Planetary Probe Entry, Descent, and Landing Systems: Technology Advancements, Cost, and Mass Evaluations with Application to Future Titan Exploration Missions.

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ABSTRACT

Heritage is the double-edged sword in space systems engineering. Reliance on heritage can ensure redundant success but will diminish advancements in science and technology that are integral to the success of future missions. Current reliance on heritage flight hardware is due to the absolute cost ceilings and short development timetables. Since the pre-phase A design stage mandates that system engineers establish complex and crucial decisions governing the mission design, system engineers would greatly benefit from an apples-to-apples comparison of the mass and cost benefits from different technologies across a range of performance parameters. The Cost and Mass Evaluation of Technology (CoMET) removes the “hand-waving” arguments in EDL technology benefits, and identifies possible points of diminishing returns for the advancement of specific technologies. Ultimately, CoMET: EDL is a design-to-cost model that answers the following question: Would further technology development just be “polishing the cannonball?”

EDL sub-systems include, but are not limited to, aeroshell and thermal protection entry systems; parachute systems; powered descent and landing systems; power systems; and in-situ exploration systems of aerobots. CoMET explores the technology trades between mass and cost in the collaborative engineering environment regarding key technology areas and launch vehicle considerations. To demonstrate CoMET’s potential in confronting future mission concepts that require new operational approaches and technology advancements, a planetary probe mission is designed around the exploration of Saturn’s moon, Titan. In January 14, 2005, the planetary probe *Huygens* befell Titan’s surface in search of life’s origins. On the Titan-*Huygens* probe, the limitations of communications relay geometry and battery power vastly restricted the operational time, scientific goals, and total returns of this mission. Without the improvement of battery efficiency or the evolution of nuclear power systems, state of the art technology will always restrict planetary scientists to short-duration missions and miniscule data sampling. Furthermore, to capitalize on each planet’s or moon’s unique environment, future probes will require innovative systems of in-situ exploration, such as blimps for mobility in dense atmospheres. This paper explores mass, cost, and technology trade-offs of an airship among several EDL technologies within general mission requirements of a mission to Titan. –

1.0 Cost and Mass Evaluation of Technology (CoMET)

During the process of spacecraft and mission design, decisions on the investment and selection of new technology are often made without a qualitative or quantitative analysis of its impact. To address this shortcoming, several partner universities are developing a technology trade evaluation tool for the Laboratory for Spacecraft and Mission Design (LSMD) at the California Institute of Technology, under the guidance of NASA's Jet Propulsion Laboratory (JPL). The purpose of the tool is to determine the technological areas that would benefit most from development and that would subsequently improve spacecraft performance.

CoMET is a technology evaluation tool designed to illuminate how specific technology choices affect a mission at each system level. CoMET accomplishes this task through its most powerful feature, a sensitivity analysis. The analysis provides the "partials with respect to technology" which allows system engineers to execute intelligent technology trade decisions. CoMET can examine the "ripple" effect one variable may or may not have on any other variables and parameters; with approximately 500 inputs and internal parameters. CoMET can calculate the effects of mass and cost of changing 23 different technology parameters. The level of sensitivity and range of interest is adjustable to mission configurations and system variations. Yielding a tabled set of values and graph, CoMET automates all calculations within its Microsoft Access Database and Excel worksheets.

Given the required inputs, each Excel worksheet ultimately computes the mass at a system and sub-system level. For example, one Excel worksheet may display the EDL system mass as 980 kg; behind that Excel worksheet are several other worksheets that have calculated sub-system masses for TPS, Parachute systems, In-situ Exploration, and Power Systems, in addition to the calculations associated with each sub-system (temperature, gas density, specific power). Microsoft Access unites the discordant Excel worksheets into a user-friendly interface, shown at the system level in Figure 1.

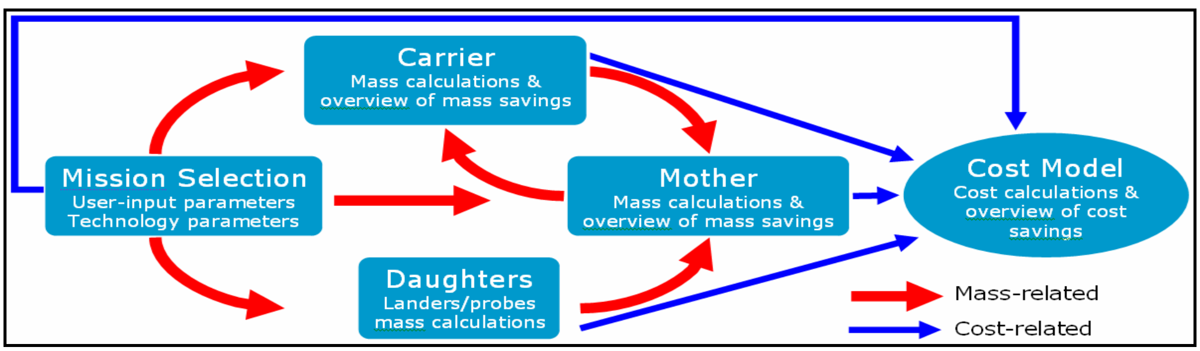

Figure 1: Cost and Mass Evaluation Tool Architecture

Previously mentioned, CoMET is a technology evaluation tool that bestows to system engineers the effect(s) of technology advancements on one or more systems, as well as its cumulative effect on the spacecraft as a whole. This critical information allows system engineers to execute the important decisions that will affect current and future missions. CoMET's range of evaluation is only limited by its mass and cost simulations of the Carrier, Mother, and Daughter Systems. The Carrier, Mother, and Daughter systems are defined as the main spacecraft bus, planetary orbiter, and planetary probe. These simulations were developed through historical data fits, exact engineering methods, and modeling relations obtained from JPL researchers; the simulations are validated to actual space probe missions i.e Mars Pathfinder; or to advanced mission studies conducted by JPL's Team X.

While CoMET can peruse technology advancements for the *entire* space mission – launch vehicle, carrier, mother, and daughter – this paper will focus on technology advancements in daughter craft, specifically with an application to a second mission to Titan. Section 2 will describe CoMET's cost and mass evaluation methods of planetary entry systems. Section 3 will showcase specific technology trade-offs for an airship mission to Titan. Titan is an invaluable moon to study unique atmospheric conditions and possibly gain new insight to the atmospheric models of Mars, Venus, and Earth.

2.0 Planetary Entry Systems

In the Daughter worksheets, CoMET can examine several Entry, Descent, and Landing (EDL) sub-systems, such as Thermal Protection System (TPS), Parachute systems, Powered Descent and Landing, Power Generation Systems, and Airships/In-Situ Exploration Craft. These subsystems are modeled separately and then integrated as needed into the daughter craft worksheets. The subsequent sections will explain the technical rational behind the engineering models for EDL sub-systems.

