ABLATION MODELING OF ARES-I UPPER STAGE THERMAL PROTECTION SYSTEM USING THERMAL DESKTOP

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ABSTRACT:
The thermal protection system (TPS) for the Ares-I Upper Stage will be based on Space Transportation System External Tank (ET) and Solid Rocket Booster (SRB) heritage materials. These TPS materials were qualified via hot gas testing that simulated ascent and re-entry aerothermodynamic convective heating environments. From this data, the recession rates due to ablation were characterized and used in thermal modeling for sizing the thickness required to maintain structural substrate temperatures. At Marshall Space Flight Center (MSFC), the in-house code ABL is currently used to predict TPS ablation and substrate temperatures as a FORTRAN application integrated within SINDA/G. This paper describes a comparison of the new ablation utility in Thermal Desktop and SINDA/FLUINT with the heritage ABL code and empirical test data which serves as the validation of the Thermal Desktop software for use on the design of the Ares-I Upper Stage project.

INTRODUCTION:
The Ares-I Upper Stage is powered by the J-2X engine, which utilizes Liquid Hydrogen fuel and Liquid Oxygen oxidizer. These large cryogenic tanks are insulated with External Tank (ET) derived polyurethane closed-cell foams, also called Spray-On Foam Insulation (SOFI) to minimize heat leak and ice/frost formation as well maintaining structural temperature limits during ascent aerothermodynamic heating. Various raised areas (protuberances), such as the feed-lines, systems tunnel, reaction control system and solid motor fairings, are insulated with ET and SRB derived TPS materials, such as Super Lightweight Ablator (SLA-561). The primary tool chosen for the in-house Upper Stage thermal design and analysis is Thermal Desktop® (TD) with SINDA/FLUINT. Other software packages are being utilized by MSFC, such as FEMAP, SINDA/G and PATRAN, but the baseline tool for integrated modeling and the bulk of the component models are with TD. Since the MSFC heritage

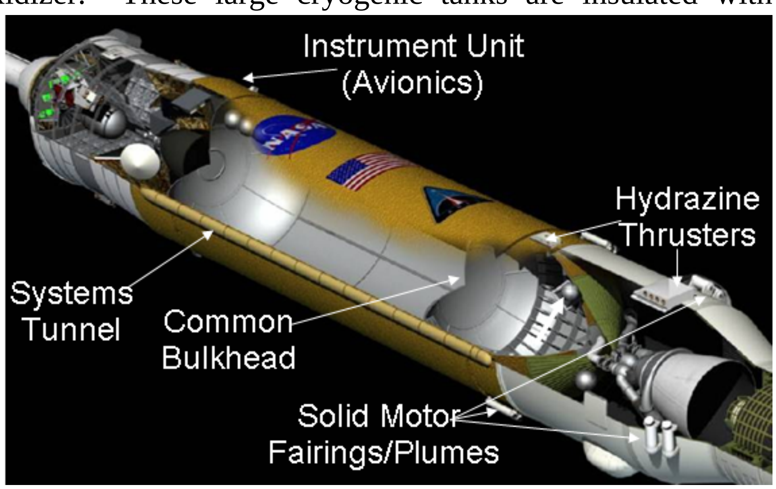


Figure 1: Ares I Upper Stage Overview

for thermal modeling of ablation has been with the in-house ABL code and the ablation capability in TD is a relatively new addition, a validation process was undertaken to benchmark the TD ABLATE subroutine for use on Ares-I. This resulted in the development of a new subroutine by Cullimore & Ring Technologies, Inc. called ABLATERATE.

PHYSICS OF ABLATION:

The process of physical ablation occurs during extreme heating environments, such as that experienced for a re-entry vehicle like the Space Shuttle Orbiter. Ablation materials undergo chemical decomposition, or pyrolysis, which forms a char layer as shown in Figure 2. During this process, energy is transferred away by the pyrolysis gasses and the surface of the material recedes with time. In addition, the heating region consists of highly ionized air that has dissociated, resulting in complex chemical reactions at the surface and within the boundary layer. The energy balance between the convective energy (sensible), chemical energy and net radiation at the TPS surface is as follows[1]:

