



JOHN F. KENNEDY SPACE CENTER



# Aerotherm Chemical Equilibrium (ACE) and Charring Material Thermal Response and Ablation Programs (CMA) Tutorial

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Virtual NESC Academy Lesson - Thermal Control & Protection Discipline





# ACE/CMA Analysis Introduction



- **Introduction**

- The main thermal design considerations in a solid rocket motor (SRM) nozzle are erosion and char of the insulation liner and the bondline temperature between the liner and overwrap
- The bondline between the liner and overwrap usually has a temperature limit it must not exceed by end of burn (EOB)
- A typical solid rocket motor nozzle is shown on Figure 1
- The ACE/CMA code calculates the thermal erosion and char of the carbon phenolic in the nozzle exit cone at each station and the heat conduction into the aft exit cone which provides bondline temperatures used for requirement validation
- The ACE/CMA model results can be validated by data obtained from a static motor test
- With the validated model, bondline temperature predictions can be made using  $3\sigma$  erosion and char
- Figure 2 shows a typical eroded exit cone, post test, also indicating the location of the char line and bondline



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# Rocket Nozzle



Figure 1: Typical SRM Nozzle



# Static Test

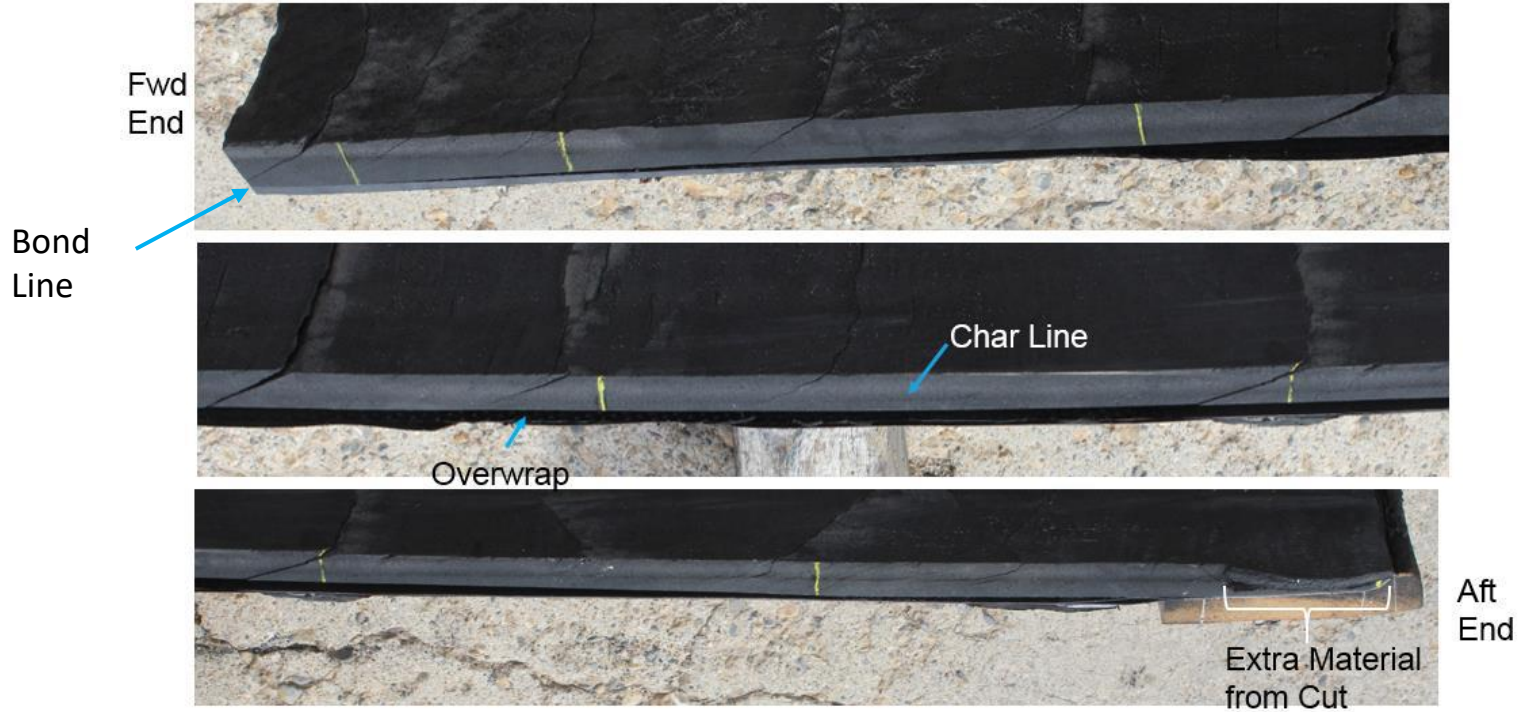


Figure 2: Static Test Motor Aft Exit Cone Post Test



# ACE/CMA Analysis



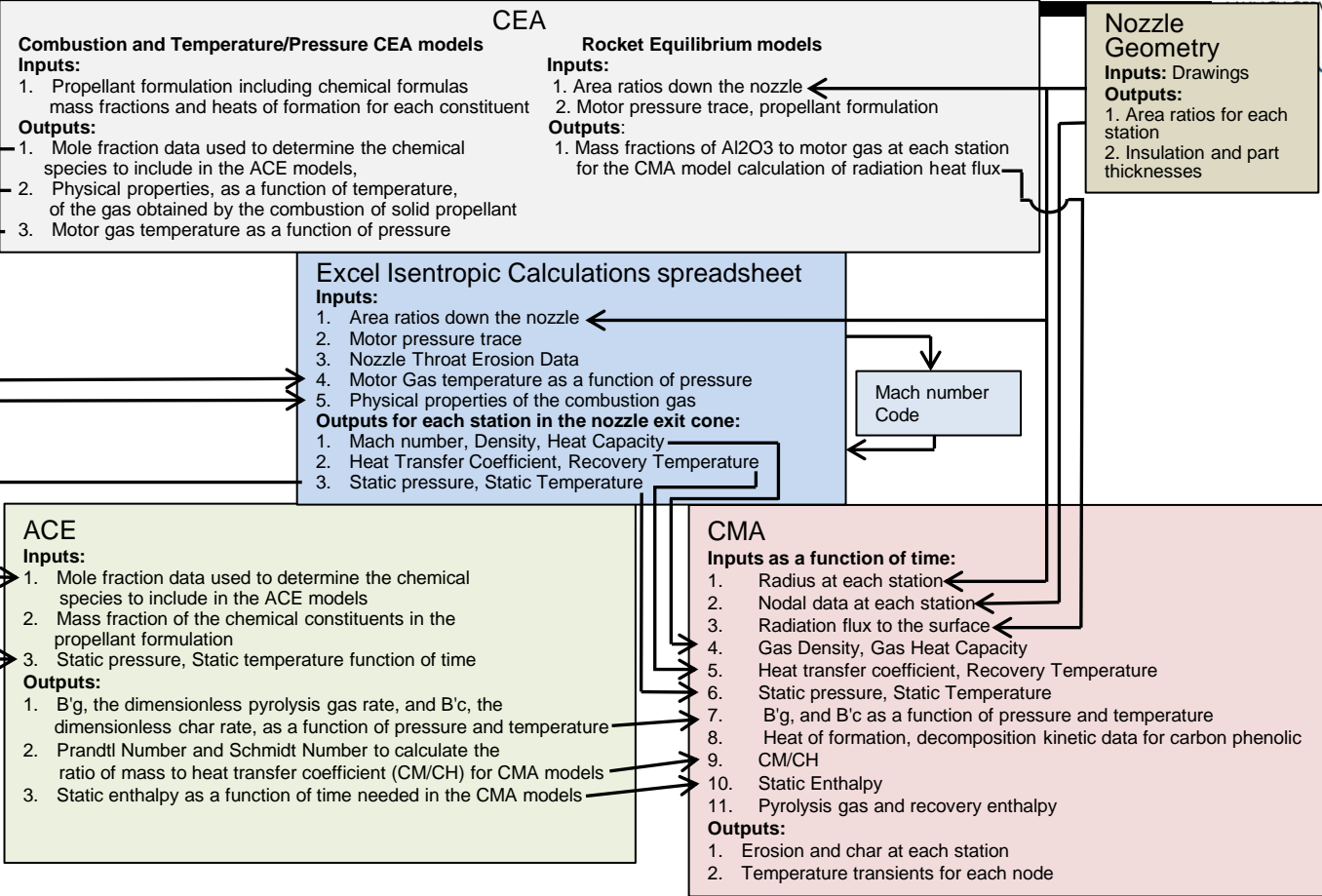
- **ACE/CMA Thermochemistry/Heat Transfer Analysis Overview**

- The procedure is as follows

- » Nozzle geometry provides area ratios for each station and insulation and part thicknesses
- » The propellant gas properties at various temperatures and motor gas temperature as a function of pressure are calculated by using the Chemical Equilibrium and Applications (CEA) code
- » The Mach number, velocity, static pressure and temperature, recovery temperature and finally heat transfer coefficients are calculated with an Excel spreadsheet using 1-D isentropic formulas
- » The Bartz heat transfer coefficient is calculated for each station for each time increment in the burn transient
- » Next, the ACE code calculates the dimensionless pyrolysis gas and char rates for a table of pressures for each station location down the nozzle
- » The ACE code also calculates the static enthalpy for each station for various pressures
- » Finally a CMA deck for each station is created
- » Inputs include the heat transfer coefficient, the recovery enthalpy, the radiation to the surface, decomposition kinetic data, nodal data, material properties of virgin and char, pyrolysis gas enthalpy and surface thermochemistry tables obtained from running the ACE code
- » The average erosion and char for each station and the measured bondline temperature is matched by adjusting the heat transfer coefficient and other variables
- » The  $3\sigma$  erosion is then matched and the required isotherm examined to see if it reaches the bondline by the end of the burn



# Analysis Procedure







# Nozzle Geometry



- **Nozzle Geometry**

- Either an existing CAD drawing of the nozzle is used, or one is created using available information
- Using the drawing, the liner, bondline, overwrap and cork thickness at each station is obtained
- The area ratio at each station and the distance between the stations along the nozzle surface is also obtained
- The drawing is also used to determine how the ply angle changes as you go aft
- This is important later when calculating the thermal conductivity of the liner insulation
- A CAD drawing of a typical nozzle is shown in Figure 3



# Nozzle Geometry

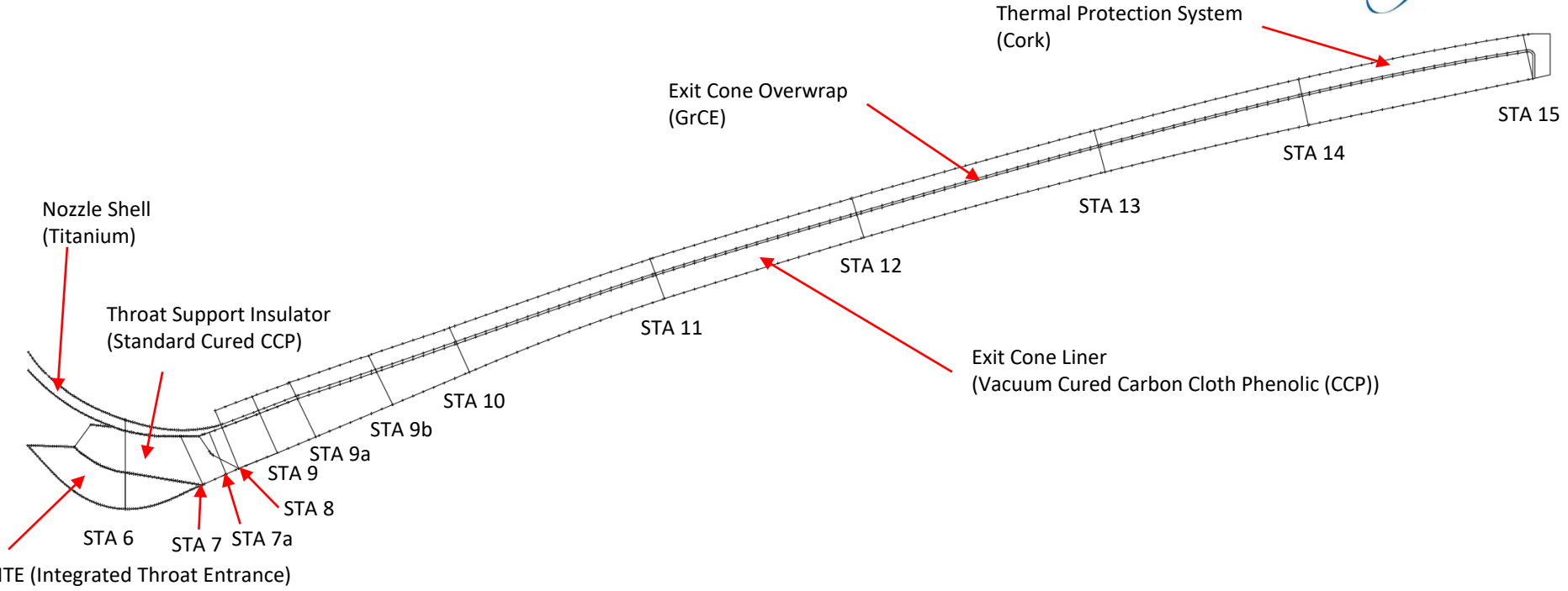


Figure 3: Drawing of a Typical Nozzle Exit Cone showing Station Locations





# CEA Analysis



- **CEA (Chemical Equilibrium and Applications) Models**
  - CEA obtains chemical equilibrium compositions for assigned thermodynamic states and calculates theoretical rocket performance for a finite or infinite area combustion chamber
  - When obtaining chemical equilibrium compositions, these states may be specified by assigning two thermodynamic state functions as follows: temperature and pressure,  $tp$ ; enthalpy and pressure,  $hp$ ; entropy and pressure,  $sp$ ; temperature and volume,  $tv$ ; internal energy and volume,  $uv$ ; and entropy and volume,  $sv$ .
  - To support the ACE/CMA analysis, three types of models are created and run, combustion ( $hp$ ), temperature/pressure ( $tp$ ), and rocket ( $tp$  and  $sp$ )
  - The combustion runs require propellant formulation information, including chemical formulas, mass fractions of the solid propellant and heats of formation for each constituent
    - » A range of pressures, up to 26, one being the Maximum Expected Operating Pressure (MEOP) are included in the input deck
    - » The more typical number of pressures is seven
    - » One of the outputs is motor temperature versus motor pressure which is used with the motor pressure versus time trace to predict the motor temperature versus time which is used in the isentropic flow spreadsheet
    - » The other output is the mole fractions of the chemical species in the combustion gas at MEOP which is converted to mass fractions and used as an input to the Temperature/Pressure model and used to determine the chemical species to include in the ACE model



