Sizing and Margin Methodology for Dual-Layer Thermal Protection Systems

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Thanks to Grant Palmer and Dinesh Prabhu for Aeroheating Simulations

15th International Planetary Probe Workshop
2018-06-12
• Increased mass efficiency of dual-layer materials allows mission designers to select shallow entry trajectories
  - Integrate a top layer with good recession performance with a bottom layer with good insulation performance

• NASA is maturing a dual-layer 3D-woven TPS called HEEET
  - Top layer made of densely woven carbon fibers (Recession Layer, RL)
  - Bottom layer made of carbon and phenolic yarns (Insulation Layer, IL)

• Need to develop a sizing process
  - Project has developed and validated a one-dimensional thermal response model based on material property and arcjet testing
  - Adapt the conventional NASA ablator sizing process for application to dual-layer materials

• Weaving width limitation drives need for a tiled system
  - This talk focuses on acreage material sizing
  - Full sizing process has been developed and accounts for the gap filler thermal response uncertainties
• TPS thickness is sized to satisfy certain mission-dependent design constraints
  - Typically for single-layer materials, the constraint is a not-to-exceed bondline temperature driven by adhesive or structure temperature limits

• There are uncertainties associated with models used in TPS sizing process
  - Trajectory dispersions
  - Uncertainties in aerothermal environments (ground-to-flight traceability)
  - Uncertainties in thermal response modelling (properties, models, initial conditions)

• TPS sizing process must include margins that protect against uncertainties in modelling
  - Margins can be applied to initial conditions, boundary conditions, design constraints or sized thickness
  - Margins are selected based on testing, uncertainty propagation or engineering judgement
Conventional NASA Ablator Sizing Process

- Aerothermal environments are computed on the bounding trajectory (typically max heat load)
- At each sizing location, TPS thickness is sized along three branches and combined in a root-sum-square (RSS) process
  - Zero margin: apply nominal environments and size thickness to bondline temperature limit
  - Material margin: account for material modelling uncertainties (typically done by reducing bondline temperature by a margin informed through Monte Carlo analysis)
  - Aerotherm margin: account for uncertainty in aerothermal environments (multiplying factors)
- Other considerations: manufacturing tolerance, factor of safety, recession margin

![Diagram of Conventional NASA Ablator Sizing Process]

- Trajectory & Atmospheric Dispersions
- Bounding Trajectory (Max Heat Load)
- Aeroheating Predictions (CFD & Radiation)
- Aerothermal Environments on Bounding Trajectory

Three-Branch Sizing (repeat for all sizing locations)

- Zero Margin Branch
- Material Margin Branch
- Aerothermal Margin Branch

TPS Sizing
- Thickness sized to maintain bondline temperature below specified limit

Margined Thickness (RSS)

Max Thickness Across All Sizing Locations *

*Assumes uniform TPS thickness
Dual-Layer Sizing Nuances

• New constraint at the interface between two layers
  - HEEET insulation layer should not be exposed to flow
  - Arcjet testing scope limited to RL

• RL is sized to be equal to the predicted recession; IL is sized to bondline temperature limit
  - Material margin must be considered for both interfaces

• Current HEEET implementation requires uniform TPS thickness for both layers
  - Need to find max required thickness for each layer across all body points and trajectories

• Max thickness for each layer may occur at different body points and trajectories
  - Higher ablation leads to lower heat conduction into TPS
Dual-Layer Sizing Nuances

- Sizing RL and IL independently and then stacking max RL thickness from one location on max IL thickness from another location is not mass efficient
  - Excess RL at some locations can serve as insulation
- More mass efficient to size IL after fixing RL to max sized thickness across all locations
Dual-Layer Sizing Process

- Proposed sizing process takes advantage of the nonessential portion of RL thickness at locations that don’t drive RL sizing
  - RL-alone calculation to determine recession for each sizing case; fix RL thickness to maximum RSSed recession across all cases (body points, bounding trajectories)
  - IL is sized for all sizing cases to bondline temperature limit using the fixed RL thickness; Final IL thickness is the maximum thickness across all cases
**Reference Missions**