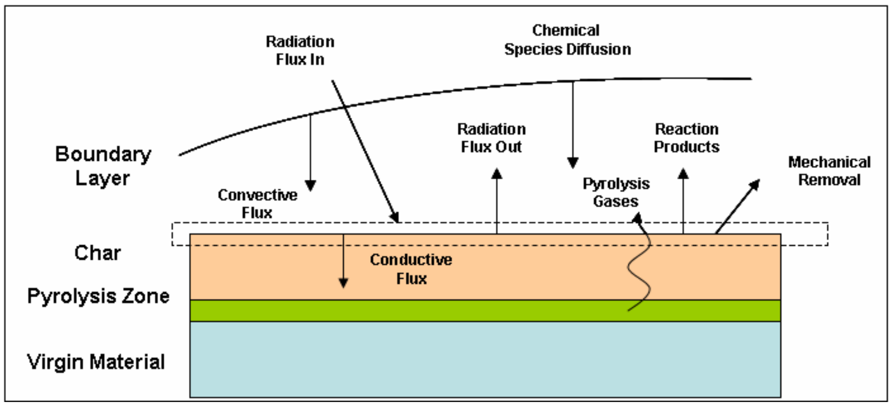


Figure 2: Surface Ablation Characteristics

$$\underbrace{\rho_e u_e C_H (H_r - h_{ew})}_{\text{Sensible Energy Rate}} + \underbrace{\rho_e u_e C_M \left[\sum \left(Z_{i_e}^{n} - Z_{i_w}^{n}\right) h_i^{T_w} - B' h_w\right] + \dot{m}_c h_c + \dot{m}_g h_g}_{\text{Chemical Energy Rate}} + \underbrace{\alpha_w q_{rad} - F\sigma\varepsilon_w T_w^4}_{\text{Net Radiation Energy Rate}} - q_{cond} = 0$$

Internally within the TPS material, the energy balance includes the effects of the surface recession and pyrolysis gas as follows:

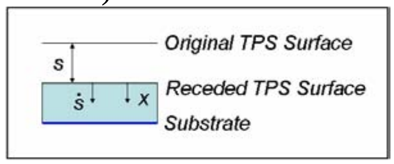
$$\underbrace{\rho c_p \frac{\partial T}{\partial t}}_{\text{Energy Storage}} = \underbrace{\frac{1}{A}\frac{\partial}{\partial x}\left(kA\frac{\partial T}{\partial x}\right)}_{\text{Conduction Rate}} + \underbrace{(h_g - \bar{h})\frac{\partial \rho}{\partial t}}_{\text{Pyrolysis Energy}} + \underbrace{\dot{s}\rho c_p \frac{\partial T}{\partial x}}_{\text{Recession Rate}} + \underbrace{\frac{\dot{m}}{A}\frac{\partial h_g}{\partial x}}_{\text{Pyrolysis Gas Convection}}$$

Without pyrolysis & ablation, the sensible gaseous convective heat transfer and enthalpy calculations including real gas effects can be simplified to the form typically provided to the thermal analyst by aerothermodynamic environments codes. This surface energy balance simplifies to:

$$\underbrace{h_c (H_r - H_w)}_{\text{Gaseous Convection}} + \underbrace{\alpha_w q_{rad} - F\sigma\varepsilon_w T_w^4}_{\text{Surface Net Radiation}} - q_{cond} = 0$$

Internally to the TPS material, the recession of the material thickness affects the conduction and thermal capacitance of the remaining material. This energy balance can be shown by the following equation (where s represents the amount of recession from the original TPS surface as shown in the Figure below):

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{A}\frac{\partial}{\partial x}\left(kA\frac{\partial T}{\partial x}\right) + \dot{s}\rho c_p \frac{\partial T}{\partial x}$$



The previous two equations more appropriately represent the governing equations inherent to the MSFC ABL and TD ABLATE modeling approaches. The complex chemical energy balance is not explicitly modeled, so an examination of the method of acquiring the TPS ablation properties empirically is discussed in the next section to illustrate how this element of the physics is addressed.

ET/SRB TPS ABLATION TESTING METHODOLOGY:

The TPS material qualification for the Space Transportation System ET and SRB programs for the ascent and plume heating environments was accomplished using various arc-jet and hot gas wind tunnel facilities. To illustrate the process used to characterize the TPS materials, the Marshall Convergent Coating (MCC-1) will be used as an example[2]. The MCC-1 is a MSFC developed TPS material formulated to replace the Marshall Sprayable Ablator-2 (MSA-2) on the SRB forward assembly, systems tunnel covers and aft skirt. The MCC-1 uses convergent spray technology and consists of 8% hollow spherical glass, 9% cork, and 83% two-part epoxy by weight. The qualification testing of the material was performed at MSFC's Improved Hot Gas Facility, which is a Mach 4 convective heating wind tunnel capable of 3.5 to 25 Btu/hr/ft^2-s heat flux and an optional 300kW radiant heat system capable of a 0 to 35 Btu/hr/ft^2-s heat flux.

Figure 3: MSFC Hot Gas Facility

The angle of incidence between a test panel and the flow can be varied to achieve various heating conditions. An aluminum calibration panel (12x19-inch) including 20 Medtherm Schmidt-Boelter type heat flux gages, pressure measurements, and backside temperature measurements was used to determine the hot wall gaseous heating rates (see Figure 4). This heating rate was then "normalized" to a cold wall heating rate using this equation:

$$\dot{q}_{cw} = \dot{q}_{hw}\left[\frac{(T_r - T_{cw})}{(T_r - T_w)}\right]$$

where:

$\dot{q}_{cw}$ = Cold wall heat rate (Btu/ft^2/s)

$\dot{q}_{hw}$ = Hot wall heat rate (Btu/ft2/s)