# CEA Analysis



- **CEA (Chemical Equilibrium and Applications) Models**
  - The temperature/pressure runs required mass fractions of the major components of the chemical species in the combustion gas
    - » A range of temperatures, up to 26, one being the temperature at MEOP are included in the input deck
    - » The more typical number of temperatures is seven
    - » The outputs are physical properties of the gas resulting from the combustion of propellant, as a function of temperature which are used in the isentropic flow spreadsheet
    - » The physical properties include heat capacity, conductivity, Prandtl number, specific heat ratio, and molecular weight as a function of motor temperature
  - The rocket equilibrium CEA model requires the motor pressure, the area ratios down the nozzle and all the inputs required in the combustion model
  - The rocket runs provide the mass fractions of  $\text{Al}_2\text{O}_3$  to motor gas at each station for the radiation flux to the surface calculation used in the CMA models



# Isentropic Spreadsheet



- **Isentropic Calculations Spreadsheet**

- An Excel spreadsheet tool is created to calculate the Mach number, static pressure, static temperature, recovery temperature and the heat transfer coefficient for each station in the nozzle exit cone
- The spreadsheet starts with the motor pressure trace from a test motor
- Thirty time increments are used to describe the transient because that is the limit in CMA
- The motor temperature versus motor pressure from the CEA model run is used with the motor pressure versus time trace to predict the motor temperature versus time
- As mentioned previously, the propellant gas properties, i.e. the heat capacity, conductivity, Prandtl number, specific heat ratio, and molecular weight as a function of motor temperature come from the CEA model run
- The area ratio changes during the firing due to erosion of the nozzle
- Erosion data from the test motor is used, assuming a linear erosion rate, to calculate the area ratio as a function of time at each station in the nozzle



# Iisentropic Spreadsheet



- **Iisentropic Calculations Spreadsheet**

- Since the isentropic Mach number equation has Mach number on both sides of the equation, a FORTRAN code using Newton's method is written to solve for the root
- With the Mach number known, the static pressure and static temperature is calculated using isentropic equations
- With the static temperature and the static pressure, the gas density is calculated
- With the static temperature and the Mach number, the recovery temperature is calculated
- Since the Bartz correlation heat transfer coefficient is widely known in the rocket industry, it is chosen for use in the CMA models
- After calculating the Characteristic Velocity,  $C^*$ , the correction factor for the Bartz correlation is calculated using the Mach number, recovery temperature and other properties
- Lastly, the Bartz correlation heat transfer coefficient is calculated using the radius,  $C^*$ , area ratio, correction factor and other properties
- Spreadsheet equations 1-6 are shown on the next two pages



# Isentropic Equations



$$Ma = \frac{1}{\left(\frac{A}{A^*}\right)} \left( \frac{\left(1 + \frac{\gamma-1}{2} Ma^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}}{\left(\frac{\gamma+1}{2}\right)} \right) \quad \text{Eq.(1):}$$

$$P_s = \frac{P_0}{\left(1 + \frac{\gamma-1}{2} Ma^2\right)^{\frac{\gamma}{\gamma-1}}} \quad \text{Eq.(2):}$$

$$T_s = \frac{T_0}{\left(1 + \frac{\gamma-1}{2} Ma^2\right)} \quad \text{Eq.(3):}$$

$$\rho = \frac{144 P_s}{\left(\frac{R_{univ}}{M_w}\right) T_s} \quad \text{Eq.(4):}$$

$$T_w = T_s \left( 1 + Pr^{1/3} \left( \frac{\gamma-1}{2} \right) Ma^2 \right) \quad \text{Eq.(5):}$$

Where:

$A^*$	= Throat area, in <sup>2</sup>
$A$	= Area at Station, in <sup>2</sup>
$Ma$	= Mach Number
$P_s$	= Static Pressure, lb/in <sup>2</sup>
$Pr$	= Gas Prandtl Number
$T_w$	= Wall or Recovery Temperature, °R
$T_s$	= Static Temperature, °R
$T_0$	= Stagnation Temperature, °R
$\gamma$	= Specific heat ratio
$R_{univ}$	= Universal Gas Constant, 1545.35 Ft-Lbf/Lbmole-°R
$M_w$	= Molecular Weight, Lb/Lbmole



# Bartz Correlation



$$h = \left[ \frac{0.026}{D_{throat}^{0.2}} \left( \frac{\mu_0^{0.2} Cp_0}{Pr_0^{0.6}} \right) \left( \frac{P_0 g}{C^*} \right)^{0.8} \left( \frac{D_{throat}}{r_{curvature}} \right)^{0.1} \left( \frac{A^*}{A} \right)^{0.9} \right] \sigma \quad \text{Eq. (6)}$$

Where,

$$\sigma = \frac{1}{\left[ \frac{1}{2} \left( \frac{T_w}{T_0} \right) \left( 1 + \frac{\gamma-1}{2} Ma^{0.2} \right) + \frac{1}{2} \right]^{0.65} \left[ 1 + \frac{\gamma-1}{2} Ma^{0.2} \right]^{0.15}}$$

and,

$$C^* = \sqrt{\frac{\left( \frac{R_{Univ}}{Mw} \right) T_0 g}{\gamma \left( \frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}}}}$$

Where:

$C_p$	= Gas Heat Capacity, Btu/lb <sup>o</sup> R
$Pr$	= Gas Prandtl Number
$D_{throat}$	= Throat Diameter, in
$\mu_0$	= Gas Viscosity at $T_0$ , Lb <sub>m</sub> /Ft-Sec
$Cp_0$	= Gas Heat Capacity at $T_0$ , Btu/lb <sup>o</sup> R
$Pr_0$	= Gas Prandtl Number at $T_0$
$P_0$	= Stagnation Pressure, Psia
$g$	= Gravitational Constant, 32.2 Lb <sub>m</sub> -Ft/Lb <sub>f</sub> -sec <sup>2</sup>
$r_{curvature}$	= Radius of Curvature, Ft
$A^*$	= Throat area, in <sup>2</sup>
$A$	= Area at Station, in <sup>2</sup>
$T_w$	= Wall or Recovery Temperature, <sup>o</sup> R
$T_0$	= Stagnation Temperature, <sup>o</sup> R
$\gamma$	= Specific heat ratio
$Ma$	= Mach Number
$R_{univ}$	= Universal Gas Constant, 1545.35 Ft-Lb/Lbmole- <sup>o</sup> R
$Mw$	= Molecular Weight, Lb/Lbmole



# ACE Analysis



- **ACE (Aerotherm Chemical Equilibrium) Models**
  - The Aerotherm Chemical Equilibrium (ACE) computer program is used for modeling thermochemical processes
  - The thermochemical processes treated are divided into two categories; closed systems and open systems
    - » Closed systems are those for which the relative amounts of each chemical element in the system are prespecified
    - » Open systems are those for which the relative amounts of each chemical element depend on various mass transfer rates due, for example, to boundary layer convection or solid surface degradation
  - For this application, the code is being used to create boundary layer edge state tables, which are a closed system calculation
  - It is also being used for calculating the thermodynamic state at the surface of an ablating material and outputting that information in a surface thermochemistry table for subsequent input to CMA
  - That is an open system calculation





# ACE Analysis



- **ACE (Aerotherm Chemical Equilibrium) Model Input**

- Elemental Mass Fractions of Propellant

- » The mass fraction of the chemical constituents in the propellant formulation are used to calculate the mass fraction of each element in the edge gas (H, C, N, O, Al, Cl)
- » First the molecular weights of the propellant constituents are calculated
- » With the mass fraction of the chemical constituents in the propellant formulation, the number of moles of each constituent is calculated
- » Then, using the molecular weight of H, C, N, O, Al, and Cl, the mass amount of H, C, N, O, Al, and Cl in each of the chemical constituents in the propellant formulation, is found
- » Then the mass amounts of H, C, N, O, Al, and Cl are summed to arrive at the elemental mass fractions in the propellant formulation and the edge gas
- » However, because according to the CEA model, 32% of the gas stream is liquid aluminum oxide and the aluminum and oxygen to form it came from the propellant, it must be subtracted out
- » The molecular weight of aluminum oxide is calculated and using the mass fraction of liquid aluminum oxide in the gas stream, the moles of  $\text{Al}_2\text{O}_3$  are determined
- » Then, using the molecular weight of Al and O, the mass amount of Al and O is found
- » These amounts of aluminum and oxygen are subtracted from the elemental mass fractions calculated above to arrive at the final elemental mass fractions in the edge gas
- » Pyrolysis gas mass fractions are not available for this analysis, so values from a similar propellant is used
- » The char is assumed to be pure carbon



# ACE Analysis



- **ACE (Aerotherm Chemical Equilibrium) Model Input**
  - Determination of ACE model chemical species
    - » The mole fraction data from the CEA model combustion run is used to determine the chemical species to include in the ACE models
    - » There are 43 species with mole fractions greater than 0.00001 and 195 species with mole fractions less than 0.00001
    - » Of the main 43 species, 9 are not included in the JANNAF table of thermochemical properties, so are not included in the ACE decks
    - » Of the other 195 minor species, 115 are not included in the JANNAF table of thermochemical properties, so are not included in the ACE decks
    - » Eleven species, all aluminum compounds, that are solid or liquid, are taken out of the ACE decks when they caused the code to produce unbelievable results
    - » The species are ordered such that the higher mole fraction species came first in the deck, the manual advises this to make the code run better



# ACE Analysis



- **ACE (Aerotherm Chemical Equilibrium) Model Input**

- A series of six ACE decks, one each for six different times in the motor pressure trace for each station, 7 through 15, are created for a total of 78 decks
  - » Models for six different times allowed a plot of static enthalpy versus time to be created for each station
- Static pressure and static temperatures for each station for the six times needed by the models are obtained from the isentropic flow spreadsheet tool
- To cover the expected temperature range, values of 500 to 4500K, incremented by 500K, totaling nine temperatures, are used to create the boundary layer edge state tables
- A matrix of 15 B'g's and 19 B'c's, shown in Table 1, are used to specify the pyrolysis and char rate tables
- The CMA model limited the pyrolysis gas rates to 15 and the char rates to 24



# ACE Analysis



- **ACE (Aerotherm Chemical Equilibrium) Model Output**
  - For the CMA model, if diffusion coefficients are not equal, or if the ratio  $C_M/C_H$  is not unity, then the surface energy balance requires data about the edge gases of the boundary layer
  - These data are provided by the ACE model in a special ‘edge table’
  - $C_H$  is the heat transfer Stanton number and  $C_M$  is the mass transfer Stanton number
  - Edge gas table
    - » The independent variables for the edge gas table are pressure and temperature
    - » The dependent variables are  $h_{ew}$  and the sum  $\sum_{i=1}^I Z_{i_e}^* h_i^{T_w}$
    - »  $H_{ew}$  is the enthalpy of the gas at the outer edge of the boundary layer and  $\sum_{i=1}^I Z_{i_e}^* h_i^{T_w}$  represents the transport of chemical energy associated with chemical reactions in the boundary layer
  - Table 2 shows a sample of the edge gas enthalpy table for one pressure
  - Each of the 78 decks produce one edge gas enthalpy table for a particular pressure and station location
  - Figure 4 shows a typical plot of  $h_{ew}$  and the sum  $\sum_{i=1}^I Z_{i_e}^* h_i^{T_w}$  versus  $T_w$
  - A plot like this is created for each ACE model to make sure the code is producing reasonable results. This is for station 7



