DRAFT

AIAA 2003-4469

PROPAGATING AND MITIGATING THE EFFECT OF UNCERTAINTY IN THE CONCEPTUAL DESIGN OF A MONOPROPELLANT PROPULSION SYSTEM

Daniel P. Thunnissen*
California Institute of Technology
Pasadena, California 91125

Barry Nakazono†
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California 91125

A method for propagating and mitigating the effect of uncertainty in conceptual level design via probabilistic methods is described. This method provides a rigorous foundation for determining design margins in complex multidisciplinary systems. As an example application, the investigated method is applied to the conceptual design and development of the Mars Exploration Rover (MER) monopropellant blowdown hydrazine propulsion system. The method begins with identifying a set of tradable system-level parameters. The variables of the design are then classified and assigned appropriate probability density function. To characterize the resulting system, a Monte Carlo simulation is used. Lastly, results of this simulation are combined with the risk tolerance of the decision maker(s) to guide in the determination of margin levels. The method is repeated until the decision maker is satisfied with the balance of system-level parameter values. For the propulsion system example, margins for dry mass, propellant mass, schedule, and cost form a set of tradable system-level parameters. Use of this approach for the example presented yielded significant differences between the calculated design margins and the values assumed in the conceptual design of MER propulsion system.

Nomenclature

A	= surface area
C	= total staff cost, FY2003$K
f	= composite overwrap factor for fiber strength
f_{burst}	= burst factor
l	= length, m
$(l/\phi)_{equiv}$	= equivalent length to diameter ratio
m	= mass, kg
P	= pressure, Pa
P_x	= x^{th} percentile value
R_{det}	= deterministic result value
s	= worforce salary, FY2003$K
T	= temperature, K
t	= thickness, m
V	= volume, m^3
ζ	= composite overwrap fiber strength, Pa
η_{tank}	= tank expulsion efficiency
η_{wrap}	= composite overwrap volume fraction
κ	= burden factor
μ	= mean of a normal probability distribution
ρ	= density, kg/m^3
σ	= standard deviation of a normal probability distribution
τ	= total workforce time, workdays
ϕ	= diameter, m
ψ	= percent value
ω	= workdays per month

Subscripts

adh	= adhesive
b	= burdened
exp_rate	= expense rate
i	= inner tank
j	= individual workforce member
k	= individual task
inf_rate	= inflation rate
lin	= liner
o	= outer tank
MEOP	= maximum expected operating pressure
prop	= propellant
prop_ACS	= attitude control propellant
s/c_s	= spacecraft prior to first ΔV maneuver
ub	= unburdened
ui	= uninflated
wrap	= composite overwrap

*Doctoral student – Division of Engineering & Applied Science; Member AIAA
† Member of Engineering – Senior, Propulsion Flight Systems Group; ~~Member AIAA~~

Copyright © 2003 by the California Institute of Technology. Published by the American Institute of Aeronautics and Astronautics, Inc. with permission.

Introduction

Space systems range widely from Earth-orbiting satellites to interplanetary spacecraft. Spacecraft are complex multidisciplinary systems with a dozen or more subsystems. Propulsion is just one example of a spacecraft subsystem (discipline). This section begins with an overview of the preliminary design process for a monopropellant propulsion system. All complex multidisciplinary systems require engineers and designers to deal with uncertainty. A classification of uncertainty for complex multidisciplinary systems follows. This is the classification that is applied to the monopropellant propulsion system example in this paper.

Preliminary design of monopropellant propulsion systems

The preliminary (conceptual) design of a monopropellant propulsion system attempts to fulfill a set of mission-level requirements. The goal is a baseline configuration that is optimal in some chosen sense and includes an estimate of performance, mass, and envelope. The baseline configuration should have enough information to develop detailed requirements for the design or procurement of individual components such as the propellant tank(s). Preliminary design uses engineering principles but also relies heavily on creativity, art, intuition, and experience.[1] This design decision-making process is an iterative procedure where a preliminary design is cycled through five stages:

1. Determine requirements & design considerations
2. Perform preliminary design decisions
3. Size/Design system and perform trade-off studies
4. Evaluate design
5. Baseline design

Reference 1 describes each of these steps in more detail. Uncertainties abound in conceptual design and are slowly reduced by decisions and analysis. This applies particularly during the development phase of the project when information about actual components, workmanship, etc., becomes available to replace estimates based on the past performances of, and the experiences with, similar projects. When the system is operating in orbit, its performance will constitute further information from which the uncertainty estimate may be revised.

Uncertainty types

A fundamental definition of uncertainty is "liability to chance or accident", "doubtfulness or vagueness", "want of assurance or confidence; hesitation, irresolution", and "something not definitely known or knowable".[2] This definition motivates a classification of uncertainty into four types: ambiguity, epistemic, aleatory, and interaction.[3] A brief definition for each type of uncertainty follows. A more detailed explanation and an overview of uncertainty taxonomies in a variety of fields are provided in Reference 3. In conceptual design it is arguably more important to determine the significant sources of uncertainty than identifying and quantifying all uncertainty sources. Hence, each of the following definitions indicate whether this form of uncertainty is included in this analysis.

Ambiguity

Because little precision is required for general communication, individuals often fall into the habit of using imprecise terms and expressions. When used with others who are not familiar with the intended meanings or in a setting where exactitude is important, this imprecision may result in ambiguity. Ambiguity can be reduced by linguistic conventions. Ambiguity is not investigated in this analysis.

Epistemic

Epistemic uncertainty is any lack of knowledge or information in any phase or activity of the modeling process. The key feature that this definition stresses is that the fundamental cause is incomplete information or incomplete knowledge of some characteristic of the system or the environment. It can be further classified into model, phenomenological, and behavioral uncertainty.

Model: Model uncertainty is the accuracy of a mathematical model to describe an actual physical system of interest. Model uncertainty arises from three sources: approximation, numerical, and programming errors. *Approximation error* is present in any model as no mathematical model can fully describe the behavior of a physical system. Approximation error can be reduced by using higher-fidelity models. *Numerical error* can arise due to finite precision arithmetic and can be reduced by using higher precision computers and software. Finally, *programming error* occurs during development of the model due to blunders or mistakes by the programmer. Although there is no straightforward method for estimating programming errors, they can be detected by the person who

committed it, resolved by better communication, or discovered by redundant organizational and operational procedures and protocols.[4] Model uncertainty is not investigated in this analysis but is discussed in a companion paper.[5]

Phenomenological: Phenomenological uncertainty arises whenever the design technique or form of development generates uncertainty about any aspect of the possible behavior of the system under development, operation, and extreme conditions. Phenomenological uncertainty is particularly important for novel projects or those which attempt to extend the 'state of the art'. Often these projects fail due to an apparently 'unimaginable' phenomenon (so called "unknown unknowns"). Evidently, only subjective estimates of the effect of this type of uncertainty can be given.[6] Phenomenological uncertainty is not investigated in this analysis.

Behavioral: Behavioral uncertainty is uncertainty in how individuals or organizations act. Behavioral uncertainty arises from four sources: design uncertainty, requirement uncertainty, volitional uncertainty, and human errors. *Design uncertainty* includes parameters over which the engineer or designer has control but has not yet decided upon. An example is the choice an engineer has in selecting a given component among a set of possible components. Design uncertainty is eliminated when a system is complete as all choices have been implemented. *Requirement uncertainty* includes variables that some organization or individual initially determines independently of the engineer or designer. Examples include the total velocity change of a maneuver or the edict to use a given component. *Volitional uncertainty* is uncertainty about what the subject him/herself will decide.[7] Other people's actions and conduct are not entirely predictable, particular in dealing with other organizations. *Human errors* occur during development of a system or project due to blunders or mistakes by an individual or individuals. Similar to the programming errors previously discussed, human errors are difficult to estimate. However, facilitative measures such as education, a good work environment, a reduction in task complexity, and improved personnel selection as well as control measures such as self-checking, external checking, inspections, and legal sanctions have proved successful in reducing human errors.[6] Design and requirement uncertainty are investigated in this analysis but volitional uncertainty and human errors are not.