T_r = Adiabatic wall recovery temp (ºF)

$$T_r = r^* \times T_{total}$$

T_{cw} = Cold wall reference temp (0ºF)

T_w = Calibration Plate Surface temp (ºF)

r^* = Corrected recovery factor

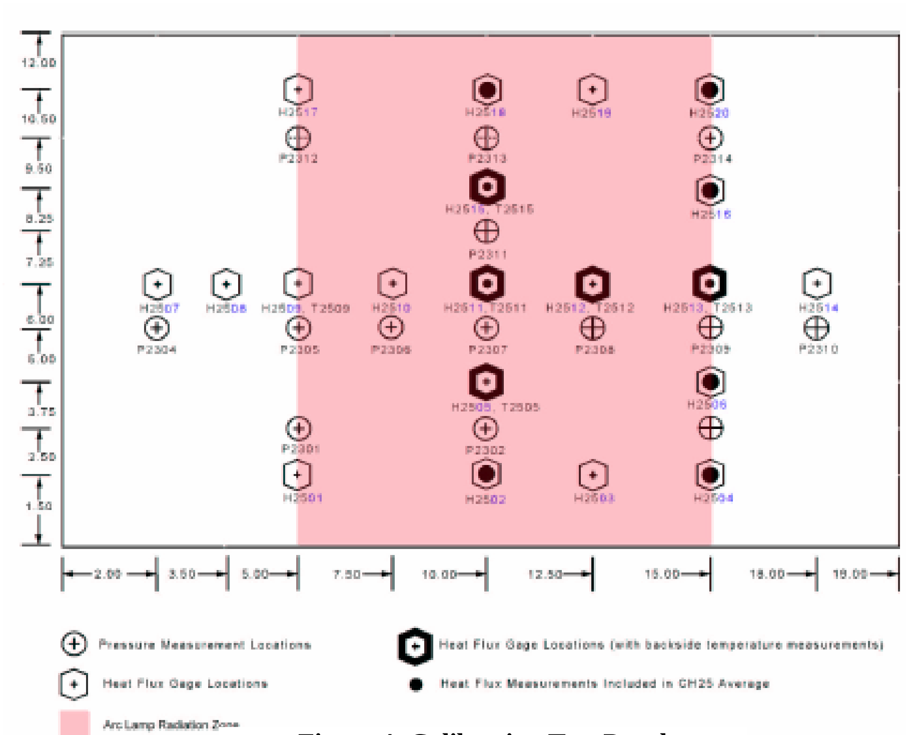


Figure 4: Calibration Test Panel

After testing of the TPS panel, the char layer is removed from tested panel and detailed micrometer measurements are used to determine recession rate down to the virgin TPS. A pre-test panel with markings where the calibration panel measurement are located and the post-test charred panel are shown in Figure 5. The data from multiple test panels and sensor locations is then used to perform a linear least squares curve fit as follows:

$$\dot{r} = k\dot{q}_{cw}^{\ x}$$

where: $\dot{q}_{cw}$ = Cold wall heat rate (Btu/ft^2/s)
k = Least squares fit y-intercept
$\dot{r}$ = Recession rate (mils/sec)
x = Least squares fit slope

The MCC-1 curve fits, including the 95 percentile upper limit, which is calculated for use as the design recession curve fit are shown in Figure 6. Since the test environment includes the flight-like flow boundary conditions and the TPS undergoes the pyrolysis and char layer formation, the affects of the chemical reactions and mechanical erosion are inherently included in the empirical recession data. By removing the char layer prior to the thickness

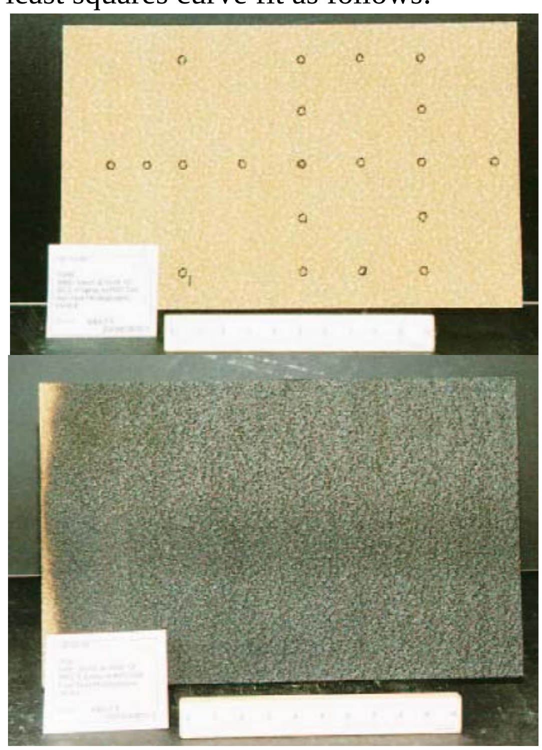


Figure 5: Pre- and Post-Test Panel

measurements, the recession to the char-to-virgin material interface is represented in the data. Since the ablation temperature is determined from Thermogravimetric Analysis (TGA) testing of the TPS material, the value represents the onset of pyrolysis and charring, which is appropriate for the char-to-virgin material interface typically set as the boundary temperature in thermal analysis codes.

