, the delta-V saving of aerobraking compared to a direct insertion is quite low (~100-200 m/s), which limits its benefits.

## CHEMICAL BALLISTIC TRAJECTORIES TO TITAN

### Earth to Saturn Trajectories

Ballistic direct trajectories as well as gravity assist trajectories were computed and gathered by Jon Sims and Carl Sauer from the Jet Propulsion Laboratory Trajectory Group for a launch period between 2010 and 2016. Table 1 summarizes the performances of these trajectories. The maximum launch injected mass could then be found given the launch C3 for a Delta 4450 and a Delta IV Heavy. These launch vehicles were picked as representative of a range of launch vehicle performance. The launch vehicle data was provided by the NASA KSC Launch Support Group[4] and a 10% margin was held against the KSC provided performance (consistent with the JPL Team X conceptual design guidelines at the time of the study). Also note that some of the direct and gravity assist trajectories require a deep space maneuver, which Delta-V can sometimes be significant.

**Table 1: Ballistic trajectories to Saturn/Titan.* EGA: Earth gravity assist, VEEGA: Venus Earth Earth gravity assist, VVVGA: Triple Venus gravity assist, JGA: Jupiter gravity assist, EJGA: Earth Jupiter gravity assist, VEEJGA: Venus Earth Earth Jupiter gravity assist.**

| | Launch date | Saturn Arrival Date | Flight time (yrs) | Vinf @ Saturn (km/s) | Approach declination (rad) | Vinf @ Titan (km/s) | Ventry inertial (km/s) | Deep Space DV (km/s) | Launch C3 (km2/s2) | Delta 4450 injected mass (kg) 10% margin | Delta IV Heavy included |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Direct | 2/4/16 | 11/29/20 | 4.8 | 6.26 | -0.401 | 5.39 | 5.84 | 0 | 109.3 | - | - |
| | 1/16/14 | 2/14/20 | 6.1 | 5.25 | -0.262 | 4.33 | 4.88 | 0 | 105.2 | - | - |
| | 1/7/12 | 1/22/20 | 8.04 | 5.48 | -0.105 | 4.10 | 4.67 | 0 | 106.1 | - | - |
| | 1/3/11 | 12/20/19 | 8.96 | 5.82 | 0.017 | 4.23 | 4.78 | 0 | 107.2 | - | - |
| | 11/26/09 | 9/18/14 | 4.81 | 5.93 | -0.105 | 4.36 | 4.90 | 0.513 | 108.7 | - | - |
| | 12/31/09 | 11/15/19 | 9.87 | 6.17 | 0.070 | 4.47 | 5.00 | 0 | 108.4 | - | - |
| EGA | 1/3/13 | 4/6/21 | 8.25 | 5.86 | -0.349 | 4.96 | 5.45 | 0.407 | 48 | - | 3119 |
| | 3/3/13 | 4/27/20 | 7.15 | 7.3 | -0.436 | 6.16 | 6.55 | 0.504 | 47.7 | - | 3141 |
| | 12/28/13 | 7/3/21 | 7.51 | 5.67 | -0.332 | 4.80 | 5.29 | 1.488 | 28 | 2250 | 4905 |
| | 3/16/14 | 9/24/21 | 7.53 | 5.49 | -0.140 | 4.16 | 4.72 | 1.693 | 26.3 | - | 5085 |
| VEEGA | 4/3/12 | 3/13/22 | 9.94 | 7.83 | 0.436 | 6.50 | 6.88 | 0 | 12.2 | 3150 | 6746 |
| | 4/3/12 | 3/13/22 | 9.94 | 6 | 0.436 | 5.39 | 5.84 | 0.217 | 12.1 | 3159 | 6759 |
| VVVGA | 7/26/10 | 12/3/18 | 8.4 | 9 | -0.445 | 7.34 | 7.67 | 1.68 | 10.9 | 3249 | 6912 |
| | 8/1/10 | 11/19/19 | 9.3 | 6.83 | -0.417 | 5.79 | 6.21 | 1.35 | 9.7 | 3339 | 7106 |
| | 7/1/13 | 12/31/23 | 10.5 | 6.5 | -0.415 | 5.59 | 6.02 | 1.29 | 13.6 | 3051 | 6593 |
| | 6/1/15 | 5/27/25 | 10 | 6.36 | -0.447 | 5.64 | 6.07 | 1.1 | 15.1 | 2943 | 6381 |
| JGA | 12/16/16 | 8/7/20 | 3.64 | 15.74 | 0.436 | 12.77 | 12.97 | 0 | 97.8 | - | - |
| | 12/16/16 | 8/6/22 | 5.64 | 7.28 | 0.436 | 6.15 | 6.54 | 0 | 82 | - | - |
| | 12/22/16 | 11/14/23 | 6.89 | 4.54 | 0.436 | 4.68 | 5.19 | 0 | 80.8 | - | - |
| | 12/23/16 | 7/19/28 | 11.57 | 2.48 | 0.436 | 3.98 | 4.57 | 0 | 76 | - | - |
| EJGA | 1/23/15 | 9/17/22 | 7.65 | 6.97 | 0.436 | 5.96 | 6.36 | 0.6695 | 25.6 | 2250 | 5162 |
| VEEJGA | 4/15/12 | 12/22/20 | 8.69 | 11.36 | 0.436 | 9.09 | 9.36 | 0 | 10.5 | 3272 | 6966 |

* The trajectories highlighted in yellow are the ones used in the subsequent analysis.

