Application of Risk Informed Decision Making to Highly Reliable Three Dimensionally Woven Thermal Protection System for Mars Sample Return

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The NASA Risk Informed Decision Making process is used to assess a trade space of three dimensionally woven thermal protection systems for application to the Mars Sample Return Earth Entry Vehicle. Candidate architectures are assessed based on mission assurance, technical development, cost, and schedule risk. Assessment methodology differed between the architectures, utilizing a four-point quantitative scale for mission assurance and technical development and highly tailored PERT techniques for cost and schedule. Risk results are presented, in addition to a review of RIDM effectiveness for this application.

I. Nomenclature

CPM	=	Critical Path Methods
EEV	=	Earth Entry Vehicle
HEEET	=	Heatshield for Extreme Entry Environments Technology
IL	=	Insulating Layer
MSR	=	Mars Sample Return
PERT	=	Program Evaluation and Review Technique
RIDM	=	Risk Informed Decision Making
RL	=	Recession Layer

II. Introduction

Due to the possibility of inadvertent release of biological samples, the Mars Sample Return (MSR) Earth Entry Vehicle (EEV) is expected to carry unprecedented requirements for planetary protection. These requirements flow down to all sub-systems, including the thermal protection system (TPS).

Accurate characterization of mission risk is necessary to support certification against requirements. NASA provides handbook guidance for Risk Informed Decision Making (RIDM), a deliberative decision-making process employed for major architecture and design decisions involving high stakes and complexity [1] [2]. The large TPS trade space coupled with a lack of quantitative risk data make MSR EEV TPS selection an excellent candidate for RIDM application.

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As part of a preliminary risk characterization conducted under a NASA Ames IRAD activity, the RIDM process was applied to a trade space of three dimensionally (3D) woven TPS variants being considered for MSR, though the methodology developed is applicable to the larger architectural trade that includes TPS options that are not 3D-woven.

The paper begins with an outline of the RIDM process, followed by a summary of the 3D woven variants considered for MSR. The risk assessment methodology is then summarized, followed by presentation of the results of the risk assessment activity. The paper concludes with an assessment of RIDM effectiveness for this application and a perspective on the utility of RIDM application more generally.

III. Risked Informed Decision Making (RIDM)

In the absence of uncertainty, decision making reduces to a deterministic multi-disciplinary optimization process, which consists of selecting from a trade space the option that best satisfies mission requirements. However, given the realities of finite testing, data and operational experience, uncertainty is an inherent aspect of the decision-making process.

Uncertainty in decision-making is significant when it results in degraded performance with respect to one or more system performance objectives. Risk, resulting from the uncertainty associated with one or more performance objectives, can be defined operationally as a set of three components [1]:

- The *Scenario(s)* leading to degraded performance with respect to one or more performance measures
- The *Likelihood(s)* or probability (quantitative or qualitative) of those scenarios
- The *Consequence(s)* (quantitative or qualitative severity of performance degradation) that would result if those scenarios were to occur

Risk Informed Decision Making (RIDM) is a deliberative process that uses information about risk to guide major architecture and design decisions. RIDM provides a framework to augment quantitative data with subject matter expert (SME) technical opinion in order to make a robust decision by considering all sources of mission risk [1].

IV. Three-Dimensionally Woven TPS

Three-dimensional weaving employs interconnections between layers that provide high interlaminar strength, in contrast with conventional structural composites that rely on resin to hold 2D plies together. This strength in the through-thickness direction should mitigate mechanical loss of char when the surface of the TPS is exposed to extreme heating and mitigate the generation of in-plane cracks due to high temperature gradients. Figure 1 provides a schematic of a generic three-dimensional weave, with different fiber types used at different locations, and varying weave density at different layers through the thickness. Material properties such as conductivity and strength can be tailored through selection of fiber type and weave pattern, to deliver an efficient TPS tailored for specific mission needs. For an ablative TPS (i.e. a system that sacrifices mass to accommodate high heating rates), it is attractive to partition the material into a region that ablates, or recedes, (the Recession Layer (RL)) and a region that insulates the underlying structure from the incident heating (the Insulating Layer (IL)). The mechanical interlock between layers provides an unprecedented opportunity for tailoring of the TPS in this manner.

