Ames Research Center

Highly Reliable 3-Dimensional Woven Thermal Protection System for Mars Sample Return

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3D Woven for MSR - Overview

- **The MSR Challenge:**
  - Reliability requirements for a Mars Sample Return (MSR) Earth Entry Vehicle (EEV) are expected to be more stringent than any mission flown to date.
    - This flows down to all EEV subsystems, including **heat-shield TPS**
    - Likely to be the key driver for design decisions in many subsystem trades.
- **The MSR formulation is holding an option to on-ramp a 3D-woven system. The goal of this effort is to:**
  - Provide a recommended 3D woven TPS architecture for MSR using Risk Informed Decision Making (RIDM).
- **Risk Informed Decision Making (RIDM):**
  - MSR formulation will institute RIDM processes to select configurations it pursues in future design cycles.
    - RIDM is a deliberative process that uses a diverse set of performance measures, together with other considerations, to inform decision making.
      - RIDM acknowledges the inevitable gaps in technical information, and the need for incorporating the cumulative wisdom of experienced personnel to integrate technical and nontechnical factors in order to produce sound decisions.

Why 3D Woven on MSR?

- **All TPS systems under consideration have their own set of challenges:**
  - **Carbon-Carbon (Hot Structure):**
    - Certification of thermal-structural performance during re-entry and at temperature under the high strain landing impact environment will be challenging.
  - **Single Piece PICA (Cold Structure):**
    - PICA has an observed aerothermal failure mode under high pressure/shear environments.
      - Challenging to match MSR conditions in the arcjet
        - » Can over test in shear/pressure – may result in false negative
        - » To match MSR conditions may require investment in arcjet facilities (i.e. new nozzles)
    - Single Piece PICA has not been manufactured in MSR size range ~1.3m diameter
      - High material variability + low through the thickness strengths will make structural certification challenging
  - **3D Woven (Tiled/Single Piece)**
    - The 3D Woven system is heavier than the PICA system *in general.*
      - Likely to be partially offset by lower carrier structure mass for HEEET vs PICA
    - HEEET has shown robust capability against aerothermal environments that exceed MSR requirements
    - Manufacturing a single piece 3D woven heat shield has not been demonstrated.
      - Industry is currently able to weave a 54” width, so the risk is perceived low.
- **In general, a 3D woven single piece heat shield offers a robust solution that minimizes the challenges associated with the certification, structural performance, and aerothermal performance that are present in the other TPS options.**

IRAD RIDM Approach – Identification of Alternatives

- **Identification of Alternatives:**
  - Three potential 3D woven architectures, all capable of handling the MSR entry environments, have been identified and are summarized below.
    - **Infused single piece 3D woven:**
      - Elimination of seams offers an easier certifiability argument.
    - **Un-infused single piece 3D woven:**
      - Elimination of seams offers an easier certifiability argument.
      - Lack of infusion is potentially beneficial for ground impact attenuation.
    - **Infused 3D woven tiled architecture (HEEET):**
      - Fabrication has been recently demonstrated by the HEEET project, which minimizes manufacturing schedule and cost risks.
      - Presence of seams increases certification challenges

HEEET Engineering Test Unit

RIDM Process

Identification of Alternatives

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Analysis of Alternatives

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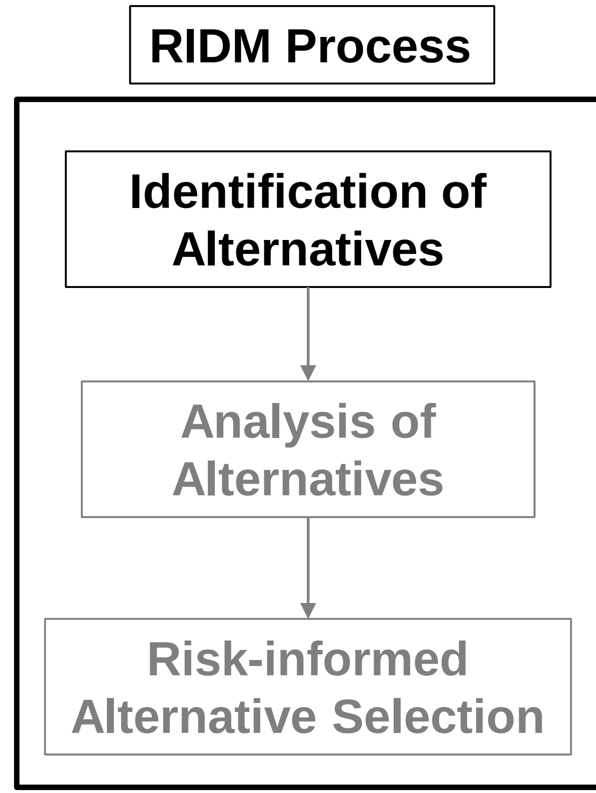
Risk-informed Alternative Selection

