ARPS Enabled Titan Rover Concept with Inflatable Wheels

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Abstract. The Decadal Survey identified Titan as one of the top priority science destinations in the large moons category, while NASA's proposed Design Reference Mission Set ranked a Titan in-situ explorer second, after a recommended Europa Geophysical Observer mission. This paper discusses a Titan rover concept, enabled by a single advanced Radioisotope Power System that could provide about 110We (BOL). The concept targets the smaller Flagship or potentially the New Frontiers mission class. This MSL class rover would traverse on four 1.5 m diameter inflatable wheels during its 3 years mission duration and would use as much design and flight heritage as possible to reduce mission cost. Direct to Earth communication would remove the need for a relay orbiter. Details on the strawman instrument payload, and rover subsystems are given for this science driven mission concept. In addition, power system trades between Advanced RTG, TPV, and Advanced Stirling and Brayton RPSs are outlined. While many possible approaches exist for Titan in-situ exploration, the Titan rover concept presented here could provide a scientifically interesting and programmatically affordable solution.

Keywords: RPS, ARPS, ARTG, Advanced Stirling, TPV, Brayton, rover, inflatable wheel.
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INTRODUCTION

The Decadal Survey (NRC, 2003) identified Titan as one of the top priority science destinations in the large moons category. The exploration of Titan in the form of future orbiter and/or lander missions was also rated high in NASA's proposed Design Reference Mission set (NASA, 2005). Titan ranked second in this list after a projected Europa Geophysical Observer mission. The complexity of a Titan mission could vary from a single element, such as an orbiter or an in-situ explorer to multiple elements with the inclusion of both orbiter and in-situ elements.

In-situ exploration could be achieved in multiple ways, all having their own advantages and disadvantages. These concepts could include, with increasing complexity, a static lander; a balloon; a surface rover; and an aerobot. A static lander could be similar in functionality to the Huygens probe, but may vary in size. A balloon could cover vast areas, but provide only vertical control for surface access. Its mass would be limited, compared to surface based assets. A surface rover could traverse significant distances on Titan, similar to that of the planned Mars Science Laboratory (MSL) mission. An aerobot would have all axis control and good surface access, but again limited in mass compared to a surface based mission. An aerobot concept has been explored in details under the recent Vision Mission studies (Zimmerman et al., 2005). When an in-situ concept is down selected, further choices should be made on the potential inclusion of an orbiter. Not having an orbiter would reduce mission costs, but would also reduce science return on atmospheric remote sensing and would certainly increase mission complexity and introduce landing location limitations due to Direct to Earth (DTE) communication constraints.

Based on these considerations, the present study focuses on a surface rover concept without the support of an orbiter. In effect, the chosen configuration would fill the gap between a Huygens Probe (NASA-JPL, 2005) derivative static lander platform and the Vision mission aerobot concept. A key goal of this study was to assess the benefits of advanced RPS systems for powering a Titan rover concept. These advanced RPSs, using more efficient power conversion technologies, would offer systems with lower mass and thermal rejection loads, thus enabling or enhancing new missions.

SCIENCE AND MISSION GOALS

Titan and Europa are the premier targets for future in-situ exploration of the outer solar system, Europa because of the possible presence of liquid water oceans that might harbor life, and Titan because of the "pre-biotic" organic chemistry that is likely taking place on the surface. Future missions to the surface of Europa face a number of daunting challenges. Landing on the surface of this airless body is difficult; the severe radiation environment allows mission survival there for very limited times; and it may be extremely difficult to obtain samples of surface materials that have been in contact with the hidden ocean. By contrast, Titan's atmosphere allows for aerobraking descents; the radiation environment is not a mission-critical factor; and the organic materials desirable for sampling should be widely distributed (and easily accessible) over the surface. The recent Titan landing by the Huygens Probe (NASA-JPL, 2005) has focused considerable scientific interest on this remarkable body, and future missions to Titan are also under consideration (NASA, 2005).

Titan represents a "natural laboratory" that could illuminate key questions relating to the origins of life. Titan's atmosphere is in some ways similar to that of the early Earth. Many organic compounds are present in Titan's atmosphere; these are produced by photolytic processes driven by solar ultraviolet radiation. These organics condense in Titan's stratosphere and may thereafter be deposited on the surface.

Imaging from the Cassini mission has revealed remarkable surface features on Titan that were previously obscured from view by atmospheric hazes, although the highest resolution was limited about 400 m/pixel. From these images and those from the Huygens descent imager, there is clear evidence of the presence of fluids on Titan's surface, and there are many features that are thought to have formed by cryovolcanic eruptions of water-rich ice materials.

The presence of organic compounds and water (in the form of ice) gives rise to speculation that Titan may at present support organic chemical processes that could be direct precursors to life.

Some of the most critical science objectives for future missions to Titan could only be addressed from lander or rover platforms. The exact surface composition; the distribution and nature of organics and the present-day chemical interactions of the surface; and atmosphere are among these. The thick, smoggy atmosphere of Titan makes it difficult (if not impossible) to study these phenomena from orbit. Surface observations could also answer questions of the nature of the geological and meteorological processes that are operating to shape the surface. For purposes of this study five interrelated potential science objectives have been identified. *Science Objective #1* is to determine the composition of Titan's surface materials; *Science Objective #2* is to characterize the organic chemistry taking place at Titan's surface; *Science Objective #3* is to describe the interactions between the surface materials and atmosphere; *Science Objective #4* is to characterize the morphology of the surface; and *Science Objective #5* is to describe the surface meteorology (pressure, temperature, and wind speeds). These science objectives are further detailed below:

Objective #1: To determine the composition of Titan's surface materials. Although theoretical models suggest what materials may be found, scientists are certain to be surprised by ground-truth measurements of what is actually there. The present mission study addresses this objective by obtaining measurements of Raman-shifted backscattered light, to characterize surface mineralogy; by assessing the elemental composition of surface materials, via Laser Induced Breakdown Spectroscopy (LIBS); and by additional mass-spectroscopic measurements obtained using a Gas Chromatograph / Mass Spectrometer (GC/MS), which allows discrimination of many organic species. Materials identification would be facilitated by imagery obtained using a sampling microscope, which could examine core samples.