2.1. Thermal Protection System (TPS)

Divided into a thermal management system and an ablative/non-ablative heat shield, the Thermal Protection System (TPS) of the planetary probe protects the daughter craft during re-entry from significant convective and radiative heating due to the probe's entry velocity and the planet's atmospheric density. The cause of convective heating is due to skin friction from atmospheric molecules traveling at hypersonic speeds; the heat rate and summarily heat load are easily calculated (or approximated) as a function of planetary density and scale height with the probe's entry velocity integrated over time. However, the root of radiative heating stems from dissociated and ionized molecules that exhibit radiative effects; in other words, at a certain threshold temperature for a given density, molecules will radiate energy (heat through photons) without the need for a fluid transfer medium. The effect of radiative compared to convective heating varies with the mission: during shuttle reentry, radiative heating is simply negligible; during the Galileo probe entry to Jupiter, the peak radiative heating was over 85% greater than peak convective heating (Ref 1).

The purpose of this section is to describe briefly approximate and exact methods that calculate the required TPS mass. For a more in depth higher reading, the reader should delve into this paper's references. The reliance on heritage is no more blatantly obvious than on TPS. Including Mars *Phoenix,* all Mars probes have used SLA-561V, developed during the *Viking* years; used on *Stardust,* PICA-15 is the latest TPS product development, with its project completion in the mid-1980s. Granted that past probe missions have not demanded a total redesign of heat shield material, the future and more difficult missions – Jupiter polar entry, Mars Sample Return -- would greatly benefit from evolutions in TPS.

In the convective heating regime, two methods exist to determine heat shield mass: a historical-based method and a recession rate model. In Figure 1, the total heat load determines the TPS Mass Fraction during entry. As probe missions increase, the historical data will increase and subsequently Figure 1's accuracy. CoMET's calculated heat load and subsequent TPS mass fraction are validated with Mars Pathfinder (MPF), Mars Exploration Rover (MER), Venus-*Pioneer,* and Mars-*Viking* in Tables 1 and 2.

CoMET's calculated heat load is an overestimate to validation results since heat load is the time integral of the heat rate, which CoMET calculates at the stagnation point by Sutton-Graves (Equ 1). The underlying cause of error in Table 2 is Figure 1's best fit curve of with R^2 of 0.80. Since not all probe missions in Figure 1 lay exactly on lay exactly on the best fit curve, CoMET calculations will always possess validation error regardless of accuracy to heat load validation. However, since the error is the same for any given mission, the relative benefit of improved TPS will still result in valid comparisons.

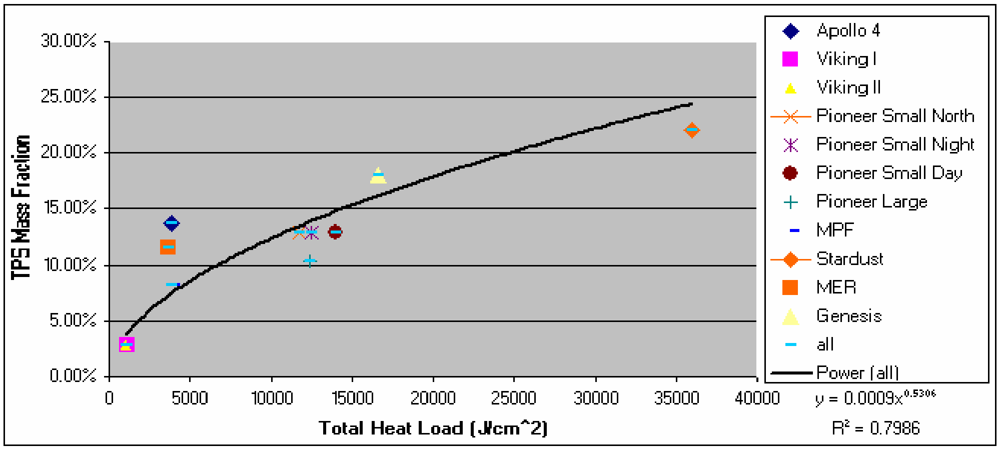

Figure 2: TPS Historical Mass Fraction (Ref 5)

Table 1: CoMET Heat Load Validation (Ref 2)

Mission	Actual Heat Load (J/cm^2)	Calculated (J/cm^2)	Error
MPF	3864.5	4201	8%
MER	3687	5674	35%
Pioneer L.	12400	14000	11%
Viking I	1100	1411	22%

Table 2: CoMET TPS Mass Fraction Validation (Ref 2)

Mission	TPS Mass Fract. from Entry	Predicted TPS Mass Fract.	Error
MPF	8.20%	7.53%	-8%
MER	11.60%	8.83%	-24%
Pioneer L.	10.35%	14.26%	38%
Viking I	2.80%	4.22%	51%

The second method available to CoMET is a recession rate method for ablative heat shields. Ablative material reduce incoming heat flux in a combined process of pyrolysis, charring, and recession. Heating "cooks" the composites' resin in a process called pyrolysis: eventually pyrolysis consumes the resin and exposes the reinforcing composite material to heating. As incoming flow heats or "chars" the reinforcing material, the thermophysical properties of the new material begin to change rapidly from its original (virgin) form. The end result is that the composite's density decreases; a low conductive char layer forms; and the pyrolysis interacts with the boundary layer absorbing the incoming heat flux. This ablative process is modeled in through Equ. 1, with the constraint that backface temperature is kept below 250ºC. From Through Equ. 2, the recession rate s is calculated; integrated over time to determine total surface recession S; and added to the required insulation thickness to determine TPS thickness.

$$\dot{q}_{CONV.} = \frac{k}{\sqrt{r_n}} \rho^{\frac{1}{2}} V^3 \qquad (1)$$

$$s = \frac{B'}{\rho} \frac{\dot{q}}{(H_{STAG} - h_w)} \cdot \frac{C_H}{C_{Ho}} \qquad (2)$$

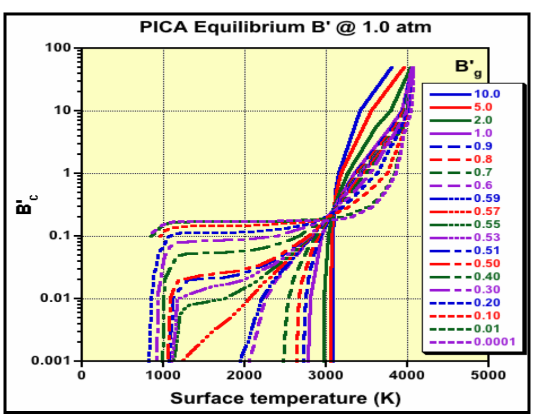

Figure 3: *Stardust* TPS PICA B' Values (Ref 5)