IRAD RIDM Approach Begins with Assessing Risk along with Analysis of Alternatives

- **A set of individual risk statements were developed.**
  - Risks were broken up into the following categories.
    - Manufacturing
    - Structural performance
    - Aerothermal/Thermal Performance
    - Other
  - 5 SME's at ARC have reviewed the risk statements
    - SME's performed an independent assessment, and selected top risks for a 3D woven TPS solution.
      - SME's risk rankings were strongly aligned.
        - » This provides a first cut at risk drivers without the need for in-depth risk analysis.
      - The full suite of risks for each category is provided in backup.



Key Manufacturing Risks

- **The top 3D woven manufacturing risks identified by SME's for MSR are identified below.**
  - The three columns on the right indicate which 3D woven architecture the risk is applicable to.

Category	Risk Title	Risk Statement	Applicable Designs		
			3D Woven Cold Structure (Single Piece)	3D Woven Dry Woven (Single Piece)	3D woven (Tiled Arch.)
Manufacturing	Weaving (Width)	Given the complexity of the weaving operation, there is a possibility that the woven product may not meet width requirements, leading to [consequence].	X	X	
	Forming (Property Variation)	Given the required forming operation, there is a possibility that material properties are altered in an unforeseen way, leading to [consequence].	X	X	
	Poor Base Bond integration (undetectable)	Given the complexity of the integration approach, there is a possibility of poor bond performance at the bondline that is undetectable by NDE and potentially by acceptance testing, leading to [consequence].	X		

Key Aerothermal Risks

- **The top 3D woven aerothermal risks identified by SME's for MSR are identified below.**
  - The three columns on the right indicate which 3D woven architecture the risk is applicable to.

Category	Risk Title	Risk Statement	Applicable Designs		
			3D Woven Cold Structure (Single Piece)	3D Woven Dry Woven (Single Piece)	3D woven (Tiled Arch.)
Aerothermal	Tunneling	Given the re-entry environment, there is a possibility that tunneling will occur, leading to [consequence].		X	
	Seam Failure	Given the re-entry environment, there is a possibility that excessive seam erosion will occur, leading to [consequence].			X
	Aerothermal Certification	Given the limitations of ground based test facilities, there is a possibility that aerothermal risks will persist for tiled concepts leading to [consequence].			X
	MMOD	Given the MMOD environment, there is a possibility that a meteoroid or debris will impact the heat shield, leading to [consequence].	X	X	X

Key Structural Risks

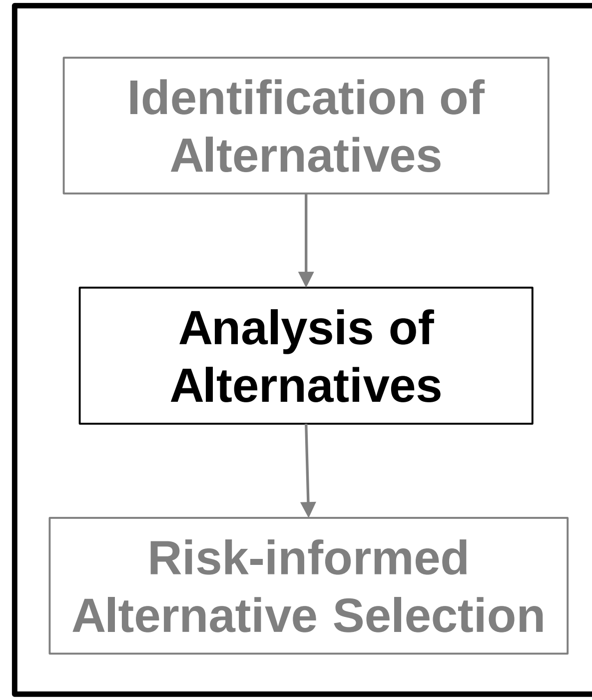
- **The top 3D woven structural risks identified by SME's for MSR are identified below.**
  - The three columns on the right indicate which 3D woven architecture the risk is applicable to.

