Thermal Protection System Sizing and Selection for RLVs Using the Sentry Code

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Technology research and development activities over the past two decades have resulted in several new material options for use as externally-bonded, passive thermal protection systems (TPS) on RLVs. These new materials each have unique thermal, structural and operating characteristics that make them well suited for protecting the underlying vehicle structure from extreme aeroheating environments associated with atmospheric flight. Depending on the material thicknesses used and the local stackup configurations, the overall weight (or weight per unit area) of these TPS solutions can vary considerably, thus optimal material selection and proper usage is critical. SpaceWorks Engineering’s Sentry software is a newly created engineering design tool for use in the conceptual and preliminary design of next-generation space transportation systems utilizing reusable, non-ablative thermal protection systems. Sentry performs a transient, 1-D thermal analysis of a vehicle’s TPS requirements at several hundred body locations throughout a given atmospheric flight trajectory and produces a weight-optimized TPS design that satisfies thermal, material and manufacturing constraints. This tool represents a unique capability update to the current suite of TPS selection and sizing tools available to engineers. The paper provides a summary of Sentry’s capabilities and reviews two case studies for which it has been successfully used.

Nomenclature

**Acronyms**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>ACC</td>
<td>advanced carbon-carbon</td>
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<tr>
<td>AFSRI</td>
<td>advanced fibrous reusable surface insulation</td>
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<tr>
<td>CA</td>
<td>contributing analysis</td>
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<tr>
<td>CRI</td>
<td>conformal reusable insulation</td>
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<tr>
<td>C/SiC</td>
<td>carbon/silicon carbide</td>
</tr>
<tr>
<td>DMSJ</td>
<td>dual-mode scramjet</td>
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<tr>
<td>DSM</td>
<td>design structure matrix</td>
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<tr>
<td>ETO</td>
<td>earth-to-orbit</td>
</tr>
<tr>
<td>RTV</td>
<td>room-temperature vulcanizing</td>
</tr>
<tr>
<td>RLV</td>
<td>reusable launch vehicle</td>
</tr>
<tr>
<td>SIP</td>
<td>strain isolation pad</td>
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<tr>
<td>TPS</td>
<td>thermal protection system</td>
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<tr>
<td>TUFI</td>
<td>toughened unifibrous flexible insulation</td>
</tr>
<tr>
<td>UHTC</td>
<td>ultra-high temperature ceramic (e.g. hafnium diboride)</td>
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**Symbols**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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</thead>
<tbody>
<tr>
<td>AOA</td>
<td>angle-of-attack, degrees</td>
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* President, SEI and Senior Member AIAA.
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Technology research and development activities over the past two decades have resulted in several new material options for use as externally-bonded, passive thermal protection systems (TPS) on next-generation reusable launch vehicles (RLVs). These new materials each have unique thermal, structural and operating characteristics that make them well suited for protecting the underlying vehicle structure from extreme aeroheating environments associated with atmospheric flight.

The TPS requirements for reusable launch vehicles can be dictated by either the aerothermal environment from their ascent trajectory or by their atmospheric reentry conditions. In general, vehicles that use all-rocket propulsion systems have a more benign ascent profile and thus their TPS is sized by their reentry flight conditions. Conversely, TPS requirements for RLVs that fly at hypersonic Mach numbers with air-breathing propulsion systems are typically driven by high speed, high dynamic pressure flight conditions experienced during ascent. Whether the ascent or reentry profile is the driver, the high heat loads and heat rates that result translate to very challenging material requirements for the fuselage, wings, and control surfaces. Given the extreme weight growth-sensitivity of both reusable rocket and air-breathing launch systems, it is critical that the TPS system be designed for minimum weight. This problem is complicated by additional design constraints such as minimum gauge material thicknesses, maximum thickness due to manufacturing limits, maximum surface temperatures, and maximum bondline temperature (between the TPS backface and the underlying vehicle fuselage structure). Furthermore, the cost and operational characteristics of the various TPS materials options must be factored into any viable vehicle design concept.

The vehicle-level design synthesis process requires a multidisciplinary analysis that typically includes multiple levels of coupling between engineering disciplines. This complex design process can be illustrated through the use of a Design Structure Matrix (DSM). A typical DSM for an all-rocket RLV is shown in Figure 1. Each disciplinary analysis is referred to as a Contributing Analysis (CA). Coupling between different CAs are conveyed via feed-forward and feedback links. Focusing on the aeroheating/TPS discipline, note that the CA is coupled with the trajectory and weights & sizing CAs. Specifically, the trajectory analysis provides the vehicle’s flight profile to the aeroheating/TPS CA. The flight profile, which includes tabular altitude, time, angle-of-attack (AOA) and velocity data, determines the convective heat rates \( \dot{Q}_{\text{conv}} \) experienced at each of the vehicle’s surface points as a function of time. In turn, the \( \dot{Q}_{\text{conv}} \) impacts the TPS material selection, thickness, and ultimately weight. The resultant TPS weights from the aeroheating/TPS CA are then provided to the overall weights & sizing CA, which produces a new vehicle weight and size with the required propellant fractions and propellant packaging volumes. The new vehicle weight and size then impacts the trajectory, which again alters the aeroheating/TPS requirements. These coupled variables, or circular references, must be iteratively resolved before a feasible solution for the vehicle can be achieved. This entire process is often referred to as vehicle performance “closure”. A typical closure process may take 5 – 10 iterations through this coupled process before a desired level of convergence is achieved.
A conceptual-level vehicle closure process can require from minutes to hours of computer computational time depending upon the fidelity of the tools being used in the analysis. Historically, the aeroheating/TPS analysis element of the DSM has been performed “off-line” in more detailed design studies and frequently not addressed at all in many early concept studies. At its worst implementation, systems engineers simply rely on historical data or rough engineering estimates for the TPS system to provide to the weight/sizing CA. The coupling with the trajectory analysis and resultant $Q_{\text{conv}}$ sensitivity is then ignored and the TPS weight (or perhaps weight per unit area) is held constant for the subsequent closure process. This quick-and-dirty method is expedient, reflects neither the true, final flight path nor the true features of the vehicle geometry. At best in current practice, the aeroheating/TPS analysis is conducted at a few select points on the vehicle outer surface for a representative trajectory. The TPS weight and thickness are determined at these few points on the vehicle and an estimate is made for the fraction of the vehicle’s surface area that this particular TPS material will cover (or acreage).