# ACE/CMA Analysis



Table 1: Chosen B'c and B'g

B'c	B'g
0.001	0.001
0.005	
0.01	
0.025	
0.05	0.05
0.1	
0.15	0.15
0.25	0.25
0.3	0.3
0.35	0.35
0.425	0.425
0.5	0.5
0.6	0.6
0.7	0.7
0.8	0.8
0.9	0.9
1.25	1.25
2	2
3	3

Table 2: Sample of Edge Gas Enthalpy Table

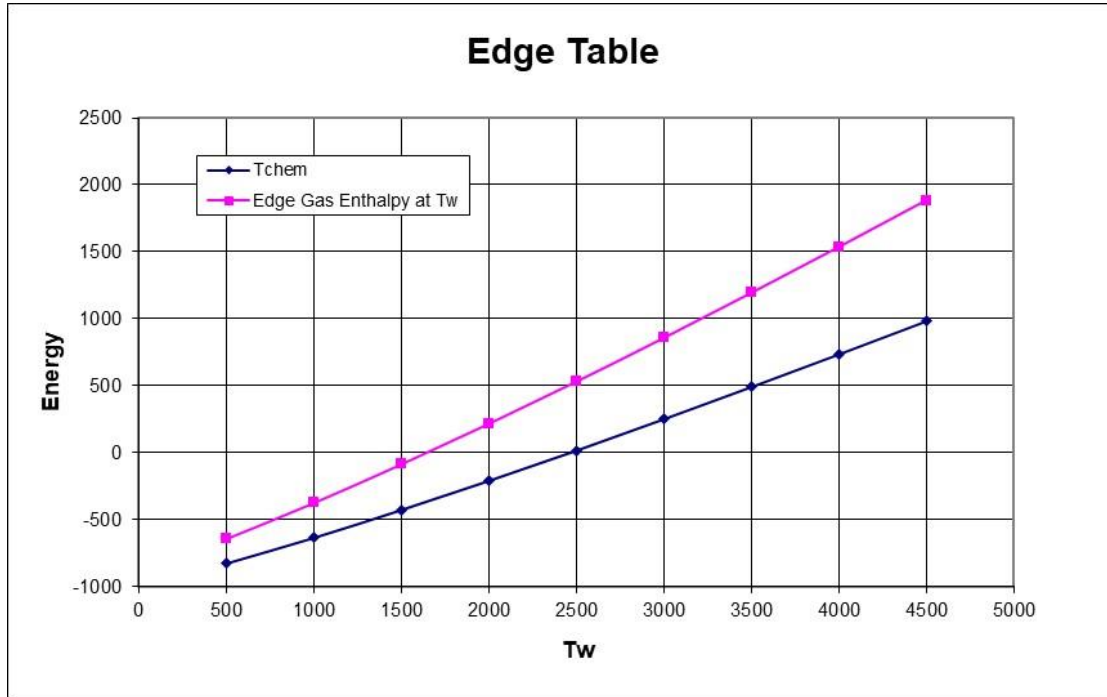
Pressure	B'g	B'c	Surface T <sub>w</sub>	Unequal Diffusion Exponent	$\sum_{i=1}^I Z_{i_e}^* h_i^{T_w}$	H <sub>ew</sub>	Minus Means Edge Table	
31.111	0	0	4500	0.667	1882.708	982.027	-1	CHAR
31.111	0	0	4000	0.667	1534.862	734.62	-1	CHAR
31.111	0	0	3500	0.667	1192.305	490.403	-1	CHAR
31.111	0	0	3000	0.667	856.047	250.007	-1	CHAR
31.111	0	0	2500	0.667	529.371	15.786	-1	CHAR
31.111	0	0	2000	0.667	214.694	-210.404	-1	CHAR
31.111	0	0	1500	0.667	-87.572	-428.165	-1	CHAR
31.111	0	0	1000	0.667	-376.186	-636.295	-1	CHAR
31.111	0	0	500	0.667	-644.949	-828.795	-1	CHAR



# ACE/CMA Analysis



Figure 4:  $h_{ew}$  and the sum  $\sum_{i=1}^I Z_{i_e}^* h_i^{T_w}$  versus  $T_w$





# ACE Analysis



- **ACE (Aerotherm Chemical Equilibrium) Model Output**
  - Table 3 shows a sample of the surface thermochemistry table for one pressure and B'g
  - Each model outputs a table like this for each of the 15 pyrolysis gas rates
  - Surface thermochemistry table
    - » The surface thermochemistry table describes the thermodynamic state at the surface of an ablating material in the form of dimensionless pyrolysis gas rates, B'g, and dimensionless char rates, B'c, as a function of pressure and temperature, normalized with respect to mass transfer coefficients
    - » The table has two subsections
    - » Above the ablation temperature
      - The independent variables are B'c, B'g and pressure
      - The dependent variables are surface temperature,  $h_w$  and the sum  $\sum_{i=1}^I Z_{i_w}^* h_i^{T_w}$
    - » Below the ablation temperature
      - The independent variables are B'g, pressure and temperature
      - The dependent variables are  $h_w$  and the sum  $\sum_{i=1}^I Z_{i_w}^* h_i^{T_w}$
    - »  $H_w$  is the enthalpy of the gas at the wall and  $\sum_{i=1}^I Z_{i_w}^* h_i^{T_w}$  represents the transport of chemical energy associated with chemical reactions at the wall
    - »  $Z_{i_w}^*$  represents the unequal diffusion driving potential for element i and  $h_i^{T_w}$  represents the enthalpy of chemical species i with respect to a base temperature equal to the surface temperature
  - Figure 5 shows a typical plot of B'c versus the sum  $\sum_{i=1}^I Z_{i_w}^* h_i^{T_w}$  for each B'g
  - A plot like this is created for each ACE model to make sure the code is producing reasonable results. This is for station 7





# ACE Analysis



Table 3: Sample of Surface Thermochemistry Table

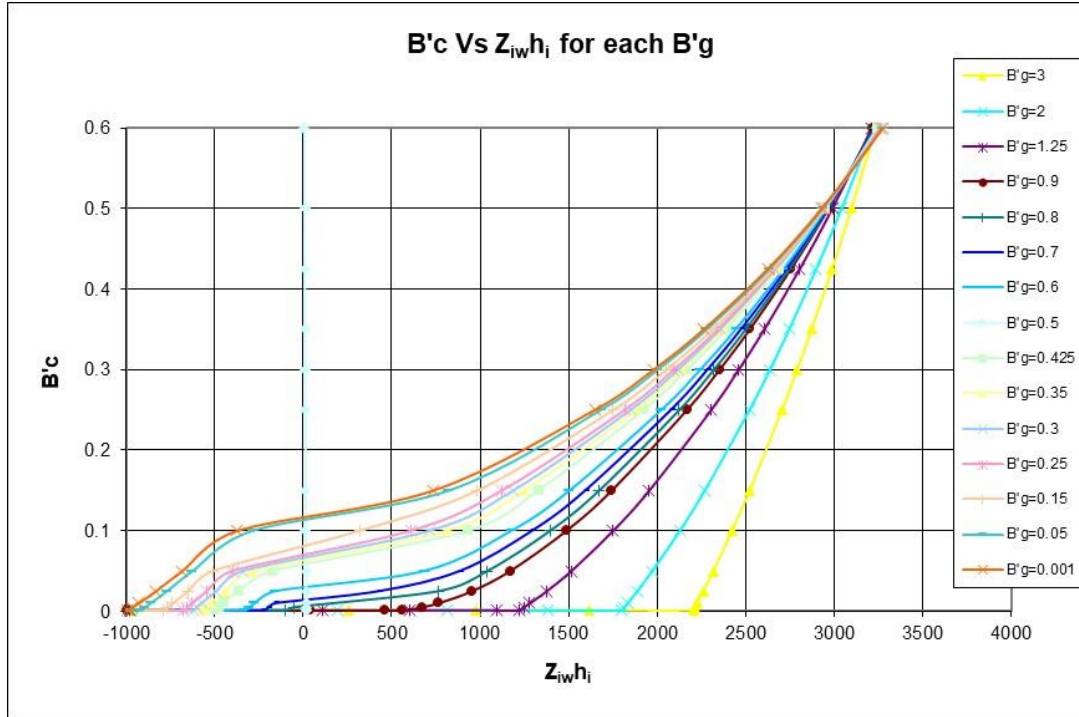
Pressure	B'g	B'c	Surface T <sub>w</sub>	Unequal Diffusion Exponent	$\sum_{i=1}^I Z_{i_w}^* h_i^{T_w}$	H <sub>ew</sub>	Plus Means Surface Thermochemistry Table
31.111	3	3	3930.0905	0.667	5072.719	3830.56	1C*
31.111	3	2	3783.6758	0.667	4533.696	3239.576	1C*
31.111	3	1.25	3609.3656	0.667	3951.666	2657.762	1C*
31.111	3	0.9	3493.9036	0.667	3598.681	2328.036	1C*
31.111	3	0.8	3454.8023	0.667	3484.882	2224.899	1C*
31.111	3	0.7	3412.2031	0.667	3364.229	2117.092	1C*
31.111	3	0.6	3365.4812	0.667	3235.872	2004.075	1C*
31.111	3	0.5	3313.7988	0.667	3098.784	1885.179	1C*
31.111	3	0.425	3271.1068	0.667	2989.402	1791.615	1C*
31.111	3	0.35	3224.3284	0.667	2873.561	1693.747	1C*
31.111	3	0.3	3190.4442	0.667	2792.253	1625.794	1C*
31.111	3	0.25	3154.0096	0.667	2707.254	1555.398	1C*
31.111	3	0.15	3071.5928	0.667	2524.087	1405.932	1C*
31.111	3	0.1	3024.2624	0.667	2424.472	1325.931	1C*
31.111	3	0.05	2971.5139	0.667	2318.087	1241.509	1C*
31.111	3	0.025	2942.643	0.667	2261.88	1197.335	1C*
31.111	3	0.01	2924.4019	0.667	2227.083	1170.131	1C*
31.111	3	0.005	2918.1764	0.667	2215.328	1160.957	1C*
31.111	3	0.001	2913.086	0.667	2205.771	1153.526	1C*
31.111	3	0.001	2500	0.667	1615.23	807.708	0CHAR
31.111	3	0.001	2000	0.667	972.208	376.651	0CHAR
31.111	3	0.001	1500	0.667	254.116	-144.93	0CHAR
31.111	3	0.001	1000	0.667	-963.288	-1090.71	0CHAR
31.111	3	0.001	500	0.667	-1621.502	-1633.12	0CHAR



# ACE Analysis



Figure 5: B'c versus  $\sum_{i=1}^I Z_{i_w}^* h_i^{T_w}$  for each B'g





# ACE Analysis



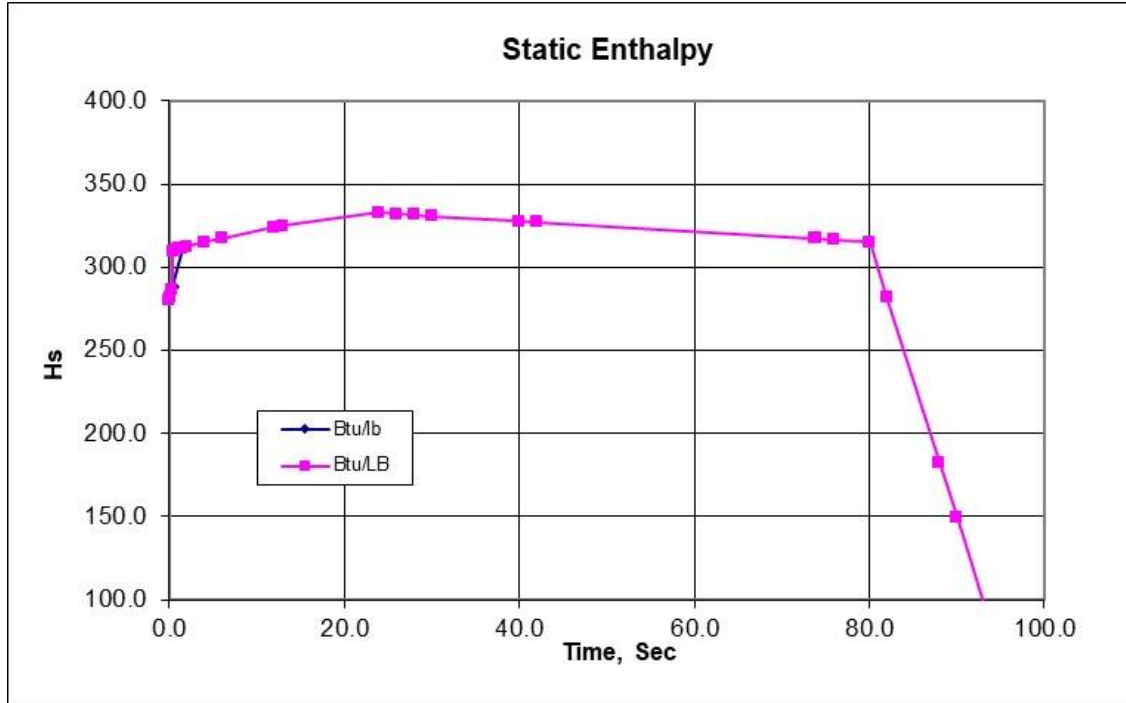
- **ACE (Aerotherm Chemical Equilibrium) Model Output**
  - For each model, the static enthalpy as a function of time is obtained
  - The static enthalpy is used in the calculation of the recovery enthalpy which is needed in the CMA models
  - Running models for six different times allowed a plot of static enthalpy versus time to be created for each station
  - Shown in Figure 6, this is curve fit for use in the CMA models
  - The ratio of mass to heat transfer coefficient ( $C_M/C_H$ ) needed in the CMA models is obtained from the Prandtl Number and Schmidt Number which both come from the ACE output