Aleatory

Aleatory uncertainty is inherent variation associated with a physical system or environment under consideration. Aleatory uncertainties can commonly be singled out from other uncertainties by their representation as distributed quantities that can take on values in an established or known range, but for which the exact value will vary by chance from unit to unit or time to time.[4] An engineer or designer has little control over aleatory uncertainty. Examples include the strength or exact dimension of a component where the manufacturing processes are well understood but variable and the parts have yet to be produced. Aleatory uncertainty is investigated in this analysis.

Interaction

Interaction uncertainty arises from unanticipated interaction of many events and/or disciplines, each of which might, in principle, be or should have been foreseeable. Interaction uncertainty is significant in complex multidisciplinary systems such as spacecraft which may have many subsystems. Potential techniques to deal with this type of uncertainty are simulation, multidisciplinary design optimization (MDO), and complexity science. These techniques have only briefly been investigated by the authors and only addressed in this analysis via simulation.

The remainder of this paper documents how to reduce the effort to design and build complex multidisciplinary systems by addressing this issue of uncertainty. First, the current method of margin management is introduced. Next, the investigated method is summarized. An application of the method to the MER monopropellant propulsion system follows. The paper ends with a validation and discussion of the example and conclusions.

Margin Management of Complex Multidisciplinary Systems

The current method for mitigating and propagating uncertainties in the design and development of a complex multidisciplinary system is the use of managed system-level margins. Margins are variations in resources measured relative to worst-case expected values. Although the definition often differs from resource to resource, many margins are expressed as percentages:

$$\% \, Margin\big|_{current} = \frac{WCE - CBE}{CBE} \cdot 100 \qquad (1)$$

where *WCE* is the worst case estimate and *CBE* is the current best estimate. Margins are implemented to allow the various elements of a design team to work in parallel as much as possible. By providing numbers with margin ("holding margin"), a team of a given subsystem or discipline is more insulated from changes occurring in other subsystems or disciplines and can proceed with their design and development. As the design progresses, CBEs of resources typically rise using up the margin that is being held. Significant design and management problems can occur when the rise in the CBEs is greater than the margin being held.

For space systems, margins of varying amounts are maintained on resources that can be measured such as mass and power. In addition, a margin is placed on the injected capability of the launch vehicle that places the spacecraft into orbit and in required estimates of change in velocity (ΔV) maneuvers. Some margins pertain to the operation of the spacecraft such as the telecommunication link. Margins are also held for cost and schedule. Margins vary throughout the design and development and their allocation is often capricious and/or "hope oriented". For space systems, margins are allocated heuristically, based on historical data, or in a crudely quantitative manner, based on such concepts as design maturity and mission environment. Relying on a limited number of heuristics can sometimes lead to severe and systematic errors.[8] Furthermore, margins maintained vary not only organization-to-organization, but from individual-to-individual (project manager-chief engineer, chief engineer-flight systems engineer, etc.) within an organization based on the risk tolerance of that organization or individual or both. Margins are supposed to account for all the uncertainties (aleatory, epistemic, behavioral, etc.) that were previously discussed. Unfortunately, margins are routinely blown in the design of complex systems. DISCUSS HERE with references!

Mars Exploration Rover Mission

A recent space system that illustrates this concept of margin management to mitigate uncertainty is the Jet Propulsion Laboratory (JPL)/NASA Mars Exploration Rover (MER) project. The MER project has a primary objective of placing two mobile science laboratories, MER-A and MER-B, on the surface of Mars in order to remotely conduct geologic investigations, including characterization of a diversity of rocks and soils that may hold clues to past water activity. The MER project will use the 2003 launch opportunity to deliver two identical rovers to different sites in the equatorial region of Mars. The MER flight system consists of four major components: an Earth-Mars cruise stage; an atmospheric entry, descent, and landing system or aeroshell (consisting of a heatshield and backshell); a lander; and a mobile science rover with an integrated instrument package. During the interplanetary transfer to Mars, the cruise stage will provide most of the traditional spacecraft subsystem functionality (such as propulsion, power, communications, thermal, and attitude control).[9] Reference 9 discusses the MER mission in detail.

MER Margin Management

The flight system margins of MER are summarized in Table 1.[10] Table 1 illustrates the complicated nature of margin management. Margins were time phased and determined on the basis of organizational (JPL) policy, the experience of the flight system chief engineer, and experience of MER team members. The many margins held throughout design and development pertained to the spacecraft itself and to the operation of the spacecraft. MER also held margins on cost and schedule (reserves) as well as ΔV and launch vehicle capability that are not listed in Table 1. The mass history of MER during its design and development is plotted in Fig. 1. Fig. 1 plots the CBE and CBE plus margin for the launch mass (injected mass) as well as the injected mass capability of the Delta II launch vehicle (LV) (which MER, which Delta II?). In Fig. 1, the first six months or so (April to October 2000) were devoted to conceptual/preliminary design. Detailed design and fabrication was carried out from about October 2000 to January 2002. Finally, the period from January 2002 until June 2003 is dedicated to assembly, test, and launch operations. MER was a little unusual in that it has a tight project schedule. Mass growth has been a problem during MER design and development. Cost and schedule were used to reduce mass. For example, the estimate for the injected capability of the launch vehicle increased eight times during design and development as additional trajectory analyses were performed and mass reduction exercises at almost $100K/kg were performed. These activities were critical since the launch mass of MER is approaching 1072 kg which is considerably greater than the original maximum mass estimates of 900 to 1000 kg that were assumed early in the project but only slightly less than the 1077 kg injected mass capability of the launch vehicle.

Table 1 MER Flight System Margins

Resource	PDR (10/00)	CDR (8/01)	ATLO start (2/02)	Ship to Cape (1/03)
[a]Mass[b]	15/5%	10/2.5%	5/1%	2/0%
[a]Energy/Power[c]	10/10/10%	10/5/5%	10/0/5%	10/0/0%
Power switches	30%	20%	10%	10%
Pyro Switches	30%	20%	10%	10%
[a]CPU utilization[d]	50%	50%	50%	40%
Memory				
DRAM[d]	50%	40%	25%	25%
Flash	30%	25%	20%	10%
[a]EEPROM[d]	50%	50%	50%	40%
Electronics				
Chassis Margin (VME slots)	1	1	0	0
PWB Margin (spare real-estate)[d]	50%	30%	10%	10%
Analog signals (e.g. temp sensors)	30%	15%	5%	5%
Telecom (link margin)	3 db	3 db	3 db	3 db
Propellant (tank margin)	30%	20%	10%	10%

[a]Critical technical margins required by project manager
[b]mass margin is specified in terms of X/Y% where X is total above CBE and Y is above CBE+uncertainty.
[c]updated based on three margins X/Y/Z, X% operation margin, Y% flight system margin, and Z% project manager reserve. These are added together for total power/energy margins required at each phase.
[d]these resources are managed at the subsystem level and allocations changes; as long as margins are met, do not require ECRs.
PDR = preliminary design review; CDR = critical design review; ATLO = assembly, test, & launch operations; CPU = central processing unit; DRAM = dynamic random access memory; EEPROM = electrically erasable programmable read-only memory; VME = VersaModule Eurocard; PWB = printed wiring board; CBE = current best estimate; ECR = engineering change requirement

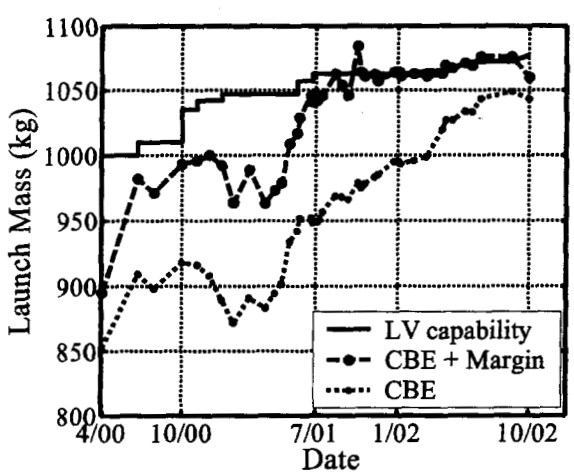

Fig. 1 MER Mass History.