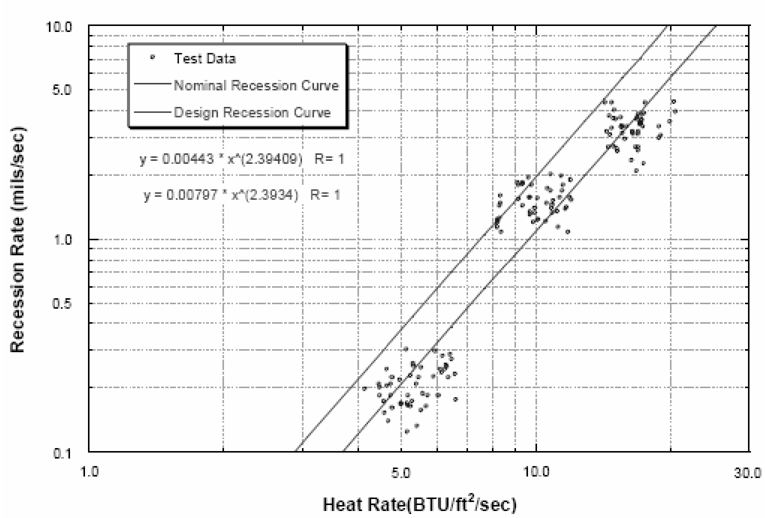


Figure 6: MCC-1 Recession Versus Heat Rate

THERMAL DESKTOP ABLATE SUBROUTINE:

The TD with SINDA/FLUINT software code includes the ABLATE subroutine to simulate 1-dimensional surface ablation and the material recession. The input parameters for this routine are heat of ablation (Q_{abl}) and the ablation temperature of the TPS. Once ablation temperature is reached, the surface node is held constant by the BDYNOD utility. Then, the surface node is "shrunk" to simulate the mass loss due to ablation, which involves altering the nodal capacitance and linear conductor to the adjacent node within the thickness of the TPS. Instead of reducing the node size to very small thicknesses, which can result in a small capacitance over sum of conductors (CSG) ratio and small numerical timesteps, the node is "collapsed" once the mass drops below 50% of its original value (based on RTMIN default). The capacitance and energy from the "collapsed" node is then reassigned to the "next" node and changed to an arithmetic node which still participates in the network. This allows the model nodalization to remain unchanged and not affect

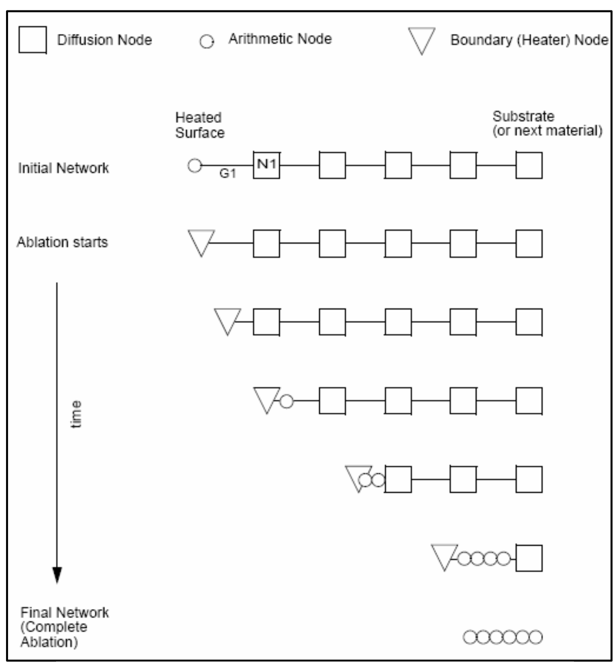


Figure 7: TD Ablation Nodal Network

surface heating logic. This process continues through the nodes representing the thickness of the material as long as the heating is sufficient to keep the surface at the ablation temperature. This process is illustrated graphically in Figure 7[3]. The user defines the number of nodes and an array of initial thicknesses. The final node can be designated such that it is not allowed to completely ablate, which would simulate a burn through scenario.

For the Ares-I TPS materials, the heat of ablation is not explicitly defined, but rather the recession rate normalized the cold wall heat flux is defined as outlined previously. An attempt was made to generate an effective heat of ablation using the recession data via the following equation:

$$Q_{abl} = \frac{12000 \times \dot{q}''_{net}}{\dot{r} \times \rho_{TPS}}$$

where:
$\dot{r}$ = recession rate (mils/sec)
$\dot{q}''_{net}$ = Net surface cold wall heat flux (Btu/sec/ft^2)
ρ_{TPS} = TPS density (lbm/ft^3)
Q_{abl} = Heat of Ablation (Btu/lbm)

This approach proved laborious and difficult to implement. Sensitivity studies were required to ensure the proper energy balance was being maintained and that the model was converging properly. Comparisons of results with MSFC's ABL code revealed inconsistencies in the accuracy of this approach, so Cullimore & Ring Technologies, Inc. (C&R) was consulted on these issues. Additionally, a request for a simplified method to enter the hot wall heating fluxes to be interpolated as a function of hot wall temperature was made.