Objective #2: To characterize the organic chemistry taking place at Titan's surface. Measurements obtained by the suite of composition instruments (GC/MS, LIBS, Raman) together with the complementary surface temperature and other environmental measurements would address this objective. By sampling in different locations, at different depths, and at different times we may constrain the nature and rates of ongoing chemical processes.

Objective #3: To describe the interactions between the surface materials and the atmosphere. As with Objective #2, this objective would require multiple observations by multiple instruments, at multiple locations and with observations spaced in time. Meteorological observations and surface imagery would contribute to this description.

Objective #4: To describe the morphology of Titan's surface. Observations by the Panoramic Camera (PanCam) could provide information on surface structures over distance scales from millimeters to hundreds of meters. This information may be difficult to obtain from orbit.

Objective #5: To describe the surface meteorology of Titan. Orbiter missions would provide global information on clouds, precipitation, hazes, and atmospheric composition. However, in-situ information on temperature, winds, and precipitation is of intrinsic interest, as it constrains key processes taking place at the surface. Among the processes of interest are chemical reaction rates and fluvial and wind-driven erosion rates. The meteorological package included in this mission study would provide measurements that address this objective. The acoustic monitor would provide complementary data.

Based on the above science objectives, the Titan rover mission concept aims to land a long-lived roving in-situ explorer on the surface of Titan. The mission would launch on an Atlas V 501 on a 7.6-year transit towards Titan. Using an aeroshell and parachutes the Titan rover would be delivered to the surface, where it would then deploy and begin its primary mission. The rover would operate on the surface for three-years mission, studying the composition and chemistry of the surface materials.

MISSION ARCHITECTURE OVERVIEW AND ASSUMPTIONS

The Titan rover mission described here has many common elements with the Mars Science Laboratory (MSL) mission, which is currently in development phase. (It is assumed that utilizing heritage from MSL could reduce mission cost.) In both cases the rover would be launched on a direct entry trajectory to their destinations. During the cruise phase the rover would be inside a Viking style aeroshell. It would be long lived on the surface, powered by a Radioisotope Power System (RPS). MSL down-selected a single Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), while this Titan rover concept assumed Advanced Radioisotope Power Systems (ARPS).

Table 1 shows six trajectories that were considered between 2012 and 2015. Initial trajectory calculations were performed for a Delta IV-H L/V, representing a boundary case scenario for the highest deliverable mass to Titan with today's technology. From these six opportunities the 2015 launch – utilizing an Earth-Jupiter (EJ) gravity assist – would allow for a launch mass or 5730 kg and an entry mass of about 4200 kg. At this opportunity the spacecraft would be launched at a C3 of 25.7 km^2/s^2 and it would arrive to Titan after a 7.6-year cruise time. The corresponding aeroshell entry velocity at Titan for direct entry is 5.9 km/s, which is comparable to the 5.4 km/s entry velocity of MER. This entry velocity, therefore, does not require dedicated technology development for the thermal protection system (TPS) of the aeroshell. Instead, it could use the same TPS materials as used on previous Mars missions or on the Huygens probe to Titan.

TABLE 1: Trajectory Options to Titan

	Date	GA	T (yrs)	C3 (km^2s^{-2})	DLA (deg)	M_{launch} (kg)	DSM (ms^{-1})	$M_{@9.5AU}$ (kg)	V_{entry} (kms^{-1})	M_{entry} (kg)	$M_{payload}$ (kg)
1	2013-14	--	6.1	105.2	10	500*	--	480	4.9	~280	~75
2	2016	J	6.9	80.8	15	1200*	--	1150	4.6	~950	~240
3	2012	VEEJ	8.7	10.6	15	7730	--	7600	8.2	~6800	~1600
4	2013	E	7.0	47.9	-22	3500	650	2800	6.6	~2000	~480
5	2013	E	8.0	47.7	-22	3500	550	2900	5.5	~2100	~550
6	2015	EJ	7.6	25.7	-12	5730	706	5000	5.9	~4200	~1050

*Atlas V 551 launch vehicle (Delta IVH incapable)

The 2015 opportunity allows for the second highest entry mass with a reasonable cruise time. In comparison, a 2012 launch opportunity with a Venus-Earth-Earth-Jupiter (VEEJ) gravity assist could deliver more, about 6800 kg at Titan entry, but programmatically it was considered too early (just two years following the second New Frontiers mission, and just before the third planned NF mission). Further to this, the trip time would be 8.7 years, over a year longer than that for the selected 2015 trajectory. Therefore, this launch opportunity would not allow time for development of the assumed advanced RPSs and the entry velocity to Titan's atmosphere would be 8.2 km/s, potentially warranting additional TPS development.