Ideally in today’s modern computing environment, a software tool should quickly perform the aeroheating/TPS analysis over an analysis grid that encompasses the entire exposed surface of the vehicle. This tool should permit a fully coupled analysis to be performed “in the loop” with the trajectory and weight/sizing CAs in the conceptual design phase and would be able to dynamically select an appropriate TPS material stackup at every location on the vehicle being analyzed as the trajectory or geometry changed. SpaceWorks Engineering’s new software tool was designed to respond to this need.

### II. Sentry Overview

Sentry is a newly created engineering design tool for use in the conceptual and preliminary design of space transportation systems utilizing reusable, non-ablative thermal protection systems. Sentry, one of many commercially available engineering tools created by SpaceWorks Engineering, Inc. (SEI), represents a unique entry into the current suite of TPS selection and sizing tools available to engineers.

When performing an analysis using Sentry, the tool performs a one-dimensional (1-D) unsteady heat transfer analysis with convection, conduction, and radiative effects and an adiabatic backface condition. Sentry can examine an unlimited number of candidate TPS materials or “stackups” at each surface node with up to 10 material layers per stackup. For a vehicle configuration, the tool will then determine the TPS requirements over the entire airframe, including the windward and leeward airframe surfaces, chines, wing(s), tail(s), vertical stabilizer(s), and aerodynamic control surfaces (e.g. body flap, ailerons). As each candidate stackup is evaluated at a particular
vehicle surface node, Sentry will optimize the thickness of the scalable insulation material to achieve the minimum weight after factoring in the material properties, temperature limitations, and any manufacturing constraints (as specified by the user). On the vehicle’s leading edges (e.g. wing, fuselage nose, etc.), Sentry will determine the stagnation point conditions for a range of representative geometries (e.g. spherical, cylindrical, swept cylinder, etc.) and select an appropriate material based on the surface temperatures experienced.

Sentry was designed from the outset to be robust, capable of automated execution, and require minimal user interaction during a run. As such, Sentry is written in the modern, object-oriented C++ programming language and will execute on Windows, Mac OS X, and SGI platforms. Setup time for a complete vehicle analysis is a few hours, with execution times on the order of 5-45 minutes, depending on the analysis grid resolution (i.e. number of vehicle nodes), the number of candidate materials, and specific design options selected by the user. The user interface options currently include a command-line executable with ASCII input and output files. Additionally, the tool has been successfully wrapped as a component for use within Phoenix Integration’s ModelCenter© environment.

III. Tool Capabilities and Operation

Sentry is a powerful and extremely capable engineering software tool for use at the conceptual and preliminary design phases of a new launch vehicle design project. In order to facilitate use of the tool in the fast turnaround conceptual design phase, a phase during which a lot of the engineering details are either unknown or still being defined, a number of assumptions are made to simplify the analysis process and improve execution speed. Specific limitations include only limiting the thermal model to 1-D analysis (through-the-thickness) at each grid point. Thus, the impact of conduction to adjacent TPS panels is not reflected in the analysis results. The conservative approach of an adiabatic backface boundary condition was also adopted in the current version. Therefore, the results do not reflect the impact of having propellant or a secondary structure heat sink behind the TPS. The emissivity of the surface material is also assumed constant with respect to surface temperature and must be specified by the user for each candidate material. SEI’s preferred method for obtaining $Q_{\text{conv}}$ heating data along the trajectory is from the Aerodynamic Preliminary Analysis System’s (APAS) S/HABP routine for analysis of arbitrary aerodynamic shapes at high speed. There are a number of assumptions associated with this method and the reader should consult the APAS User’s manual for details. With slight modification of the data files, Sentry could easily utilize $Q_{\text{conv}}$ data from other sources that may offer even higher analysis fidelity.

The general analysis procedure for operation of Sentry is as follows:

1) Obtain trajectory profile data for vehicle concept, typically from POST or OTIS
2) Generate $Q_{\text{conv}}$ data using APAS’s S/HABP routine (at bounding points for Database option)
3) Construct input file with S/HABP model data and candidate TPS materials
4) Execute Sentry executable
5) Perform initial or cursory results examination of main output file
6) Obtain vehicle results using graphical output data in Tecplot
7) Perform detailed examination of specific node results at selected points on vehicle

Generating the trajectory data can be accomplished in a few minutes assuming the necessary flight parameters are readily available from the trajectory simulation tool being used. SEI typically uses either the POST or OTIS trajectory programs for obtaining this data. The S/HABP runs generally require about a half work day to generate, depending upon the size of the run matrix. In a few instances, only a few runs are required and they can be completed in a matter of minutes assuming the vehicle geometry model in APAS is pre-existing.