# ACE Analysis



Figure 6: Static Enthalpy





# CMA Analysis



- **CMA (Charring and Material Ablation) Models**

- The CMA models are run to calculate predicted erosion of the carbon phenolic in the nozzle during the firing
- Description and Features of the Code
  - » The CMA code is an implicit, finite-difference computational procedure for computing the one-dimensional transient transport of thermal energy in a three-dimensional isotropic material which can ablate from a front surface and which can decompose in-depth
  - » Decomposition reactions are based on a three-component model
  - » The program permits up to eight different back-up materials of arbitrary thickness, five of which can decompose
  - » The back wall of the composite material may transfer energy by convection and radiation
  - » The ablating surface boundary conditions may take one of three forms
    - Option 1: General convection-radiation heating with coupled mass transfer, using a transfer coefficient approach, including the effects of unequal heat and mass transfer coefficients and unequal diffusion coefficients
    - Option 2: Specified surface temperature and surface recession rate
    - Option 3: Specified radiation view factor and incident radiation flux, as functions of time, for a stationary surface
  - » Any combination of options may be used for a single computation
  - » Option 3 is appropriate to cool down after termination of convective or radiative heat input and is often useful in conjunction with Options 1 and 2



# CMA Analysis



- **CMA (Charring and Material Ablation) Model Input**

- The models required heat of formation of carbon phenolic, radius at each station, decomposition kinetic data for carbon phenolic, nodal data at each station, pyrolysis gas enthalpy, and recovery enthalpy, radiation flux to the surface, heat transfer coefficient and static pressure at each station as a function of time
- Also required are density, heat capacity, and thermal conductivity for standard and vacuum cured carbon cloth phenolic, graphite epoxy overwrap, titanium alloy, adhesive and cork as a function of temperature, if possible
- As mentioned before, the CMA models also required the B'g and B'c tables, and the ratio of mass to heat transfer coefficient from the ACE models
- The heat of formation of standard and vacuum cured carbon cloth phenolic used is the same as the Shuttle RSRM motor CCP
- The radius at each station is obtained from the nozzle CAD drawing
- Table 8 shows how the various materials are divided into individual nodes in the CMA model
- The different colors correspond to different materials
- “1” signifies the ablating material in CMA, the other numbers indicate to the model which material the node is made of
- The code limits the number of nodes to fifty



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# CMA Analysis



NODAL DATA														
Number	Station 6	Station 7	Station 7a	Station 8	Station 9	Station 9a	Station 9b	Station 10	Station 11	Station 12	Station 13	Station 14	Station 15	
1	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	
2	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	
3	0.0040	0.0040	0.0040	0.0040	0.0040	0.0040	0.0040	0.0040	0.0040	0.0040	0.0040	0.0040	0.0040	
4	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	
5	0.0080	0.0080	0.0080	0.0080	0.0080	0.0080	0.0080	0.0080	0.0080	0.0080	0.0080	0.0080	0.0080	
6	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	0.0100	
7	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120	
8	0.0140	0.0140	0.0140	0.0140	0.0140	0.0140	0.0140	0.0140	0.0140	0.0140	0.0140	0.0140	0.0140	
9	0.0160	0.0160	0.0160	0.0160	0.0160	0.0160	0.0160	0.0160	0.0160	0.0160	0.0160	0.0160	0.0160	
10	0.0180	0.0180	0.0180	0.0180	0.0180	0.0180	0.0180	0.0180	0.0180	0.0180	0.0180	0.0180	0.0180	
11	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200	
12	0.0300	0.0300	0.0300	0.0300	0.0300	0.0300	0.0300	0.0300	0.0300	0.0300	0.0300	0.0300	0.0300	
13	0.0400	0.0400	0.0400	0.0400	0.0400	0.0400	0.0400	0.0400	0.0400	0.0400	0.0400	0.0400	0.0400	
14	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	0.0500	
15	0.0600	0.0600	0.0600	0.0600	0.0600	0.0600	0.0600	0.0600	0.0600	0.0600	0.0600	0.0600	0.0600	
16	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	0.0700	
17	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	0.0800	
18	0.0900	0.0900	0.0900	0.0900	0.0900	0.0900	0.0900	0.0900	0.0900	0.0900	0.0900	0.0900	0.0900	
19	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	
20	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	
21	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	
22	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	
23	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.0800	0.0800	0.0900	0.1000	0.1000	
24	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.0600	0.0600	0.0800	0.1000	0.0800	
25	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.0500	0.0400	0.0600	0.1000	0.0700	
26	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.0800	0.0400	0.0200	0.0400	0.0800	0.0600	
27	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.0600	0.0200	0.0090	0.0200	0.0600	0.0400	
28	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.0400	0.0190	0.0125	0.0070	0.0400	0.0200	
29	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.0800	0.0400	0.0125	0.0125	0.0140	0.0120	
30	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.1000	0.0600	0.0200	0.0125	0.0500	0.0125	0.0125	
31	0.0221	0.1000	0.1000	0.1000	0.1000	0.0900	0.0400	0.0150	0.0500	0.0500	0.0500	0.0125	0.0125	
32	0.2000	0.1000	0.1000	0.1000	0.1000	0.0800	0.0200	0.0125	0.0500	0.3650	0.0500	0.0500	0.0500	
33	0.2000	0.1000	0.0800	0.0800	0.0600	0.0600	0.0140	0.0125	0.3650	0.3650	0.3650	0.0500	0.0500	
34	0.2000	0.1000	0.0600	0.0600	0.0400	0.0400	0.0125	0.0583	0.3650	0.3650	0.3650	0.3650	0.3650	
35	0.2000	0.1000	0.0400	0.0300	0.0200	0.0200	0.0125	0.0583				0.3650	0.3650	
36	0.2000	0.1000	0.0160	0.0140	0.0110	0.0140	0.0667	0.3650						
37	0.2000	0.0800	0.0125	0.0125	0.0125	0.0125	0.0667	0.3650						
38	0.2000	0.0600	0.0125	0.0125	0.0125	0.0125	0.3650							
39	0.2000	0.0400					0.3650							
40	0.2000	0.0300	0.1130	0.0734	0.0750	0.0750								
41	0.1991	0.0230	0.4000	0.3900	0.3650	0.3650								
42	0.0125	0.0125	0.4000	0.3900	0.3650	0.3650								
43	0.0125	0.0125												
44	0.2619	0.1607												
45	0.2619	0.1607												
46	0.4104	0.4430												
47	0.4104	0.4430												

Table 4: Nodal Data

- 1 Green carbon carbon for station 6
- 1 Blue SC carbon phenolic 30° ply angle for station 7, 7a
- 1 Purple VC carbon phenolic 4° ply angle for stations 8 and greater
- 4 Grey titanium
- 5 Orange glass overwrap
- 6 Yellow adhesive
- 7 Black cork

Note "1" signifies the ablating material in CMA





# CMA Analysis



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## • CMA (Charring and Material Ablation) Model Input

### – Decomposition kinetics

- » Since many decomposing char-forming materials appear to behave as three independently pyrolyzing components, the program uses a three-component decomposition model for the main material and for any decomposing back-up materials
- » The resin filler is presumed to consist of two components which decompose separately, while the reinforcing material is the third component which can decompose. The instantaneous density of the composite is given by:

$$\rho = \Gamma(\rho_A + \rho_B) + (1 - \Gamma)\rho_C \quad \text{Eq. (7)}$$

Where:

$\Gamma$  = Resin volume fraction

$\rho_A, \rho_B$  = Density of resin filler,

$\rho_C$  = Density of reinforcing material

- » Each of the three components can decompose following the relation:

$$\left(\frac{\partial \rho}{\partial \theta}\right)_y = -B_i \exp\left(\frac{-E_{a_i}}{RT}\right) \rho_{o_i} \left(\frac{\rho_i - \rho_{r_i}}{\rho_{o_i}}\right)^{\phi_i} \quad \text{Eq. (8)}$$

Where:

$\rho_{r_i}$  = Residual density of component i,

$\rho_{o_i}$  = Initial density of component i,

$B_i$  = Pre-exponential factor,

$E_{a_i}$  = Activation energy,

$\phi_i$  = Decomposition reaction order



# CMA Analysis



## • CMA (Charring and Material Ablation) Model Input

- » The decomposition kinetic data for standard and vacuum cured carbon cloth phenolic is needed for the model
- » This includes the pre-exponential factor, B, for reactions A, B and C (1/Sec), density factor exponent,  $\phi$ , for reaction A, B and C, activation energy factor, E/R, for reaction A and B ( $^{\circ}$ R) and minimum reaction temperature for reaction A, B and C ( $^{\circ}$ R)
- » The activation energy factor, E/R, for reaction C is obtained from RSRM CCP
- » The virgin and char density for standard cured CCP is available for this analysis, however the initial and residual density of component i for reaction A, B and C ( $\text{Lb}/\text{Ft}^3$ ) is not
- » The CMA manual (Ref. 4) had a example problem using carbon phenolic in a rocket nozzle with reactions A, B and C
  - The example CCP had a virgin and char density of 89.8425 and 73.0755  $\text{Lb}/\text{Ft}^3$  with a resin content of 0.345  $\text{Lb}/\text{Ft}^3$
  - The standard cured carbon cloth phenolic had a virgin and char density of 93.01 and 75.35  $\text{Lb}/\text{Ft}^3$  and an unknown resin content
  - The decision is made to use the virgin and char resin densities of the example problem for the A and B reactions and increase the density of the reinforcing material of the example problem (94.5  $\text{Lb}/\text{Ft}^3$ ) to account for the greater density of standard cured CCP
  - The resin content of the example problem CCP would also need to be lowered slightly to help increase the overall density
  - Using equation 7, a reinforcing material virgin density of 99.0  $\text{Lb}/\text{Ft}^3$  and a resin content of 0.333 is determined
  - Using equation 7 and a resin content of 0.333, a reinforcing material char density of 96.8  $\text{Lb}/\text{Ft}^3$  is determined



# CMA Analysis



- **CMA (Charring and Material Ablation) Model Input**

- » The virgin and char density for vacuum cured carbon cloth phenolic is available, however the initial and residual density of component  $i$  for reaction A, B and C ( $\text{Lb}/\text{Ft}^3$ ) is not
- » The virgin and char density for vacuum cured CCP is 78% of the virgin and char density for standard cured CCP
- » To obtain the initial and residual density of component  $i$  for reaction A, B and C ( $\text{Lb}/\text{Ft}^3$ ) for vacuum cured CCP the values for standard cured CCP are multiplied by 0.78
- » This results in a resin content of 0.351 by use of equation 7
- » Table 5 shows the results for the decomposition kinetic data



# CMA Analysis



Table 5: Decomposition Kinetic Data

DECOMPOSITION KINETIC DATA		
MX4926N Carbon Phenolic		
Standard	Vacuum Cure	
75.35	58.932	CHAR DENSITY
93.01	72.292	VIRGIN DENSITY
0.333	0.351	RESIN CONTENT
20.2500	15.7950	INITIAL DENSITY OF COMPONENT i FOR REACTION A (LB/FT3)
0.0000	0.0000	RESIDUAL DENSITY OF COMPONENT i FOR REACTION A (LB/FT3)
5.0120E+21	5.0120E+21	PRE-EXPONENTIAL FACTOR, B, FOR REACTION A (1/SEC)
4.3000	4.3000	DENSITY FACTOR EXPONENT, $\psi$ , FOR REACTION A
52620.0000	52620.0000	ACTIVATION ENERGY FACTOR, E/R, FOR REACTION A (DEG RANKINE)
671.6000	671.6000	MINIMUM REACTION TEMPERATURE FOR REACTION A (DEG RANKINE)
60.7500	47.3850	INITIAL DENSITY OF COMPONENT i FOR REACTION B (LB/FT3)
32.4000	25.2720	RESIDUAL DENSITY OF COMPONENT i FOR REACTION B (LB/FT3)
1.2590E+07	1.2590E+07	PRE-EXPONENTIAL FACTOR, B, FOR REACTION B (1/SEC)
3.1800	3.1800	DENSITY FACTOR EXPONENT, $\psi$ , FOR REACTION B
27240.0000	27240.0000	ACTIVATION ENERGY FACTOR, E/R, FOR REACTION B (DEG RANKINE)
671.6000	671.6000	MINIMUM REACTION TEMPERATURE FOR REACTION B (DEG RANKINE)
99.0000	77.2200	INITIAL DENSITY OF COMPONENT i FOR REACTION C (LB/FT3)
96.8000	75.5040	RESIDUAL DENSITY OF COMPONENT i REACTION C (LB/FT3)
4.6470E+16	4.6470E+16	PRE-EXPONENTIAL FACTOR, B, FOR REACTION C (1/SEC)
4.5000	4.5000	DENSITY FACTOR EXPONENT, $\psi$ , FOR REACTION C
34800.0000	34800.0000	ACTIVATION ENERGY FACTOR, E/R, FOR REACTION C (DEG RANKINE)
671.6000	671.6000	MINIMUM REACTION TEMPERATURE FOR REACTION C (DEG RANKINE)



# CMA Analysis



- **CMA (Charring and Material Ablation) Model Input**

- Material Properties

- » With and across ply thermal conductivity, density, and heat capacity for standard and vacuum cured carbon cloth phenolic, graphite epoxy overwrap, titanium alloy, adhesive and cork as a function of temperature are obtained
- » For this model, carbon phenolic thermal conductivity is a function of ply angle
- » The ply angle and the inner flame surface x,y points from the CAD drawing are used to calculate the ply angle at each station
- » With the ply angle and the with and across ply thermal conductivity, Equation 9 is used to calculate the thermal conductivity for each station

$$K = C \times K_0 \left\{ 1 + \left[ \left( \frac{K_{90}}{K_0} \right) - 1 \right] \left[ (\sin \Theta)^n \right] \right\} \quad \text{Eq. (9)}$$

where,

K = through thickness conductivity

C = conductivity multiplier

K<sub>0</sub> = cross-ply conductivity

K<sub>90</sub> = with-ply conductivity

n = power law exponent, 1.0 used for original Aerotherm model, 2.0 used for more conventional angle dependence.