**Venus Lander**
- 2010 NASA study VITaL (shallow)
- 45-deg spherecone
- $D=3.5\text{m}$, $M_E=2750\text{kg}$
- $V_E=11.3\text{ km/s}$, $\gamma_E=-9\text{ deg}$
- Aeroheating simulations by Grant Palmer
- 9 sizing cases (9 body points, 1 trajectory)
- **Highlights location impact on sizing**

**Saturn Probe**
- NF-4 proposal (SPRITE), PI: Amy Simon (GSFC), managed by JPL
- 45-deg Spherecone, $1.25\text{m}$ diameter, 447kg entry mass
- $V_E=26.9\text{ km/s}$, $\gamma_E=-14\text{ deg}$
- Aeroheating simulations by Dinesh Prabhu
- Total of 8 sizing cases (4 body points for max heat rate and load trajectories)
- **Highlights trajectory impact on sizing**
Sizing for Venus Reference Mission

- Sizing done at 9 locations on the heatshield
  - Figure on left: RL and IL sized independently
  - Figure on right: RL sized first; then IL sized while for fixed RL thickness
- Taking advantage of the nonessential portion of RL thickness at locations that don’t drive RL sizing provides mass benefits
  - 62% reduction in IL thickness, 19% reduction in areal mass
Sizing for Saturn Reference Mission

- Sizing done at four locations on the heatshield and for two bounding trajectories, Max Heat Rate (MHR) and Max Heat Load (MHL)
- Maximum RL thickness occurs at shoulder for max heat rate trajectory
- Maximum IL thickness occurs at stagnation point for max heat load trajectory
- Independent RL and IL sizing would have resulted in 21% increase in IL thickness and 9% increase in areal mass
Summary and Conclusions

• Sizing based on only stagnation point environments in early mission phases may not bound required thickness
  - Both for single-layer and dual-layer materials
  - The size of impact is likely larger for dual-layer materials if each layer has to be constant thickness across the heatshield
  - In applications where off-stagnation environments are suspected to be higher, utilizing CFD simulations early in the design is highly recommended

• Proposed sizing methodology takes advantage of the insulation properties of the excess recession layer at locations that don’t drive RL thickness

• Allowing the insulation layer to be exposed to flow will provide more flexibility in TPS sizing and design
  - Requires arcjet testing of insulation layer to establish its max capability
  - Sizing process needs to be modified for a different interface constraint (ex. limit on combined aerothermal environment experienced by insulation layer)

• Allowing varying TPS thickness across the heatshield will offer mass benefits
  - Manufacturing challenges should not be underestimated
Complete HEEET Sizing Process (Including Gap Filler and Manufacturing Considerations)

I. Inputs for $k$ Cases
1. Nominal Branch
   - Nominal Environments
   - Nominal Properties

2. Mat. Unc. Branch
   - Nominal Environments
   - Add 50% recession fail

3. Aero. Unc. Branch
   - Margined Environments
   - Nominal Properties

II. Recession Layer Calculation
- FIAT calculations for three branches for $k$ cases
  - Thermal analysis of a thick slab of recession layer to determine the recession.
  - $R_k = R_{1k} + \sqrt{(R_{2k} - R_{1k})^2 + (R_{3k} - R_{1k})^2}$
  - RSS of three branches for $k$ cases
  - Find Max Value $RL = \max R_k$

III. Insulating Layer Sizing
- FIAT sizing for three branches for $k$ cases
  - Recession layer thickness is fixed at RL from above.
  - Size the insulating layer thickness to maintain internal temperatures below specified limits.
  - $I_k = I_{1k} + \sqrt{\max(0, I_{2k} - I_{1k})^2 + \max(0, I_{3k} - I_{1k})^2}$
  - RSS of three branches for $k$ cases
  - Find Max Value $IL = \max I_k$

IV. Gap Filler Margin
- Add 25% to RL for Gap Filler
- Differential Recession $RL_{final} = RL \times 1.25$

V. Dimensions for Manufacturing
- Manufacturing Margins
- Add 0.15” to RL
- Add 0.20” to IL
- Required Weaving Thickness
- Convert Thickness to # of Weave Layers and Loom Heddles
- Required Loom Capability (# of Heddles)

* Each case represents a single location on the heatshield for a single trajectory. To capture the maximum required thickness for each layer, calculations are performed for bounding trajectories and at multiple locations on the heatshield.

^ Factor of 1.1 is inserted on branch 2 in lieu of a bond line margin.