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Titan and Enceladus $1B Mission Feasibility Study Report

Prepared for NASA's Planetary Science Division

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The following members of an Expert Advisory and Review Board contributed to ensuring the consistency and quality of the study results through a comprehensive review and advisory process and concur with the results herein.

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1. Executive Summary

Two of Saturn's icy moons, **Titan** and **Enceladus,** have been identified in NASA's 2006 Solar System Exploration Roadmap and Science Mission Directorate (SMD) Science Plan as targets warranting extensive investigation. Recent discoveries from the Cassini-Huygens mission have uncovered a Titan landscape and atmosphere rich in complex organics, as well as active hydrocarbon rich plumes of water, hydrocarbons and other gases emanating from the south polar region of Enceladus. While many long held science questions have been answered by the Cassini-Huygens mission, many more have been raised. Within the context of scientific interest and recent Cassini-Huygens discoveries, NASA's Planetary Science Division directed that JPL and a science team from the broader community determine the feasibility of conducting missions to Titan and Enceladus and to characterize the science return within a $1B FY06 cost cap.

The Study concludes that, at this time, no missions to Titan or Enceladus that achieve at least a moderate increase in understanding beyond Cassini-Huygens were found to fit within the cost cap of 1 billion dollars (FY'06).

1.1 Study Objectives and Guidelines

NASA's Planetary Science Division developed the objectives that drove this study as shown below:

- Determine feasibility of conducting missions to Titan or Enceladus within a $1B FY06 cost cap.
- Characterize the science return achievable within a $1B FY06 cost cap.
- Identify technologies required by the missions.

In addition, the following guidelines were stipulated:

- The cost cap includes the spacecraft and mission elements, including launch vehicle, science instruments, radioactive power system, and reserve. The cost cap does not include technology development and/or maturation costs.
- Acceptable mission science return should enable at least a moderate advancement in scientific understanding beyond Cassini-Huygens.
- Mission concepts are to minimize use of new technology.
- Foreign contributions should not be considered for this study.
- Mission concepts are to assume launch opportunities no earlier than 2015.

1.2 Relation to Cassini-Huygens, New Horizons and Juno

Cassini-Huygens is a >$3B Flagship class mission with a powerful instrument complement, capable spacecraft and highly flexible mission design that enables it to visit many destinations in the Saturnian system. This mission sets high expectations for follow-up missions in the sub $1B category. Any new mission to Titan or Enceladus must be capable of enabling a significant advancement in scientific understanding.

While the Huygens (Titan entry probe) mission is complete, Cassini is still only two and a half years through its prime mission and an additional four years of productive observations at Titan and Enceladus are being planned. This study has attempted to anticipate likely results of this ongoing Cassini exploration although unanticipated surprises could influence the science objectives and mission concepts that were examined.

In contrast to Cassini-Huygens, there are two outer planet missions currently being implemented in the sub $1B cost range: New Horizons (NH) will explore a previously unexplored object (Pluto and KBOs); Jupiter Polar Orbiter (Juno) will apply a new technique from a new vantage point to a previously studied object (Jupiter). While these missions are much more constrained from a science perspective than Cassini-Huygens, they each provide a unique perspective on lower cost outer solar system missions and implementation approaches.

Experience as well as technical and cost data from Cassini-Huygens, NH and Juno have been applied to this study and also provide a benchmark against which to compare the results.

1.3 Technical Approach

A small Science Definition and Engineering Team was formed to quickly evaluate and integrate science objectives with mission concepts. Two science definition teams (one for Titan and one for Enceladus) were populated with members that NASA's SMD Planetary Science Division (PSD) selected from the planetary community and more specifically the Outer Planet Assessment Group (OPAG). The balance of the study team was comprised of management, mission architecture, system engineering and cost analysis disciplines.

Given the short period of performance stipulated for this study (~2.5 months), the approach drew heavily upon existing information and was structured to limit scope as described below:

- Made use of results from previous Titan and Enceladus studies.
- Applied experience and data from the Cassini-Huygens mission and two cost-capped outer solar system missions, New Horizons and Juno.
- Minimized new feasibility and cost assessment efforts by culling a small set of missions with potential to meet study objectives from a broader set.

To address the science guidelines for this study, science objectives were developed for Titan and Enceladus investigations and traced to measurement requirements, which then led to the definition of applicable instruments. In concert with science definition, a broad set of candidate mission concepts were identified. To address the cost cap (<$1B FY06), costs for key mission elements, less payload and science activities, that are typically well defined (e.g., launch vehicles, power sources, propulsion systems, LA/NEPA, spacecraft bus, mission operations….) were estimated to provide an understanding of the practical lower limit of mission cost and to establish anticipated budget allocations for science and payload. Twenty-four (24) candidate science missions were identified as shown in Figure 1-1. As stated earlier, the scope and schedule for this study did not allow the development of detailed conceptual designs and cost estimates for each of the 24 options so a feasibility down-selection (based on science and cost) was used to identify a smaller set of missions for further study. Of the 24 candidate missions identified, eleven (11) missions were ruled out because they were judged likely to exceed the cost cap by a wide margin. This assessment was based on previous results from studies involving similar complex multi-element architectures. Two (2) were ruled out because they were judged to fall short of the science guideline by a wide margin. An additional four (4) were ruled out because they were judged as unlikely to meet both the cost cap and the science guideline. There remained a total of seven (7) missions that showed promise in meeting the science or cost guidelines that were selected for additional scrutiny. Five of these appeared to meet the science guideline and were initially judged to have a possibility of meeting the cost cap. The remaining two appeared more likely to meet the cost cap, but were judged by the science team not to meet the science guideline.

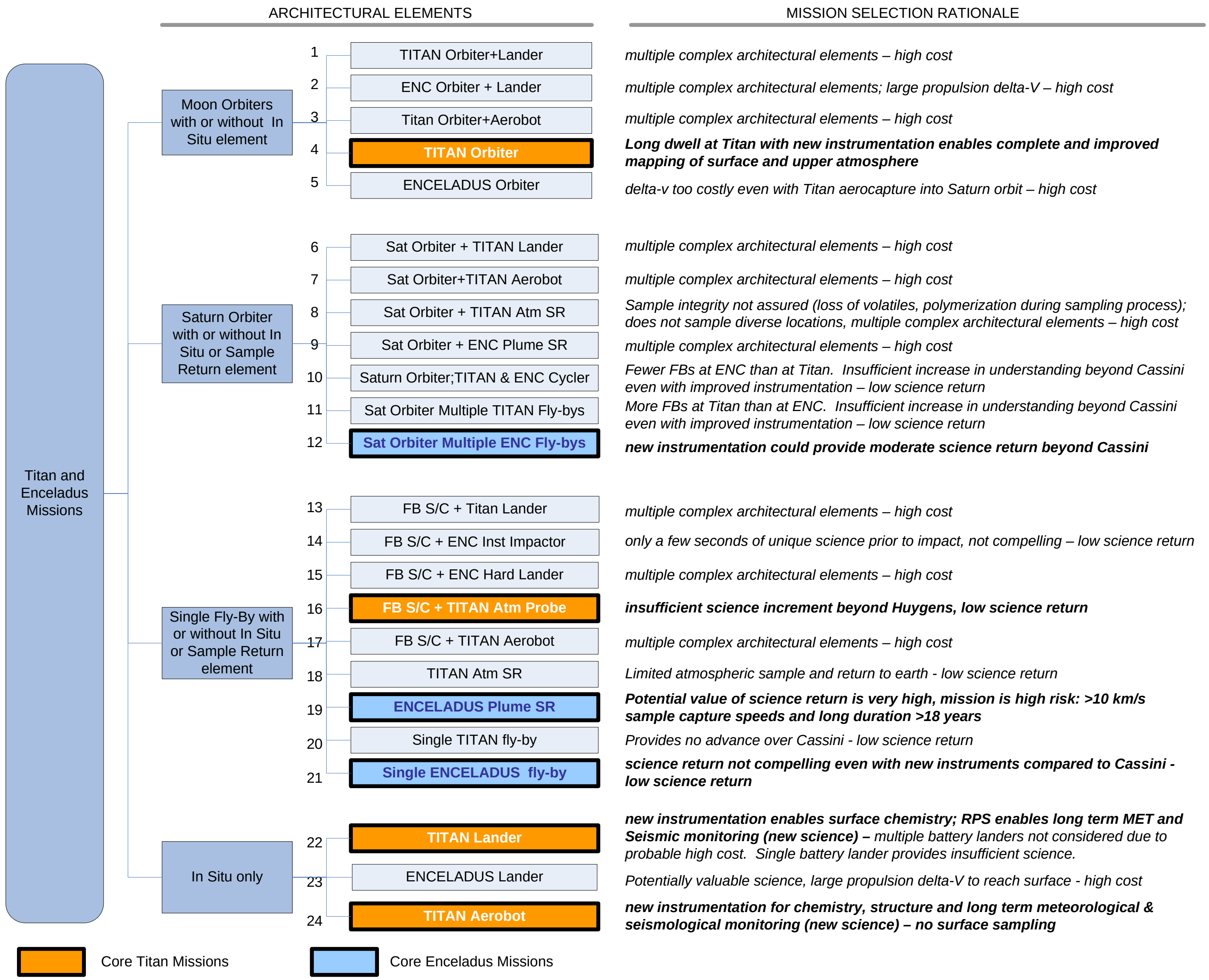
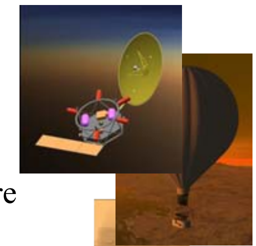


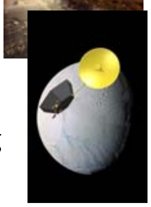
Figure 1-1 Twenty-four missions initially examined.

The resulting set of seven (7) missions considered for feasibility costing included four Titan missions and three Enceladus missions as described below.



1) **Titan Orbiter**: aerocapture and braking into Titan's atmosphere; 1500 km orbit; 2-year global mapping and atm. measurements.
2) **Titan Aerobot**: direct entry into Titan; Montgolfiere hot air balloon at 10 km altitude; 1-year in situ science survey of atmosphere and surface.

3) **Titan Lander**: direct entry into Titan; Huygens style parachute soft landing; 3-month Viking-like surface sampling and imaging followed by 21-month seismic and meteorological monitoring
4) **Titan Atmospheric Probe**: simple fly-by s/c for Huygens-Like atmospheric probe delivery and comm. relay; 4-8 hr encounter. Note: science return is below guideline due to high bar set by Cassini-Huygens.



5) **Saturn Orbiter/Multiple Enceladus Fly-Bys**: aerocapture into Saturn's orbit using Titan's atmosphere; targeted plume and global science via >30 Fly-Bys of Enceladus over 2-year period.

6) **Enceladus Plume Sample Return**: Stardust-like in situ sample capture >10 km/s; remote sensing and in situ measurements; Earth free-return trajectory

7) **Enceladus Single Fly-By**: NH-like mission using NH spacecraft with new but similar payload, single fly-by science return. Note: science return is below guideline due to high bar set by Cassini's campaign of Enceladus fly-bys.

1.4 Costing Methodology

A conceptual design was developed as a costing baseline for each of the 7 selected missions based on a flow down of science requirements and application of existing design information from previous studies and ongoing missions. This effort resulted in quantified technical parameters for each mission that were used as input to a comprehensive outer planet mission cost model. Since the Enceladus Single Fly-By mission (#7 above) was heavily based on use of the NH flight system, its cost was uniquely derived using actual costs from the NH mission directly. The outer planet cost model includes a mix of parametric cost models, analogies to previous/ongoing missions as well as historic wrap factors and provides an estimate of Total Mission Cost (TMC). JPL's work breakdown structure (WBS) and WBS dictionary were applied to ensure that all mission cost elements for the entire life cycle were adequately captured.

All critical parameters as well as an assessment of reserves were entered into the cost model to derive Total Mission Cost for each concept. In addition, an uncertainty model was developed to account for immaturity of mission concepts at this early stage of definition and limitations of the costing model. These uncertainty estimates were then added to the TMC to provide a quantification of the variability of expected costs for each mission. Finally, the costing results were examined by the team as well as external independent reviewers to ensure reasonableness of results.

1.5 Cost Results

The estimated total mission costs and associated uncertainty for the set of seven missions are shown in Figure 1-2. Note that the total mission cost (current best estimate plus reserves) for each of the missions is indicated in the Figure by the red rectangular symbol and the uncertainty around each estimate is indicated by the vertical bar. Due to the low level of maturity of these mission concepts, the required reserves are higher and uncertainty is broader than what would typically be carried at the beginning of a project's Phase B, Preliminary Design.

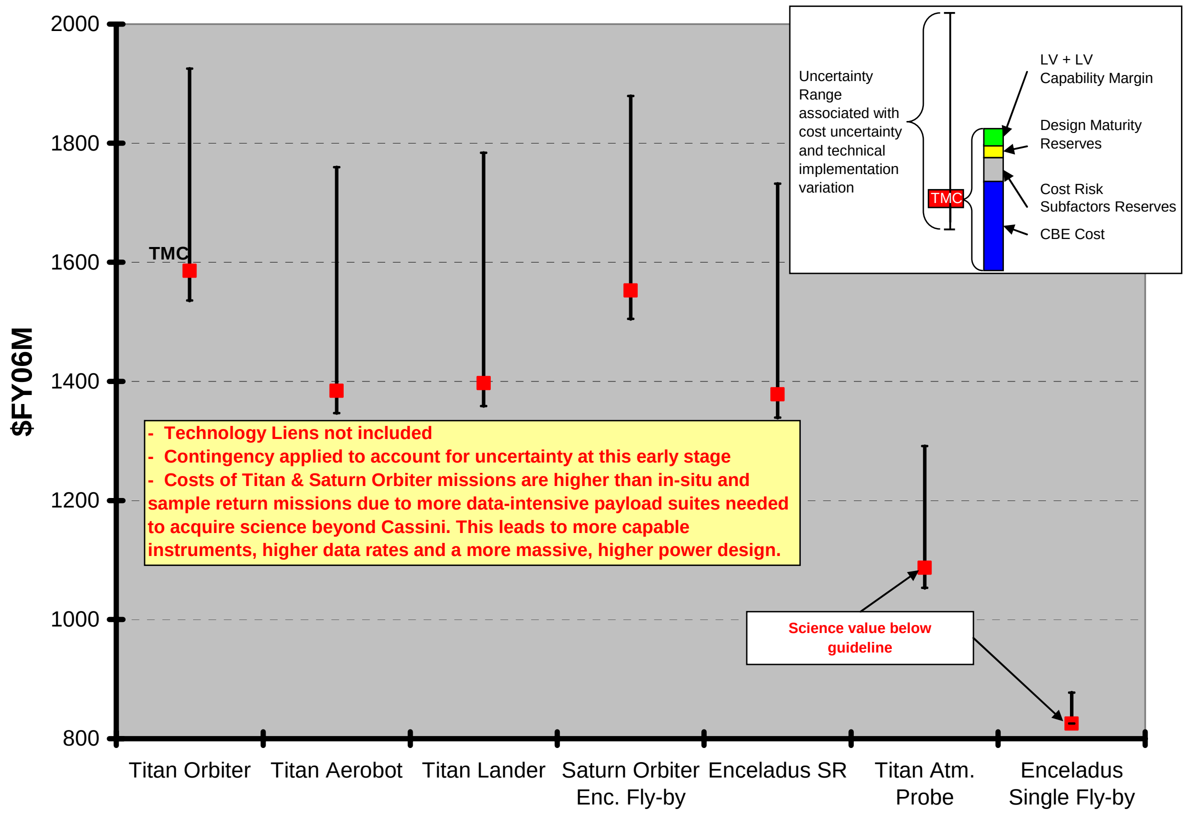


Figure 1-2 Total Mission Cost.

From Figure 1-2 it can be seen that relative costs of the Titan Orbiter and Saturn Orbiter missions are higher than costs for the other missions. These missions are driven by the more data-intensive instrument suites needed to acquire science results moderately beyond Cassini-Huygens. The more data intensive instruments lead to higher data rates and more massive, higher power designs for the orbiting mission concepts; hence higher cost. Note that the risks associated with orbiter missions are likely to be moderate-to-low because the environment and implementation aspects of planetary orbiters are better understood based on a large body of experience. Therefore, somewhat lower levels of reserves for cost risk are included in the TMC as well as smaller relative uncertainty estimates.

Titan in situ aerobot and lander concepts take full advantage of the favorable Titan environment to minimize mass and achieve valuable science results beyond Cassini-Huygens with modest instrumentation. These concepts incorporate a science payload with relatively low power and data rate demands resulting in lower relative mission cost. These missions are generally perceived as moderate-to-high risk due to the uniqueness and uncertainty of the environment during the entry, descent and landing phases and the minimal experience of implementing in situ planetary missions. Therefore their estimates are characterized by higher reserves and relative uncertainty bars.

The Enceladus Plume Sample Return concept includes a minimal instrument suite and Stardust-type sample capture and return system. The spacecraft travels on a SEP assisted ballistic trajectory to achieve a single pass through the Enceladus plume and then follows a free-return ballistic trajectory to transfer the collected samples to earth. While the mission life is long, the total mission costs are relatively low because the spacecraft and instrument configuration are minimal. By its nature, this mission has a high potential science value, given that the entire mission completes successfully. However due to the high particle capture velocities at Enceladus (>10 km/s compared to ~6 km/s for Stardust) and long lifetime (>18 years), this concept has a high level of perceived risk associated with its ability to yield science results.

Even though the Titan Atmospheric Probe and Enceladus Single Fly-By missions fail the science guidelines for this study by a significant margin, they were studied further because it was believed that they provide a perspective on the cost floor for missions to Titan or Enceladus. Other than the shorter interplanetary transfer time, the Enceladus Single Fly-By mission is very similar to the New Horizons Pluto mission in that it makes a single relatively high speed pass by Enceladus for a very short encounter. The mission cost assumes a highly constrained capability driven development similar to New Horizons (its cost is only slightly higher than the NH mission) and therefore has lower uncertainty relative to the other missions studied. The Titan Atmospheric Probe mission is scaled down dramatically from Cassini-Huygens in that it uses a very simple fly-by spacecraft to deliver and provide data relay for a Huygens-like probe that would achieve a several-hour descent in Titan’s atmosphere. Since this mission does not include an orbiter and the probe is limited to atmospheric science only, the cost is low relative to the other candidates. Both missions are expected to have a relatively low risk since they are based on missions and systems that have already been demonstrated. The assessment of these options demonstrates that the cost of flying a mission to Titan or Enceladus, even with unacceptable science, is ~ $1B.

Of the seven (7) missions costed for feasibility, the Enceladus Single Fly-By mission marginally meets the cost cap but falls well below the science guidelines for this study because of the high bar set by Cassini-Huygens performance for similar scenarios. Even with improved instrumentation it was determined that these missions would not achieve a science floor beyond Cassini-Huygens that would be worth the required $1B or greater investment. The Titan Atmosphere Probe comes close to meeting the cost cap, but was judged to fall short of the science guideline by a wide margin. The remaining 5 missions do meet the science guidelines as stated earlier; however, they exceed the cost cap significantly because they require the implementation of more complex architectures.

It is important to acknowledge that while the TMC estimates from this study do consider development risk in the reserves model, they do not account for mitigation of all risks. Costs for technology maturation through flight readiness (NASA definition of TRL6) and for a small subset of development tasks that could not be accurately quantified within the limited timeframe and scope of this study have been identified as liens against the estimated costs.

1.6 Risk Assessment

Risk plays a key role in performing an analysis of alternatives. Most development risks were addressed and their mitigation costs included in the cost reserve element. However cost associated with key mission risks – which encompass the risk associated with achieving the specified science return – and a small set of development risks that could not be adequately estimated within the scope of this study were considered as an independent variable in performing the overall assessment of whether a credible $1B mission to Titan or Enceladus could be implemented. These risks and the magnitude of their potential impact (uncosted liens) are shown in Figure 1-3. A relative ranking of these risks based on consequence and likelihood scoring (ref: JPL D-15951, “Risk Management Handbook for JPL Projects,” which is compliant with NPG 7120.5C, NASA Program and Project Management Processes and Requirements) indicates that the Enceladus Sample Return mission has the highest overall perceived risk to mission success due to challenges associated with hypervelocity sample capture and extremely long mission life. The Titan Orbiter and Saturn Orbiter missions have medium risk primarily due to uncertainty in flight readiness of the aerocapture technology. The Titan Lander and Aerobot missions have medium risk associated with uncertainty in entry, descent and landing performance in a new environment.

Significant Risks	Mitigation Approach	Cost impact H:C>$50 M M:$10M< C<$50M L:C<$10	Titan Orbiter	Titan Aerobot	Titan Lander	Titan Atmospheric Probe	Enceladus Sample Return	Saturn Orbiter w Multiple Enc FBs	Single Enceladus FB
EDL proves more challenging than anticipated	EDL simulation, modeling and test	M		3,3	3,2	1,1			
Aerocapture technology not validated	Flight validation	H	4,3					4,3	
Materials and systems don't meet cryogenic env rqmts	Low temperature materials and systems technology	L		2,3	2,3				
Existing sample acq handling inadequate for mission need	In situ instrument and sample handling technology	M			3,2				
Plume does not exist at time of arrival	Plume analysis and modeling using Cassini data	L					5,1	3,1	4,1
Plume particle impact hazard has high uncertainty	S/C Armor	L					3,3	3,3	1,3
Existing high speed particle capture capability not applicable	Sample capture and test technology	H					5,5		
Current capability not qualified for >18 year mission life	Reliability analysis, life testing, robust design	M					5, 5		
Existing curation facilities not adequate for sample return	Curation facility	H					5,1		
Overall Mission Risk Rating			med	med	med	low	high	med	low

Figure 1-3 Relative Risk Assessment for Titan and Enceladus Missions. Quantification indicates consequence and likelihood scores based on scale of 1-5; 1 being the lowest.

The Titan Atmospheric Probe and Single Enceladus Fly-By missions have the lowest risk because they are based on missions and systems that have already been demonstrated in flight and require no additional technology maturation. Clearly, a more thorough assessment of these risks and associated mitigation costs will be needed to understand the full investment required for implementation of each mission.

1.7 Science Value

Overall results of the study are summarized in Figures 1-4 and 1-5 which illustrate a relative measure of science value for the 24 Titan and Enceladus missions. The Science Rating (Y-axis) was established by the SDTs by evaluating the various mission concepts and assessing their ability to address the various science objectives. For each mission the team estimated whether it would provide a small, large, or very large increment in scientific understanding of each objective, beyond Cassini. Then, each mission concept was assigned an overall numerical rating from 1 to 10, to reflect how well that mission would advance the overall knowledge of Titan or Enceladus. The overall rating differed slightly from the average rating in the various science categories, reflecting the fact that not all science goals are of comparable importance. These ratings were influenced not only by the past results of Cassini-Huygens but also by the projected future results from the continuing Cassini mission. The approach was simplistic and linear but did yield a reasonable measure of the placement of these missions relative to one another (this summary was not intended to rate Titan missions relative to Enceladus missions).

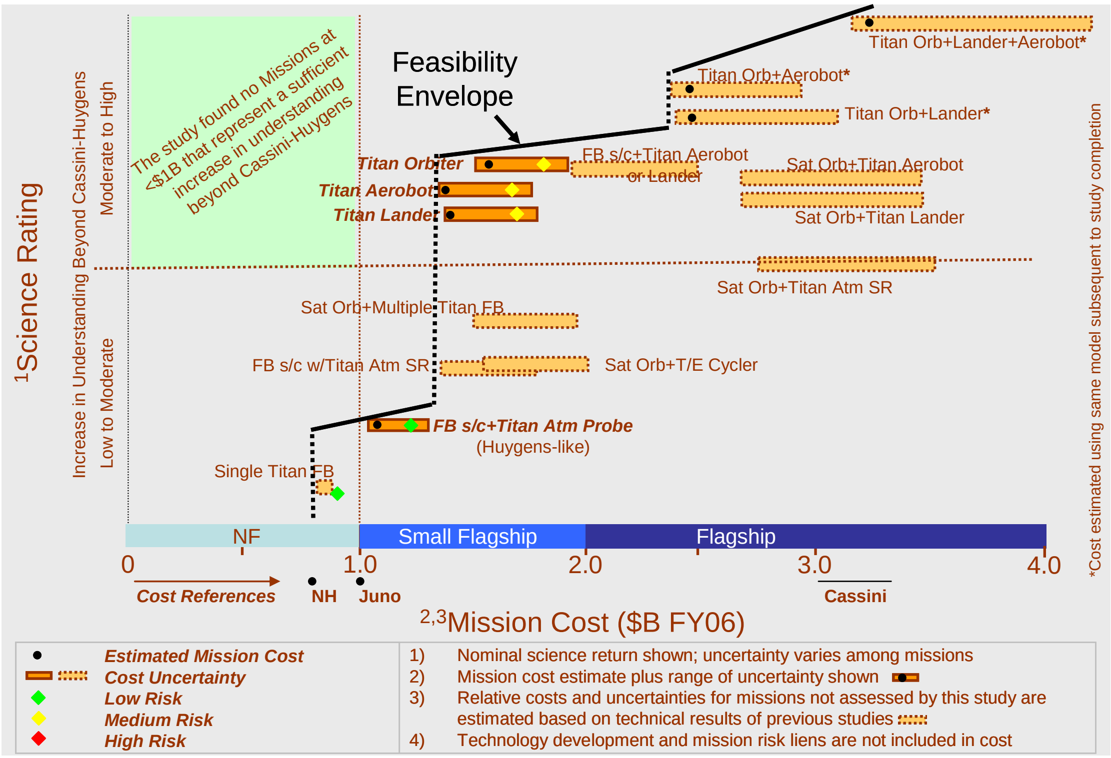


Figure 1-4 Titan Feasibility Assessment – Summary of Results.

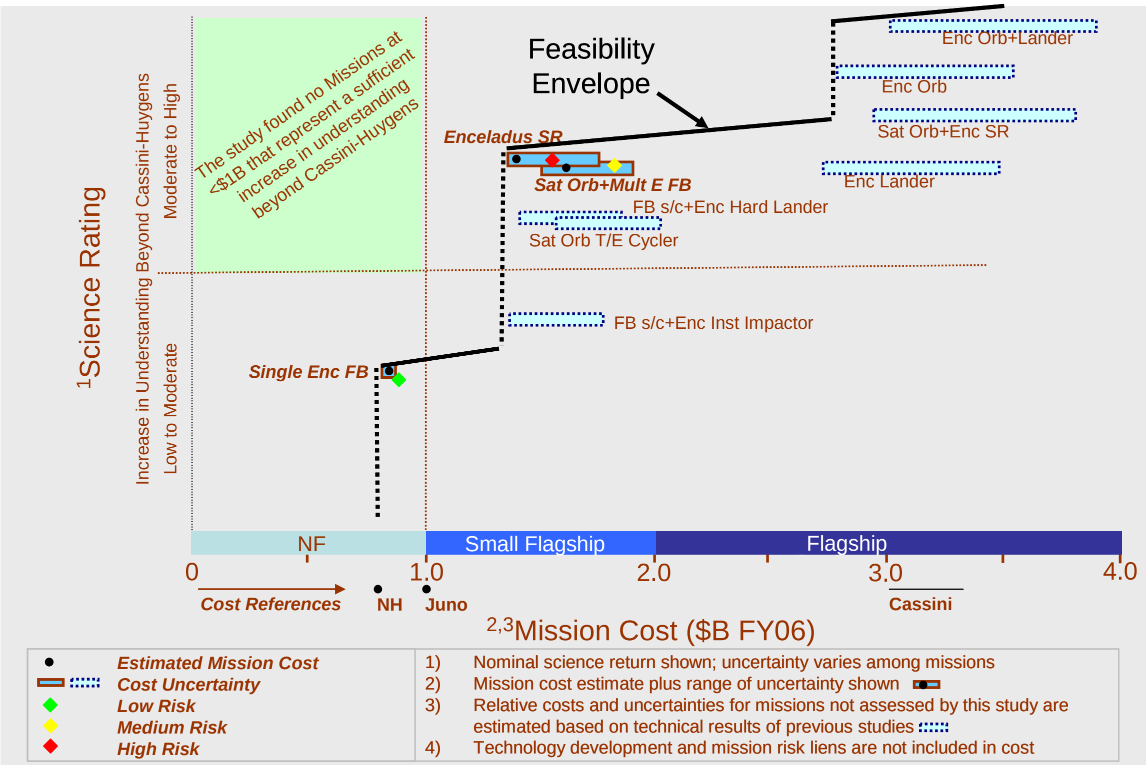


Figure 1-5 Enceladus Feasibility Assessment – Summary of Results.

Quantification of Mission Cost and associated uncertainty ranges (x-axis) for options not specifically costed as part of this study were derived from information available from previous studies and ongoing missions. For missions costed specifically as part of this study (indicated by Bolded text and Bold outlined rectangle), values for cost estimates and uncertainty ranges were generated using the outer planet costing model and actual costs from the NH mission.

As shown in the figures, five of the seven missions that were studied in detail were ranked sufficient in science value at small flagship class cost (following the classification scheme used by the Solar System Exploration Roadmap of 2006) and the remaining two were ranked insufficient in science value at New Frontiers class cost. Some of the missions rejected early appear to have high cost but low value. Missions that were ranked highest in science value were judged to fall within the Flagship class category.

1.8 Feasibility Assessment and Conclusions

The objective of the study was to determine the feasibility of implementing a mission to either Titan or Enceladus that would fit within a $1B FY06 cost cap and yield sufficient advancement in science understanding beyond that obtained by Cassini-Huygens. To accomplish that, information developed in prior sections on mission science value, cost and risk was synthesized to determine if there are any missions that meet the science guideline and cost cap. In addition, an examination of the underlying cost drivers for science value, cost and risk was undertaken as well as an assessment of robustness of results.

1.8.1 Titan Missions

In Figure 1-4, the science value rating is plotted against cost for the 14 Titan missions studied. For the four for which detailed costing was performed, an assessment of mission risk (taken from Figure 1-3) is shown. Several conclusions can be drawn from these results:

1. None of the Titan missions studied fall in the quadrant shaded green which represents missions that are less than $1B in cost with sufficient science value. In fact there are no missions that are close to the sufficient range.
2. Two missions – ***Single Titan FB*** and ***FB s/c with Titan Atmospheric Probe*** – plot either in the lower left quadrant or close to it. These missions do not meet the science guideline although at lease one of them meets the cost cap.
3. Three missions – ***Titan Orbiter, Titan Aerobot*** and ***Titan Lander*** – meet the science guideline but have cost estimates in the range of $1.3B to $1.8B. These have been characterized as small Flagship missions following the classification scheme used by the Solar System Exploration Roadmap of 2006. It is important to note that there is a significant step in cost and science capability at around $1.3B or greater (there is not a continuum of other mission options in that range from $0.8B to $1.3B).
4. Three other missions, all involving multiple architectural elements and science platforms – ***Titan Orbiter plus Lander plus Aerobot, Titan Orbiter plus Aerobot,*** and ***Titan Orbiter plus Lander*** – have very high science value but at costs in the $2.5B and greater range. These missions were not examined in as much detail as those discussed earlier and therefore their cost and science value are somewhat less defined. These have been characterized as Flagship missions again following the Roadmap scheme discussed above.

1.8.2 Enceladus Missions

In Figure 1-5, the science value rating is plotted against cost for the 10 Enceladus missions studied. For the three for which detailed costing was performed, an assessment of mission risk (taken from Figure 1-3) is shown. Several conclusions can be drawn from these results:

1. None of the missions studied fall in the quadrant shaded green which represents missions that are less than $1B in cost with sufficient science value. In fact there are no missions that are close to the sufficient range.
2. One mission – ***Single Enc FB*** – appears in the lower left quadrant. This mission meets the cost cap but falls short of sufficient science value.
3. Two missions – ***Saturn Orbiter with Multiple Enceladus Fly-Bys (FB)*** and ***Enceladus Sample Return (SR)*** – meet the science guideline with a significant margin but have costs in the $1.3B to $1.8B range. One of these missions, Enceladus Sample Return, is also considered to be of high risk with two major risk elements as shown in Figure 1-3. These missions are in the small Flagship category as defined above. As with the Titan missions, there is a significant step in cost and science capability at around $1.3B or greater.
4. Several missions have been identified with still higher science value but also significantly higher costs. The highest value science missions are the ***Enceladus Orbiter*** and the ***Enceladus Orbiter plus Lander***. These missions were not examined in as much detail as those discussed earlier and therefore their cost and science value are somewhat less defined. These have been characterized as Flagship missions again following the Roadmap scheme discussed above.

1.8.3 Conclusions

As a result, the following conclusions were made:

1. No missions to Titan or Enceladus, that achieve a sufficient advancement in scientific understanding beyond Cassini-Huygens, were found to fit within the cost cap of $1.0 billion dollars (FY'06).
2. Three of the missions studied have the potential to meet the cost cap but fall below the science guidelines established for this study.
   a. Single Fly-By of Enceladus
   b. Single Fly-By of Titan
   c. Single Fly-By of Titan with Atmospheric entry Probe (Huygens-like)
3. Even the lowest cost mission studied, without the cost of science payload, has a minimum expected cost of ~$800M making it highly unlikely that unexplored approaches exist that achieve sufficient science value for $1B.
4. All Titan and Enceladus missions that meet science guidelines require some maturation of existing technology for flight readiness

1.9 Recommendations

The following recommendations are provided:

1. Results of this study should be considered as a stepping off point for follow-on NASA Studies.
2. Maturation of technologies necessary to implement Titan and Enceladus concepts should be considered for programmatic funding. For example:
   a. Aerocapture (flight validation)
   b. Aerial mobility (aerobots, onboard autonomy)
   c. Low temperature materials and systems
   d. Sample acquisition and organic analysis instrumentation
   e. High speed sample capture (>10 km/s)
   f. Returned sampling handling (biological potential)

2. Methodology

2.1 Overview

The objective of this study was to determine the feasibility of conducting missions to Titan and Enceladus and characterize the science return within a $1B FY06 cost cap. A key aspect of the approach was to leverage from Cassini-Huygens results and achieve advancement in scientific understanding beyond the Cassini-Huygens mission. Since the duration of the study was limited to 2.5 months, the team built upon previous Titan study results and emerging Enceladus assessments. As a result, the mission definitions are conceptual and the total mission cost is parametric in nature.