Summary of Method

The following section describes a method for propagating and mitigating the effect of uncertainty in conceptual level design via probabilistic methods. Application of this method produces a rigorous foundation for determining design margins in complex multidisciplinary systems. The method comprises six distinct steps: identification of tradable parameters, model formulation, classification of variables, probabilistic modeling of variables, Monte-Carlo simulation, and analysis. Each step is described in detail.

Identification of Tradable Parameters

The first step is identification of the tradable parameters. The design and development of a propulsion system is motivated by requirements. A

propulsion system may have more than one requirement: high-thrust ΔV maneuvers for orbit insertion, 3-axis attitude control, and/or benign exhaust products that do not interfere with sophisticated observation instruments. The decision maker must understand the system being analyzed to determine which parameters are truly important in satisfying the requirements placed on the system. Engineering parameters will necessarily result from this analysis. Parameters such as schedule, cost, and risk, must usually be considered as well. The resulting list of tradable parameters helps guide the design and development of the complex multidisciplinary system.

Model Formulation

Once a list of tradable parameters has been identified, an analytic model must be generated to calculate each of these parameters. A model that determines engineering parameters often includes dozens or hundreds of equations and relations. A model that calculates the design and development schedule of an engineering system might subdivide the tasks required and estimate workforce requirements for each. A cost model might incorporate the schedule and include additional equations relating procurements, inflation, and burden factors. A risk model might estimate whether the engineering system will fail during development or operation. Determining how accurate models need to be to effectively determine the margin levels in conceptual design is discussed in a companion paper.[5]

Classification of Variables

Once models have been created for all desired tradable parameters, the variables used are classified. A propulsion system may have dozens, even hundreds, of these variables. Classifying the variables into their uncertainty types is useful in understanding their respective impact on the overall design. For this paper, aleatory and behavioral, specifically design and requirement, uncertainties were considered. Definitions and examples of each are provided in the Introduction. It should be stressed that this classification is not universal and not always clear with a complex multidisciplinary system. That is to say, a certain variable may be deemed a requirement uncertainty when viewed from a system level but a design uncertainty when viewed at the discipline (subsystem) level. For example, a spacecraft may have a requirement on a final orbit to achieve but leave the orbit insertion design to the mission designer making the change in velocity of the spacecraft a design variable. The change in velocity of the spacecraft, however, would likely be a requirement variable for the propulsion system.

Probabilistic Modeling of Variables

The next step in the investigated method is probabilistic modeling of each variable previously described. Variables are characterized by a probability density function. Although normal (Gaussian) distributions are by far the most common, other probability distributions are often used. For example, a uniform distribution may be used to model variables whose value is known to be within a range but not about any one particular value. An exponential distribution is often used in lifetime applications. A custom distribution might be used to represent design uncertainty. The probability density distribution applied to each variable may be determined from existing data, analogy, analysis, expert opinion, or a combination of these.

Monte-Carlo Simulation

Once all the variables involved in the design have been given a probability density function, a Monte-Carlo simulation of the complex multidisciplinary system is performed. A Monte-Carlo simulation involves hundreds to thousands of simulations, each using different variables generated by their relevant probability distributions. For each simulation, the tradable parameters are recorded. Hence, the Monte-Carlo simulation generates probability density distributions of each tradable parameter. The more simulations performed, the smoother the resulting tradable parameter distributions. Unfortunately, Monte-Carlo simulations are often computationally expensive, especially for complex systems analysis.[11] Using parallel high-performance computer systems is one way to alleviate this issue. Otherwise, less computationally intense methods, such as metamodels and Fast Probability Integration (FPI), exist but these methods are not as accurate as a Monte-Carlo simulation and were not investigated.[12]

Analysis

With distributions of each tradable parameter provided by the Monte-Carlo simulation, analysis and of the complex multidisciplinary system is performed. Each tradable parameter distribution yields a mean and three percentiles. A percentile is defined as the value that is greater than a specified percent of all the values in a set. A percentile of 50 is simply the statistical median of a sample. Percentiles provide a confidence indication in the value of a tradable parameter. The 95, 99, and 99.9 percentiles of a tradable parameter provide a decision maker with a low-, medium-, and high-confidence

grace / scott

estimate in the probability that a tradable parameter will not be exceeded. The difference between these 95, 99, and 99.9 percentiles and the deterministic result provide the decision maker with a margin value to be maintained at the current stage of the design. The percent margin is this margin divided by the deterministic result (and multiplied by 100):

$$\% \, Margin\Big|_{proposed} = \frac{P_x - R_{det}}{R_{det}} \cdot 100 \tag{2}$$

Once the distributions, means, and percentiles are analyzed, the decision maker may wish to investigate one or more different designs. As uncertainty in the values of variables decrease with time, the probability density distributions of each variable can be improved and updated. Repeating the process will yield updated margins as the design progresses. In summary, this method redefines the concept of design margin that was introduced earlier. Here, margins are a function of risk tolerance and are measured relative to mean expected system performance, not variations in design parameters measured relative to worst-case expected values.

Application of Method

The investigated method is applied to a propulsion system, specifically the monopropellant blowdown propulsion system on the Mars Exploration Rover (MER) cruise stage. A propulsion system is chosen for this analysis since it is a representative spacecraft subsystem and amenable to both deterministic and probabilistic modeling and analysis. The analysis was performed twice: at a period assumed to be just before the preliminary design review (PDR) and at a period assumed to be just before the critical design review (CDR). These two reviews are two of the most important periods for determining and updating margins in the development of the propulsion system.

Tradable Parameters

The tradable parameters identified for the MER propulsion system were dry mass, propellant required, schedule, and cost. The dry mass of the propulsion subsystem is the mass of the propulsion components, propellant tanks, tubing, fittings, and pressurant. The propellant required is the mass of propellant required for ΔV maneuvers and/or attitude control. The schedule and cost are the total time and cost it takes to design, build, test, and deliver the propulsion system, respectively. The margin values assumed by the MER project for propulsion dry mass, schedule, and cost during conceptual design were 15% (on ? kg), 6% (on 707 days), and 10% (on FY$2002?M). The MER project assumed early in conceptual design 99% confidence numbers for propellant required (42.8 kg).[9]

The power requirements and risk (the likelihood of catastrophic failure) of the propulsion system were not deemed important early in the design compared to the rest of the spacecraft. No decisions concerning these two parameters were made during design and development that significantly impacted the tradable parameters of dry mass, usable propellant, schedule, or cost. Hence, power and risk, parameters that are often tradable in the design of other propulsion systems, are not tradable parameters for the MER propulsion system.

Model Formulation

Three models were created for the four tradable parameters: mass (engineering), schedule, and cost. The mass (engineering) model determines both the dry mass and propellant mass of the propulsion system via several submodels. The schedule model determines the total time to design, develop, test, and deliver the propulsion system. The results of the schedule model are used in the cost model to determine the total cost to design, develop, test, and deliver the propulsion system. Each model is described in detail.

Mass (Engineering)

The mass model utilizes several submodels to determine the total dry and propellant mass required. This model is the high-fidelity model that is described in detail in a companion paper.[5] Reference 5 describes the submodels assumed via various subsections: components, tubing, propellant properties, pressurant properties, flow properties, pressure drop, and mass totals. The analysis for the MER propulsion system added one additional tank submodel to determine the mass and dimensions of a custom composite overwrapped pressure vessel (COPV) that was being considered for use as the propellant tank. This tank submodel is based on thin-wall and composite material theory and follows closely a model of a cylindrical COPV.[13] However, in this analysis the COPV for MER is assumed spherical. Hence, the tank inner diameter is instead

$$\phi_i = 2\sqrt[1/3]{\frac{3 \cdot V_i}{4\pi}} \tag{3}$$

The tank inner surface area is

$$A_i = \pi \phi_i^2 \tag{4}$$

The volume of the propellant management device (PMD) required to hold propellant over outlet ports of tank in micro gravity is[14]

$$V_{PMD} = \frac{1}{2} A_i \, t_{PMD} \tag{5}$$

The mass of the PMD is

$$m_{PMD} = V_{PMD} \, \rho_{PMD} \tag{6}$$

The burst pressure is

$$P_{burst} = f_{burst} \, P_{MEOP} \tag{7}$$

The overwrap thickness of the tank is

$$t_{wrap} = \frac{2 P_{burst} \left(\phi_i / 2 + t_{lin} + t_{adh} \right)}{\zeta \, f \, \eta_{wrap}} \tag{8}$$