THERMAL DESKTOP ABLATERATE SUBROUTINE:

The C&R response was the development of the alternate ablation subroutine, ABLATERATE. In this version, the user defines the linear recession curve instead of heat of ablation. This has only been released as a Beta test version at this point.

Either the ABLATE or ABLATERATE subroutine is invoked when the "Use Ablation" checkbox is checked within the thermophysical property definition panel as shown in Figure 8. Once this is checked, the user enters the ablation temperature and if the heat of ablation property is entered, the existing ABLATE routine is utilized. However, if the user checks the "Use Rate Eqn" checkbox, then the recession rate equation discussed in this paper can be entered via the linear least squares intercept and slope (Figure 9), which invokes ABLATERATE.

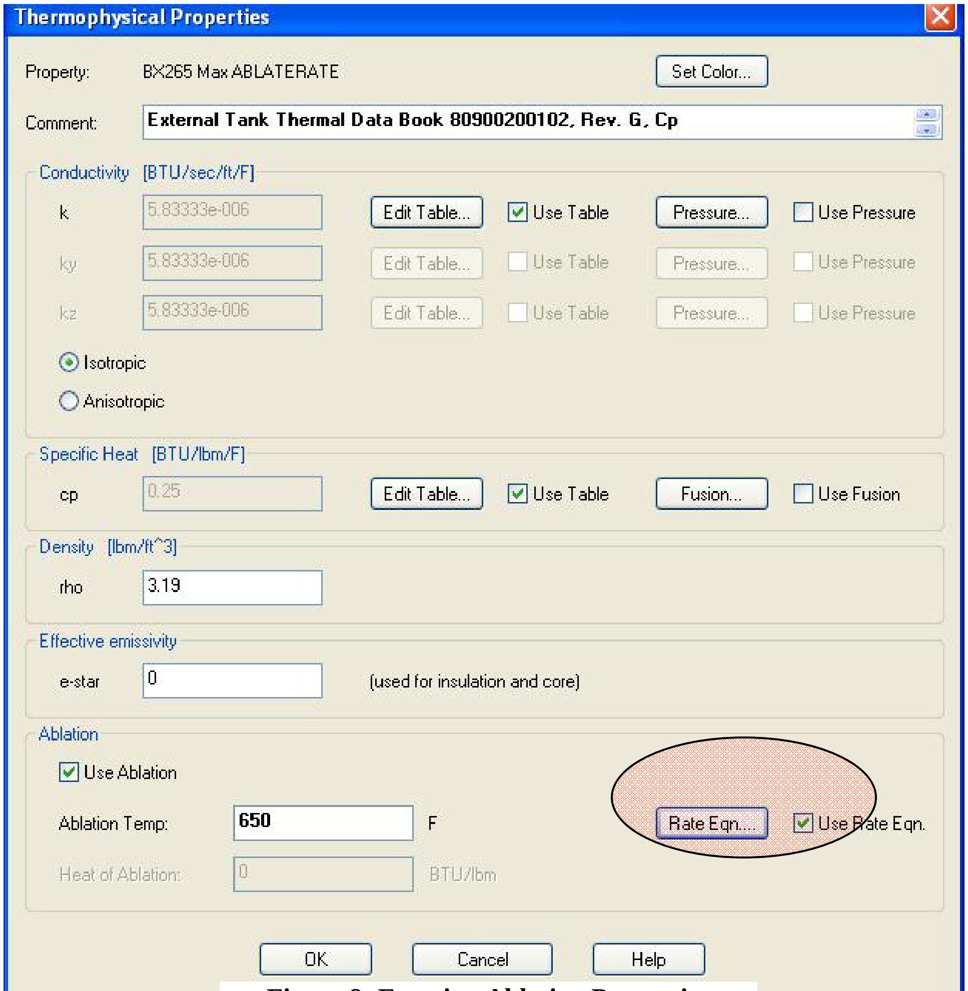


Figure 8: Entering Ablation Properties

Another parameter added for the user is the "Fraction of Top Node for Surface", which defaults to 0.01 as shown at the bottom of Figure 9. This parameter allows the user to assign a finite capacity to the surface node, which assists in the numerical stability for very high heating rate problems. It is recommended that the user perform a sensitivity study of this parameter to ensure optimum run-time with accurate results. The user can also alter the nodal thicknesses representing the TPS below the surface node.