The initial setup of the Sentry input file (Step 3) requires of few hours including debugging and some verification runs. Once the input file has been established for a concept, changes like adding or modifying a candidate TPS material require only a few minutes. As previously mentioned, the computational time for Step 4 is on the order of 5 to 45 minutes. Recent efforts at SEI with parallel execution of the vehicle analysis through splitting the vehicle into its major components (e.g. fuselage, wings, tail) have reduced run-time proportional to the number of computers available. The initial examination of the results, Step 5, can be completed in 10 to 15 minutes, with the more detailed examinations (Steps 6 and 7) requiring a full work day or more to examine and post-process the
results. The time required for this is primarily due to the large amount of data being generated by Sentry. Note that in an automated environment, the analysis is centered around Steps 4 and 5 with Step 2 being performed only once.

A. Sentry Input Parameters

The primary input file, or configuration deck, is a simple ASCII file that can be edited with any text editor. Data is organized into three groupings: a) general specifications, b) component specifications, and c) candidate stackup specifications.

The ‘General Specifications’ data required by Sentry includes the following:

- S/HABP version being used, either Mark-3 or Mark-5 file formats
- Specification method for $Q_{\text{conv}}$, either ‘Direct’ or ‘Interpolate’. This will be discussed in more detail later.
- A default panel multiplier, with a value of either 0 or 1, permits user to make analysis grid panels initially wetted (“on”) or un-wetted (“off”). This enables the analysis of specific regions of the vehicle. A separate input file that identifies the specific nodes of interest replaces the default multiplier value to make an un-wetted panel wet or vice versa.
- Specification (yes or no value) of whether to override the angle-of-attack (AOA) value provided by trajectory profile. This option can be used for sensitivity analysis or can be used to permit estimation of thermal environment from control surface deflections.
- Option flag to perform only stagnation point analysis on specified components.
- Option flag to identify areas where active cooling or heat exchangers are needed on the vehicle and what the average unit weight of this TPS hardware is. The identification criteria will be discussed later in more detail.
- Scalar value for the vehicle linear scale factor relative to the reference S/HABP vehicle geometry provided.

The ‘Component Specifications’ data required by Sentry includes the following parameters for each vehicle component contained in the S/HABP output data file:

- Initial temperature at which to initialize airframe components at the start of analysis
- If applicable for the component, the stagnation point specifications including the radius, shape, sweep angle, and emissivity. Shapes can include swept and unswept cylinders, cone, or a sphere.
- $Q_{\text{conv}}$ margin to apply to S/HABP and stagnation point values. Typically, an additional margin of 10-15% is applied over and above the raw calculated values for conservatism.

The ‘Candidate Stackup Specifications’ data for Sentry includes:

- Total number of candidate stackups defined for the vehicle. This is typically in the range of 5 to 15.
- A user-defined name for each stackup
- The vehicle components for which a particular stackup should be considered. For example, it may be desired to have Sentry consider AFRSI blankets for the fuselage but not for wings.
- Number of material layers in particular stackup. Typically from 2 to 5, with a maximum of 10.
- Backface, or bondline, temperature requirement for the TPS. This limit is usually based on the backface structure’s operating temperature limit. For example, it the TPS is attached to an aluminum airframe, a backface temperature limit of 810 R may be imposed.
- Flag to use the built-in optimizer. If elected, the optimizer will vary a material layer thickness in the stackup to meet the desired backface temperature. The user specifies the particular layer to vary as well as the perturbation/stepsize increment to be used by the optimizer.
- Maximum height (sum of all layers) permitted by the stackup. This value varies depending upon the manufacturing limit of the stackup.
- For each material layer in a stackup: the material identification number from the NASA TPSX database (discussed later), the minimum gauge thickness, and the maximum temperature of the outermost layer. This limit is generally the maximum reuse temperature when designing for RLVs. For an expendable system, the maximum single use temperature for the material can be used.
B. Sentry Output Parameters

After Sentry completes its analysis and optimization at all the vehicle TPS nodes, a single ASCII output file that contains summary information of the results is generated. This file includes:

- Total TPS weight and smeared weight per unit area for entire vehicle (or all components analyzed)
- TPS weights and weight per unit area by component (e.g. wing, tail, etc.) that comprise the total
- Acreage material fractions by component (e.g. forebody is made up of 25% CRI and 75% TUFI AETB-8)
- Maximum stagnation and non-stagnation point temperatures encountered

Additionally, Sentry will generate the following files:

- Tecplot© formatted visualization software input file with maximum surface temperature, material/stackup thicknesses, and material type over entire analysis grid
- Surface temperature history versus time at user specified locations on the vehicle as well as the temperature history into the material stackup structure vs. time (through the thickness temperature profiles)

IV. Sentry Analysis Components

The Sentry tool is composed of five analysis modules. They area: 1) Convective Heat Rate Generation, 2) Material Properties Database and Stackup Definition, 3) Heat Transfer Analysis, 4) Material Selection and Sizing Algorithm, and 5) Stagnation Point Analyzer. Each of these modules will be briefly discussed next.