If this value of the overwrap thickness is less than the minimum fabrication thickness (assumed to be 0.196 mm), the minimum fabrication thickness is assumed. The total tank thickness is therefore

$$t_{total} = t_{lin} + t_{adh} + t_{wrap} \tag{9}$$

The outer tank diameter is

$$\phi_o = \phi_i + 2 t_{total} \tag{10}$$

With the geometry of the tank known, the volumes of the liner, the adhesive, and the overwrap can be determined as

$$\begin{aligned} V_{lin} &= \frac{4\pi}{3} \left[\left(\phi_i / 2 + t_{lin} \right)^3 - \left(\phi_i / 2 \right)^3 \right] \\ V_{adh} &= \frac{4\pi}{3} \left[\left(\phi_i / 2 + t_{lin} + t_{adh} \right)^3 - \left(\phi_i / 2 + t_{lin} \right)^3 \right] \\ V_{wrap} &= \frac{4\pi}{3} \left[\begin{array}{l} \left(\phi_i / 2 + t_{lin} + t_{adh} + t_{wrap} \right)^3 \\ - \left(\phi_i / 2 + t_{lin} + t_{adh} \right)^3 \end{array} \right] \end{aligned} \tag{11}$$

The mass of the liner, adhesive, and overwrap can then be calculated from the relations

$$\begin{aligned} m_{lin} &= V_{lin} \, \rho_{lin} \\ m_{adh} &= V_{adh} \, \rho_{adh} \\ m_{wrap} &= V_{wrap} \, \rho_{wrap} \end{aligned} \tag{12}$$

Finally, the total tank mass is the sum of these three masses and the mass of the PMD

$$m_{per_tank} = m_{lin} + m_{adh} + m_{wrap} + m_{PMD} \tag{13}$$

For cases where a custom spherical COPV was assumed, equation (13) replaced the mass per tank that would be looked up the component database described in reference 5.

Schedule Model

A schedule model was developed to determine the time in workdays required to design, develop, integrate, test, and deliver *two* monopropellant propulsion systems (MER-A and MER-B). A nominal, deterministic schedule of 208 individual tasks was created. An abbreviated version of this schedule is shown in Fig. 2. The nominal, deterministic schedule delineates all required predecessor tasks (if any) for each task listed. Three types of predecessors exist: finish-to-start (FS), start-to-start (SS), and finish-to-finish (FF) tasks. A task with an FS predecessor task begins only when that predecessor has been completed. A task with a SS predecessor task begins at the same time as the predecessor. Finally, a task with a FF predecessor is completed as the same time as the predecessor. Tasks often have more than one predecessor and sometimes more than one predecessor type. The nominal, deterministic schedule assumes no uncertainty in the task durations and all slack/margin in the schedule was removed.

ID	Task Name	Baseline Start	Baseline Finish	Dur
1	Management & System Engineering	9/25/00	7/8/03	446 d
2	Propulsion Key Milestones	11/15/00	5/1/02	162 d
3	Propulsion Peer Review	11/15/00	11/15/00	0 d
4	Propulsion PDR	11/16/00	11/17/00	2 d
5	CDR Peer Review	6/26/01	6/26/01	0 d
6	Propulsion CDR	7/20/01	7/20/01	0 d
7	Receivables / Deliverables	12/1/00	6/12/02	436 d
76	Component Engineering & Procurement	9/15/00	5/20/02	563 d
85	Component Procurements	9/15/00	5/20/02	563 d
97	Thrusters Procurement	9/15/00	4/18/02	311 d
86	Tanks Procurement	9/25/00	5/20/02	563 d
106	RCS Components	9/25/00	12/10/01	327 d
77	System Design & Component Selection	9/25/00	5/14/01	152 d
137	Fabrication, Assembly, & Test	9/25/00	7/1/02	538 d
138	Preparations	9/25/00	10/25/01	294 d
147	Assembly and Test	5/1/01	7/1/02	395 d
148	Subassembly Fabrication	5/1/01	2/8/02	200 d
169	FM1 Prop Build	1/7/02	5/15/02	199 d
190	FM2 Prop Build	2/15/02	7/1/02	140 d
240	Propulsion Mission Operations	12/1/00	6/30/03	627 d
243	Fluid System ATLO Support	1/2/01	7/23/03	629 d
212	Ground Support Equipment	1/16/01	7/31/03	626 d
239	Integration & ATLO Support	3/1/02	4/11/03	274 d
250	Launch Operations Support	8/5/02	7/9/03	226 d

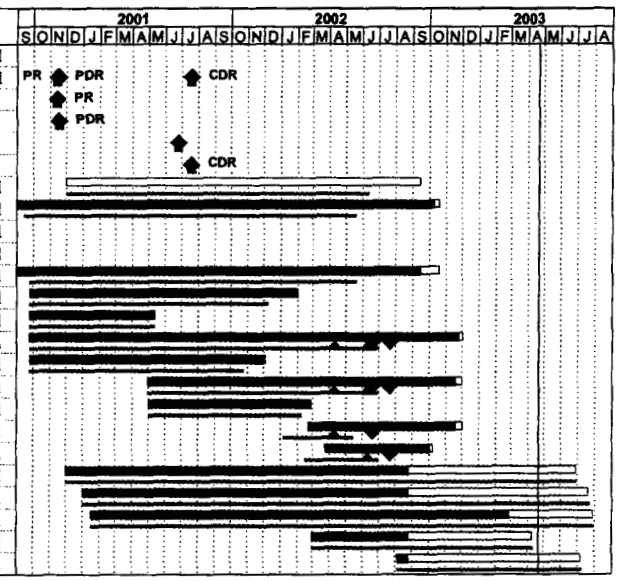

Fig. 2 Baseline Propulsion System Schedule (abbreviated).

The duration and workforce required is then estimated for the tasks. Ideally this is done for each task listed but often because of time and resource constraints it is often done only for the rolled-up (summary) tasks. For example, it is estimated that three individuals were needed for component engineering and procurement (task #76 in Fig. 2): an analyst, a project element manager (PEM), and a supervisor. The duration of this (rolled-up) task is 563 workdays. This task actually includes 53 subtasks. Over the duration of this task, the analyst is estimated to average two-tenths time, the PEM eight-tenths time, and the group supervisor fifteen-one hundredths time. Table 2 lists this workforce allocation of individuals for the various tasks that comprise the MER propulsion system development. Since component engineering and procurement is the first task, no prerequisites are required for this task to proceed. In summary, the

Table 2 Workforce Estimate

Workforce Member	Task Names (% of Full-time Work Allocated)
Analyst	Component engineering & procurement (20)
ATLO engineer	Launch operations support (133)
	Fluid system ATLO support (50)
ATLO technician	Fluid system ATLO support (100)
CTM – Engines	Thrusters procurement (50)
CTM – Tanks	Tanks procurement (200)
CTM – Components	RCS components procurement (50)
GSE engineer	Ground support equipment (230)
I&T engineer	Integration & ATLO support (50)
Project element manager	Component engineering & procurement (80)
Propulsion systems engineer	Fabrication, assembly, & test (200)
	Propulsion mission operations (50)
Propulsion technician	Fabrication, assembly, & test (375)
	Ground support equipment (230)
	Integration & ATLO support (60)
	Launch operations support (333)
Review board	Propulsion peer review (400)
	Propulsion PDR (400)
	CDR peer review (400)
	Propulsion CDR (400)
Supervisor	Component engineering & procurement (15)

schedule model determines the total time to development the MER propulsion system in addition to the time and workforce required to complete individual tasks. Time and workforce allocations will be different for different propulsion system developments and are usually updated for a given propulsion system as the development proceeds.

Cost Model

A cost model was developed to determine the total inflated cost required to design, develop, integrate, test, and deliver *two* monopropellant propulsion systems (MER-A and MER-B). The cost model used the time and workforce estimates generated by the schedule model. The workforce is separated into two categories for cost estimation: staff and services. Staff is defined as employees of the organizational division tasked to design and build the propulsion system. Services is defined as either another division of the organization (or an entirely separate organization) tasked to assist in the design and development of the propulsion system. The inclusion of services in the cost model is representative of current industry practice where one organization often does not have the capability or workforce to complete the entire design and development themselves. The workforce types, their classification, and their assumed annual salary are provided in Table 3.