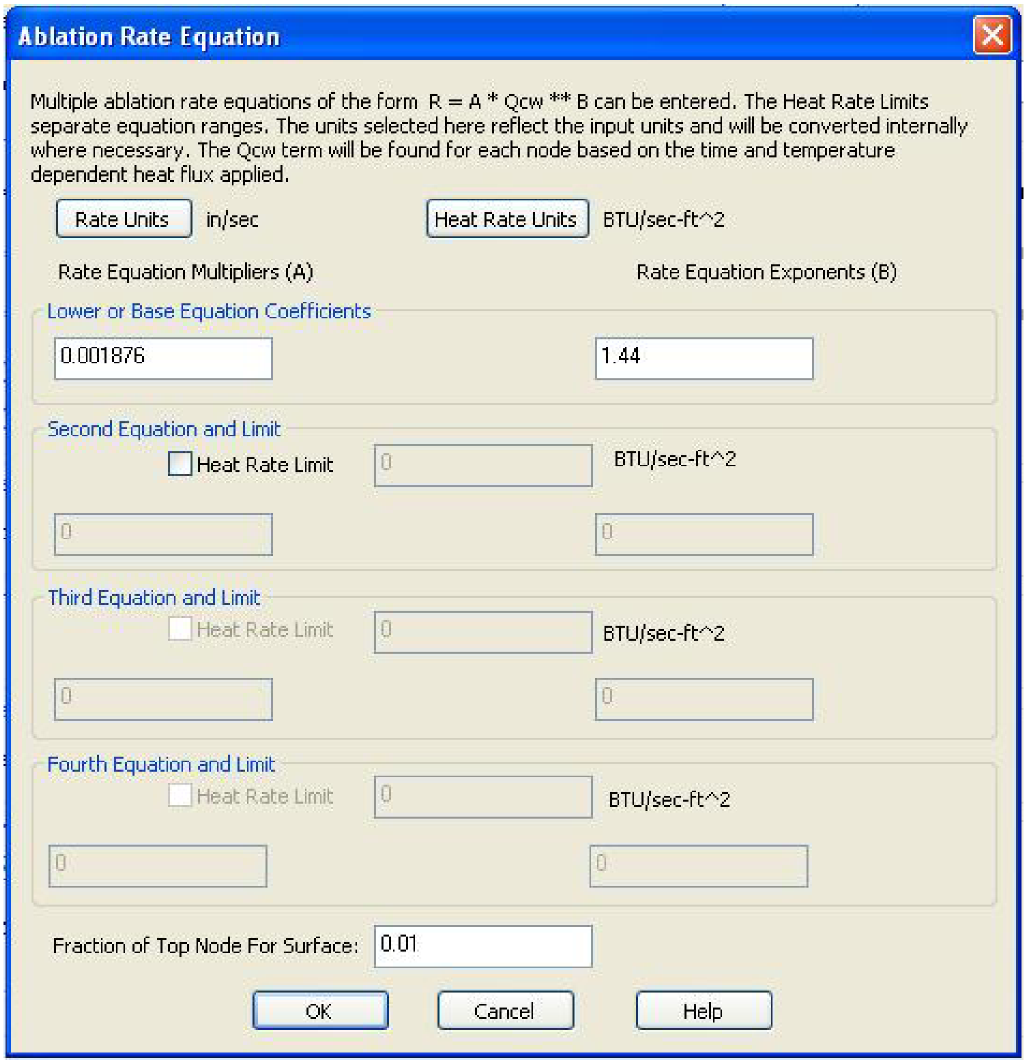


Figure 9: Entering Recession Rate Equation

Another change to Thermal Desktop implemented to improve the ease of entering aero-thermal heating rates is the ability to enter a heat load that is a function of both time and temperature. If the user adds this type of heat load, an input bivariate array can be defined with the temperatures for which aero-thermal data is available and the corresponding heat load versus time at each of these temperatures. Example panels demonstrating this feature are shown in Figure 10.