A. Convective Heat Rate Generation

Sentry must be supplied with convective heat rate (Q_{conv}) values over the entire vehicle surface and as a function of the vehicle’s flight conditions. The S/HABP analysis routine of APAS has proven to be a useful tool in obtaining this data. S/HABP is also used to provide the vehicle surface geometry model which is also the analysis grid. The TPS requirements will be assessed on this aerodynamic grid which typically contains from 1,000-3,000 quad panel vertices. Note that some accommodation is made within APAS when generating the aerodynamic surface grid to better allow the subsequent use of this grid in Sentry. Sentry utilizes centroid locations and associated local Q_{conv} data from each APAS quad panel. Additional cross sections and grid points are added to the APAS aerodynamic grid to create smooth transitions between geometric components and to also eliminate gaps along the vertical plane of symmetry between the left and right sides of a vehicle’s geometric model. Figure 2 provides a sample analysis grid that results from S/HABP.
Convective heating in S/HABP is calculated at the centroid of each quad panel concurrently with the calculation of local surface pressures. $Q_{\text{conv}}$ is a function of total flow enthalpy (related to altitude and velocity), the inclination of the quad panel to the flow, the state of the boundary layer (laminar or turbulent), and the local surface temperature. When executing the S/HABP routine, the authors typically use the reference enthalpy analysis method with the radiation equilibrium temperature option selected to estimate the surface temperature. For this supporting calculation, an approximate surface emissivity is used (actually material emissivity is used in Sentry). Boundary layer transition is typically estimated based on a user-specified value for momentum thickness based on local Mach number. For 3-D or axisymmetric bodies, a momentum thickness value of 350 or above is typically used to indicate turbulent flow. Radiative heating from the shock layer to the vehicle surface is not modeled in S/HABP. Therefore, this model cannot be used with confidence for very high reentry speeds (i.e. reentries from lunar return orbits) but should yield acceptable results for reentries from low earth orbits where radiative heating contributions are not large.

Sentry can operate in two modes when extracting the $Q_{\text{conv}}$ data from the S/HABP results. These modes are either the ‘Direct’ method or the ‘Database’ method. In the direct mode, S/HABP is run at the actual flight trajectory conditions which is defined by the Mach number, angle-of-attack, and altitude. Typically, the trajectory can be adequately represented as 30-40 datapoints, each of which requires a S/HABP analysis run. The advantage of the direct method is that it only requires a relatively few number of S/HABP runs. The disadvantage of this method is that if the trajectory profile changes any (excluding time variations), the S/HABP runs must be performed again for the new profile.

The ‘Database’ method is generally preferable because it eliminates the need to re-execute the S/HABP analysis if the trajectory profile changes (in most cases). The user is required to generate a large matrix of $Q_{\text{conv}}$ data over a bounding flight corridor that contains the nominal flight profile (velocity, altitude, and angle-of-attack). Sentry will then perform a multi-variable interpolation from the database to compute any $Q_{\text{conv}}$ data needed based on the actual trajectory. The disadvantage of this method is that the setup time is greater, requiring from 60-120 (or more) S/HABP runs at various Mach number and altitude combinations initially. For automated or batch runs of Sentry, the Database method should be utilized because, once created the database can be automatically interpolated without the need for a human user to reenter trajectory points into an APAS analysis run.

### B. Material Properties Database and Stackup Definition

Compiled into the Sentry code is the TPSX material property database from NASA Ames Research Center (ARC). This database includes over 100 different TPS and structural materials (e.g. metals, composites, blankets, etc.). For each database entry, the material’s specific heat ($C_p$), thermal conductivity ($k$), and density are provided. Both $C_p$ and $k$ are functions of temperature. A material is identified through the use of a numerical ID tag, which permits ease in specification by the user. The database was originally written in Fortran, but has been converted to C++ for more efficient integration with other Sentry analysis routines. Table 1 provides a listing of the more common TPS materials contained in the database.

<table>
<thead>
<tr>
<th>Table 1. Common Materials from TPSX Database</th>
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<tbody>
<tr>
<td>Advanced Flexible Reusable Surface Insulation (AFRSI)</td>
</tr>
<tr>
<td>FRCI 12 and 20</td>
</tr>
<tr>
<td>AETB-8, 12, 16, and 20</td>
</tr>
<tr>
<td>Flexible Reusable Surface Insulation (FRSI)</td>
</tr>
<tr>
<td>Rohacel Foam</td>
</tr>
<tr>
<td>Saffil</td>
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<tr>
<td>Aluminum-2219</td>
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<tr>
<td>Advanced Carbon-Carbon (ACC)</td>
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<tr>
<td>Internal Multiscreen Insulation (IMI)</td>
</tr>
<tr>
<td>Stainless Steel</td>
</tr>
<tr>
<td>Carbon/SiliconCarbide (C/SiC)</td>
</tr>
</tbody>
</table>

American Institute of Aeronautics and Astronautics
Candidate TPS options can be specified as either a single layer of material or as a stackup consisting of up to 10 material layers (see Figure 3). For instance, a Toughened Unifibrous Flexible Insulation (TUFI) ceramic tile could be represented as a layup of six material layers. They would be: 1) TUFI exterior coating, 2) AETB diffusion layer, 3) AETB-8 (an 8 pcf fibrous insulation substrate), 4) room temperature vulcanizing (RTV-560) silicone adhesive, 5) Strain Isolation Pads (SIP), and 6) RTV-560. The SIPs and RTV-560 adhesive are used to attach each tile to the airframe and permit some thermal expansion. For each layer, the user would specify the nominal thickness and maximum temperature. Additionally, specification of the emissivity for the surface layer of the stackup is also required to be provided by the user.

C. Heat Transfer Analysis

For a specified TPS stackup and location on the vehicle surface, Sentry will proceed to solve the one-dimensional (1-D), unsteady heat transfer equation. The form of this equation is:

$$\frac{\partial T}{\partial t} = \gamma \frac{\partial^2 T}{\partial x^2}$$  \hspace{1cm} (1)

The boundary condition on the top or exposed surface of the stackup accounts for conduction, convection and radiation forms of heat transfer. The form of this equation is:

$$q_{conv} - \varepsilon \sigma T_1^4 + k \frac{dT}{dx} = 0$$  \hspace{1cm} (2)

The backface surface is assumed to be adiabatic (dT/dx = 0) which will yield a conservative design as no additional heat transfer, either by conduction or radiation, is permitted upon reaching the internal, backside of the stackup.