θ = angle between plies and surface in radians



# CMA Analysis



- **CMA (Charring and Material Ablation) Model Input**

- The pyrolysis gas enthalpy for standard and vacuum cured carbon cloth phenolic is obtained from references
- Surface boundary conditions
  - » Table 6 shows the surface boundary conditions
    - To calculate the recovery enthalpy, the motor gas heat capacity, static and recovery temperature, needed, comes from the isentropic flow spreadsheet tool and the static enthalpy as a function of time comes from the ACE model
    - To calculate the radiation flux to the surface, static temperature and the motor gas density, needed, comes from the isentropic flow spreadsheet tool
    - The Bartz correlation heat transfer coefficient needed to calculate the Stanton number and the static pressure also come from the spreadsheet tool
    - The code allows a maximum of 30 entries
  - » The recovery enthalpy is obtained from this equation:

$$H_r - H_s = C_p (T_r - T_s) \quad \text{Eq. (10)}$$

where,

- $H_r$  = Recovery enthalpy
- $H_s$  = Static enthalpy
- $C_p$  = Motor gas Heat Capacity
- $T_r$  = Recovery temperature
- $T_s$  = Static temperature



# CMA Analysis



## • CMA (Charring and Material Ablation) Model Input

- » The radiation flux to the surface is calculated by:

$$\frac{Q}{A} = \sigma \epsilon_g T_g^4 \quad \text{Eq. 11)}$$

Where:

$\sigma$  = Stefan-Boltzmann Constant

$\epsilon_g$  = Gas emissivity

$T_g$  = Static gas temperature

- » The gas emissivity is calculated from eq. 17-143 from Siegel and Howell Ref.(5):

$$\epsilon = 1 - \frac{1}{\left[ 1 + \left( \frac{kCS}{C_2} \right) T \right]^4} \quad \text{Eq. (12)}$$

Where:

k = Experimental constant (0.05)

C = Average volume of particles per unit volume of cloud

S = Mean path length (nozzle diameter at station location)

$C_2$  = Constant in Planck's spectral energy distribution (1.4388 cmK)

T = Particle temperature (static temperature)

- The C variable uses the grams of  $\text{Al}_2\text{O}_3$  to grams of motor gas ratio from the CEA runs multiplied by the gas density and divided by the  $\text{Al}_2\text{O}_3$  density to arrive at the average volume of particles per unit volume of cloud





# CMA Analysis



Table 6: Surface Boundary Conditions

Time	Motor Gas Heat Capacity, Cp	Recovery Temperature	Static Temperature	Static Temperature	Static Enthalpy from ACE	Recovery Enthalpy	Density	Density	Emissivity	Radiation to the Surface	Bartz corellation h	Stanton Number	Static Pressure	Static Pressure
SEC	Btu/Lbm-R	R	R	K	Btu/LB	Btu/Lb	Lb/Ft3	Gr/Cm3	Siegel And Howell Equation (17-143)	Btu/ft2-sec	Btu/Ft2-sec-R	Lb/ft2-sec	Lbf/In2	Atm
0.0	0.198414548	546.2583275	420.0190664	233.3439258	279.8181818	304.8659	0.020848584	3.33962E-04	0.037079455	0.0005	0.006009677	0.0303	3.054292855	0.2078
0.1	0.494137872	5678.096978	4908.141597	2726.745332	281.9336364	662.3977	0.009930127	1.59065E-04	0.186089092	51.4159	0.053560594	0.1084	17.39311574	1.1835
0.3	0.491953384	6126.04717	5306.371413	2947.984118	286.1645455	689.4068	0.095905062	1.53625E-03	0.827449086	312.3491	0.345838813	0.7030	184.7177957	12.5693
0.400	0.491618315	6147.711474	5325.665841	2958.703245	309.9615409	714.0942	0.107106932	1.71569E-03	0.854173122	327.1522	0.378655302	0.7702	207.2579104	14.1031
0.7	0.491233288	6170.822854	5346.467692	2970.259829	310.3998694	715.3506	0.120521875	1.93058E-03	0.87981241	342.2679	0.4171114725	0.8491	234.3916558	15.9494
0.8	0.491019436	6182.957052	5357.456708	2976.364838	310.5451269	715.8818	0.128232465	2.05409E-03	0.892048614	349.8900	0.438807726	0.8937	250.0501991	17.0149
1.1	0.489961346	6236.927517	5405.67667	3003.153706	310.978343	718.2591	0.168994142	2.70703E-03	0.936247669	380.6268	0.550191033	1.1229	333.4232277	22.6881
1.2	0.489898899	6239.863743	5408.324809	3004.624894	311.1218963	718.4919	0.171555037	2.74805E-03	0.938195529	382.1665	0.557038038	1.1370	338.6940275	23.0468
1.5	0.489826673	6243.297727	5411.698924	3006.499402	311.55	718.8893	0.174610907	2.79700E-03	0.940430039	384.0337	0.565099949	1.1537	345.0035075	23.4761
2.0	0.489840203	6242.823809	5411.894354	3006.607975	312.2549855	719.2776	0.17421253	2.79062E-03	0.940158549	383.9783	0.563900361	1.1512	344.2173321	23.4226
4.0	0.489863285	6242.316635	5413.728766	3007.627092	314.968419	720.8632	0.173852448	2.78485E-03	0.939948966	384.4135	0.562489243	1.1483	343.6028748	23.3808
6.0	0.489806009	6245.535359	5418.894114	3010.49673	317.5114388	722.4053	0.176834214	2.83261E-03	0.942097669	386.7648	0.569905726	1.1635	349.878678	23.8078
12.0	0.489537679	6259.344357	5437.851645	3021.028692	324.1180162	726.2697	0.190073512	3.04469E-03	0.950515931	395.7101	0.603272446	1.2323	377.6345107	25.6965
13.0	0.489520867	6260.414111	5440.104839	3022.280466	325.0700005	726.6285	0.191172642	3.06229E-03	0.951158993	396.6345	0.605771428	1.2375	379.9909063	25.8569
24.0	0.489707879	6255.052684	5447.711962	3026.506646	332.7300016	728.0911	0.186512189	2.98764E-03	0.94870209	397.8274	0.591031802	1.2069	371.0785228	25.2504
26.0	0.489945775	6244.366321	5439.503637	3021.946465	329.1071429	726.4462	0.176648057	2.82963E-03	0.94242062	392.8169	0.564395803	1.1531	350.7188041	23.8650
28.0	0.490284618	6228.073791	5425.071253	3013.928474	331.4842858	725.1841	0.162542245	2.60368E-03	0.931644695	384.2204	0.527621426	1.0762	321.5821061	21.8824
30.0	0.490492405	6217.68683	5415.897462	3008.831923	330.8614286	724.1330	0.154148705	2.46923E-03	0.924042667	378.5141	0.505122282	1.0298	304.2965415	20.7062
40.0	0.491155572	6182.193059	5384.816599	2991.564777	327.7471429	719.3830	0.128634608	2.06053E-03	0.89355737	357.6963	0.435158188	0.8860	252.0193113	17.1489
42.0	0.491217181	6178.688843	5381.771783	2989.873213	327.1242858	718.5836	0.126359636	2.02409E-03	0.890160853	355.5314	0.428790032	0.8729	247.3790348	16.8332
73.7	0.491210868	6179.405578	5383.853282	2991.029601	315.2520001	708.0359	0.126867731	2.03223E-03	0.890979027	356.4090	0.429378353	0.8741	248.474277	16.9077
74.0	0.491226009	6178.530318	5383.056283	2990.586824	317.1585715	707.9161	0.126302493	2.02317E-03	0.890121014	355.8550	0.427815476	0.8709	247.3199644	16.8291
76.0	0.491338755	6172.033241	5377.546925	2987.52607	316.5357144	706.8976	0.122197728	1.95742E-03	0.883647989	351.8232	0.416235844	0.8471	238.9599579	16.2603
80.0	0.491435238	6166.33913	5372.635469	2984.797483	315.2900001	705.3439	0.118708518	1.90153E-03	0.877769617	348.2077	0.406369601	0.8269	231.8595854	15.7771
82.0	0.491624052	6154.809557	5362.44904	2979.138356	282.1466664	671.6902	0.111940964	1.79312E-03	0.865278692	340.6568	0.387215593	0.7876	218.1043555	14.8411
88.0	0.49431359	5777.62282	5024.068113	2791.148952	182.7166664	555.2090	0.016569874	2.65442E-04	0.2921634	88.6250	0.080552623	0.1630	29.79399745	2.0274
90.0	0.493399115	5542.697567	4812.021298	2673.345165	149.573333	510.0884	0.005080174	8.13766E-05	0.09931595	25.3535	0.030412533	0.0816	8.690752919	0.5914
94.0	0.485304768	4878.044905	4210.544661	2339.191478	83.28666635	407.2277	0.000182113	2.91717E-06	0.003317388	0.4964	0.001937796	0.0040	0.269735855	0.0184



# CMA Analysis



- **CMA Model Results**

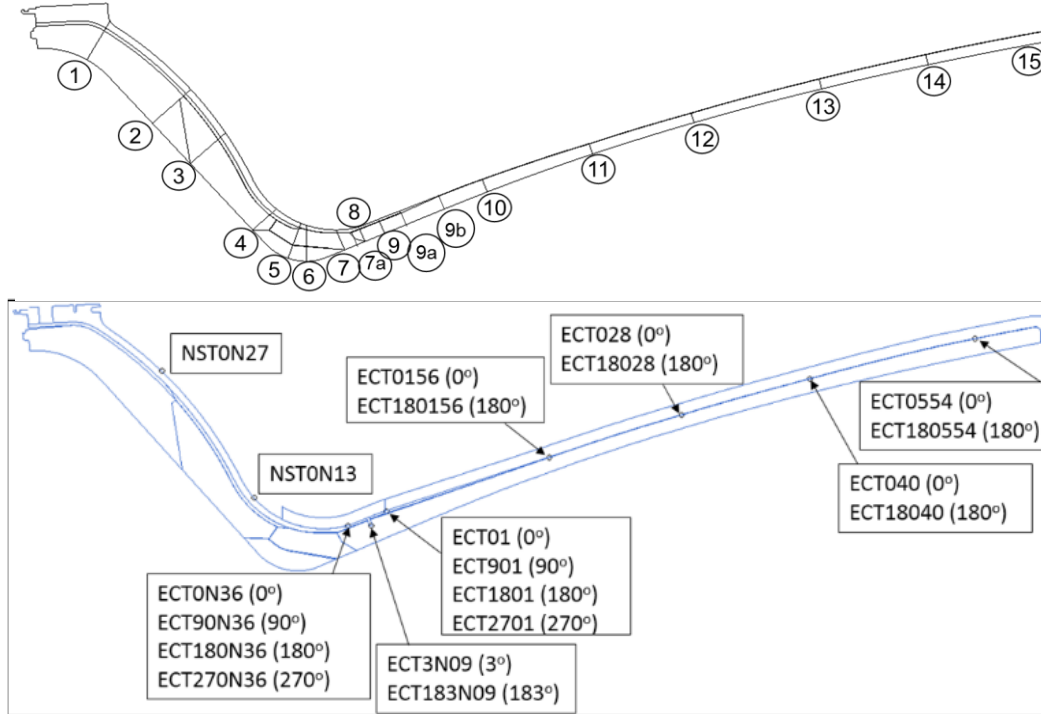
- The first step is to validate the model by matching the thermocouple response, erosion and char data from a static motor
- The static motor used was instrumented with 20 thermocouples
- Figure 36 shows thermocouple locations in relation to station locations
- If the figures are overlaid it shows:
  - » ECT0N36, ECT90N36, ECT180N36 and ECT270N36 are located at station 8
  - » ECT3N09 and ECT183N09 are located at station 9
  - » ECT01 and ECT2701 are located at station 9a
  - » ECT028 and ECT18028 are located at station 12
  - » ECT040 and ECT18040 are located at station 13
- Station 9 is at the location of the spring pin where the insulation is thinner, resulting in the quicker rise rate shown in Figure 9