The workforce cost is estimated for each staff type, for each task. The total unburdened cost, is defined by

$$C_{ub} = \sum_{j=1}^{208}\sum_{k=1}^{13}\frac{\tau_{j,k}s_k}{12\omega} \tag{14}$$

It should be noted that the total workforce time of each individual for each task is determined by the schedule model and the workdays per month was assumed to be 20.5 for this analysis. The total burdened cost is determined by applying a burden factor to the unburdened costs:

$$C_b = \kappa C_{ub} \tag{15}$$

The burden factor accounts for expenses such as the office infrastructure, secretarial salaries, janitorial services, electricity, and so on. The burden factor is generally inversely proportional to the size of the company. An expense rate is applied to the burdened cost to yield the total uninflated cost:

$$C_{ui} = \psi_{\exp_rate} C_b \tag{16}$$

The expense rate accounts for computer, network, and telephone support. The workforce cost is also estimated for each services type, for each task. Services cost are unburdened and no expense rate is applied to the total unburdened cost. The base salary for services, however, is significantly higher than staff, embedding burden and expense costs in the base salary. Based on the schedule model, the uninflated staff and services costs are inflated per a specified inflation rate to yield the total inflated cost. The cost model also includes miscellaneous (procurement) and travel expenses. Procurement and travel expenses are summarized in Table 4. It should be noted that typically only a few tasks in a given project require procurements or travel

Table 3 Workforce Classification and Salary

Workforce Member	Variable	Classification	Salary (FY2003$K/year)
Analyst	s_1	staff	80
ATLO engineer	s_2	staff	80
ATLO technician	s_3	service	150
CTM – Engines	s_4	staff	80
CTM – Tanks	s_5	staff	80
CTM – Components	s_6	staff	80
GSE engineer	s_7	staff	80
I&T engineer	s_8	staff	80
Project element manager	s_9	staff	100
Propulsion systems engineer	s_{10}	staff	80
Propulsion technician	s_{11}	service	150
Review board	s_{12}	staff	125
Supervisor	s_{13}	staff	100

TCM ΔVs

The ΔV required to perform TCMs during the cruise to Mars is uncertain. Mission designers perform analyses to quantify this uncertainty. These results are summarized by the probability density functions (PDFs) of the ideal TCMs ΔVs in Fig. 3. To estimate propellant values, the implemented ΔV values must be calculated. Implemented values account for thruster cant angle losses, spin arc losses by the lateral thrusters, and vectoring losses. A rough estimate of the penalty factor for converting ideal ΔV to implemented ΔV estimates is 50%. That is, any ideal ΔV value must be multiplied by 1.5 to get an approximate value for the corresponding implemented ΔV. Hence, implemented ΔV values based on the ideal ΔV values shown in Fig. 3 were used in the mass (engineering) model in this analysis.

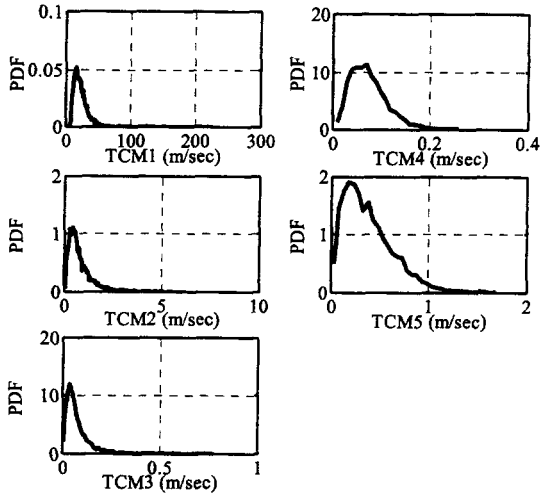

Fig. 3 Ideal TCM ΔVs.

fixed.

Attitude Control Propellant Required

The total mass of propellant required to perform attitude control during the cruise to Mars is also uncertain. Engineers estimated several potential activities that would require expending propellant for attitude control. These estimates are summarized in Table 6. Since all the distributions listed in Table 6 are normal, it is a simple manner to analytically convolve them into a total.[15] Hence the total attitude control propellant mass requirement, m_{prop_ACS}, can also be represented by a normal distribution with a mean of 3.85 kg and a standard deviation of 0.0812 kg.

Component selection

MER propulsion system design was not typical. In an effort to minimize development cost, MER project management wished for the propulsion system to be a replica ("build-to-print") of the monopropellant blowdown propulsion system flown on Mars Pathfinder in 1996-1997 insofar as possible. Because of this edict, typical design uncertainties that an engineer would be faced with (such as selecting a particular latch valve from all potential types and vendors) were nonexistent. All component selection and quantities were predetermined with the exception of the propellant tanks. The original plan was to use four PSI 80275-1 titanium propellant tanks, the exact number and type Mars Pathfinder used. Shortly after PDR, mass growth in the overall spacecraft forced to MER project to seriously consider ultra-lightweight composite overwrapped pressure vessels (COPVs) that were concurrently being developed by a JPL technology program instead. These COPVs assumed aluminum liners and a poly (p-phenylene-benzobisoxazole) [PBO] overwrap. At CDR the baseline was to infuse $1.8M fiscal year 2003 (FY$2003) into developing and using two of these COPVs instead of the four titanium propellant tanks assumed at PDR. Fig. 4 and Fig. 5 illustrate these design changes via the propulsion system schematics assumed at PDR and CDR, respectively. Table 4 summarizes the different estimates for procurements and travel at PDR and CDR. Since the only uncertainty in components was the

Table 6 Attitude Control Propellant Mass Estimates

Activity	Distribution	Parameter 1	Parameter 2
Spindown	Normal	μ: 0.31	σ: 0.041
ACS/NAV characterization	Normal	μ: 0.11	σ: 0
Attitude maintenance	Normal	μ: 0.143	σ: 0.018
TCM tax	Normal	μ: 1.0	σ: 0.067
TCM-1 turns	Normal	μ: 0.210	σ: 0.007
Fault protection	Normal	μ: 2.0	σ: 0
Turn to entry	Normal	μ: 0.077	σ: 0.007
TOTAL CONVOLVED	Normal	μ: 3.85	σ: 0.0812

ACS = attitude control subsystem; NAV = navigation

Table 4 Procurements and Travel

Expense Type	Estimated Cost (FY2003$K) at PDR	at CDR	Associated Task
Engines	900	900	Get on contract (thruster procurement)
Titanium tanks	920	560	New tank procurement
Composite tanks	0	1800	Get on contract (tanks procurement)
Service valves	50	50	Get on contract (service valves procurement)
Pressure transducers	35	35	Get on contract (pressure transducers procurement)
Latch valves	275	275	Get on contract (latch valves procurement)
Filters	28	28	Get on contract (filter procurement)
Materials	80	80	Fabrication, assembly, & test
Miscellaneous	50	50	Preparations
Travel	45	45	Component procurements
	200	200	Launch support

expenses. For the design and development of the propulsion system discussed, only eleven of the 208 tasks anticipate such expenses. In additional to total costs, the cost model generates cost required per workday for the design and development of the propulsion system.

Classification and Probabilistic Modeling of Variables

The variables discussed in the previous sections are classified as aleatory, design, or requirement uncertainties. This classification aids in understanding the impact of uncertainty in the design and development of the tank. Table 5 lists these uncertainties and their assumed probabilistic representation in the analysis. For each variable, the probability distribution assumed and the corresponding parameters that define that probability distribution are provided. A few additional uncertainties are assumed in the analysis that are not listed in Table 5: trajectory correction maneuver (TCM) ΔVs, mass of attitude control propellant required, component selection, and task durations/workforce costs.