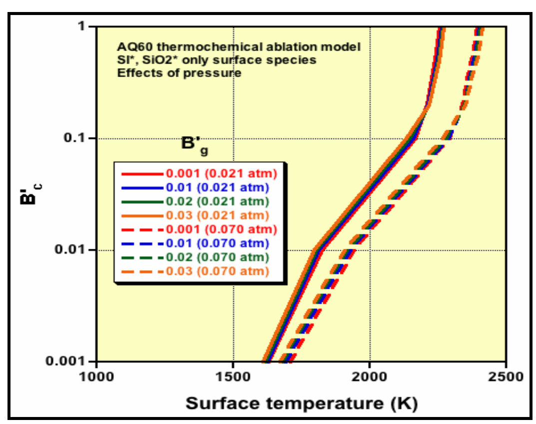

Figure 4: *Huygens* TPS AQ60 B' (Ref 5)

While the recession rate model is more accurate, Equ. 2 is dependent on the non-dimensional mass loss rate, B' (B prime). Shown in Figures 2 and 3, B' varies by material, temperature, and pressure; for Figure 3's AQ60 (*Huygens* TPS), the B' curve follows a linear fit for various temperature segments and does not vary much with pressure. Figure 2's PIA (*Stardust* TPS) is a totally different story. Choosing between the historical TPS method and the recession rate model for CoMET's evaluation depends on B' information publicly available and the mission type under CoMET evaluation. TPS trade studies for a Jupiter entry would have great value, while trade studies to Titan would have only nominal worth.

CoMET has acquired the ability to measure radiative heat rates for a Mars and Earth entry (Ref 3). However, these radiative heat rate approximations by authors Tauber and Sutton are only best-fit curves to the plethora of probe entry data to Mars and Earth. Currently, CoMET cannot adapt these equations for other planets and must rely on approximations for thermal management from Team X.

$$\left.\begin{aligned} \frac{dV}{dt} &= \frac{-\rho V^2}{2\beta} + g\sin\gamma \\ V\frac{d\gamma}{dt} &= \frac{-V^2\cos\gamma}{(R_{eth})} + g\cos\gamma \\ \frac{dh}{dt} &= -V\sin\gamma \end{aligned}\right\} (3) \qquad \left.\begin{aligned} V &= V_{entry} e^{Ce^{-h/H}} \\ C &= \frac{-\rho_0 H}{2\beta\sin\gamma} \\ \beta &= \frac{m}{C_D A} \end{aligned}\right\} (4) \qquad \rho = \rho_O \cdot \exp(-h/H) \quad (5)$$

Both TPS methods are reliant on an appropriate trajectory scheme and density profile. The density profile of any planet is approximated exponentially by Equ.5 with inputs of planet scale height and initial density. The probe trajectory is calculated either through a 3-DOF numerical computation (set Equ 3) or an Allen-Eggers approximation (set Equ.4). Allen-Eggers is only valid for ballistic entries of zero lift and a relatively constant flight path angle γ, but Allen-Eggers is computationally easier for CoMET; produces slight overestimations in trajectory; and generates agreeable heat rate calculations.

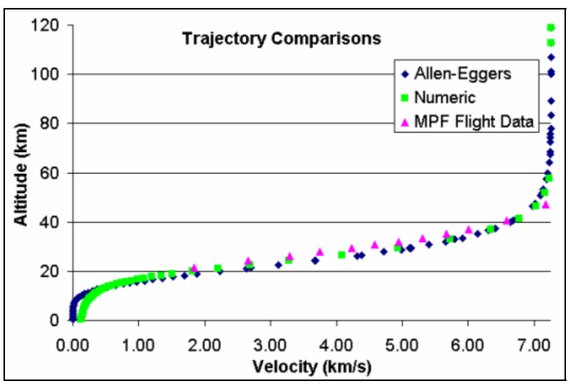

Figure 5: CoMET Trajectory Validation

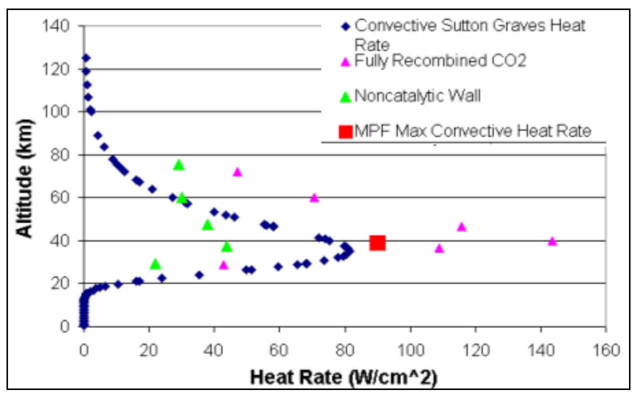

Figure 6: CoMET Heat Rate Validation

2.2. Parachute Systems

The importance of the parachute system is illustrated in the descent phase of atmospheric probes. The parachute system serves not only to provide probe deceleration at specific descent rates and timelines but also to provide probe stability for precision landings. Historically, all atmospheric probes – *Viking, Pathfinder, Huygens,* etc. – have utilized a parachute system deployed in the transonic regime consisting of two to three parachutes: a pilot parachute; the main parachute; and a stability drogue parachute. The pilot parachute must lead the main parachute to deploy and decelerate the probe; after a certain altitude, the main parachute detaches and the stability drogue parachute guides the probe to its landing site. This process is illustrated in Figures 7 for the Titan *Huygens* probe.

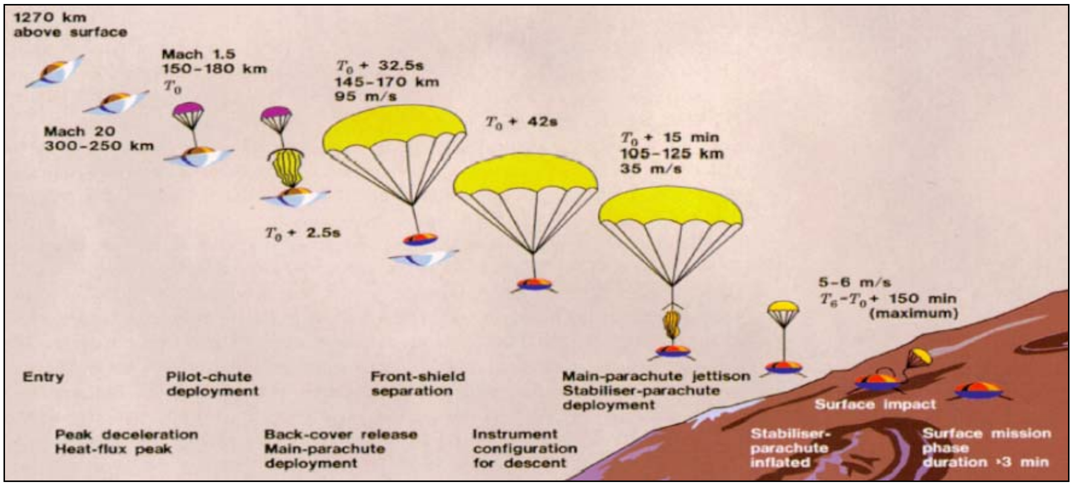

Figure 7: *Huygens* 3-Parachute Deployment (Ref 5)

CoMET's parachute model allows a user choice of parachute type and number; the parachute model calculates the size and mass of the parachute system and its subsystems which include a deployment device, mortar, and container. Originating from Mars *Viking*, the disk-gap-band (DGB) is the most common planetary parachute type which has an extended lifetime to Mars Science Lander (MSL). While DGB parachutes provide heritage and peace of mind to system managers, the ring sail parachute design holds high potential for improved stability and increased drag performance over DGB.