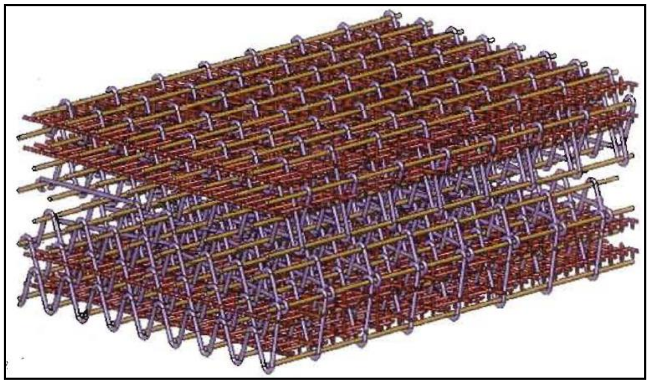
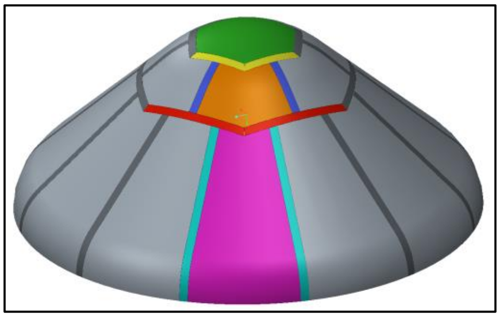


Figure 1. Schematic of generic three-dimensionally woven material [3].

The size of a woven part is limited by the number of yarns that can be controlled by a loom: warp yarns are raised and lowered by hooks attached to the loom head, and fill yarns are inserted between the raised and lowered yarns. The weave pattern is defined by the different sets of raised yarns for each insertion of a fill yarn.

Using fine (low diameter) yarns reduces the volume of material delivered for a given number of yarns. A large thickness reduces the width that can be delivered by a given number of hooks. While it is attractive to make a complete heatshield from a single woven piece, restrictions on yarn diameter and requirements for large thickness may require assembly of several woven tiles, particularly if the heatshield is large (diameter exceeds width of material off the loom).

The dry woven material is commonly infused with phenolic to enhance its thermal protection performance [4]. The material is typically formed to near-final shape prior to infusion, which rigidizes it, and then machined to match the contour of the substrate. The amount of infusion (density of phenolic in the final part) can be adjusted to trade thermal performance against convenience of integration.



Tile Type	Tile Color	Tile Quantity for 1x Tile Set
Nose Cap		1
Inner Circumferential Gap Filler		6
Inner Radial Gap Filler		6
Inner Tile		6
Outer Circumferential Gap Filler		6
Outer Radial Gap Filler		12
Outer Tile		12

Figure 2. HEEET engineering test unit has demonstrated manufacturing and integration at 1-meter scale [3].

The woven material can be integrated into a complete heatshield in a number of ways. Seven different 3D woven variants have been considered as part of the study, as described below:

A. Heatshield for Extreme Entry Environments Technology (HEEET)
A dual layer, tiled TPS, consisting of a high density, all carbon upper layer to manage recession and a lower density, carbon-phenolic yarn insulation layer to manage heat transfer to the entry vehicle structure. The weave is infused using phenolic resin and machined into tiles, as illustrated in Figure 2.

B. HEEET 6k Recession Layer
A variant of HEEET that is woven with a 6k recession layer (6000 fibers per bundle) instead of the nominal 3k tow (3000 fibers per bundle), resulting in a coarser weave.

C. Insulation Layer Only Tiled
A tiled architecture consisting of only the lower density HEEET insulation layer.

D. 3D Woven Single Piece
An architecture consisting of the same dual-layer structure as HEEET, but manufactured and attached to the vehicle as a single piece.

E. Dry Woven Single Piece
A variant of 3D woven single piece that retains the dual-layer structure of HEEET but without phenolic impregnation.

F. Insulating Layer Only Single Piece

A variant of 3D woven single piece consisting of only the HEEET insulation layer, infused with phenolic resin.

G. 3D Carbon-Carbon

A single-piece, hot-structure architecture, with a nominal composition similar to a carbonized HEEET recession layer.