Category	Risk Title	Risk Statement	Applicable Designs		
			3D Woven Cold Structure (Single Piece)	3D Woven Dry Woven (Single Piece)	3D woven (Tiled Arch.)
Structural	Seam Failure	Given the loading environments during various mission phases, there is a possibility that the adhesive bond between tiles will fail, leading to [consequence].			X
	Landing Impact	Given the rigidity of the 3D Woven system, there is a possibility that an off-nominal landing will increase landing loads on the payload, leading to [consequence].	X		X

RIDM Approach – Status of Analysis of Alternatives

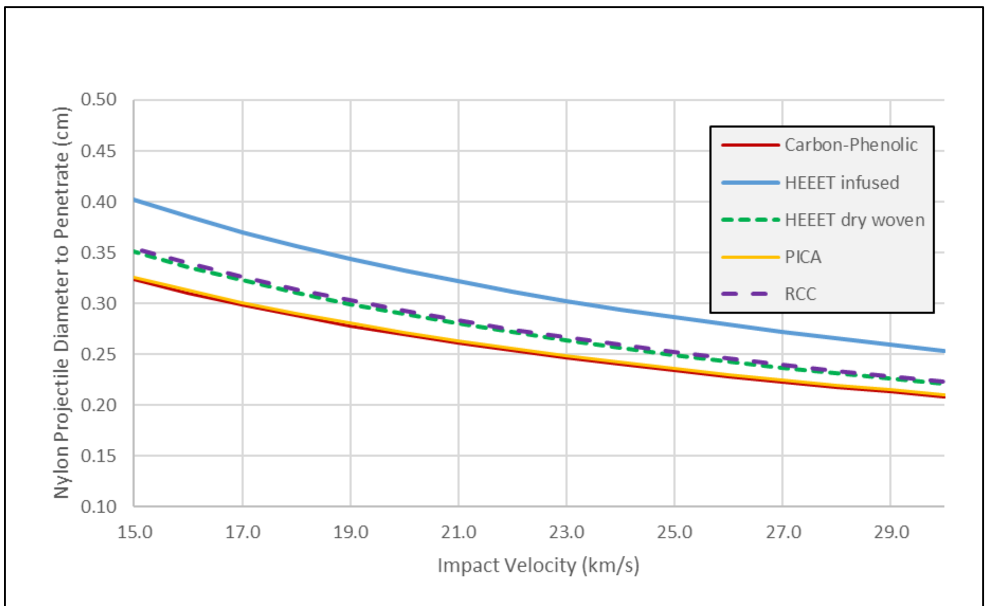
- **Evaluation of alternatives will leverage MSR efforts:**
  - Trajectory/CFD analysis
  - Thermal analysis
  - MMOD damage and consequence probability analysis
- **IRAD analysis efforts include:**
  - Thermal/Structural analysis
  - Manufacturability – Single Piece:
    - Working with industrial partners to evaluate the design, feasibility, cost, risks, and schedule to upgrade weaving for ~1.5 meter width
      - Mid-task review planned for July, with final report expected in August.

RIDM Process



MMOD Performance

- **Analyses to be performed cont'd:**
  - Initial MMOD Impact Assessment has been completed by Eric Christiansen at JSC:
    - For an equivalent areal mass (different TPS thicknesses), MMOD performance of TPS options are similar:
      - » Infused HEEET has slightly better performance
      - » Analysis assumes penetration through TPS to bondline for the same areal mass (different thicknesses based on material density)
  - Additional weave designs and layer stacking sequences will also be evaluated in the future



