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Introduction of the PIRATE Program for Parametric Reentry Vehicle Plasma Effects Studies

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Design procedures for hypersonic flight systems have changed dramatically over the years. To this end, a new capability (PIRATE) to analyze the interaction of reentry systems with their enveloping plasma is introduced. PIRATE is a driver program to solve the coupled physics problem of motion, heating, thermal response, chemistry, inviscid flowfield, and electromagnetic wave propagation/interaction for hypersonic flight systems in an automated fashion. A total of thirteen programs are coupled and controlled from a single software procedure to iteratively solve a complex design problem. The immediate benefit of this type of analysis is to guide design work as well as to more wisely choose costly test flights in regions that may be most stressing for a design concept. Sample results of a parametric study for a standard hypersonic flight system are presented to illustrate the utility of the program.

Nomenclature

A, B, C	= heatshield constituent subscripts; resin components A & B, reinforcement component C
C, B	= differential corrections curve fit coefficients for electron density profile equation
E	= activation energy in Arrhenius equation
e	= electron charge
f_p	= plasma frequency
G_p	= Gibbs energy function for the products of a reaction
h	= enthalpy
i	= subscript for *i-th* component in Arrhenius equation
k	= Boltzman's constant
k_i	= pre-exponential factor of *i-th* in Arrhenius equation
Me	= boundary layer edge Mach number
m	= density factor exponent in Arrhenius equation (a.k.a. reaction order)
m	= electron mass
N_e	= electron number density
N_i	= molecular species i number density
o, r	= subscripts for original and char residual density in Arrhenius equation
P	= pressure
S_e	= electron collision cross section
s	= entropy
RT	= gas constant & temperature product in Arrhenius equation
T	= temperature
$\bar{U}$	= boundary layer mean velocity
y	= boundary layer profile location normal to wall
δ	= boundary layer thickness
ε_o	= dielectric constant (a.k.a. permittivity)) of free space
Γ	= resin volume fraction
γ	= specific heat ratio
ρ	= current heatshield density
θ	= time vriable in Arrhenius equation
w_g	= electron collision frequency
w_p	= characteristic plasma angular frequency

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I. Introduction

Design procedures for hypersonic flight systems have changed dramatically over the years. A fundamental part of that change has been the move away from an experimental test based design to one governed by computational procedures. In part, this has been driven by the desire to reduce costs incurred during multiple flight tests of a perspective system. As the shift has occurred, greater demands have been placed on the computational tools and the people using them. Simulation models must have more fidelity and be applied over a wider range of conditions. A design area where this has been pointedly demonstrated is radar system interaction with the plasma sheath surrounding a reentry body. To address this problem, a number of Sandia programs have provided funding for continuing development of the **P**oly-**I**terative **R**eacting **A**ero-**T**hermal **E**valuation **(PIRATE)** tool set. This document describes PIRATE in detail and demonstrates its utility by performing a parametric evaluation of plasma effects for a standard reentry system over a variety of flight conditions.

II. PIRATE Framework

PIRATE is a Fortran code that acts as a driver program to solve the heating, thermal response, chemistry, inviscid flowfield, and electromagnetic wave propagation/interaction design problem for modern hypersonic systems. To accomplish this task, it employs a number of thermophysics programs executed iteratively and sequentially as necessary from a primary routine. All codes executed by the controlling routine are referred to from this point as constitutive programs. A total of thirteen programs make up the constitutive pool. Evaluation of the design problem requires performing a coupled physics solution between the imposed aerodynamic surface heating and the ablating decomposing heatshield thermal response. To address this, PIRATE executes heating, thermal response, and chemistry analysis tools iteratively as required from the main program until a user-defined convergence criterion is met. The solution is performed over the entire vehicle surface for a complete reentry trajectory.

III. Solution Procedure Description

Following is a brief description of the solution procedure. Body geometry, flight trajectory, and material property information are supplied as inputs to the program. The trajectory may be internally calculated or supplied in its entirety to PIRATE. On the initial pass, non-ablating baseline aerodynamic heating is calculated. The heating results are used to perform an initial thermal response solution for each specified body station over the entire flight path. Surface temperature and mass blowing rates from the thermal response evaluation are combined with surface pressure conditions calculated in the heating evaluation and supplied as input to perform a thermochemical evaluation of the molecular species in the boundary layer. To complete the first pass, resulting species, as well as surface pressure, temperature, and mass blowing rate information are then used as input to perform an ablating reacting chemistry boundary layer heating evaluation.

After the initial reacting boundary layer evaluation, the iterative process begins. The reacting heating solution, just completed, is substituted for the non-ablating baseline heating in the thermal response program. A revised set of surface temperatures and mass blowing rates are produced. PIRATE then calculates a full body least squares temperature difference between the current and previous surface temperature distributions for the entire time history. When the required temperature convergence criterion is satisfied, solution control passes on to the inviscid flowfield section of the program. If the criterion is not met, the cycle is continued by supplying current surface temperature and mass blowing information to the reacting boundary layer heating program. Iterations between the reacting heating and thermal response programs are continued until full body, full trajectory convergence is reached for surface temperature. Subsequent to convergence, a reacting gas inviscid flowfield evaluation is performed. The electron density and collision frequency profiles calculated in the boundary layer and inviscid evaluations are then merged by PIRATE and passed on as input to the plasma interaction programs. From the plasma programs, come the final quantities of interest, electromagnetic (EM) wave signal loss and modulation.

An iterative evaluation of this nature has its roots in manual computer program analyses performed by staff members a number of years ago. At that time, they did not have the luxury of the advanced computing systems available today. Evaluations were limited to a few stations, at a few trajectory points, for a few iterations. With the implementation of an advanced code development approach, the PIRATE suite provides a powerful tool for coupled analyses of heating, thermal response, and plasma interaction phenomenon.