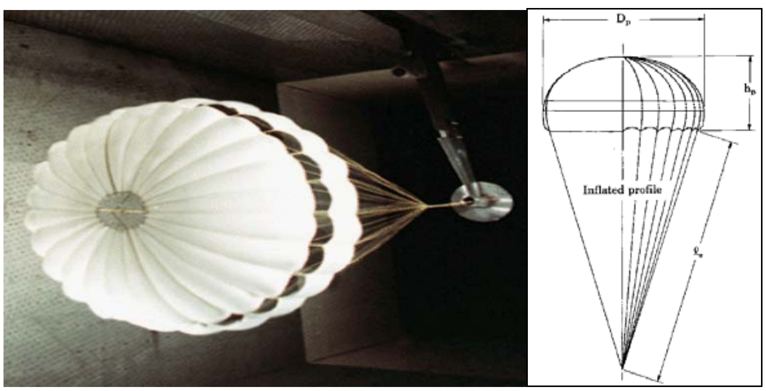

Figure 8: Disk Gap Band Parachute (Ref 7)

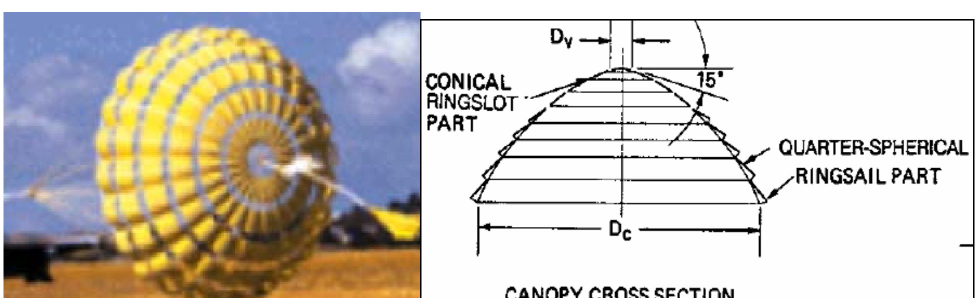

Figure 9: Ring Sail Parachute (Ref 7)

To approximate the mass of a single parachute and its mortar system, CoMET utilizes Equ. 6 and Equ. 7 as functions of the parachute surface area; note that these are rules of thumb developed after decades of parachute testing and design. The nominal surface area S_o of any parachute in terminal descent (velocity) is determined through Equ. 8. The nominal surface area is the area based on canopy constructed surface area and is generally used as the reference area of the parachute.

$$m_p = 0.1055 S_0 \quad (6) \qquad m_{MORTAR} = 2.2 m_p^{0.5} \quad (7) \qquad S_O = \left(\frac{mg}{q} - C_{DEV} S_{EV}\right) / C_{DO} \quad (8)$$

Table 3: Validation of Parachute Worksheet to Mars-*Pathfinder* Data

MPF	Value		Actual Value	Percent Error
Parachute.Main.SurfaceArea	82.4	(m^2)	126.7	34.953
Parachute.Main.Mass	8.7	(kg)		
Mortar Mass	6.49	(kg)		
Total Mass	**15.18**	**(kg)**	**17.5**	**13.257**

If the parachute system consists of one parachute, Equ. 6-8 predict *Pathfinder's* parachute system to 13% error. If the parachute system consists of two parachutes, then an additional variable called the ballistic coefficient β is required. The ballistic coefficient is defined as the ability of a body to overcome the resistance of a fluid. CoMET executes Equ. 9 to determine the pilot parachute's (PC) surface area by equating the probe's ballistic coefficient before and after the deployment of the pilot parachute. If the parachute system consists of three parachutes, then Equ. 10 is needed in addition to Equ. 6-9. When the heat shield is jettisoned, CoMET uses Equ. 10 to calculate the main parachute's (MP) surface area. The previous parachute system mass sizing methods result in a 9% error with Titan *Huygens* parachute mass.

$$\frac{m_{BC} + m_{PC} + m_{MP}}{C_{dPC}\mathbf{S_{PC}} - C_{dBC} S_{BC} \chi} = \beta_{release} = 0.7\beta_{probe} = \frac{m_{probe}}{C_{dFS} S_{FS}} \quad (9)$$

$$\frac{m_{probe} - m_{FS}}{C_{dMP}\mathbf{S_{MP}}} = \beta_{probe} = 0.7\beta_{FS} = 0.7\frac{m_{FS}}{C_{dFS} S_{FS}} \quad (10)$$

Table 4: Validation of Parachute Worksheet to Titan *Huygens* Probe Data

Huygens	Value		Actual Value	Percent Error
Parachute.Pilot.SurfaceArea	3.534	(m^2)	5.269	32.922
Parachute.Pilot.Mass	**0.3729**	**(kg)**	**0.638**	**41.552**
Parachute.Main.SurfaceArea	51.3	(m^2)	54.106	5.1863
Parachute.Main.Mass	**5.413**	**(kg)**	**4.527**	**18.3623**
Parachute.Drogue.SurfaceArea	5.681	(m^2)	7.211	21.214
Parachute.Drogue.Mass	**0.599**	**(kg)**	**0.751**	**20.240**
Parachute.Mass.DeploymentDevice	1.3434	(kg)	1.257	6.874
Parachute.Mass.Jettison	1.2407	(kg)	2.123	41.559
Parachute.Mass.Container	1.9584	(kg)	1.685	16.226
Total Mass	**10.9274**	**(kg)**	**12.008**	**8.999**