MMOD TPS Robustness Comparison

RIDM Process

Identification of Alternatives

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Analysis of Alternatives

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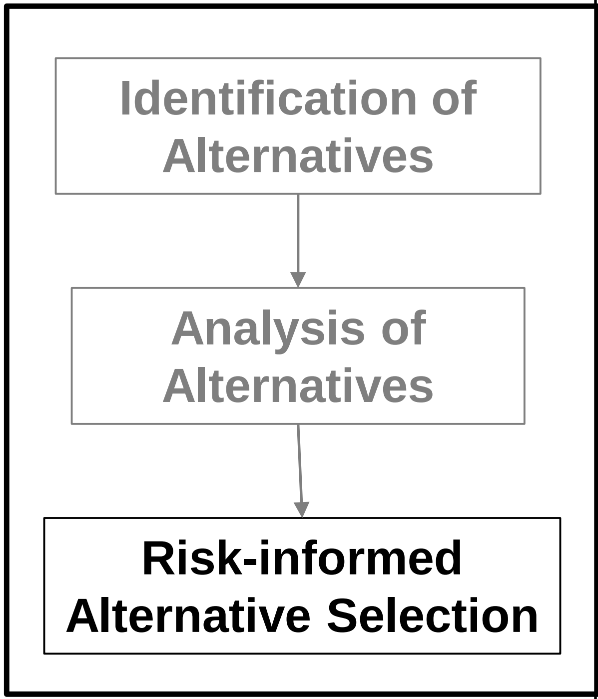
Risk-informed Alternative Selection

RIDM Approach – Risk-Informed Alternative Selection & Summary

- **MSR is considering 3D Woven TPS as a potential solution.**
  - Goal is to provide a recommended 3D woven TPS architecture to the MSR using RIDM
  - Will allow MSR to on-ramp the best 3D Woven architecture.
    - RIDM approach ensures that selections are made with an awareness of specific risks associated with each option
      - Critical since MSR will ultimately be responsible for retiring these risks

RIDM Process

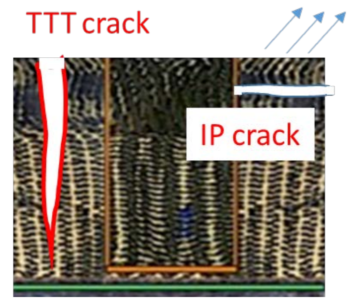


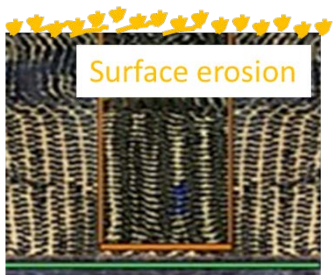
Backup

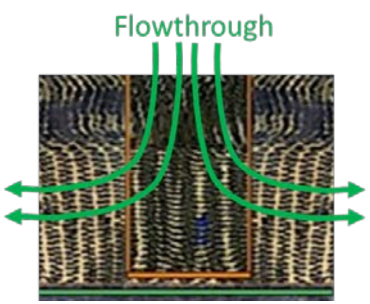
3D Woven Failure Modes

- **Typical failure modes of tiled systems include:**
  - Tile and gap-filler failure
    - Through Thickness cracks causing "heat leaks"
    - In plane cracks causing reduced thickness
    - Surface erosion (mechanical failure causing spallation or accelerated layer loss)
    - Flowthrough (permeability permits interior flow)
  - Loss of attachment of tiles or gap fillers, causing complete loss of thermal material over the full tile area
    - Adhesive mechanical failure
      - Substrate failure adjacent to adhesive
    - Adhesive thermal failure
  - Cracking and opening of seams, permitting a "heat leak" in the gaps between tiles
    - Adhesive mechanical failure
      - Tile failure adjacent to adhesive
    - Adhesive char and erosion
  - Material response prediction error
    - Recession rate error
      - Differential recession at seam
    - Conduction