IV. PIRATE Structure

PIRATE is a driver program that acts as the constitutive architecture to iteratively solve the coupled aerodynamic boundary layer heating and material thermal response problem for spherically capped, zero angle of attack, axisymmetric reentry bodies. Further, it solves for the corresponding reacting inviscid flowfield solution. Ultimately, using output from these solutions, it evaluates the reentry plasma sheath interaction with EM waves transmitted from the vehicle. A schematic of the program is presented by Figure 1.

In practice, the solution procedure uses Fortran system calls to access independent thermophysics programs to accomplish this task. Programs employed by PIRATE are summarized here and discussed in detail in the following subsections. Program discussions (in part extracted from references) are of a general nature with rigorous mathematical details left to the references.

The schematic outer dashed line encompasses the elements comprising PIRATE. A reentry trajectory can be calculated during execution from a choice of two simulation programs ran by PIRATE or provided in its entirety to the reference heating codes. Trajectory simulation programs contained in the procedure are TAOS[1] (3 DOF) or the system specific SIXDOF[2] code. Non-ablating baseline heating is calculated by one of two programs. Depending upon geometry, either BLUNTY[3] or SANDIAC/HIBLARG[4,5] is used to establish the initial reference heating. Should the problem require the use of SANDIAC/HIBLARG, it is currently POSTHEAT that may be executed from the driver routine. It is a post-processing program that operates on SANDIAC/HIBLARG solutions performed prior to the execution of PIRATE. This is followed by execution of CMA[6] to determine the thermal response. Using output from the first two programs as input, ACE[7] is then executed to determine molecular species by performing a chemistry evaluation of the boundary layer. The fourth step uses results from all three of the above solutions as input to run BLIMP[8,9] in an evaluation of the reacting boundary layer heating environment. Under standard usage, CMA and BLIMP iterate until surface temperature convergence is reached. At this point, RAZIBB[10] is then executed to evaluate the molecular species in the reacting inviscid flowfield. Results from RAZIBB and the final BLIMP run are merged by PIRATE to establish electron density and collision frequency profiles. The profiles and flowfield information are used by EMLOSS[11,12], TPPC[13], NERMS[14], BURFIT[15], and STOP[16] (Temporal EM) to determine the plasma interaction parameters of interest.

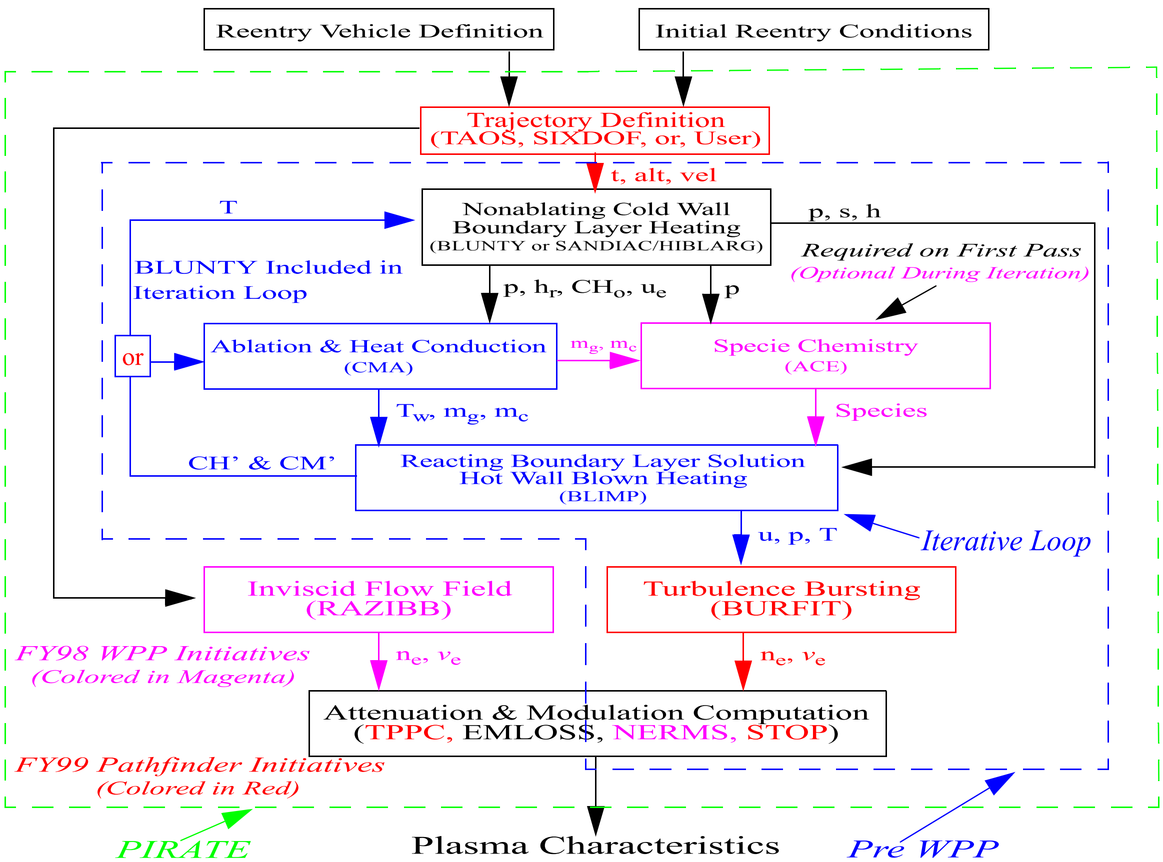

Figure 1 - Schematic of PIRATE Procedure

A. Trajectory Simulations:

As indicated in the general PIRATE structure discussion, the trajectory may be treated completely as input or calculated internally by one of two codes controlled by PIRATE. The **T**rajectory **A**nalysis and **O**ptimization **S**oftware ***(TAOS)*** and SIXDOF programs are the two simulations in use. TAOS is used by PIRATE for three degree of freedom motion analyses for general sphere cone vehicles. Whereas, ***SIXDOF*** (as its name implies) is used to perform more detailed **SIX D**egree **O**f **F**reedom trajectory analyses. However, it is limited to a single predefined specific sphere cone reentry system.