The trajectories highlighted in Table 1 were chosen for the overall mission trade as they represented a set of good performance trajectories. Careful consideration of all parameters (deep space Delta-V, approach velocity (Vinf) at Titan, launch C3, etc...) was used to make the choice of this set of trajectories.

The spread in entry velocity is depicted in Figure 2 for these trajectories. Thus for aerocapture purposes, most of the trajectories have inertial entry velocities between 5 and 7 km/s. This information will help select a baseline inertial entry velocity for a detailed aerocapture design, as will be discussed later.

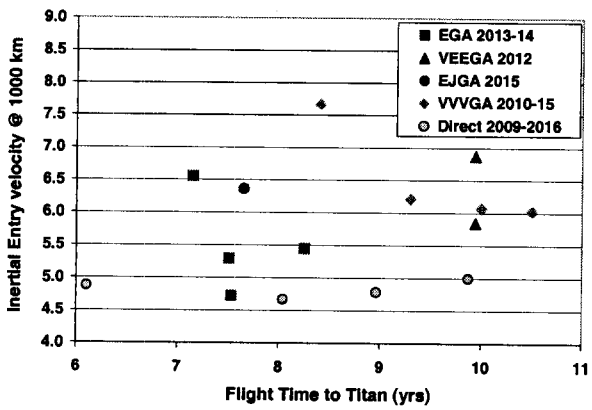


**Figure 2: Titan inertial entry velocities for set of direct and gravity assist ballistic trajectories.**

As can be seen from Figure 2, direct trajectories offer lower inertial entry velocities, since the time it takes to perform the gravity assist has to be made up for in the cruise to Saturn. Also, increasing the number of gravity assists (for instance from a single Earth gravity assist to a triple Venus gravity assist) increased flight time and launch mass, and if not, it then increased significantly the inertial entry velocity.

## Chemical Insertion Delta-V assumptions

The chemical insertion Delta-V into a 1700-km altitude circular orbit around Titan can be computed given the Titan hyperbolic velocity (Vinf) and the approach declination. However, this Delta-V does not take into account a possible tour design around Saturn to pump down the initial orbit around Saturn using its satellites and to reduce the approach velocity around Titan. For the three trajectories picked, Table 2 summarizes the insertion Delta-V. The assumption was made that this Delta-V could be reduced by a moon tour down to 3 km/s with a flight time penalty of 1-2 years. No trajectory analysis has been done to verify this assumption, and further analysis needs to be done to confirm this estimate.

**Table 2: Titan insertion ΔV for sample trajectories.**

| | Flight time (yrs) | Vinf at Titan (km/s) | Titan insertion ΔV (km/s) |
|---|---|---|---|
| EGA 2013 | 7.5 | 4.8 | 3.8 |
| VEEGA 2012 | 9.9 | 5.4 | 4.3 |
| VVVGA 2010 | 9.3 | 5.8 | 4.7 |

## Chemical Propulsion system assumptions

To perform the chemical deep space maneuvers or insertion burns, a generic bi-propellant system was assumed. The dry mass for this system is summarized in Table 3. The specific impulse of the chemical system was assumed at 325 sec. In addition, 10% of the deterministic propellant mass was held as propellant contingency for maneuver clean-ups.

**Table 3: Chemical propulsion system mass breakdown (includes 30% contingency).**

| Subsystem | Growth Mass (kg) |
|---|---|
| Not scaled with propellant mass: | |
| - Propulsion | 19.5 |
| - Thermal | 16.5 |
| - Telecom+electronics | 2.3 |
| - Structure | 261.5 |
| Scaled with propellant mass: | |
| - Tank | 5% |
| - Tank structure | 4% |
| - Thermal | 1% |

# SEP TRAJECTORIES TO TITAN

Early on, an extensive database of Venus gravity assists SEP trajectories on a Delta 4240 was built, as they clearly provided better delivered mass for equivalent flight times compared to direct (no gravity assist) SEP trajectories. These trajectories served the purpose of evaluating the sensitivities in launch date, number of thrusters, power levels and inertial entry velocities. Subsequently, a smaller set of Earth gravity assist and Venus gravity assist on the Delta 4450 and Delta IV Heavy was calculated and used.

Carl Sauer (JPL) ran the SEP trajectory optimization code named SEPTOP for Solar Electric Propulsion Trajectory Optimization Program, which is based on the calculus of variations. This code optimizes two body interplanetary trajectories and can model discrete numbers of operating Xenon thrusters throughout the trajectory. Carl allowed for a coast time duty cycle of 10% to simulate times when the spacecraft is not thrusting due to housekeeping activities, and assumed a constant 250 W from the solar arrays for the spacecraft.

## Solar Electric Propulsion system assumptions

The ion thruster used to calculate the SEP trajectories is and advanced 5-kW 5000 sec version of the flown NSTAR engine. The characteristics of the NSTAR technology can be found in many references.[5,6,7] The description of the 5-kW derivative of NSTAR named NGN for "Next Generation NSTAR" can be found in reference [8, 9]. This thruster is characterized by differences in four major parameters compared to NSTAR: engine input power, maximum specific impulse, and engine total impulse (or throughput) capability. Table 4 shows the projected performances of NGN.