It was also assumed that the 4.5 m aeroshell, in which the Titan rover is stowed (see Figure 1), would fit into the fairing of a Delta IV Heavy launch vehicle, when launched to Titan on an Earth-Jupiter gravity assist trajectory. From the original analysis with the Delta IV-H L/V the assumed 800 kg cruise stage and the 730 kg for the 706 m/s Deep Space Maneuver (DSM) represented ~12.3% and ~14% of the launch mass, respectively. However, following the completion of the rover design, the entry mass requirement at Titan was found to be less than 780 kg, significantly less than the ~4200 kg delivery capability of a Delta IV-H L/V. Consequently, alternatives were explored from which smaller L/Vs were selected, namely a Delta IV 4040-12 or an Atlas V 501. Both of these could deliver the S/C to Titan with the inclusion of a downscaled cruise stage and mass allocation for an adjusted DSM. The launch mass for these L/V options would correspond to 1285 kg and 1455 kg, respectively. The mass breakdown for the rover/lander/aeroshell configuration is provided below.

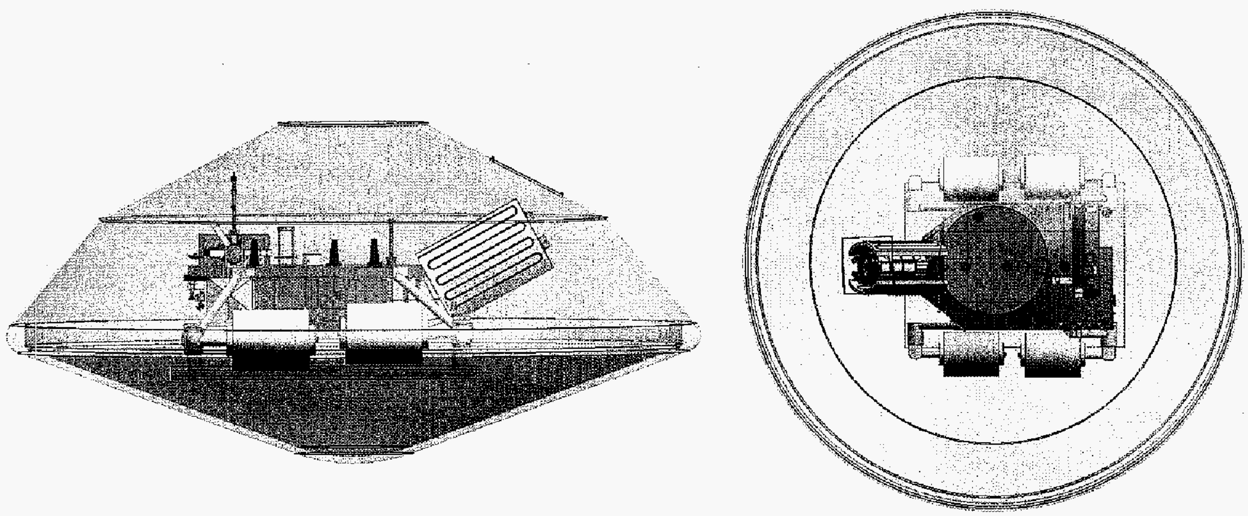

FIGURE 1. Conceptual view of the Titan rover stowed inside a 4.5 m Viking type aeroshell.

Alternatively, this larger delivered mass could allow for the delivery of multiple aeroshells to Titan, or a combination or an in-situ explorer and an orbiter. Both of these options would rapidly escalate the mission cost towards a large Flagship class mission (set at about 4 times the NF cost cap), and consequently could render the mission not feasible. Therefore, as a baseline the smaller mission concept was adopted with a lower category launch vehicle (Atlas V 501) combined with a single aeroshell entry.

Throughout the study the assumed 2015 launch date corresponded to a 2012 technology cut-off date. This class A/B mission warranted full redundancy, although the cost implication of this assumption was not assessed. The full mission duration was assumed at 10.6 years, which includes the 7.6 years cruise phase and the 3 years surface operations.

After arriving to Titan, the MSL-class rover would enter the atmosphere stowed inside an aeroshell on a "dead" un-powered pallet lander – which would include crushable materials to absorb landing shocks. The aeroshell would be used to slow down the atmospheric entry, followed by a Viking style parachute landing. The aeroshell was not designed in detail. Instead, it was assumed that it would account for 35% of the entry mass. Upon completion of the rover design, it became apparent that the aeroshell was much larger than needed for the size and mass of the rover. In addition, the ballistic coefficient of 33 kg/m^2 for the 4.5 m diameter was found to be too low. The minimum diameter to accommodate the rover was determined at 4.15 m, which would only increase the ballistic coefficient to about 38 kg/m^2, a virtually inconsequential change since the desirable value would be between 50 kg/m^2 and 150 kg/m^2. As the difference was small, it was decided to keep the aeroshell diameter at the flight proven 4.5 m for an easier accommodation of the rover and ARPS. The ballistic coefficient issue could be resolved by adding ballast mass to the aeroshell; and for stability, moving the center of gravity forward.

The rover would make a hard landing atop the rectangular lander platform ~1.5 m by 2.0 m in size. Based on the aeroshell and parachute configuration the velocity at landing would be ~6 m/s. To withstand the impact, the pallet lander would need an approximately 2 cm thick crushable material base, allowing the mission to stay within the assumed 40 g acceleration/deceleration load tolerance of the ARPS.

The Titan rover would use an MSL chassis and electronics layout, with a mast mounted Pan Cam, rear mounted ARPS, and forward mounted robotic arm with the sample gathering drill. Once landed, the rover would deploy its inflatable wheels and perform initial system checks. Next, the rover would start its three-year surface mission. The wheel deployment process is shown in Figure 2. The four 1.5 m diameter inflatable wheels offer the Titan rover advantages in traversing the surface of Titan, compared to smaller rigid wheels used on MER and planned for MSL. Unlike the dry and sandy surface of Mars, Titan could potentially have a gummy, organic surface that could bog down small wheels. The large inflatable wheels could also offer the rover concept the ability to float on the surface of liquid methane lakes, which are suspected on Titan. The rover would receive electric power and thermal energy for heating from its ARPS. The baseline configuration assumes an Advanced-RTG, however, other ARPS options could also be considered without a significant volume and mass impact.