2.3. Powered Descent and Landing (PD&L)

Even after deployment of the parachute system, an additional decelerator system is required to remove the remaining kinetic energy from the atmospheric probe and to achieve a soft landing. To that end, a powered descent and landing system is employed. A monopropellant, bipropellant, and solid rocket propulsion compose the powered descent system. Crushable materials, landing struts, and airbags comprise the landing system. The PD&L model provides for rapid and accurate estimates of key characteristics and performances of propulsive and landing technology options for specific mission requirements. Initial inputs to the model are from the mission profile (initial masses, ΔV, etc.) and selected subsystem options (tank material, landing options, etc.). Through iteration among several propulsive and landing combinations, CoMET can examine the effects of synergetic technologies. CoMET calculates the propellant and tank masses with Equ. 11 and 12 respectively. From the required propellant tank mass, CoMET calculates the amount of pressurant.

$$M_p = M_O\left(1 - e^{\frac{-\Delta V}{g_o Isp}}\right) \quad (11) \qquad M_{TPT} = \frac{\rho_b V_{TPT}}{g_o \cdot \phi_{TPT}} \quad (12)$$

For powered descent, CoMET can assume either spherical or cylindrical shaped tanks. From these equations, CoMET can vary the tank material, propellant fuel, and pressurant gas type to examine their effect on mass and volume relative to the entire system.

Materials	Energy absorption
Balsa wood	High
Aluminum Honeycomb (w/ balsa)	
Aluminum Honeycomb	
Frangible Aluminum cylinder	
Air bag	
Stryrofoam	
Liquid spring	
Air-oil cylinder	Low

Figure 10: Material Types for Landing

$$s = \frac{(V_1^2 - V_2^2)}{2g(n\eta - 1)} \quad (13) \qquad m_{crush} = 2\left(\frac{m \cdot a_{max}}{\phi_{cr}}\right)\left(\frac{V^2}{\frac{2a_{max}}{S}}\right)\rho \quad (14)$$

Options for landing methods are chosen in the mission profile. These include crushable materials, landing struts and an option for airbags. Equ.13 and 14 calculate the mass required for crushable materials based on the required deceleration distance. These calculations are based on impact loads and initial height, stresses exerted on a particular material.

2.4. In-situ Exploration: Airships

To date, all in-situ exploration has taken the form of rovers and probes. Unlike other EDL subsystems, this heritage adherence is not due to lack of funding or short mission planning times, but rather due to simplicity (probes) and the planetary environment – i.e. rovers for rocky, stable ground on Mars. However, as mission architects look forward to new bodies with completely different environments than previously encountered, engineers may require radically new methods in in-situ exploration.

For planets and moons with dense atmospheres and harsh surface conditions, JPL engineers are considering an airship as one method to bypass these high temperature surface conditions and to capitalize on the body's atmospheric environment. On Mars, airships would provide an incredible level of mobility unseen by current rovers. Venus' very dense atmosphere and high temperature surface conditions are an ideal location for airship operations and might provide for some mass reduction in electronic shielding. Shown later, an airship on Titan would expand the scientific exploration envelope.

Figure 11: JPL Titan Airship Design

Airships may take the form of blimps or balloons. Montgolfiere balloons, or colloquially, “hot air balloons”, utilize heated ambient gas to provide only vertical mobility; blimps possess both vertical and horizontal mobility. Superpressure blimps have a sealed envelope that contains a lighter-than-ambient gas such as helium or hydrogen, which provides the buoyancy. The crux of airships is the reliance -- and further development – of an advance radioisotope power system (RPS).

Balloons and blimps consist of two main sections. The envelope is the skin and supporting structure of the balloon/blimp. Hanging from the envelope is the gondola, which contains the instrument payload and the subsystems that sustain the probe. The basic sizing relations for airships are obtained through Archimedes’ Principle and the ideal gas law. If all atmospheric conditions and gas properties are known, the amount of gas needed to create enough buoyancy is calculated from the floated mass; the envelope mass and size is calculated through the airship’s geometry. The geometric relationships of blimps were derived using regression of data obtained from a survey of earth airships (Ref 16). The payload is specified first, and combined with mission parameters, allows an estimate of the mass of the rest of the gondola. The envelope is then calculated based on the mass it has to carry. All of these calculations are iterative, to increase accuracy, and to improve its analytical capability.

Archimedes' floatation principle

$$m = \rho \cdot V \quad (15) \qquad F_B = m \cdot g = \rho \cdot V \cdot g \quad (16)$$

Aerostatic Lift

$$B = (\rho_{air} - \rho_{gas}) V \cdot g \quad (17)$$

$$V = \frac{B}{g(\rho_{air} - \rho_{gas})} = \frac{m}{\rho_{air} - \rho_{gas}} \quad (18)$$

$$B = \frac{p_{air}}{R_{air} T_{air}} \frac{m_{gas} R_{gas} T_{gas}}{p_{gas}} g = \frac{R_{gas} p_{air} T_{gas}}{R_{air} p_{gas} T_{air}} m_{gas} g \quad (19)$$

$$m_{gas} = m_{tot} \frac{p_{gas} R_{air} T_{air}}{p_{air} R_{gas} T_{gas}} \quad (20)$$

2.5. Cost Model

In addition to mass, size, and certain performance calculations in EDL, Carrier, and Mother systems, CoMET can also produce cost values and cost savings for each system, from pre-Phase A development to Phase E operations. Through changes in technology and cost parameters; and mass values generated from other system’s workbooks, CoMET’s cost analysis can calculate “cost deltas.” Cost deltas are the cost savings between the State of the Art (SOA) and Advanced values that indicate the sensitivity of the mission cost to specific parameters. These cost deltas are calculated through the JPL Parametric Cost Model (JPL PMCM 2005 v4). JPL PMCM operates through regression-based Cost Estimating Relationships (CER) that are designed using data from historic JPL science missions and Team X studies. Integrating the JPL PMCM with the Mother, Carrier, and Daughter workbooks, CoMET computes the cost estimates for both SOA and Advanced Values.

Currently, the CoMET cost model requires up to 514 inputs to adequately analyze the effect of advanced technologies. These inputs may include the following: major subsystem masses, peak power, and heritage checks (exists or not). However, system engineers may evaluate the cost deltas of a single system – i.e. Daughter systems only. Missions are added at the Mission Selection level and then cascaded throughout CoMET. There are additional cost-inputs throughout the cost model that need to be set up based on the Team X reports. After the inputs are programmed into the cost model, CoMET calculates a baseline cost estimation, using the JPL Work Breakdown Structure (WBS), from which cost deltas can be produced. After a cost estimate for a mission has been calculated, a sensitivity analysis is run based on any number of technology parameters. To accomplish this, CoMET iterates the worksheets while changing the indicated parameter and it then produces graphs showing the results of the changed parameter in terms of the cost or mass savings.