**Table 4: High-level NGN versus NSTAR characteristics.**

| | NSTAR | NGN |
|---|---|---|
| Max. thruster processed power (kW) | 2.3 | 5 |
| Engine diameter (cm) | 30 | 30 |
| Maximum Isp (sec) | 3100 | 5000 |
| Xe throughput (kg) | 130 | 250 |

The ion propulsion system (IPS) was designed more as a propulsion module than just thrusters and power processing units. Figure 3 shows a simplified block diagram of the NSTAR IPS (single string). To that basic configuration was added redundancy, structural and thermal considerations. Figure 3 also shows an example of what the IPS module designed here could look like.

The solar arrays were sized based on a projection of the AEC-Able Ultraflex array capability. Since this array technology scales with power from ~ 1 kW up to ~ 30 kW, it was used as a representative potential technology for SEP applications. The specific mass was assumed to be 200 W/kg at 24 kW. A 14% degradation factor was applied to the array Beginning-of-Life (BOL) power to account for various degradation phenomena. Also, in order to support power demand during launch, a primary battery was used prior to solar array deployment.

The number of thrusters and PPUs was calculated on the basis of power requirements (4 minimum plus 1 redundant) and thruster propellant throughput. The system architecture followed a conventional approach with parallel strings of PPUs and thrusters. Each PPU drives one thruster but is cross-strapped to two engines. One spare ion engine, one spare PPU and DCIU were also included for single-fault tolerance. Each thruster was gimbaled separately. The PPUs were assumed to be 95% efficient.

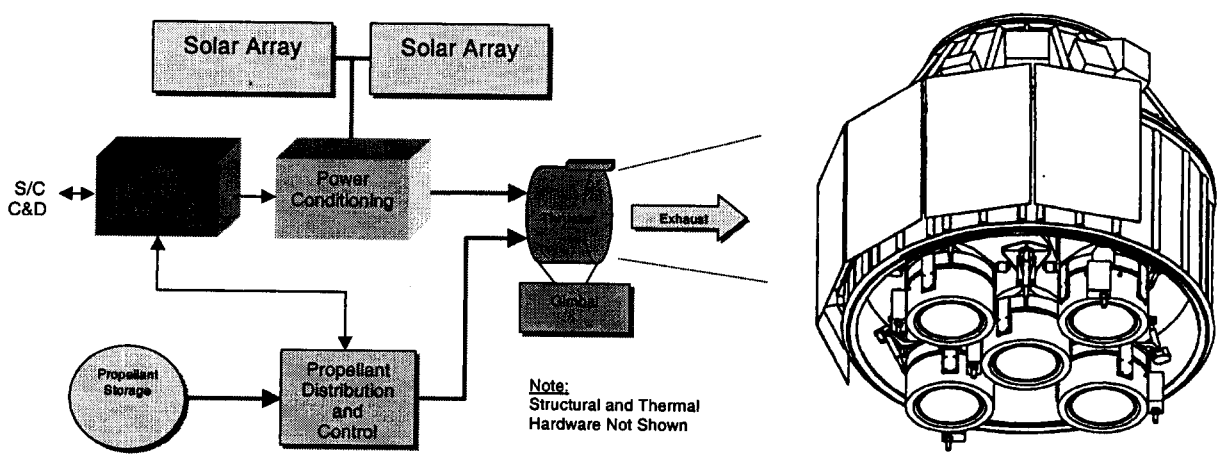


**Figure 3: Ion propulsion module block diagram and conceptual configuration for system sizing.**

The tank mass fraction was assumed to be 3.5% for Xenon when stored as a supercritical gas (~2000 psia). Furthermore, a 10% propellant contingency was added to the deterministic propellant mass to account for flow rate characterization, residuals, attitude control and margin.

Since the system masses are function of mainly power level, launch mass and propellant mass, each trajectory was uniquely considered and had a system mass associated with it. The component and subsystem sizing assumptions are given in Table 5. To be consistent with the JPL Team X conceptual design guidelines at the time of the study, 30% mass contingency was applied to all spacecraft subsystems, and a 10% launch vehicle margin was assumed.

**Table 5: Ion propulsion system mass breakdown (includes 30% contingency).**

| Subsystem | Growth Mass (kg) |
|---|---|
| Not scaled with propellant mass: | |
| - Propulsion | 168.5 |
| - Power | 192.8 |
| - Thermal | 59.2 |
| - Telecom+ACS +electronics | 7.6 |
| - Structure | 340.5 |
| Scaled with propellant mass: | |
| - Tank | 3.5% |
| - Tank structure | 4% |
| - Thermal | 1% |

With the appropriate thruster model, trajectories were run for power level of 24 kW. Results are in terms of net delivered mass. The net delivered mass is defined as the spacecraft dry mass minus the dry mass of the ion propulsion system. Therefore the net delivered mass is everything on the spacecraft that isn't propellant or part of the ion propulsion module.

## Net delivered mass and inertial entry velocity sensitivities to launch date, arrival date, SEP power level and thruster technology

Figure 4 shows results of net delivered mass as a function of flight time and launch years for the NGN thruster and for the NSTAR thruster (for reference). These trajectories were run for a Delta 4240 launch vehicle. The desired net delivered mass for the spacecraft was on the order of 2000 kg.