Following is a discussion paraphrased for expediency from reference one and serves as a general description of the problem of body motion simulated by the TAOS and SIXDOF programs. The motion of an object relative to a fixed point in space is obtained from a set of differential equations known as the equations of motion. They are based on Newton's Second Law of Motion as it applies to rigid bodies of constant mass. There are three force equations and three moment equations. Position and velocity of the object's center of mass are obtained from the force equations and its angular motion attributes are obtained from the moment equations. The axial and angular acceleration vectors each have three directional components and as such form six second order differential equations to be solved for a complete description of the body's motion. Thus, the six degree-of-freedom name is taken directly from its function (SIXDOF).

If it is assumed that the vehicles angular motion is known a priori, the system of equations can be reduced by making solution of the moment equations unnecessary. This reduces the system to three degrees of freedom for motion analysis. This simplification is known as a point-mass trajectory simulation or a three degree-of-freedom simulation. The simplification is justified if it can be assumed that the vehicle is designed to fly automatically in a predetermined fashion or an attitude control system is included in the design to force a desired angular orientation.

B. Non-Ablating Cold Wall Boundary Layer Heating:

As stated above, non-ablating cold-wall baseline heating is calculated by either BLUNTY or SANDIAC/HIBLARG. The ***cold-wall*** designator refers to a 536^{o}R reference temperature for an enthalpy data base to be consistent with surface thermochemistry decks generated by an external chemistry program (ACE in this case) and used in the thermal response code. Both the surface chemistry and thermal response codes use the Joint Army Navy Air Force (JANAF) data base[17] as this common reference. Vehicle geometry determines which heating program to employ. Simple sphere-cone bodies should be evaluated with BLUNTY. SANDIAC/HIBLARG may be used to do this, but it is unnecessary. The two programs give comparable answers for sphere-cones; however, SANDIAC/HIBLARG is more computationally intensive and thus causes an unwarranted slow down in the solution procedure. SANDIAC/HIBLARG should be used if the geometry under consideration is a multi-conic or some other spherically capped axisymmetric smooth geometry. General descriptions of the solution technique for both programs are contained in the following paragraphs. Rigorous mathematical details may be obtained from the reference documents.

The **BLUNT** bod**Y** ***(BLUNTY)*** heating program is a two-dimensional axisymmetric heating code for sphere-cone geometries at zero angle of attack in supersonic flow. It uses a mass conservation integral stream-tube approach conserving entropy along streamlines. The program calculates the flow conditions in the free stream, behind the shock, at the stagnation point, throughout the boundary layer, and at the body wall. The procedure uses curve fits of shock shape and static pressure distributions obtained from exact inviscid flowfield calculations. In this way, vorticity and pressure over-expansion effects can be included without performing time consuming inviscid flowfield computations for each flight condition considered. The stream-tube mass balancing technique is used to couple the inviscid flowfield to a boundary layer mass flux correlation and, thereby, determine the boundary layer edge properties. Calculations can be performed for air in thermodynamic equilibrium. Established heat transfer theories are used to compute local heat transfer rates: Fay and Riddell for the stagnation point; Kemp, Rose, and Detra for laminar flow; and a modified version of Rose, Probstein, and Adams for turbulent flow.

For geometries other than sphere-cones, PIRATE has the option of using SANDIAC/HIBLARG to determine reference heating. SANDIAC/HIBLARG computes the inviscid flowfield and boundary layer for two-dimensional spherically capped geometries in supersonic flow. This is actually two separate programs run by processing software. The **SAND**ia **I**nviscid **A**ft body **C**ode ***(SANDIAC)*** solves the three-dimensional, steady state, Euler equations in finite difference form for the inviscid solution. The equations are solved in a transformed computational plane. A parabolic grid generation scheme is used to provide body normal grids for complex configurations. It has options to solve the conservative and non-conservative Euler equations using either upwind or centered differencing. Calculations may be performed for a gas in chemical equilibrium. The second half of the inviscid/boundary layer approach is performed by the **H**ypersonic **I**ntegral **B**oundary **L**ayer **A**nalysis of **R**eentry **G**eometries ***(HIBLARG)*** program. HIBLARG solves the integral form of the momentum equation and energy equation along inviscid streamlines to determine the cold wall heat transfer. Closure is achieved by specifying various boundary layer parameters from correlations. This formulation permits the calculation of either laminar, transitional, or turbulent flow as determined by the transition criterion of choice.

C. Material Thermal Response:

Material thermal response in the PIRATE suite is predicted by a modified version of an industry standard program, CMA. The **C**harring **M**aterial **A**blation ***(CMA)*** code is a one-dimensional, implicit, finite difference, transient heat conduction thermal response code which allows for ablation at one surface and in-depth material decomposition. Although, the code is inherently one-dimensional, it may be applied to a large class of two and three-dimensional problems where transverse temperature gradients produce negligible heat transfer in off-axis directions relative to the surface normal axis energy transfer rates. This includes the class of problems containing reentry vehicles.

The program provides the thermal response solution for general convective and radiative boundary condition problems. Surface phenomena are determined by a surface energy balance which employs convective film coefficients for heat and mass transfer. The actual computation of the surface energy balance involves considerations of thermochemistry. Surface thermochemical reactions are complex and an iterative procedure is required to complete their solution. In theory, the chemistry calculations could be done internal to CMA. However, it is more computationally expedient for these reactions to be evaluated externally and the results input in tabular form for CMA to access in a interpolative fashion. A thermochemistry program, mentioned earlier as ACE and discussed below in the Boundary Layer Chemistry section, produces the required input. This is the connective juncture between the heating and thermal response evaluations that requires the JANAF data base reference.