# CMA Analysis



Figure 7: Thermocouple locations in relation to station locations





# CMA Analysis



- **CMA Model Results**

- Post fire Measurements

- » To evaluate the erosion and char condition in the nozzle ablatives, the nozzle exit cone liner is sectioned at 0°, 20°, 60°, 100°, 140°, 180°, 220°, 260°, and 300°, 340° azimuths
    - » Both the erosion and char are measured from either the nozzle shell metal or the overwrap, depending on the station location.
    - » Erosion is calculated by subtracting the eroded thickness from the nominal thickness
    - » Char is calculated as the nominal thickness of the nozzle minus the remaining virgin material
    - » Char thickness is calculated as the eroded thickness minus the remaining virgin material
    - » Digital char and erosion data for stations 3-15 was made available for analysis in the form of a spreadsheet
    - » The data from each angular location on either side of the cut is used to calculate the average and standard deviation for each axial station location that is then used to calculate the  $3\sigma$  char and erosion at each station



# CMA Analysis



## • CMA Model Results

- Six variables were chosen to be adjusted to facilitate data matching:
  - » The heat transfer coefficient multiplying factor
    - Increasing the heat flux usually increases the erosion the most, speeds up the thermocouple response, with a lesser effect on char depth
  - » The CM/CH, the ratio of mass to heat transfer coefficients
    - Raising this gives you more erosion for the same amount of heat flux with a lesser effect on char depth
  - » The blowing reduction parameter which is a measure of the cooling effect of pyrolysis gases in the boundary layer
    - Raising this lowers the erosion and char but to a lesser degree than changing the CM/CH
  - » The minimum reaction temperature for reactions A and B (resin components)
    - This is mainly used to affect the char depth, the lower the minimum reaction temperature the higher char depth
  - » Virgin and char heat capacity for the CCP
    - Only used for stations 8 and 9a, a 20% increase resulted in a slower rise rate to match the thermocouple response
  - » Radiation exchange post burn
    - Stations nearer the throat are effected by the post burn quench but stations 9a and aft required re-radiation from the nozzle surfaces to keep the nozzle from cooling off faster than the thermocouple data indicated
- A trial and error process is employed because changing a variable to effect, say the erosion or char, would affect the temperature response
- The model results, Figures 8 through 12, show an acceptable match of thermocouple data while matching erosion and char depth



# CMA Analysis



## CMA matching of Thermocouple data

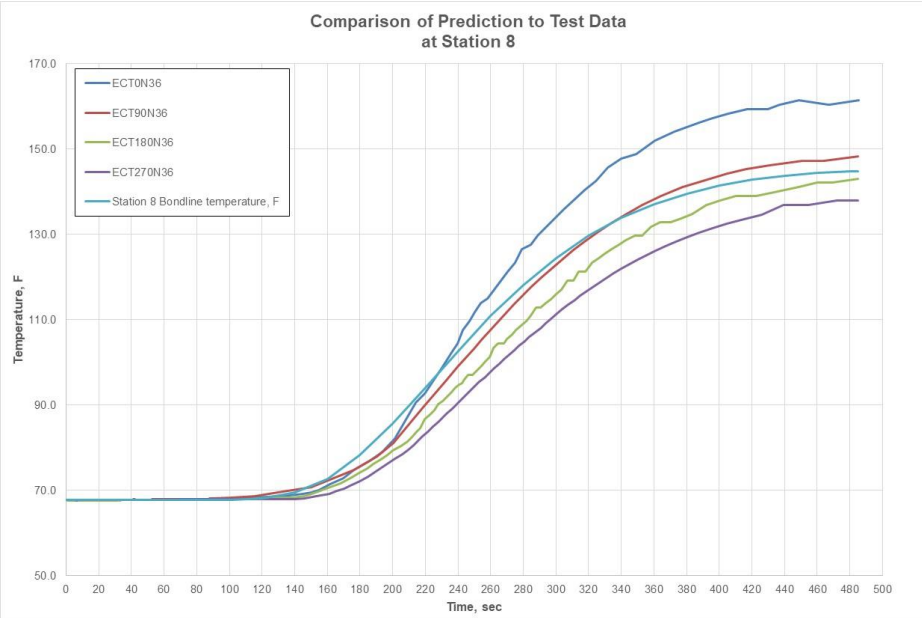


Figure 8: Station 8

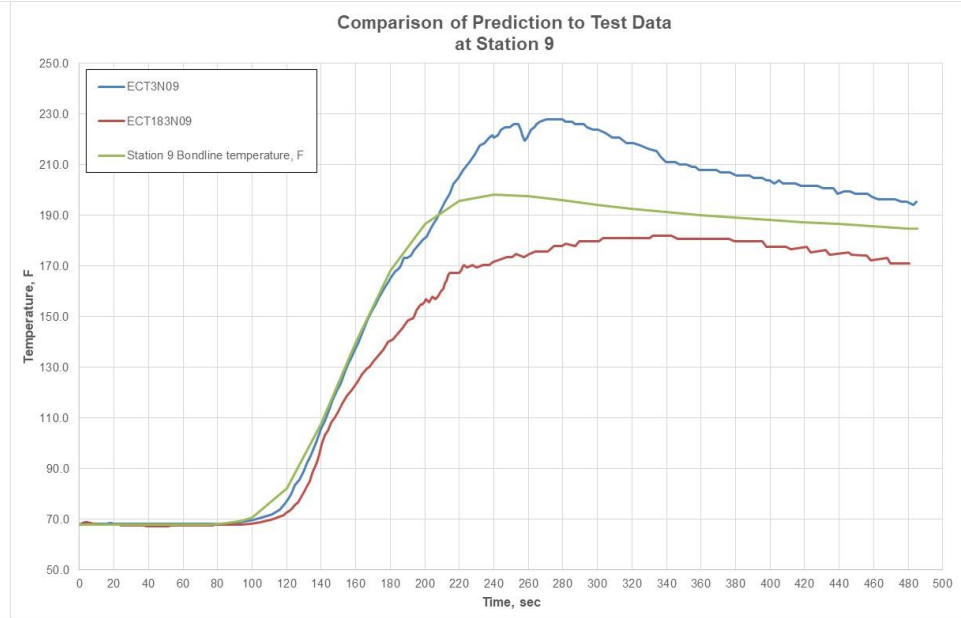


Figure 9: Station 9



# CMA Analysis



## CMA matching of Thermocouple data

Comparison of Prediction to Test Data at Station 9a

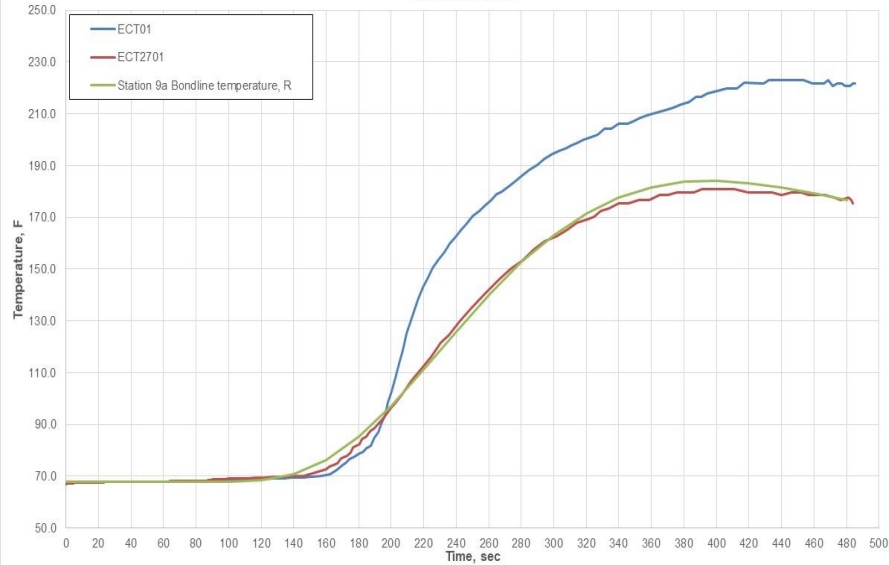


Figure 10: Station 9a

Comparison of Prediction to Test Data at Station 12

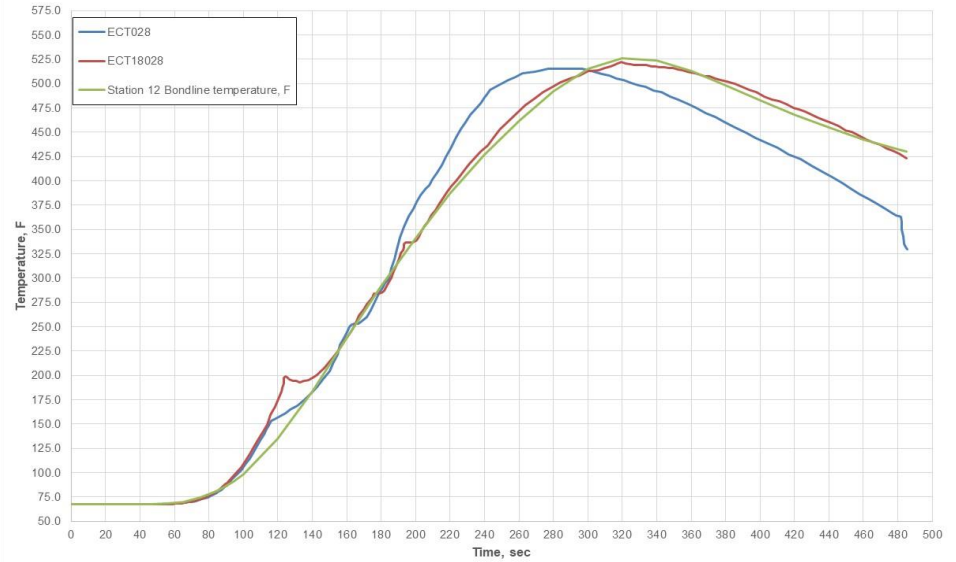


Figure 11: Station 12



# CMA Analysis



## CMA matching of Thermocouple data

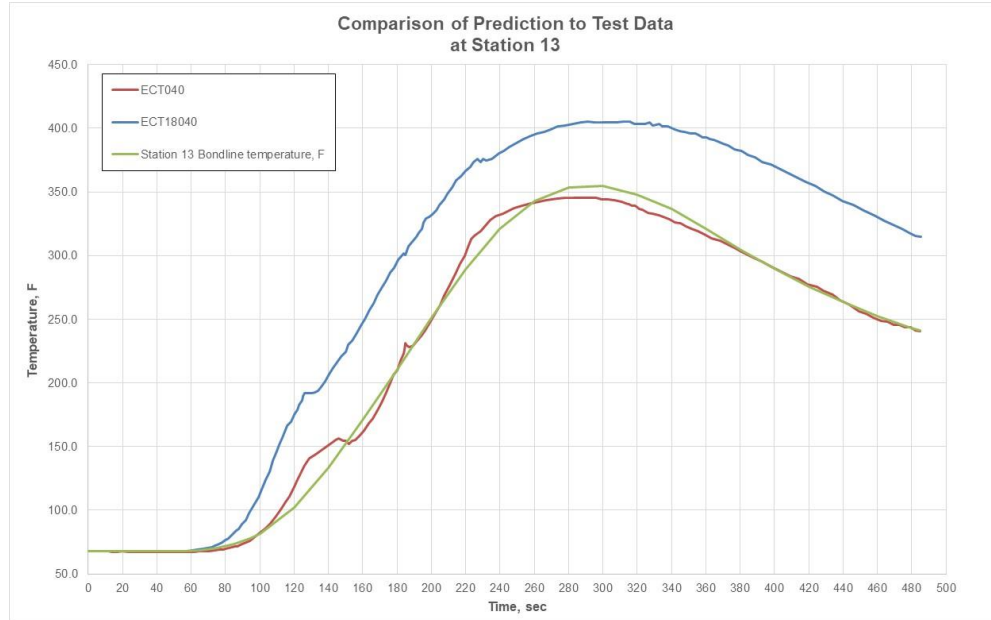


Figure 12: Station 13





# CMA Analysis



## • CMA Model Results

- » Figure 13 shows the erosion prediction matches the test motor erosion at all stations
  - The largest difference between prediction and measurement is 0.0012 in.
  - The heat transfer coefficient multiplier shown on the plot starts increasing at station 12 to 2.5 due to the augmentation of the chemical erosion by particle erosion due to the nozzle turn back angle
  - The plot also shows the CM/CH ratio increasing after station 13 for the same reason
- » Figure 14 shows the char prediction matches the test motor char at all stations
  - The largest difference between prediction and measurement is 0.028 in.
  - The chart also shows the char depth is less than the liner thickness
- » Figures 15-16 shows the average erosion bondline temperature prediction for Stations 8, 9a, 9b, 10, 11, 12, 13 and 14
- » The plots are grouped together based on whether the liner thickness is decreasing or increasing
- » For example, Figure 15 shows the temperature response rising faster as you go aft down the nozzle
- » This is due to the liner thickness reducing from station 8 to 12 shown on Figure 14
- » The trend reverses on Figure 16 because the liner thickness increases from station 12 to 14
- » There is only 5 stations with measured data and 7 predicted by the model, plotting them up together and seeing them lineup reasonably with the measured data increases confidence in the predicted temperatures
- » The 250°F isotherms are plotted for each station to demonstrate the bondline never exceeds the required temperature limit until significantly after EOB
- » As an example, Figure 17 and 18 show the 250°F isotherm for stations 10 and 11