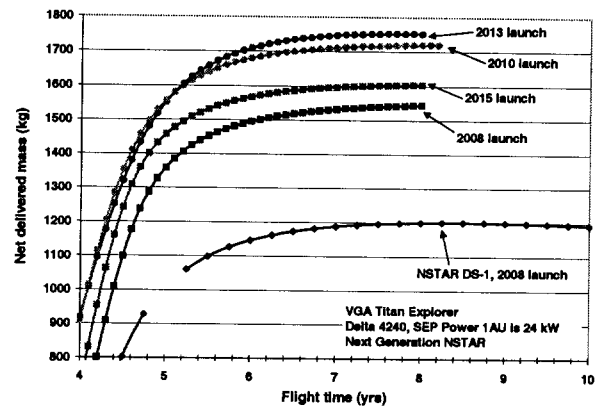


**Figure 4: Venus Gravity Assist SEP trajectories to Saturn as a function of launch date.**

Figure 5 shows the corresponding inertial entry velocities. As can be seen, the inertial entry velocity increases significantly for flight times below 5 years. It is also very dependent on flight time, launch date, and thruster technology. However, as Figure 6 shows, the inertial entry velocity was only weakly dependent on SEP power for a given launch date and thruster technology. There is also a significant variability in the choice of gravity assist. Thus choosing a flight time range will determine a range of inertial entry velocities. Flight times around 6 to 7 year offer the most "net delivered mass" benefit and result in entry velocities less than 7 km/s for most launch opportunities.

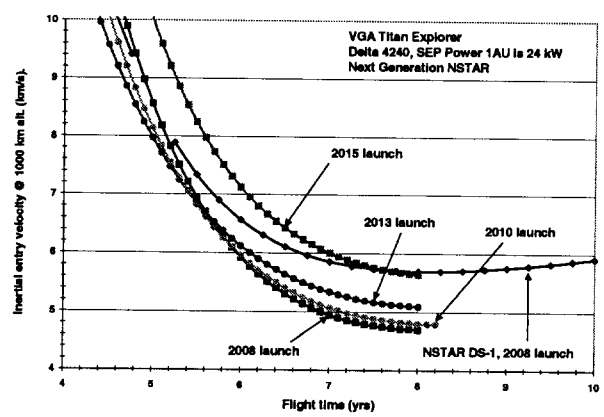


**Figure 5: Titan inertial entry velocity at 1000 km altitude as a function of flight time.**

The weak sensitivity to the SEP power level is mostly due to the fact that over the range of power looked at, the trajectory optimization code is going to try to follow the same optimum acceleration path. Thus for high power level, it will optimize the trajectory at lower launch C3, thus injecting more mass. The acceleration, which is proportional to the power level to mass ratio will be roughly the same as a low power, large C3, low launch mass case. Since it will follow almost the same

trajectory profile, the arrival hyperbolic velocity will only vary slightly (such variation could be seen by zooming in Figure 6). This is true for a fixed flight time and launch date.

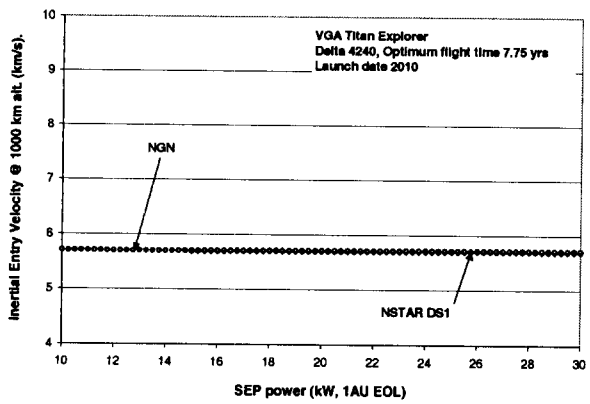


**Figure 6: Inertial entry velocity at 1000 km altitude for Venus Gravity Assist SEP trajectories to Saturn with Delta 4240, fixed flight time (7.75 years) but varying SEP power level.**

The launch window to perform a given gravity assist (VGA or EGA) is about one month. The sensitivity in propellant mass for that window is included in the 10% propellant margin.

Careful consideration was given to the sensitivity in arrival date. Since Titan's orbital period around Saturn is 16 days, the orbit geometry varies significantly depending on the arrival day. Figure 7 illustrates that point. However, it is possible to tune the arrival date with the SEP system or with a small chemical Delta-V at the end of the SEP phase to target a desired entry condition. The pattern shown in Figure 7 repeats every 16 days.

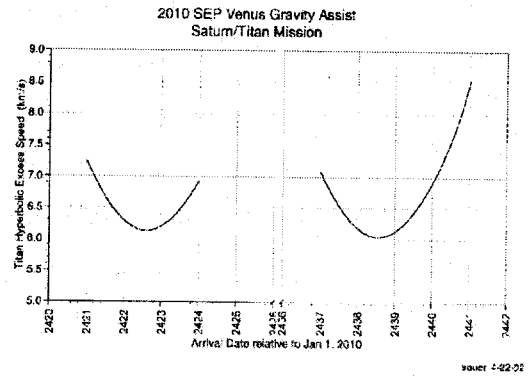


**Figure 7: Sensitivity of Titan hyperbolic excess velocity as a function of arrival date.**

## Net delivered mass and inertial entry velocity sensitivities to gravity assist and launch vehicle

After looking at sensitivities in launch dates, arrival dates, SEP power level and thruster technology for a given gravity assist type and launch vehicle, the study called for more trajectories to perform the overall trade study. The SEP trajectories presented here assume a 2010 launch date and 24-kW SEP system with 4 operating NGN thrusters. The launch vehicle selected were the Delta 4450 and Delta IV Heavy, to enable more mass to be delivered, for both a Venus and Earth gravity assist. Figure 8 shows the net delivered mass for all 4 trade options. Figure 9 shows the corresponding inertial entry velocities. Also added to these figures are the points selected for the trade study.