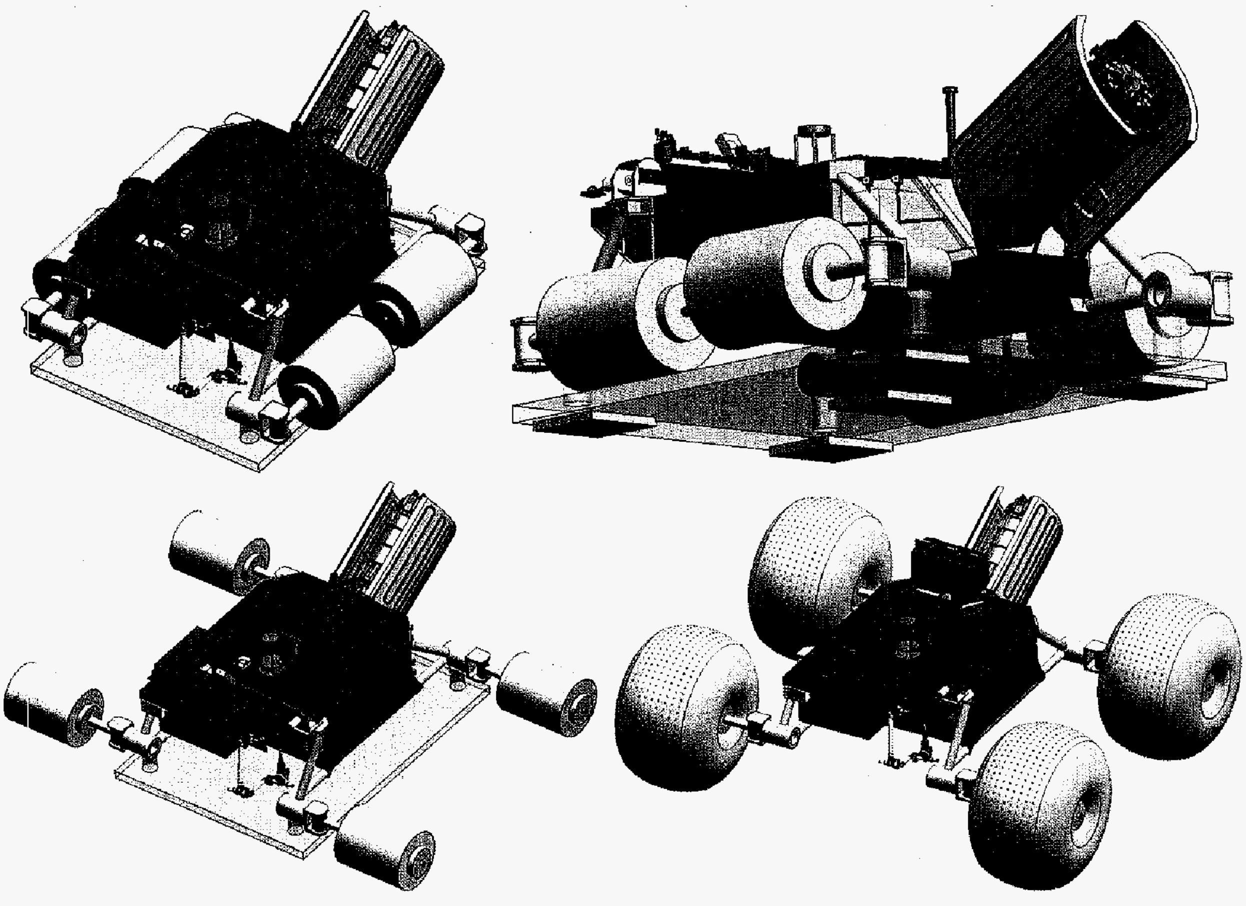

FIGURE 2. Deployment concept of the Titan rover from stowed configuration on a palate, in counter clockwise, through wheel deployment to inflated wheels and deployed mast

POWER SYSTEM OPTIONS

The following section discusses power system trades, and then outlines the characteristics of the Advanced-RTG, selected for the baseline configuration. A comparison is also provided to the Advanced-Radioisotope Thermoelectric Generator (ARTG), Advanced-Stirling, Advanced-Brayton and Advanced-Thermal Photovoltaic (ATPV) power systems.

Power Source Trades Comparison

In this ARPS focused mission study the power system trade space included ARPSs; solar power generation; batteries; and fuel cells. Fuel cells would be impractical, because the energy requirement over the three-year surface mission would correspond to a prohibitively high fuel mass, well beyond the capacity of the launch vehicle. (Fuel cells and flywheels are better suited for near Earth short duration missions, with the possibility of replenishment.) Primary batteries would not be sufficient for this long-lived rover concept, again due to mass allocation limits. Typically, the primary battery's mass and volume linearly increases with the mission duration. Since the landing location is assumed at or near the pole, the Sun would be in view from the rover on a nearly continuous basis. However, at 9.53 AU the Sun's solar insolation is only ~1% of that at Earth's orbit, without taking into account any loss due to Titan's thick obscuring atmosphere. Therefore, the low insolation would be insufficient to recharge secondary batteries with "rover-size" solar panels and to support operational scenarios. Potentially, a Titan surface mission could consider the use of Low Intensity Low Temperature (LILT) photovoltaic arrays. To meet the energy level of the baseline Advanced-RTG, a corresponding LILT solar array would have to produce an average of 93 We power in order to support an equivalent duty cycle for the rover. LILT solar arrays are used on the European Space Agency's Rosetta spacecraft, producing ~395 We with a 64 m^2 panel at 5.25 AU. Assuming the same efficiency, the present Titan rover concept would require ~50 m^2 of solar arrays to match the electrical output of an Advanced-RTG (assuming the solar insolation to be the same on the surface as it is at Titan's orbit, which is a simplification). In addition, a solar powered spacecraft would require a resistance heating based thermal management system, while the ARPS based rover could utilize the excess heat from the power system, resulting in mass savings. Furthermore, during the cruise phase, powering and thermal managing the spacecraft would require external LILT solar panels, thus further reducing the mass margin for the mission. The mass of these two large arrays (during cruise and on the surface), combined with the structural support, gimbals, and associated equipment to allow the concept to maneuver with the array without blocking the telecom system, would be prohibitively massive and complex, compared to the simple and efficient configuration of a single Advanced RTG based configuration. Consequently, the baseline configuration assumed an ARTG.