To this point the thermal response discussion has focussed on the surface phenomena. Given the complicated nature of the in-depth decomposition process and its impact on boundary layer constituents and thus plasma interaction parameters, a detailed discussion of this facet of thermal response is included. Decomposition related parameters of specific interest to the thermal response program are ablator resin fraction, pyrolysis gas enthalpy, and Arrhenius decomposition rate equation constants for the material's constituents. In CMA terminology, the ablator in its original state is referred to as virgin plastic. The resin fraction of the virgin plastic is the constituent proportion of the ablator comprised of phenolic, epoxy, etc. Pyrolysis gas enthalpy represents the energy content of the gases being expelled from the material as a result of the in-depth decomposition reactions occurring in the complex ablator. They are a function of temperature and the specific binder molecular formulation being decomposed. Usually, the gas enthalpies are determined by separate runs of a chemical equilibrium program (ACE in our case) knowing the elemental mass fractions of the decomposing binder.

The most complex and difficult to define material properties are the constants used in the Arrhenius reaction rate equations. In general terms, a virgin plastic ablator may be modeled as three decomposable constituents with the composite material density given by Equation 1, where Γ is the resin volume fraction discussed previously.

$$\rho = \Gamma(\rho_A + \rho_B) + (1 - \Gamma)\rho_C \qquad \textbf{(1)}$$

The constituents are two resin components (A & B) and a single reinforcement component (C). An example of the reinforcement component would be the carbon fiber cloth in a carbon phenolic ablator. Division of the resin into two parts is the result of the experimental observation of a two stage decomposition process of phenolic resin. Decomposition rates of three organic constituents are modeled by kinetic equations of the Arrhenius form shown in Equation 2.

$$\frac{\partial\rho}{\partial\theta} = -k_i e^{-E_i/(RT)} \rho_o \left(\frac{\rho_i - \rho_{r_i}}{\rho_{o_i}}\right)^{m_i} \qquad i = \text{A, B, \& C} \qquad \textbf{(2)}$$

The time variable in this formulation is θ. Constants k_i, E_i/RT, and m_i are the pre-exponential factor, activation energy factor, and density factor exponent, respectively, using CMA terminology. The density exponent is better known in the literature as the reaction order. Subscripts *o*, *r*, and *i* refer to the original value, char residual value, and the *i-th* component, respectively. The constants used in the above equation are determined experimentally by Thermo-Gravimetric Analysis (TGA) and Differential Thermal Analysis (DTA). Essentially, the constants are curve fit coefficients derived from experimental results to fit the decomposition behavior of a complex ablator test sample. Normally, a sample of the composite material is subjected to a known heating environment while its weight change behavior is monitored during the process.

D. Boundary Layer Chemistry:

Boundary layer chemistry evaluations in PIRATE are also performed by a standard industry program. A version of this program is included in the procedure. The **A**erotherm **C**hemical **E**quilibrium ***(ACE)*** code is an extremely versatile tool for calculating the chemical state and transport properties of a system undergoing a broad variety of thermochemical processes. In ACE, equilibrium is defined by an iterative procedure whereby the Gibbs free energy function is minimized. The Gibbs function for the products of a reaction is defined by Equation 3 where *h*, *T*, and *s* are enthalpy, temperature, and entropy, respectively.

$$G_p = \Sigma(h_i - Ts_i) \qquad \textbf{(3)}$$

This procedure can be invoked for open or closed systems. For the purposes of this report, closed means non-ablating and open means an ablating surface. The chemical and thermodynamic state for closed systems may be determined when closure is obtained by specifying two independent variables (e.g., P and T) in addition to the elemental composition. For open systems, the relative amounts of mass crossing into the system (i.e. an open system) must be supplied in lieu of the temperature before closure can be achieved. Despite the programs name, it can treat both systems in chemical equilibrium and systems for which certain reactions are kinetically controlled. For the processes under consideration in a typical reentry body environment, an equilibrium assumption is sufficient. Finally, chemical evaluations performed by ACE within PIRATE assumed equal diffusion coefficients (Fick's Law) for species migration in the boundary layer.

E. Reacting Boundary Layer Heating:

Reacting boundary layer heating in the PIRATE procedure is also predicted by a program used heavily in the industry since the 60's. The Boundary Layer Integral Matrix Procedure ***(BLIMP)*** code is a two-dimensional finite difference program that includes the ability to treat laminar and turbulent chemically homogenous or heterogeneous reacting flows around axisymmetric blunt body geometries. Currently, one of the latest versions of this code (originally written by Aerotherm of California) is in use in the Aero-Sciences Department. A version of BLIMP88 modified to include self contained boundary layer profile models has been coupled with the PIRATE program. It is based on a fourth order Galerkin procedure in which the primary dependent variables and their derivatives in the normal direction are related by Taylor series expansions and represented by connected quadratics or cubics. A nodal network is defined through the boundary layer and the series expansions are assumed valid between each set of nodes. By keeping the third or fourth term in the series, a higher accuracy is obtained with fewer nodal points. The conservation equations are integrated across each strip between nodal points to simplify the normal derivative terms in the energy and species conservation equations. For linear series expansions and linear boundary conditions, a sparse matrix is formed which has to be inverted only once for a given problem. The nonlinear equations and boundary conditions are solved using a Newton-Raphson iteration procedure.

F. Reacting Inviscid Flowfield:

The reacting chemistry inviscid flowfield is determined by yet another code originally written by Aerotherm of California. In the early seventies, the **R**eal gas **A**xisymmetric **Z**ero **I**ncidence **B**lunt **B**ody ***(RAZIBB)*** program was formulated to address reentry problems of the current variety. RAZIBB is an equilibrium air chemistry finite difference program for evaluating blunt axisymmetric bodies with a supersonic free stream. Specifically, the subsonic/transonic region is computed by the time asymptotic approach with the bow shock treated as a discontinuity. The interior points are computed using a second order differencing technique. A modified method of characteristics procedure is used at the body and at the shock points. The supersonic afterbody flowfield is computed by the same finite difference procedure with the bow shock treated as a discontinuity across which the Rankine Hugoniot jump conditions are employed. From the interior, the method of characteristics is used at the body and shock points. As originally written, the program was designed to do single flight condition calculations. To suit PIRATE's purpose, it was modified during the current work to evaluate a full trajectory.