## Selection of the inertial entry velocity

In view of these results, it was decided that an entry velocity of 6.5 km/s would represent the best compromise between short flight times and high net delivered masses. Although somewhat arbitrary, it was felt that the aerocapture design would not change significantly for inertial entry velocities between 6 and 7 km/s. Using inertial entry velocities below 5.5 km/s or so would probably be feasible but would reduce the aerocapture performance and robustness.

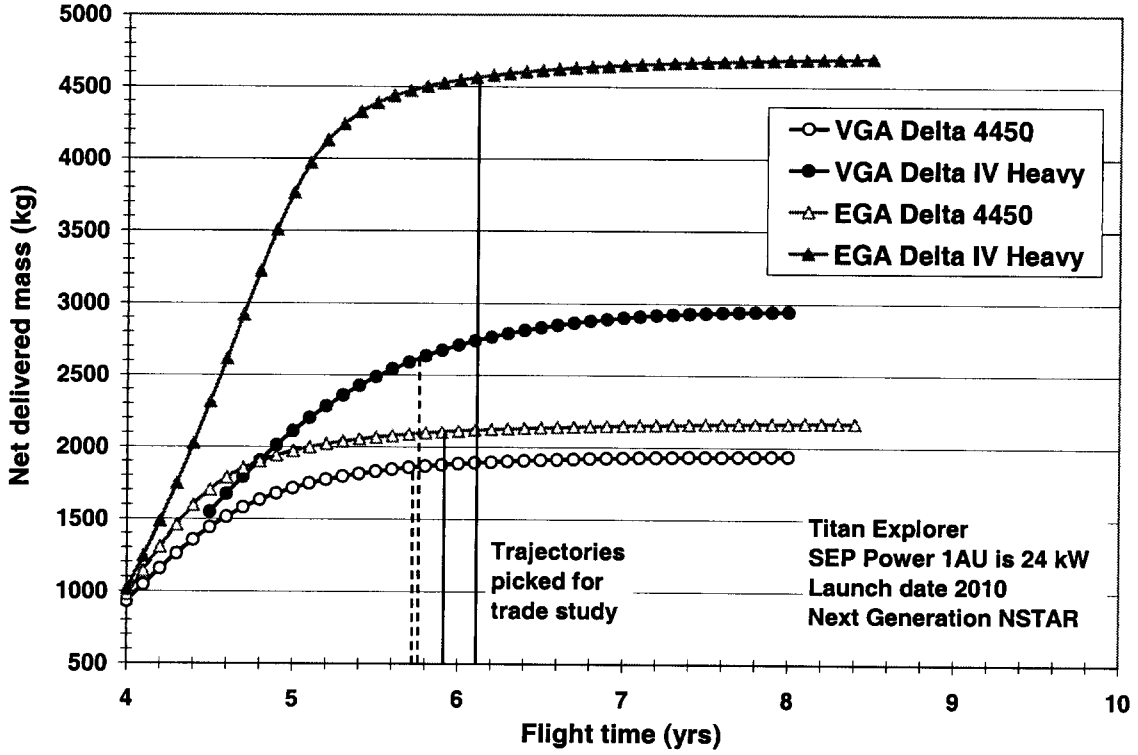


**Figure 8: Venus and Earth gravity assist SEP trajectories to Saturn as a function of launch vehicle.**

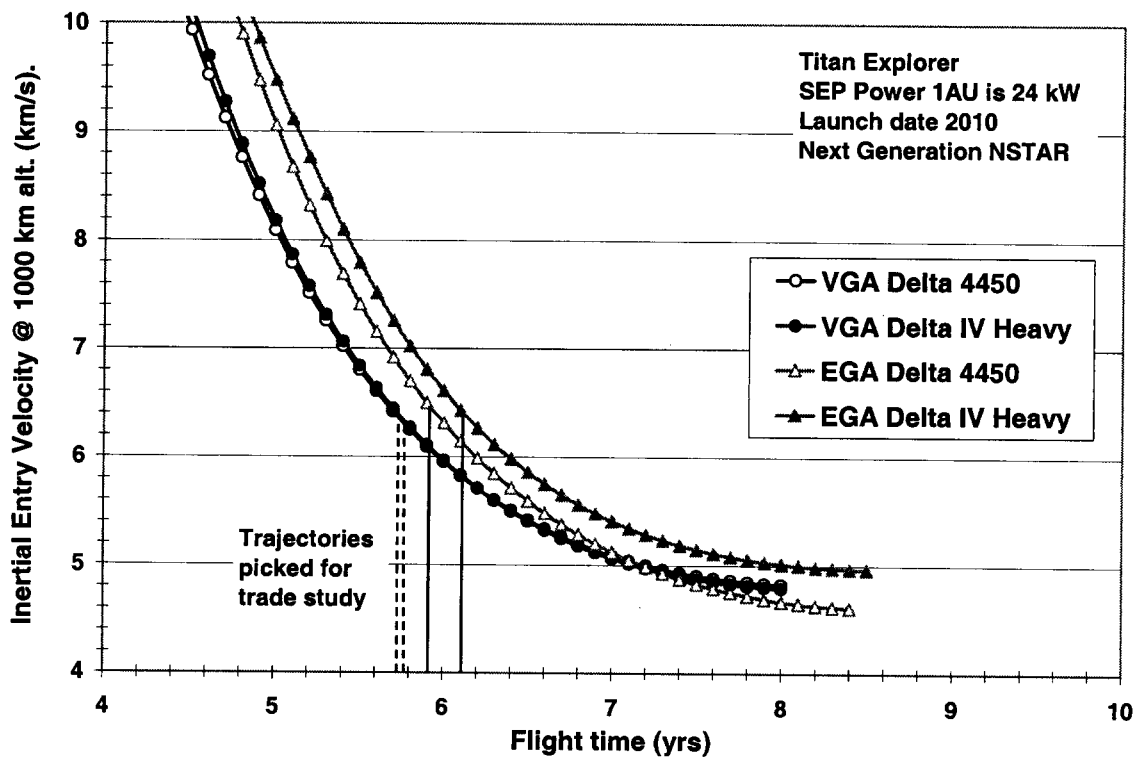


**Figure 9: Titan inertial entry velocity at 1000 km altitude as a function of flight time.**

## Baseline trajectory

The baseline trajectory for the design of the aeroshell and other components of the aerocapture system was selected based on the following criteria:

- The mission architecture should use the smallest launch vehicle possible to reduce cost;
- The trajectory performance should provide adequate system mass margin (30%) for growth, and adequate system reserves (> 10%);
- The trajectory should provide a Titan inertial entry velocity close to 6.5 km/s consistent with the design of the aeroshell.

Thus the trajectory selected featured (see Figure xx):

- Launch vehicle: Delta 4450 (5 m fairing)
- Flight time: 5.9 years