Table 5 Summary of Uncertainty Variables

Variable	Type	Distribution	Parameter 1	Parameter 2
f	Aleatory	Normal	μ: 0.806	σ: 0.00217
l_{tubing}	Design	Normal	μ: 7.62	σ: 0.762
$(l/\phi)_{equiv}$	Aleatory	Normal	μ: 30	σ: 3
$m_{fittings}$	Design	Normal	μ: 0.1	σ: 0.05
m_{s/c_s}	Requirement	Normal	μ: 1072	σ: 10.72
P_{MEOP} [e]	Design	Normal	μ: 2.944	σ: 0.028
T_{prop}	Design	Normal	μ: 298	σ: 2
t_{adh} [f]	Design	Normal	μ: 0.0127	σ: 0.00254
t_{lin} [f]	Requirement	Normal	μ: 0.1524	σ: 0.0254
t_{PMD} [f]	Design	Normal	μ: 1.524	σ: 0.01524
ζ [e]	Aleatory	Normal	μ: 2410	σ: 8.04
η_{tank}	Aleatory	Beta	A: 330	B: 1
η_{wrap}	Aleatory	Normal	μ: 0.65	σ: 0.00217
κ	Aleatory	Normal	μ: 2	σ: 0.2
ρ_{adh}	Aleatory	Normal	μ: 1384	σ: 4.61
ρ_{lin}	Aleatory	Normal	μ: 2710	σ: 9.03
ρ_{PMD}	Aleatory	Normal	μ: 1100	σ: 1.1
ρ_{tubing}	Aleatory	Normal	μ: 7750	σ: 7.75
ρ_{wrap}	Aleatory	Normal	μ: 1605	σ: 5.35
ψ_{exp_rate}	Aleatory	Normal	μ: 8	σ: 0.8
ψ_{inf_rate}	Aleatory	Normal	μ: 3	σ: 0.2
ψ_{ullage}	Aleatory	Normal	μ: 31	σ: 3

[e]MPa; [f]mm

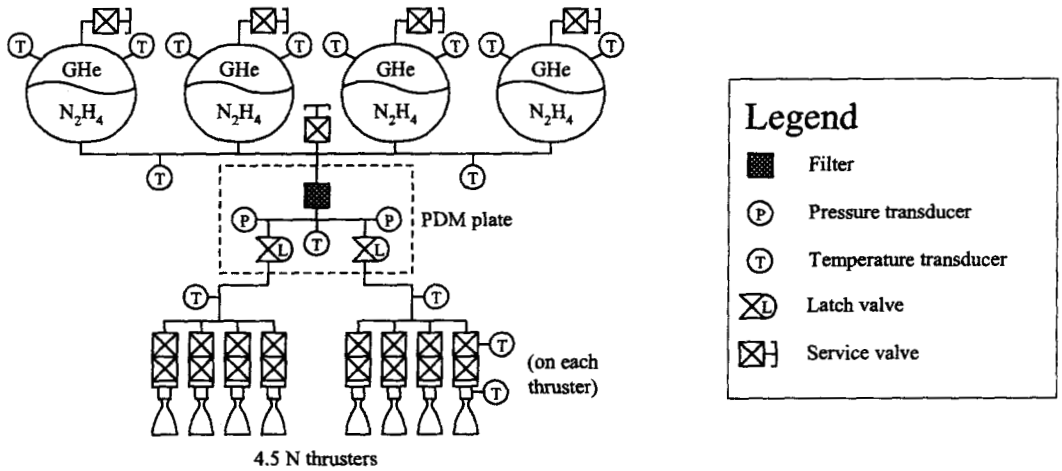

Fig. 4 MER Propulsion System at PDR.

quantity and type of tanks, the analysis just prior to PDR assumed a 90% chance that four PSI 80275-1 titanium propellant tanks would fly and only a 10% chance that the four COPVs would be used. This assumption flipped for the analysis just prior to CDR where only a 10% chance that two PSI 80275-1 titanium propellant tanks would fly and a 90% chance that the two COPVs would be used. Table 7 provides the propulsion system component types and quantities used by MER and in these analyses. MER uses ¼" (35 mil) stainless steel tubing. Finally, a custom distribution was assumed for the number of tubing bends in the propulsion system since the exact number was not known: 4 (20%), 5 (30%), 6 (30%), 7 (10%), and 8 (10%).

Task Duration and Workforce Costs

The estimated time to complete each task and the procurement/travel expenses are also uncertain. As was mentioned in the schedule model section, the time to complete each task is estimated along with the workforce required. These estimates are provided in Fig. 2 and Table 2. All tasks, except single-day tasks such as reviews, are given normal distributions with a mean provided in the fifth column of Fig. 2 and a standard deviation equal to a tenth of the mean. The one-day tasks are given normal distributions with a mean of one workday and a standard deviation of zero. The workforce allocations of Table 2 are not varied probabilistically as uncertainty in workforce is assumed in the distributions given to the task durations. The procurements and travel expenses are given normal distributions with the mean provided in the second column of Table 4 and a standard deviation equal to a tenth of the mean. It should be noted that Table 5 includes three costs related variables, the burden factor, the expense rate, and the inflation rate, that are uncertain.

Monte-Carlo Simulation and Analysis of Results

As was previously mentioned, the analysis was performed twice: at a period assumed to be just before the preliminary design review (PDR) and at a period assumed to be just before the critical design review (CDR). The PDR analysis represented the establishment of margins for the propulsion system.

Table 7 Component Mass Summary Assumed at PDR

Component Type	Manufacturer/ Model Number	Qty	Unit Mass (kg)	Total Mass (kg)
Filter	VACCO/F0D10672-01	1	0.18	0.18
Engine	Aerojet/MR-111C	8	0.33	2.64
Latch valve	VACCO/V1E10864-A	2	0.34	0.68
Pressure transducer	Tavis Corp./30001-0500	2	0.22	0.44
Service valve (gas)	VACCO/V1E10483-01 FDV	4[g]	0.11	0.44
Service valve (liq)	VACCO/V1E10483-02 FDV	1	0.11	0.11
Tank	PSI/80275-1	4[g]	5.76	23.04

[g]2 service valves (gas) and 2 custom COPV tanks assumed at CDR

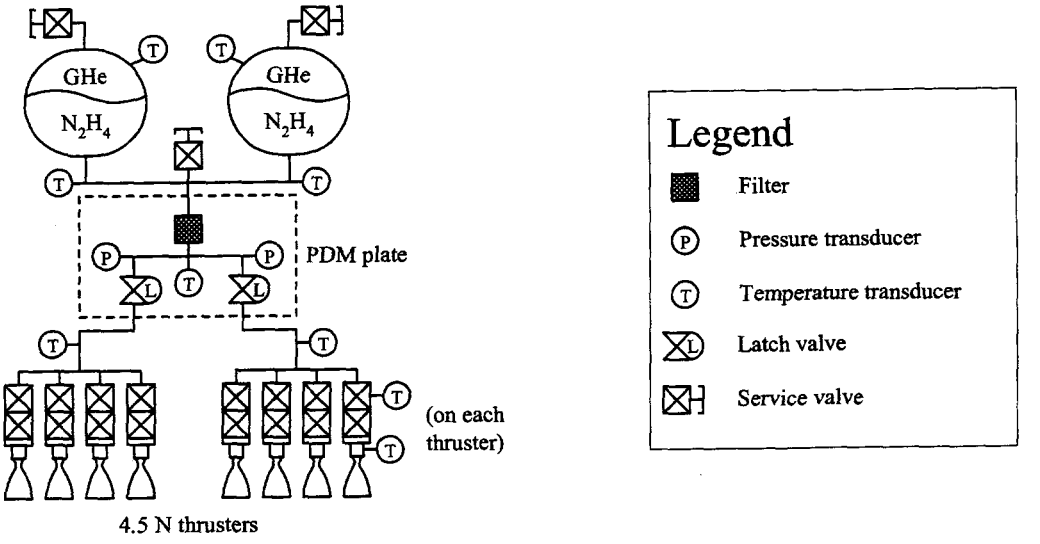

Fig. 5 MER Propulsion System at CDR.

The CDR analysis updates these margins.