G. Plasma Interaction Analysis:

In the current version of PIRATE, the analysis of electromagnetic signal interaction with reentry body plasmas is handled by five programs. Two of the tools predict signal attenuation characteristics. EMLOSS and TPPC are used to evaluate transmitted signal reduction. The remaining three codes attempt to characterize the unsteady nature of the boundary layer and quantify its modulating effect on transmitted signals. NERMS and BURFIT estimate modulation frequencies imposed on the signal as the result of boundary layer turbulence. Further, the STOP program quantifies the oscillation effects on the radar system resulting from the boundary layer bursting frequency predictions from NERMS and BURFIT.

1. EMLOSS:

The **E**lectro**M**agnetic signal **LOSS** ***(EMLOSS)*** program and analysis procedure were formulated concurrently by Cooper[11] and Russo[12] in the 60's. This methodology calculates the signal reduction passing through an inhomogenous plasma including both attenuation and reflection phenomena. Transmitted waves are assumed to be planar, but may be transmitted at oblique angles through the media. The media traversed is assumed to be constructed serially of a finite number of slabs of plasma with infinite dimensions transverse to the plasma depth dimension. Individual slabs are assumed to be homogenous. Depth-wise gradients in relevant parameters (i.e., electron density, etc.) are assumed to be accounted for by finite changes in properties from slab to slab.

With these assumptions in place, EMLOSS uses Maxwell's field equations to solve for the transmission characteristics of an EM wave through the plasma. It uses the electron density and collision frequency profiles, determined by BLIMP and RAZIBB in the boundary layer and inviscid region, respectively, as input. Electron density is required to determine the "characteristic plasma angular frequency" (see Equ. 4), which in turn is basic to the dielectric constant and electrical conductivity of the medium.

$$w_p = \sqrt{(N_e e^2)/(m\varepsilon_0)} \quad \textbf{(4)}$$

In the expression, N_e, e, m, and ε_o are electron number density, electron charge, electron mass, and dielectric constant (a.k.a. permittivity) of free space, respectively. Units for plasma frequency as defined in Equation 4 are rad/sec. The angular frequency is related to the plasma frequency (f_p) in Hz by Equation 5.

$$w_p = 2\pi f_p \quad \textbf{(5)}$$

The collision frequency (also fundamental to the plasma dielectric constant and electrical conductivity) refers to the rate at which electrons collide with other molecular species within the plasma and is a function of temperature, pressure, and species collision cross sections (see Equ. 6).

$$w_g = \sqrt{\frac{8kT}{\pi m}\sum_i N_i^2 S_{e_i}^2} \quad \textbf{(6)}$$

Variables k, T, N_i, and S_e in the relation are Boltzman's constant, temperature, molecular species number density, and electron collision cross section. This relation is summed across all species i present in the plasma. In essence, the relation can be thought of as the product of the average electron thermal velocity (based on an integration of the Boltzman equation over a Maxwellian distribution) and the collective probability of a collision considering all molecular species encountering electrons at that velocity. Currently, collision frequency calculations in EMLOSS are tailored specifically to chemically reacting air with Equation 6 reducing to Equation 7.

$$w_g = 5.814x10^{12} P/\sqrt{T} \quad \textbf{(7)}$$

P and T are pressure and temperature respectively in atmospheres and Kelvin. Units for collision frequency are in *collisions/sec* per electron. EM wave reflection and attenuation are calculated from the profiles defined in this fashion.

2. TPPC:

The **T**angent **P**lane **P**lasma **C**ode ***(TPPC)*** employed by PIRATE was originally developed in the latter 70's at the Aerospace Corporation in California and used in analyses in the industry in the late seventies and early eighties. Similar to EMLOSS, the methodology also calculates the signal reduction passing through an inhomogenous plasma including both attenuation and reflection phenomenon. It differs from the previous code in that it does not make an infinite plane assumption. Instead it calculates the performance of a slot antenna on a dielectric and/or plasma clad ground plane assumed to be parallel with the conical surface of a reentry body heatshield. Like EMLOSS, the multi-layered slab model approach is maintained for a description of the plasma media. That is; the media traversed is assumed to be constructed serially of a finite number of slabs of plasma with infinite dimensions transverse to the plasma depth dimension. Individual slabs are assumed to be homogenous. Depth-wise gradients in relevant parameters (i.e., electron density, etc.) are assumed to be accounted for by finite changes in properties from slab to slab. The program calculates the antenna equivalent circuit, input admittance, VSWR, efficiency, antenna ohmic loss, plasma ohmic loss, far field radiation patterns, and antenna directivity.

3. NERMS:

In addition to the signal reduction programs, PIRATE contains programs capable of electron density variation and frequency modulation analyses. One such code is the electron density (**NE**) **R**oot **M**ean **S**quare ***(NERMS)*** program. It performs two distinct numerical evaluations. NERMS makes an estimate of the RMS variation of temperature around the mean profile values determined by BLIMP. As well, it provides an analysis of the modulation frequency spectrum imposed by the oscillating nature of a turbulent boundary layer upon EM signals transmitted from or received by a reentry body. The original version of the code was written by Carlos A. Lopez while at the Naval Surface Weapon Center (NSWC)-White Oak. It was obtained recently and modified to be compatible with the PIRATE suite while including some minor changes to a differential corrections curve fitting procedure for increased robustness.