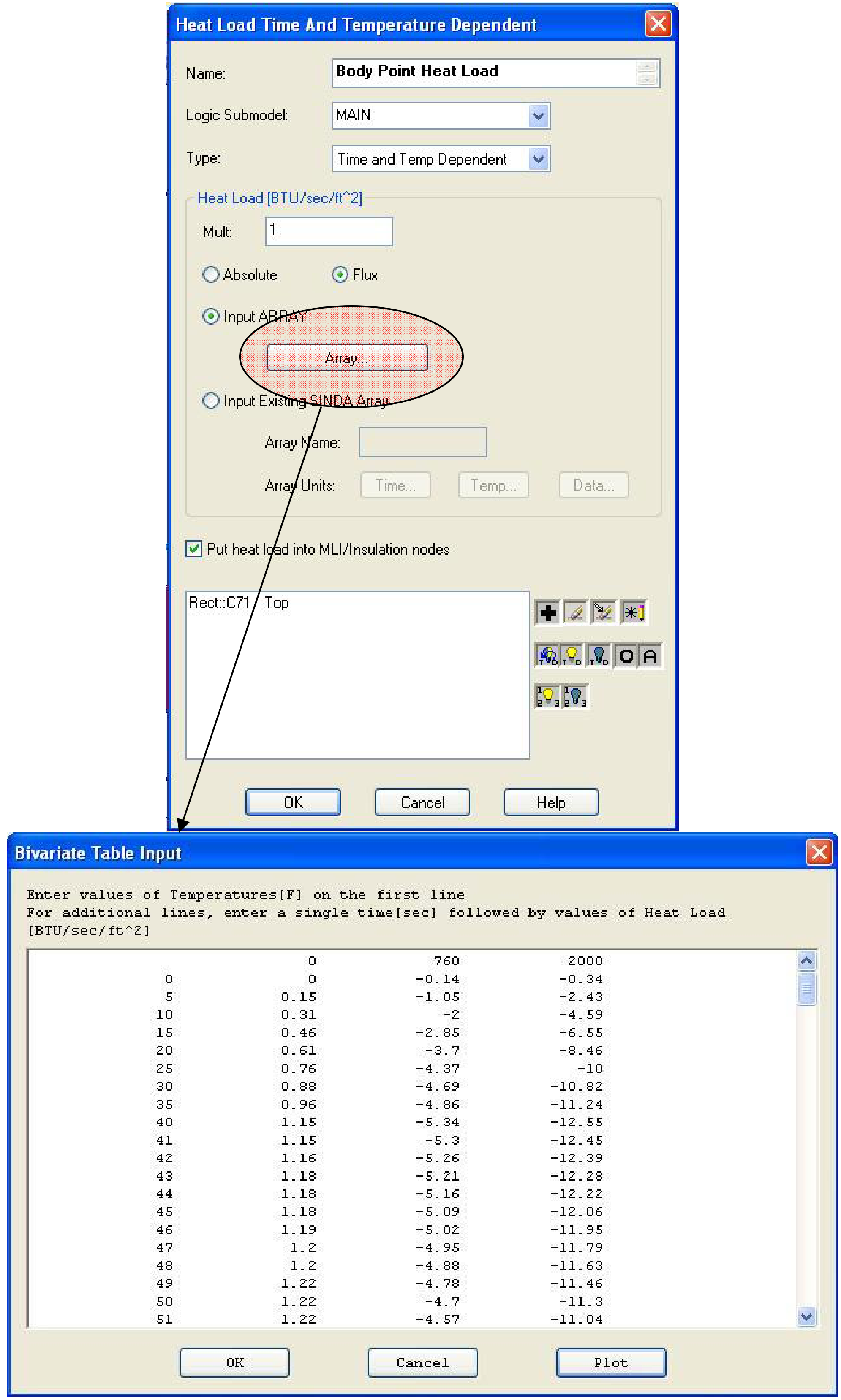


Figure 10: Alternate Method of Entering Bi-Variate Aero-Thermal Heat Loads

COMPARISON TO MSFC HERITAGE ABL CODE:

A parametric study of cases has been performed to compare the new C&R ABLATERATE subroutine to the empirical recession rate data as well as to the results from the MSFC heritage code ABL. The ultimate indicator of accuracy for these model results is whether the material recession calculations match the test data, since this is the real grounding aspect of this approach. The primary purpose of benchmark comparisons to the MSFC ABL code is to verify that through thickness temperatures and substrate temperature predictions are comparable using the "collapsing" nodal network approach.