3.0 Return to Titan

3.1. Titan-*Huygens* Mission Summary

In 2005, after a 6.7 year space journey (not including development time), the *Cassini* orbiter deployed the *Huygens* probe into Saturn's largest moon, Titan. The main objective of the *Huygens* mission was to study Titan's atmospheric composition and the interaction with Titan's surface. Payload packages such as the Huygens Atmospheric Structure Instrument; Doppler Wind Experiment; and a Descent Imager/Spectral Radiometer would give detailed in-situ measurements of the chemical composition of the moon; dynamics of the atmosphere; and local characterization of Titan's surface.

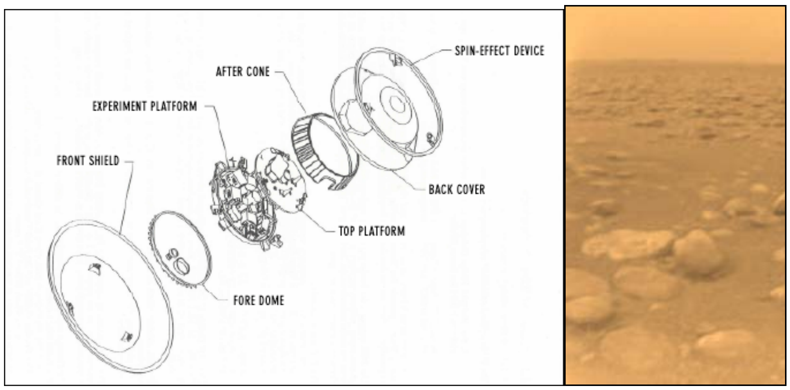

Figure 12: (L) Huygens Probe (R) Titan Surface Image (Ref 5)

While the European Space Agency hailed the Titan mission as a success, two subsystems of the *Huygens* probe limited scientific exploration: the power system and the descent phase. The *Cassini* orbiter is powered by three radioisotope thermal generators (RTG) that produce a total of 285 watts of power from 32.8 kilograms of plutonium. The *Huygens* probe is powered only by five lithium-ion type batteries. For a billion dollar mission that lasted for a decade from conceptual design to probe landing, the real time *Huygens* spent collecting precious scientific data amounted to less than four hours. Because *Huygens* possesses no vertical propulsion system, sensors only collected one atmospheric reading from 140 km to the surface, severely denying any general trend scientists might form about Titan's atmosphere.

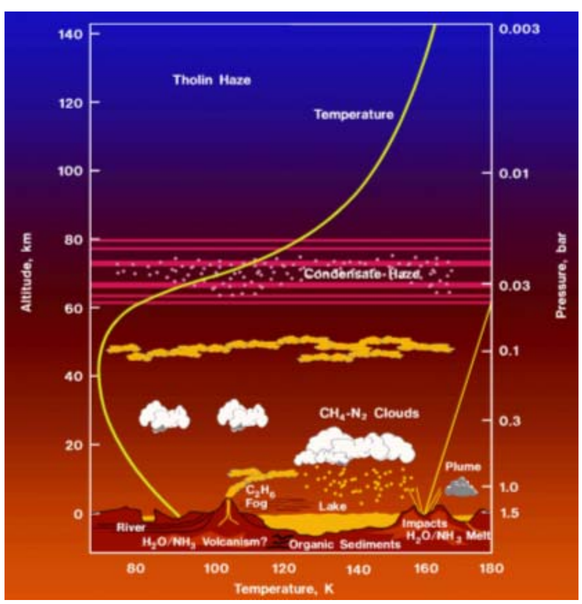

Figure 13: Titan Atmosphere (Ref 5)

3.2. JPL Titan Airship

Based on the National Research Council of the National Academies' Decadel Survey New Frontiers in the Solar System: An Integrated Exploration Strategy, a second mission to Titan is a high science priority for understanding not only Titan's planetary atmospheric chemistry but also possible correlations to the atmospheric chemistry of Mars, Venus, and Earth. Engineers from Team X at the Jet Propulsion Laboratory are considering an airship-lander mission to Titan. (Ref 18). As designed, the mission has a launch date of Aug 2010, July 2013, or June 2015, with a technology cutoff in 2007 for the Aug 2010 date. The airship lifetime is evaluated for one year on Titan. With a contingency of 30% for mass, the launch mass is estimated at 3037.9 kg; the entry mass at 400 kg; and the blimp (floating mass) at 200 kg. The entry aeroshell is composed of AQ-60 (*Huygens* heritage) and is 27% of the entry mass. Assuming a drag coefficient of 1.2 and an entry shell diameter of 3.0 m, the blimp-lander ballistic coefficient is 58.8 kg/m^2. The aeroshell will slow descent prior to the mortar deployment of a parachute at a pre-determined altitude that is measured using the LIDAR altimeter.

The total power system required for the blimp is 100 W. Autonomous operation is required because the orbital data relay does not allow ground interference. Blimp operations will occur up to 10 km above the surface, where the blimp will float on winds up to 10 m/s. Near the surface two electric motors will provide forward thrust to the blimp to overcome the weaker winds of less than 1 m/s. The blimp's mass at deployment is 200.5 kg, including 30 kg of helium. The helium mass is high because it must inflate the blimp at an operating temperature of approximately 80 K. The blimp will carry a scanning LIDAR altimeter to identify smooth landing sides, and the craft will touch the ground with a surface-rolling/flotation wheel underneath the blimp material to conserve mass. The blimp gas envelope is estimated at 20 kg, with dimensions of 10 m long; 2.4 m in diameter; and a volume of 29 m^3. The envelope requires 15 kg of helium to inflate due to the low temperatures on Titan (93K at surface). The volume of the helium tanks for the blimp is 0.2 m^3; the cabling is 3.8 m and 0.5 kg.

The propulsion system provides a tank, lines, and associated hardware to provide the required helium to inflate the blimp. The helium is stored at approximately 6000-8000 psi, and this high pressure minimizes the volume of the helium tank. This tank will be a metal lined COPV (Composite Overwrapped Pressure Vessel) that requires some technology development due to the high pressure. The propulsion system design includes a COPV tank with a figure of merit (PV/W) of approximately 2 million, two normally closed pyro valves in parallel to provide redundancy, a service valve, a pressure transducer, a pressure regulator, and two temperature sensors.

The Team X total mission cost is $1144M (FY2001 $), which includes $160M for the blimp science module, $285M for the orbiter module, and $34M for the propulsion module. These costs reflect the 50% confidence level -- 50% chance of higher or lower values. The primary cost drivers for the blimp science module are $42M for all the instruments and $42M for power. Additional costs of possibly $2 to $5M are required for the development and test of the system, but are not included in this estimate.