Mathematically, the electron density variation estimates are obtained by making use of a Saha equation correlation method pioneered by Demetriades and Grabow[18,19] in the 60's and 70's. The methodology involves curve fitting the Saha relation, shown in Equation 8, to known temperature and electron density information.

$$N_e = CP^{1/2}T^{1/4}e^{-B/(2T)} \qquad \textbf{(8)}$$

C and *B* in the equation are the coefficients determined by a differential corrections curve fit, while *P* and *T* are pressure and temperature, respectively. Temperature and electron density information curve fit to the equation are supplied by the BLIMP boundary layer solution mean profiles. The Saha equation is the classic formulation for estimating species number density assuming thermochemical equilibrium conditions exist in the gas. Use of this approach to estimate electron density fluctuations requires the assumption that the variation is driven by gas temperature fluctuations. RMS temperature variation from the BLIMP mean profiles is determined from empirical correlations of the supersonic test data reported by Kistler[20] for a flat plate. An RMS temperature parameter from this data, shown in Equation 9, is correlated as a function of non-dimensional boundary layer position.

$$\frac{\sqrt{\overline{\Delta T^2}}}{\bar{T}}\left\{\frac{1}{2} + \frac{2}{(\gamma - 1)M_e^2}\right\} = f\left(\frac{y}{\delta}\right) \qquad \textbf{(9)}$$

By making use of this correlation, the Saha equation, and the chain rule of differentiation (Equation 10), the RMS electron density variation around the BLIMP mean values can be calculated.

$$\frac{dN}{N} = \frac{dN}{dT}\frac{T}{N}\frac{dT}{T} \qquad \textbf{(10)}$$

In this relation, *dT/T* is approximated by $\Delta T/T$ evaluated from equation 8; whereas *dN/dT* comes directly from differentiation of the Saha equation while holding pressure constant at a given boundary layer axial station. *N* and *T* are the mean values in the profile supplied by BLIMP. There are deficiencies to this approach, most notably approximating hypersonic flow with supersonic data. However, worthwhile engineering estimates can be achieved in this fashion.

Following determination of the electron density variation across the boundary layer, NERMS undertakes a second numerical evaluation. It estimates the turbulence frequency spectrum imposed on an EM signal traversing the boundary layer. Signal modulation is a direct result of the electron density oscillations in the boundary layer brought on by the production of large scale turbulence structures. Oscillations in electron density result in a time varying media for the signal to traverse; producing temporal variations in signal attenuation and reflection. The rate of production of the turbulent structures is referred to as the bursting frequency in the literature[21] and scales to the zeroth order by the mean boundary layer velocity and the hydrodynamic boundary layer thickness. Equation 11 shows the relationship between the mean velocity ($\bar{U}$) and the boundary layer thickness (δ).

$$\dot{f} = \bar{U}/(5\delta) \qquad \textbf{(11)}$$

This calculation has been included in BLIMP. As an improvement over the zeroth order estimate, an empirical in NERMS uses the data of Klebanoff[22] to characterize the frequency spectrum beyond the raw scaling parameters. As with the Kistler data, hot wire measurements were made for turbulent flow over a flat plate to characterize the structure and magnitude of the flow oscillations. Unfortunately, the Klebanoff evaluation was for low speed subsonic incompressible flow. This is of obvious concern when viewing numerical results from the code. Results should be viewed as trend estimators and not taken at face value as exact quantitative determination of the modulation frequencies.

4. BURFIT:

A second program used to determine the modulation frequencies applied by the boundary layer turbulent behavior is the **BUR**sting **F**requency prediction in **I**ncompressible **T**urbulent boundary layers ***(BURFIT)*** code.[15] Contrary to the empirical approach taken by NERMS, BURFIT endeavors to predict the bursting phenomenon occurring in a turbulent boundary layer through a fundamental mathematical formulation. Many experimental results have indicated the existence of coherent structures in turbulent flows. The quasi-deterministic occurrence of large-scale organized structures is collectively called the bursting process. Following is a brief synopsis of the approach taken by Liou and Fang in the mathematical work at Western Michigan University performed for Sandia to create BURFIT. Currently, only flat plate incompressible flows are considered. As such the same comments and restrictions apply here as with NERMS.

This approach begins with the assumption that the formation of large scale counter-rotating spanwise rolls of vortical structures are associated with the bursting process and that this plays a dominant role in the development of turbulent boundary layers. Experimental evidence suggested that a hydrodynamic wave description could be applicable to these structures. It was further postulated by predecessors to the current work based on weakly nonlinear theory that a dynamic resonance could occur when Eigenmodes of the Orr-Sommerfeld stability equation correspond to those of the Vertical Vorticity equation. It is this resonance that is theorized to give birth to the vortical structures. Both of these equations are modelled as ordinary differential equations. A global method (described in the reference) finite difference scheme using second and fourth order terms is employed in the solution procedure. At resonance, following simultaneous solution of this dual system of equations, the resulting bursting frequency is produced for further use in the PIRATE suite.

5. STOP:

Bursting frequency information produced by any of the three methods discussed above is used by the **S**ingle **T**hin-slab **O**scillating **P**lasma ***(STOP)*** program[16] to determine the modulation effects of the turbulent boundary layer on the transmitted microwave signal. The plasma produced around the vehicle during reentry has electrical properties that vary with time due to changing flight conditions and the oscillatory nature of the turbulent flow boundary layer. Turbulent bursting impresses time-varying changes (i.e. modulation) on the EM wave propagating through it. STOP solves the relevant differential equations based on first principles (i.e. Maxwell's Equations) for an electromagnetic wave traversing a plasma. It takes into account the interaction of the wave with the ions, which have minimal reaction due to their mass, and with the electrons which will respond with a time varying velocity due to the field associated with the wave. Thus, the current density in the plasma depends on both the applied electromagnetic field and the turbulent fluid motions produced by the bursting process. This current is related by a constitutive relation back to the electric field and thus evidenced by modulation on the signal. The effect may take the form of frequency or amplitude (i.e. attenuation) modulation. Oscillations in electron density produced by the fluid motions are slow compared to the wave propagation velocities and allows for the solution to be approximated with a quasi-static thin-slab model making use of mean electron densities (from BLIMP) within the plasma layer.

V. Sample Parametric Study Trajectories

A sphere cone vehicle with a carbon phenolic heatshield was evaluated parametrically with PIRATE over a range of reentry conditions. Comparison of the flight profile for the six trajectories examined is shown in Figure 2.