V. Risk Assessment Methodology

Four categories of risk were identified for 3D woven TPS: mission assurance, technical development, cost, and schedule. Mission assurance addresses sources of residual risk that may result in failure during the mission. Technical development addresses the possibility that planned technical capability may not mature due to unforeseen technical deficiencies, or that capability cannot be verified to the certification levels required by the mission. Even if technology is capable of being matured to deliver adequate mission performance, there is risk that the resource demand will be unacceptable. Hence cost and schedule risk are also evaluated. Illustrations of these risk categories is given in Figure 3 below.

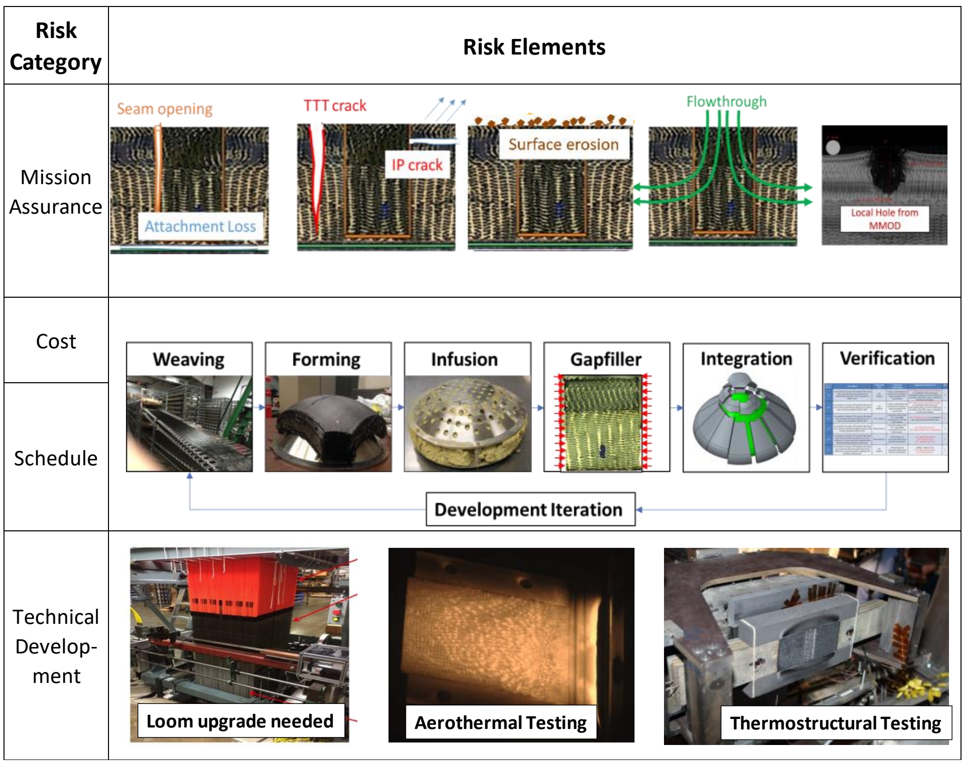


Figure 3. Summary of Risk Elements

Assessment methodology differed between the risk categories. For mission assurance and technical development, a four-point quantitative scale was developed to capture both the risk and uncertainty associated with each selection in the trade space. A description of the ranking scale is given in Table I below.

Table I. Mission Assurance and Technical Development Scoring Scale

Rating Scale	
0	Inadequate
1	Marginal
2	Adequate Margins
3	No Credible Risk

0 - Inadequate
The option is known to have sub-marginal or unacceptable performance.

1 - Marginal
Either the option is known to have marginal performance, or there is sufficient uncertainty that performance cannot be characterized as having adequate margins within a reasonable degree of certainty.

2 – Adequate Margins
The option has demonstrated adequate performance, within accepted margins.

3 – No Credible Risk
The option demonstrates no credible risk of failing to meet the performance objective. Either the risk does not apply to the option considered, or performance data shows no credible way in which the option could fail to meet the performance objective.

A highly tailored Program Evaluation and Review Technique (PERT) was employed to perform a quantitative analysis of cost and schedule risk for a sample of the 3D woven trade space. Data was gathered from program development experience (particularly the HEEET engineering test unit (ETU) development), contractor estimates, and subject matter expert technical opinion. Estimated cost/schedule values and uncertainties were developed for each process, and the results were used to generate total estimates and uncertainties along the critical path. Accurate characterization of uncertainty in SME data was made difficult by the low information state at the time of analysis. The objective of these uncertainty estimates is to provide a cursory estimate of the relative risk to discriminate between alternatives. Uncertainty estimates provide approximate bounds on cost and schedule for each item analyzed at a reasonable confidence level.