- Launch date: 12/24/2010
- Arrival date: 11/17/2016
- Earth Gravity Assist: 12/03/2012
- Launch C3: 8.6 $km^2/s^2$
- Launch mass: 3423 kg
- Propellant mass: 460 kg deterministic
- Vhyp @ Saturn: 7.97 km/s
- $Vent_{ry}$ inertial: 6.5 km/s @ 1000 km
- Thrusters: 4 operating NGN
- SEP power level: 24 kW

A detailed approach and navigation analysis was performed[10] and suggested the timeline shown in Figure 11 for this baseline trajectory. This timeline includes Trajectory Correction Maneuvers (TCM) for both the lander and the orbiter targeting.

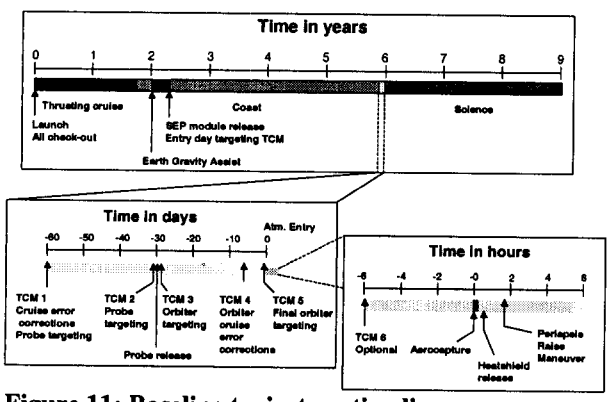


**Figure 11: Baseline trajectory timeline.**

## AEROCAPTURE SYSTEM

The aerocapture system is described in detail in reference [2] and [11]. It has been designed for the baseline trajectory, which lead to an inertial entry velocity of 6.5 km/s.

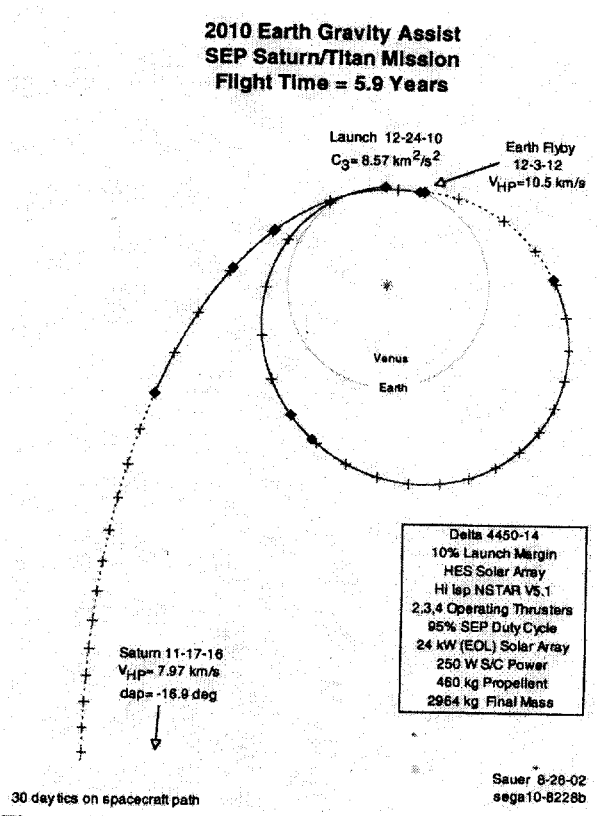


**Figure 10: Baseline SEP trajectories to Saturn.**

The heatshield design was based on a 70 deg. half cone-angle using the Viking-Pathfinder heritage, and was sized to fit the orbiter 2.4 meter diameter high gain antenna.. Table 6 summarizes the mass breakdown for the aeroshell system. As can be seen, the total dry mass of the aeroshell system is 426 kg for a total entry dry mass of 1026 kg (~ 41.5% aeroshell entry dry mass fraction). Other aerocapture-related hardware was ejected before entry. This hardware is also summarized in Table 6.