Velocity as a function of altitude is presented. Reentry velocities ranged from approximately 15 to 25 kft/sec at an altitude of 200 kft. Sea level impact velocities for the specified reentry flights varied from approximately 10 to 2.5 kft/sec respectively. Crossovers in the velocity profiles occurred for the chosen trajectories (blown up in right hand plot). The highest impact velocities were not the highest at reentry. Impact velocity is a function of integrated drag and as such flight path angle; which was varied in this analysis as well.

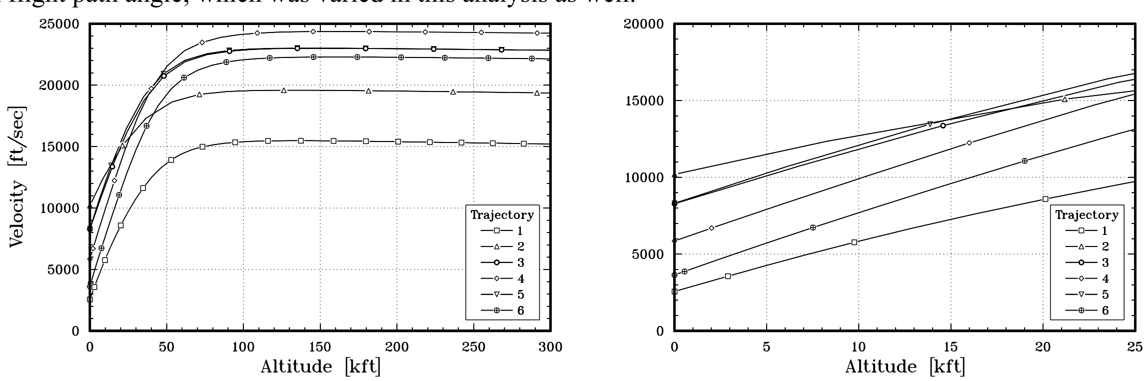

Figure 2 - Trajectory Comparison

VI. Sample Parametric Study Analysis Results

Attenuation and bursting frequency analysis results for the study are summarized in the following sections. Attenuation results are presented for the parametric trajectory analysis for a frequency of 0.5 GHz. Frequencies were also examined parametrically from 0.5 to 2.5 GHz for each trajectory. For illustrative purposes, results are shown for all frequencies for trajectory two.

A. Transmitted Signal Loss - Trajectory Parametrics:

The energy contained in an electromagnetic wave incident upon a plasma is divided into three segments while traversing the ionized gas. Part of the energy remains in the wave exiting on the opposite side. A second portion will be reflected away from the direction of the original path. The remaining fraction is absorbed by the plasma. This portion goes into increasing the motion of the constituent molecular species as a result of the force applied to the charged particles by the EM field of the wave. The combined energy loss contained in the reflected and absorbed segments is what is predicted by the EMLOSS program in PIRATE and shown in Figure 3 for the parametric trajectories.

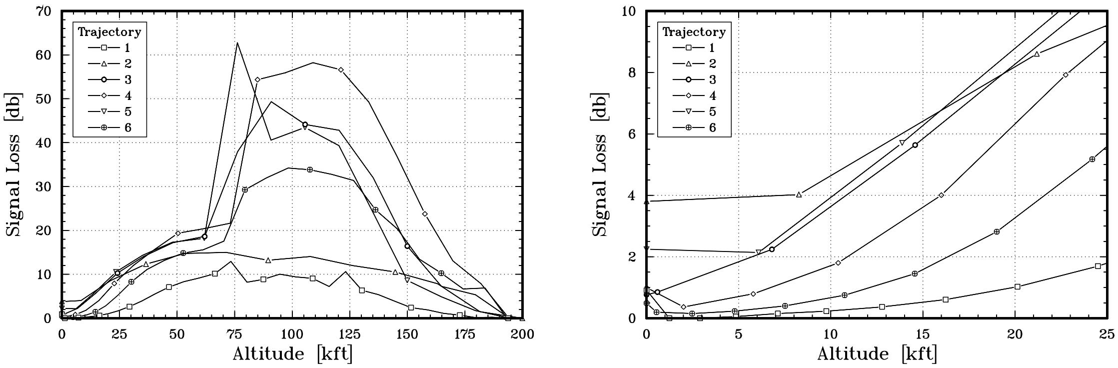

Figure 3 - Attenuation for Parametric Trajectories

The heatshield was assumed to have a sodium contamination level of fifty parts per million. This is consistent with historical specifications for production vehicle heatshields. The illustration is combined transmission signal loss across the boundary and inviscid layers for all six trajectories. Illustrated loss is for a 0.5 GHz wave transmitted in a transverse electric polarization mode normal to the plasma at the 48 inch axial location. BLUNTY was the reference heating code used and it was included in the iterative cycle to account for changes in boundary layer edge entropy with hot wall effects. Peak loss predictions varied with altitudes ranging from 60 to 110 kft. Some numerical irregularities were observed with higher laminar loss predictions of some flights dominating turbulent predictions. This is a development topic of the current effort funded by the ASCI Design Integration work. In general, case four exhibited the highest predicted loss; approximately 58 db in the laminar region at 110 kft. This was the highest reentry velocity trajectory. Based on radar group information, transmission blackout for practical purposes occurs when one-way signal loss reaches 50 to 60 db. Worst case trajectory predictions are skirting this region. Maximum loss for the lowest reentry velocity case was on the order of 10 db centered around 100 kft. Signal loss in all cases dropped below 4 db at impact (see left hand illustration in Figure 3). Highest loss at impact occurred for the steepest reentry angle case (i.e. trajectory two) due to maintenance of higher low altitude velocities.

B. Transmitted Signal Loss - Frequency Parametrics:

Due to its position of maximum attenuation at impact, trajectory two analysis results for the probing frequency parametrics are shown in Figure 4.