ARPS Characteristics

The Titan rover is based on an MSL styled chassis with the ARPS mounted at the back of the rover. The Advanced-RTG is assumed to produce 110 We (BOL). This degrades over time at a constant rate of ~1.6% per year, due to natural decay of the Plutonium-238 isotope combined with the degradation of the thermoelectrics. Consequently, after 10.6 years at the end of mission (EOM) the power output would reduce to ~93 We (EOM). This mission duration is within the 14 year lifetime requirement of an MMRTG, which requirement is also assumed for the ARTG. The rover would land on the surface using parachutes, necessitating methods – such as the use of crushable materials – to reduce deceleration loads to or below 40 g. Five GPHS modules, providing 250 Wt each, produce the thermal power, which is then converted into electric power. At an assumed conversion efficiency of ~9% for the ARTG, a large portion of the 1250 Wt (BOL) / 1054 Wt (EOM) is considered excess heat, which can be utilized to keep the warm electronics box (WEB) above the required temperature. The heat is transferred with a heatpipe system from the heat collector, facing the ARPS, to the WEB. The unused thermal energy convected and radiated to the environment through the ARTG's radiator fins. On the surface of Titan these radiators benefit from the extremely cold temperatures and convection to the atmosphere. Thus, in-situ the ARTG requires only 0.4 m^2 of surface area to reject the excess heat and in effect eliminate the need for radiator fins. However, during cruise phase the rover would be enclosed inside an aeroshell, and consequently it would require active cooling to remove the waste heat generated by the ARTG. The assumed auxiliary coolant loop, similar to the one planned for MSL with an MMRTG, would be connected to the ARTG during cruise and would be discarded before the entry/descent/landing (EDL) phase.

TABLE 2. Titan Rover Mass for ARPS Options

	ARTG (kg) 1 unit (kg)	TPV 1 unit (kg)	ASRG (kg) 2 unit (kg)	Brayton 1 unit (kg)
Rover Mass	375.9	359.0	388.7	381.8
Baseline Delta	0.0	-16.9	+12.8	+5.9

Alternative RPS Power Systems

While the baseline configuration of the Titan rover concept was assumed with a single ARTG, mission success could be also achieved by employing alternative ARPS options, after implementing slight modifications to the design in order to accommodate these new power systems.

As shown in Table 2, there is a negligible mass impact on the rover mass for the examined power configurations. The total system mass difference between the highest (Advances Stirling) and lowest (ATPV) allocation was found to be only ~30 kg. From the standpoints of rover mass allocation and mission safety, the ATPV option offers the best choice. The performance would be also similar to the ARTG, with 110 We (BOL) and 89 We (EOL). However, the ATPV requires larger radiators during cruise and also on the surface among the four ARPSs and could result in volume accommodation difficulties.

The Advanced Stirling Radioisotope Generators utilize a dynamic power conversion method. According to design principles for this configuration the rover requires a redundant power unit to assure mission success. This would necessitate a configuration with two or three ASRGs. A single ASRG generates less power than an ARTG, but with the required redundant the two ASRG units would provide ~50% higher power output. For this configuration, the failure of the redundant unit would limit rover operations, compared to the ARTG configuration. In case of using 2 ASRGs with a redundant unit, the total power output would be more than twice of the baseline configuration, and even following a loss of the redundant unit the rover would have significant surplus power. This excess power would allow for an expanded duty cycle, translating to longer traverse over the mission lifetime. Both of these ASRG configurations, however, would have a mass impact on the rover. Conversely, Advanced Brayton units do not require redundancy, because the failure of one of the two generators would still allow the rover to operate at full capacity, once the remaining turbine is sped up to compensate for the power loss from the other unit. Although there might be a resulting torque increase for the operating side, the now unbalanced Brayton generator is not expected to create problems for the rover during surface operation or for the spacecraft during cruise.

For an additional comparison, it should be noted that this Titan rover concept could use an MMRTG instead of an ARPS. The corresponding a mass penalty would be only ~17 kg, which is considered an insignificant mass increase. For the same electric power output an ARTG generates about 750 Wt less heat, which reduces the cruise phase radiator size requirement. These mass benefits for ARPSs, however, are only enhancing rather than enabling.

SCIENCE INSTRUMENTS

The Titan Rover described in this study carries a suite of instruments to satisfy the science goals for the mission. The environmental and engineering instruments (radiation sensor, acoustic monitor, meteorology package) are relatively simple. The *Meteorology Package* was included to obtain in-situ data on atmospheric pressure, temperature, and winds, and would directly addresses Science Objectives #3 and #5. This type of instrument has been used on Pathfinder and MER. The *Acoustic Monitoring System* would record the distribution of ambient sound waves at Titan's surface, thus addressing Science Objectives #3 and #5.