# CMA Analysis



## CMA matching of test motor Average Erosion and Char

Comparison of CMA Predictions with Average Erosion Data

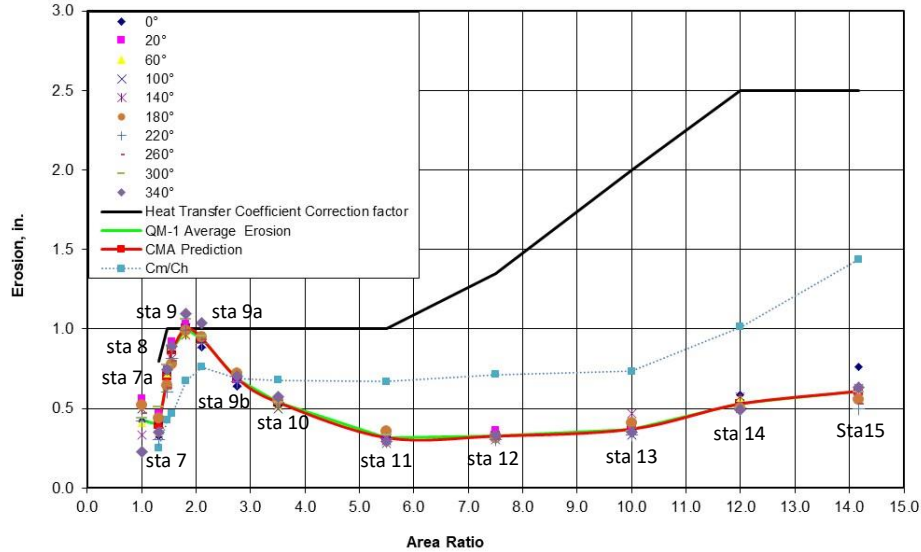


Figure 13: Average Erosion

Comparison of CMA Predictions with Average Char Data

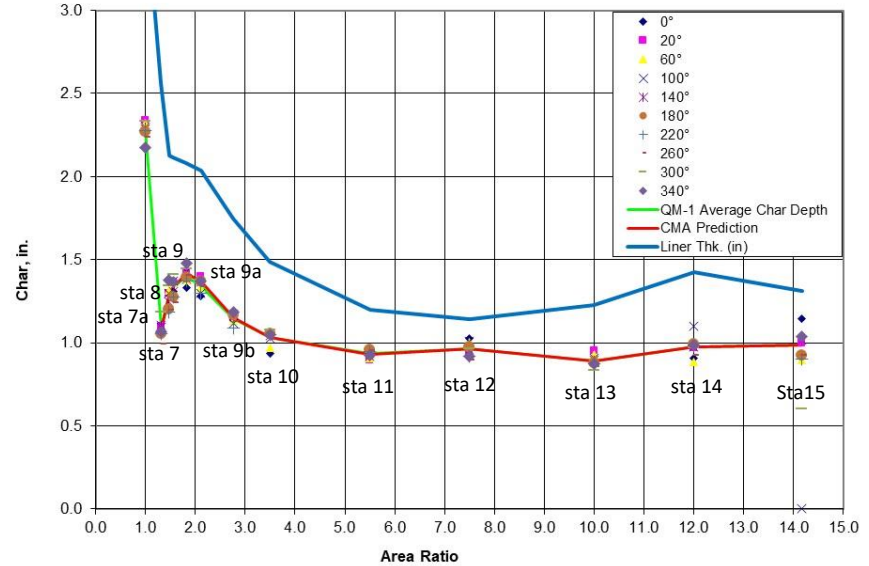


Figure 14: Average Char



# CMA Analysis



## CMA Average Erosion Bondline Temperature Prediction

Bondline Temperatures  
Average Erosion and Char

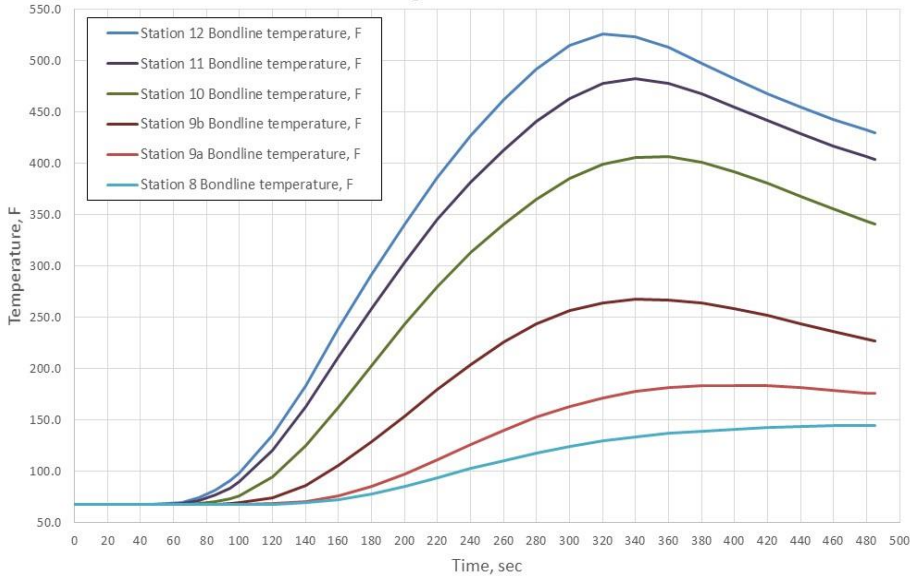


Figure 15: Station 8, 9a, 9b, 10, 11, 12

Bondline Temperatures  
Average Erosion and Char

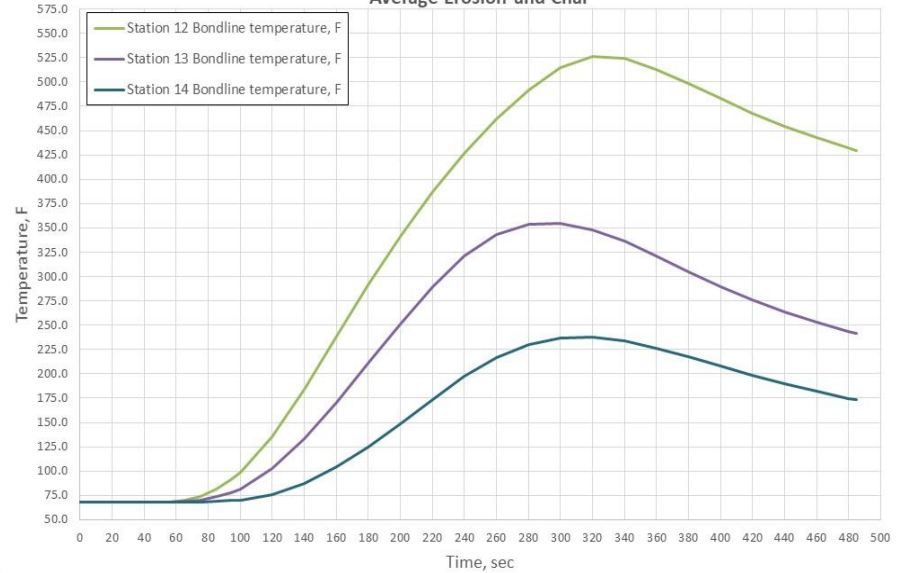


Figure 16: 12,13,14



# CMA Analysis



## CMA Average Erosion Isotherm Prediction

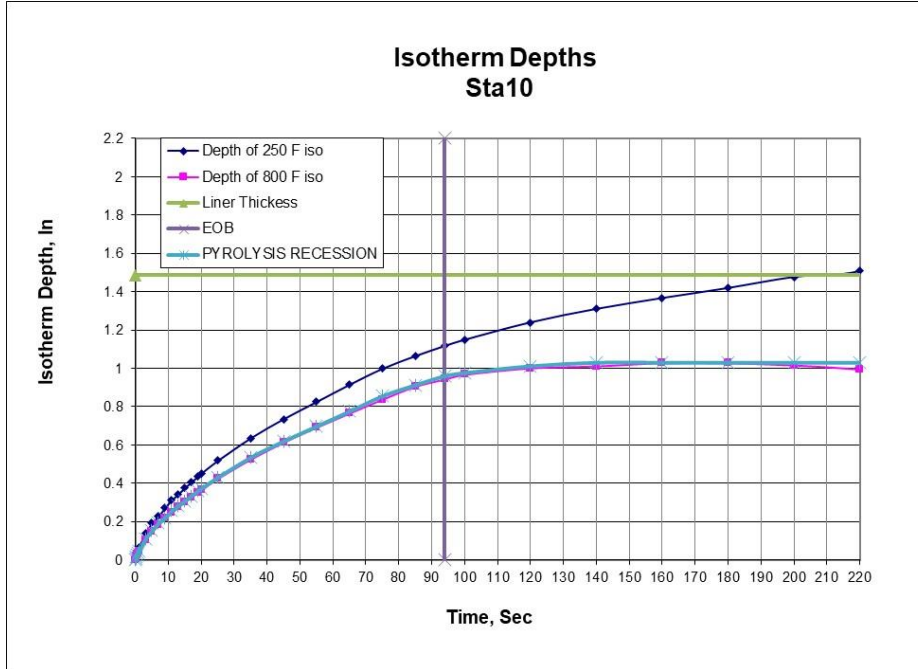


Figure 17: Station 10

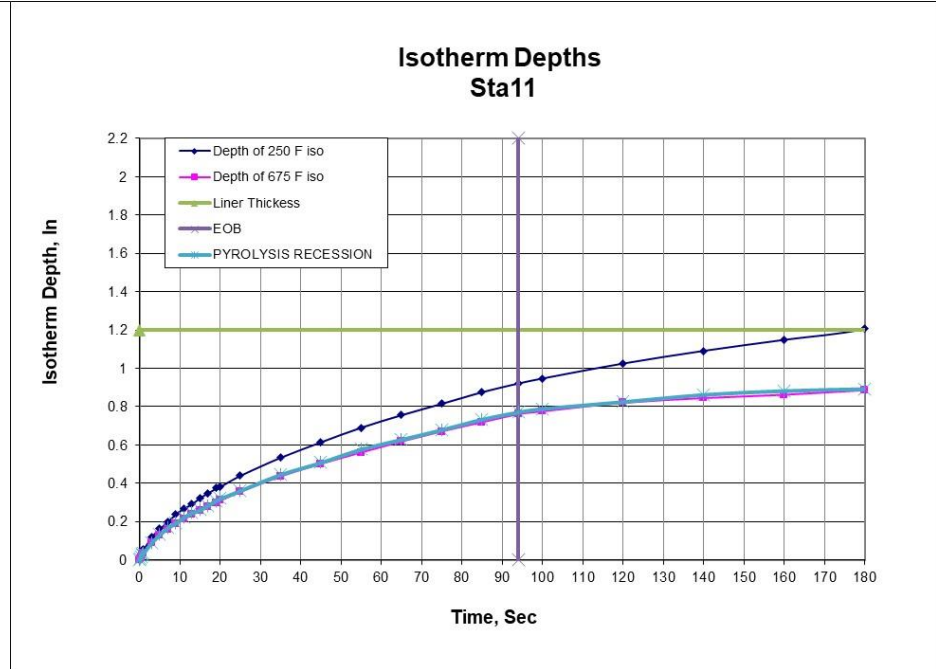


Figure 18: Station 11



# CMA Analysis



- **CMA Model Results**

- With the model validated, a bondline temperature prediction is made assuming  $3\sigma$  erosion and  $3\sigma$  char occurring at the same location, a very conservative assumption
- In order to boost the erosion and char from the average case to the  $3\sigma$  case the, heat transfer coefficient multiplying factor is raised to 3 for stations 14 and 15, the  $C_M/C_H$ , the ratio is raised about 10%, the blowing reduction parameter is lowered, the minimum reaction temperature for reactions A and B is lowered to  $400^\circ\text{F}$  for all stations and the radiation exchange post burn is increased