PDR

An initial deterministic analysis was first performed for the PDR analysis with the uncertainty variables discussed. The tradable parameters total dry mass, total propellant required, schedule, and cost of the PDR analysis were determined to be 28.9 kg, 21.5 kg, 707 workdays, and FY2003$8.968M, respectively. A second analysis followed in which the variables were randomly generated 5,000 times based on their probability distributions. Task durations and procurements that were completed prior to PDR were given their actual value in the analysis. The results of this 5,000-sample analysis are summarized in Fig. 6 and Fig. 7. Fig. 6 illustrates the probability density functions (PDFs) of the dry mass, propellant mass, schedule, and cost. Two humps are seen in the total dry mass subplot, one large hump near 30 kg and a second small hump near 10 kg. The large hump represents the ~90% of simulation cases where four titanium tanks were assumed and the small hump represents the ~10% of simulation cases where four COPVs were assumed. The PDFs of propellant mass, schedule, and cost appear normal or lognormal. Fig. 7 illustrates the cumulative distribution functions (CDFs) of the dry mass, propellant mass, schedule, and cost. Both the deterministic and 95, 99, and 99.9 percentile values of these four tradable parameters are listed in Table 9. By comparing these 95, 99, and 99.9 percentile values with the corresponding deterministic values establishes a low-, medium-, and high-confidence estimate of the margin to hold at the PDR. In the case of dry mass, the low-, medium-, and high-confidence estimates of margin (percent margin) are 0.2 kg (0.7%), 0.3 kg

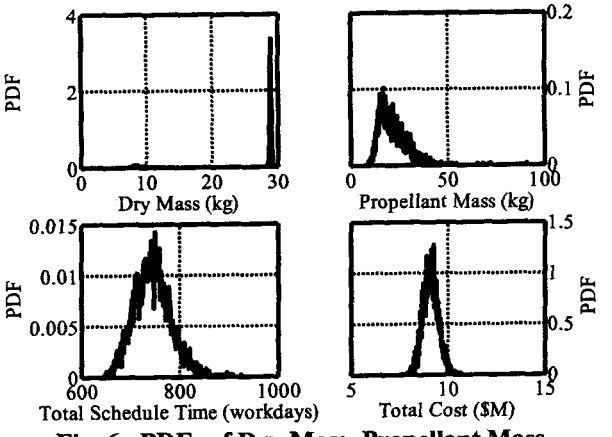

Fig. 6 PDFs of Dry Mass, Propellant Mass, Schedule, and Cost at PDR.

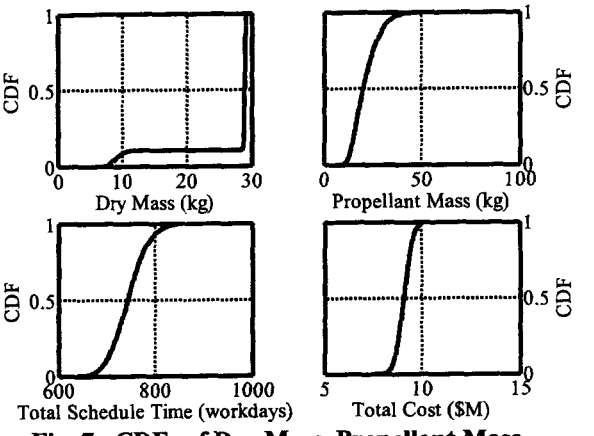

Fig. 7 CDFs of Dry Mass, Propellant Mass, Schedule, and Cost at PDR.

Table 8 CDR Monte Carlo Simulation Results

Value	Dry mass (kg)	Propellant mass (kg)	Schedule (workdays)	Cost (FY$2003)
Deterministic	9.0	21.6	707	10.408M
95%	17.1	34.5	811	11.265M
99%	17.2	41.7	844	11.625M
99.9%	17.3	71.3	890	12.039M

(1.0%), and 0.3 kg (1.0%), respectively. In the case of propellant mass, the low-, medium-, and high-confidence estimates of margin (percent margin) are 12.9 kg (60.0%), 19.9 kg (92.6%), and 48.0 kg (223.3%), respectively. The low-, medium-, and high-confidence estimates of schedule margin are 102 workdays (14.4%), 136 workdays (19.2%), and 190 workdays (26.9%), respectively. Finally, the low-, medium-, and high-confidence estimates of cost margin are FY2003$0.772M (8.6%), FY2003$1.053M (11.8%), and FY2003$1.490M (16.6%), respectively.

CDR

An initial deterministic analysis was first performed also for the CDR analysis with the uncertainty variables discussed. The tradable parameters total dry mass, total propellant required, schedule, and cost of the CDR analysis were determined to be 9.0 kg, 21.6 kg, 707 workdays, and FY2003$10.408M, respectively. A second analysis followed in which the variables were randomly generated 5,000 times based on their probability distributions. Task durations and procurements that were completed prior to CDR were given their actual value in the analysis. The results of this 5,000-sample analysis are summarized in Fig. 9 and Fig. 8. Fig. 9 illustrates the probability density functions (PDFs) of the dry mass, propellant mass, schedule, and cost. Two humps are also seen in the total dry mass subplot for this analysis, one large wide hump around 10 kg and a second small narrow near 20 kg. The large hump represents the ~90% of simulation cases where two COPVs were assumed and the small hump represents the ~10% of simulation cases where two titanium tanks were assumed. As with the PDR analysis, the PDFs of propellant mass, schedule, and cost appear normal or lognormal. Fig. 8 illustrates the cumulative distribution functions (CDFs) of the dry mass, propellant mass, schedule, and cost. Both the deterministic and 95, 99, and 99.9 percentile values of these four tradable parameters are listed in Table 8. By comparing these 95, 99, and 99.9 percentile values with the corresponding deterministic values establishes a low-, medium-, and high-confidence estimate of the margin to update at the CDR. In the case of dry mass, the low-, medium-, and high-confidence estimates of margin (percent margin) are 8.1 kg (90.0%), 8.2 kg (91.1%), and 8.3 kg (92.2%), respectively. In the case of propellant mass, the low-, medium-, and high-confidence estimates of margin (percent margin) are 12.9 kg (59.7%), 20.1 kg (93.1%), and 49.7 kg (230.1%), respectively. The low-, medium-, and high-confidence estimates of schedule margin are 104 workdays (14.7%), 137 workdays (19.3%), and 183 workdays (25.9%), respectively. Finally, the low-, medium-, and high-confidence estimates of cost margin

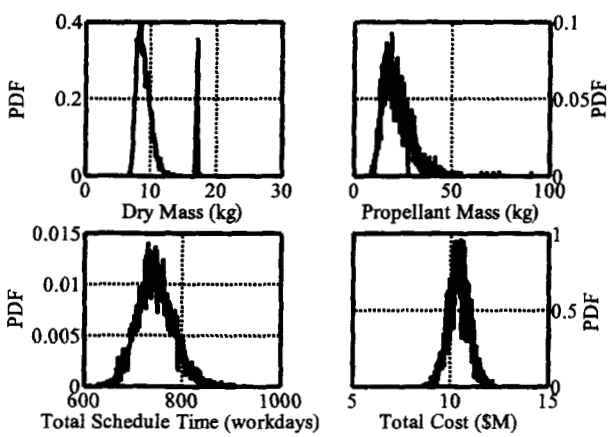

Fig. 9 PDFs of Dry Mass, Propellant Mass, Schedule, and Cost at CDR.

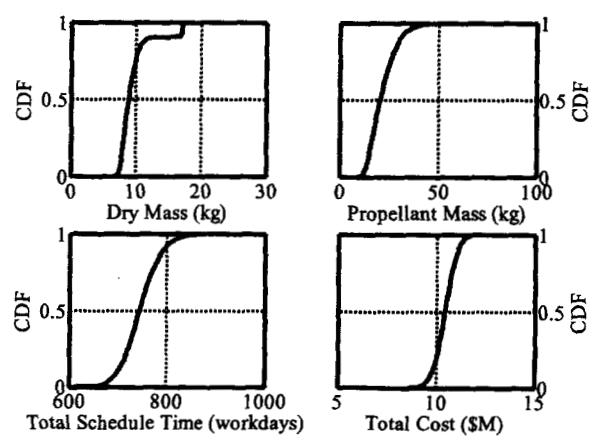

Fig. 8 CDFs of Dry Mass, Propellant Mass, Schedule, and Cost at CDR.

Table 9 PDR Monte Carlo Simulation Results

Value	Dry mass (kg)	Propellant mass (kg)	Schedule (workdays)	Cost (FY$2003)
Deterministic	28.9	21.5	707	8.968M
95%	29.1	34.4	809	9.740M
99%	29.2	41.4	843	10.021M
99.9%	29.2	69.5	897	10.458M

are FY2003$0.857M (8.2%), FY2003$1.217M (11.7%), and FY2003$1.631M (15.7%), respectively.