2.2 Guidelines

Key guidelines established for the study include:

1. The cost cap includes the spacecraft and mission elements, including launch vehicle, science instruments, radioisotope power system, and reserve. The cost cap does not include technology development and/or maturation costs.
2. Acceptable mission science return should enable at least a moderate advancement in scientific understanding beyond Cassini-Huygens.
3. Mission concepts are to minimize use of new technology
4. Foreign contributions should not be considered for this study
5. Mission concepts are to assume launch opportunities no earlier than 2015
6. Planetary Protection (PP) category:
   a. Orbiters, category 2; "Of significant interest relative to the process of chemical evolution but only a remote chance that contamination by spacecraft could jeopardize future exploration."
   b. Aerobots and Landers, category 2
   c. Sample Return, Category 2 (uncosted lien for Category 3-outbound / Category 5-inbound)

2.3 Team

An integrated science and engineering team was formed to perform this study. This team included a Titan Science Definition Team (SDT) led by Ralph Lorenz, an Enceladus Science Definition Team led by John Spencer and an Engineering team led by Kim Reh (overall study lead). NASA SMD-PSD chose SDT members from the outer planet community, namely Outer Planet Assessment Group (OPAG). JPL (with the concurrence of PSD) augmented each SDT with a cognizant study scientist. Table 2-1 provides a listing of team members and their organizations.

An independent review and advisory group was formed for the purpose of ensuring thoroughness and quality of results. Members of that group included recognized experts in key disciplines from JPL, APL and SAIC as shown in Table 2-2.

Table 2-1 Integrated Science and Engineering Team.

Titan SDT	
Ralph Lorenz (lead)	APL
Elizabeth Turtle	APL
Frank Crary	SwRI
Hunter Waite	SwRI
Eric Wilson	JPL
Rosaly Lopes*	JPL
Enceladus SDT	
John Spencer (lead)	SwRI
Andy Ingersoll	CalTech
Amy Simon-Miller	GSFC
Bill McKinnon,	WUStL
Chris McKay	ARC
Rich Terrile*	JPL
Engineering Team	
Kim Reh (Study lead), JPL	JPL
Ed Jorgensen — Cost engineering, data input and analysis	JPL
Andrew Dantzler — Cost engineering, data input and analysis	APL
Tom Spilker — Mission Architecture	JPL
John Elliott — Flight System Engineering	JPL
Theresa Kowalkowski — Mission Design	JPL
Greg Welz — MOS, GDS, DSN utilization	JPL
Navid Dehghani — MOS, GDS, DSN utilization	JPL
Norm Beck — LV services	KSC
* denotes JPL augmentation to SDT with concurrence from NASA SMD PSD	

Table 2-2 Expert Review and Advisory Group.

Name	Function/Org
Glen Fountain	NH Project Manager/John Hopkins University-Applied Physics Laboratory (APL)
Gentry Lee	Chief Engineer/Jet Propulsion Laboratory (JPL) Planetary Flight Projects Office
Duncan MacPherson	JPL Planetary Flight Projects Office
John Niehoff	Senior Research Engineer/Science Applications International Group (SAIC)
Bob Pappalardo	Planetary Scientist/JPL Science Division

2.4 Approach

A structured approach was taken to identify Titan and Enceladus mission concepts and to systematically evaluate whether they in fact satisfied the cost cap and science guidelines. This approach is illustrated in Figure 2-1.

2.4.1 Science and Measurement Objectives:

For each moon a set of science objectives was developed by the Science Teams. These objectives were guided by the more general science goals for solar system exploration that have been formulated by the NRC's Decadal Survey and the 2006 Solar System Exploration Road Map team. For each science objective, measurement objectives were defined and used to establish the types of instruments and operational scenarios that would be needed to implement those objectives. This process established the flow down of science requirements.

2.4.2 Platforms and Mission Concepts

Given the science requirements, instrument accommodation needs, and cost constraints, a number of potential platforms for carrying out those measurements were considered. These included Saturn orbiters, moon orbiters, moon probes, landers and balloons and a hypervelocity sample return concept. Mission concepts were then devised in which one or more of the platforms were employed as part of an integrated mission to carry out the required operational scenario at either Titan or Enceladus. A high-level description of each concept, including science scenarios and data flows, was developed in order to characterize the science value, cost and risk of each concept. The set of mission concepts considered in this study appear in Figure 2-2. Those that were determined on the basis of Science Value or Cost to be the best candidates for a future $1B class Titan or Enceladus mission are highlighted in light green (Figure 2-2) and are described more thoroughly in Sections 5 and 6.

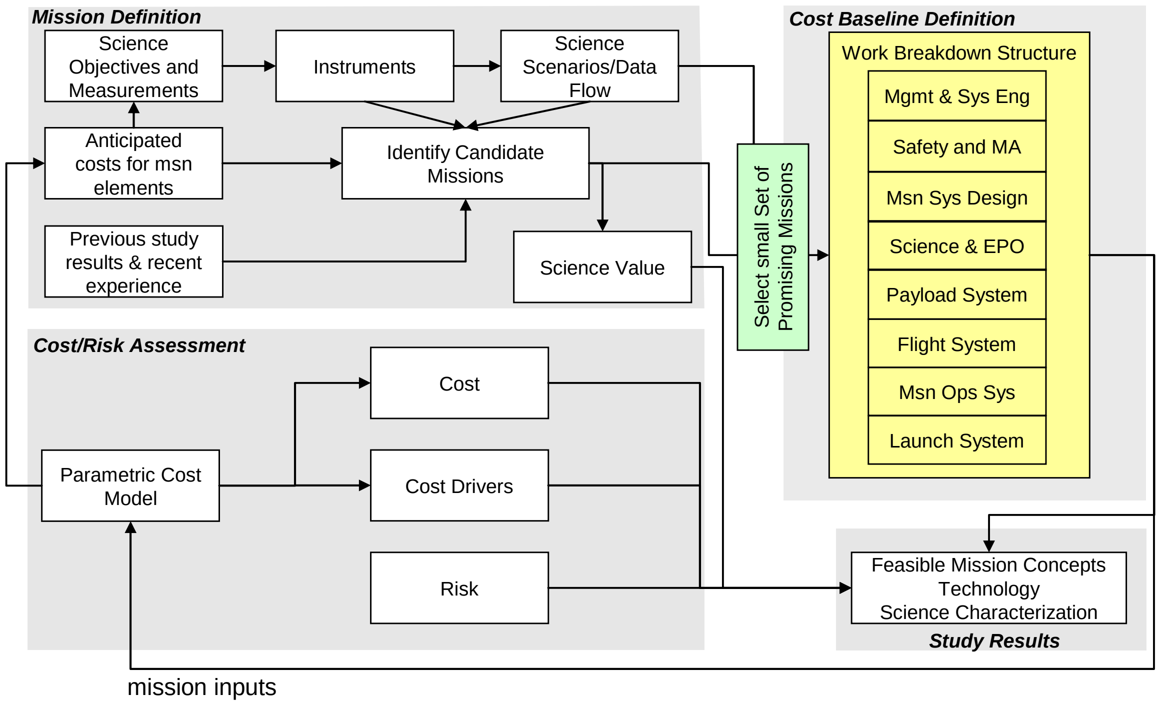


Figure 2-1 Structured Systematic Approach.

	Target	In Space Flight System	In Situ Flight System	Sample Return System	Cost	Science
1	Titan	Moon Orbiter	Lander		Fails by wide margin	Highest Value
2	Enceladus	Moon Orbiter	Lander		Fails by wide margin	Highest Value
3	Titan	Moon Orbiter	Aerobot		Fails by wide margin	Highest Value
4	Titan	Moon Orbiter			Fails by small margin	Succeeds by small margin
5	Enceladus	Moon Orbiter			Fails by wide margin	Succeeds by large margin
6	Titan	Saturn Orbiter (multiple moon fly-bys)	Lander		Fails by wide margin	Succeeds by small margin
7	Titan	Saturn Orbiter (multiple moon fly-bys)	Aerobot		Fails by wide margin	Succeeds by small margin
8	Titan	Saturn Orbiter (multiple moon fly-bys)	Atmospheric sampler	Earth entry capsule	Fails by wide margin	Succeeds by small margin
9	Enceladus	Saturn Orbiter (multiple moon fly-bys)	Plume sampler	Earth entry capsule	Fails by wide margin	Succeeds by large margin
10	Titan/Enc (cycler)	Saturn Orbiter (multiple moon fly-bys)			Fails by small margin	Fails by small margin
11	Titan	Saturn Orbiter (multiple moon fly-bys)			Fails by small margin	Fails by small margin
12	Enceladus	Saturn Orbiter (multiple moon fly-bys)			Fails by small margin	Succeeds by small margin
13	Titan	Fly-By Spacecraft	Lander		Fails by wide margin	Succeeds by small margin
14	Enceladus	Fly-By Spacecraft	Impactor		Fails by small margin	Fails by small margin
15	Enceladus	Fly-By Spacecraft	Hard Lander		Fails by small margin	Succeeds by small margin
16	Titan	Fly-By Spacecraft	Atmospheric probe		Fails by small margin	Fails by wide margin
17	Titan	Fly-By Spacecraft	Aerobot		Fails by wide margin	Succeeds by small margin
18	Titan	Fly-By Spacecraft	Atmospheric sampler	Earth entry capsule	Fails by small margin	Fails by small margin
19	Enceladus	Fly-By Spacecraft	Plume Sampler	Earth entry capsule	Fails by small margin	Succeeds by small margin
20	Titan	Fly-By Spacecraft			Succeeds by small margin	Fails by wide margin
21	Enceladus	Fly-By Spacecraft			Succeeds by small margin	Fails by small margin
22	Titan	Simple Cruise Stage	Lander		Fails by small margin	Succeeds by small margin
23	Enceladus	Simple Cruise Stage	Lander		Fails by wide margin	Succeeds by small margin
24	Titan	Simple Cruise Stage	Aerobot		Fails by small margin	Succeeds by small margin

Missions Costed for Feasibility (rows 4, 12, 16, 19, 21, 22, 24)
Fails by wide margin
Fails by small margin
Succeeds by small margin
Succeeds by large margin
Highest Value

Figure 2-2 Missions Selected for Feasibility Costing.

2.4.3 Science Value

Determining the science value of each of the concepts and determining whether this satisfies the threshold for inclusion as a credible mission candidate was a significant challenge. The team adopted a structured approach of evaluating the expected contribution of each of the mission concepts to each of the science objectives. For each mission concept, each objective was assigned a rating based on its perceived ability to advance scientific understanding beyond Cassini-Huygens. Rating values ranged from 1 (small increase) to 3 (very large increase). An overall rating for each mission was then determined by considering the relative importance of each objective. This approach was influenced not only by the past results of Cassini-Huygens but also by the projected future results from the continuing Cassini mission. The approach was simplistic and linear but did yield a reasonable measure of relative science value for the mission set.

Any process for attempting to characterize science value, no matter how structured, has a subjective element. In applying this method, the team recognized that comparison of the science value for missions to the same target with similar observational strategies is most credible. For instance, comparing the science value of a Saturn Orbiter with Titan Fly-Bys and a Titan Orbiter with similar payloads is straightforward. Comparison of the science value from a Titan Orbiter with a Titan balloon mission was much more subjective. No attempt was made to, in some sense, normalize the scoring system to enable direct comparisons between a Titan mission and an Enceladus mission.

2.4.4 Mission Cost

As stated earlier, seven (7) missions were selected for detailed feasibility costing within the scope of this study. A conceptual design was developed as the costing baseline for six (6) of the selected missions based on a flow down of science requirements, consideration of cost constraints and application of existing conceptual design information from previous studies. Since the Enceladus Single Fly-By mission was heavily based on use of the NH flight system, its design (and therefore cost) was uniquely derived using actual cost data from the NH mission.

The quantified technical parameters for each mission were used as input to a comprehensive outer planet mission cost model. The cost model includes a mix of parametric cost models, analogies to previous/ongoing missions as well as historic wrap factors and provides an estimate of Total Mission Cost (TMC). JPL's work breakdown structure (WBS) and WBS dictionary were applied to ensure that all mission cost elements for the entire life cycle were adequately captured. In addition, an uncertainty model was developed to account for immaturity of mission concepts at this early stage of definition and fidelity limitations of the costing model. These uncertainty estimates were then added to the TMC to provide a quantification of the uncertainty associated with estimated costs for each mission.

Finally, the costing results were examined by the team as well as external independent reviewers within the context of results from previous missions as well as Cassini-Huygens, NH and Juno experience to ensure reasonableness of results. See Section 8 of this report for a more detailed discussion of the costing approach and results.

2.4.5 Risk

Risk plays a key role in performing an analysis of alternatives. Risk mitigation costs associated with development risk have been included as a cost reserve element. However, due to scope limitations of this study, mission risk – which encompasses the risk associated with achieving the specified science return – and mitigation cost was considered as an independent variable in performing the overall assessment of whether a credible $1B mission could be implemented. The risk assessment and a list of uncosted liens are shown in Section 1, Figure 1-3.

2.4.6 Assessment of feasibility

The final step in the assessment was to bring together the information on science value, cost and risk into an overall evaluation of the feasibility of scientifically useful missions within a $1B FY06 cost cap.

As part of this assessment, it was important to include elements that provide contextual understanding of results such as including the minimal cost of delivering a spacecraft to the Saturn system in the vicinity of Titan and Enceladus regardless of the nature of the scientific experiments. It is also important to have as context the science value (return vs cost) of not only a rudimentary mission that might meet science objectives but to be able to contrast it with more capable missions with much more powerful investigative and exploratory capabilities. The missions that were investigated provide this context.

A key attribute considered is the ability for a mission to respond to the unexpected and pursue investigation of phenomena that either were not expected or were speculative in nature. The science investigations of Cassini are an outstanding example of this where the flexibility in executing multiple encounters of the spacecraft has enabled a range of complementary measurements to be made building upon knowledge of the geyser phenomena in the southern polar region of Enceladus. The orbiter and aerobot missions assessed in this study generally enable more mission flexibility than fixed landers, probes, impactors or fly-by spacecraft. Combinations of orbiters with landers or aerobots represent an optimal solution for science value however multi-architectural element missions such as these clearly fall in the Flagship class from a cost and complexity perspective.

See Section 1.0 for a discussion of feasibility conclusions.

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3. Titan Science and Payload

3.1 The Importance of Titan – An Appealing and Broad Scientific Target

The most Earth-like body in the solar system is not another planet, but Saturn's largest moon, Titan (Figure 3-1). This strange new world, between Mars and Mercury in size, has a thick nitrogen atmosphere laden with organic smog that hid its surface from view until only recently. Far from the sun, methane plays the active role on Titan that water plays on Earth (Figure 3-2), acting as a condensable greenhouse gas, forming clouds and rain, and pooling on the surface as lakes. As Cassini-Huygens has discovered, Titan's icy surface is shaped not only by impact craters and tectonics, but also by volcanism in which the lava is liquid water ('cryovolcanism'), by rivers of liquid methane, and by tidally-driven winds which sculpt drifts of aromatic organics into long linear dunes (Figure 3-3)

Ground-based observations have shown Titan to vary visibly on seasonal timescales, its haze structure in the north and south hemispheres alternating in thickness over the 29.5 year Titan annual cycle, as well as on much shorter timescales, with methane clouds puffing up and dissipating over a few hours. Titan's 16-day orbit defines another periodicity, with Titan dipping in and out of the Saturnian magnetosphere, whose energetic particles lance into the organic-rich upper atmosphere, driving exotic nitrogen-organic chemistry more energetically than the Sun's ultraviolet light, which drives most of the methane destruction.

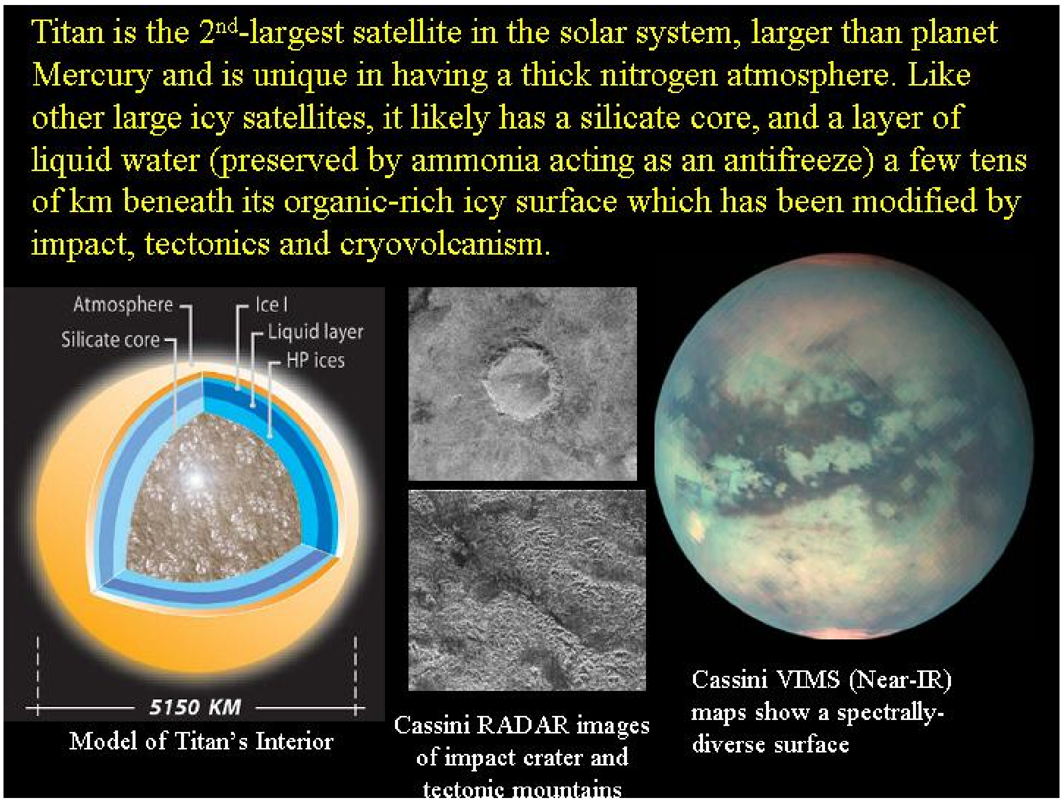

Figure 3-1 Titan is the 2nd largest satellite in the solar system.

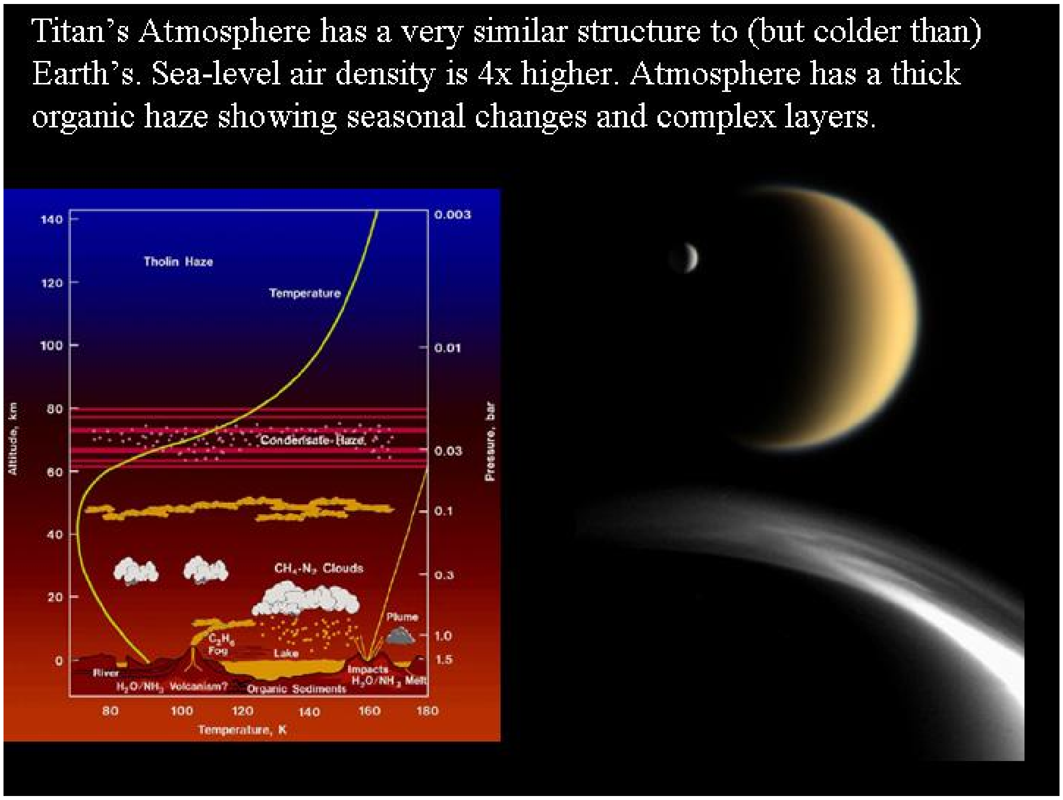

Figure 3-2 Titan is the most Earth-like body in the solar system.

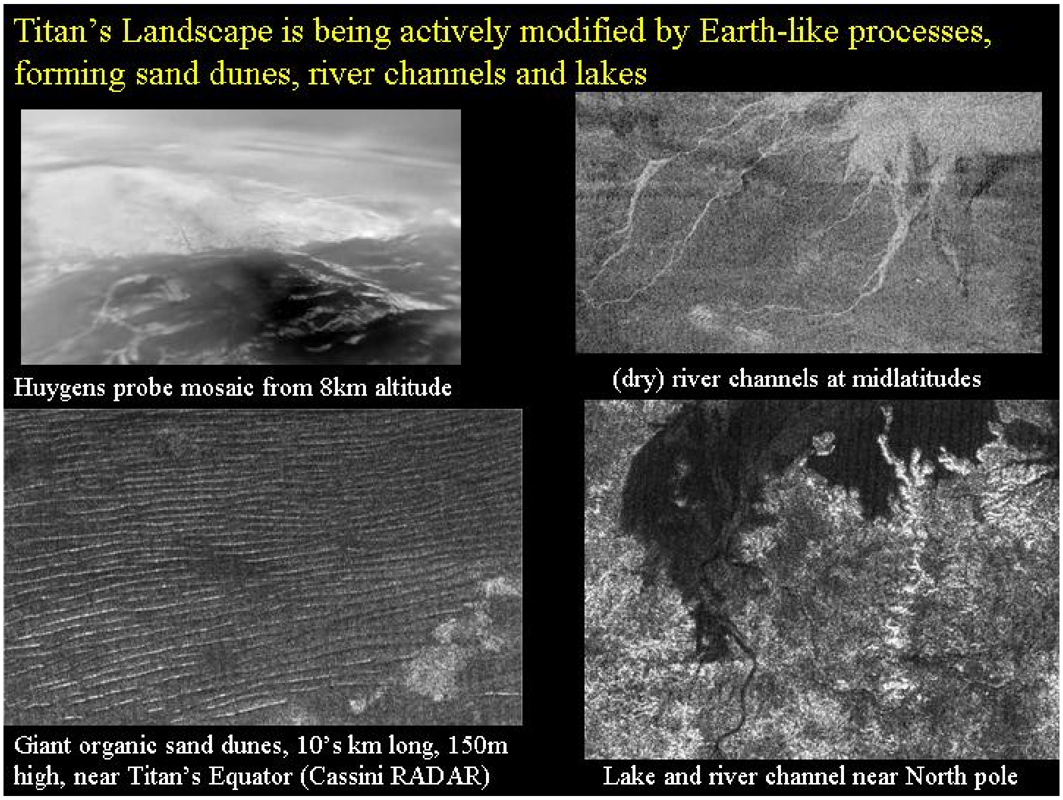

Figure 3-3 Titan's landscape is being actively modified by Earth-Like processes.

Thus, Titan is a phenomenologically rich world, with variety at all scales and levels, that embraces a wide range of scientific disciplines, including several such as oceanography and cloud physics that have traditionally been considered only Earth sciences. It is furthermore the most organic-rich environment known in the solar system and thus is a prime astrobiology target.

3.2 Cassini Limitations and the Foundation for New Science

The Cassini mission, while returning wonderful findings about Titan, is a mission designed to observe the whole Saturnian system. During its 4-year nominal mission, it flies by Titan approximately 44 times. An extended mission currently being planned for an additional two years of observations will potentially add another 20 flybys, adding substantially to the science return. During each flyby, however, Cassini spends only about an hour at ranges closer than 10,000km to Titan – this proximity is required to sample in situ the upper atmosphere and plasma environment, to sense geophysical fields such as gravity and magnetism, and to achieve high-resolution remote sensing observations of the surface and lower atmosphere.

Thus a long-lived follow-on mission can achieve worthwhile scientific return even with a more modest (but focused) instrument suite than Cassini, because it can sample Titan's diversity in space and time. It would spend more time immersed in the Titan environment in its first three days than Cassini will have in its entire mission.

The other major aspect of Titan science to be addressed by future missions is one that Cassini-Huygens was simply not equipped to tackle, namely the detailed composition of the organic-rich surface. Here, the organics drizzling out from the atmosphere (already complex, but lacking any oxygen content) maybe further processed, most notably by interaction with transient exposures of liquid water from cryovolcanism or impact melt. This interaction is of particular astrobiological importance – laboratory studies show that haze-type organics (‘tholin’) can be converted by water into pyrimindines (a DNA component) and amino acids (protein-forming molecules). Thus, these sites of hydrolysis may be the most promising sites of prebiotic chemistry presently understood. It is already known that there are four spectrally distinct surface types, plus the hydrocarbon lakes. It would be desirable to analyze the composition (molecular, elemental, isotopic and stereochemical) makeup of each of these different surface materials.

3.3 Titan Science Goals

The primary science goal for any new mission to Titan would be to define the methane cycles at Titan - both the short term methane hydrological cycle (like the water cycle on Earth) and the long term conversion cycle of methane to complex organics (like the carbon cycle on Earth).

This scientific goal is very broad and quite complex, therefore only a flagship class mission can address the topic in a comprehensive manner. However, smaller missions could address specific elements of this topic, which are listed below (without assigned priority) in a roughly chronological sequence in the overall cycle. Astrobiology considerations apply across many of these goals – but particularly the last – and so are not called out as a separate objective.

3.3.1 Sources of Methane

Infrared and/or radar observations that survey the extent of volcanology or venting and its time history are important. In situ sampling of the composition of outgassing from possible vents, geysers or cryo-volcanoes, (including measurement stable isotopic abundances) is critical to understanding the source mechanism. Understanding Titan’s present internal structure by gravity and magnetic measurements, and how that structure may have evolved, is also embraced under this goal, since the methane may be produced in the interior, and its delivery to the surface is intimately linked with the thermal evolution of its icy crust and internal water ocean (like Europa, only deeper).

3.3.2 Condensation and Cloud Formation

The meteorological processes that lead to methane rainfall (and hail) on Titan are an appealing analog to rainstorms in the Earth's evolving climate. Near-Infrared remote sensing is important to characterize daily and seasonal patterns of cloud systems and the precipitation beneath them, as well as the tropospheric and stratospheric wind patterns that control the spatial variation of methane humidity. In situ observations are also critical for understanding the condensation and precipitation process: while cumulus convection appears very analogous to that seen in terrestrial storms, the microphysics of precipitation with a non-polar material like methane is likely to differ in interesting ways from ice and water on Earth.

3.3.3 Conversion of Methane to Complex Organics in the Upper Atmosphere

Cassini data indicate that ion and neutral chemistry in the upper atmosphere initiated by ionization and dissociation of methane and nitrogen is the key to complex organic formation. To fully understand this process, ion and neutral mass spectra that can measure a wide range of masses (thereby measuring more complex molecules than Cassini is equipped to detect - including both negative ions and small -1000 Dalton - condensation nuclei) will be needed. In addition, instrumentation to document the energy supplied to the atmosphere from the Saturnian magnetospheric environment is essential.

3.3.4 Aerosol Formation

The formation and modification of complex organic aerosols takes place from 1000 km down to the surface, although remote observation of many of these altitudes is challenging. In situ measurements might include aerosol mass spectrometer like those used on earth onboard airplanes and balloons. This is an intriguing process that may effectively transport and deposit volatiles from the thermosphere/mesosphere into the warm stratosphere and almost certainly produces the larger aerosols Huygens observed in the troposphere. Determination in the far infrared and/or microwave of the gas composition in the stratosphere and its seasonal variation, and the measurement of winds, is also important in this region.

3.3.5 Surface Organic Inventory

It is important to understand how much methane is in communication with the atmosphere (notably, this is a factor in determining long-term stability of Titan's climate), as well as to determine the amount of processed organic material that has accumulated on the surface. Mapping of the extent of surface deposits may be partly accomplished by Cassini, but subsurface radar and/or sonar or seismic sounding will be required to measure the depth of deposits and thus determine the total amount.

3.3.6 Geomorphological Processes and Transport of Organics

Titan's strikingly varied landscape appears to be the result of a balanced mix of geomorphological processes seen on Earth – erosion and transport by methane rainfall and rivers, transport by Aeolian processes – as well as impact, tectonism and cryovolcanism. High-resolution imaging and topographic data are needed to characterize these processes.

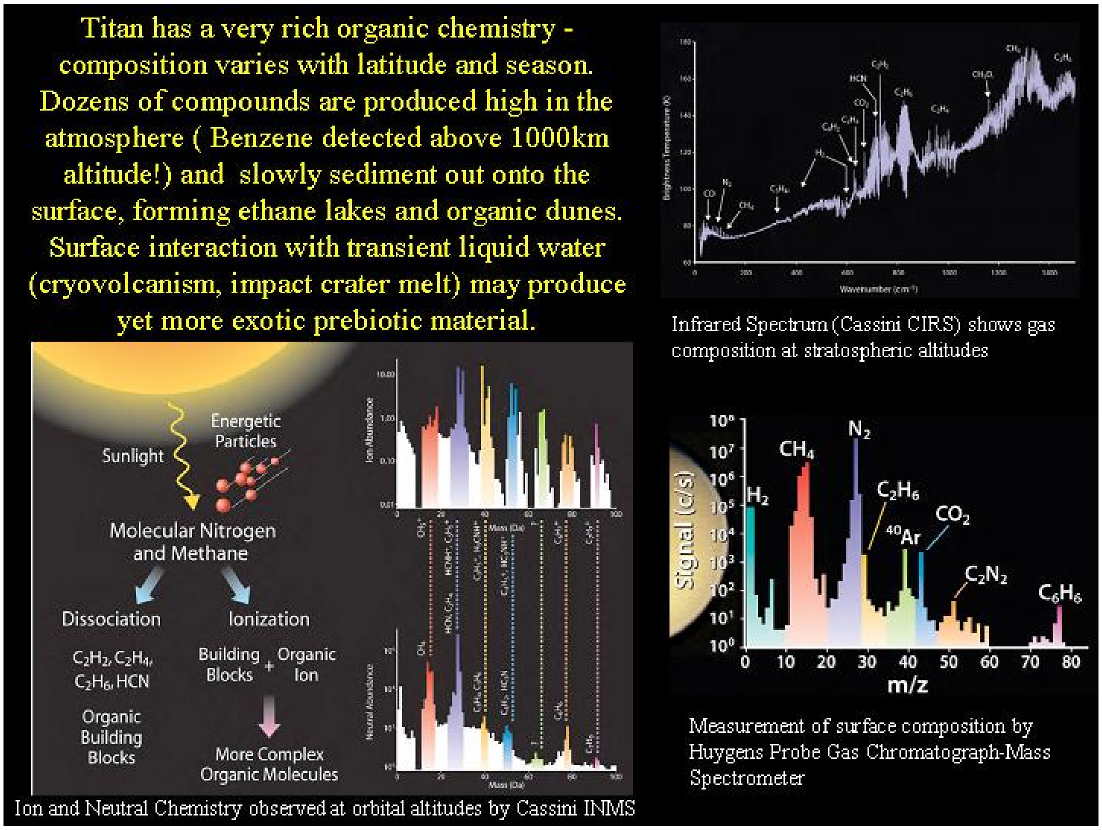

Figure 3-4 Titan has a very rich organic chemistry.

3.3.7 Surface Composition and Astrobiology

The varied organic surface composition on Titan is of critical astrobiological interest. Beyond the mere accumulation of aerosols, surface processing by physical processes (erosion, deposition) and, crucially, chemical modification (cryovolcanism, impact melt) leads to higher degrees of chemical complexity that demand sophisticated in-situ characterization.

Candidate instrumentation may include Raman and GCMS techniques, but liquid chromatography or labeling techniques and other approaches may be appropriate to seek specific prebiotic molecules. This should include careful isotopic characterization at the <0.1 per mil level, as well as radiocarbon measurement to age-date deposits.