VI. Risk Assessment Results

Results for the four risk categories described above are summarized below:

A. Mission Assurance

A matrix showing risk levels for the mission assurance risk candidates is in Table II below.

Table II. Mission Assurance Risk Assessment Results

Risk		Trade Space						
		HEEET	6K Recession Layer Tiled	Insulating Layer Only Tiled	3D Woven Single Piece	Dry Woven Single Piece	Insulating Layer Only Single Piece	3D C-C Single Piece
Mission Assurance								
Failure Mode	Load Case							
Local Hole	MMOD, Shock, Integration	2	2	1	2	1	1	1
Surface Erosion (Mechanical)	Entry	2	1	1	3	1	1	3
Seam Opening	Cold Soak, Entry	2	1	2	3	3	3	3
Flow Through	Entry	2	2	1	3	1	2	3
Cracking	Cold Soak, Shock	3	3	3	3	3	3	3
Attachment Failure	Cold Soak, Entry	2	2	2	2	2	2	1
Shape Stability	Entry	2	2	2	2	2	2	1

In the left hand column of the table are the failure modes associated with mission assurance risk, along with their associated load cases. The TPS ranking against the associated risks are organized in columns, with comments on the scoring given at right. 3D woven single piece has the highest aggregate score with respect to mission assurance.

B. Technical Development

Technical development risks are summarized below in a similar fashion.

Table III. Technical Development Risk Results

	Trade Space						
Risk	**HEEET**	**6K Recession Layer Tiled**	**Insulating Layer Only Tiled**	**3D Woven Single Piece**	**Dry Woven Single Piece**	**Insulating Layer Only Single Piece**	**3D C-C Single Piece**
Technical Development							
Weaving 60" Width	3	3	3	1	1	2	1
Areal Property Variation in Formed Part	3	3	3	2	2	2	1
Attachment to Substrate	2	2	2	2	2	2	1
Certifiability	1	1	1	2	2	2	1

The four technical development risks assessed are given at right. The three tiled architectures share the maximum score for technical development, but carry marginal performance with respect to certifiability.

C. Cost

Analysis of system cost was conducted on a representative sample of the 3D woven trade space. Results for HEEET, 3D Woven Single Piece, and Insulating Layer Only Single Piece are given in Table IV below.

Table IV. Relative Cost Comparison

<table>
<tr><th colspan="2">System Cost</th><th colspan="2">HEEET MSR</th><th colspan="2">3D Woven Single Piece</th><th colspan="2">Insulating Layer Only Single Piece</th></tr>
<tr><th>Cost Categories</th><th>Detail</th><th>Cost (Norma-lized Relative to Baseline HEEET)</th><th>Uncertainty (±)</th><th>Cost (Norma-lized Relative to Baseline HEEET)</th><th>Uncertainty (±)</th><th>Cost (Norma-lized Relative to Baseline HEEET)</th><th>Uncertainty (±)</th></tr>
<tr><td rowspan="4">Dev. Cost</td><td>Weave Dev.</td><td>0</td><td>-</td><td>4</td><td>2</td><td>4</td><td>2</td></tr>
<tr><td>Design</td><td>1</td><td>-</td><td>2</td><td>1</td><td>2</td><td>1</td></tr>
<tr><td>Components + Integration</td><td>2.5</td><td>-</td><td>2.5</td><td>-</td><td>2.5</td><td>-</td></tr>
<tr><td>Testing</td><td>5</td><td>1</td><td>4</td><td>1</td><td>4</td><td>1</td></tr>
<tr><td rowspan="3">Mfg. and Integration</td><td>Weave</td><td rowspan="3">12</td><td rowspan="3">2</td><td rowspan="3">6</td><td rowspan="3">2</td><td rowspan="3">6</td><td rowspan="3">2</td></tr>
<tr><td>Forming + Infusion + Machining</td></tr>
<tr><td>Carrier + Integration</td></tr>
<tr><td colspan="2">Property Testing</td><td>0</td><td>-</td><td>1</td><td>-</td><td>1</td><td>-</td></tr>
<tr><td colspan="2">Certification</td><td>10</td><td>3</td><td>5</td><td>2</td><td>5</td><td>2</td></tr>
<tr><td colspan="2">Documentation</td><td>0</td><td>-</td><td>0</td><td>-</td><td>0</td><td>-</td></tr>
<tr><td colspan="2">Project Mgmt. + Systems Eng.</td><td>6</td><td>-</td><td>5</td><td>-</td><td>5</td><td>-</td></tr>
<tr><td colspan="2">Total</td><td>36.5</td><td>6</td><td>29.5</td><td>8</td><td>29.5</td><td>8</td></tr>
</table>