Structural
Aero/Material







HEEET System Requirements

Level 1 Requirements	Requirement #	Level 2 Requirements
The TPS System shall function throughout all mission phases.	1	The acreage TPS material shall have predictable thermal response at heat flux, pressure, shear and enthalpy combinations of the (mission specific) entry environment.
	2	The seam TPS material shall have predictable thermal response at heat flux, pressure, shear and enthalpy combinations of the (mission specific) entry environment.
	3	An assembly of acreage TPS material with seams onto a relevant substructure shall survive structural loads experienced during all mission phases
	4	The virgin TPS material shall have surface properties that meet thermal control requirements during cruise
The TPS System shall be operable.	5	The TPS thermal (conductivity) and mechanical (stiffness, strength) properties shall not change by more than 10% (TBR) after exposure to (mission specific) natural environments (dust, moisture,etc).
	6	The TPS shall be robust or repairable to handling damage of (mission specific) level(s).
	7	The TPS thermal (conductivity) and mechanical (stiffness, strength) properties shall not change by more than 10% (TBR) after exposure to planetary protection processes and loads.
	8	The TPS shall not generate dust for any (mission specific) load case
	9	The TPS shall not out-gas more than (mission specific) amount.
	10	The TPS thermal (conductivity) and mechanical (stiffness, strength) properties shall not change by more than 10% (TBR) after exposure to purge and purge outage environment.
	11	The TPS shall have a service life of (mission specific) days (or years) in (mission specific) environment
	12	The TPS shall have a shelf life of (mission specific) months (or years) in (mission specific) environment.
The TPS system shall be manufacturable.	14	The TPS material shall be manufacturable to a thickness upto (mission specific) inches
	15	The TPS material shall conform to IML curvature of (mission specific) radii
	16	The TPS assembly shall cover an aeroshell of at least (mission specific) surface area
	17	Any contaminants from Manufacturing processes shall be included in development of system capability databases
	18	The TPS shall be machinable to a tolerance of +/- (mission specific) inches
The TPS System shall interface with the entry vehicle.	19	The TPS shall accommodate Penetrations of (mission specific) size and shape.
	20	The TPS shall include closeout(s) that meet (mission specific) seal.
	21	The TPS shall include closeout(s) that meet (mission specific) load transfer.
	22	The TPS shall include closeouts that support (mission specific) assembly/disassembly requirements.
	23	The TPS shall accommodate (mission specific) instrumentation.
The TPS System shall be certifiable.	24	The TPS acreage shall be inspectable against the acceptance criteria in the system specification.
	25	The seams shall be inspectable against the acceptance criteria in the system specification.
	26	The TPS-substructure bond shall be inspectable against the acceptance criteria in the system specification.
The TPS System manufacturing and integration technology shall be transferrable to industrial partners.	27	Process specifications shall be developed and formally documented for each manufacturing and integration step of the TPS system
	28	Acceptance criteria shall be developed and formally documented for each manufacturing and integration step of the TPS system
	29	All manufacturing, processing and assembly operations and specifications developed by industrial partners shall be the property of NASA.
	30	The project shall document an assessment of raw material supply and manufacturing process sustainability based on experience with MDU and ETU

IRAD Risks Being Tracked

Category	Risk Title	Risk Statement	3D Woven Cold Structure (Single Piece)	3D Woven Dry Woven (Single Piece)	3D woven (Tiled Arch.)
Manufacturing	Weaving (Width)	Given the complexity of the weaving operation, there is a possibility that the woven product may not meet width requirements, leading to [consequence].	X	X	
	Forming (Property Variation)	Given the required forming operation, there is a possibility that material properties are altered in an unforeseen way, leading to [consequence].	X	X	
	Integration Undetectable Poor Base Bond integration	Given the complexity of the integration approach, there is a possibility of poor bond performance at the bondline that is undetectable by NDE and potentially by acceptance testing, leading to [consequence].	X		
Structural	Seam Failure	Given the loading environments during various mission phases, there is a possibility that the adhesive bond between tiles will fail, leading to [consequence].			X
	Landing Impact	Given the rigidity of the 3D Woven system, there is a possibility that an off-nominal landing will increase CAM loads on landing impact, leading to [consequence].	X		X
Aerothermal	Tunneling	Given the re-entry environment, there is a possibility that tunneling will occur, leading to [consequence].		X	
	Seam Failure	Given the re-entry environment, there is a possibility that excessive seam erosion will occur, leading to [consequence].			X
	MMOD	Given the MMOD environment, there is a possibility that a meteoroid or debris will impact the heat shield, leading to [consequence].	X	X	X
	Aerothermal Certification	Not sure how to write this either but something along the lines of unrecognized residual aerothermal risk due to limitations in ground based test faciltiies of systems incorporating seams.			X
Other	Schedule	Given the developmental effort of a large scale weaving operation, there is the possibility that the TPS will take longer to fabricate, leading to [consequence].	X	X	