A fully implicit solver using a Newton-Rhapson iteration is used to solve Equations 1 and 2. Both equations are discretized with central differencing at the interior nodes and forward/backward differencing schemes at surface and backface nodes. The interior nodes are first-order accurate in time and second order accurate in space (FTSS). The boundary nodes are first-order accurate in both space and time (FTFS).
The S/HABP code provides the heating rate \( Q_{\text{conv}} \) as a function of time using the trajectory data (e.g. Mach, altitude and AOA vs. time) and an interpolation algorithm. The emissivity for the surface material is specified by the user and is constant throughout the analysis. The thermal conductivity \( k \) and specific heat capacity \( C_p \) are functions of temperature and their values are provided by the TPSX database.

D. Material Selection and Sizing Algorithm (MSSA)

The Material Selection and Sizing Algorithm, or MSSA, in Sentry is responsible for determining which nodes are analyzed, ensuring that all possible TPS candidates are considered, eliminating non-viable TPS options, and selecting the final TPS material at any given node. The algorithm processes the analysis grid moving from one vehicle component to the next, as contained in the S/HABP geometry file. Each vehicle component typically contains several hundred centroid nodes. For a particular component and wetted node, the MSSA examines the TPS candidate stackup database and identifies which options should be considered at the node. Each applicable TPS stackup is then analyzed by the heat transfer analysis algorithm. If appropriate, the optimizer is also activated in conjunction with the heat transfer analysis. When specified by the user, the optimizer will vary the thickness of one material in the TPS stackup in order to meet the backface temperature limit. Once all TPS options have been analyzed and sized at a node, the MSSA will then eliminate any options that either exceed any temperature limits of the materials and/or exceed the maximum stackup height specified by the user. The weight is then computed for all remaining TPS options at the node. The MSSA will then select the TPS stackup for the node as the option with the minimum weight.

A few additional sizing scenarios can sometimes occur and Sentry has algorithms in place to handle these. One possible scenario is that no viable TPS candidates exist. This can occur if the maximum surface temperature at a node exceeds the material limits of all the stackup options. If this situation occurs and the user has elected to use the active cooling/heat exchanger option (see General Specifications section of the Input Parameters), then this node is identified as a location needing active cooling and the user specified unit weight is used in place of any passive TPS candidate weights. If the user did not elect to use the active cooling option, then the candidate material that minimizes the maximum surface temperature violation, regardless of weight, is applied. This anomaly is then reported to the user in the main output file. It should also be noted that if the unit weight for any passive TPS option exceeds that specified for the active cooling/heat exchanger TPS, then the passive TPS is replaced and the lower weight of the active cooling system reported.

E. Stagnation Point Analysis

Sentry is capable of computing approximate convective heat rate values for stagnation areas on the vehicle. This option is commonly used for the vehicle nose, wing leading edges, and tail leading edges. As previously mentioned, the user must specify the representative geometric shape of the stagnation region as being either a cylinder, a swept cylinder, cone, or sphere. For spherical and cylindrical shapes, the user must specify the leading edge radius. For the cone option, the user must specify the cone half angle. In the case of the swept cylinder, the user must also provide the sweep angle of the cylinder. In all cases, the user must provide the emissivity and heat flux margin to apply. The computation of the stagnation point \( Q_{\text{conv}} \) for these shapes is based on work by Tauber (Ref. 3).

Upon specification of the geometric shape, Sentry will then generate the \( Q_{\text{conv}} \) data based on the trajectory profile provided with the S/HABP data. As with the non-stagnation locations on the vehicle, the MSSA will determine which candidate stackups should be applied in the stagnation region and a similar selection process is invoked after all candidate stackups have been analyzed. Note that the applicable surface area to be used for computation of the stagnation point material weight is based on the true component’s geometry in the stagnation region and is input as a fraction of the total surface area for that entire component. This value typically ranges from 0.5% to 2.0% for nosecaps and leading edges of wings.
V. Verification Analysis – Space Shuttle Orbiter

As a verification of the Sentry tool and TPS sizing methodology, SEI conducted an analysis of the United States’ Space Shuttle Orbiter. Data was gathered on the TPS materials in use on the shuttles and these materials were specified as candidates for Sentry to select from\textsuperscript{55}. The candidate materials are shown in Table 2. In all cases, the RCC was set to be 0.5 inches thick. The LI-2200 and LI-900 had a minimum gauge thickness of 0.5 inches. The AFRSI and FRSI had a minimum gauge thickness of 0.41 and 0.14 inches respectively.

<table>
<thead>
<tr>
<th>Vehicle Component(s)</th>
<th>Material(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuselage/Body</td>
<td>RCC, LI-2200, LI-900, AFRSI, FRSI</td>
</tr>
<tr>
<td>Lower Wing</td>
<td>RCC, LI-2200, LI-900</td>
</tr>
<tr>
<td>Upper Wing</td>
<td>RCC, LI-2200, LI-900, FRSI</td>
</tr>
<tr>
<td>Vertical</td>
<td>RCC, LI-2200, LI-900, FRSI</td>
</tr>
<tr>
<td>Wing and Vertical Leading Edges</td>
<td>RCC</td>
</tr>
<tr>
<td>Body Flap</td>
<td>RCC, LI-2200, LI-900</td>
</tr>
<tr>
<td>OMS Pods</td>
<td>RCC, LI-2200, LI-900, AFRSI, FRSI</td>
</tr>
</tbody>
</table>

The convective heat rate data was generated for the Space Shuttle using a geometry model supplied to the authors by NASA Langley Research Center (LaRC). A trajectory simulation that modeled the entry profile for the Shuttle was performed using the POST trajectory tool and the necessary flight profile data was obtained. The Mach number and altitude versus time for this trajectory is shown in Figure 4.