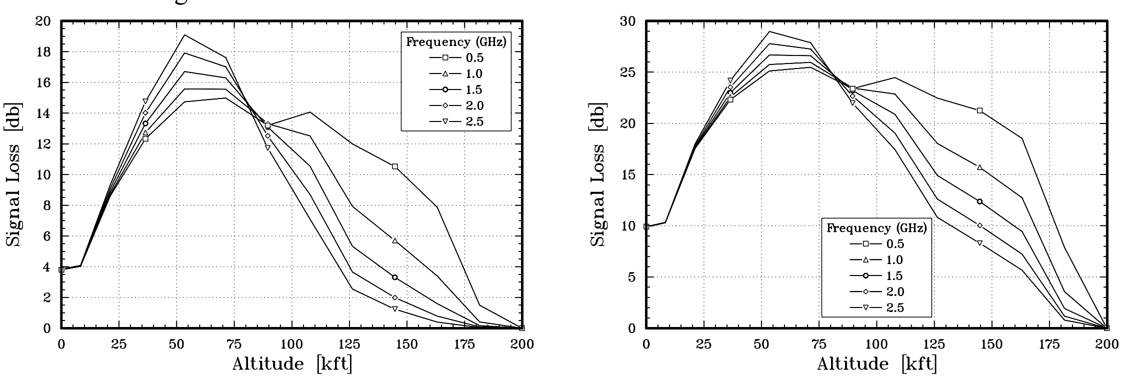

Figure 4 - Attenuation for Trajectory 2 Frequency Parametrics

As in the trajectory parametrics, the left hand illustration is for waves transmitted in a transverse electric polarization mode normal to the plasma at the 48 inch axial location. They also included BLUNTY in the iterative process to account for hot wall entropy effects. Peak loss is approximately 19 db at 55 kft for the 2.5 GHz probing frequency. An interesting aspect of this parametric study was the manner in which the curves crossed over relative to attenuation levels as a function of frequency. At high altitudes, increasing attenuation went with decreasing probing frequency. Contrary to this, at low altitudes, increasing attenuation levels followed increasing probing frequency. This is the result of the complex competing roles played by electron collision frequency with larger species and the effect of electron density producing a characteristic plasma frequency for transmission cutoff. Solution of the controlling differential equations yields a wave function that includes both parameters in the transmission coefficient. The right hand figure shows the results when the transmission angle across the plasma is increased from 0 to 75 degrees relative to the surface normal. Relative positioning of the curves is unchanged for the frequency spectrum. However, maximum attenuation is increased to 29 db for the 2.5 GHz signal.

C. Turbulence Modulation Frequency:

Turbulent modulation frequency estimates predicted by the zeroth order relation (Equ. 11) discussed in the NERMS code section are shown in Figure 5 for all six trajectories.

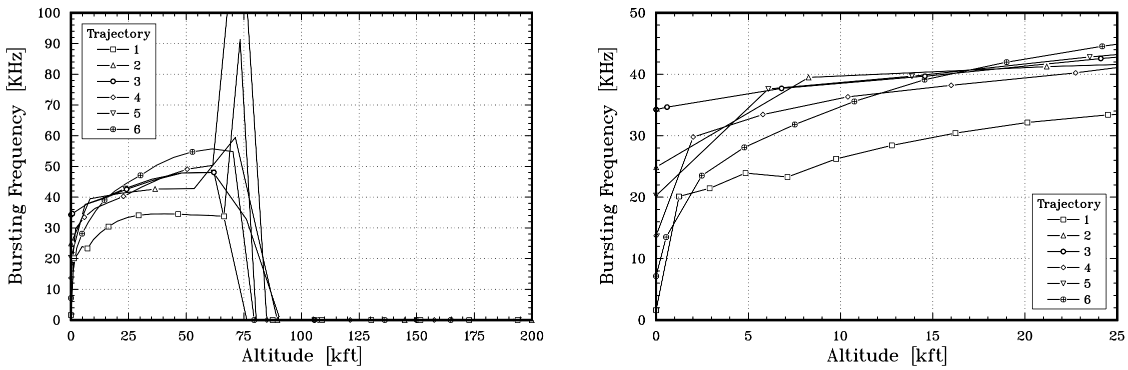

Figure 5 - Zeroth Order Bursting Frequency

As in the attenuation analyses, this was calculated at the 48 inch axial location. Since this is a turbulent flow phenomenon, there are no values represented above the transition altitudes (approximately 75 kft). The initial values calculated after transition to turbulent flow are erratic. This may be the result of a mismatch between the boundary layer thickness value and the codes declaration of transition. A laminar value (smaller than its turbulent counterpart) may be in use in the initial calculation. When ignoring the initial point, bursting frequencies varied from approximately 20 to 40 KHz till just before impact. The impact region is shown in more detail in the right hand illustration. Cases one, four, and six drop to bursting frequencies of less than 15 KHz at impact. Two, three, and five remain in the 20 to 40 KHz range.

VII. Closing

A new capability (PIRATE) to analyze the interaction of reentry systems with their enveloping plasma has been introduced. PIRATE combines thirteen different tools to solve a coupled physics design problem. The driving potential for this teamed code development project was the current national and lab culture of faster, cheaper, and better. All of these goals have been obtained by combining technology and managing the expertise from four centers within the lab and with the assistance of external industrial, government, and university entities. The tool solves the coupled physics problem surrounding the motion, heating, thermal response, chemistry, and electromagnetic wave aspects included in a reacting boundary layer during vehicle reentry. To demonstrate this, a system was solved parametrically examining 6 trajectories and 5 probing microwave frequencies. This was accomplished with a mere fraction of the manpower effort that would have been required in days past. Signal attenuation and frequency modulation effects were examined over a myriad of flight conditions. The immediate benefit of this type of analysis is to guide design work as well as to more wisely choose costly test flights in regions that may be most stressing for a design concept. Execution time and computing platforms required for this type of effort will be discussed in the final paper.

Acknowledgements

PIRATE was developed as part of a team effort. Two members of the team that I would like to acknowledge specifically are Billy Brock and Bill Liou. Both contributed heavily to the development of the plasma interaction analysis tools. The codes they wrote are referenced in the text and both provided valuable phenomenology discussions.

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