The *Panoramic Camera* (PanCam) is becoming a standard instrument on surface mission concepts; and it reflects heritage from the highly successful Mars Exploration Rovers. This instrument directly addresses Science Objective #4 of the present mission, through description of the morphology of Titan's surface. In addition, PanCam imaging would provide needed context for interpreting all of the compositional measurements by other instruments. The PanCam would be mounted atop a 1.5 m tall mast that would fold against the deck of the rover in its stowed configuration during cruise and EDL phases. The mast would also accommodate two *Navigation Cameras* (NavCam) and a *fisheye camera* pointed to the sky. The latter would allow the rover to gather detailed information on its position and orientation throughout its surface operational lifetime.

Compositional measurements would be enhanced by obtaining subsurface samples with an *Ultrasonic Drill Coring System* from as deep as ~10-20 cm. The corer would be mounted on the *robotic arm* in a retractable pod. This robotic arm could position the corer against targets of interest. Samples collected with the corer would be placed inside a *rotating sample carousel* for further processing with a "compositional analysis" instrument. Coring and post analysis operations target Science Objectives #1, #2 & #3.

The "compositional analysis" instruments are included to obtain complementary information on the collected samples. Specifically, a *Raman spectrometer* could nondestructively determine molecular compositions of ice, minerals, and some organics. The *Laser Induced Breakdown Spectrometer* (LIBS) would ablate the surface of a small sample, generating short-lived plasma, whose emissions constrain its the elemental composition. The *Gas Chromatograph / Mass Spectrometer* (GC/MS) would characterize organics more precisely than is possible with Raman and LIBS, and is particularly valuable for detecting the most volatile species. These instruments address Science Objectives #1, #2 and #3.

Finally, the addition of a *Sampling Microscope* would greatly aid the categorization of the surface material physical properties. By resolving textures, colors, and crystallinity of samples, this instrument would address Science Objectives #1, #2, #3, and to a lesser extent #4 and #5.

OPERATIONS AND ENVIRONMENTS

The following section discusses power usage and sizing; data and communication issues; mobility and navigation; and thermal and radiation environments.

Power Issues

The Titan rover is designed with a hybrid power system, which includes an Advanced-RPS and a secondary battery. The baseline configuration carries the single Advanced-RTG and a 12 A-hr rated Li-Ion battery, optimized for total energy availability over repeatable operational cycles. The ARPS provides a constant 94 We (EOM) of power to the rover's systems. Power requirements for high-powered operations are above this constant power. High-power daily operating modes include 2 hrs of telecom (142.3 W), 5.1 hrs of driving (138.4 W), and 3.1 hrs of high data rate science operations (146.7 W), when the systems and instruments draw power from both the ARPS and the battery. At low-power science operating modes (66.1 W) the ARPS would recharge the battery. These operating power modes for the rover are outlined in Table 3. The rover was designed with DSA/X2000 power electronics. Electrical systems on the rover are run from an unregulated 28V DC power bus, without the need for power conditioning. The

TABLE 3. Titan Rover Power Modes.

	Science Low (W) 1.55 hrs/day	**Science High (W) 3.1 hrs/day**	**Telecom (W) 2 hrs/day**	**Drive (W) 5.1 hrs/day**	**Recharge (W) 12.25 h/d**
ACS	10.6	11.6	7.8	49.8	0
C&DH	6.5	6.5	6.5	6.5	6.5
Power	3.1	6.9	6.7	6.5	2.0
Struct. & Mech.	0.0	0.0	0.0	20.0	0.0
Thermal	18.7	18.7	18.7	18.7	18.7
Telecom	5.0	5.0	69.8	5.0	5.0
Instruments	7.0	64.2	0.0	0.0	0.0
Total (CBE)	50.8	112.9	109.4	106.5	32.1
Contingency	30%	30%	30%	30%	30%
Total (CBE + Cont.)	**66.1**	**146.7**	**142.3**	**138.4**	**41.8**

duty cycle is driven by the constant power output of the ARPS. Adding further units to the system would enhance the science gathering capabilities of the rover and could eliminate the need for long battery recharge times. However, continuous operation would also translate to added operational load on ground resources and personnel. Autonomous navigation with input from the NavCams and HazCams could also enhance extended operations, but would potentially require significant technology investment. Therefore, changes to the power system should be assessed in an integrated manner in order to evaluate the full impact on the mission.

Data and Communications Issues

Information onboard the rover would be processed by a dual string Command & Data Handling (C&DH) system. Mission critical and science data would be stored on flash memory cards (up to 16 Gbits), and would be transferred through a daily 2 hours Direct-to-Earth (DTE) telecom link. Data compression could reduce the average transmitted data volume to about 28.8 Mbits per day. This data rate is significantly less than the rover's on-board storage capacity, however, it would provide robustness for potential missed telecom opportunities. Data rate and volume information are summarized in Table 4. Each of the two C&DH strings would utilize an advanced Power PC processor. (The electronics used in the C&DS system are assumed to tolerate up to 50 krad TID radiation with an RDF of 2.) The telecom system on the Titan rover would communicate back to Earth at an 8.4 GHz X-band frequency, through a 0.5 m diameter / 2 axis gimbaled High Gain Antenna (HGA). The rover would communicate to the upgraded antenna array of the Deep Space Network. The DSN would dedicate 180 of its 12 m antennas (out of the planned 400) to the rover mission over the telecom window. (The mission architecture could also assume the use of the 70 m DSN antenna, but that would increase the required telecom time to ~8 hours, which would reduce resources to other operational scenarios.) The assumption of DTE communication plays a critical driving role in choosing a suitable landing site, as only one of the poles would allow for direct daily communications with Earth. From the polar region of Titan, Earth would stay ~20° to 25° above the horizon for the entire telecom period. HGA pointing to Earth would require control of the mechanical boresight within 1 degree (3 sigma, RSS of 2 axes). As a backup to the HGA, two omni-directional low gain antennas (LGA) would be also installed on the rover. The two LGAs would be located on opposite sides of the rover's top deck. In case of communication loss through the HGA, the rover could reorient until Earth would falls into the boresight of an LGA and reestablish contact with the DSN. When pointing back from Saturn, Earth lies very close to the Sun. Therefore, in an emergency scenario the Sun sensor could be used to reorient the rover towards Earth.