3.4 Rating and Down Selection of Mission Concepts

There is clearly some subjectivity in assessing both science value and instrumentation costs. The missions and payloads of this study are based the best determinations of the small science team appointed for this study: other individuals may have made different choices. The science floor was determined by knowledge of what Cassini is achieving (with an investment of several billion dollars) and an awareness of what Discovery-class missions (~$0.4B FY06) are able to accomplish. Notable grey areas exist in the definition of a science floor for an orbiter (whose science return would scale incrementally with the number of instruments added), and in the ranking both between the very different concepts and of concepts relative to the perceived affordability criterion and minimal worthwhile science criterion. As an example, observation of large areas by an aerobot with atmospheric/aerosol sampling is difficult to discriminate from a lander with detailed surface sampling at a single location. The aerobot has at least a higher perceived technical risk because NASA has not attempted such a mission before, while lander missions have higher operational and scientific risk because of uncertainties in the diverse terrain.

A point needs to be made with regard to in situ vs. remote investigations. Because Cassini will have made substantial accomplishments by the end of its extended mission (radar mapping of 30-40% of the surface at ~300 - 1000 m/pixel; some spectral mapping, and multiple fly-throughs of the upper atmosphere), the science floor payload for an orbiter is much higher than for the in situ investigations studied. In situ platforms (long-lived lander and aerobot) can provide exceptionally novel science with relatively simple instrument payloads because they are new platforms in an unexplored but rich environment.

The SDT evaluated the various mission concepts by assessing their ability to address each of the various science questions listed above. For each mission the team estimated whether it would provide a small, large, or very large increment in scientific understanding of each objective, beyond Cassini, as shown by color coding in Table 3-1. Based on these ratings, each mission concept was assigned an overall numerical rating from 1 to 10, to reflect how well that mission would advance the overall knowledge of Titan.

For the mission concepts studied in detail it may be seen that the orbiter and in situ investigations (as seen from the science trace matrix – Table 3-2) are scientifically complementary (in this connection we may note that the exploration of Mars is an excellent template for the exploration of Titan.) There are additional technical synergies that exist between cooperating assets that are not apparent from the table (e.g. orbiter providing data relay services to an aerobot; a lander acting as a navigation beacon for an orbiter, shared cruise stages, etc.) Thus the science return per dollar invested is likely to be higher for a combined Flagship-class mission than the cost-constrained missions evaluated here, although the present study could not quantify this in detail.

3.5 Missions Rejected or Not Considered

Based on experience and results from previous studies, missions that were judged to fall well below either the cost cap or science guidelines for this study were eliminated as candidates for further study. Surface rovers were not considered, because their cost was judged to exceed the cost cap by a large margin and the associated science return does not represent a significantly broad sampling of the diverse Titan surface. (Demonstrated rover mobility is only a few km, while Cassini resolution is only a factor of a few better than this – thus rovers are unlikely to find a site where usefully different locations are within achievable distance without a precursor or concurrent Titan orbiter). The trafficability of Titan's surface is furthermore uncertain due to known areas of steep slopes, dunes and probable stickiness.

Aerial mobility by a buoyant vehicle (blimp or balloon) was assumed to be viable because of its operational simplicity. However, heavier-than-air vehicles were not considered in this study. Such vehicles (e.g. airplanes) are likely to be feasible, with possibly higher technical risk but lower operational risk than balloons, but have received minimal attention in studies to date, and the constraints of the present study did not permit adequate exploration.

A Titan atmosphere sample return mission offers some promise of affordability however the Titan SDT judged its scientific value modest and risky. A flythrough sample capture, via capture plates, aerogel etc. would likely catch a large amount of upper atmosphere organic material, including volatiles as well as more refractory haze. However, some of the volatiles would likely be influenced by the capture process at several km/s and/or during the long return. If samples could be obtained from several different latitudes/altitudes/solar times there would be interpretable variety between samples, regardless of the systematic effects of capture and transfer, but a single integrated sample suffers severe interpretation risks and only modest scientific value.

Multiple Titan flybys, by a Saturn orbiter either in a dedicated orbit for Titan science, or an Enceladus-Titan cycler, were not judged to offer adequate advance relative to Cassini. An affordable mission could not be as heavily instrumented as Cassini, and the scientific return would be limited to a modest number of flybys (more modest for the cycler than a dedicated orbit) – in other words the return from this type of mission would be comparable with a Cassini mission extension, but would be far more expensive.

3.6 Missions and Payload Studied

3.6.1 Titan Orbiter

A Titan orbiter was considered a scientifically attractive stand-alone mission. This would be able to accomplish, over a modest mission duration of two years, a complete mapping of Titan in the near-infrared (2 microns) at 100m/pixel (a factor of 10-100 times better than Cassini will achieve) and with radar (a factor of 3-10 better than Cassini will achieve over ~3 times the area, Cassini coverage presently expected to be 30-40% of the surface). The radar/infrared combination (‘Imager’ + ‘RADAR’ in table 3.1) is proving essential to understand the relationship of landform to composition on Titan. An integrated plasma instrumentation suite (‘Plasma’) will measure the magnetospheric and solar wind inputs to Titan's ionosphere, and its response, at a vastly better sampled range of conditions and locations. To fully exploit this capability, an 'aerobraking' phase with an elliptical orbit is employed for a few months prior to the mapping orbit. The low-altitude dipping aspect of the orbit is essential to investigate the aerosol precursor chemistry via an in-situ chemical analyzer (‘CHEM’). Radio science (‘Radio’) permits Titan's gravity field, and its response to the changing tidal potential, to be measured more accurately than Cassini will achieve, and may also provide atmospheric temperature profiles.

It should be emphasized that this payload is relatively austere, being chosen to meet the science floor.

3.6.2 Aerobot

An aerobot or balloon was another attractive mission (both aerobots and orbiters have been considered together as a formidable Flagship-class combination). This would be dropped into the atmosphere, inflate its envelope during descent and float at a more-or-less constant altitude indefinitely. The Montgolfiere ('hot air' balloon – powered by 'waste' heat from the MMRTGs) approach is more mass-efficient in Titan's cold, dense atmosphere than a buoyant gas balloon. In principle a Montgolfiere permits altitude control for active navigation in a varying wind profile as performed by balloonists on Earth. Descent for surface sampling is also a capability of Montgolfiere concepts however, for cost and complexity reasons these capabilities were not exploited in the concept costed here. No obvious life-limiting factors are known, so a nominal mission of one year is assumed. Communications is direct-to-Earth via a steerable antenna (large telescopes are routinely pointed from stratospheric balloons on Earth) using the sun and/or a terrestrial beacon for attitude reference. This downlink permits only a couple of kilobits per second, for perhaps one third of the time (Earth visibility depends on location and season) – over one year this yields a data return comparable with Mars Pathfinder, or ~1000 times more than the Huygens probe. Intelligent on-board data selection and compression would be used to optimize this downlink via autonomous algorithms, and ground interaction teams (e.g. transmission of thumbnails for science team to prioritize downlink of full images). The payload would be relatively modest. First, a camera suite ('SURVEY') to perform mapping, navigation and meteorological studies. A lightweight subsurface radar sounder ('PROFILER') would generate topographic profiles and detect subsurface layering (e.g. measure the depth of lakes, thickness of sand deposits in dune areas, possibly look for near-surface cryomagmas) – this instrument would resemble those used in terrestrial ice-sheet surveys, with a wavelength somewhat shorter than those used in Mars/Europa sounders, to keep antenna length down. A meteorology package ('MET') would monitor short-period winds, pressure and temperature and variations of major species (methane, ethane, HCN) would be monitored with a simple Tunable Diode Laser ('TDL') spectrometer. A GCMS would perform more detailed chemical analyses at less frequent intervals, and would incorporate an aerosol sampler.

3.6.3 Long-Lived Lander

The lander mission would be distinct from Huygens in several ways. While it would take images ('DESCAM') during parachute descent to derive context, its on-the-surface imaging ('LANDCAM') would be analogous to that from Mars landers or rovers, with a turret-mounted high-resolution camera able to pan the entire scene and use a variety of filters for geochemical and atmospheric studies. Equipped with a radioisotope power supply, and direct-to-Earth downlink, it would be able to provide a data return volume comparable with the aerobot, but focused on one location. A sampling arm or drill would acquire several surface samples, and introduce them into a sophisticated on-board laboratory ('SURFCHEM') for detailed analysis of elemental, molecular, stereo chemical and isotopic composition, answering key questions about how far chemical evolution has proceeded on Titan's surface. The intensive surface-sampling part of the mission should be achieved within 2-3 months, but the lander itself can last much longer than this. A seismometer ('SEIS') and meteorological package ('MET') would monitor earthquakes and winds (both, perhaps, driven primarily by the 16-day tidal period), and occasional imaging would be conducted, for a less intensive monitoring phase of 2 years.

3.6.4 'Huygens-Like' Probe

A Huygens-like (i.e. short-lived, battery-powered) probe was introduced late into the study as a benchmark – such a probe was immediately judged not to provide incremental science beyond Huygens worth the cost, but was included in order to define a cost floor for Titan in-situ missions. It would conduct a parachute descent mission of several hours, performing descent imaging and haze/gas sampling of the atmosphere. As with Huygens, any surface science would be opportunistic: the short mission duration enforced by battery power and flyby relay prevents ground intervention in landing guidance or surface sampling. An uncontrolled surface sampling of a single location on Titan's diverse surface was judged to have modest probable science value and high science risk. Multiple small battery-powered probes could address that difficulty but were not considered likely to meet the cost constraint and in any case do not provide the sustained science delivery that the three long-lived missions offer.

Table 3-1 Relative science value of Titan missions.

Relative Science Value of Titan Missions
Increase in Understanding Beyond Cassini-Huygens

	Mission															
	Flagship Class Total Mission Cost (TMC)>$2B									**Small Flagship Class $2B>TMC>$1B**						**NF Class TMC<$1B**
Science Objectives	Titan Orbiter + Lander + Aerobot	Titan Orbiter + Lander	Titan Orbiter + Aerobot	Saturn Orbiter + Titan Lander	Saturn Orbiter + Titan Balloon	Saturn Orbiter + Titan Sample Return	Saturn Orbiter; Titan/Enc Cycler	Fly-By S/C + Titan Lander	Fly-By S/C + Titan Aerobot	Titan Orbiter	Titan Lander	Titan Balloon	Saturn Orbiter w/Multiple Titan Fly-Bys	FlyBy S/C + Atm Sample Return	Single Titan Fly-By w/Atm Probe	Single Titan Fly-By w NH s/c
Sources of Methane																
Condensation and Cloud Formation																
Methane Conversion																
Aerosol Formation																
Surface Organic Inventory																
Geomorphology and Transport																
Surface Composition																
Overall Mission Rating	**10.0**	**8.0**	**8.5**	**6.3**	**6.8**	**5.0**	**3.0**	**6.0**	**6.0**	**7.0**	**6.0**	**6.5**	**4.0**	**3.0**	**2.0**	**0.5**

Code for rating of Science Objectives (relative

- Very large increment beyond Cassin
- Large increment beyond Cassini-H
- Small increment beyond Cassini-H
- Redundant with Cassini-H

Code for Overall Science Rating of Mission (1-10 relative to Cassini Huygens with 5 being sufficient)

1,2	fails by large margin
3,4	fails by small margin
5,6,7	succeeds by small margin
8,9	succeeds by large margin
10,	optimal solution

Indicates missions chosen for costing

Objective	Orbiter					Lander					Aerobot					Probe				
	Imager	Plasma	RADAR	CHEM	Radio	URFCHE	ANDCAM	SEIS	MET	DESCAM	SURVEY	MET	PROFILEF	GCMS	TDL	IMAGER	GCMS	ASI	ALTIM	TRACK
Sources of Methane Condensation and Cloud Formation	X		X	X	X	X		XX		X	X		X	XX	XX	X	X			
	XX				XX		X		XX		X	XXX		XX	XXX	X	X	X		X
Methane Conversion		XXX		XXX														X		
Aerosol Formation	X	X		XX		X								X			X			
Surface Organic Inventory	XX		XXX							X	X		XXX			X			X	
Geomorphology &Transport	XX		XX				XX	X	XX	XX	XX	X	X			X			X	
Surface Composition	X					XXX	X													

Table 3-2 Science Trace Matrix.

4. Enceladus Science and Payload

4.1 The Importance of Enceladus

Enceladus has captured the attention of planetary scientists since the early 1980s. Voyager revealed Enceladus' extraordinarily high albedo and its youthful and heavily modified surface, and around the same time ground-based observations demonstrated that the diffuse E-ring is concentrated at the orbit of Enceladus. The very short estimated lifetime of E-ring particles seemed to require a constant source of replenishment, perhaps Enceladus itself, and even 25 years ago there was speculation about geyser activity supplying the ring.

However it was a series of Cassini observations in 2005 that provided definitive proof that Enceladus is one of the very few solid bodies in the solar system that is currently geologically active. Multiple Cassini instruments detected plumes of gas and ice particles emanating from a series of warm fractures centered on the South Pole, dubbed the "tiger stripes". It seems likely that the plume is indeed the source of the E-ring, as well as the extensive neutral O and OH clouds that fill the middle Saturnian magnetosphere. Enceladus thus plays a pivotal role in the Saturnian system similar to Io's role in the Jovian system.

Enceladus also provides currently active examples of tidal heating, cryovolcanic processes, and tectonism, giving us a chance to understand phenomena that are likely to have been important throughout the outer solar system. More importantly, the plume source region on Enceladus provides a warm, chemically rich environment, perhaps including liquid water, which is an at least plausible site for complex organic chemistry and even biological processes. Best of all, fresh samples from this environment can be obtained and studied by simply flying past Enceladus and sampling its plume, allowing relatively easy investigation of Enceladus' interior and its biological potential. No other icy satellite, to our knowledge, offers this opportunity.

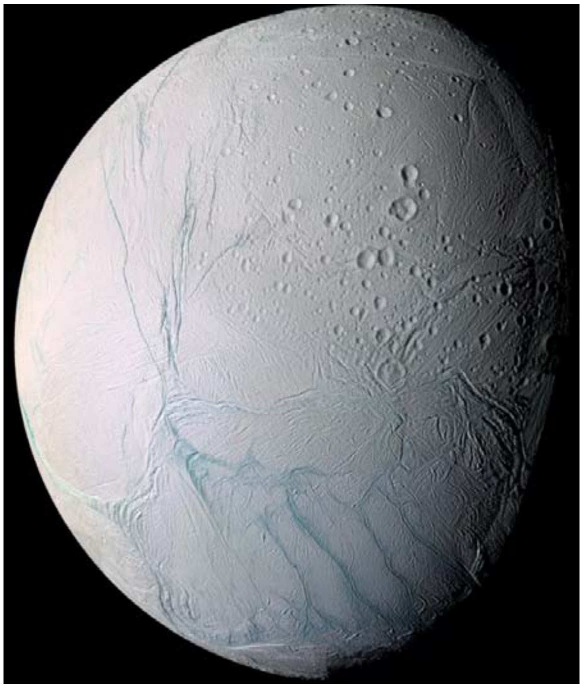

Figure 4-1 Global Cassini view of Enceladus (diameter 500 km). The active South Polar Region is ringed by a scalloped fracture zone and includes the four parallel "tiger stripe" fractures in its central region.

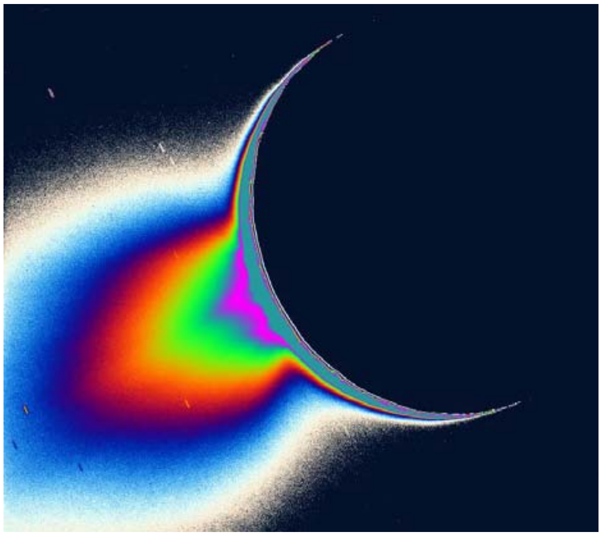

Figure 4-2 False-color image of the Enceladus south polar plume seen in forward-scattered light.

4.2 Enceladus Science Goals

This section describes the most compelling questions about Enceladus that one can hope to answer either with Cassini or with future missions.

4.2.1 Tidal Heating

It is almost certain that tidal dissipation, maintained at present by the 2:1 mean motion resonance with Dione, powers Enceladus' activity, but the details remain mysterious. Scientists do not yet know the site of the dissipation (silicate core, icy mantle, or near-surface fractures), its total magnitude (the Cassini observations provide only a lower limit), and whether dissipation is global or, as is suspected, is localized beneath the South Pole.

The time history of the dissipation is also unknown. Has it been continuous through Enceladus' history, or episodic? Because the dissipation is probably self-maintaining (a cold, rigid, Enceladus would have little dissipation and would stay cold, like Mimas), it is also not clear what initial heat source warmed Enceladus sufficiently to initiate tidal heating.

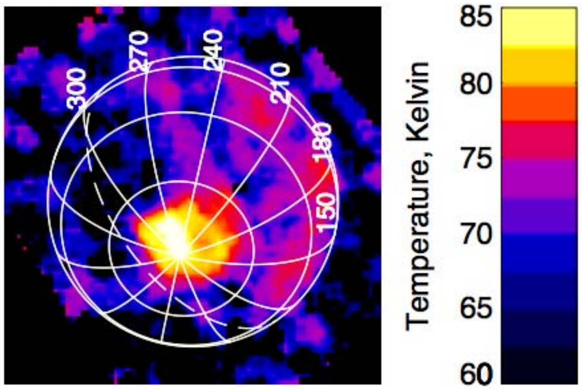

Figure 4-3 False-color image of 12-16 micron color temperatures on Enceladus, showing the heat radiation from the warm tiger stripes in the South Polar Region. Peak temperatures are much warmer, at least 145 K, than the low-resolution averages shown here.

4.2.2 Interior Structure

It seems likely that Enceladus is at least partially differentiated, but there is no direct evidence for this. Scientists also do not know the size and density of the presumed silicate core, the thickness of the rigid icy lithosphere, or whether there is a liquid water ocean, or more isolated bodies of liquid water. These questions are intimately related to the tidal heating mechanism.

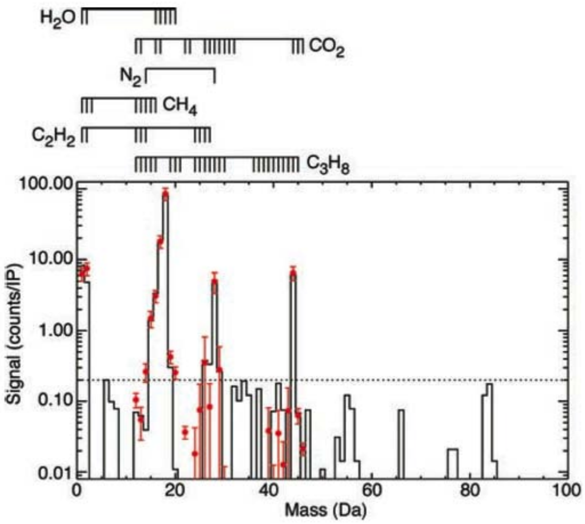

Figure 4-4 Mass spectrum of the Enceladus plume obtained by Cassini in July 2005, showing mass peaks due to H2O, CO2, N2, CH4, and possibly C2H2 and C3H8.

4.2.3 Composition

Enceladus' high density of 1.61 g cm^{-3} indicates a relatively high silicate/ice ratio, but the composition of the silicates or the details of the abundance and physical state of other volatiles in the ice fraction, or the degree of chemical processing that has occurred are unknown. It is possible that volatiles are stored in the form of clathrates, which would have implications for plume generation and internal temperatures (clathrates are highly insulating). Ammonia is an expected interior component and potentially potent anti-freeze, and its absence from the plume is a puzzle. The abundance and complexity of organic molecules is of great interest.

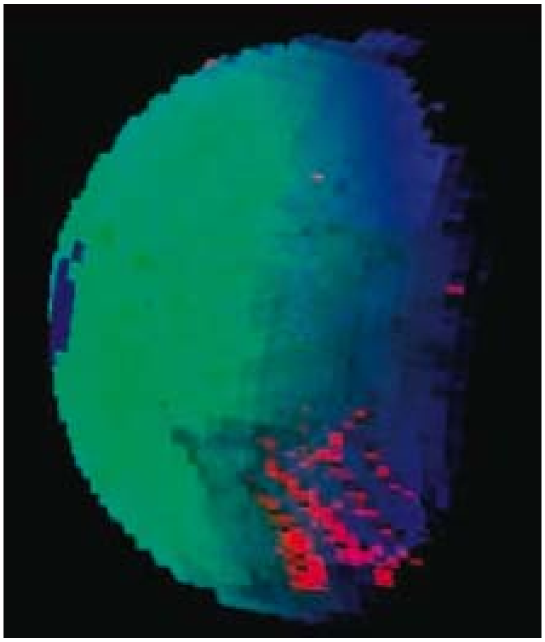

Figure 4-5 Near-infrared composite image of Enceladus showing the concentration of the 3.44 µm C-H stretch band (red) along the south polar tiger stripes.

4.2.4 Tectonism

The abundant tectonism evident on Enceladus' surface has many similarities to that seen on other icy satellites. It has not been determined whether the complex tectonic patterns we see are driven by convection in the ice mantle, possibly organized into plate tectonics-like processes, tidal or spin-related stresses, or some combination. For many features it is not even clear whether they are controlled by compressive, extensional, or shear stresses. The dramatic spatial variations in tectonic intensity are also a puzzle.

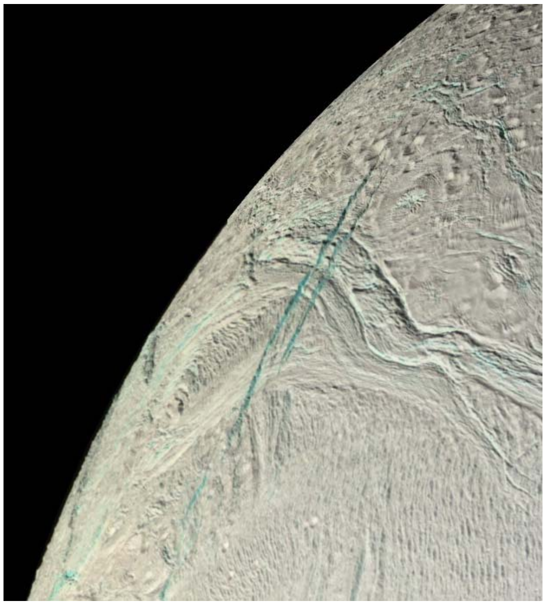

Figure 4-6 An example of the wide variety of terrain types on Enceladus, including intense tectonic modification. The area shown is about 150 km across.

4.2.5 Cryovolcanism

The origin of the spectacular plumes is one of the major mysteries of Enceladus. Sublimation of warm ice, boiling of liquid water, and decomposition of clathrates has all been proposed, and how the energy is continually supplied to the plume sources is not understood. The resurfacing rates due to plume particles and gas, and their spatial distribution, are unknown. Escape rates are also not well known- it is possible that escape fluxes are large enough to have had a significant effect on Enceladus' long-term chemical evolution. Scientists do not know the temporal variability of the plumes, whether low-level plume activity occurs in regions other than the south polar terrain, or whether extrusive and intrusive cryovolcanism occurs in addition to the obvious cryoclastic activity.

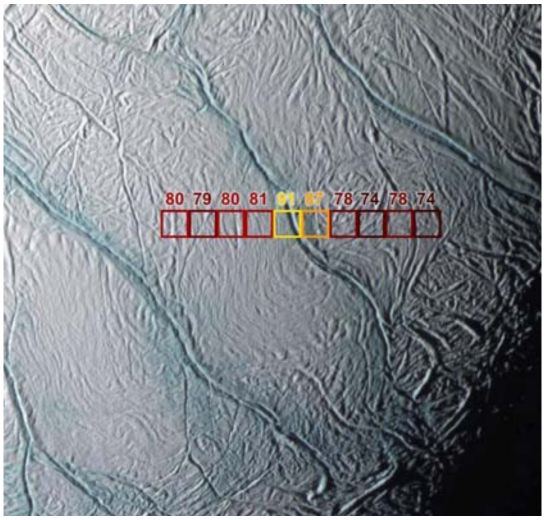

Figure 4-7 Close-up of the south polar "tiger stripe" fissures that are the probable source of the plume, showing their blue color due to large ice grain sizes, and their enhanced thermal emission. The numbers are brightness temperatures in K, averaged over each 6x6 km mid-IR field of view.

4.2.6 Surface Processes

Apart from the omnipresent water ice, little is known about the surface composition of Enceladus, and less about the photolytic, radiolytic, or other chemical processes that occur there. It has been proposed that surface chemistry could have a significant impact on the interior chemistry and perhaps even provide a significant energy source.

4.2.7 Biological Potential

Most intriguing of all is the biological potential of Enceladus. This depends critically on the presence of liquid water, its long-term persistence, its organic and inorganic chemistry, and the availability of chemical energy to power biochemistry, and is thus dependent on the answers to all the previous questions that have been asked. In the case of Enceladus, one may even hope to answer the question of whether life is present now.

4.3 Cassini Limitations

Cassini is well equipped to address many of these questions but is limited in several important respects. By the end of the extended mission (if approved) there will have been up to 12 flybys with ranges less than 3000 km, some perhaps as close as 25 km. However, the configuration of the spacecraft allows optimization each flyby for only a few measurement goals (e.g., gravity, in-situ plume sampling, or remote sensing) so we may, for instance, have only two gravity passes in the tour, insufficient to map local gravity anomalies. The lack of dust shielding may limit the spacecraft's ability to penetrate deeply into the plume while obtaining useful data, limiting our ability to investigate near-vent conditions that may reveal the plume source, and limiting sensitivity to potentially critical trace species in the plume.

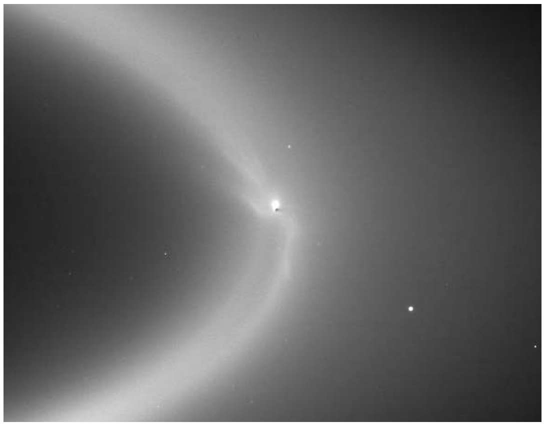

Figure 4-8 The complex interaction between Enceladus and the E-ring, seen at high phase angles by Cassini.

Cassini's instrumentation also has important limitations. The remote sensing instruments are not designed for rapid coverage of large areas during close flybys, allowing only "postage stamp" coverage at maximum resolution: wide-field push broom sensors would make better use of precious time near closest approach. The mass resolution and range of the mass spectrometers in the INMS and CDA instruments is insufficient to uniquely identify organic molecules that might be critical in determining the biological potential of Enceladus. Cassini also does not carry instrumentation, such as a ground-penetrating radar, that can provide detailed information about the subsurface structure, and presence of liquid water, near the plume source, and has no ability to directly measure tidal flexing, which would provide information on the possible presence of an ocean and the nature of the tidal heat source.

4.4 Rating and Down Selection of Mission Concepts

Despite these limitations, Cassini is a very capable mission for Enceladus science, and compelling follow-on missions must provide major advances over Cassini capabilities. The Enceladus SDT briefly considered multiple mission architectures as shown in the science traceability matrix (Table 4-1), and selected the two that seemed most likely to deliver worthwhile science within the cost cap for more detailed study.

The SDT evaluated the various mission concepts by assessing their ability to address the various science questions listed above. For each mission the team estimated whether it would provide a small, large, or very large increment in scientific understanding of each objective, beyond Cassini, as shown by color coding in Table 4-2. Then, each mission concept was assigned an overall numerical rating from 1 to 10, to reflect how well that mission would advance the overall knowledge of Enceladus. The overall rating differed slightly from the average rating in the various science categories, reflecting the fact that not all science goals are of comparable importance (for instance we considered an understanding of Enceladus' biological potential to be more important than understanding surface processes).

A single Enceladus flyby mission was considered and rejected: even with improved instrumentation compared to Cassini, the science return would be too small to be worthwhile. However, the Study team did determine costs for this very simple mission concept so its potential scientific value is briefly described in the next section. The team also considered passive or instrumented impactors as mission components and rejected these on scientific grounds: a passive impactor to produce a plume for analysis was thought to be of limited use given the presence of the natural plumes, and an instrumented impactor would provide only a few seconds of data at ranges closer than could be achieved with a flyby mission.

Mission components that were considered to be scientifically valuable, but almost certainly too expensive for this study, included hard landers (designed to survive impact), soft landers, and Enceladus orbiters. The team also briefly considered combined Titan/Enceladus missions, but it seemed likely that attempting to address the very different science goals for each target, while perhaps more cost-effective than sending a separate mission to both targets, would be unlikely to fit within the study cost cap. In addition, orbital tours designed to maximize both Titan and Enceladus flybys would produce fewer Enceladus flybys than Enceladus-only missions, reducing their scientific value for Enceladus.

The remaining missions that were chosen for more detailed study were an Enceladus sample return on a free-return trajectory to Earth, and a Saturn orbiter with multiple Enceladus flybys, and the single Enceladus flyby. For each of these missions a straw man payload was selected that the SDT believed was representative of the minimum necessary for a worthwhile mission.

Table 4-1 Science Trace Matrix.

Objective		Saturn Orbiter / Multiple Flybys								Sample Return						Single Flyby				
		Overall Score	Imager	Thermal Mapper	Magneto-meter	Doppler Gravity	Sounding Radar	Dust Analyzer	Gas Analyzer	Overall Score	Imager	Thermal Mapper	Dust Analyzer	Gas Analyzer	Sample Return	Overall Score	Imager	Thermal Mapper	Dust Analyzer	Gas Analyzer
Tidal Heating	Dissipation mechansim, spatial distribution, time variability	XXX	XX	XXX	X	X	XX			X	X	XX				X	X	XX		
Interior Structure	Size of core, thickness of lithosphere, presence of ocean	XXX	XX	X	XXX	XX	XX	X	X	X	X		X	X	X	X	X		X	X
Buik Composition	Compositon of interior	XX				X		X	XX	XXX			X	XX	XXX	X			X	XX
Tectonics	Lithospheric stresses, tectonic mechanisms	XX	XX	XX	X	X	X			X	X	X				X	X	X		
Cryovolcanism	Nature of plume source, resurfacing and escape rates, spatial distribution, other forms of cryovolcanism	XXX	XXX	XXX	X		XXX	XX	XX	XX	XX	XX	X	XX	XXX	XX	XX	XX	X	XX
Surface Processes	Photolytic or radiolytic chemistry, interaction with E-ring	X	X	X				X	X	X			X	X	x	X			X	X
Biological Potential	Presence and longevity of liquid water, chemistry, energy sources, presence of life	XX	X	XX	XX	X	XX	XX	XX	XXX		X	XX	XX	XXX	XX		X	XX	XX

Table 4-2 Relative science value of Enceladus missions**.**

Relative Science Value of Enceladus Missions: Increase in Understanding Beyond Cassini/Huygens

	Mission									
	Flagship Class TMC>$2B							Small Flagship Class $2B>TMC>$1B		NF Class TMC<$1 B
Science Objectives	Enceladus Orbiter + Lander	Enceladus Orbiter	Enceladus Lander	Saturn Orbiter + Enceladus SR	Saturn Orbiter; Titan/Enc Cycler	Fly-By S/C + Enc Inst Impactor	Fly-By S/C + Enc Hard Lander	Enceladus Sample Return	Saturn Orbiter w/Multiple Enc Fly-Bys	Single Enceladus Fly-By
Tidal Heating										
Interior Structure										
Bulk Composition										
Tectonics										
Cryovolcanism										
Surface Processes										
Biological Potential										
Relative Mission Science Value	10	9	7	8	6	4	6	7	7	3

Indicates missions chosen for costing

Code for rating of Science Objectives (relative to Cassini-Huygens)	Code for Overall Science Rating of Mission (1-10 relative to Cassini Huygens with 5 being sufficient)	
Very large increment beyond Cassin	1,2	fails by large margin
Large increment beyond Cassini-H	3,4	fails by small margin
Small increment beyond Cassini-H	5,6,7	succeeds by small marg
Redundant with Cassini-H	8,9	succeeds by large marg
	10	optimal solution

4.5 Enceladus Plume Sample Return

Enceladus provides the unique opportunity to obtain samples from the interior simply by flying past the moon and collecting plume particles or gas. It thus may provide the only opportunity, for the foreseeable future, to study the interior of an icy satellite using the full future capabilities of terrestrial laboratories. Plume samples may reveal much about conditions in the plume source region and the deeper interior (for instance, the presence of nitrogen rather than ammonia has recently been used to argue for high temperatures in Enceladus' interior), and would probably, for instance, allow determination of whether liquid water was present at the plume source. Characteristics such as stable element isotope ratios would provide valuable insights into the formation of Enceladus and the Saturn system as a whole.

Most intriguing, however, is the opportunity to investigate the biological potential of Enceladus at a level of detail impossible with *in situ* or remote sensing observations. Laboratory analysis of returned organic compounds would be able to determine organic signatures such as chirality that are difficult to measure *in situ* (at least, without entering Enceladus orbit to allow collection of gas samples at low speed). There is also the real possibility of returning biological structures entrained in the plume, should any exist: on Earth, thermophilic bacteria are found in Yellowstone geyser spray and plankton is found in terrestrial cirrus clouds after hurricanes.