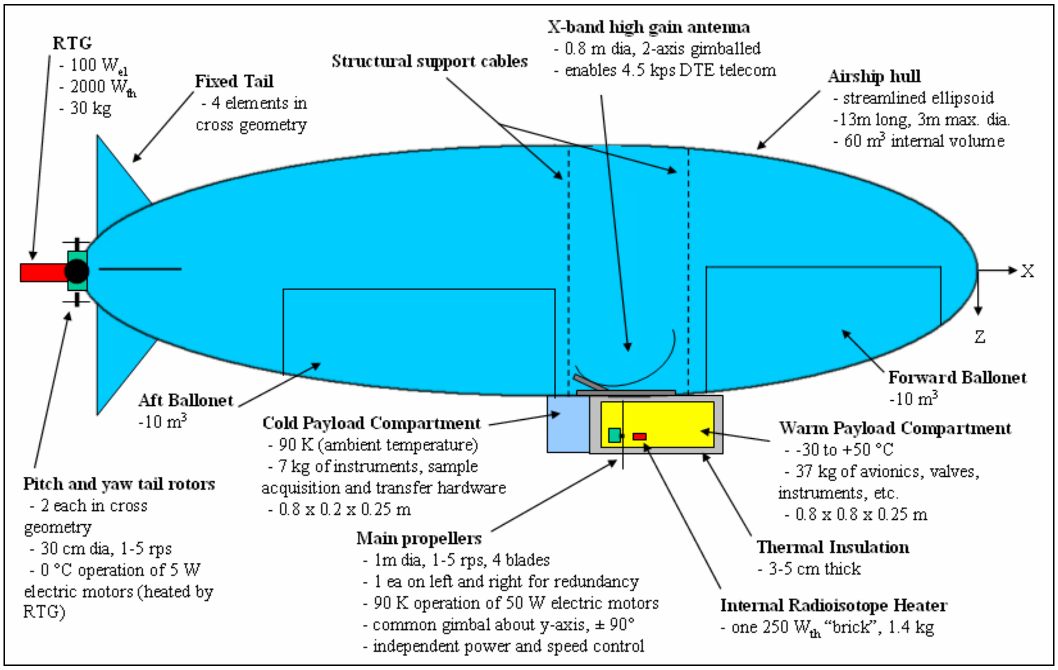

Figure 14: Proposed JPL Blimp Configuration (Ref 18)

3.3. CoMET Analysis on Titan Airship

The sensitivity analysis feature of CoMET is able to examine the floating mass of a Titan blimp as a function of antenna efficiency and antenna areal density, two important parameters in the blimp's telecomm system. The technologies improvements under consideration are efficiency increases of the antenna and areal density decreases of the antenna. CoMET reveals that if the current technology is able to sustain antenna efficiencies of greater than 30-40%, then further development in this area yields diminishing returns. However, if the efficiency is much lower than 40%, research to improve the efficiency would significantly decrease the mass of the blimp (Figure 15).

In contrast to Figure 15, Figure 16 shows that the areal density has an almost linear relationship with the floating mass. Thus, researching ways to reduce the antenna areal density will provide constant improvements to the blimp's floating mass, regardless of the current technology level. In this case, the linear trend reflects the antenna areal density's direct impact on the antenna mass, which is summed with other components to total the blimp's floating mass. In this case, assuming that the antenna efficiency is already relatively high, it would be wiser to invest in reducing the antenna areal density.

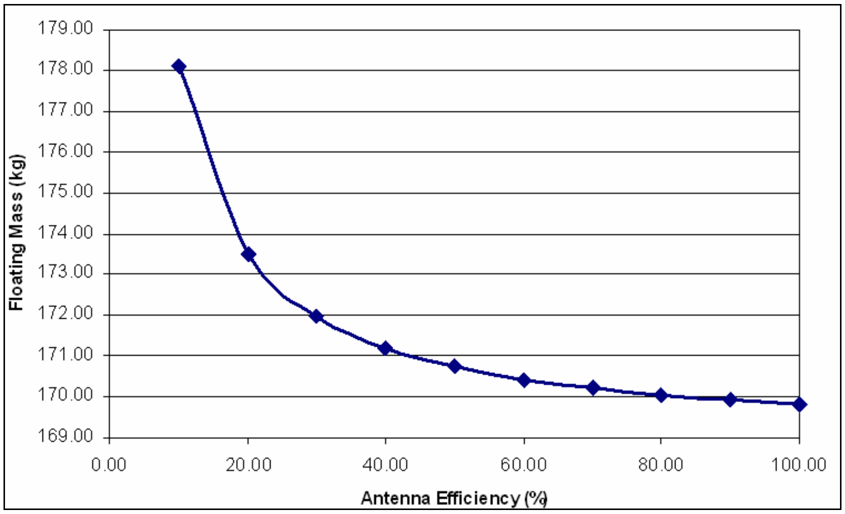

Figure 15: Floating Mass of a Titan Blimp as Function of Percent Efficiency of Antenna