TABLE 4. Titan Rover Data Rates.

Instrument	Data Rate/Volume
Met Package (wind sensor, pressure, temperature)	57.4 kbit/day
Radiation Monitor	10 kbit/day
Acoustic Monitor	100 kbit/day
Sampling Camera/ Microscope	8 Mbits/frame
Chemistry Package (GCMS/ES-IMS/CE etc.)	1 Mbit/analysis;
Raman Spectrometer	17 bits/spectra (raw); 50 Raman spectra/hour
Panoramic Camera	50.4 Mbits per frame (raw); 12 frames for full panorama
LIBS	30 kbits/sprectra

Mobility and Navigation Issues

The Titan rover was designed with four large (1.5m diameter) inflatable wheels. Each wheel would be constructed out of PBO (polybenzoxazole)/Xylon and would carry a small electric pump to inflate it by pumping in the ambient atmospheric gas. The rover's inflatable wheels and compliant suspension configuration would allows it to easily adapt to a wide variety of terrain, that could be encountered throughout the lifetime of the mission. As Titan has only 1/7th of Earth's gravity, each wheel would require ~5 W of power to operate, totaling ~20 W for the entire rover. During driving periods the rover would traverse the surface at a maximum speed of 0.15 m/hr, covering up to 750 m each day. Over the course of the 3-year mission, the rover could drive up to ~800 km, although the actual distance would likely be less due changing operational scenarios driven by daily science priorities. Although the angular velocity of the rover's axis was assumed to be similar to that of the MER rovers (~35 m/hr with 25 cm wheels), the larger diameter wheels translate to these higher velocities. This would also result in higher requirements for autonomy and hazard avoidance. In a typical driving scenario, the rover would receive a driving trajectory from mission controllers that would include relative directions and distances. From there the rover would rely on its onboard processing and cameras (NavCam; HazCam; & PanCam) to execute the command and negotiate the local terrain. The rover's orientation could be determined at any moment using the accelerometers, the Sun sensor, the nadir pointing star sensor and the various onboard cameras. Local landmarks could be identified, stored and monitored by the NavCams. Pictures taken and processed at regular intervals during short stops, could help to calculate the rover's relative position. Additional information could be gained from the Inertial Momentum Unit (IMU) and from the wheel tachometers. After completing a traverse activity, the new absolute position could be determined and adjusted by mission controllers from the transferred data. PanCam and NavCam images could be pieced together during post-reconstruction of a traverse to generate a contiguous pictorial map. Absolute position estimates taken over the course of the mission would be used to determine the map scale and cross referenced with PanCam images of the surface of Titan.

Furthermore, many scientists believe that bodies of liquid methane may exist on Titan. With its large inflatable wheels, if required, the Titan rover concept would be able to float on a liquid methane body. The rover's weight on Titan would be 526.8 N. This corresponds to ~0.84 m^3 of displaced liquid methane, which is less than 20% of the volume of the wheels. This could also allow for intentionally entering bodies of liquid and collecting scientific samples from there.

Similarly to MSL, the Titan rover would interface with the environment through MER heritage navigation cameras (NavCam) and hazard avoidance cameras (HazCam). The NavCams, with 2 Degrees of Freedom (DOF) movement, are mounted on mast near the PanCam, providing a function for identifying obstacles that would interfere with traversing. The obtained information would allow for autonomous hazard navigation, thus significantly enhancing the rover's ability to traverse. The Titan rover could travel at a rate of up to 0.150 km/hr for up to 5 hours a day. This would allow the rover to cover considerable grounds over its mission duration.

The Attitude Control System (ACS) would provide control and knowledge during traversing. The direction heading would be controlled within 2 degrees of commanded trajectory (3 sigma, zero-to-peak); while the heading knowledge to less than 1 degree (3 sigma, zero-to-peak); the knowledge of absolute position on the surface would be maintained within 5 km (2 sigma, RSS of 2 axes); and knowledge of relative position would be kept within 10 meters (3 sigma, RSS of 2 axes). The baseline Direct to Earth (DTE) communication would require high gain antenna-pointing control of the mechanical boresight within 1 degree (3 sigma, RSS of 2 axes) allowing for post-reconstructed position knowledge, using Earth resources for data post-processing. The high gain antenna is assumed to have 2-axis articulation with accuracy able to meet the pointing requirement of 1.0 degree of control and 0.5 degree of knowledge to communicate DTE. Earth's position would be established in relations to the Sun. The PanCam and sky cameras would be able to measure direction of the Sun within 0.5 degrees (3 sigma), allowing the telecom system to meet its pointing requirements.