Cost values and uncertainties were developed relative to baseline HEEET, specifically leveraging SME experience with HEEET ETU development, construction, and testing. Based on these preliminary results, HEEET adaptation for MSR would be more expensive than a single piece configuration, but with a lower cost uncertainty. However, this list of cost categories may not be exhaustive, and additional input on cost categories and risks is necessary to make a robust decision.

D. Schedule

A schedule for each option includes all steps associated with technical development, production, and certification through the flight readiness review (FRR). An accepted method for analyzing schedule risk is Critical Path Methods (CPM). CPM involve identifying the critical path, or the longest mean path through a schedule network, and treating it as the schedule risk driver. This is not always a valid assumption, as variation in the actual event duration during the project can result in changes to the critical path. A comprehensive Monte Carlo analysis can capture the effect of critical path changes in different schedule instances, but such analysis is beyond the scope of the current study.
Estimates for the duration and uncertainty of each event are collected from SMEs and/or relevant contractors. Several methods for this exist, including collecting best-case, worst-case, and most-likely estimates for each event, then using these values to construct a Normal distribution of possible durations. In this case, SME estimates were collected for each option with SME estimated uncertainties for only a subset of events. The results comparing HEEET with a single piece 3D woven are shown in Table V below.

Table V. Relative Schedule Comparison

HEEET			3D Woven Single Piece		
Event Description	**Time (months)**	**Uncertainty (months)**	**Event Description**	**Time (months)**	**Uncertainty (months)**
Weave Procurement	6	-	Weave Procurement	6	-
Raw Material Purchase/Processing, Loom Startup and Verification	7	1	Loom Development (from construction to startup and verification)	24	6
Time to weave ESH Dev Coupons, MDU, and flight material	9	2.25	Time to weave flight material (no MDU/ESH)	3	0.75
Form last batch of flight material	1	-	Form flight material	3	-
Infuse last batch of flight material	1.5	0.5	Infuse flight material	2	0.5
Machine last batch of flight material	4	-	Machine flight material	2	-
Integration	6	-	Integration	1	-
CT Scan	2	1	CT Scan	1	1
Certification	6	3	Certification	6	3
Total	**42.5**	**7.75**	**Total**	**48**	**11.25**

Since a firm mission timeline has not been established, the emphasis of the analysis is on event duration. From the analysis it is evident that a 3D woven single piece carries both a longer total duration, as well as larger schedule uncertainty, relative to the tiled baseline. However, if multiple units are needed, advantage quickly shifts to the single piece. For three units or more, assuming that integration is performed serially, the single piece would have a lower mean critical path as compared to the tiled architecture.

VII. Conclusion

A risk analysis framework has been developed that employs the RIDM process to assess relative risk between different 3D woven TPS alternatives for MSR EEV. RIDM was utilized due to the high stakes associated with TPS architecture selection and the scarcity of quantitative performance data for the 3D woven variants. RIDM provides a framework to elicit SME estimates of performance for elements of the trade space, based on experience with HEEET program development. In some cases, the process confirmed expectations regarding system performance. However, in other cases the formal procedures of RIDM process brought to light surprising results. For example, the perceived certifiability benefits to cost and schedule for a single piece architecture did not show up for a single mission, due to non-recurring engineering development constituting a significant fraction of mission resource allocation.

The main difficulty in applying RIDM is uncertainty quantification for problems with a low information state, due to the conservatively high uncertainties that are predicted. SME estimates gathered as part of this study have variance that exceeds the mean difference between alternatives for cost and schedule risk. Despite this limitation, which is probably common at the conceptual design phase, the RIDM process provides a useful formal framework for guiding risk discussion for high level design decisions. As the scope of the trade space is decreased, program requirements are refined, and additional data becomes available, increasingly quantitative analysis tools can be employed to support more accurate estimation and uncertainty characterization.

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