**Table 6: Aerocapture system mass breakdown (includes 30% contingency).**

| Subsystem | Growth Mass (kg) |
|---|---|
| Mass that entered the atmosphere: | |
| - Heatshield, backshell and structure | 426 |
| - Hydrazine propellant | 89 |
| Aerocapture mass jettisoned prior entry: | |
| - ACS, telecom, thermal radiators and loop heat pipes for the RTG, intruments | 72 |

## MISSION ARCHITECTURE TRADE RESULTS

The overall mission architecture trade results are summarized in Table 7. This table shows first the type of launch vehicle followed by the gravity assist type, the transit propulsion system and the Titan capture system. It assumes that the full capability of the launch vehicle is used and calculates the payload surplus or deficit mass compared to the mass required at Saturn before insertion.

Table 7 also shows additional structure mass not part of the aerocapture system. The Pre-insertion ejected mass includes about 62 kg for the orbiter to lander interface structure and about 71 kg for ACS, telecom, thermal radiators and loop heat pipes for the MMR RTG and other. In the case of chemical insertion, the orbiter to lander interface is assumed not to be jettisoned and thus is included in the Payload in Titan orbit mass. The detailed mass breakdown can be found in [2]. Figures 12 and 13 render some of the results of Table 7. They show the **payload surplus or deficit mass** as a function of transit propulsion, gravity assist and launch vehicle for chemical or aerocapture insertion. The payload surplus or deficit mass is the mass above or below the necessary mass to deliver the lander and orbiter around Titan. It does not include the lander or orbiter mass. Both figures clearly show the advantages of aerocapture, which in every case looked at provided more payload reserve and shorter flight times than for a chemical insertion burn. However, they also show that it is possible to deliver sufficient payload mass (low margin) with an all chemical insertion system. Here again, the penalty will be flight time.

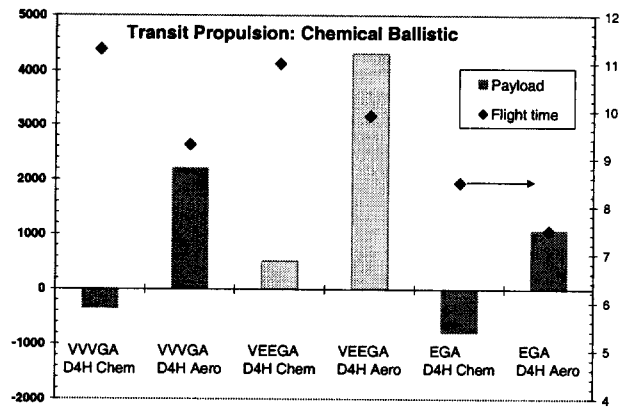


**Figure 12: Payload surplus or deficit mass for the chemical ballistic transit cases for the Delta IV Heavy.**

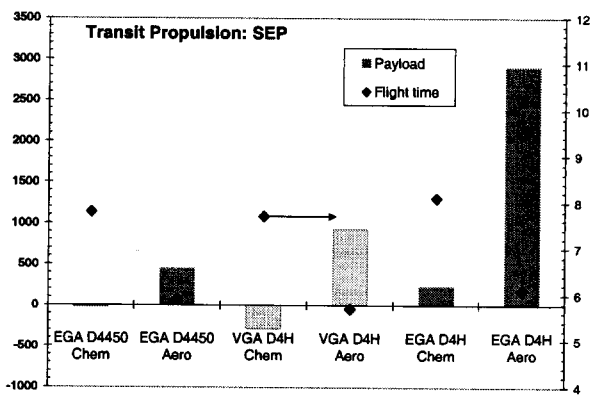


**Figure 13: Payload surplus or deficit mass for the SEP transit cases for the Delta 4450 and Delta IV Heavy.**

## CONCLUSIONS

This paper summarizes the transit trajectory options for the Titan Explorer and derives the range of entry conditions for the aerocapture maneuver inside Titan's atmosphere. This survey shows that inertial entry velocities in the range of 5.5 –7 km/s are to be expected. This range offers the best combination of highest delivered mass to Titan's orbit and lowest entry heating. The study chose to baseline an inertial entry velocity of 6.5 km/s for the detailed design of the aerocapture system, and the corresponding SEP trajectory is provided.

This paper also summarizes the mission transportation trades performed during the study to show the benefits of aerocapture. The study shows that aerocapture as a norbit insertion option provides more delivered mass in every launch vehicle and gravity assist case looked at than chemical insertion, and shorter flight time (typically by 2 years). However, all chemical or SEP with chemical insertion cases exist that would deliver the necessary mass in Titan's orbit with a Delta IV Heavy with flight times between 8–11 years. The baseline trajectory case for this study is an SEP aerocapture case on a Delta IV 4450 with a flight time of 5.9 years.