Thermal Issues

To maintain system operating temperatures, the Titan rover would use passive and active Thermal Control Systems (TCS) throughout its mission lifetime. In order to reduce power loads on the electrical system, the rover was designed without electric heaters. The required thermal environment would be maintained by utilizing the radio-isotopic decay of the ARPS and Radioisotope Heater Units (RHU), combined with insulation of the warm electronic box (WEB). During waste heat utilization, a portion of the heat generated by the RPS is collected and transferred to the WEB by ammonia heatpipes. A second set of variable conductivity heatpipes were assumed for a tight temperature control of specific components, such as the telecom transmitter. Flight electronics are contained within the insulated WEB. The Advanced-RTG used in the baseline design produces 1138 Wt (BOL) or 1054 Wt (EOM) of thermal energy after electrical conversion. Due to the cold environment on the surface of Titan, only the TPV option would require radiator fins, while the other ARPS designs could reject the heat through their housing alone. During the cruise phase, the aeroshell would trap in the heat, generated by the RPS. This would necessitate a thermal design, where the heat would be rejected through second set of external radiators. To protect the spacecraft from the heat generated by the aerocapture maneuver in Titan's atmosphere, the spacecraft would carry a heat shielded aeroshell. During the aerocapture maneuver, when the external radiators are no longer used, Phase Change Material (PCM) could be utilized to store the excess heat from ARPS. This PCM would be ejected with the aeroshell after entry into Titan's atmosphere.

Driver motors and arm actuators are outside of the WEB and the heatpipe loop. To keep these components warm, 30 fixed and variable power RHUs were assumed in order to provide local spot heating. Variable power RHUs would use movable conduction plates for the regulating the amount of heat transferred by their constant heat output. This would allow for tighter temperature control of the components compared to standard RHUs.

Radiation Issues

Saturn's radiation environment is benign compared to that of the Jovian system. Therefore, the Total Ionizing Dose (TID) radiation experienced by the rover on Titan during the 3 years of surface operation is virtually negligible. The largest TID contribution is assumed to be the result of the Jupiter flyby during the chosen Earth-Jupiter gravity assist trajectory. However, this would only amount to less than 40 krad of radiation behind 100 mils of aluminum with a typical Radiation Design Factor (RDF) of 2. In addition to environmental sources, the rover concept would accrue a small amount of radiation dose from its Advanced RTG. MSL with a single MMRTG will receive ~2 krad TID from the RPS (with an RDF of 2) over the course of the cruise phase to Mars and the assumed 1000 sol surface operation (Jun, 2002). The Advanced-RTG (with 5 GPHS modules) has only 63% of the Plutonium-238 used for an MMRTG (with 8 GPHS modules). Consequently, the ARTG has a correspondingly lower TID rate. Over the 10.6 year long mission of the Titan rover this results in up to ~3.6 krad TID with a RDF of 2; nearly twice that of MSL. The summed up TID, including all contributing sources, would be less than ~44 krad with an RDF of 2. It is well within the radiation tolerance limit of today's electronic components. Therefore, to accommodate this the electronics onboard the rover are designed to be radiation hardened to 50 krads with an RDF of 2.

MASS

The mass breakdown of the Titan rover concept and that of the associated stages are shown in Table 5. For the baseline configuration the rover mass is calculated to be 376 kg, including 30% contingency. With an Atlas 501 L/V a total mass of 1455 kg could be delivered on a direct trajectory to Titan, at a C3 of 25.7 km^2/s^2. When the Titan rover's entry mass of 778 kg (including rover, lander and aeroshell) is deducted from the delivered mass, the resulting mass of 677 kg is assumed to be available for the cruise stage, the Deep Space Maneuver (DSM) and launch vehicle contingency. Since the cruise stage requires less than 200 kg for the present configuration, the large launch margin would be available to accommodate any growth in the rover's mass during development. Additional unallocated mass for the rover could be used for more science instruments or potentially for adding further ARPS units to increase the power and thus increase the rover's traversing capability.

TABLE 5. Titan Rover Concept Mass Breakdown.

Subsystem	Mass (kg)	Contingency %	CBE + Contingency (kg)
Rover Total	289.1	30%	375.9
Instruments	38.0	30%	49.4
ACS	13.1	21%	15.9
C&DS	3.0	30%	3.8
Power	35.2	30%	45.8
Structures	149.4	30%	194.2
Telecom	19.5	12%	21.7
Thermal	31.0	28%	39.7
Landing Pallet	91.0	30%	130.0
Aeroshell	272.4	(35% of total mass)	272.4
Entry Mass	**652.5**		**778.3**

CONCLUSIONS

This Advanced-RPS technology focused mission study demonstrated the feasibility of an MSL class Titan rover concept, using four 1.5m diameter inflatable wheels. The RPS trades used for this study included an ARTG; a ATPV; a Advanced-Brayton; an Advanced-SRG; and an MMRTG. The mission concept addressed five defined science objectives for the in-situ exploration of Titan. The initial mission drivers also included small scale and simplify.

Six launch opportunities were evaluated, from which a trajectory with an Earth-Jupiter gravity assist was selected. The mission would launch in 2015, while the cruise would take 7.6 years. An Atlas 501 launch vehicle would deliver 1455 kg of mass to Titan. Following atmospheric entry, the rover on the surface would have a total mass of 376 kg, including 30% contingency. The rover would operate on the surface over a nominal lifetime of 3 years, powered by a single advanced RTG. Additional trade calculations indicated that other Advanced-RPSs, such as Advanced-Stirling, Advanced-Brayton and Advanced-TPV could substitute the ARTG without a significant mass penalty. Furthermore, it was found that a standard MMRTG could also enable this Titan rover concept and would only increase the rover mass by less than 5%. It should be noted that this design is not optimized, therefore, the mass and power values only provide a first order approximation.

Technology challenges for a Titan rover mission include: Direct to Earth communications; extreme environments issues, such as materials for the cold (94K) surface operations, inflatable wheels, actuators, joints; sticky tholin deposits on imaging systems; development of advanced RPSs; and autonomy and navigation issues.

Note that this study was performed on a small budget. Therefore, a follow on detailed point design is recommended on a suitable configuration, driven by science objectives, in order to better understand the trade space, the size and affordability of such a mission.

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