![Figure 4. Space Shuttle Orbiter Trajectory Profile for Verification Analysis](image)

For this application, Sentry was operated using the ‘direct’ mode for specification of the $Q_{conv}$ data. Approximately 54 trajectory points were utilized to represent the flight path of the Shuttle and thus 54 runs of S/HABP were also performed. In addition to the entry trajectory, a two hour, post-landing cool down phase for the Shuttle was also added into the Sentry analysis. The addition of this phase increased the TPS weight significantly from what it would have been without it as this additional time permitted the heat trapped in the TPS materials to...
continue to conduct towards the backface material. The end result is that the TPS tiles and blankets were required to be thicker to prevent a violation of the backface temperature constraint.

Table 3 provides the summary of the total TPS weight by component computed with Sentry versus that of the actual Space Shuttle. In general, very good agreement is obtained. The difference in total TPS weight is less than 5%. Note that neither of the weights reflect additional TPS hardware items like gap fillers, bonds, joints, closeouts, thermal barriers, and carrier strips. In the vehicle design process, these items are bookkept separately and reflect the true “installed weight” of the TPS. The total weight for these additional items for the Space Shuttle is about 4,600 lbs, or ~18% of the total TPS weights shown here. It should also be noted that as standard practice in next-generation conceptual design, the TPS weight results from Sentry would have a 15-20% weight margin added to them. As the Shuttle is an existing system and for this verification analysis, the Sentry results presented do not have any margin added.

Table 3. Summary Results for Verification Analysis

<table>
<thead>
<tr>
<th>Component</th>
<th>Space Shuttle Weight (lb.)</th>
<th>Sentry Analysis Weight (lb.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuselage/Body</td>
<td>6,693</td>
<td>6,649</td>
</tr>
<tr>
<td>Wings</td>
<td>8,443</td>
<td>8,517</td>
</tr>
<tr>
<td>Tail</td>
<td>800</td>
<td>665</td>
</tr>
<tr>
<td>OMS/RCS Pods</td>
<td>1,167</td>
<td>549</td>
</tr>
<tr>
<td>Body Flap</td>
<td>806</td>
<td>734</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>17,910</strong></td>
<td><strong>17,114</strong></td>
</tr>
</tbody>
</table>

Figure 5 provides the maximum surface temperature distribution for the Orbiter. It should be noted that while not entirely evident in the figure, the surface temperatures at the tip of the wing lead edges (LE) were in excess of 3,600 R. Differences between the Orbiter’s actual LE at the wing tip and the LE radius present in the APAS geometry model account for these differences. The geometry model used for this verification analysis reflects a smaller leading edge radius than the true Orbiter LE radius. Similar geometry differences were seen in the nosecap region of the forward fuselage. The authors plan to continue refining the S/HABP geometry model for the Shuttle to obtain a more accurate representation in the future. Other than the aforementioned areas, the APAS geometry model was very representative of the true Orbiter geometry. A comparison of the total surface areas for the true Orbiter and the APAS model yielded less than a 1% difference (~100 ft²).
Figure 5. Shuttle Orbiter Maximum Surface Temperatures from Sentry

Figure 6 provides the TPS material distribution for the entire Space Shuttle Orbiter. A detailed comparison of the TPS materials selected for use on each component showed good overall agreement. In a few locations, Sentry selected heavier or higher temperature capable TPS materials due to the temperatures being encountered. As an example, there was a small amount of RCC selected for use on the OMS pods. It should also be noted that the Orbiter’s windshields have been ignored and have been replaced with one of the candidate TPS stackups.

Figure 6. Shuttle Orbiter TPS Material Distribution from Sentry
VI. Case Study – Quicksat Military Space Plane

A. Concept Overview

The Quicksat SOV is the first element of a two-stage MSP concept that uses combined-cycle air-breathing propulsion (see Figure 7). The nominal system takes off and lands horizontally and uses non-cryogenic propellants for improved operability in support of on-demand and responsive launch scenarios. The booster is capable of supporting three different missions: a) space maneuvering vehicle (SMV) delivery to orbit, b) a hypersonic strike mission, and c) cargo delivery to LEO and polar orbits by configuring the upperstage with mission-specific hardware.

The nominal mission for the Quicksat is the delivery of an SMV to an elliptic 70x197 nmi. orbit at a 28.5 inclination. The SMV is a reusable vehicle capable of remaining on-orbit for extended periods of time. The SMV features a small, kerosene/H$_2$O$_2$ liquid rocket engine (Rocketdyne AR2-3) for on-orbit maneuvering. The total SMV weight is 13,090 lbs, which includes an experiment bay with up to 500 lbs. of payload. Its length from nose-to-tail is 27.5 ft and the wingspan is 15.0 ft.

The Quicksat booster is configured as a lifting-body design, derived from the National Aerospace Plane (NASP) program vehicle configurations and similar to the NASA Hyper-X (X-43) integrated-scramjet flight test program. Upperstage modules are mated on the leeward, aft portion of the vehicle in a partially recessed cavity. The upperstage (not shown) is in turn mated to the SMV payload and provides delta-V from the Mach 9 staging point to orbit insertion. The SMV is inserted into low Earth orbit fully fueled. The Quicksat booster’s air-breathing propulsion systems are arranged in an over-under configuration with turbine-engines embedded in the vehicle airframe and an underslung dual-mode scramjet (DMSJ) system. These engines share a common external compression system (i.e. the vehicle forebody) and aftbody expansion zones. In addition to providing engine airflow matching and optimal flow expansion, the variable geometry inlet and exit ramps can shield the turbine systems from the freestream flow when not being operated. All propulsion system elements use JP-7 hydrocarbon fuel. The rocket systems also use a hydrogen-peroxide (H$_2$O$_2$ at a 95% purity level) oxidizer.