Validation and Discussion

Arguably the most important result of these analyses with respect to this research is that the established and updated margins determined by this method are not the values the MER project assumed during the conceptual design stage (15% for dry mass, 6% for schedule, and 10% for cost). In hindsight, holding 15% margin at PDR on the dry mass seemed conservative compared to the negligible uncertainty assumed in a "build-to-print" system. However, this changed dramatically at CDR where 15% margin seemed reckless compared to the 90% margin numbers determined by this analysis due to the change in propellant tanks. Holding 6% schedule margin was risky but unavoidable for MER because of its tight overall schedule. Holding 10% for cost seems reasonable so long as cost is not traded for schedule margin. Otherwise holding a 10% margin number for cost is precarious.

At the time of this writing, MER is on schedule to launch both the MER-A and MER-B spacecraft by June 2003. It is worth comparing the real values of the MER propulsion system with those of the CDR analysis. The total dry mass of the MER propulsion system (including helium pressurant) has come in at 16.4 kg which is approximately a 90th CDR percentile number. The current plan calls for 47 kg of propellant to be loaded prior to launch which is greater than the 42.8 kg requirement (99% number). This 47 kg is approximately a 99.7 percentile CDR number and provides a 117.6% margin on propellant as defined in this paper (a 9.8% fill margin based on the 99 percentile requirement). The MER project schedule allowed 749 workdays for the propulsion system design and development which is approximately the 56th CDR percentile value. The total inflated propulsion system cost appears to be topping out at ~$11.6M which is approximately a 99th CDR percentile value. However, it should be noted that cost was traded to gain schedule. If this cost was not included, the cost total would be much closer to $11.0M which is an 86th percentile number. In summary, if 99 percentile values were assumed at PDR, the propulsion system would not have exceeded its cost margin (XX% vs. 10%). It should be noted that the margins for dry mass and schedule of the current method were not exceeded. The proposed method for these same two margins would not have been exceeded either indicating that in this case for these two parameters the current method was adequate.

$11M

$10.4M

As demonstrated, uncertainties play a significant role early on in the design of a complex multidisciplinary system. Engineers often think that displaying uncertainty is displaying a lack of understanding.[16] However, an understanding of the impact of uncertainty must be understood for successful design, development, and operations. The method outlined in this paper provides a path toward this understanding through probabilistic methods. The 99 percentile ΔV values that the MER project assumed early in the design were reasonable for this mission since it is a lander and must successfully arrive at Mars to have a chance at mission success. However, assuming the 99% ΔV numbers with their large margins on propellant, instead of 95% numbers increased the total ΔV requirement on the propulsion system significantly since the tails of these distributions are long (see Fig. 6 and Fig. 9). This in turn drove the propulsion system mass. Without doing a probabilistic analysis on the propulsion system, this impact would not be understood. For certain missions where most of the ΔV maneuvers occur once the spacecraft arrives in orbit about a ephemeral body, it may be worth going to 95% ΔV numbers and using the mass savings of less propellant (and hence less propulsion system mass) for other elements of the spacecraft. Making the spacecraft a little less reliable in terms of achieving the ΔV requirement could make the overall spacecraft much more reliable by using this mass savings for other elements of the spacecraft, more reliable mechanisms for example. Furthermore, filling the tanks to capacity (fill margin) which invariably occurs during launch preparations will undoubtedly raise the 95% ΔV number higher, potentially returning to 99% number so widely assumed if the tanks have significant fill margin.

Conclusions

A method for propagating and mitigating the effect of uncertainty in conceptual level design via probabilistic methods has been presented. The goal of this research is to develop a rigorous foundation for determining design margins in complex multidisciplinary systems. A result of this work is a redefinition of the concept of design margin. Here, margins are a function of risk tolerance and are measured relative to mean expected system performance, not variations in design parameters measured relative to worst-case expected values. The investigated method was applied to the design and development of the monopropellant blowdown hydrazine system of the Mars Exploration Rover (MER) mission. For the propulsion example presented, margins for dry mass, propellant mass, schedule, and cost formed a set of tradable system-level parameters. Assuming a medium-confidence approach to design and development, the preliminary design review (PDR) analysis established margins of 1.0%, 92.6%, 19.2%, and 11.8% should be maintained for dry mass, propellant mass, cost, and schedule, respectively. The critical design review (CDR) analysis updated these margins to 91.1%, 93.1%, 19.3%, and 11.7%. Both cases indicate an important difference from the margins typically assumed during conceptual design stage. The medium-confidence margins did not exceed the final values for the MER propulsion system.

Acknowledgements

The authors thank Fred Culick and Joel Sercel (Division of Engineering and Applied Science, California Institute of Technology, CA); Mark Adler, Louis D'Amario, Barry Goldstein, Genvieve Lopez, Behzad Raofi, Ralph Roncoli, and Grace Tan-Wang (Mars Exploration Rover Project, JPL; Pasadena, CA); and Seung Chung (Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, MA). This research is funded in part by the National Reconnaissance Office (Chantilly, VA) through the Space Systems, Policy, and Architecture Research Consortium (SSPARC).

References

[1]Humble, R., Henry, G., and Larson, W., "The Design Process," *Space Propulsion Analysis and Design*, McGraw-Hill Co., New York, New York, 1995, pp. 19-30.

[2]Murray, J., "The Oxford English Dictionary," Vol. XI, Clarendon Press, Oxford, United Kingdom, 1961.

[3]Thunnissen, D., "Uncertainty Classification for the Design and Development of Complex Systems," be Presented at the 3rd Annual Predictive Methods Conference, Newport Beach, CA, June 16-17, 2003.

[4]Oberkampf, W., DeLand, S., Rutherford, B., Diegert, K., and Alvin, K., "A New Methodology for the Estimation of Total Uncertainty in Computational Simulation," AIAA Paper 99-1612, April 1999, pp. 3-4.

[5]Thunnissen, D., Engelbrecht, C., and Weiss, J., "Assessing Model Uncertainty in the Conceptual Design of a Monopropellant Propulsion System," Paper 2003-4469, to be Presented at the 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Huntsville, Alabama, July 20-23, 2003.

[6]Melchers, R., "Uncertainties in Reliability Assessment," *Structural Reliability Analysis and Prediction*, 2nd edition, John Wiley & Sons, Chichester, United Kingdom, 1999, pp. 34-45.

[7]Bedford, T. and Cooke, R., "Different Types of Uncertainty," *Probabilistic Risk Analysis: Foundations and Methods*, Cambridge University Press, Cambridge, United Kingdom, 2001, p. 35.

[8]Tversky, A. and Kahneman, D., "Judgment under Uncertainty," *Science*, Vol. 185, 1974, pp. 1124-1131.

[9]Roncoli, R. and Ludwinski, J., "Mission Design Overview for the Mars Exploration Rover Mission," Paper AIAA 2002-4823, August 2002.

[10]Welch, R., "Flight System Technical Resource and Margin Policy: Mars Exploration Rover Project," Jet Propulsion Laboratory, Report JPL Document: D-19844, Pasadena, CA, June 18, 2001, p. 4.

[11]DeLaurentis, D., "Uncertainty Modeling and Management in Multidisciplinary Analysis and Synthesis," AIAA Paper 2000-0422, January 2000, p. 5.

[12]Fox, E., "The Pratt & Whitney Probabilistic Design System," AIAA Paper 94-1442, April 1994.

[13]Thunnissen, D., "A Method for Determining Margins in Conceptual Design," *AIAA Journal of Spacecraft & Rockets*, to be published.

[14]Ballinger, I., Lay, W., and Tam, W., "Review and History of PSI Elastomeric Diaphragm Tanks," AIAA Paper 95-2534, July 1995, p. 4.

[15]Ross, S., "Jointly Distributed Random Variables," Introduction to Probability Models, 7th edition, Harcourt Academic Press, San Diego, CA, 2000, pp. 56-57.

[16]Seife, C., "Columbia Disaster Underscores the Risky Nature of Risk Analysis," Science, Vol. 299, February 14, 2003, p. 1001.