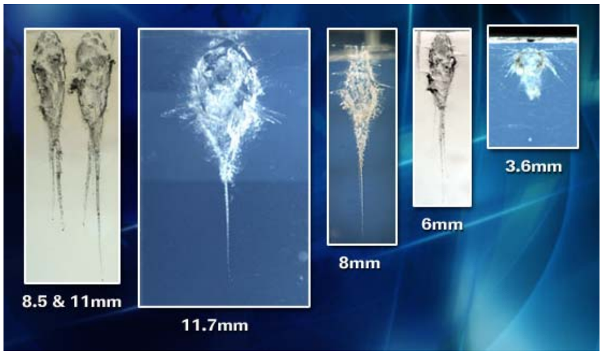

Figure 4-9 Tracks of comet grains captured in aerogel by the Stardust mission.

The potential of a sample return mission depends greatly on the degree of sample preservation that is possible both during capture and delivery back to Earth. Stardust successfully obtained samples from comet Wild-2 at 6.1 km/sec using aerogel, but Enceladus encounter speeds on a free-return trajectory may be as high as 14 km/sec, well beyond current aerogel capabilities, and round trip times may be greater than 18 years. It is not necessary to return ice grains themselves to Earth, but it would be important to bring back, and to be able to identify and analyze, intact organic molecules (or even any biological structures) that might be present within the ice grains at the time of capture. Tracks in the Stardust aerogel indicate that ice grains were captured intact by the aerogel and later sublimed, leaving behind their less volatile contents. Indeed, the Stardust aerogel contains species that would not have survived aerocapture unless protected within ice grains, providing some hope that icy Enceladus plume particles might similarly protect during capture any delicate molecules or other structures that they contained, and allow them to be returned to Earth.

This mission depends on the Enceladus plume being active during the single flyby of the moon. The fact that the plume seen by Cassini is derived from over 1 dozen sources spread over the ~130 km extent of the tiger stripes makes it unlikely that all or most sources would shut off in the next 20 years, unless there is some central control mechanism that operates on timescales less than a few decades, which seems unlikely. The E-ring, thought to consist of Enceladus plume particles, is known to be stable on several decade timescales and is thus likely to provide at least some samples even in the event of plume inactivity.

Return of gas samples, if feasible, would enhance science return, as some chemical species may be enhanced in the gas relative to the plume particles.

The Enceladus sample return mission concept includes some remote sensing (visible camera and thermal mapper) and in situ science (gas and dust analyzers) to improve understanding of the plume source, because the science risk for this mission was considered to be unacceptably high without some science return before delivery of samples back to Earth. These instruments are identical to those carried on the Saturn Orbiter / Multiple Enceladus Flyby mission concept (Section 4.6), and will be discussed in more detail there.

4.6 Saturn Orbiter with Multiple Enceladus Flybys

This mission concept is somewhat Cassini-like, with multiple Enceladus flybys from Saturn orbit, but carries greatly improved instrumentation compared to Cassini in order to make compelling advances in answering science questions. The concept also includes nearly 40 flybys, about three times as many as are currently planned by Cassini. It is likely that the spacecraft would require armoring with Stardust-like shields to allow flybys close to the plume source that might be considered too dangerous for Cassini. The minimum instrument complement includes the following:

- Push broom CCD imager with 3-4 colors in the visible and nearest IR, perhaps similar to MVIC on New Horizons. Such an instrument could cover a 200 x 35 km swath at 7 m/pixel from 300 km range on each flyby, greatly improving on Cassini's resolution and coverage over the course of the mission (Cassini has so far taken only a single image at comparable resolution, covering 2 x 2 km). This instrument would address many of our science goals, in particular the understanding of the plume source, cryovolcanism in general, and tectonics.

- Push broom thermal mapper covering the 8 – 20 micron wavelength range at two wavelengths, perhaps similar to THEMIS on Mars Odyssey. This instrument could cover a 200 x 30 km swath at 100 m/pixel per flyby, compared to Cassini's best resolution in the thermal IR, with extremely limited coverage, of about 1 km. Mapping thermal emission from the tiger stripes at this resolution will constrain the nature of the plume source, tidal heating mechanisms, and perhaps tectonic and other surface processes.

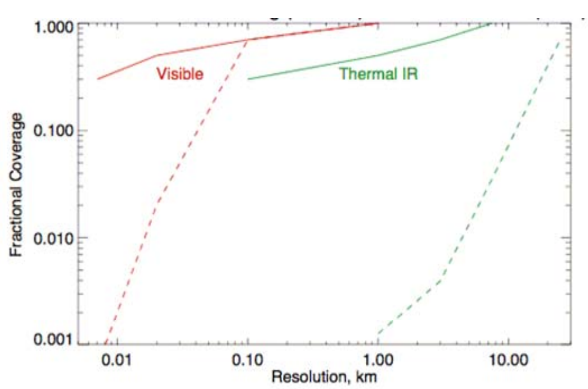

Figure 4-10 Comparison of resolution vs. Enceladus coverage expected for Cassini in the visible and thermal infrared through the end of the extended mission (dashed lines), to that possible with our proposed Saturn orbiter with multiple Enceladus flybys (solid lines). Major improvements in high-resolution coverage are possible.

- Sounding radar, comparable to that proposed for the original Europa orbiter in 1999. This would allow subsurface sounding of the plume source region and other areas on Enceladus, providing important information on the subsurface nature of the source region, the possible presence of liquid water, and the structure of the lithosphere that is inaccessible to Cassini.
- Mass spectrometer with much improved mass resolution and coverage compared to Cassini, covering masses up to 200 at resolution better than 1 AMU. This instrument would be sufficient to identify quite complex organic molecules in the plume gases. Increased sensitivity compared to Cassini would be possible thanks to multiple passes through the plume at closer range than may be safe with Cassini. Such a mass spectrometer has the potential to test for the presence of life on Enceladus: for instance enhanced concentrations of a small subset of organic molecules, compared to others that would be equally likely to be produced by abiotic processes, would be strong evidence for the presence of life.
- Dust analyzer capable of determining particle masses, velocities and compositions. The Cassini CDA instrument includes a mass spectrometer that can determine particle compositions, but tenfold improvement in mass resolution are now possible and would allow identification of organic molecules, or their fragments, from the vapor plume produced by a particle impact. The detailed composition of the ice particles is likely to reveal much about their source, including whether liquid water was involved in their production.
- Magnetometer similar or identical to that carried by Cassini, for magnetic sounding of Enceladus' interior. The advantage over Cassini here comes from the large number of flybys, many of which will have identical geometry except for ~1.5% amplitude changes in

the ambient Saturnian magnetic field due to the small rotational modulation of the field, and the additional similar-sized modulation due to changes in Enceladus' distance from Saturn as the orbit precesses (precessional period is 1.31 years compared to the 0.55 year duration of each planned campaign of similar-geometry flybys). This may allow detection of a subsurface ocean, as has been done for the icy Galilean satellites by Galileo.

- Doppler tracking for gravity measurements, using the main communications antenna. The large number of possible gravity passes will allow mapping of Enceladus's gravity field in considerable detail, providing information on the degree of differentiation and the structure of the lithosphere. For instance, the presence of a gravity anomaly at the South Pole would provide a test of the hypothesis that a low-density diapir or other mass anomaly caused reorientation of Enceladus to align the mass anomaly with the south rotation pole. Tidal flexing due to the precession of the orbit may also be measurable, constraining global interior structure.

Additional instruments would of course be desirable if resources permitted, particularly a near-IR spectrometer to map surface composition.

4.7 Single Enceladus Flyby: The Simplest Possible Mission

This mission concept would involve flying a low cost lightweight New Horizons-like spacecraft, with instrumentation optimized for Enceladus, on a trajectory that would provide a single close Enceladus flyby without entering Saturn orbit. The straw man payload is very similar to the Saturn orbiter described above, but without the magnetometer or Doppler tracking that, in a single flyby, would provide no advantage over Cassini, and without the radar sounder. A single pass through the plume near closest approach with an advanced mass spectrometer and dust instrument could provide valuable information on the organic chemistry of the plume source beyond what is possible with Cassini, but the information would be limited compared to the multiple passes possible with a Saturn orbiter. The single imaging and thermal mapping swath would also provide valuable information on the nature of the plume source region, with spatial resolution and coverage that would be a significant improvement over Cassini. The radar sounder is not included because though it might produce unique science on its single pass over the plume source region, science return would be very limited because only a very small region could be probed on a single flyby, and there would be no chance to fine-tune the investigation to optimize it for the completely unknown subsurface properties of Enceladus. Overall, the total science return, while not negligible, would be much less than either of the above missions, and was not considered to be scientifically compelling.

5. Mission Architecture Concepts

5.1 Overview

5.1.1 The Saturn System

Both Titan and Enceladus are parts of the Saturn system, so a brief overview of that system and its place in the solar system is useful. Saturn orbits the sun at an average distance of ~9.5 AU. Its orbit is somewhat more eccentric than Earth's so its heliocentric distance varies seasonally (over the course of a Saturn year, which is 29.46 terrestrial years) from 9.05 to 10.03 AU. Insolation over those distance extremes varies from 1/82 down to 1/101 of that at 1 AU, making solar electric power challenging at best.

Within the Saturn system Saturn's *obliquity*, the inclination of its equatorial plane to the plane of its heliocentric orbit is 26.73°, as shown in Figure 5-1. This results in large seasonal variations of a spacecraft's arrival geometry with respect to Saturn's equatorial plane, along with the variations in heliocentric distance. Over one Saturn "season" (1/4 of a Saturn year) an approaching spacecraft can see Saturn's equatorial plane anywhere from edge-on to open by ~30° or more.

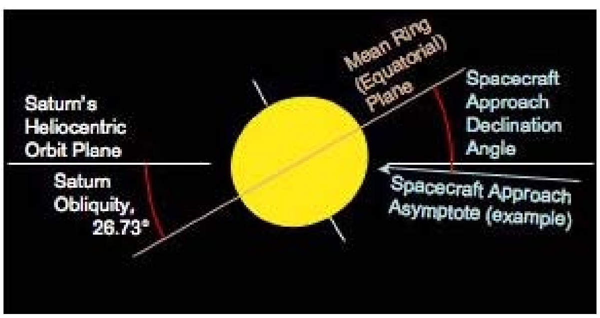

Figure 5-1 Saturn obliquity.

Also within the Saturn system is a large retinue of satellites, some associated with the spectacular and diverse ring system. All the rings and associated "ringmoons" have orbits that are aligned almost exactly with Saturn's equatorial plane. All the regular satellites from Titan inward are also closely aligned with the equatorial plane, though not as tightly as the rings, and have small but non-zero eccentricities. Table 5-1 gives mass, size, and orbit parameters for the four satellites pertinent to potential Titan and Enceladus missions: Titan and Enceladus themselves, and Dione and Rhea.

Table 5-1 Satellite characteristics.

	Enceladus	Dione	Rhea	Titan
GM, km^3/s^2	7.21	73.11	154.1	8978.2
Radius, km	252	562	764	2575
a, km	238040	377420	527020	1221870
e	0.0047	0.0022	0.0010	0.0288
i, deg	0.009	0.028	0.331	0.280
Period, days	1.370	2.737	4.518	15.95
V_{ORBIT}, km/s	12.62	10.03	8.48	5.57

Figure 5-2 is a polar-view illustration of the system's gross geometry, highlighting the locations of the four satellites' orbits. In that figure the main ring system, rings A, B, C, D, and F, are seen in the tan color relatively near Saturn. The E ring is roughly centered around Enceladus orbit. Cassini data suggest that Enceladus plumes are the source of material for the E ring.

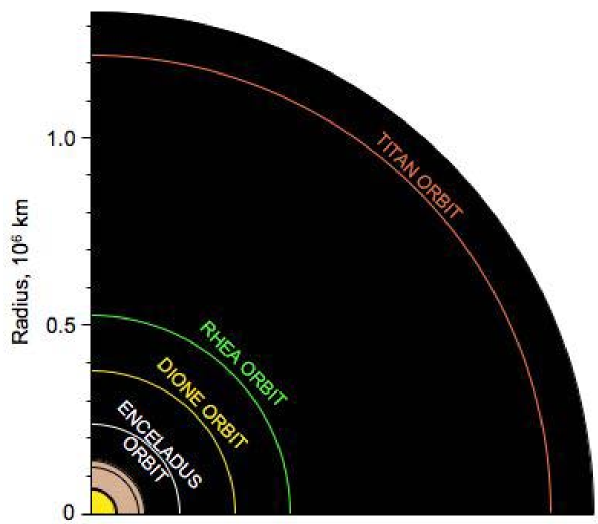

Figure 5-2 Satellite orbits in the Saturn system.

5.1.2 Architectures Studied

Clearly, detailed studies of a comprehensive set of science objectives for Titan and Enceladus, convolved with all possible mission architectures for addressing those objectives, greatly exceeds the scope of this study. The approach taken to reduce the task to a tractable level was to examine at a high level the range of appropriate architectures, rejecting those that were almost certain to exceed by far the $1B cost limit or to provide insufficient science return. This process yielded five mission concepts deemed most likely to provide worthwhile science while meeting the $1B cap. To those five were added two missions whose science was deemed insufficient but whose simplicity almost guaranteed meeting the cost cap. Table 5-2 below lists these seven mission concepts. They are discussed in much greater detail in Section 5.5 below.

Table 5-2 Summary of mission concepts studied.

Mission Concept Name	Mission Type	Science Acceptability
Titan Orbiter	Target body orbiter	Acceptable
Titan Aerobot	In situ balloon	Acceptable
Titan Lander	In situ lander	Acceptable
Titan Entry Probe	Atmospheric entry probe	Unacceptable
Enceladus Multiple Flyby	Saturn orbiter with Enceladus flybys	Acceptable
Enceladus Plume Sample Return	Sample return from single flyby	Acceptable
Enceladus Single Flyby	Simple flyby	Unacceptable

5.2 Travel to Saturn

Saturn's distant location in the sun's gravity well makes for high-energy and long-duration transfers from Earth. The two Voyager spacecraft demonstrated four-year transfers to Saturn using a Jupiter gravity assist (JGA), but only one of the mission concepts studied here, the Enceladus Single Flyby, could make use of a JGA. That concept's flight system is sufficiently low in mass that it could use a direct Earth-to-Jupiter trajectory, arriving at Jupiter while it is still in position for a gravity assist to Saturn. The other concepts require inner solar system gravity assists to reach Jupiter, which will have moved out of GA position by the time they arrived.

A survey of Earth-to-Saturn transfer trajectories from previous studies and from this study shows a wide range of trip times and payload capacities for a given launch vehicle. Figure 5-3 plots delivered mass vs. trip time for a variety of chemical propulsion and SEP trajectories, all using at least one inner solar system gravity assist. All but three use the performance figures of an Atlas V 531 launch vehicle for ease of comparisons among different trajectories, and the remaining three use an Atlas V 551 to show the mass capacity increase available from launch vehicle upgrades. The naming convention for these trajectories lists the first letter of planets encountered (including launch from Earth) in the order of encounter, so "EEJS" is a trajectory that launches from Earth, then performs an Earth gravity assist (EGA) flyby, then a JGA flyby, and finally arrives at Saturn. Number designations after the planet-encounter sequence refer to trajectories between successive Earth encounters. Designations of "2+" or "2-", for example, mean Earth-to-Earth transfers of slightly more than or slightly less than 2 years, respectively. The "2-3" designation indicates a 2-3 Earth-resonant, such that the spacecraft orbits the sun twice while Earth orbits three times; it can be quasi-resonant, i.e. not exactly 3 years to complete the transfer. SEP trajectories use Solar Electric Propulsion (SEP), while "Chem" trajectories use only conventional chemical rocket propulsion for maneuvers. Some chemical trajectories that encounter the same planet without a different planet in between require a relatively large (many hundreds of m/s to over a km/s) propulsive deep-space maneuver (DSM), with the concomitant decrease in delivered mass due to the mass of the large propulsion system for the DSMs. The EEES trajectories are good examples of this, each requiring *two* DSMs. Note that trajectories using a direct Earth-to-Jupiter leg are not included in this chart.

Figures 5-4 and 5-5 show example chemical and SEP transfer trajectories, respectively.

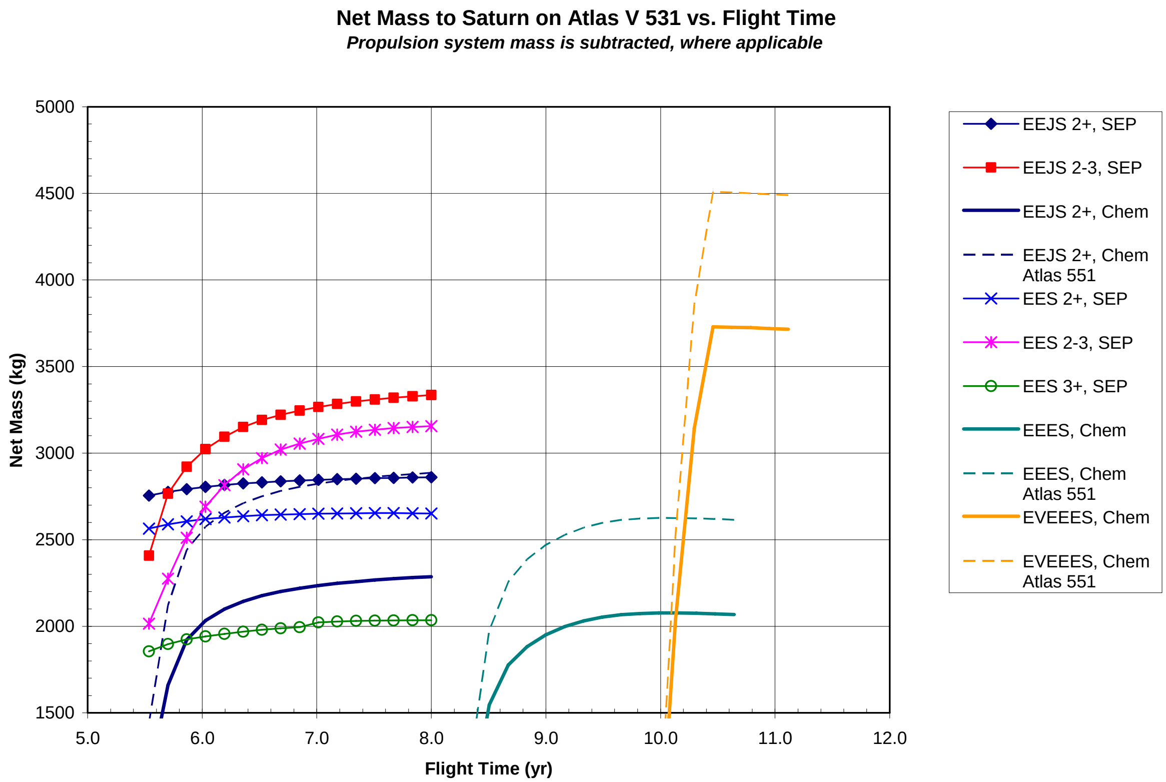

Figure 5-3 Mass delivered to Saturn approach and transfer time, parametric in trajectory type.

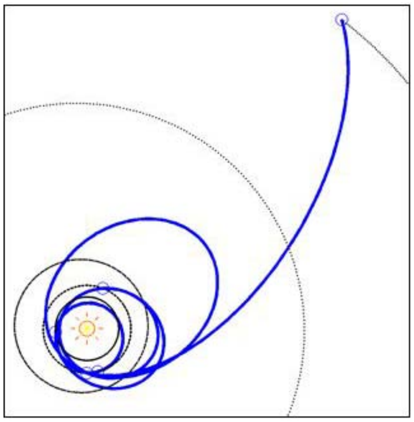

Figure 5-4 Example chemical trajectory to Saturn.

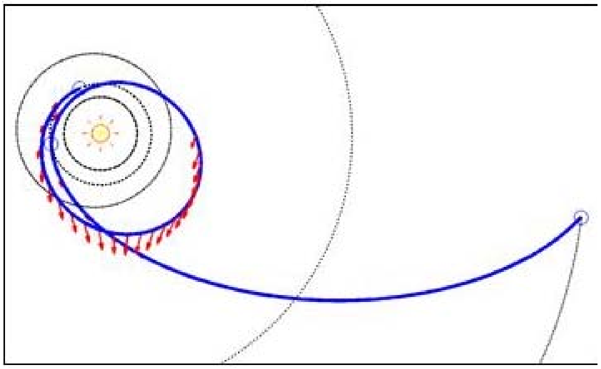

Figure 5-5 Example SEP trajectory to Saturn.

The chemical trajectory is the purely ballistic EVEEES from Figure 5-4, and the SEP one is an EES XIPS trajectory. Dotted curves in those figures represent, in order of increasing radius, the orbits of Venus, Earth, Mars, Jupiter, and Saturn. Red arrows in the SEP example show SEP thrusting directions.

5.3 Mission Option Trades

Most of these mission concept studies made specific choices regarding transfer and, where appropriate, orbit insertion. First, the use of SEP was assumed as a means to shorten trip time to Saturn while increasing delivered mass for a given launch vehicle, and to provide greater programmatic flexibility in the form of greater launch date flexibility. Orbit insertions, whether into Titan or Saturn orbit, use aerocapture in Titan's atmosphere, again to greatly increase mass delivered into orbit from a given launch vehicle.

Given the focus of this study on minimizing mission costs, these assumptions were tested by developing mission and flight vehicle designs that evaluated alternative approaches, using the Titan Orbiter mission as an example. For transfer trajectories the alternative to SEP would be a chemical transfer, in which the launch vehicle must impart to the flight system the energy needed to reach the location for the first DSM or non-Earth gravity assist, and thereafter gravity assists (and possibly additional DSMs) lead to the final ballistic transfer to the Saturn system. For shorter trip times studied (9 to 10 years) the transfer requires at least one DSM of roughly 1.5 km/s, and the flight system must provide this significant delta-V. Purely ballistic trajectories with good delivered mass characteristics were also identified, but involve trip times on the order of 10.5 to 11 years.

For orbit insertion propulsive capture is an alternative to aerocapture. Propulsive capture could potentially simplify spacecraft design by eliminating the packaging restrictions of the aeroshell and the complexity of aerocapture-associated hardware. However, the required delta-V for Titan capture is ~4 km/s or more, which would add a very large propulsion subsystem and *significant* propellant mass to the flight system.

Flight system designs were developed and costed for the four mission options as shown in Table 5-3. Flight system masses shown represent total mass at Titan approach, which was used to determine flight time and required launch vehicle. Flight system costs include the costs of all flight elements needed to carry out the mission.

Table 5-3 Mission Option Trade.

		Titan Orbit Insertion	
		Aerocapture	Propulsive Capture
Transfer Method	SEP	Mass at Titan Approach: 1970 kg Elements: SEP Stage, Orbiter, Aeroshell Flight System Cost: $488M Flight Time: 6 yr Launch Vehicle: Atlas 521	Mass at Titan Approach: 7350 kg Not practical within Launch Vehicle constraints
	Chemical	Mass at Titan Approach: 2185 kg Elements: Orbiter, Aeroshell Flight System Cost: $396M Flight Time: >9 yr Launch Vehicle: Atlas 531	Mass at Titan Approach: 7350 kg Not practical within Launch Vehicle constraints

The simplest conclusion drawn from this trade is that propulsive capture at Titan is not an option for this study, given the desire to avoid the most costly launch vehicles. The mass penalty incurred for the inclusion of the large propulsion system required places the flight system mass well beyond the range of the largest launch vehicles appropriate to this study.

The trade between SEP and chemical transfer options is certainly more open. The difference in flight system cost between the two transfer options is ~$92M. However, this difference is somewhat offset by the chemical option's 50% greater flight time to Titan, which incurs additional mission operations costs and mission risk. Additionally, the chemical option's upgraded propulsion capability for performing DSMs requires somewhat greater flight system mass and could drive the need for a more capable launch vehicle, incurring additional mission cost.

The team decided that for this study the benefits derived from a SEP-based mission architecture were sufficiently valuable that all scientifically justifiable mission concepts use the SEP option. Should any of these missions go forward, further trades are appropriate to refine and confirm this conclusion.

5.4 Aerocapture

Aerocapture is a means of capturing into a useful orbit at a target body, from a hyperbolic (non-captured) approach, using aerodynamic drag instead of rocket propulsion to reduce the spacecraft's energy for capture. Although the concept is fundamentally simple, implementing a practical aerocapture using a real atmosphere, with all its uncertainty and variability, is a complex and demanding task. Notably it has never had a flight demonstration, though such a demonstration might happen in the near future, as discussed below. Figure 5-6 illustrates at the simplest level the steps of the aerocapture process.

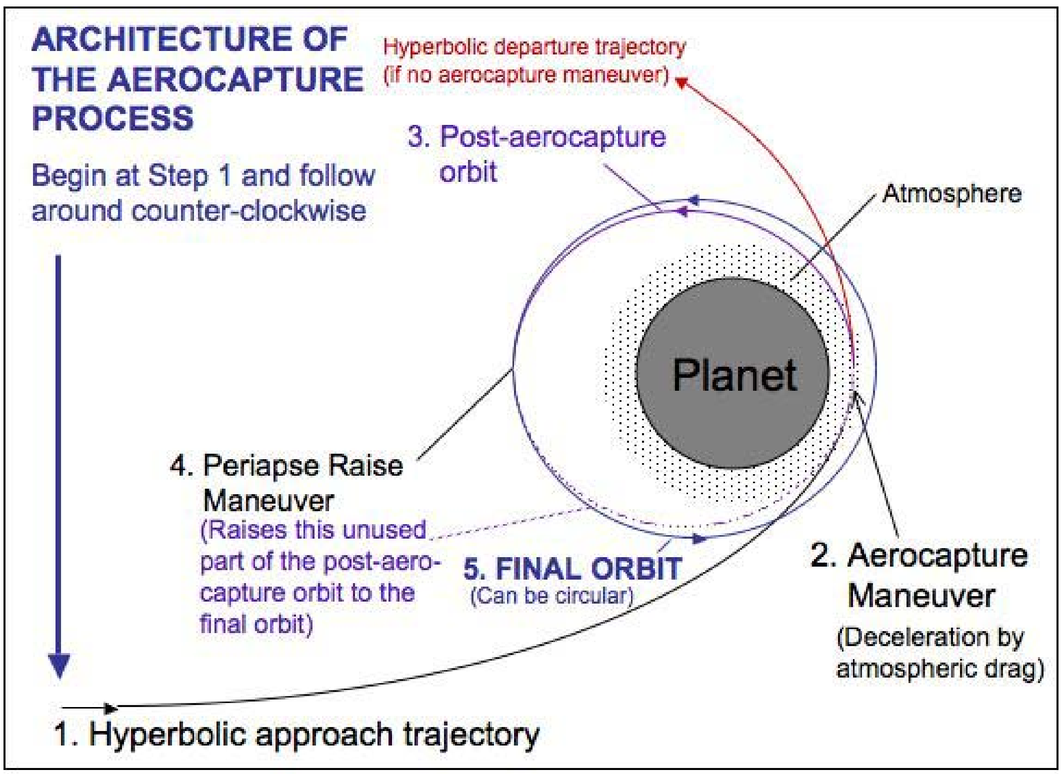

Figure 5-6 Fundamental architecture of the aerocapture process.

The process begins with Step 1 in the lower left of the figure with a spacecraft's hyperbolic approach to the target planet (or any body with a sufficiently dense atmosphere), navigated such that the spacecraft enters the planet's atmosphere. The navigation must be sufficiently accurate to prevent two problematic outcomes: 1) excessively deep penetration of the atmosphere, where the spacecraft encounters atmosphere so dense that is causes burn-up or complete, irretrievable entry into the atmosphere; and 2) excessively shallow penetration of the atmosphere, where it is not sufficiently dense to effect the speed reduction needed for capture.

Even given perfect navigation to the entry point, Step 2 of the process, the actual atmospheric flight of the spacecraft or "aerocapture maneuver", requires real-time navigation and flight path control. Real atmospheres never agree exactly with even the best of models, and are also subject to unpredictable variations with time. The flight system must measure the actual atmosphere encountered and reconstruct the flight path actually taken, adjust its flight path to encounter atmosphere within tolerances of the desired densities, and guide it to an exit from the atmosphere near the preplanned location and at the proper velocity. The same monitor-and-adjust approach handles entry navigation and delivery errors. This is not possible without on-board, real-time flight path measurement, orbit propagation and comparison to the desired result, and corrections that involve the aerodynamic equivalent of maneuver design and execution. Multiple methods for flight path control are in the aerocapture literature, but the method currently at the highest Technology Readiness Level (TRL) is the "rigid lifting body" method. This places the spacecraft within a rigid-body aeroshell with a significant lift coefficient, and control of the aeroshell's roll angle (and possibly attack angle) steers the system along the proper path.

One by-product of this high-speed (hypersonic) atmospheric flight is aerodynamic heating. The aeroshell must have a surface Thermal Protection System (TPS) to prevent damage to spacecraft components either by heat or aerodynamic forces. Over the course of an aerocapture maneuver, practical TPS materials become heat-soaked. If the heat absorbed is sufficiently large and the aeroshell is retained after atmospheric exit, heat propagating inward ("soak back") could heat the spacecraft to the point of failure. For this reason, some aerocapture maneuvers must be followed immediately by jettisoning the aeroshell to prevent this heat soak back.

Upon exit from the atmosphere the spacecraft is in an eccentric orbit whose periapse is within the atmosphere and whose apoapse is outside it, illustrated by Step 3 in Figure 5-6. This is a very temporary situation because reentry into dense regions of the atmosphere is undesirable. Upon reaching the first apoapse of this orbit a "periapse raise maneuver" (PRM), Step 4 in the figure, lifts periapse out of the atmosphere and establishes the final stable orbit, which can be eccentric or circular. Additional minor maneuvers might be needed to correct aerocapture maneuver errors such as apoapse altitude errors, or to modify the orbit for other purposes.

Although aerocapture might seem an unduly risky means for achieving delta-V, the mass savings it offers enables some missions. Orbit insertions using propulsive capture have been demonstrated many times in the past. However, the delta-V requirements for orbit insertion at some solar system destinations overtax current chemical rocket propulsion technology. As the delta-V needed from a chemical propulsion system grows, the propellant mass needed for that delta-V grows quasi-exponentially. However, detailed analyses by NASA's Aerocapture Systems Analysis Team (ASAT) indicate that the mass of an aerocapture system grows only quasi-linearly with delta-V required, so beyond some threshold delta-V an aerocapture system's mass would be lower than a propulsion system's mass. With current technologies that threshold is ~2 km/s. Delta-V for orbit insertion at Titan is 4 km/s or more, so the anticipated mass savings from using aerocapture is substantial, to the point that it enables the mission if the mission's launch vehicle is limited by cost to capabilities no greater than an Atlas V 551.

Use of aerocapture for a NASA science mission will come only after a system-level demonstration of the technology, most cost-effectively done at Earth. An Earth demonstration of aerocapture is expected to cost somewhere around $100M (in FY2006$). Such a demonstration has been proposed for flight before 2011 by the New Millennium Program's ST-9 technology demonstration mission. However, aerocapture competes with four other worthwhile technologies for that ST-9 flight slot, and its selection for that flight is by no means assured. If it is not selected, the next opportunity for an aerocapture demonstration is not well defined. For this reason the current study places an uncosted technology lien on the two mission concepts using aerocapture technology at Titan.

5.5 Mission Architectures

This section gives more detailed descriptions of the seven mission concepts discussed in the Titan and Enceladus science chapters, focusing on mission architectures. The five missions judged to have acceptable science returns are covered first, followed by the two with unacceptable science returns.

5.5.1 Titan Orbiter

The Titan Orbiter concept's science goals are to:

- Complete the global mapping of Titan begun by Cassini/Huygens, with multi-channel 2-μ infrared and SAR mapping at 100 m resolution
- In Titan's upper atmosphere measure *in situ* atmospheric composition and its spatial variation, with emphasis on complex organic synthesis, and the plasma environment
- Measure the magnetic field beneath Titan's ionosphere

The global mapping objectives require a spacecraft in a low, circular or near-circular, polar or near-polar orbit, while the atmospheric composition and magnetic field objectives require some time in an eccentric orbit whose periapse dips well below the minimum altitude for long-duration stability. Calculations based on Cassini/Huygens data suggest that the minimum altitude at Titan for a sustainable circular orbit is 1400-1500 km, consistent with the global mapping objectives. Drag make-up delta-V at that altitude would be a few m/s per year. However, the atmospheric composition and magnetic field measurements must be made at altitudes below 1000 km, not sustainable in a circular orbit.

To satisfy these requirements, and to enable a flight system of sufficiently low mass that it can be launched on an Atlas V launch vehicle, aerocapture is used for orbit insertion at Titan. Even for very eccentric orbits at Titan, periapse speeds are limited to ~2 km/s or less, 1.48 km/s for a circular orbit at 1500 km altitude. Typical hyperbolic approach speeds are 6 to 10 km/s, depending on transfer trajectory and arrival date, yielding periapse speeds from 6.4 to 10.2 km/s. Thus the delta-V needed for capture at Titan is greater than 4 km/s, firmly in the range where aerocapture is more mass efficient than chemical propulsion. Flight system design analysis for a propulsive capture architecture at Titan verified that the propulsion system's wet mass would be far greater than the orbiter's mass, so the integrated system's mass would be larger than the launch capability of an Atlas V 551.