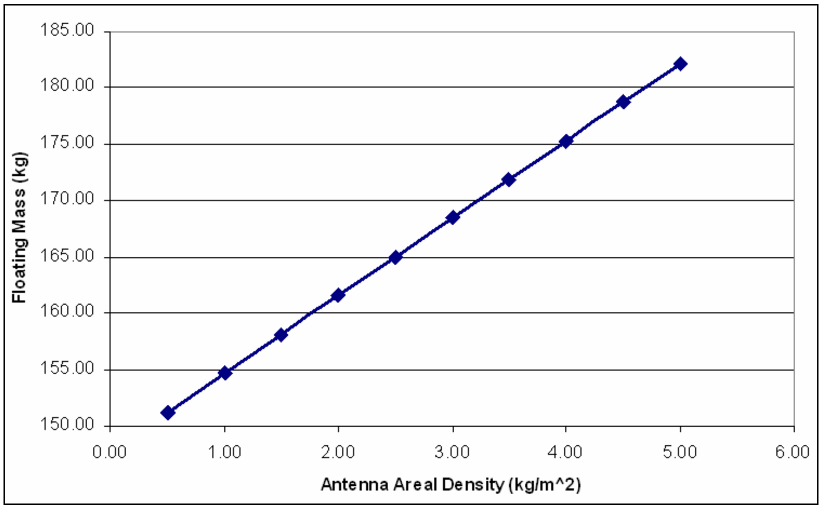

Figure 16: Floating Mass of a Titan Blimp as Function of Antenna Areal Density

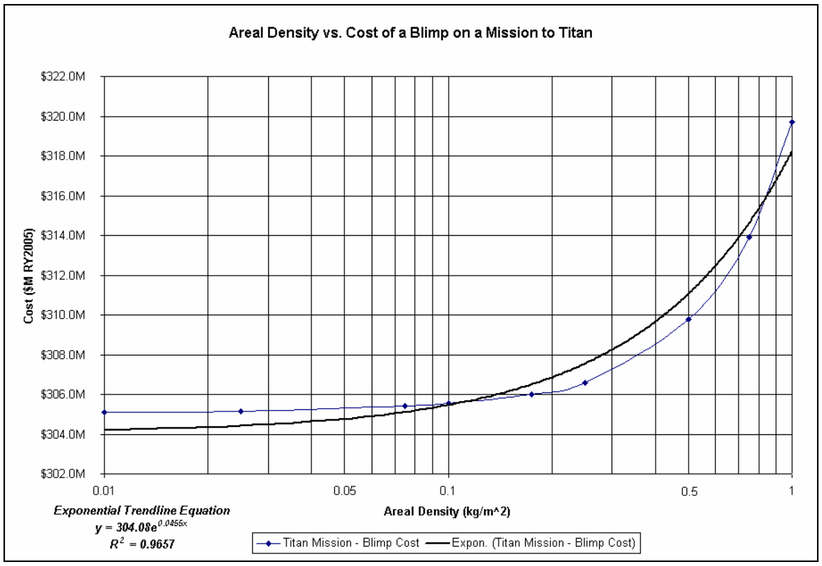

Figure 17: Cost of a Titan Blimp as Function of the Envelope Areal Density of the Blimp

This conclusion serves as a good example of the decision-making information CoMET is capable of providing. In this case, the data set is not fully conclusive because the power subsystems of the blimp model are underdeveloped. Since improvements in antenna efficiency only affect the floating mass through power reduction, more detailed power system calculations will provide a more accurate picture.

Helium and hydrogen are the two lightest gases and the most viable options for use as a pressurant in any superpressure airship. On Earth, Hydrogen is significantly more dangerous to use because of its flammability, as witnessed by the Hindenburg disaster. However, in extraterrestrial environments like Titan, either gas is usable. CoMET offers a valuable comparison between using Helium and Hydrogen as the blimp pressurant.

Figure 18 displays the floating mass of the blimp as a function of the payload mass with either hydrogen or helium as the blimp pressurant. The payload mass is the instrument mass on the airship. As defined in CoMET, the floating mass includes the mass of the instruments and subsystems on the blimp, along with the blimp envelope and backup tanks. It excludes all the jettisoned systems such as the parachute and aeroshell, and it does not include the mass of the pressurant itself. The graph conclusively shows that the pressurant type has little effect on the mass of the craft once it has been deployed. The two linear fits are nearly parallel and differ by less than 2 kg.

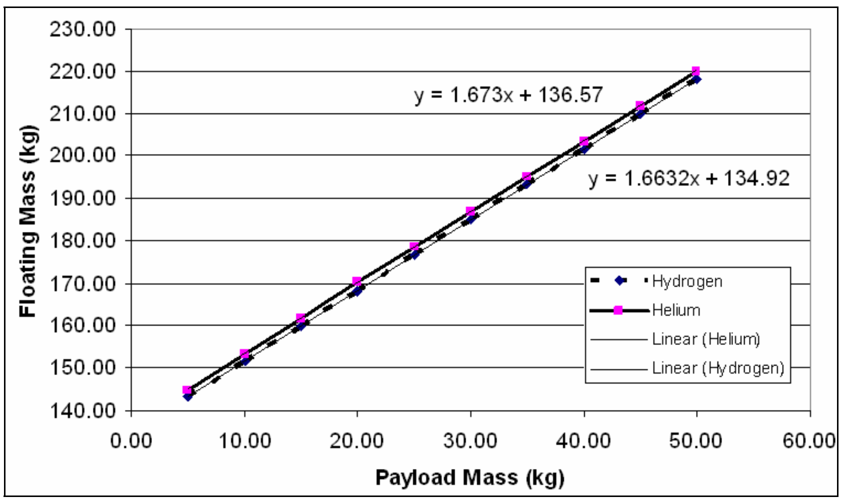

Figure 18: Floating Mass of Titan Blimp as Function of Payload Mass - Hydrogen or Helium Pressurant

However, the difference in the two pressurants is clear in Figure 19, which shows the total mass of the mission as a function of the payload mass and pressurant type. As defined in CoMET, the total mass is the mass of all subsystems while in transit to their destination. Thus, the total mass includes the launch vehicle adapter, parachute, aeroshell, and all inflation hardware which are jettisoned during descent. In this case, the pressurant type makes a significant difference, with hydrogen having about 27% mass savings over helium. This analysis reveals that while the pressurant type does not affect the other systems in the blimp, hydrogen is much more practical than helium to reduce the mass during the propulsive and launch stages of the mission

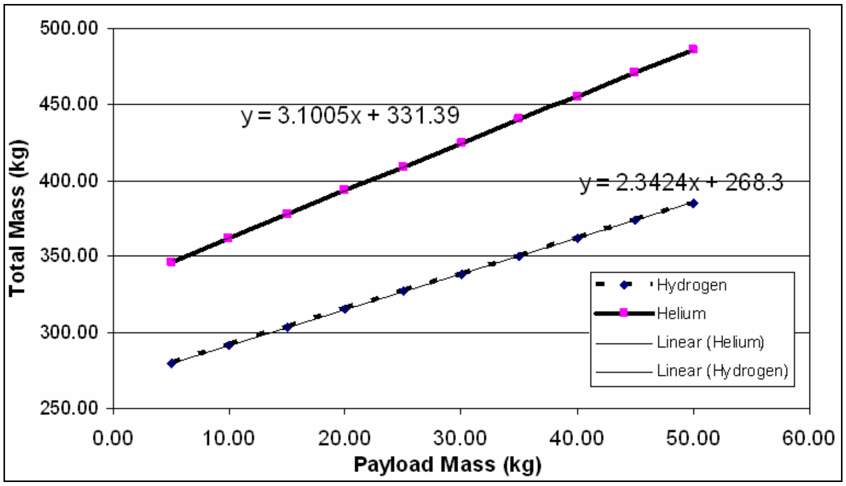

Figure 19: Total Mass as Function of Blimp Payload Mass – Helium or Hydrogen Pressurant

4.0 Conclusion

The ultimate result of CoMET is a technology assessment program that removes the arbitrary decision-making in planetary probe mission design. Replacing the “hand-waving” involved in mission design with a standard method of decision-making is critical to reduce mass requirements, to optimize taxpayer funds, and to increase performance of planetary probe missions. Given the baseline mission parameters, CoMET can evaluate the masses and cost for mother, carrier, and daughter subsystems. For Entry, Descent, and Landing systems on daughter craft, CoMET can compute the mass, size, and certain performance parameters for the thermal protection system, parachute system, powered descent and landing system, and airship in-situ exploration systems. This paper has examined CoMET’s method of mass and cost analysis; validated these values to historical missions; and demonstrated CoMET’s practicality to a Titan airship case study. CoMET has enormous potential to become a mission manager’s greatest tool for deciding where to allocate funds in the research and development stages of interplanetary robotic missions.

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