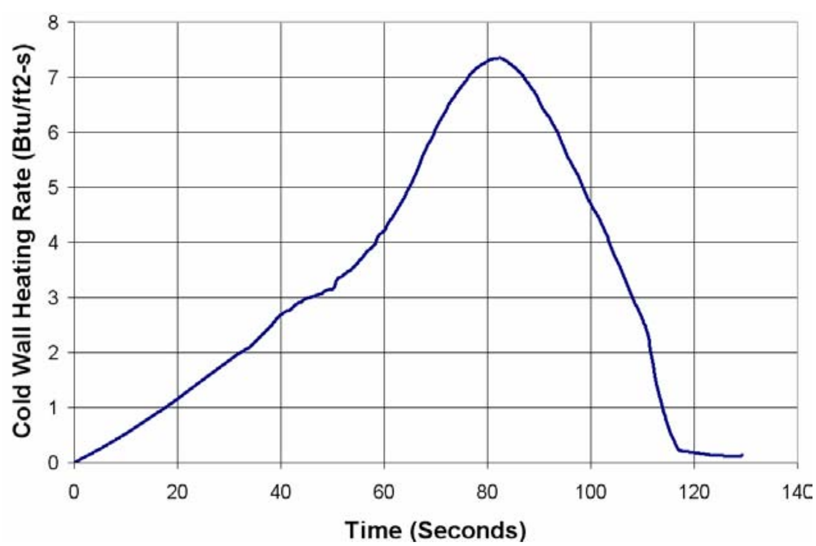


Figure 11: Example Cold Wall Heating Rate Benchmark Case

In order to bracket the TPS cases anticipated for Ares I Upper Stage design, a range of TPS materials and associated ablation temperatures, recession rates, and thermo-physical properties were assessed. Also, a range of material thicknesses and convective heating rates were simulated in ABLATERATE and ABL for comparison. The thicknesses were varied to simulate cases where the substrate is only slightly heated to a case where the TPS is completely ablated. The cases were initialized to 80ºF at TIME=0.0 and utilized typical heating profiles for some current Ares I aerothermodynamic heating environments with scaling as necessary to achieve the desired test case. Figure 11 gives an example heating profile for a timeline consistent with First Stage burn. Other heating profiles representing the full Upper Stage burn were also utilized, which span approximately 9.5 minutes. Table 1 details the parameters that were compared. The matrix of cases and associated results to compare these parameters is shown in Table 2.

Table 1: Benchmarking Comparison Parameters

#	Analysis Result Parameter	Basis of Comparison
1	Time to reach ablation temperature (sec)	% Difference Compared to ABL
2	Ablation duration (sec)	% Difference Compared to ABL
3	Thickness ablated (inch)	% Difference Compared to ABL
4	Percent of original thickness remaining (%)	% Difference Compared to ABL & Manual Recession Calculation
5	Substrate maximum temperature (ºF)	Temperature Difference Compared to ABL

Table 2: Thermal Desktop Benchmark Results

Case	Material	Original Thickness (in)	Peak q_{cw} (Btu/ft^2-s)	Analysis Benchmark Parameter Difference: 1 (% Difference)	2 (% Difference)	3: % Diff Vs ABL	3: Δ (inch)	4 (% Difference): vs. ABL	4 (% Difference): vs. Manual	5 (Temperature Difference) (ºF)
1	BX-265	0.5	8.4	0.0%	6.3%	4.2%	-0.021	4.2%	0.5%	3.6
2	BX-265	0.5	4.3	0.0%	6.1%	2.8%	-0.014	2.8%	1.2%	4.8
3	BX-265	1	7.3	-1.3%	0.0%	2.1%	-0.021	2.1%	0.6%	0.3
4	NCFI-24-124	0.5	8.4	-1.2%	0.0%	1.1%	-0.005	1.1%	0.2%	2.9
5	NCFI-24-124	1	7.3	-1.3%	-3.0%	0.3%	-0.003	0.3%	0.2%	0.5
6	SLA-561	0.5	29.4	-1.1%	0.0%	1.4%	-0.007	1.4%	0.3%	3.1
7	SLA-561	0.3	29.4	-2.2%	-8.7%	1.7%	-0.005	1.7%	0.3%	20.0
8	Cork	0.3	29.4	0.0%	5.7%	-0.3%	0.001	-0.3%	0.4%	3.1
9	Cork	0.3	36.7	0.0%	2.9%	1.9%	-0.006	1.9%	1.4%	25.2
10*	Cork	0.3	58.7	13.6%	N/A	0.0%	0.000	0.0%	N/A	N/A

* Case to analyze full TPS recession to substrate. Total time to burn-through compared for this case.

SUMMARY & CONCLUSIONS:

In summary, applying the new empirical recession methodology for ablation modeling in Thermal Desktop matches the test data and MSFC ABL code very well in predicting the amount of TPS ablation time and the remaining thickness. The maximum substrate temperature compares well for seven of the nine applicable cases. The two cases that differ by 20°F and 25.2°F are for relatively high heating rate cases where a significant amount of TPS has been ablated and the remaining thickness is only 0.10-inch or less. The rate of temperature increase for these sample cases is very high near the end of the simulation, which also tends to magnify the error in the temperature difference. And the final case, which allows the TPS to completely ablate, differs in the time it takes to heat up and burn through by 13.6% between ABL and TD.

The sample cases that didn't compare as favorably are beyond the combination of expected Ares-I Upper Stage aero-thermodynamic heating rates and are hotter than Ares-I substrate allowable temperatures. The cases that are more typical to Upper Stage compared very well. Therefore, the use of Thermal Desktop's new ABLATERATE routine for in-house Ares-I Upper Stage ascent convective aero-thermal heating of TPS appears valid for design sizing. When re-entry, off-nominal or contingency cases representing full TPS ablation are to be analyzed, further comparisons of the substrate response will be needed to ensure accurate, or at least conservative, conclusions.

Due to Environmental Protection Agency regulations, some of the heritage ET/SRB materials are being reformulated for Ares I and will undergo re-qualification testing. Additional validation of the TD analysis methodology will be done as part of this testing.

Future analytical studies of plume impingement areas from solid rocket motor firings or hydrazine thrusters will be performed to determine the viability of the ABLATERATE approach for these very high heat flux, but short duration events. More important than the operation of Thermal Desktop numerically for these environments is the derivation of the proper empirical data to represent the material performance under these unique loading environments.

Additionally, comparisons of ABLATERATE results to the Aerotherm Charring Material Thermal Response and Ablations Program (CMA) code are planned for materials with sufficient property data available.

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