# CMA Analysis



- **CMA Model Results**

- Results

- » Figure 19 shows the erosion prediction matches the test motor  $3\sigma$  erosion at all stations
      - The largest difference between prediction and measurement is 0.0044 in.
    - » Figure 20 shows the char prediction matches the test motor char at all stations except 12 and 15 because the  $3\sigma$  char depth exceeds the liner thickness and the code can only char to the liner thickness
      - The largest difference between prediction and measurement is 0.0043 in.
    - » Figures 21-22 shows the  $3\sigma$  erosion bondline temperature prediction for Stations 8, 9a, 9b, 10, 11, 12, 13 and 14
    - » As in the average erosion cases, Figure 21 shows the temperature response rising faster as you go aft down the nozzle due to the liner thickness reducing from station 8 to 12
    - » The trend reverses on Figure 22 because the liner thickness increases from station 12 to 14
    - » Plotting them up together and seeing them lineup reasonably increases confidence in the predicted temperatures
    - » Figure 21 and 22 show the 250°F isotherm for stations 12 and 15
    - » These plots demonstrate the bondline never exceeds the required temperature limit at any station
    - » This result stands out because the  $3\sigma$  char depth exceeds the liner thickness at stations 12 and 15
    - » Burning through the liner would obviously make the bondline exceed 250°F
    - » The analysis shows this happens at 160 and 150 seconds respectively, substantially after the 94 second burn time



# CMA Analysis



## CMA matching of $3\sigma$ Erosion and Char

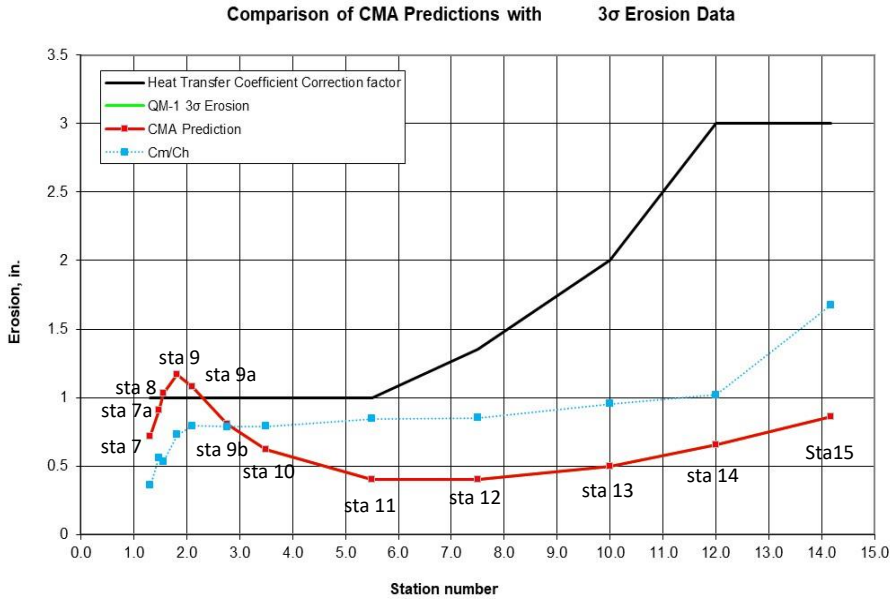


Figure 19:  $3\sigma$  Erosion

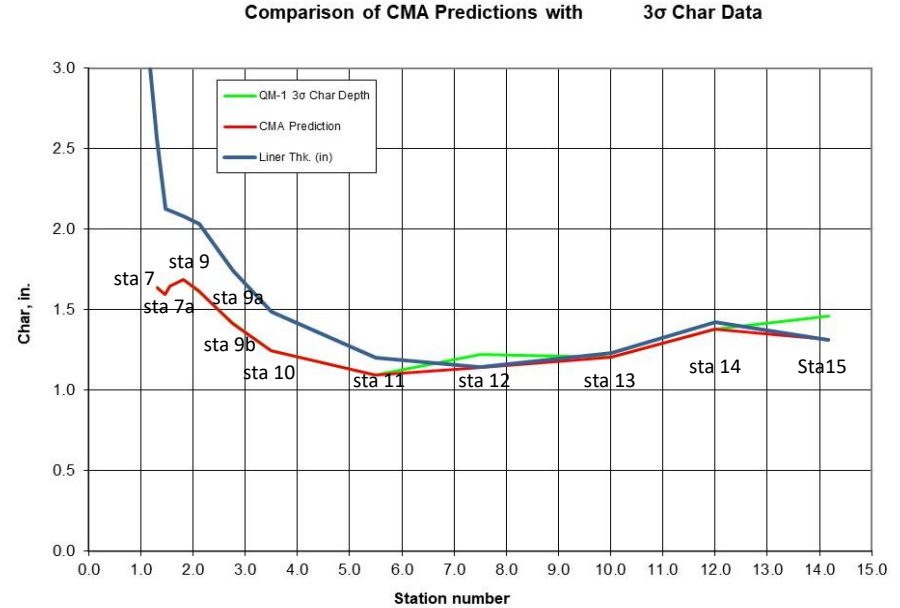


Figure 20:  $3\sigma$  Char



# CMA Analysis



## CMA 3 $\sigma$ Erosion Bondline Temperature Prediction

Bondline Temperatures  
3 $\sigma$  Erosion and Char

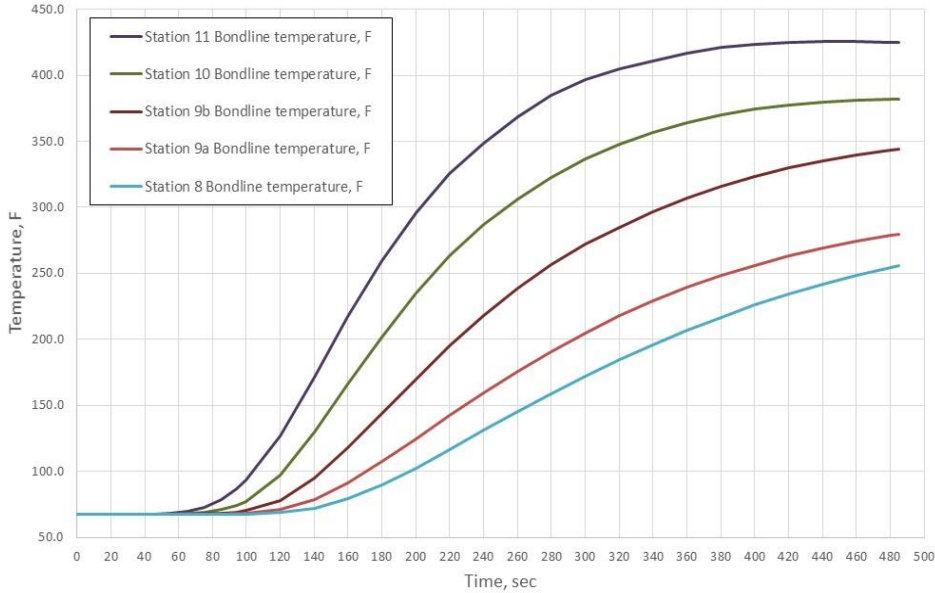


Figure 21: Station 8, 9a, 9b, 10, 11

Bondline Temperatures  
3 $\sigma$  Erosion and Char

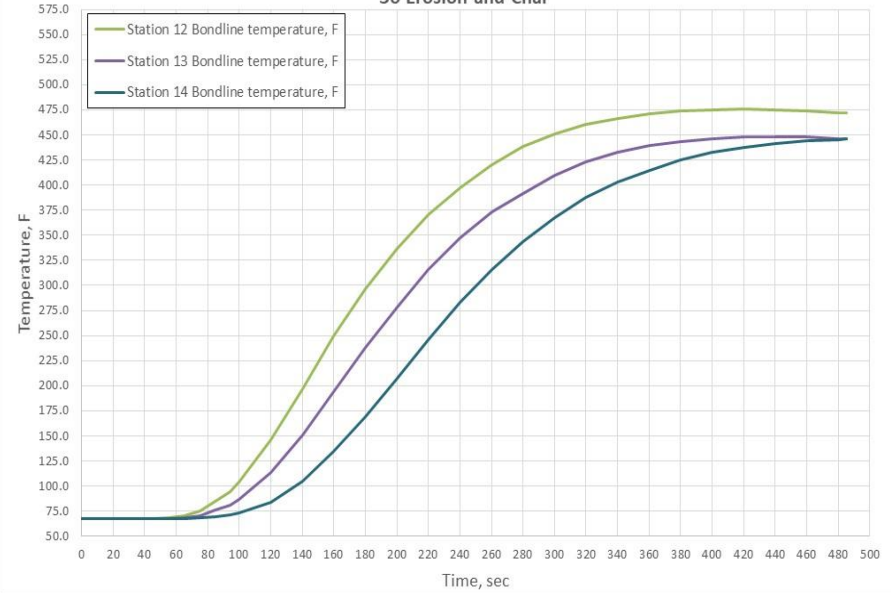


Figure 22: Station 12,13,14





# CMA Analysis



## CMA 3 $\sigma$ Erosion Isotherm Prediction

### 3 $\sigma$ Isotherm Depths Sta12

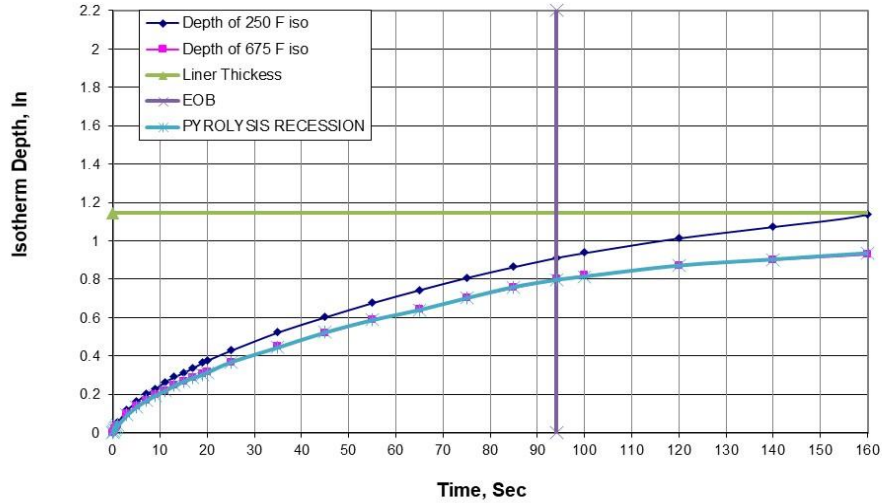


Figure 23: Station 12

### 3 $\sigma$ Isotherm Depths Sta15

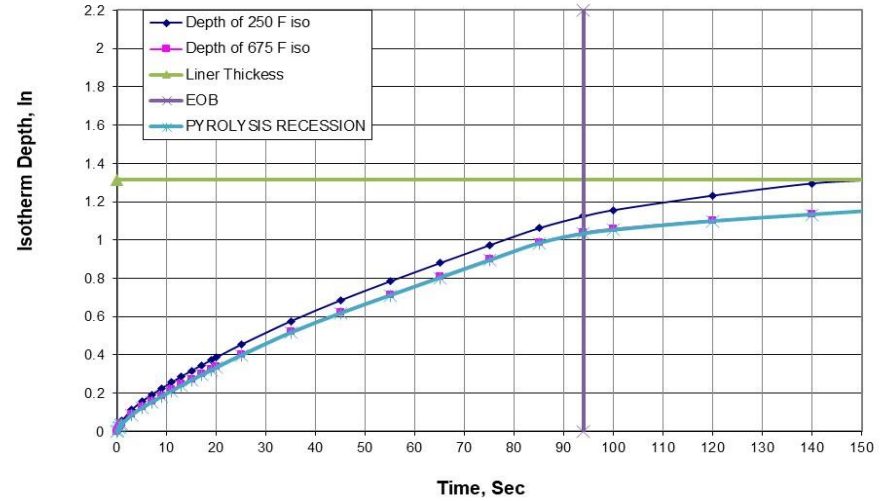


Figure 24: Station 15



# Conclusions



- **Conclusions**

- Even though this effort is very complicated and time-consuming it fully models the complex thermochemistry involved with an ablating and charring material
- Other so called ablation models usually just allow for the input of an erosion rate to change the thickness of the material during the burn
- Without a way to model the chemical reactions the thermal gradient can't be correctly modeled
- The model demonstrated it can match test data accurately and then be used to predicted worst cases without the need for additional, very costly testing
- For this example, the significant conclusion is, even with a predicted  $3\sigma$  char depth exceeding the liner thickness at stations 12 and 15, the bondline temperature remains below the required temperature during motor burn



# References



Reference Number	Document number	Document Title
1		"Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications, Part 1 Analysis", NASA Reference Publication 1311, Sanford Gordon and Bonnie McBride, Oct. 1994
2		"Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications, Part 2 Users Manual and Program Description", NASA Reference Publication 1311, Sanford Gordon and Bonnie McBride, June. 1996
3		"User's Manual for Aerotherm Chemical Equilibrium (ACE) Computer Program", Charles A. Powars and Robert Kendall, May 1969
4		"User's Manual Non-Proprietary Aerotherm Charring Material Thermal Response and Ablation Program", Acurex Corporation Aerotherm Division, November 30, 1987
5		"Thermal Radiation Heat Transfer", 2nd Edition, Siegel and Howell, Hemisphere Publishing Company, McGraw-Hill Book Company, 1981 Pages 658-672