The feasibility and viability of the Quicksat system is dependent upon technology advances in a number of key areas. Specific technologies employed by the booster system include: graphite-epoxy (Gr-Ep) airframe primary and secondary structures, cylindrical non-integral Gr-Ep fuel tanks and aluminum oxidizer tanks, electro-hydraulic actuators (EHAs) for control surfaces, and all-moving vertical tails.

Figure 7. Quicksat External Views.

The Quicksat booster is configured as a lifting-body design, derived from the National Aerospace Plane (NASP) program vehicle configurations and similar to the NASA Hyper-X (X-43) integrated-scramjet flight test program. Upperstage modules are mated on the leeward, aft portion of the vehicle in a partially recessed cavity. The upperstage (not shown) is in turn mated to the SMV payload and provides delta-V from the Mach 9 staging point to orbit insertion. The SMV is inserted into low Earth orbit fully fueled. The Quicksat booster’s air-breathing propulsion systems are arranged in an over-under configuration with turbine-engines embedded in the vehicle airframe and an underslung dual-mode scramjet (DMSJ) system. These engines share a common external compression system (i.e. the vehicle forebody) and aftbody expansion zones. In addition to providing engine airflow matching and optimal flow expansion, the variable geometry inlet and exit ramps can shield the turbine systems from the freestream flow when not being operated. All propulsion system elements use JP-7 hydrocarbon fuel. The rocket systems also use a hydrogen-peroxide (H$_2$O$_2$ at a 95% purity level) oxidizer.

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The length of the Quicksat, from the nose-to-tail section is 123.6 feet, with a wingspan of 65 feet and tail height of 26 feet. The weight of the booster, without propulsive fluids, is 167,840 lbs. Without its SMV + upperstage module, the weight of the fully loaded booster with the JP-7 fuel and H2O2 oxidizer propellants is 651,455 lbs, yielding a total gross takeoff weight (GTOW) of 741,670 lbs. (less startup losses) for the SMV deployment mission. Further details of the Quicksat space-lift system are provided in Reference 6.

B. Analysis and Results

The Sentry tool was integrated into SEI’s vehicle closure model that was constructed using Phoenix Integration’s ModelCenter© environment, as shown in Figure 8. Additional tools contained in the model included the NASA Langley Program to Optimize Simulated Trajectories version 2 (POST-2) trajectory analysis tool, SEI’s REDTOP and REDTOP-2 liquid rocket engine analysis tools, and SEI-Sizer for mass properties estimation and system sizing. The air-breathing propulsion system analysis was performed using NASA GRC’s NEPP tool for the turbine engines and SRGULL from NASA LaRC for the dual-mode scramjet engine analysis. The aerodynamic analysis was performed using the Aerodynamic Preliminary Analysis System (APAS) code. Note that both the air-breathing propulsion data and aerodynamics (lift and drag coefficients) can be photographically scaled about a reference geometry directly within SEI-Sizer and thus do not have to be reanalyzed “in the loop” during the vehicle closure process.

The vehicle closure model consisted of both an inner and outer convergence loops that used a fixed-point iteration method to resolve variable coupling. The inner convergence loop contained coupled variables with the mass properties/sizing and trajectory (ascent and flyback) variables. The outer convergence loop contained coupled variables for the aeroheating/TPS, trajectory, and mass properties/sizing disciplinary analysis. For this particular application, this setup was found to yield faster convergence times compared to a setup with a single, all-encompassing convergence loop.
A database of $Q_{conv}$ versus Mach number, altitude, and angle-of-attack, for the booster was generated using the S/HABP routine of APAS. This database contained results at over 320 unique flight conditions that encompassed the Quicksat booster’s ascent profile from Mach 1.25 to approximately Mach 9. Figures 9 and 10 display the ascent profiles for the Quicksat booster used by Sentry. Figure 11 shows the S/HABP analysis grid that contained over 2,000 centroid nodes at which Sentry assessed the thermal environment and to selected appropriate TPS material stackup.

The aeroheating analysis included the flyout, pullup, staging maneuver, flyback and a two-hour cool down period. A constant emissivity of 0.8 was used for all surfaces and the vehicle was assumed to have a leading edge radius of two inches. The backface temperature for the airframe was required to not exceed 760 R, while the backface temperature for the wings and tails was limited to 950 R. Also, the maximum material temperature for the AFRSI blankets, TUFI tiles and ACC were 1660 R, 2860 R and 3360 R, respectively. The CRI, C/SiC and UHTC materials had a maximum temperature of 2000 R, 3460 R and 4460 R, respectively. The optimal TPS type was determined at each node by considering the thickness manufacturing constraints, maximum reuse surface temperatures, and the minimum weight. The resulting materials and their raw unit weights selected by the analysis are listed in Table 4. The average unit weight for all the TPS materials for the Quicksat was determined to be 1.348 lbs/ft², prior to the inclusion of a 15% weight growth margin that was used in the closure process for conservatism.

**Figures 9 and 10. Mach Number and Altitude Histories for Quicksat Space-Access Mission**

The aeroheating analysis included the flyout, pullup, staging maneuver, flyback and a two-hour cool down period. A constant emissivity of 0.8 was used for all surfaces and the vehicle was assumed to have a leading edge radius of two inches. The backface temperature for the airframe was required to not exceed 760 R, while the backface temperature for the wings and tails was limited to 950 R. Also, the maximum material temperature for the AFRSI blankets, TUFI tiles and ACC were 1660 R, 2860 R and 3360 R, respectively. The CRI, C/SiC and UHTC materials had a maximum temperature of 2000 R, 3460 R and 4460 R, respectively. The optimal TPS type was determined at each node by considering the thickness manufacturing constraints, maximum reuse surface temperatures, and the minimum weight. The resulting materials and their raw unit weights selected by the analysis are listed in Table 4. The average unit weight for all the TPS materials for the Quicksat was determined to be 1.348 lbs/ft², prior to the inclusion of a 15% weight growth margin that was used in the closure process for conservatism.