**Table 7: Overall mission architecture trade results.**

| Launch Vehicle | Delta 4450 | | | | | Delta IV Heavy | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gravity Assist | VVVGA | VGA | EGA | | | VVVGA | | VEEGA | VEEGA | VGA | | EGA | | | |
| Earth to Saturn Prop System | Chem | SEP | Chem | SEP | SEP | Chem | | Chem | Chem | SEP | | Chem | | SEP | |
| Titan Capture | Aero | Aero | Aero | Chem | Aero | Chem | Aero | Chem | Chem | Chem | Aero | Chem | Aero | Chem | Aero |
| | | | | | 7 | | | | | | | | | | |
| Cruise Time to Titan (yrs) | 9.3 | 5.7 | 7.5 | ~7.6 | 8.8 | ~11.3 | 9.3 | 9.9 | ~11 | ~7.7 | 5.7 | ~8.5 | 7.5 | ~8.1 | 6.1 |
| Launch C3 (km2/sec2) | 9.7 | 10.2 | 28 | 8.4 | 8.6 | 9.7 | 9.7 | 12.1 | 12.1 | 36.2 | 36.2 | 28 | 28 | 17.8 | 17.8 |
| SEP Power (kW) | --- | 24 | --- | --- | 24 | --- | --- | --- | --- | 24 | 24 | --- | --- | 24 | 24 |
| Entry Velocity (km/s) | 6.2 | 6.4 | 5.3 | 5.3 | 6.5 | 6.2 | 6.2 | 5.9 | 5.9 | 6.4 | 6.4 | 5.3 | 5.3 | 6.5 | 6.4 |
| Earth to Saturn Cruise ΔV (km/s) | 1.35 | 8.3 | 1.49 | 6.4 | 5.7 | 1.35 | 1.35 | 0.2 | 0.2 | 6.9 | 6.9 | 1.49 | 1.49 | 4.6 | 4.6 |
| Titan Insertion Chem ΔV (km/s) | 0 | 0 | 0 | 3 | 0 | 3 | 0 | 4.3 | 3 | 3 | 0 | 3 | 0 | 3 | 0 |
| | | | 3 | | | 5 | | | 5 | 5,6 | | 5 | | 5,6 | |
| Launch Capability | 3339 | 3298 | 2250 | 3439 | 3429 | 7106 | 7106 | 6759 | 6759 | 4135 | 4135 | 3141 | 5450 | 6019 | 6019 |
| Propellant Mass[1] | 1239 | 619 | 893 | 1485 | 506 | 5464 | 2671 | 5160 | 4363 | 2015 | 715 | 2253 | 2208 | 3257 | 633 |
| LV to Prop Module Adapter | 78 | 78 | 78 | 78 | 78 | 78 | 78 | 78 | 78 | 78 | 78 | 78 | 78 | 78 | 78 |
| Prop Module Dry Mass | 424 | 820 | 389 | 808 | 810 | 846 | 567 | 816 | 736 | 1257 | 828 | 525 | 521 | 1383 | 821 |
| Available Payload Mass to Saturn | 1598 | 1781 | 890 | 1068 | 2029 | 718 | 3790 | 705 | 1582 | 784 | 2514 | 285 | 2644 | 1301 | 4488 |
| Prop Mod to Payload Adapter | 61 | 61 | 61 | 61 | 61 | 61 | 61 | 61 | 61 | 61 | 61 | 61 | 61 | 61 | 61 |
| Direct Entry Payload Mass (Lander) | 364 | 364 | 364 | 364 | 364 | 364 | 364 | 364 | 364 | 364 | 364 | 364 | 364 | 364 | 364 |
| Payload in Titan Orbit (Orbiter) | 511 | 511 | 511 | 573 | 511 | 573 | 511 | 573 | 573 | 573 | 511 | 573 | 511 | 573 | 511 |
| Aerocapture System[2,4] | 515 | 515 | 515 | | 515 | | 515 | | | | 515 | | 515 | | 515 |
| Pre-Insertion Ejected Mass | 133 | 133 | 133 | 73 | 133 | 73 | 133 | 125 | 73 | 73 | 133 | 73 | 133 | 73 | 133 |
| Required Mass to Saturn | 1584 | 1584 | 1584 | 1071 | 1584 | 1071 | 1584 | 1123 | 1071 | 1071 | 1584 | 1071 | 1584 | 1071 | 1584 |
| Payload Surplus (Deficit) Mass | 14 | 197 | (694) | (3) | 445 | (353) | 2206 | (418) | 511 | (287) | 930 | (786) | 1060 | 230 | 2904 |
| System Mass Margin | | | | | 29.9% | (LV - CBE) / LV | | | | | | | | | |
| System Reserve | | | | | 13% | (LV - Growth) / LV | | | | | | | | | |

**Assumptions and Notes:**

All masses are growth mass listed in kg

[1] Propellant mass calculated using "Launch Capability" as system total mass; Isp = 325, includes 10% mass contingency

[2] Aerocapture mass for Chemical Earth to Titan Prop Modules may change slightly (entry velocity not equal to 6.5 km/s)

[3] This launch capability is extrapolated data

[4] Aerocapture mass includes propellant for circularization delta-V

[5] Assumes delta V required for capture can be reduced to 3 km/s through Saturn/moon tour with flight time penalty. No supporting analysis

[6] Propellant mass and Prop Module Dry Mass for SEP / Chem options includes propellant and dry mass for both SEP and chemical stages

[7] Titan Aerocapture Study Reference Mission


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