Risk List - 1

Design Category	Risk Title	Risk Statement	3D Woven Hot Structure (Single Piece)	3D Woven Cold Structure (Single Piece)	3D Woven Dry Woven (Single Piece)	3D woven Tiled
Weaving	Weaving (Width)	Given the complexity of the weaving operation, there is a possibility that the woven product may not meet width requirements, leading to [consequence].	X	X	X	
	Weaving (Thickness)	Given the complexity of the weaving operation, there is a possibility that the woven product will not meet minimum material thickness requirements, leading to [consequence].	X	X	X	X
	Weaving (Complete Failure)	Given the complexity of the weaving operation, there is a possibility that the woven product cannot be fabricated to meet requirements such as FVF, picks per inch, or other NCR's, leading to [consequence].	X	X	X	X
	Contaminants	Given the location and hardware utilized during weaving, there is a possibility that contamination will occur, leading to [consequence].	X	X	X	X
Forming	Forming (Large Scale fiber breakage)	Given the required forming operation, there is the possibility that during the forming operation that fibers are damaged, leading to [consequence].	X	X	X	X
	Forming (Large Scale Thickness)	Given the required forming operation, there is the possibility that excessive compression of the dry woven product is required resulting in inadequate thickness of the final product, leading to [consequence].	X	X	X	X
	Forming (Property Variation)	Given the required forming operation, there is a possibility that material properties are altered in an unforeseen way, leading to [consequence].	X	X	X	X
	Contaminants during forming	Given the hardware and processes implemented during forming, there is a possibility that contamination will occur, leading to [consequence].	X	X	X	X
Infusion/ Hot Structure Related Processing	Excessive shape change during infusion/For Hot structure this means dimensional stability during processing	Given shrinkage during the infusion process, there is a possibility that excessive shape change during infusion of large parts will occur, leading to [consequence].	X	X		X
	Excessive shape change during infusion/For hot structure this means thickness stability during processing (thickness)	Given the infusion process, there is a possibility that excessive shrinkage will result in the TTT direction, leading to [consequence].	X	X		X
	Contaminants during infusion	Given the hardware and processes implemented during infusion, there is a possibility that contamination will occur, leading to [consequence].	X			X
	Infusion Uniformity (For Hot Structure this is uniformity of the final C matrix)					

Risk List - 2

Design Category	Risk Title	Risk Statement	3D Woven Hot Structure (Single Piece)	3D Woven Cold Structure (Single Piece)	3D Woven Dry Woven (Single Piece)	3D woven Tiled
Integration	Thickness reduction during bonding	Given the required pressure during substrate attachment, there is a possibility that excessive deformation will occur, leading to [consequence].			X	
	Poor seam integration (Voids/cracks)	Given the complexity of the tiled integration approach, there is a possibility that voids/cracks will be present in the seams, leading to [consequence].				X
	Poor seam integration (undetectable)	Given the complexity of the tiled integration approach, there is a possibility of poor seam performance that is undetectable by NDE and potentially by acceptance testing, leading to [consequence].				X
	Poor Base Bond integration (Voids)	Given the complexity of the integration approach, there is a possibility that voids will be present in the base bond, leading to [consequence].	X	X	X	X
	Poor Base Bond integration (undetectable)	Given the complexity of the integration approach, there is a possibility of poor bond performance at the bondline that is undetectable by NDE and potentially by acceptance testing, leading to [consequence].	X	X	X	X
	Poor Base attachment (undetectable)	Given the need for direct attachment of the hot structure, there is a possibility of poor joint performance during re-entry that is not testable in ground based facilities, leading to [consequence].	X			
	Integratability	Not sure how to write this yet but its really a risk around the utilization of a dry woven system and and issues with closeout at edges, etc…				
Structural	Flimsy Heat Shield	Given the stiffness of the virgin and charred HEEET material, there is a possibility that extensive deformation will occur during re-entry pressures, leading to [consequence].	X		X	
	TTT Vibe	Given the strength of 3D woven in TTT tension and ILS, there is a possibility that resin softening will occur, leading to [consequence].	X	X		X
	MMOD	Given the MMOD environment, there is a possibility that a meteoroid or debris will impact the heat shield, leading to [consequence].	X	X	X	X
	Seam Failure	Given the loading environments during various mission phases, there is a possibility that the adhesive bond between tiles will fail, leading to [consequence].				X
	Attachment Failure	Given the loading environments during various mission phases, there is a possibility that the attachment from TPS to substructure will fail, leading to [consequence].	X	X	X	X
	Ground Handling	Given the potential impact environment during ground handling and assembly, there is a possibility that the TPS will be damaged, leading to [consequence].	X	X	X	X
	Landing Impact	Given the rigidity of the 3D Woven system, there is a possibility that an off-nominal landing will increase CAM loads on landing impact, leading to [consequence].	X	X		X