Fortunately, Titan is the solar system's most aerocapture-friendly destination. Although entry speeds can be high they are within our experience at Earth, not like the horrendous entry speeds at the gas giant planets themselves. Also like Earth the atmosphere is mostly nitrogen, without troublesome abundances of other more problematic species. The primary non-nitrogen component of Titan's atmosphere is methane (CH4); Cassini/Huygens measured the methane abundance there at less than 2%, so radiative heating is not a serious issue for aeroshells at Titan. Titan's relatively low mass and thus low gravitational acceleration results in large atmospheric scale heights at all altitudes, decreasing the consequences of altitude errors. The net effect for flight systems is that aerocapture at Titan can be achieved with a current-technology, low lift-to-drag ratio (L/D) aeroshell. ASAT studies indicate an L/D of 0.2 is sufficient, with margin, for successful aerocapture at Titan. Many previous aeroshell geometries, including the Apollo Command Module and the MER entry aeroshells, demonstrated L/D at this level or greater. As soon as an Earth demonstration of aerocapture is achieved, the technology will be ready for Titan.

Aerocapture at Titan follows the classical example closely. Navigation to entry is tight but within demonstrated capabilities. The orbiter spacecraft handles all computations, and commands the attitude control RCS systems in the aeroshell. The vehicle descends to 2-300 km altitude during the 10 to 15 minute maneuver and jettisons the aeroshell upon exit. A 120 m/s maneuver roughly 2.5 hours later raises periapse to 1500 km altitude, where a much smaller maneuver completes the circularization. The Titan b-plane approach aspect ("clock angle") is chosen to yield a polar orbit for global mapping.

Classical aerocapture at Titan would deprive the atmospheric composition and magnetic measurements of their multiple deeper dips into the atmosphere, so a modification of the classical approach restores that capability. Instead of aerocapturing directly into the circular mapping orbit, the spacecraft aerocaptures into an initially eccentric orbit with apoapse altitude of ~4000 km. The PRM raises the periapse to an altitude less than 1500 km, but high enough to be consistent with spacecraft safety for an initial checkout period. After that checkout period periapse is decreased to less than 1000 km altitude, perhaps 800 or 900 km, to begin an aerobraking phase that also affords the compositional and magnetic measurements, as illustrated in Figure 5-7a. Aerobraking has been demonstrated successfully at Venus and is used regularly at Mars. At both those targets the atmospheric flight speeds are much greater than at Titan, so aerodynamic heating is much less an issue: single-pass delta-V of one or two m/s is no problem at all for the spacecraft. About 20 days of such aerobraking drops apoapse to ~1500 km, so a PRM then circularizes the orbit for mapping, illustrated in Figure 5-7b. The composition and magnetometry objectives are satisfied in that 20-day period.

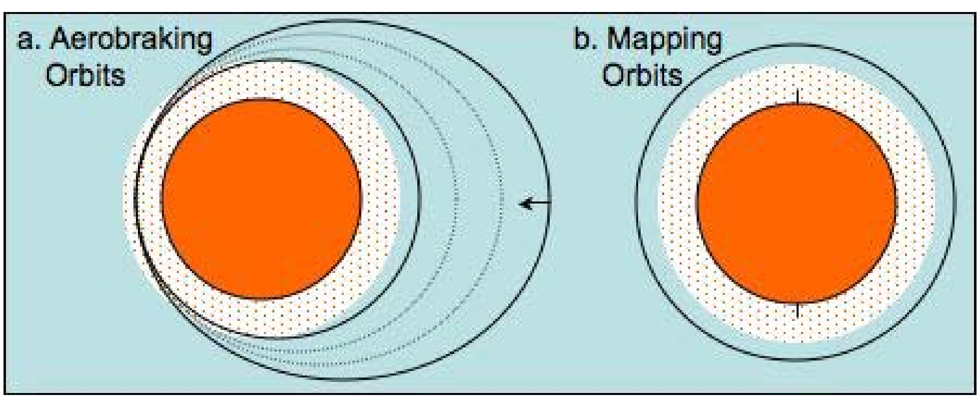

Figure 5-7 Science orbits for the Titan Orbiter mission concept.

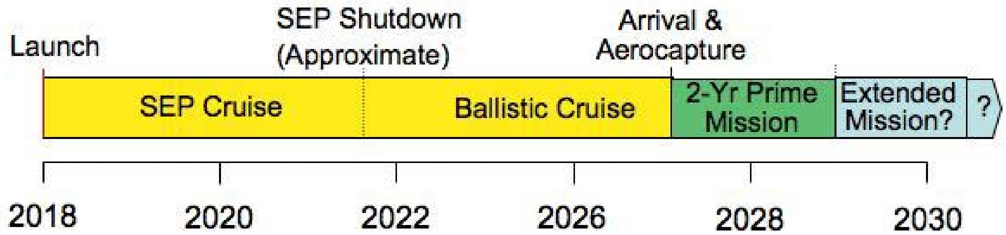

Figure 5-8 Example mission timeline for the Titan Orbiter mission concept. 2018 launch assumed.

After the aerobraking/*in situ* science phase is complete the mission settles into routine orbital mapping science operations for the remainder of the 2-year science mission. IR and SAR data are acquired and stored during ~2-hr mapping passes. Those data are downlinked to Earth via a Ka-band radio link at ~50 kbps (to a 34-m ground station). Most likely the downlink cannot be performed as a single transmission stream because Titan will occult the spacecraft for part of the orbit. However, the time equivalent of two 8-hour DSN passes is sufficient to downlink all data from one mapping pass. The project science team evaluates data as they are available and provides observational "tweaks", but does not engage in wholesale replanning of the operational strategy. This operational concept achieves global mapping, with all data on the ground, by the end of the 2-year prime mission. Figure 5-8 gives an example timeline for the mission, assuming launch in 2018.

5.5.2 Titan Aerobot

The Titan Aerobot concept's science goals are to:

- Spend a minimum of one terrestrial year drifting in Titan's tropospheric winds, accessing diverse locales.
- At areas of interest image at 1 m resolution and acquire subsurface radar data.
- Make atmospheric *in situ* compositional measurements without ground contact.
- Make frequent meteorological measurements.

Of course these objectives require placing a long-duration balloon, possibly a Montgolfiere design, into Titan's atmosphere. The Huygens entry and initial descent under a parachute is very similar to those events in the aerobot mission. The balloon would deploy at an altitude somewhat above its cruise altitude of ~10 km, while in a stable descent under the parachute. Unlike Huygens this mission would not insert into Saturn or Titan orbit before entry, but instead would enter directly, without first decelerating from the hyperbolic interplanetary trajectory. Thus no science data would be acquired until delivery into Titan's atmosphere. Fortunately, as discussed above, such entry at Titan is relatively benign and does not unduly challenge entry system and TPS technologies.

For cost reasons this mission concept's architecture does not include an accompanying orbiter, so the aerobot must communicate directly-to-Earth (DTE). Earlier studies show that for a given mission duration, this DTE architecture reduces the total data volume between one and two orders of magnitude when compared to a mission with an orbiter that serves as a data relay platform. For this study's aerobot mission concept the aerobot's DTE communications system uses a monopulse-steered HGA operating at X-band (atmospheric effects negate the normal advantages of Ka-band operation in a vacuum environment) to downlink ~2 kbps to a 70-m ground station. The link also provides navigation information as the aerobot drifts in Titan's atmosphere. This study assumed two 8-hr DSN passes per day when the aerobot is visible from Earth. Since Titan rotates with a period equal to its 15.95-day orbital period around Saturn, and the lower tropospheric winds are generally light, zonal (aligned with latitude lines), and prograde, the aerobot will spend almost half its time out of contact with Earth, and in the dark as well. Assuming the aerobot is placed in the hemisphere of Titan that is in summer at the time, during each Saturnian orbit it will be in contact, sunlit, and downlinking data somewhat longer than it will be out of contact and dark.

Once stabilized and checked out, the balloon's payload begins data acquisition, controlled via a combination of ground-generated guidelines (or commands) and autonomous operation. Once the payload has sensed that it is approaching an area of particular interest, latency prevents the ground ops team from being in the loop to initiate data acquisition activities, including altitude control. Instead, the science team will establish the guidelines for detecting areas of interest, and those will be uplinked to the aerobot. The aerobot will use the data it collects during normal quiescent cruise, comparing them to the guidelines and initiating specific activities when deemed appropriate. It also mines the data for those of highest priority, filling the downlink bandwidth with the highest-priority data. To make maximum use of the combination of the *in situ* aerobot and ground resources the science team evaluates data as they come down, providing quick-response updates to guidelines and commands when appropriate. Titan's atmosphere allows tremendous flexibility in targeting, so the entry site could be chosen to place the aerobot initially near a high-priority location identified from Cassini/Huygens data.

Unlike an orbital mission, the aerobot's flight path once at Titan is highly uncertain. It is at the mercy of Titan's winds that, though understood (to some extent) in principle, are not accurately predictable. On a global scale, below ~20 km altitude Titan has a largely – but not exclusively – zonal and prograde general flow with a superposed tidally induced flow, and with smaller topographically induced components and other minor effects. Some current General Circulation Model (GCM) results suggest that there can be local meriodonal components to the general flow and at some altitudes below 10 km the winds might be retrograde. The tidal flow is locked to Titan's orbit period and has both zonal and meridional components that oscillate, offset in phase, with the tidal forcing. The result is a general prograde zonal path over the ground that can wander meridionally to an unknown extent, modified by the tidal winds to a quasi-cycloidal appearance. Figure 5-9 *notionally* illustrates this complex motion; GCMs are not sufficiently accurate yet to make accurate predictions of the precise rate of net prograde motion, the range of long-period (if indeed they are periodic) meridional excursions, and the amplitude of the cycloidal excursions. The colored dotted lines in Figure 5-9 trace a series of example "orbits" by the aerobot, with red for the initial orbit, progressing through yellow to green, blue, and finally violet for subsequent orbits. Note that if the aerobot is a Montgolfiere or some other kind of balloon with at least some altitude control, using the altitude dependence of Titan's winds could afford some degree of flight path control.

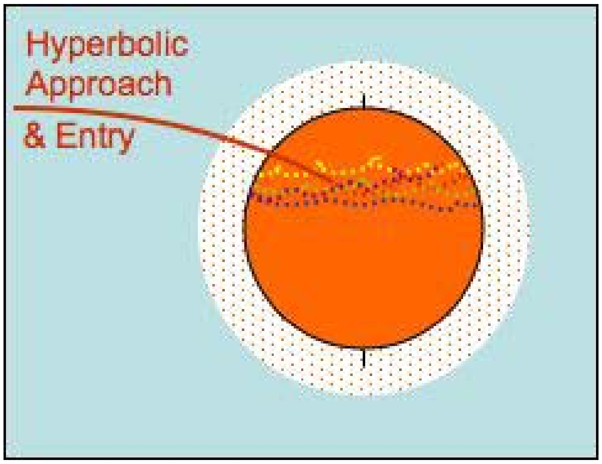

Figure 5-9 Notional Titan Aerobot atmospheric trajectory.

This uncertain aerobot trajectory precludes a deterministic, *i.e.* "routine", operations approach, and requires that at least a part of the science team be closely involved in mission operations. Science opportunities, in the form of specific locales the aerobot will over fly, in general will not be predictable until hours before the over flight, so the onboard autonomous systems must handle those. However, possible general areas of over flight, each containing multiple and possibly diverse specific locales identified from Cassini/Huygens data or by previous over flights, might be predicted up to a few days in advance. The science team would then generate or adapt the proper set of guidelines or commands for the area, and the ops team would translate and uplink updates to those already on board. Operations for such a mission are unavoidably more expensive than for a mapping orbiter with routine operations, and would be such for at least the duration of the prime mission. It would be possible (but not assured) that for an extended mission the operations could be simplified with a more "take what we get" approach. Preliminary analyses of Montgolfiere balloon life limiters at Titan suggest long expected lifetimes. At altitudes below 20 km the low level of ultraviolet light, low-speed winds, and absence of strong wind shear (and thus turbulence) lead to expected lifetimes dictated by the natural decay of a radioisotope heat source, not deterioration of the balloon envelope, as long as the balloon does not enter a strong convective cell, the equivalent of a terrestrial thunderstorm. It might be possible to entertain *decades* of extended mission if programmatics permit. Figure 5-10 gives an example mission timeline, assuming a 2018 launch.

5.5.3 Titan Lander

The Titan Lander concept's science goals are to:

- Characterize the landing area with survey and contextual multispectral imaging, and sampling of surface materials with compositional measurements
- Perform this characterization over a minimum 90-day period
- Follow the 90-day characterization period with 21 months of lower-level observations: seismic and meteorologic measurements, and imaging to detect any changes

This concept assumes delivery of the lander with a Huygens-like entry and descent under a parachute. As is the case for the Titan Aerobot entry site, Titan's atmosphere allows tremendous flexibility in targeting. The targeting decision would be based on a combination of science priority and survivability with the Huygens-like landing, established from Cassini/Huygens data. Also, as is the case for the Titan Aerobot entry, this mission would not insert into Saturn or Titan orbit before entry, but instead would enter directly, without first decelerating from the hyperbolic interplanetary trajectory.

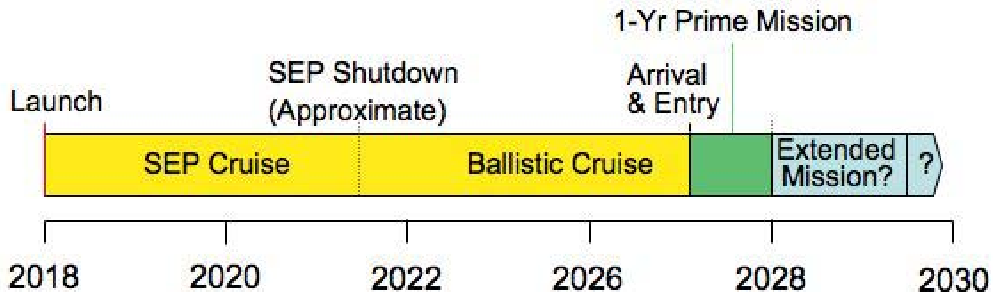

Figure 5-10 Example mission timeline for the Titan Orbiter mission concept. 2018 launch assumed.

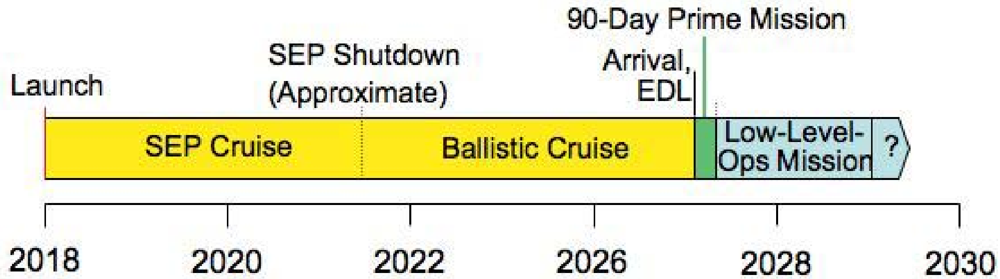

Figure 5-11 Example mission timeline for the Titan Lander mission concept. 2018 launch assumed.

Thus no science data would be acquired until delivery into Titan's atmosphere. This study did not consider roving capability because the science team considered the traverse range needed to provide a significant science benefit unachievable.

Once landed on Titan's surface the lander would perform typical fixed-lander operations. An initial general survey phase would be followed by more interactive operations, such as acquisition and documentation of surface samples and distribution of those samples to analysis instruments. After the initial survey the science team participates heavily in characterization-phase operations, guiding those science operations.

Like the Titan Aerobot concept, the Titan Lander has no associated orbiter asset to act as a data relay station. For this study the Titan Lander data communications parameters are essentially indistinguishable from those of the Titan Aerobot. All downlink is DTE, using a steered HGA operating at X-band to downlink ~2 kbps to a 70-m ground station, with two 8-hr DSN passes per day when the lander is visible from Earth. The same Titan-rotation considerations apply, except that the lander would not move with respect to the surface as the Aerobot would. The lander would use data priorities established on the ground to autonomously select data for downlink unless overridden by ground commands.

Following the characterization phase the mission enters 21 months of routine, low-level monitoring operations. Downlinks for this phase average one DSN pass every 8 days, modulated by Titan's rotation. There are opportunities of unknown duration for an extended mission. The duration of the prime mission necessitates a radioisotope power system that could provide sufficient power for decades. Most likely it would be a mechanical component such as an HGA gimbal that would limit the mission duration. Since the lander carries a radioisotope heat source to Titan's surface there are planetary protection requirements that must be met. Figure 5-11 gives an example mission timeline, assuming a 2018 launch.

Although various lunar and Mars missions have demonstrated long-duration surface operations they have not done so in a cryogenic environment such as Titan's. This study placed an uncosted technology lien on extended low-temperature operations.

5.5.4 *Enceladus Plume Sample Return*

The Enceladus Plume Sample Return concept's science goals are to:

- Return a sample from Enceladus's geyser (if that is indeed what they are) plumes with complex organic materials intact
- Make ancillary and contextual observations, such as imaging, during the flyby

The Apollo missions to the Moon, and the more recent Genesis and Stardust sample-return missions, have demonstrated the science power of sample analyses in laboratories on Earth. This study's science team recognizes the fact that if complex organic materials are found at Enceladus, especially if they indicate biological processes at work, the implications are astounding. Because this mission concept has the potential for such phenomenal science return, it attempts a very difficult feat – but it carries significant risk. There is a non-zero probability that the mission could be flown as designed and return without a single useful sample, or could fail even seconds before delivering the sample to Earth, reducing the science return to less than that of a much simpler single-flyby mission. Unlike the previously discussed Titan missions, all of which have their science instruments tucked inside an aeroshell until arrival at Titan, this mission concept has the potential for science observations and data return before arriving at Enceladus, but such operations were not costed for this study.

This mission concept represents a large departure from those previously discussed in that it must return the spacecraft to Earth after the trip out to Saturn. That transfer to Saturn is done with a SEP trajectory similar to those used by the others, so it takes more than 7 years from launch to arrival at Enceladus. However, this one is a "free-return" trajectory, meaning that after the Enceladus flyby it comes back into the inner solar system without a significant maneuver. A maneuver that would make any significant difference to the approach or return trajectories would be prohibitive due to the severe mass penalties incurred by such a large delta-V. It might be possible to bring it back to Earth directly from Saturn, but the physical lower limit on the entry speed for such a return is greater than 15 km/s, significantly more even than the Stardust return entry speed, the fastest Earth entry ever attempted. Since Enceladus has biological potential, sample return from there gets a high Planetary Protection classification, at least Class IV if not Class V, and approval to bring in a sample under unproven conditions is by no means assured. The most likely scenario is an inner solar system pump down tour, something like an inner solar system gravity assist trajectory to Saturn done in reverse. As discussed in Section 5.2 such a trajectory takes much time, at least 10 years. Both the outbound (Earth to Saturn) and inbound legs are probably lengthened by the free-return requirement, so the total mission duration is greater than 18 years and cannot be descoped.

In addition to Planetary Protection requirements on the sample return, probably there will be fairly stringent requirements for any spacecraft that might approach Enceladus.

There are significant engineering and technology ramifications to this approach to Enceladus exploration, in general spacecraft design and especially in sample acquisition. No solar system science mission has ever flown with a *required* mission duration more than ten years. Of course there are examples of missions that have lasted longer, but only in extended missions beyond their design lifetimes. Building a spacecraft to last more than 18 years will challenge current reliability engineering practices. The free-return trajectory also requires that the flyby speed at Enceladus, and hence the impact speeds of plume particles upon the capture apparatus, will be greater than 10 km/s, and likely much greater. The Stardust sample return capsule and its mechanisms provide a good paradigm for this study, but the sample deceleration system would not suffice to capture organic material intact at such speeds. An apparatus to achieve this truly challenging task is a technology development described by Peter Tsou as being of a magnitude similar to the development of the Stardust system. When that system was first conceived, the Stardust science team had almost no idea how to achieve intact capture of refractory materials at 6+ km/s. Although that has now been demonstrated, the leap to intact capture of organics is as great as the leap Stardust accomplished. Thus this study carries the development of that intact capture system as an uncosted technology lien. This study also assumes the availability of an appropriate sample curation facility that is not developed exclusively for this mission, so it is not costed as a part of this mission, nor as a lien.

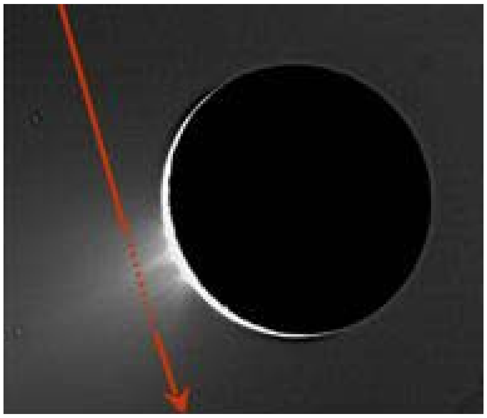

Figure 5-12 Notional Enceladus sampling pass geometry.

Operations for this mission concept are not particularly demanding except for duration. Activity levels are low for most of the outbound and inbound cruises, increasing for the SEP-powered portions and gravity-assist flybys. In the months leading up to the sampling pass there is significant navigation activity, including optical navigation. The sampling pass itself, including acquisition of all ancillary data, is only hours in duration, and flies directly through the south polar plumes at a relatively low altitude, on the order of 100 km, as illustrated in Figure 5-12. The flyby is at such a high relative speed that the trajectory deviates only slightly from a straight line.

Multiple downlinks of the complete ancillary data set require only a few days of one pass per day at ~4 kbps to a 34-m DSN station. During low-level operations the contact frequency reduces to one pass every 2 weeks. Figure 5-13 gives an example mission timeline for this concept, assuming a 2018 launch. Note that the time scale of Figure 5-13 is compressed with respect to those representing the other missions, to accommodate dates approaching 2038 at end of mission.

5.5.5 Saturn Orbiter with Enceladus Flybys

The Saturn Orbiter with Enceladus Flybys concept's science goals include:

- Global multispectral mapping at 10-m resolution
- Plume imaging and *in situ* sampling
- Gravity field measurements for degree of differentiation and internal mass distribution
- At least 30 Enceladus flybys

Among its many other science objectives, the Cassini/Huygens mission has used a large number of Titan flybys to study that object in detail. The Saturn Orbiter with Enceladus Flybys concept would use the same approach to study Enceladus in detail, without being burdened with other non-Enceladus science objectives.

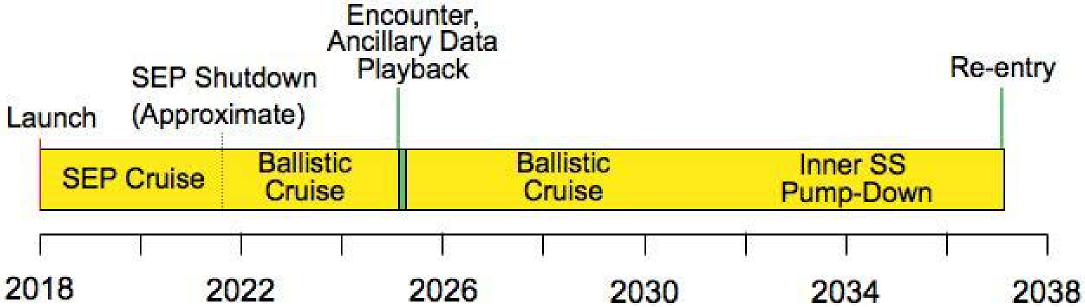

Figure 5-13 Example mission timeline for the Enceladus Plume Sample Return concept. 2018 launch assumed.

The lack of other science objectives and Enceladus's relatively small size allow detailed observation, far beyond what Cassini/Huygens can accomplish even in extended missions, in a science mission duration of only two years.

For this study the Enceladus-resonant orbit chosen has a period of 12.33 days and visits Enceladus once every revolution. Flyby V_∞ is about 4.2 km/s. Of course this is not the only option, but it is fairly easily established using Titan either as an aerocapture body or a gravity-assist engine. In about 200 days the spacecraft would encounter Enceladus 16 times, with brief science data acquisition periods up to a few hours each. As would be any of the Enceladus-resonant orbits, over a 200-day period this one encounters Enceladus at a Kronocentric solar longitude, and hence a solar phase angle, that varies less than 7°: the 16 passes all see the same side of tidally-locked Enceladus sunlit and can't see the other hemisphere in reflected sunlight. Since Enceladus's mass is so small the flyby trajectory deviates only slightly from a straight line, and thus the precise flyby geometry of each pass is not critical. The trajectory's "clock angle" as seen in the Enceladus b-plane can be adjusted at will, so it can be rotated around Enceladus as shown in Figure 5-14 to yield half-global coverage in ten or so passes, with the remainder of the 16 passes devoted to detailed coverage of particular locales of interest, including flying through the plumes.

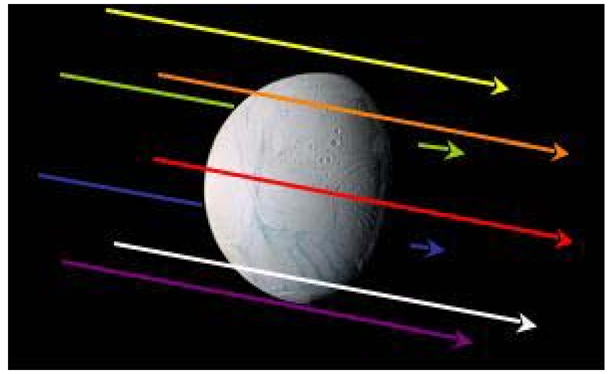

Figure 5-14 Multiple flybys of Enceladus from the resonant orbit.

After the first 200-day observation period orbital maneuvering is needed to see Enceladus on the other side of its Saturnian orbit so the other hemisphere is sunlit. The orbit is designed such that after the initial 200-day period the spacecraft encounters Titan, which it had avoided so far after the aerocapture maneuver, to begin a few-month tour of Titan flybys to rotate the resonant orbit's line of apsides by ~180°. This moves the Enceladus encounters by ~180° in solar phase angle as needed. Following that, another 200-day campaign of Enceladus flybys every 12.33 days completes the prime mission, with a total of 32 Enceladus flybys. Like Cassini the spacecraft would be expected to be in operating order after the prime mission so an extended mission is possible, and might even target one or two of the other interior icy moons such as Dione or Rhea.

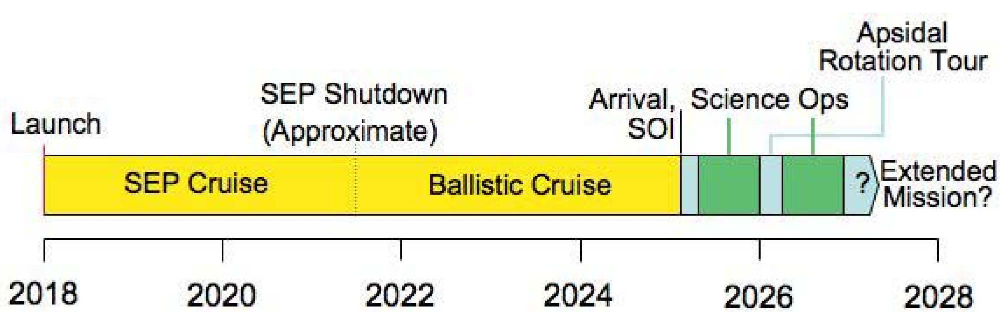

Figure 5-15 Example mission timeline for the Saturn Orbiter with Enceladus Fly-bys concept. 2018 launch assumed.

The typical science orbit divides activities into the brief Enceladus flybys for data acquisition and the remainder for data downlink to Earth orbit maneuvering. Data are downlinked at ~50 kbps via a Ka-band link to a 34-m DSN station, one 8-hour pass per day during the two 200-day campaigns.

Orbital maneuvering steers the spacecraft to the flyby geometry desired for the next flyby, and involves significant navigation activities. The science team uses its data to guide updates for science operations, such as instrument and spacecraft targeting, later in the mission. In normal operations this does not involve quick-response updates. Operations during the tour to adjust the line of apsides would be at a level similar to the non-encounter parts of the science campaigns due to the Titan flybys and associated Trajectory correction maneuvers (TCMs). Figure 5-15 gives an example mission timeline, assuming launch in 2018.

5.5.6 Titan Entry Probe

Note that this mission concept is one of two whose science objectives were deemed by the study science team to be <u>grossly insufficient to justify a $1B cost</u>. The Titan Entry Probe concept's science goals include:

- Composition of the atmosphere and its hazes, clouds, and other particulates
- Atmospheric structure (temperature and pressure as a function of altitude), winds
- Surface imaging

This mission concept involves flying an atmospheric entry probe, in principle very similar to the Huygens Probe, into Titan's atmosphere, with the goal of providing a Huygens-like data set at a different location on Titan. Unlike Huygens this probe enters Titan's atmosphere directly from approach from the hyperbolic interplanetary trajectory. Its Carrier/Relay Spacecraft (CRSC) is capable of independent operation (just barely) and does not perform any kind of orbit insertion maneuver, either at Titan or at Saturn, nor does it carry science instruments. After targeting the probe's entry and releasing it, the CRSC flies by Titan during the probe's mission to provide probe data relay to Earth.

Unlike mission concepts previously discussed this one does not use a SEP system to reach the Saturn system. This flight system would be smaller in mass than those others, so instead it uses a trajectory based on inner solar system gravity assists and chemical propulsion. The EVEEES used for this mission concept is an 11-year transfer from a launch in 2018. The flight system mass is not small enough to allow launching directly on an Atlas V vehicle from Earth to Jupiter in 2016 for a direct JGA to Saturn, as the Enceladus Single Flyby (see below) does.

This probe's mission is very Huygens-like but is implemented as a build from scratch. It performs a single, longer-duration descent to the surface, without the transition to a smaller parachute Huygens performed to limit its descent duration. Landing survival is not required. The project uses Cassini/Huygens data to select the entry site; as mentioned in previous discussions Titan's "soft" atmosphere provides significant flexibility in targeting. Once the probe separates from the CRSC the ground is out of the data acquisition sequence loop, with all sequences pre-generated and stored on board the probe. The descending probe sends data via an LGA at a few kbps to the CRSC for storage and later playback to Earth, as illustrated in Figure 5-16. Playback uses a Ka-band link to a 34-m DSN station at ~4 kbps. A single full playback takes about two 8-hr DSN passes. Multiple playbacks are scheduled until all the data are confirmed on the ground. Figure 5-17 gives an example mission timeline for the Titan Entry Probe mission concept, assuming launch in 2018. There is no option for an extended mission with this concept.

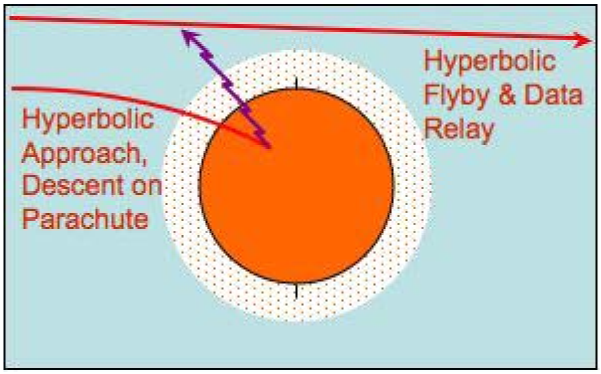

Figure 5-16 Entry and data relay strategy for the Titan Entry Probe mission concept.

5.5.7 Enceladus Single Flyby

Note that this mission concept is the other of two whose science objectives were deemed by the study science team to be grossly insufficient to justify a $1B cost. The Enceladus Single Flyby concept's science goals include:

- Multispectral mapping at 10-m resolution of the sunlit portion of the globe
- High-resolution multispectral mapping of high-priority locales
- Global mapping at thermal-IR wavelengths
- Plume imaging and *in situ* sampling
- Payload optimized for Enceladus observations

This mission concept is viewed as a New-Horizons-like single flyby of Enceladus. Unlike Pluto, there are abundant Cassini data on Enceladus, including *in situ* sampling of the plumes and a large suite of observation types from distances a low as ~100 km. Thus flying the exact New Horizons payload to Enceladus does not provide the high-value science that payload provides at Pluto, and the payload must be updated to address Enceladus science objectives. Despite such an update, the science return for this concept was deemed obviously insufficient for a $1B cost.

One of this concept's best features is a very low flight system mass, sufficiently low to allow using a direct JGA to Saturn without SEP. That JGA trajectory launches in 2016, not unrealistic for a 2008 New Frontiers AO, and arrives at Saturn between 3 and 4 years later, with no inner solar system gravity assists, no deep-space maneuvers, and no orbit insertions. The flight system would not be a New Horizons build-to-print (it is far too late for that) but would be a scratch-build under circumstances similar to those for New Horizons.

Operations would be similar to those for New Horizons except that the mission duration is much shorter and no hibernation periods were assumed. At the Enceladus flyby there would be a single brief (hours) science data acquisition period with data stored on board, preceded by almost a year of navigation activities to steer to a fly-through of the plumes. The flyby geometry would be similar to that shown in the discussion of the Enceladus Plume Sample Return mission concept, Figure 5-12, but the flyby speed would be considerably slower.

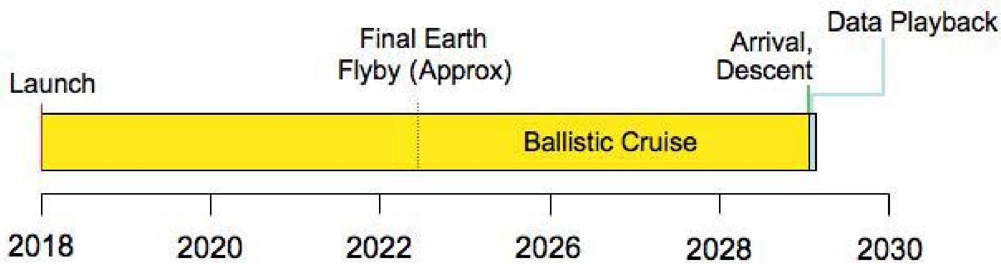

Figure 5-17 Example mission timeline for the Titan Entry Probe mission concept. 2018 launch assumed.