**Table 4. Quicksat TPS Material Requirements from Sentry**

<table>
<thead>
<tr>
<th>Component – Fuselage</th>
<th>Material Stackup</th>
<th>Avg. Unit Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leeward and Fuselage sidewalls</td>
<td>AFRSI Blankets and CRI</td>
<td>0.75 psf</td>
</tr>
<tr>
<td>Windward Forebody and Aftbody Nozzle</td>
<td>TUFI AETB-8 Ceramic Tiles and CRI</td>
<td>1.47 psf</td>
</tr>
<tr>
<td>Nose</td>
<td>ACC</td>
<td>12.6 psf</td>
</tr>
<tr>
<td>Component – Wings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leading Edges</td>
<td>ACC</td>
<td>12.6 psf</td>
</tr>
<tr>
<td>Windward Side</td>
<td>CRI</td>
<td>1.37 psf</td>
</tr>
<tr>
<td>Leeward Side</td>
<td>CRI</td>
<td>0.82 psf</td>
</tr>
<tr>
<td>Component – Tails</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leading Edges</td>
<td>ACC</td>
<td>12.6 psf</td>
</tr>
<tr>
<td>Windward Side</td>
<td>CRI</td>
<td>0.82 psf</td>
</tr>
<tr>
<td>Leeward Side</td>
<td>CRI</td>
<td>0.82 psf</td>
</tr>
</tbody>
</table>
The majority of the windward surfaces of the airframe are covered with CRI, although the nozzle employs TUFI ceramic tiles. The leeward surfaces of the airframe are covered with AFRSI blankets. The vehicle has sharp leading edge radius of 2 inches, which results in stagnation point temperatures exceeding 3,000 R and requires the use of ACC. The bulk area of the upper and lower wing and tail surfaces are covered with CRI, while the control surfaces and leading edges are covered with ACC.

The maximum temperatures calculated for each vehicle panel is shown in Figure 11. Away from the hot leading edges that are not visible in the figure, the peak surface temperature is approximately 2500 R. The aft portion of the windward surface of the airframe experiences higher temperatures, because the propulsive flow field is simulated by directly imposing a representative surface temperature. For the Sentry analysis, the wing control surfaces are deflected upward 5 degrees and downward 15 degrees over the entire flight profile causing the increased temperatures seen in Figure 11 for the control surfaces.

VII. Conclusions

SpaceWorks Engineering, Inc. (SEI) has created a newly developed engineering software tool for aeroheating analysis and TPS sizing. This tool, called Sentry, is applicable for use in the conceptual and preliminary design of space transportation systems utilizing reusable, non-ablative thermal protection systems. The tool represents a unique addition to the current suite of TPS selection and sizing tools available to advanced design engineers.

A verification exercise was conducted using Sentry and the Space Shuttle Orbiter as the vehicle concept. Results showed generally good overall agreement, with a difference in total TPS weight of less than 5%. Small differences in the Sentry solution and the Shuttle’s actual TPS system can be attributed to a number of sources, including the S/HABP Q_{conv} predictions, wing leading edge geometry differences, material properties from TPSX, and the 1-D assumption used in the unsteady, heat transfer model.

Finally, Sentry was shown to have performed very well in a “real-world” case study involving the design of a fully-reusable, lifting body booster that used air-breathing propulsion to Mach 8. Sentry was fully coupled with both the trajectory simulation and the weights/sizing model. For this case study, results that included the maximum
surface temperatures and TPS material property distribution were provided. Additionally, the total TPS weight and average unit weight for the entire vehicle were computed by Sentry.

VIII. Future Work

As an ongoing development, the capabilities and functionality of the Sentry code continues to be expanded by engineers at SEI. Some specific new capabilities and options being considered include:

1) A user option to conduct the analysis with an isothermal backface condition instead of just the current adiabatic backface condition. This would permit the heat transfer modeling through the airframe/tank structure and include the impact of heat transfer into propellants on the opposite side of the airframe/tank wall. While this is a less conservative approach to TPS sizing, it may be justifiable in certain scenarios.

2) Incorporate a scale-factor output parameter that represents the impact to the vehicle outer mold line (OML) due to changing TPS thicknesses. This scale-factor could then be used by the aerodynamic and trajectory analysis to more accurately reflect the OML of the vehicle as seen by the freestream flowfield. Additionally, the height of any stand-off mechanisms required on the back side of a TPS panel to provide a smoothly varying OML could be determined.

3) Expansion of the TPSX property database by incorporating material cost and maintenance data, such as required installation and inspection times. This would permit an alternate optimization variable besides the weight metric or definition by the user of an Overall Evaluation Criteria (OEC) on which to base TPS selection.

4) Enable option to permit radiative heat transfer to occur on the backface of the stackup. This would be useful for cases where the TPS stackup is not in direct contact with the airframe structure and a gap or standoff distance is present.

Acknowledgements

The authors at SpaceWorks Engineering, Inc. (SEI) would like to thank Dr. Bandu Pamadi of the NASA Langley Research Center (LaRC) for providing the original Space Shuttle S/HABP geometry model. Additionally, SEI would like to acknowledge the preliminary tool development encouragement and support that was provided by the Advanced Concepts Group at NASA’s Marshall Space Flight Center (MSFC).

References