Risk List - 3

Design Category	Risk Title	Risk Statement	3D Woven Hot Structure (Single Piece)	3D Woven Cold Structure (Single Piece)	3D Woven Dry Woven (Single Piece)	3D woven Tiled
Aerothermal	Bondline Temperature	Given the re-entry environment, there is a possibility that the IML of the TPS will reach a higher temperature than anticipated, leading to [consequence].	X	X	X	X
	Recession	Given the re-entry environment, there is a possibility that excessive recession will occur, leading to [consequence].	X	X	X	X
	Mechanical Loss	Given the re-entry environment, there is a possibility that mechanical loss of material (Spallation) will occur, leading to [consequence].	X	X	X	X
	Tunneling	Given the re-entry environment, there is a possibility that tunneling will occur, leading to [consequence].	X	X	X	X
	Seam Failure	Given the re-entry environment, there is a possibility that excessive seam erosion will occur, leading to [consequence].				X
	MMOD	Given the MMOD environment, there is a possibility that a meteoroid or debris will impact the heat shield, leading to [consequence].	X	X	X	X
	Compression	Not sure how to word this but a risk related to the aerothermal performance of a dry weave and does it compress resulting in off nominal response, potentially just a thermal conductivity issue with higher TTT conductivity.				
	Aerothermal Certification	Not sure how to write this either but something along the lines of unrecognized residual aerothermal risk due to limitations in ground based test faciltiies of systems incorporating seams.				
Other	Dust	Given the nature of the phenolic infusion process and the associated loading environments there is the possibility that the TPS will generate dust, leading to [consequence].	X	X		X
	Outgassing	Given the nature of the woven product and infusion process there is the possibility that excessive outgassing will occur, leading to [consequence].	X	X	X	X
	Service Life	Given the duration of the time in space for an MSR mission, there is a possibility that the woven TPS system will degrade over time, leading to [consequence].	X	X	X	X
	Shelf Life	Given the potential for delays in the mission, there is a possibility that the woven TPS system will sit for extended periods of time resulting in performance degradation, leading to [consequence].'	X	X	X	X
	Schedule	Given the developmental effort of a large scale weaving operation, there is the possibility that the TPS will take longer to fabricate, leading to [consequence].	X	X	X	
	Cost	Given the developmental effort of a large scale weaving operation, there is the possibility that the TPS will be more expensive to fabricate, leading to [consequence].	X	X	X	

3D Woven TPS Subsystem Objectives and Requirements

- **High level objectives and requirements for MSR EEV are still evolving.**
- **The HEEET project generated generic requirements with involvement from mission implementation engineers that can be tailored for specific mission needs.**
  - These will be used as a placeholder until MSR requirements are fully developed.
    - Modifications for MSR include a Level 1 certifiability requirement and several level 2 requirements to incorporate MMOD functional performance.
      - The full suite of level 1 and 2 requirements are provided in backup.

3D Woven IRAD Level 1 Requirements
The TPS System shall be certifiable.
The TPS System shall function throughout all mission phases.
The TPS System shall be operable.
The TPS system shall be manufacturable.
The TPS System shall interface with the entry vehicle.
The TPS shall satisfy planetary protection reliability requirements