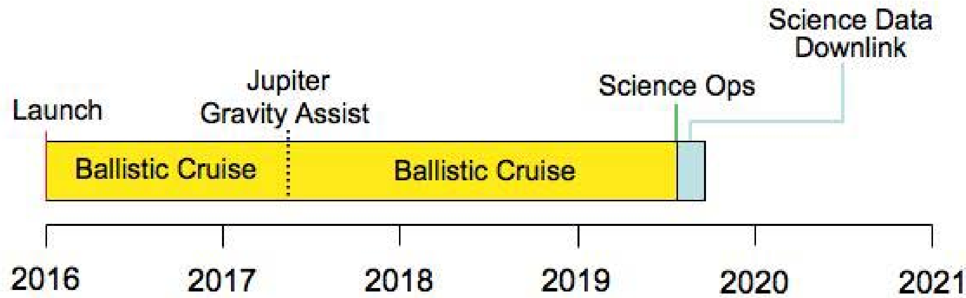

Figure 5-18 Example mission timeline for the Enceladus Single Flyby mission concept. 2016 launch to a direct JGA trajectory assumed.

Afterward the data would be played back to Earth via a Ka-band link to a 34-m DSN at a few kbps, one pass per day until all data are confirmed on the ground. Figure 5-18 gives an example mission timeline for the Enceladus Single Flyby mission concept, assuming a 2016 launch.

6. Flight System Concepts

6.1 Overview

Seven mission concepts were chosen from a broader mission set for detailed cost evaluation. Five of these were considered to have significant science return, while two others were judged not to be scientifically valuable, but were thought to potentially provide a lower limit on achievable mission cost.

The constraints of the study limited the amount of detailed analysis that could be performed to develop flight system designs for the missions under consideration. However, in the case of Titan, and to a lesser extent Enceladus, a rich body of studies exists from which representative designs could be extrapolated. None of the flight elements or techniques baselined in the mission architectures is unique to this study. The three main elements of the architectures, SEP stage, orbiters, and aerobot/landers, have been the subject of numerous recent investigations, in varying degrees of detail. The references used for input into the flight system designs are shown in Table 6-1. Concepts developed in these references were evaluated for applicability, and then modified to the extent possible to derive the lowest cost flight system that would be supportive of mission goals.

6.2 SEP Stage Design

The conceptual design for the SEP stage used for this study was taken from a detailed description and Master Equipment List (MEL) developed in the 2003 Titan Aerocapture mission study. The design was evaluated and found to be sound and applicable with the exception of the electric propulsion subsystem (EPS), which was based on conceptual designs available at the time the study was performed. To update this subsystem, members of JPL's electric propulsion staff developed an alternative EPS design, guided by lessons learned from the current DAWN EPS development. This updated design makes use of components with proven operational heritage to minimize cost and risk. Overall, this approach resulted in a somewhat higher mass for some components (e.g., Xenon tankage is based on use of multiple units of an existing qualified tank design rather than assuming qualification of a single new tank), but should return a benefit in a lower overall system cost and an avoidance of many of the qualification issues associated with custom designs. The original SEP MEL was updated with the new subsystem component masses, and other subsystems adjusted accordingly.

The SEP stage concept is shown in Figure 6-1. In the case of the orbiter missions it is intended to operate as a simple propulsion stage, with all non-propulsion spacecraft functions provided by subsystems on the payload vehicle. The EPS consists of five ion thrusters, a maximum of four of which would be used at any time, with one thruster provided as a spare. Power is supplied to the EPS by four solar arrays providing a total of 24 kW at 1 AU.

Table 6-1: Design References.

Study	Elements Included in Study
Titan aerocapture study (2003)	SEP, orbiter & unspecified lander
Titan Vision Mission Study (2005)	SEP, direct entry aerobot only
TiPEx Study (2006)	SEP, orbiter & Montgolfiere
Team X Titan Orbiter Study (2006)	SEP, orbiter
Team X Enceladus Studies (2006)	SEP and ballistic trajectories, aerocapture and propulsive capture, orbiter & lander
Europa Explorer Study (2006)	Orbiter

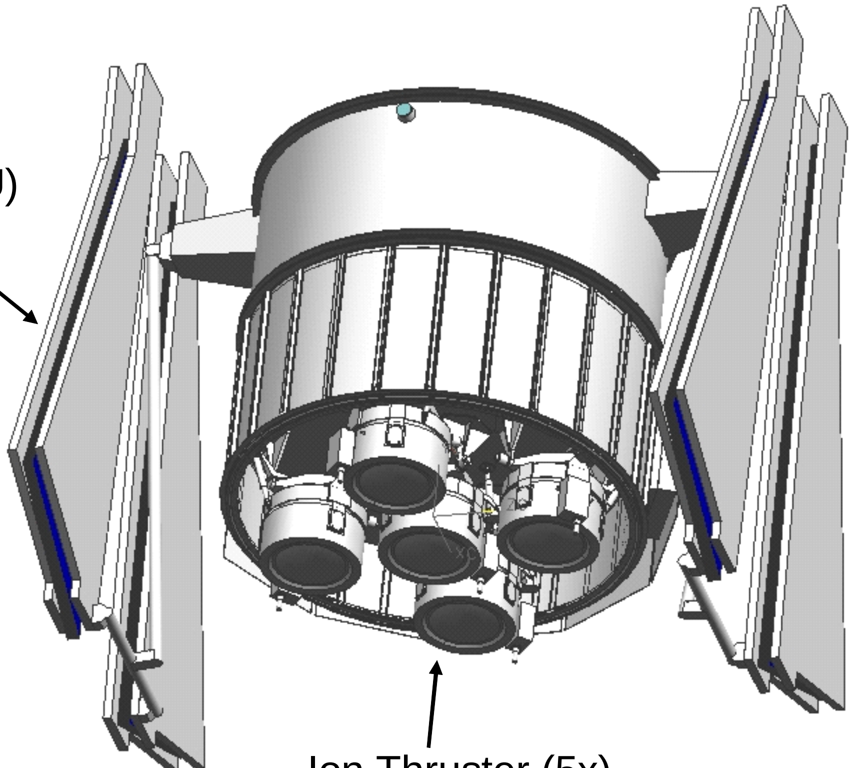

Figure 6-1 Solar Electric Propulsion Stage Design Concept Configuration.

The SEP stage would be operated to a solar range of about 2 AU, and would accommodate reduced power both by throttling and by reducing the number of active thrusters. For the orbiter missions the SEP stage would be jettisoned after its thrust period is completed.

For the aerobot and lander mission concepts a modification to the SEP stage is made to include a monopropellant Hydrazine reaction control subsystem (RCS). Unlike the orbiter and sample return missions, the aerobot and lander do not require an onboard propulsion subsystem to perform their missions. Normally, such missions would include a "cruise stage" that would provide this and other spacecraft functions during the transfer to the target body. For the aerobot and lander missions it is assumed that the SEP stage will be retained for the entire transfer portion of the mission, providing the functions of a traditional cruise stage, including attitude control with the addition of the RCS.

Master Equipment Lists for the two SEP stage variants are shown in Table 6-2. Note that Xenon mass is not included in these MELs, since it is variable with each mission concept. Xenon mass is included in the MELs for each concept's flight system presented in later sections

The MELs shown in this report represent subsystem masses used in the parametric cost models as part of the input used to estimate flight system element cost. MELs list subsystem current best estimate (CBE) masses, and apply a contingency to each subsystem according to the level of maturity of its components and design. An additional "system margin" is added to the overall dry mass of the element to bring the overall dry mass contingency to 43% in keeping with JPL design principles.

Table 6-2 SEP Stage MELs.

SEP Stage

	CBE Mass (kg)	Cont. (%)	Total Mass (kg)
Instruments (0)	0.0	30%	0.0
C&DH	1.7	29%	2.2
Power	148.3	30%	192.8
Telecom	0.2	33%	0.2
Structures	254.2	30%	330.5
Thermal	46.1	28%	59.2
Propulsion	237.7	12%	266.9
GN&C	4.0	30%	5.2
Cabling	40.0	30%	52.0
Stage Dry Mass Total	732.2	24%	909.0
System Margin			138.0
FS Dry Mass Total	732.2	43%	1047.0
RCS Propellant			0.0
Wet Mass Total	732.2		1047.0

SEP/Cruise Stage

	CBE Mass (kg)	Cont. (%)	Total Mass (kg)
Instruments (0)	0.0	30%	0.0
C&DH	1.7	29%	2.2
Power	148.3	30%	192.8
Telecom	0.2	33%	0.2
Structures	254.2	30%	330.5
Thermal	46.1	28%	59.2
Propulsion	266.5	14%	304.4
GN&C	4.0	30%	5.2
Cabling	40.0	30%	52.0
Stage Dry Mass Total	761.0	24%	946.5
System Margin			141.7
FS Dry Mass Total	761.0	43%	1088.2
RCS Propellant			100.0
Wet Mass Total	861.0		1188.2

6.3 Titan Orbiter

The Titan Orbiter flight system derives from a JPL Team X design performed in September of 2006 in support of the Titan Prebiotic Explorer (TiPEx) flagship mission study. This study focused on a synergistic architecture including both an orbiter and an aerobot. The orbiter was used for global mapping of Titan and, equally importantly, as a high capacity data relay between the aerobot and earth. The TiPEx orbiter was baselined with SEP and aerocapture, similar the current feasibility study concepts. Since arguably the most unique aspect of the design of this flight system derives from the need to package the orbiter inside an aeroshell during cruise, it was felt that the conceptual design developed in this Team X study would be an excellent basis from which to derive our more modest Titan Orbiter design.

6.3.1 TiPEx Orbiter Design

The spacecraft bus contains all the subsystems needed to control the orbiter during launch, cruise and science operations. Additionally, the orbiter provides control to the SEP stage and mission element stack during powered flight. The configuration of the orbiter is driven by its need to be packaged in an aeroshell for protection during the aerocapture event. The stowed configuration is shown in Figure 6-2.

The TiPEx study assumed the use of a 5-m launch fairing, which provides for a maximum aeroshell diameter of 4.57m. Trades performed on the telecommunications system resulted in the choice of a 4-m X/Ka band high gain antenna for science data return. Coupling this dish with a 100 W Ka-band TWTA allows data rates of about 200 kbps to a DSN 34m ground station.

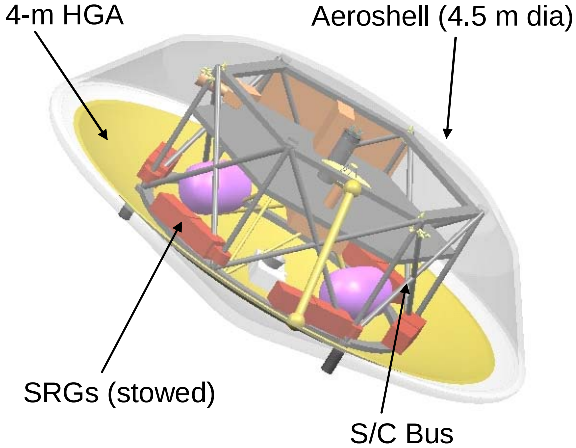

Figure 6-2 Orbiter Stowed Configuration – Design Concept.

The packaging of this large dish in the aeroshell required that the HGA be mounted within the curved heatshield section during cruise. Other massive components of the orbiter are mounted low on the spacecraft bus structure to ensure a favorable center of mass for the aerocapture event. Power would be provided to the orbiter by five Stirling Radioisotope Generators (SRGs) which would be tucked into the spacecraft bus structure during cruise and cooled by an active thermal transport loop, rejecting waste heat through the remote radiators mounted external to the aeroshell structure as illustrated in Figure 6-3. The efficiency of SRGs makes them particularly attractive for this application since heat rejection requirements for the encapsulated cruise portion of the flight are minimized.

The deployed configuration of the orbiter is shown in Figure 6-4. Major deployments include the HGA on its articulated boom and the synthetic aperture radar (SAR) antenna. The baseline design included rotation of each of the SRGs out and away from the bus as shown to accommodate heat rejection requirements. The orbiter would fly with the science deck oriented in the nadir direction, using the articulated HGA to maintain the data link with Earth.

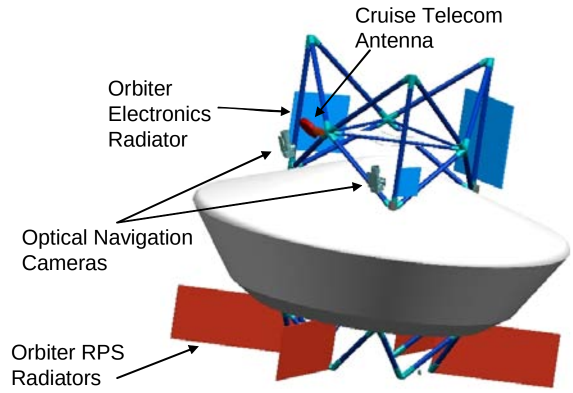

Figure 6-3 TiPEx Post-SEP Cruise Configuration – Design Concept.

During the study, detailed subsystem designs were developed and mass estimates were compiled. The detailed MEL for this orbiter design has been used to derive designs for the missions included in the feasibility study as described in the following sections.

6.3.2 Cost Drivers

To derive a simplified design for the Titan Orbiter flight system it was first necessary to identify the major cost drivers in the orbiter design. Foremost among these was technology. A stated ground rule of the study was to avoid the assumption of new technologies where possible. This led directly to a decision to replace the ASRGs (currently in development but with no specific identified mission application) used in the power system with Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs) of the type currently planned to be flown on the Mars Science Laboratory (MSL) mission in 2009.

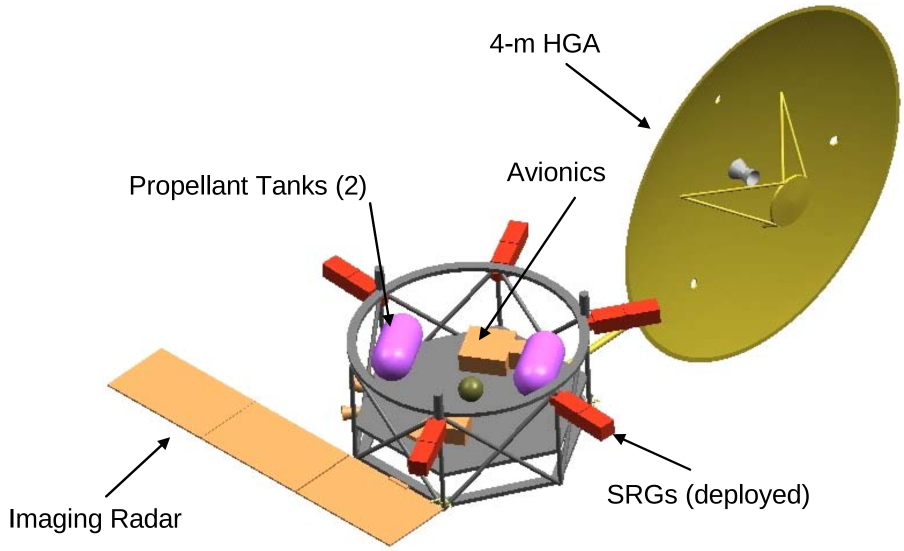

Figure 6-4 TiPEx Orbiter Science/Relay Configuration – Design Concept.

The use of MMRTGs, while avoiding a new technology development, still represents considerable cost on a per-unit basis, which led to the second cost driver to minimize power requirements. The TiPEx orbiter was planned to operate in the range of 700 to 800W, performing considerable science and relay functions. It was felt that, by optimizing science activities and lowering the capability of some subsystems it would be feasible to lower these power requirements to the range where they could be met using a complement of four MMRTGs, giving an end of mission (EOM) power of slightly more than 400W. Specific reductions included:

- Reduce telecom power from 100W to 35W RF
- Reduce HGA size from 4m to 3m to loosen pointing requirements and avoid the need for reaction wheels (ACS using minimum impulse thrusters only)
- Replace solid state recorder with non-volatile memory

It should be noted that these changes in the telecommunications subsystem result in a reduction in the maximum downlink data rate from 200 kbps for TiPEx to about 47 kbps for the Titan Orbiter mission.

Finally, mass is a driver in any flight system design, primarily in the desire to minimize launch costs. In this case the major mass trades performed resulting in significant launch vehicle benefits were the mission architecture decisions to make use of SEP and aerocapture, although credit was taken for mass reductions wherever subsystem modifications were made.

It is worth noting that radiation, which has often been found to be a cost driver in deep space missions involving Jupiter and its moons, is not a significant issue for any of these missions. The radiation environment both in transit and at the destinations for the five missions evaluated in this study is benign, requiring no additional development or extra mass for radiation shielding. This is especially true for the missions to the surface of Titan, where the Titan atmosphere essentially eliminates environmental radiation dose altogether.

6.3.3 Titan Orbiter MEL

The master equipment list for the Titan Orbiter (derived from the TiPEx design) is shown in Table 6-3 alongside the original TiPEx MEL. Changes include:

- **Instruments**: Mass changed to reflect feasibility study instrument suite
- **C&DH:** Change from SSR to non-volatile memory
- **Power**: Change from 5 ASRGs to 4 MMRTGs
- **Telecom**: Change from 4m to 3m HGA, 100W to 35W Ka TWTA, deletion of aerobot and telecom relay

Although selected subsystems show mass reductions as a result of the design changes listed above, the overall flight system dry mass is actually slightly higher for the simplified orbiter. This is a result of a combination of a higher mass instrument suite and the greater mass of the MMRTG power system, compared to the ASRGs.

Note that these and subsequent MELs include the mass of the SEP stage and Xenon propellant required for each mission concept.

6.4 Titan Aerobot

The flight system design for the Titan Aerobot mission is taken directly from that developed for the TiPEx mission study. That study developed a flight system that was capable of communicating directly with the earth as well as performing data relay through the orbiter. Absent the orbiter, the aerobot alone was fully capable of carrying out an independent science mission.

Table 6-3 TiPEx and Titan Orbiter MELs.

TiPEx Orbiter

	CBE Mass (kg)	Cont. (%)	Total Mass (kg)
Instruments	59.8	30%	77.7
C&DH	26.1	26%	32.8
Power	162.3	30%	211.0
Telecom	72.4	12%	80.8
Structures	197.9	30%	257.3
Thermal	85.1	30%	110.3
Propulsion	24.8	16%	28.8
GN&C	21.3	7%	22.8
Cabling	43.9	30%	57.1
SC Dry Mass Total	693.6		878.6
Aeroshell	424.2	30%	551.4
Cruise Equipment	48.3	30%	62.8
Cruise Thermal	33.8	30%	43.9
System Margin			179.2
FS Dry Mass Total	1199.9	43%	1715.9
Propellant			225.8
Wet Mass Total	1425.7		1941.7
Aerobot		30%	493.4
SEP Stage Dry Mass		30%	810.4
Xenon Propellant			515.2
Launch Mass Total			3760.7

Titan Orbiter

	CBE Mass (kg)	Cont. (%)	Total Mass (kg)
Instruments (4)	85.0	30%	110.5
C&DH	19.6	27%	24.8
Power	187.4	30%	243.3
Telecom	48.9	12%	55.0
Structures	197.9	30%	257.3
Thermal	85.1	30%	110.3
Propulsion	24.8	16%	28.8
GN&C	21.3	7%	22.8
Cabling	43.9	30%	57.1
SC Dry Mass Total	713.9		909.9
Aeroshell	424.2	30%	551.4
Cruise Equipment	48.3	30%	62.8
Cruise Thermal	33.8	30%	43.9
System Margin			176.9
FS Dry Mass Total	1220.2	43%	1744.9
Propellant			225.8
Wet Mass Total	1446.0		1970.7
SEP Stage Dry Mass		43%	1047.0
Xenon Propellant			565.0
Launch Mass Total			3582.7

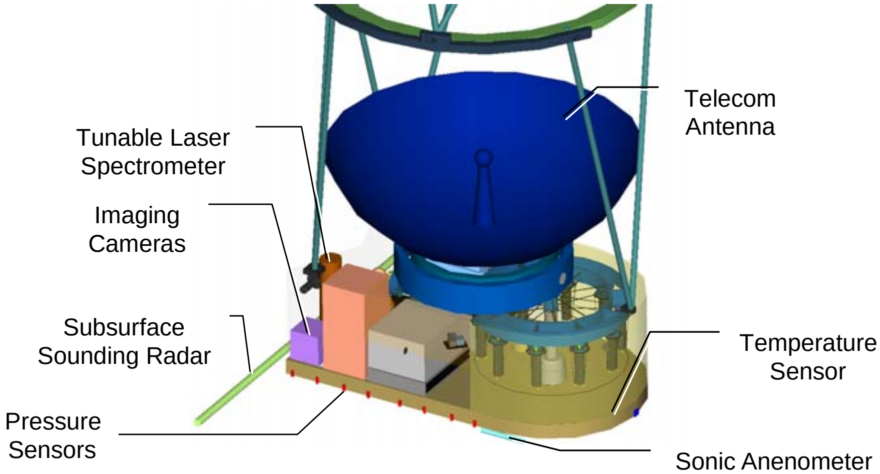

Figure 6-6 Montgolfiere Gondola Showing Notional Instrument Layout.

A conceptual design of the Montgolfiere is shown in Figure 6-5. This approach uses a double-walled envelope design to reduce heat transfer from the hot air through the balloon with an upper vent, which would be actuated to effect altitude control. A Montgolfiere system using two MMRTGs for heating, as baselined in this study, would be about 8-m in diameter. The mass of the envelope would be about 30 kg. Such a design would be able to carry a substantial payload (>160 kg) to altitudes over 20 km in the Titan atmosphere. Operational scenarios envisioned for the mission concept developed in this study would have the aerobot operating at altitudes no higher than about 10 km, providing substantial margin in the design.

The payload for the aerial vehicle is packaged in the suspended gondola (Figure 6-6). This gondola contains all of the subsystems necessary for deployment and operation of the balloon, as well a providing a platform for the science instrument suite.

Mounted above the payload is the 1-m X-band HGA which provides communication directly to earth at a data rate of about 2 kbps using a beacon mode from earth to facilitate pointing. The two MMRTGs would provide power to the gondola, as well as heating the Titan atmosphere inside the balloon envelope to provide buoyancy.

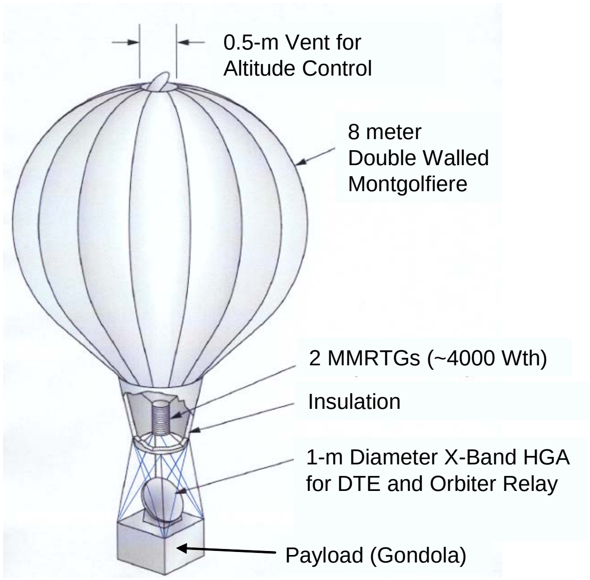

Figure 6-5 Aerial Vehicle Configuration.

The TiPEx Montgolfiere would have performed surface sampling by dropping “harpoons” from an altitude of 100-m above the surface. For the simpler Titan Aerobot mission this capability has been removed and the Montgolfiere is assumed to operate at a relatively constant altitude.

The MEL for the Titan Aerobot flight system is shown in Table 6-4. As discussed above it is derived directly from that developed for the TiPEx mission, with the replacement of the instrument mass to reflect the feasibility study instrument suite.

Table 6-4 Titan Aerobot MEL.

	CBE Mass (kg)	Cont. (%)	Total Mass (kg)
Instruments (5)	22.8	30%	29.6
C&DH	14.6	20%	17.5
Power	86.4	30%	112.3
Telecom	17.2	30%	22.4
Structures	20.0	30%	26.0
Thermal	15.0	30%	19.5
GN&C	5.0	15%	5.8
Balloon	30.0	30%	39.0
Floating Mass Total	211.0	29%	272.1
Aeroshell	75.5	30%	98.2
Cruise Thermal	43.0	30%	56.0
Parachute	12.0	30%	15.6
System Margin			46.6
FS Mass Total	341.6	43%	488.4
SEP Stage Dry Mass		43%	1088.2
Hydrazine RCS Prop			100.0
Xenon Propellant			505.0
Launch Mass Total			2186.6

6.5 Titan Lander

The Titan Lander flight system concept assumes an equipment list nearly identical to the aerobot. Given the very benign descent and landing environment, it is assumed that minimal changes would be needed to convert the subsystems comprising the aerobot gondola into a landed system. These changes involve eliminating the balloon envelope from the MEL and adding mass to structure to account for a minimal landing system. Parachute landing, without any active propulsive braking or guidance capability (as demonstrated by Huygens) is assumed. The resulting MEL for the Titan Lander flight system is shown in Table 6-5.

Table 6-5 Titan Lander MEL.

	CBE Mass (kg)	Cont. (%)	Total Mass (kg)
Instruments (5)	36.0	30%	46.8
C&DH	14.6	20%	17.5
Power	86.4	30%	112.3
Telecom	17.2	30%	22.4
Structures	50.0	30%	65.0
Thermal	15.0	30%	19.5
GN&C	5.0	15%	5.8
Balloon	0.0	30%	0.0
Landed Mass Total	224.2	29%	289.3
Aeroshell	75.5	30%	98.2
Cruise Thermal	43.0	30%	56.0
Parachute	12.0	30%	15.6
System Margin			48.3
FS Mass Total	354.8	43%	507.3
SEP Stage Dry Mass		43%	1088.2
Hydrazine RCS Prop			100.0
Xenon Propellant			505.0
Launch Mass Total			2200.5

6.6 Saturn Orbiter with Multiple Enceladus Flybys

The design of the Saturn Orbiter mission includes the use of aerocapture at Titan to establish the Saturn orbit. The use of aerocapture again requires the flight system design to be configured for packaging in an aeroshell. The design of the Saturn Orbiter will thus share many characteristics of the Titan Orbiter and the flight system design was derived from that mission accordingly.

The major difference between the two designs, apart from the different instrument suites stipulated for the two missions, is in the propulsion system. The Saturn Orbiter mission includes a large number of close flybys of Enceladus as well as Titan; each flyby has propulsive maneuvers associated with it that must be accommodated by the flight system. To account for this the Saturn Orbiter has been designed with a significantly larger propulsion system, capable of providing on the order of 1 km/s of delta-V to the flight system over the course of the mission. The Saturn Orbiter MEL is shown in Table 6-6.

Table 6-6 Saturn Orbiter MEL.

	CBE Mass (kg)	Cont. (%)	Total Mass (kg)
Instruments (6)	40.0	30%	52.0
C&DH	19.6	27%	24.8
Power	187.4	30%	243.3
Telecom	48.9	12%	55.0
Structures	270.0	30%	351.0
Thermal	85.1	30%	110.3
Propulsion	206.0	17%	240.0
GN&C	21.3	7%	22.8
Cabling	43.9	30%	57.1
SC Dry Mass Total	922.2		1156.3
Aeroshell	424.2	30%	551.4
Cruise Equipment	48.3	30%	62.8
Cruise Thermal	33.8	30%	43.9
System Margin			228.4
FS Dry Mass Total	1428.5	43%	2042.8
Propellant			755.0
Wet Mass Total	2183.5		2797.8
SEP Stage Dry Mass		43%	1047.0
Xenon Propellant			627.0
Launch Mass Total			4471.7

6.7 Enceladus Plume Sample Return

The Enceladus Plume Sample Return mission allows for potentially the simplest flight system design of the five studied. While a detailed spacecraft design was beyond the scope of the study, it was possible to once again extrapolate a MEL from the basic Titan Orbiter design, with consideration of experience gained from the Stardust spacecraft.

In the case of the Sample Return mission the first simplification is to remove the aeroshell and associated cruise equipment masses, since aerocapture will not be used. Additionally, the very brief period during which science observations will be made and the relatively small amount of data taken during this period allowed simplification of the telecom and associated systems to the level that the power system was able to be reduced to two MMRTGs. Telecom was reduced to a 10W Ka band system, using a fixed 3m HGA providing a data rate of about 4 kbps at Saturn distances. The Sample Return flight system MEL is shown in Table 6-7. Note that the instrument mass includes a 45 kg estimate for the sample capture and return capsule, based on the Stardust mission equipment.

Table 6-7 Enceladus Plume Sample Return MEL.

	CBE Mass (kg)	Cont. (%)	Total Mass (kg)
Instruments (5)	75.0	30%	97.5
C&DH	19.6	27%	24.8
Power	106.6	30%	138.6
Telecom	48.9	12%	55.0
Structures	197.9	30%	257.3
Thermal	85.1	30%	110.3
Propulsion	24.8	16%	28.8
GN&C	21.3	7%	22.8
Cabling	43.9	30%	57.1
SC Dry Mass Total	623.1		792.2
Aeroshell	0.0	30%	0.0
Cruise Equipment	0.0	30%	0.0
Cruise Thermal	0.0	30%	0.0
System Margin			98.9
FS Dry Mass Total	623.1	43%	891.0
Propellant			100.0
Wet Mass Total	723.1		991.0
SEP Stage Dry Mass		43%	1047.0
Xenon Propellant			505.0
Launch Mass Total			2543.0

6.7.1 Solar v. RPS Trade

During the course of the study consideration was given to the possibility that some or all of these missions could be performed using solar power alone, perhaps extrapolating from the solar array technologies being developed for the current Juno project to Jupiter. This possibility was considered and dismissed early on for the Titan Aerobot and Lander missions, given the structural, mass and packaging implications of trying to deploy very large arrays from simple surface systems.

Likewise, the two orbiter missions were considered not to be adaptable to solar power for similar reasons. The sheer size of the arrays required at Saturn distances would overwhelm already complex packaging constraints, as well as presenting serious challenges to attitude control for both the Titan and Saturn orbiters.

The Sample Return mission, however, has the benefit of not requiring aeroshell packaging and being designed to operate at a lower power. It was felt that there might potentially be some chance that retaining the SEP stage solar arrays with the flight system might provide sufficient power for the limited operations required by the flyby and sample capture. While it would require a more detailed analysis than was possible within the constraints of this study to determine what, if any, solar array system might be able to perform in this dual role, perhaps the biggest impediment comes in the nature of the mission itself. The sample capture phase envisions flying through the Enceladus plume, the characteristics of which are not well known. However, it is quite likely that this passage would present a serious engineering challenge to ensuring the integrity of the solar arrays, and protecting them from high-speed particle impacts. While a similar issue was successfully addressed in the Stardust mission, the characteristics of the Enceladus plume capture phase are sufficiently different to render a direct comparison inadvisable.

For these reasons, the team has concluded that, without significant further study, an all-solar powered option was not pursued for any of the missions studied.

6.8 Titan Atmospheric Probe

The Titan Atmospheric Probe mission was determined by the science team to have insufficient science return. However, this mission was felt to represent a very low cost concept and a flight system design was developed for costing purposes.

The mission would consist of two elements: a simple carrier spacecraft and a single battery-powered Huygens type atmospheric probe. The carrier would provide cruise stage services to the probe prior to release on Titan approach. The carrier would then serve as a data relay for the probe during its brief entry and descent science phase. It was stipulated that the carrier would include no instruments of its own.

Design of the carrier spacecraft was derived from the simple Enceladus Sample Return flight system. Changes included removal of mass for instruments, and augmentation of the propulsion subsystem to support limited deep space maneuvers, since the architecture for this mission does not incorporate the SEP transfer option. The carrier MEL is presented in Table 6-8.

Table 6-8 Titan Atmospheric Probe Carrier MEL.

	CBE Mass (kg)	Cont. (%)	Total Mass (kg)
Instruments (0)	0.0	30%	0.0
C&DH	19.6	27%	24.8
Power	106.6	30%	138.6
Telecom	48.9	12%	55.0
Structures	197.9	30%	257.3
Thermal	85.1	30%	110.3
Propulsion	115.0	30%	149.5
GN&C	21.3	7%	22.8
Cabling	43.9	30%	57.1
SC Dry Mass Total	638.3		**815.4**
Aeroshell	0.0	30%	0.0
Cruise Equipment	0.0	30%	0.0
Cruise Thermal	0.0	30%	0.0
System Margin			97.4
FS Dry Mass Total	638.3	43%	**912.8**
RCS Propellant			640.0
Wet Mass Total	1278.3		**1552.8**

The atmospheric probe design is meant to be very similar to Huygens. The MEL developed for this flight system resulted from a modification of the Titan Lander equipment list to remove the MMRTG power system and its associated "cruise thermal" subsystem and replace it with 1600 W-hr batteries. The instrument suite was also adjusted to represent the modified mission. The overall mass (including contingency) resulting from these changes (Table 6-9) came out to ~330 kg, quite close to the Huygens probe flight mass of 319 kg.

Table 6-9 Titan Atmospheric Probe MEL.

	CBE Mass (kg)	Cont. (%)	Total Mass (kg)
Instruments (5)	22.8	30%	29.6
C&DH	14.6	20%	17.5
Power	20.0	30%	26.0
Telecom	17.2	30%	22.4
Structures	50.0	30%	65.0
Thermal	15.0	30%	19.5
GN&C	5.0	15%	5.8
Balloon	0.0	30%	0.0
Landed Mass Total	144.6	28%	**185.8**
Aeroshell	75.5	30%	98.2
Cruise Thermal	0.0		0.0
Parachute	12.0	30%	15.6
System Margin			32.4
Launch Mass Total	232.1	43%	**331.9**

6.9 New Horizons-Based Enceladus Single Flyby

An additional mission concept was costed that was thought to represent the least expensive achievable mission. This concept would involve a single flyby of Enceladus using a very low mass, high-speed flight system based on the New Horizons spacecraft.

The flight system for this mission concept was assumed to be identical to the New Horizons design. No independent equipment list was developed for this concept, nor was independent flight system costing performed. Mission cost estimates made use of New Horizons actuals for flight system entries.

6.10 Flight System Cost Estimates

Cost estimates for the flight system elements were generated using JPL's Parametric Mission Cost Model (PMCM), a discussion of which may be found in Section 7. The cost model takes as input details on the performance characteristics of the flight system, as well as inputs regarding design and mass of each individual subsystem. The flight system conceptual designs and MELs presented earlier in this section were used for masses and performance characterization. A summary of the cost outputs from the PMCM models for the flight systems for each mission are presented in Table 6-10.

The relative costs of the flight systems illustrate the differences between orbiters and in-situ elements. The orbiters' more sophisticated instruments and higher data return lead to more massive, higher power designs than the smaller, simpler lander and aerobot concepts. Predictably, the simplicity of the Enceladus Sample Return flight system is reflected in its place as the lowest cost of the six flight systems for which the PMCM model was run.

Table 6-10 Flight System Cost Estimates.

Element	Flight System Cost ($M)					
	Titan Orbiter	Titan Aerobot	Titan Lander	Saturn Orbiter	Enc SR	Titan Atm Probe
Flight System Total	$487M	$386M	$385M	$509M	$354M	$386M
SEP Stage	103	118	118	103	103	-
Atmospheric Probe	-	-	-	-	-	143
Spacecraft	385	269	267	407	251	243

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7. Ground System

7.1 Overview

Missions to the outer solar system planets present major challenges in the mission operations phase, which drive costs to levels beyond those experienced typically with inner solar system missions. First, mission times are always long and include extensive cruise phases some of which involve gravity assist maneuvers in the inner solar system. Second, communications distances are very large at the target destination, which impacts both achievable data rates, and command latency, which in turn drives mission operations complexity. To deal with the data rate challenge, it may be necessary to commit a significant fraction of DSN resources in order to acquire the data return, which the mission objectives require. Pre-planning and on board autonomy are effective methods used to deal with command latency.

In this section, the approach used to assess cost of the Ground System (composed of Mission Operations System and Ground Data System) as well as unique cost drivers are discussed.

7.2 Introduction

A summary of the seven Titan and Enceladus mission concepts and related mission operations drivers are shown in Table 7-1. All estimates are built upon approaches used on ongoing and planned outer solar system planetary missions: the Flagship class mission Cassini-Huygens (Saturn system), and two New Frontiers class missions - New Horizons (Pluto) and Juno (Jupiter). See Appendix A for a detailed functional description of the Ground System. The cost basis is comprised of elements that are common to all mission concepts studied and elements that are unique to each as discussed below

7.3 Common Elements

For all options the development period was assumed to be 5 years with each phase broken into the following durations:

- Phase A: 12 Months
- Phase B: 12 Months
- Phase C/D: 36 Months, for Ground cost estimating used Phase C: 16 months, and Phase D: 20 months
- Phase E: Starts at Launch + 30 days and has variable length based on the mission concept

The following assumptions were made in regards to the development tasks:

- MOS workforce levels are scoped to address risk and management profiles consistent with a competed New Frontiers class (~$800M+) mission, such as Juno or NH. Relative to Flagship class missions, this results in reduced staffing profiles for development and operations, fewer reviews and layers of oversight and fewer new developments and more customization of existing tools.
- No foreign partnerships or instruments. This minimizes ITAR issues and associated overhead.
- Science Operations were assumed to be centered at JPL for this exercise. This minimizes new interfaces and related costs.
- JPL performs MOS and GDS development and mission operations using the existing multi-mission tools and capabilities.
- A full time MOS development manager is included during phases A-D and a full time Mission Manager in phase E.

Table 7-1 Mission Options and Operations Drivers.

Mission Concept	General Description	Driving Features	Phase E
Titan Orbiter – SEP	7 year cruise to Titan, Aerocapture into orbit, 1 month Aerobraking for atmospheric science, and 2 years orbital science	Once on science orbit mission becomes very repetitive and routine	109 months (9.1 years)
Titan Aerobot – SEP	7 year cruise to Titan, direct entry into atmosphere, 12 months of aerobot operations	Directing the aerobot is comparable to MER operations with very short turn around times	95 months (7.9 years)
Titan Lander – SEP	7 year cruise to Titan, direct entry onto surface, 3 months of heavy surface operations, 21 months of meteorology operations	After prime science can reduce to almost minimal operations staff	107 months (8.9 years)
Enceladus Sample Return – SEP	7 year cruise to Enceladus, fly-by of the plume to collect sample, 11 year return cruise	Very long and quiet cruise permits low staffing and minimal DSN	215 months (17.9 years)
Saturn Orbiter with Multiple Enceladus Fly-bys – SEP	7 year cruise to Saturn, enter into orbit around Saturn, Fly-by Enceladus roughly every 12 days for 2 years, for a total of 42 fly-bys	Fly-bys every twelve days creates very busy operating environment	107 months (8.9 years)
Enceladus Single Fly-by – Chemical Propulsion	4 year direct trajectory to Enceladus, short fly-by followed by 3 months of science data return	Direct trajectory permits very short cruise and limited science collection period - hours	51 months (4.25 years)
Titan Atmospheric Probe – Chemical Propulsion	11 year trajectory to Saturn, fly-by spacecraft provides data relay for probe that performs direct entry into Titan's atmosphere, hours of science taking and 2 8-hour DSN passes for data return	Long quiet cruise and limited science collection period - hours	133 months (11 years)

- A half time GDS development manager is estimated throughout development. Since all development is planned to be completed prior to launch, funding for the GDS manager ends after launch (any additional post launch development activities would be managed by the Mission Manager).
- Existing multi-mission GDS is used with tailoring of sequence and planning tools and telemetry displays to meet mission specific needs.
- GDS deliveries during development occur every 6 months starting ~3 months prior to ARR, which coincides with one of the first deliveries of the flight software. This delivery cycle follows the pattern established over the last several missions and reflects phased delivery and integration of major functionality.
- Post-launch GDS deliveries occur every 18 months to keep in sync with the multi-mission common delivery schedule.
- JPL staff is responsible for limited instrument operations and data processing.
- JPL staff performs instrument commanding and health monitoring (versus an instrument provider). The science team performs the target selection and data analysis.
- JPL staff performs the processing of instrument telemetry data to level 0' (i.e., the raw telemetry data stream is decommutated to return it the format it was in on board the spacecraft prior to

transmission). Relevant spacecraft context information is provided to aid in the data analysis.
- Science team members perform data processing beyond level 0'.
- JPL staff archives level 0' data into the PDS.
- Minimal hardware procurements consistent with what is required to support NF class missions.
  - 1 MSA suite (15 workstations, 2 servers)
  - 1 GDS test bed support suite (5 workstations, 2 servers)
  - 1 GDS ATLO support suite (4 workstations, 1 server)
  - Maintenance/replenishment throughout life of mission

7.4 Unique Elements

The first five mission concepts shown in Table 7-1 follow a similar trajectory and therefore assume the same staffing profile for the cruise to Saturn. This trajectory includes 3 years of continuous solar electric propulsion (SEP) thrusting including at least one Earth gravity assist, followed by roughly 4 years of ballistic coasting to arrive at Saturn.

During the 3 years of SEP operations the spacecraft team is maintained at regular staffing levels, to support thrusting operations, sequence updates, and health monitoring. Also during this period the tracking is averaging two 8-hour passes per week to support navigation and general health monitoring and commanding. In addition once per year, through out cruise, a weeklong health check is performed with daily tracking passes.

At the end of SEP operations the spacecraft enters into a quiet ballistic coast phase lasting 3.25 years. During this period very little is performed and the general spacecraft activity is low including an annual health verification. For this period the spacecraft team is reduced to minimum levels and the tracking is held to one 8-hour pass every two weeks.

The last 9 months of cruise is spent preparing for the encounter and science activities. This involves ramping up the spacecraft team and performing the related training and operational readiness testing. In addition, long-range observations are assumed to occur in preparation for the encounter and increased tracking is included to support navigation analysis for orbit insertion or targeted entry.

The DSN profile common to these five missions is shown in Table 7-2. The following sections discuss unique aspects of the missions studied and the specific DSN utilization assumptions as shown in tables 7-3 through 7-9.

Table 7-2 Common DSN Profile.

DSN Profile used		Antenna	Op year	Hrs/pass	Pass/wk	# weeks
1	LEOP	34BWG	2018-2025	8	21.0	4.0
2	Cruise Nav & health checks	34BWG	2018-2025	8	2.0	147.0
3	Annual check-outs (x7)	34BWG	2018-2025	8	7.0	7.0
4	EEGA	34BWG	2018-2025	8	20.0	2.0
5	Cruise Quiet	34BWG	2018-2025	8	0.5	179.0
6	Prep for Encounter Cruise	34BWG	2018-2025	8	2.0	20.0
7	Approach-Hvy Track	34BWG	2018-2025	8	21.0	3.0
7	DDOR	34BWG	2018-2025	4	4.0	3.0
8	Approach + Science	34BWG	2018-2025	8	14.0	3.0
8	DDOR	34BWG	2018-2025	4	2.0	3.0
9	Orbit Insert	70	2025	8	3.0	1.0
9	Orbit Insert	34BWG	2025	8	11.0	1.0

Table 7-3 Titan Orbiter Details.

Titan Orbiter		Antenna	Op year	Hrs/pass	Pass/wk	# weeks
10	Aerobrake	34BWG	2025	8	21	4
11	Orbit Science	34BWG	2025-2027	8	7	108

Table 7-4 Titan Aerobot Details.

Titan Aerobot		Antenna	Op year	Hrs/pass	Pass/wk	# weeks
9	Aerobot EDL	70	2025	8	3	1
9	Aerobot EDL	34BWG	2025	8	11	1
10	Aerobot Science	70	2025-2026	8	14	22
11	Aerobot Science	70	2025-2026	8	4	23

7.4.1 Titan Orbiter

The Titan Orbiter uses aerocapture to achieve an eccentric orbit around Titan followed by aerobraking to enable atmospheric science. Once the final orbit is achieved, the system performs relatively simple repetitive observations. The initial observations last three months during which a regular operating routine is established and the operating environment is characterized. This permits reducing the spacecraft team for the remaining 21 months of remote observational science as shown in Table 7-3.

7.4.2 Titan Aerobot

The Titan Aerobot mission delivers an aerobot (Montgolfiere hot air balloon) directly into Titan's atmosphere. After deployment, the aerobot drifts with the atmosphere at controlled altitudes. By changing altitudes the direction of the aerobot can be modified, permitting some directional control and in turn the ability to target specific features and regions for observation. Since the aerobot is always moving, the ability to stop and plan an observation does not exist; instead the operating tempo is comparable to MER without the ability to pause. To support this mission, new planning tools will need to be developed. The science mission duration is12 months, with an observation cycle of 9 days on and 7 days off. This cycle reflects Titan's sidereal rotation and aerobot communication opportunities. Given the communication system on the aerobot, two 8-hour passes per day to a DSN 70-m station (or equivalent) are required during the 9 days out of 16 that communication is possible. Because of the difficulty of pre-pointing the communication antenna from the aerobot, a beacon tone from the DSN station performing the tracking needs to be transmitted prior to the data return starts. This beacon tone enables the aerobot communication system to point to and acquire the DSN station. DSN utilization details unique to this mission are shown in Table 7-4.

7.4.3 Titan Lander

This mission option directly delivers a lander to a targeted area on the surface of Titan. This lander has been described as being Mars Viking-like in the nature of science collection activities. The primary science activities last for 3 months during which images are taken, samples are collected and analyzed, and the surface is characterized. After 3 months the science is reduced to meteorology for the remaining 21 months.

Table 7-5 Titan Lander Details.

Titan Lander		Antenna	Op year	Hrs/pass	Pass/wk	# weeks
9	Lander EDL	70	2025	8	3	1
9	Lander EDL	34BWG	2025	8	11	1
10	Lander Science	70	2025	8	14	6
11	Lander Science	70	2025	8	4	5
12	MET Science	70	2025-2026	8	0.875	91

During the prime science phase spacecraft team support is heavy and two 8-hour passes per day (for the 9 out of 16-day communication cycle) to a DSN 70-m station (or equivalent) are conducted to return all of the collected data through the low power communication system. See Figure 7-5. Similar to the aerobot, a beacon tone from the DSN is required for the initial contact, after which predicts and ephemera can be uploaded to support future communication activities.

7.4.4 Enceladus Sample Return

This mission collects plume samples from the south polar region of Enceladus and delivers them back to Earth for analysis. This is the simplest to operate and longest mission of the set. The mission critical sample collection fly-by event requires careful planning and preparation, full spacecraft team staffing, and heavy navigation support. However once the samples are captured, the spacecraft can be put into hibernation for the return trip up until 6 months prior to Earth entry. Preparation for Earth entry will at least be comparable to that of Genesis or Stardust, with a ramp up of spacecraft team, navigation, and mission planning support at least 6 months prior to entry. Details specific to DSN utilization costs for this mission are shown in table 7-6

Though this is the longest mission of the set, and the overall MOS costs reflect that, the average level of effort is the lowest as are the DSN tracking costs.

Table 7-6 Enceladus Sample Return Details.

Enceladus Sample Return		Antenna	Op year	Hrs/pass	Pass/wk	# weeks
9	Fly by week	70	2025	8	3	1
9	Fly by week	34BWG	2025	8	11	1
10	Fly by Science return	34BWG	2025	8	7	4
11	prep for return cruise	34BWG	2025	8	4	5
12	Cruise Nav & health checks	34BWG	2025-2032	8	2	4
13	Annual check-outs (x7)	34BWG	2025-2032	8	7	7
15	Cruise Quiet	34BWG	2025-2032	8	0.5	527
16	Prep for EDL	34BWG	2032	8	2	20
17	Approach-Hvy Track	34BWG	2032	8	21	3
19	Approach + Lt trking	34BWG	2032	8	14	3

Table 7-7 Saturn Orbiter with multiple Enceladus Fly-bys Details.

Enceladus Fly-by		Antenna	Op year	Hrs/pass	Pass/wk	# weeks
9	Orbit Insert	70	2025	8	3	1
9	Orbit Insert	34BWG	2025	8	11	1
10	Orbit Science	34BWG	2026-2026	8	7	104

Table 7-8 Enceladus Single Fly-by Details.

Enceladus New Horizon Fly-by		Antenna	Op year	Hrs/pass	Pass/wk	# weeks
1	LEOP	34BWG	2018	8	21	4
2	Cruise Nav & health checks	34BWG	2018-2022	8	2	12
3	Annual check-outs (x7)	34BWG	2018-2022	8	7	2
4	TCMs (x4)	34BWG	2018-2022	8	20	4
5	Cruise Quiet	34BWG	2018-2022	8	0.5	164
6	Prep for Encounter Cruise	34BWG	2018-2022	8	2	20
7	Approach-Hvy Track	34BWG	2018-2022	8	21	3
7	DDOR	34BWG	2018-2022	4	4	3
8	Approach + Science	34BWG	2018-2022	8	14	3
8	DDOR	34BWG	2018-2022	4	2	3
9	Fly-by	70	2022	8	3	1
9	fly-by	34BWG	2022	8	11	1
10	return Fly-by Science	34BWG	2022	8	7	13

7.4.5 Saturn Orbiter with Multiple Enceladus Fly-bys

This option delivers a spacecraft that orbits Saturn and achieves multiple fly-bys of Enceladus. Because of the nature of the orbit, and the operational tempo, this is likely the most operationally complex concept. Roughly every 12 days a fly-by of Enceladus occurs, usually along a slightly different trajectory requiring updating and coordination of the instrument pointing and data collection plans and frequent navigation updates. At about the time this might start to get routine the orbit is then altered by use of Titan gravity assists to enable fly-bys over the opposite side of Enceladus. Single daily 8-hour passes to a DSN 34m are used for data return and navigation support as shown in Table 7-7.

7.4.6 Enceladus Single Fly-By

This Enceladus mission assumes a New Horizon-like spacecraft to execute a fast fly-by of Enceladus. The transfer to Saturn takes only 4 years and has few maneuvers permitting low levels of staffing throughout the mission. These factors make this the least expensive mission in the set to operate. As shown in Table 7-8, heavy tracking is assumed around the fly-by period, followed by daily 8-hour passes for the next 3 months to return all of the collected science data.

7.4.7 Titan Atmospheric Probe

This option delivers a Huygens-like probe to Titan. This option differs from the baseline in two significant ways, it uses a long duration chemical propulsion trajectory and the encounter is very short. These differences are illustrated in Table 7-9, describing the tracking profile.

Though the cruise is the longest of the options at 11 years, it is generally very quiet and the spacecraft team can be reduced after the first year of cruise. Then roughly six months before each Earth gravity assist the team is increased to support the activity and then reduced shortly afterwards.

The preparation for encounter is similar to the other options, but the actual encounter lasts a couple months. The encounter starts a month prior to reaching Titan and includes the deployment of the probe and playback by the fly-by spacecraft of the probe data.

The Probe entry and science collection coincides with the fly-by and is tracked by both 70-m and 34-m DSN antennas ensure adequate coverage for navigation and quick first look data return. The actual period of science collection and relay to the fly-by spacecraft lasts only a few hours. After the fly-by several weeks of daily passes are scheduled for repeated playback to ensure all of the data collected is returned.

The very simple spacecraft keep development and operating costs low. The spacecraft is a carrier and relay for the probe, without any instruments of note. The probe is programmed prior to launch, with the provision that event timing can be updated prior to deployment, but little else is modifiable. These two items make operating the spacecraft very simple and enable a minimal team, making this the lowest cost Titan mission in the set even though it is one of the longer missions.

7.5 Ground System Cost Summary

Ground System (MOS/GDS) cost estimates were developed using JPL's Ground Segment Team (GST) cost models. See Appendix A for a more detailed functional description of the Ground System. The GST models have undergone V&V and have demonstrated to be within 20% or better of actual costs for a broad range of missions. The model produces results consistent with the current JPL practices and cost guidelines. All MOS/GDS estimates in this report are in fixed year FY06$. These estimates are intended to be used for pre-decisional planning only.

Table 7-9 Titan Atmospheric Probe Details.

Titan Atmospheric Probe		Antenna	Op year	Hrs/pass	Pass/wk	# weeks
1	LEOP	34BWG	2018	8	21	4
2	Cruise Nav & health checks	34BWG	2018-2029	8	2	78
3	Annual check-outs (x7)	34BWG	2018-2029	8	7	9
4	Multiple GA + 2x DSM	34BWG	2018-2029	8	20	4
5	Cruise Quiet	34BWG	2018-2029	8	0.5	376
6	Prep for Encounter Cruise	34BWG	2018-2029	8	2	20
7	Approach-Hvy Track	34BWG	2018-2029	8	21	3
7	DDOR	34BWG	2018-2029	4	4	3
8	Approach	34BWG	2018-2029	8	14	3
8	DDOR	34BWG	2018-2029	4	2	3
9	Fly-by	70	2029	8	3	1
9	Fly-by	34BWG	2029	8	11	1
10	Additional data return	34BWG	2029	8	7	4

The estimate follows the standard JPL WBS: MOS and GDS cover WBS element 07.xx and 09.xx. Per this WBS the Navigation and Mission Planning Development is estimated under WBS 12.x by the Mission designer and is not included in the MOS/GDS estimate. However, all phase E costs for Mission Design and Navigation are estimated under WBS 07.x by the Mission designer and inserted in the MOS estimate.

A summary of MOS costs is shown for each of the missions in Table 7-10.

Table 7-10 Mission Operations Cost Summary.

Option	Development Cost	Operations/ DSN Cost	Discussion
Titan Orbiter – SEP	$ 31.4 M	$ 67.0 M $ 26.3 M	Small uppers for operations preparation. Routine orbit activities keep operations cost in line.
Titan Aerobot – SEP	$ 32.7 M	$ 63.5 M $ 44.4 M	Complex operating scenario requires new planning tool development and heavier staffing during science
Titan Lander – SEP	$ 31.1 M	$ 57.8 M $ 23.7 M	Floor mission for MOS/GDS costs. Once landed several members of S/C team can be released, once MET mission started team can be further reduced
Enceladus Sample Return – SEP	$ 31.6 M	$114.6 M $ 19.4 M	Slight upper in development for Earth EDL planning and coordination. Most expensive operations because of very long mission, but overall very low staffing and light tracking during cruise keep monthly operations costs low.
Saturn Orbiter with Multiple Enceladus Fly-bys – SEP	$ 32.4 M	$ 77.6 M $ 23.5 M	Additional instruments (+2) increase development costs, complexity of repeated fly-bys increase operations cost
Enceladus Single Fly-by – Chemical Propulsion	$ 32.4 M	$ 27.5 M $ 11.5 M	Direct trajectory cuts down mission duration reducing overall costs, More work required up front to handle fly-by critical event and fault protection planning
Titan Atmospheric Probe – Chemical Propulsion	$ 28.3 M	$ 51.7 M $ 14.5 M	Very Long quiet cruise, simple spacecraft with probe, and a short encounter all contribute to inexpensive development and operations. The actual timing of the fly-by coordination is challenging and affects staffing levels, however the overall mission costs remain low

8. Cost Assessment

8.1 Cost Assessment Overview

The objective of this study was to determine the feasibility of scientifically worthwhile missions that can be implemented within a $1B FY'06 cost cap. Seven mission concepts (four Titan missions and three Enceladus missions) were selected for development of life cycle cost estimates. Science and payloads, architectural concepts, flight systems and MOS/GDS designs that were used as the basis of the cost estimates are discussed in earlier sections of this document. The selected mission options that were costed are:

1) Titan Orbiter
2) Titan Aerobot
3) Titan Lander
4) Titan Atmospheric Probe
5) Saturn Orbiter/Multiple Enceladus Fly-Bys
6) Enceladus Plume Sample Return
7) Enceladus Single Fly-by

8.2 Cost Model Description

Cost estimates were developed using JPL's Outer Planet Mission Cost Model (OPMCM). OPMCM is a hybrid cost model integrating existing cost models. Wrap factors based upon JPL historic averages were used for WBS elements 01 Project Management, 02 Project Systems Engineering and 03 Safety and Mission Assurance. Estimates for WBS 04 Science were scaled from the value of the payload system per historic averages. The beta version of the NASA Instrument Cost Model (NICM) was used to estimate WBS 05 Payload System instruments for each mission option. Instrument management, systems engineering, product assurance and payload integration and test costs were included in each instrument cost estimate. WBS 06 Flight Systems and 10 Project Systems I&T costs were estimated using JPL's Parametric Mission Cost Model (PMCM) and the JPL Assembly, Test and Operations Cost Model (JACM) respectively. PMCM and JACM are internal JPL cost models routinely used in Step 1 and Step 2 AO proposal cost comparisons. The Department of Energy provided RPS cost estimates for the MMRTG and GPHS RTG options. WBS 07 MOS and 08 GDS costs were developed using JPL's Ground Segment Team cost model using a parametric-grassroots methodology. A $10M estimate for WBS 11 Education and Public Outreach was used. WBS 12 Mission Design cost estimates were generated using a parametric-grassroots approach. All costs are consistent with version 4 of the JPL Standard Work Breakdown Structure (WBS) and dictionary. This WBS provides the structure for all cost estimation and reporting. The cost estimates are life cycle, and include the Radioisotope Power Source, launch system and DSN aperture fees. All launch system costs include estimates for nuclear handling associated with the radioisotope power sources. Table 8-1 provides a description of the model used at level 2 of the WBS. All final cost estimates have been reviewed by the science and engineering team members as well as the expert advisory team and additional experts external to the study.

Reserves and range of uncertainty were calculated based upon the perceived cost risk and associated design uncertainty for each mission using the approach illustrated in Figure 8-1. A discussion of how the reserves and uncertainty were determined follows and Table 8-2 summarizes these results for each mission option.

-Total Mission Cost

TMC = CBE Cost + Reserves (A) + Reserves (B) + (LV + LV Reserves) where

Reserves (A) = A1*[A-D CBE Cost] + A2*[E CBE Cost]

Reserves (B) = B1*[A-D CBE Cost] + B2*[E CBE Cost]

-Range of Uncertainty

Upper limit = TMC + (C1+D)*CBE Cost

Lower limit = TMC + C2*CBE Cost

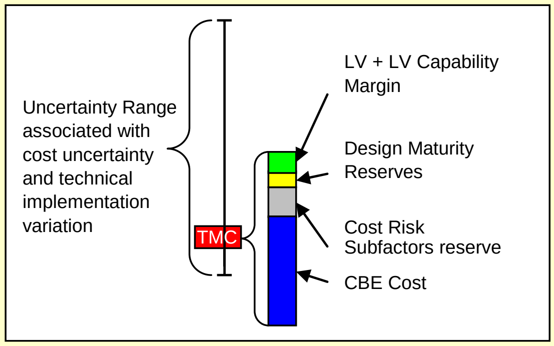

Figure 8-1 Total Mission Cost.

Table 8-1 Cost Model Description.

WBS	Model Description
01 Project Management	Wrap factor based upon recent proposals and historic cost data analysis
02 Project System Engineering	Wrap factor based upon recent proposals and historic cost data analysis
03 Safety & Mission Assurance	Wrap factor based upon recent proposals and historic cost data analysis
04 Science Team	Scaled form historic cost data relationship between Science Team and instrument costs
05 Payload System	NASA Instrument Cost Model (NICM), analogy, Science Team evaluation
06 Spacecraft System	JPL Parametric Mission Cost Model (PMCM)
Radioisotope Power System	RPS prices provided by DOE
07 Mission Operations System	JPL Ground Segment Team Cost Model
08 Launch System w/ Nuclear Support	KSC deflated to $FY06 using NASA inflation rates
09 Ground Data System	JPL Ground Segment Team Cost Model
DSN Aperture	JPL Ground Segment Team Cost Model
10 Project System Integration & Test	JPL Assembly, Test and Operations Cost Model (JACM)
11 Education and Public Outreach	Scaled at $10 FY06M
12 Mission Design	JPL Mission Design Cost Model
Reserves	JPL Cost Risk Subfactors and design maturity evaluation

To calculate reserves for each of the missions under study, the JPL Cost Risk Subfactor analysis was used to identify the minimum budget reserve requirements for each mission assuming a Phase B (preliminary design) level of concept maturity. Eight criteria (e.g., mission complexity, system architecture) each with lower level characteristics (e.g., multiple flight elements, new system architecture) were rated according to primary and secondary risk subfactors. Reserves were calculated using a base level of 20% with each primary subfactor adding 5% and each secondary subfactor adding 2%. Operations phase reserves were held at 15%. Results are shown in

Table 8-2, Row A. Each mission option was then evaluated for additional design maturity risk associated with the fact that the concepts under study (pre-Phase A level of maturity) were much less mature than what would be expected at the start of Phase B Preliminary Design. That evaluation established an additional increment of reserves to be included in the overall reserves pool. Finally, a launch capability reserve (or contingency) was established to mitigate the risk associated with the low maturity of flight system mass estimates. This was estimated as the difference in cost between the selected launch capability and the next higher level of performance. As shown in Figure 8-1, all three elements were added to the current best estimate (CBE) to form the TMC.

The uncertainty range (upper and lower ends) of the cost estimate was determined by adding the uncertainty associated with the cost models (Table 8-2, Row C) with uncertainty associated with degree of difficulty associated with technical implementation of each concept (Table 8-2, Row D) as shown in Figure 8-1.

It is important to acknowledge that while the TMC estimates do consider development risk in the reserves model, they do not account for mitigation of all risks. Costs for technology maturation through flight readiness (NASA definition of TRL6) and for a small subset of development tasks that could not be accurately quantified within the limited timeframe and scope of this study have been identified as liens against the estimated costs as shown in Section 1.6, Figure 1-3.

Figure 8-2 shows a comparison of Total Mission Costs and uncertainty ranges for each of the mission costed as part of this study. All costs are reported in $FY06M.

8.3 Cost Estimate Comparison

A comparison of each mission reported at WBS level 2 is given in Table 8-3 with detail for provided in Tables 8-4 through 8-10. Since the Enceladus Single Fly-By mission assumed the NH flight system, its costs were derived from the NH WBS based historical costs. Because the NH WBS and the breakout used for this study differed significantly, values for the Enceladus Single Fly-By mission in Table 8-3 cannot be compared with the other missions directly.

Of the seven (7) missions costed for feasibility, the Titan Atmospheric Probe and Enceladus Single Fly-By missions marginally meet the cost cap but fall short of the science guidelines. The remaining 5 missions exceed the cost cap significantly because they require more complex architectures to implement.

The Titan Orbiter and Saturn Orbiter missions have the highest costs of the mission options. The primary cost driver for these missions is the data intensive science payloads necessary to achieve science returns above Cassini-Huygens. This results in more capable instruments associated higher data rate and power demands. This all leads to high relative costs. These orbiter missions have relatively lower implementation and operation risks because of the large body of experience. This risk is reflected in Table 8-2 for category (A1) Development Risk.

The Enceladus Sample Return includes a minimal science payload and Stardust type sample capture and return system. The simpler science payloads have smaller data rate and power demands leading to lower relative costs. This mission has higher implementation and operation risks due to the uniqueness and uncertainty associated with the high particle capture velocity at Enceladus (>10 km/s compared to Stardust at 6 km/s), long mission life time (>18 years) and limited experience base. These risks result in the relatively high values reported in Table 8-2 for category (A1) Development Risk.

Table 8-2 Reserves and Uncertainty model are consistent with maturity of study. Reserves are indicated by shading.

		Titan Orbiter	Titan Aerobot	Titan Lander	Saturn Orbiter Enc. Fly-by	Enceladus SR	Titan Atm Probe	Enceladus Single Fly-By
		Reserves and Uncertainty						
A: JPL Cost Risk Subfactor Analysis Cost risk evaluation using JPL process for Phase B/C/D Risk Assessment. Covered in Project Reserves.	A1: Development Phase	31%	44%	38%	31%	44%	24%	24%
	A2: Operations Phase	15%	15%	15%	15%	15%	15%	15%
B: Design Maturity (Knowledge of existing design) Understanding of technical design and potential changes from concept study to PMSR. Covered in Project Reserves	B1: Development Phase	15%	30%	30%	15%	20%	10%	
	B2: Operations Phase	5%	5%	5%	5%	5%	0%	
C: Cost Variation Uncertainty of cost estimate based on comparison with historic actuals or cost analogies	C1: All Phases (Upper)	30%	30%	30%	30%	30%	30%	10%
	C2: All Phases (Lower)	-5%	-5%	-5%	-5%	-5%	-5%	0%
D: Difficulty of technical implementation (Understanding of implementation) E.g., Aerocapture in the Titan atmospheric environment	D: All Phases	4%	20%	20%	4%	15%	0%	0%
E: Technology Liens (Reported separately)	All Phases	Uncosted	Uncosted	Uncosted	Uncosted	Uncosted	Uncosted	Uncosted

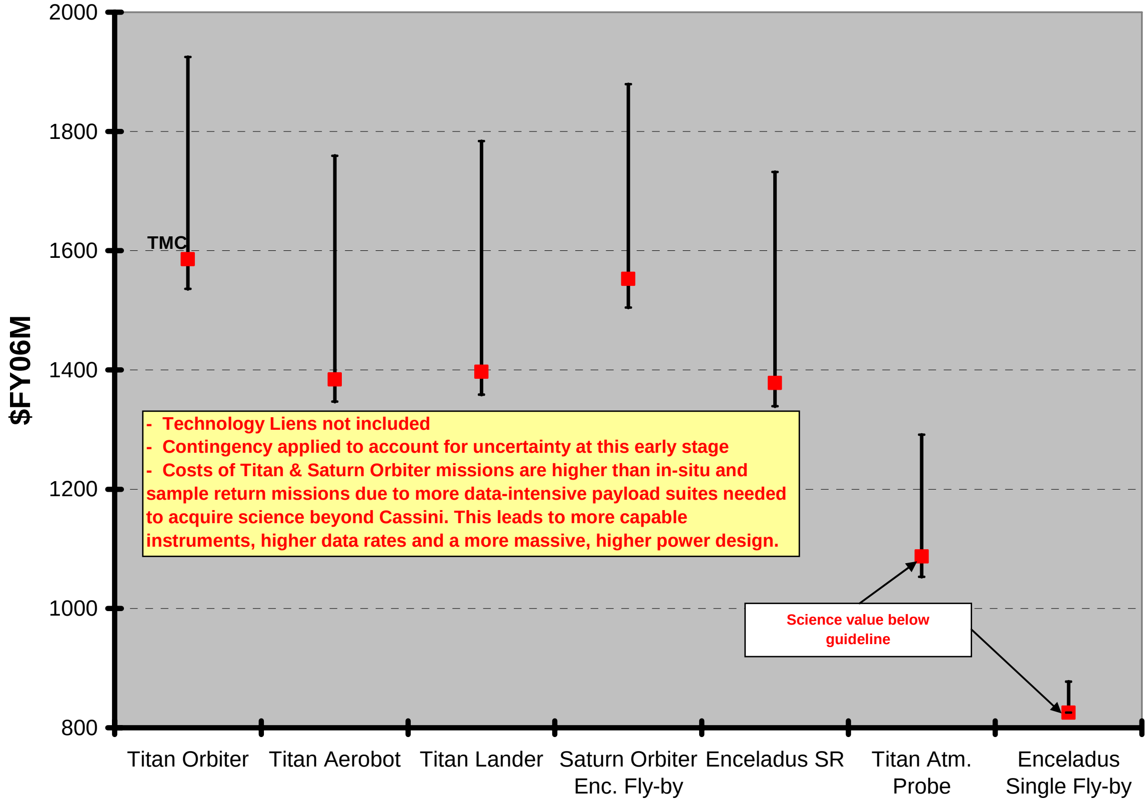

Figure 8-2 Mission Option Total Mission Cost with Range.

Table 8-3 Total Mission Cost Comparison.

	Titan Orbiter	Titan Aerobot	Titan Lander	Saturn Orbiter Enc. Fly-by	Enceladus SR	Titan Atm. Probe	Enceladus Single Fly-by
01 Project Management	35	26	27	34	27	24	In WBS 06
02 Project System Engineering	30	23	23	29	24	20	In WBS 06
03 Safety & Mission Assurance	40	30	31	38	31	27	In WBS 06
04 Science Team	83	42	54	58	49	32	40
05 Payload System	156	65	102	109	92	60	75
06 Spacecraft System	323	294	293	345	262	294	220
Radioisotope Power System	164	92	92	164	92	92	92
07 Mission Operations System	74	72	64	83	114	56	60
09 Ground Data System	25	24	25	27	32	24	In WBS 07
DSN Aperture	26	44	24	23	19	14	11
10 Project System Integration & Test	23	20	20	25	21	15	18
11 Education and Public Outreach	10	10	10	10	10	10	In WBS 06
12 Mission Design	9	7	8	13	11	13	In WBS 06
CBE Cost (Reserves Base)	997	750	773	960	786	681	517
Reserves	413	468	459	399	418	212	114
08 Launch System w/ Nuclear Support	166	139	139	175	166	175	194
LV Reserve	10	27	27	19	10	19	N/A
Total Mission Cost ($FY06M)	1,586	1,384	1,397	1,553	1,378	1,087	826

Table 8-4 Titan Orbiter Cost Summary.

	Phase A/B	Phase C/D	Phase E	Total ($FY06)
Phase Duration (Months)	24	36	109	
01 Project Management	3	26	6	35
02 Project System Engineering	3	22	5	30
03 Safety & Mission Assurance	4	29	7	40
04 Science Team	6	16	60	83
05 Payload System	16	140	0	156
2 Micron Imager	3	28		31
Plasma package (orbiter only)	3	28		31
Imaging Radar / Altimeter	6	53		59
Chemical Analyzer	3	27		30
Radio Science	1	5		6
06 Spacecraft System	49	439	0	487
06.01 S/C Management	1	12		13
06.02 Spacecraft System Engineering	2	17		19
06.03 Spacecraft Product Assurance	Included in WBS 03			0
06.04 Power SS	17	156		174
Power SS	1	9		10
Radioisotope Power System	16	148		164
06.05 C&DH SS	1	13		15
06.06 Telecom SS	2	22		24
06.07 Mechanical SS	3	30		33
06.08 Thermal SS	4	40		45
06.09 Propulsion SS	1	11		12
06.10 GN&C SS	2	21		24
06.11 Harness	In 06.07 Mechanical			0
06.12 FSW	1	11		12
06.13 SC M&P	In 06.07 Mechanical			0
06.14 SC Testbeds	1	13		14
06.20 SEP	10	92		103
07 Mission Operations System	1	15	58	74
09 Ground Data System	2	13	9	25
DSN Aperture	0	2	24	26
10 Project System Integration & Test	0	23		23
11 Education and Public Outreach	1	3	6	10
12 Mission Design	4	6		9
CBE Cost (Reserves Base)	88	734	176	997
Reserves	40	338	35	413
08 Launch System w/ Nuclear Support	17	149		166
LV Reserve	1	9		10
Total Mission Cost ($FY06)	145	1,229	211	1,586

Table 8-5 Titan Aerobot Cost Summary.

	Phase A/B	Phase C/D	Phase E	Total ($FY06)
Phase Duration (Months)	24	36	95	
01 Project Management	2	18	6	26
02 Project System Engineering	2	16	5	23
03 Safety & Mission Assurance	2	21	6	30
04 Science Team	3	7	33	42
05 Payload System	7	59	0	65
Survey Camera Suite	0	4		5
Met Package	1	5		5
Profiling/Subsurface Radar	2	15		17
Gas Chromatograph Mass Spectrometer	4	32		35
TDL Spectrometer (ethane, methane, HCN)	0	4		4
06 Spacecraft System	39	348	0	386
06.01 S/C Management	1	8		9
06.02 Spacecraft System Engineering	1	12		13
06.03 Spacecraft Product Assurance	Included in WBS 03			0
06.04 Power SS	10	91		101
Power SS	1	8		9
Radioisotope Power System	9	83		92
06.05 C&DH SS	1	11		13
06.06 Telecom SS	2	16		18
06.07 Mechanical SS	3	24		27
06.08 Thermal SS	2	20		22
06.09 Propulsion SS	0	0		0
06.10 GN&C SS	3	26		29
06.11 Harness	In 06.07 Mechanical			0
06.12 FSW	2	19		22
06.13 SC M&P	In 06.07 Mechanical			0
06.14 SC Testbeds	1	13		15
06.20 SEP	12	106		118
07 Mission Operations System	1	15	55	72
09 Ground Data System	2	14	9	24
DSN Aperture	0	2	42	44
10 Project System Integration & Test	0	20		20
11 Education and Public Outreach	1	3	6	10
12 Mission Design	3	5		7
CBE Cost (Reserves Base)	61	528	161	750
Reserves	45	391	32	468
08 Launch System w/ Nuclear Support	14	125		139
LV Reserve	3	24		27
Total Mission Cost ($FY06)	123	1,068	193	1,384

Table 8-6 Titan Lander Cost Summary.

	Phase A/B	Phase C/D	Phase E	Total ($FY06)
Phase Duration (Months)	**24**	**36**	**107**	
01 Project Management	**2**	**20**	**5**	**27**
02 Project System Engineering	**2**	**17**	**4**	**23**
03 Safety & Mission Assurance	**3**	**23**	**6**	**31**
04 Science Team	**4**	**10**	**40**	**54**
05 Payload System	**10**	**92**	**0**	**102**
Chemical Analyzer with Surface Sampling	7	66		73
Lander Camera	1	5		5
Seismometer	2	14		16
Met Package	1	5		5
Descent Camera	0	3		3
06 Spacecraft System	**39**	**347**	**0**	**385**
06.01 S/C Management	1	8		9
06.02 Spacecraft System Engineering	1	12		13
06.03 Spacecraft Product Assurance	Included in WBS 03			0
06.04 Power SS	10	91		101
Power SS	1	8		9
Radioisotope Power System	9	83		92
06.05 C&DH SS	1	11		12
06.06 Telecom SS	2	16		18
06.07 Mechanical SS	3	24		27
06.08 Thermal SS	2	20		22
06.09 Propulsion SS	0	0		0
06.10 GN&C SS	3	26		29
06.11 Harness	In 06.07 Mechanical			0
06.12 FSW	2	19		22
06.13 SC M&P	In 06.07 Mechanical			0
06.14 SC Testbeds	1	13		14
06.20 SEP	12	106		118
07 Mission Operations System	**1**	**14**	**49**	**64**
09 Ground Data System	**2**	**14**	**9**	**25**
DSN Aperture	**0**	**2**	**21**	**24**
10 Project System Integration & Test	**0**	**20**	**0**	**20**
11 Education and Public Outreach	**1**	**3**	**6**	**10**
12 Mission Design	**3**	**5**		**8**
CBE Cost (Reserves Base)	**67**	**567**	**139**	**773**
Reserves	**46**	**385**	**28**	**459**
08 Launch System w/ Nuclear Support	**14**	**125**		**139**
LV Reserve	**3**	**24**		**27**
Total Mission Cost ($FY06)	**129**	**1,101**	**167**	**1,397**

Table 8-7 Saturn Orbiter – Enceladus Flyby.

	Phase A/B	Phase C/D	Phase E	Total ($FY06)
Phase Duration (Months)	24	36	107	
01 Project Management	3	25	6	34
02 Project System Engineering	3	21	5	29
03 Safety & Mission Assurance	3	28	7	38
04 Science Team	4	11	42	58
05 Payload System	11	99	0	109
Visible Imager	2	14		15
Thermal Mapper	2	14		15
Radar sounder	3	23		25
Magnetometer	0	3		3
High-Resolution INMS	3	27		30
Advanced Dust Analyzer	2	14		15
Radio Science	1	5		6
06 Spacecraft System	51	458	0	509
06.01 S/C Management	1	13		14
06.02 Spacecraft System Engineering	2	18		20
06.03 Spacecraft Product Assurance	Included in WBS 03			0
06.04 Power SS	17	156		174
Power SS	1	9		10
Radioisotope Power System	16	148		164
06.05 C&DH SS	1	13		15
06.06 Telecom SS	2	22		24
06.07 Mechanical SS	4	33		37
06.08 Thermal SS	4	40		45
06.09 Propulsion SS	2	15		17
06.10 GN&C SS	3	25		28
06.11 Harness	In 06.07 Mechanical			0
06.12 FSW	2	15		16
06.13 SC M&P	In 06.07 Mechanical			0
06.14 SC Testbeds	2	15		16
06.20 SEP	10	92		103
07 Mission Operations System	1	15	67	83
09 Ground Data System	2	14	11	27
DSN Aperture	0	2	21	23
10 Project System Integration & Test	0	25	0	25
11 Education and Public Outreach	1	3	6	10
12 Mission Design	5	8		13
CBE Cost (Reserves Base)	84	711	164	960
Reserves	39	327	33	399
08 Launch System w/ Nuclear Support	18	158		175
LV Reserve	2	17		19
Total Mission Cost ($FY06)	143	1,213	197	1,553

Table 8-8 Enceladus Sample Return.

	Phase A/B	Phase C/D	Phase E	Total ($FY06)
Phase Duration (Months)	24	36	215	
01 Project Management	2.2	18.5	6.8	27.50
02 Project System Engineering	2	16	6	24
03 Safety & Mission Assurance	3	21	8	31
04 Science Team	4	9	36	49
05 Payload System	9	83	0	92
Visible Imager	2	14		15
Thermal Mapper	2	14		15
High-Resolution INMS	3	27		30
Advanced Dust Analyzer	2	14		15
Sample Collection System	2	15		17
06 Spacecraft System	35	318	0	354
06.01 S/C Management	1	8		9
06.02 Spacecraft System Engineering	1	11		12
06.03 Spacecraft Product Assurance	Included in WBS 03			0
06.04 Power SS	10	91		101
Power SS	1	8		9
Radioisotope Power System	9	83		92
06.05 C&DH SS	1	12		13
06.06 Telecom SS	2	22		24
06.07 Mechanical SS	3	28		31
06.08 Thermal SS	1	7		8
06.09 Propulsion SS	1	11		12
06.10 GN&C SS	2	14		15
06.11 Harness	In 06.07 Mechanical			0
06.12 FSW	1	13		14
06.13 SC M&P	In 06.07 Mechanical			0
06.14 SC Testbeds	1	10		11
06.20 SEP	10	92		103
07 Mission Operations System	1	15	98	114
09 Ground Data System	2	14	16	32
DSN Aperture	0	2	17	19
10 Project System Integration & Test	0	21	0	21
11 Education and Public Outreach	1	3	6	10
12 Mission Design	4	7		11
CBE Cost (Reserves Base)	64	528	194	786
Reserves	41	338	39	418
08 Launch System w/ Nuclear Support	17	149		166
LV Reserve	1	9		10
Total Mission Cost ($FY06)	122	1,024	232	1,378

Table 8-9 Titan Atmospheric Probe.

	Phase A/B	Phase C/D	Phase E	Total ($FY06)
Phase Duration (Months)	24	36	133	
01 Project Management	2	18	4	24
02 Project System Engineering	2	15	3	20
03 Safety & Mission Assurance	3	21	4	27
04 Science Team	2	6	23	32
05 Payload System	6	54	0	60
Probe System				0
Met Package	1	5		5
Profiling/Subsurface Radar	2	15		17
Gas Chromatograph Mass Spectrometer	4	32		35
Descent Camera	0	3		3
06 Spacecraft System	39	347	0	386
06.01 S/C Management	1	8		8
06.02 Spacecraft System Engineering	1	11		12
06.03 Spacecraft Product Assurance	Included in WBS 03			0
06.04 Power SS	10	91		101
Power SS	1	8		9
Radioisotope Power System	9	83		92
06.05 C&DH SS	1	12		13
06.06 Telecom SS	2	22		24
06.07 Mechanical SS	3	26		29
06.08 Thermal SS	1	8		9
06.09 Propulsion SS	2	18		20
06.10 GN&C SS	1	10		11
06.11 Harness	In 06.07 Mechanical			0
06.12 FSW	0	4		5
06.13 SC M&P	In 06.07 Mechanical			0
06.14 SC Testbeds	1	9		10
Probe System	14	128		143
07 Mission Operations System	1	13	42	56
09 Ground Data System	2	13	10	24
DSN Aperture	0	2	12	14
10 Project System Integration & Test	0	15	0	15
11 Education and Public Outreach	1	3	6	10
12 Mission Design	5	8		13
CBE Cost (Reserves Base)	63	514	104	681
Reserves	21	175	16	212
08 Launch System w/ Nuclear Support	18	158		175
LV Reserve	2	17		19
Total Mission Cost ($FY06)	103	864	119	1,087

Table 8-10 Enceladus Single Fly-By

	NH Based Enceladus Fly-by
Spacecraft through Phase C/D	**220**
Instruments through Phase C/D	**75**
Visible Imager	15
Thermal Mapper	15
High-Resolution INMS	30
Advanced Dust Analyzer	15
Science through Phase C/D	**2**
I&T	**18**
MOS/GDS through Phase C/D	**Reported in S/C**
Total Observatory	**316**
DOE	92
Phase E costs	60
Science Phase E	38
DSN Aperture	11
CBE Cost (Reserves Base)	**517**
Reserves	**114**
ELV	**194**
Boeing-3rd Stage	
Total ($FY06M)	**826**

The Titan Atmospheric Probe and Enceladus Single Fly-by missions fail the science guidelines, but are included in the analysis because it was judged that they provide the lowest cost implementations of missions to Titan or Enceladus. The Titan Atmospheric Probe provides a very simple fly-by spacecraft sized to deliver and provide a data relay for a Huygens-like probe that slowly descends through the Titan atmosphere. The Enceladus Single fly-by is based on the New Horizons Pluto mission and uses New Horizons as the cost analogy for the spacecraft and associated wrap costs. Costs were adjusted to account for the Enceladus specific science, payload, MOS/GDS, operations, and DSN aperture costs. Both the Titan Atmospheric Probe and Enceladus Single Fly-By missions have low cost uncertainty (Figure 8-2) as well as low implementation and operation risk (Table 8-2) since the assumed mission systems have been previously flight demonstrated (Huygens and NH respectively). Project reserves are held for development risk, but there is no additional reserves increment for design maturity.

Figure 8-3 shows a comparison of the mission costs by six areas of aggregation and illustrates differences in science and payload and spacecraft costs. Figure 8-4 shows cost elements for the New Horizons mission (actuals through Phase D and plans for Phase E) and the Juno plan. It should be noted that the New Horizons cost actuals include expended development reserves. The Juno estimate represents a 2011 launch. These two missions provide a benchmark of comparison to the mission options studied with each mission exceeding $800 FY06M.

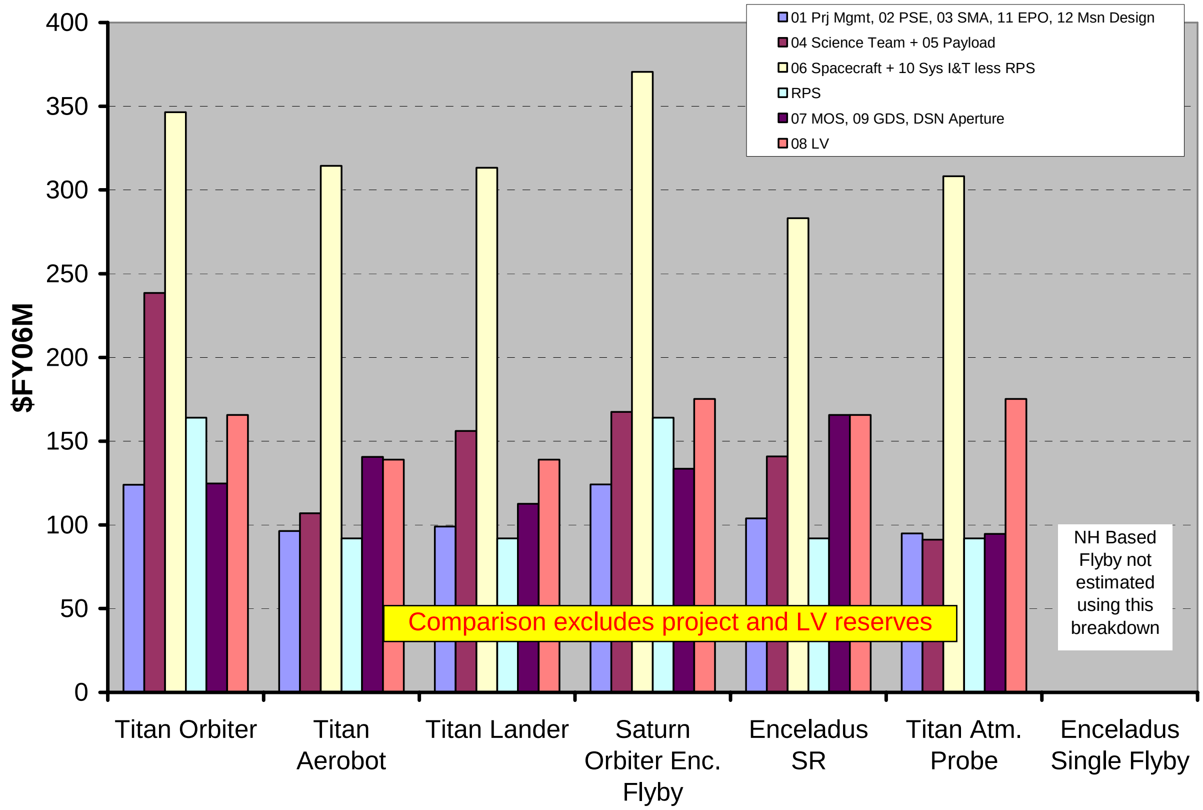

Figure 8-3 Mission Option Comparison.

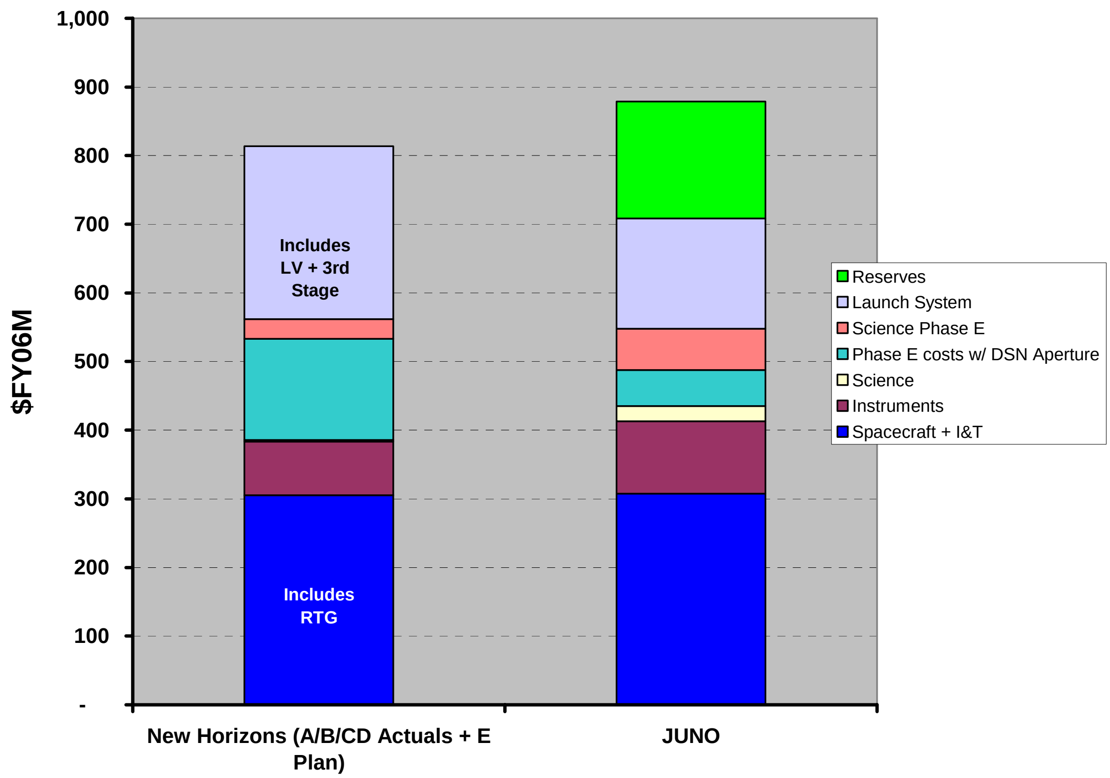

Figure 8-4 Elements for cost for New Horizons and Juno missions.

9. Summary

The study objective to determine the feasibility of conducting missions to Titan and Enceladus and characterize the science return within a $1B FY06 cost cap was met as described in Section 1.0, Executive Summary and in the Findings below.

9.1 Findings

The following conclusions resulted from this study:

1. No missions to Titan or Enceladus, that achieve at least a moderate advancement in scientific understanding beyond Cassini-Huygens, were found to fit within the cost cap of $1.0 billion dollars (FY'06).
2. Three of the missions studied have the potential to meet the cost cap but fall below the science guideline established for this study.
    a. Single Fly-By of Enceladus
    b. Single Fly-By of Titan
    c. Single Fly-By of Titan with Atmospheric entry Probe (Huygens-like)
3. Even the lowest cost mission studied, without the cost of science payload, has a minimum expected cost of ~$800M making it highly unlikely that unexplored approaches exist that achieve sufficient science value for $1B.
4. All Titan and Enceladus missions that meet science guidelines require some maturation of existing technology for flight readiness

The following recommendations are provided:

1. Results of this study should be considered as a stepping off point for follow-on NASA studies.
2. Maturation of technologies necessary to implement Titan and Enceladus concepts should be considered for programmatic funding, e.g.
    a. Aerocapture (flight validation)
    b. Aerial mobility (aerobots, onboard autonomy)
    c. Low temperature materials and systems
    d. Sample acquisition and organic analysis instrumentation
    e. High speed sample capture (>10 km/s)
    f. Returned sampling handling (biological potential)

9.2 Robustness of Findings

Could there be other approaches to implementing the five missions that were deemed to be of sufficient science value such that they would fall within the $1B cost cap? The study team believes that this is highly unlikely.

The basis for this statement relies on results from the two lowest cost missions that were studied – the Single Titan flyby and the Single Enceladus Flyby. These missions are each estimated to cost about $800M and the team has substantial confidence in these numbers given their close relationship to New Horizons, which was conceived as part of a competitive process in which cost was a major factor. A substantial portion of these costs are driven by the nature of outer planet missions including the need for a very capable launch vehicle, radioisotope power system (RPS) and long duration mission operations. The team did not identify any credible way of raising the science value of a strictly flyby mission above the science threshold.

All of the missions that are in the acceptable category require substantial additional capabilities above those embodied in a New Horizons type mission. These capabilities include the following:

- The capability of conducting an aeroassist maneuver at Titan in order to either enter Titan orbit or Saturn orbit (for the multiple Enceladus flyby mission). This adds to spacecraft costs and navigation costs.
- An entry, descent and either landing or balloon deployment capability at Titan coupled with an additional RPS for an extended lifetime on Titan.
- A number of major technical hurdles that need to be overcome to implement an Enceladus sample return mission such as high speed sample capture, mission life and returned sample handling.
- Contamination control capabilities to meet planetary protection requirements.

Meeting the $1B cost cap would require that these additional capabilities be implemented with an additional $200M beyond a basic flyby mission. This is not credible for even a mission that has a minimal science payload. These results are hardly surprising given the extraordinary capabilities of the Cassini-Huygens mission which sets a high bar for follow on missions.

To ensure consistency and quality of results an expert advisory board was established and engaged in a comprehensive review and advisory process. Concurrence of those board members is indicated by their signatures shown on page i of this report.

9.3 Implications for Follow on Mission Studies

This study has investigated a spectrum of missions that range in cost from $0.8B up to $3B. Results have shown that missions to Titan or Enceladus that significantly advance scientific understanding beyond Cassini-Huygens results will likely require Flagship missions.

NASA is about to embark on follow on studies of Flagship class missions to Titan and Enceladus. The challenge facing the follow on Flagship studies will be different than the one confronted here. This study team was asked to find a mission within a $1B cost cap that provides a sufficient increase in understanding beyond Cassini-Huygens – cost driven paradigm. For the new studies, it will be important to look more carefully at the science value as a function of cost – science driven paradigm.

In the case of Titan, for example, there are missions which would represent a significant advance over Cassini-Huygens in the Small Flagship category. However, the Titan missions in the Large Flagship category studied here would provide a couple of orders of magnitude higher data return, a greater diversity of science return and greater resilience to failures of mission elements. It will be the role of the new Flagship studies to explore the option space further in order to guide NASA in the identification of attractive options for Flagship missions and to define the technology investment needs for these future missions.

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APPENDIX A — Functional Description of Ground System

Typical data flow and operations functions used as the basis for MOS/GDS costing are shown in Figure A-1.

A-1 Tracking System

For launch support up through final injection burn the tracking system consists of 9-12m S/X-band ground stations used to support launches out of the eastern test range. The actual stations depend significantly on the ascent trajectory and are not specified until the final trajectory is set. These stations include a mix of NASA, USAF, commercial, and international assets used as needed to track the launch vehicle through all critical events.

During the mission, the DSN 34m and 70m stations are used for tracking, ranging, and communicating with the spacecraft.

The current 70-m stations are approaching end of life. For this study it is assumed that equivalent DSN apertures will be available in the 2015 time frame.

Interface with the tracking stations is expected to be per CCSDS Space Link Extension Service Management protocols for data and command file transfers, scheduling and session management. These are a set of standard protocols developed to enable easy interaction between different tracking providers and users. The DSN, ESA, and many commercial vendors have committed to meeting these standards over the next few years.

The tracking system will receive command and uplink files for transmission to the spacecraft from the Mission Operations Center (MOC).

The tracking system will send the returned spacecraft data stream, files, and tracking data to the MOC for distribution to telemetry processing and navigation teams.

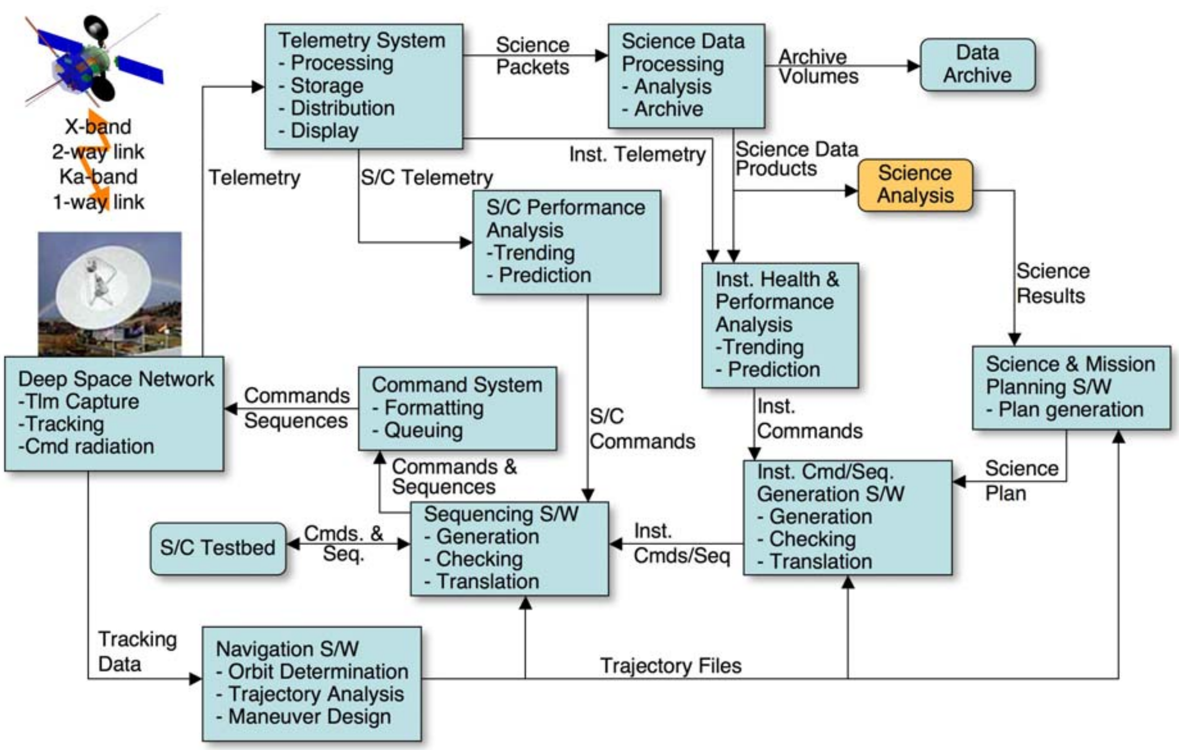

Figure A-1 MOS GDS Diagram.

Tracking system performance beyond existing capability is not needed to support the missions studied.

A-2 Telemetry System

The telemetry data from the spacecraft is processed to Level 0 by the tracking system before delivery to the MOC. Level 0 processing removes the transmission wrappers and puts the data back in the formats they were in on the spacecraft prior to transmission.

The telemetry system at the MOC provides additional processing to separate the instruments data from the spacecraft data, stores the data in the project database for non-real-time analysis, and distributes telemetry data to the appropriate customers.

The current Telemetry system would require the usual adaptation work to handle this mission.

A-3 Science Data Processing

The next level of instrument telemetry processing links associated spacecraft data to the instrument data to provide context. Additional processing may be performed but this has been generally left to the science teams for each specific instrument.

Part of the science data processing is preparing data products for long-term data archiving into the Planetary Data System or similar archive.

The current science processing tools would require the normal adaptation needed to support the instrument complements of this study.

A-4 Science Analysis

Project and instrument PIs perform analysis of the returned science products at their member institutions and in theory use this to guide or alter the long-range observation plan.

A-5 Science and Mission Planning

Project PI leads the instrument PIs in setting up the overall science observation plan that will be used for the mission, and is likely to evolve over the life of the mission as conditions change and spacecraft and instrument health change.

The mission plan is updated during development as the trajectory is refined and science goals evolve. Once the mission is underway there is typically a need to change the trajectory to handle unexpected changes in the spacecraft or environment.

The science and mission plans are used by the instrument, spacecraft, and navigation teams for the overall operations plan and sequence and command builds.

A-6 Spacecraft Performance Analysis

The spacecraft subsystem engineers use the spacecraft Engineering Health and Housekeeping (EH&H) data to perform general spacecraft health analysis and trending. This is used for predicting future behavior, flight software (FSW) autonomy improvements, long term planning, and sequence development.

A-7 Instrument Health and Performance Analysis

Instrument support engineers use the instrument EH&H data to perform general instrument health analysis and trending. This is used to predict behavior, changes to the operating modes, and support spacecraft operations.

The support engineers work with the project scientists in changing instrument modes and settings keeping the scientist appraised of the overall impact on the spacecraft associated with these changes.

A-8 Sequencing

The sequence integration team collects the command files from spacecraft, instrument, and navigation teams and creates a single integrated sequence upload for the spacecraft, taking into account tracking schedules.

The sequences are tested on the spacecraft test bed to ensure correct and safe operations on the spacecraft with out any unexpected violations of the flight rules.

The tested sequence is then translated into a command file for uploading to the spacecraft. In turn this file is forwarded to the command system for actual transmission to the spacecraft at the appropriate time.

A-9 Navigation

Using the RF tracking data provided by the DSN perform the orbit determination and trajectory analysis for all spacecraft. In turn this information is used in conjunction with the mission plan to perform maneuver planning.

This team produces the trajectory files used in commanding and science analysis activities.

A-10 Mission Control Team

The Mission Control Team (MCT) handles and monitors the interfaces between the DSN and the telemetry and command systems. The key functions they perform are ensuring that the command uploads occur as scheduled and to monitor the reception and completeness of the telemetry. If problems occur anywhere along the transmission/reception data path they correct them or if not able to, ensure that the appropriate parties are informed so that the problems can be resolved in a timely fashion.

A-11 Infrastructure support

To enable teams to function and to meet various mission requirements there are additional people costed to support the infrastructure.

The most visible members of this group are the system administrators responsible for maintaining all of the computers, networks, and voice nets used in operations, and monitoring the computer and network security.

In addition the underlying GDS system undergoes periodic revision, about every 18 months, and this requires a delivery of the GDS. This delivery is required if the project is using multi-mission resources to support the mission. To support this delivery there are engineers that configure, install, and test the updates. This team will come on board for 4 months every 18 months.

Any errors or changes to the GDS will need to be made by supporting programmers, and in turn these need to be tested. These people are usually brought in as needed during operations.

Trainers are required to prepare for mission operations. These trainers prepare the Operation Readiness Testing (ORT) plans and conduct the tests. These tests check the procedures and prepare the team for upcoming critical events. Missions always conduct operational readiness tests (ORTs) for launch, and the first major maneuver, and for any mission critical event that could cause a loss of mission if done incorrectly. In the case of this mission there should also be an ORT for at least the first VGA.