UPDATED ABLATION AND THERMAL RESPONSE PROGRAM FOR SPACECRAFT HEATSHIELD ANALYSIS

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ABSTRACT

The Fully Implicit Ablation and Thermal response program (FIAT) simulates one-dimensional transient thermal energy transport in a multilayer stack of thermal protection system (TPS) materials and structure that can ablate from the top surface and decompose in-depth. Recently, a number of upgrades have been incorporated into a second version of FIAT. This new version, named FIATv2, is available from NASA Ames Research Center to qualified individuals and organizations. The purpose of this paper is to describe and demonstrate the expanded capabilities of FIATv2.

INTRODUCTION

Spacecraft heatshields typically use thermal protection system (TPS) materials that pyrolyze and ablate at high temperature for efficient rejection of the aerothermal heat load. Pyrolysis is an internal decomposition of the solid that releases gaseous species, whereas ablation is a combination of processes, including chemical reaction, sublimation and vaporization, that consumes material at the heatshield surface. For design and sizing of ablating spacecraft TPS materials, it is important to have a reliable numerical procedure that can predict in-depth conduction and pyrolysis as well as the surface recession rate.

A simplified diagram of the geometry under consideration is shown in Figure 1. The outer surface of the heatshield is exposed to an aerothermal heating environment (convective and radiative) that can be predicted with modern computational tools. The TPS material may be a single layer or a multilayer composite. The inner surface of the heatshield usually is bonded, rather than mechanically attached, to a structural component. The structural mass should be included in the thermal response simulation to correctly predict the bond-line temperature history. The maximum allowable bond-line temperature is often a key parameter in determining the TPS thickness.

A number of analysis programs have been written to simulate one-dimensional heatshield pyrolysis and ablation. The CMA code,[1] developed by Aerotherm Corporation in the 1960's, was the first to couple the internal energy balance and decomposition equations with a general surface energy balance (SEB) boundary condition and a thermochemical ablation model. The FIAT code,[2] developed at NASA Ames Research Center in 1997, solves essentially the same equations as CMA with a fully implicit solution methodology to achieve greater numerical

stability. Some representative applications of FIAT are TPS sizing for planetary entry capsules,[3-4] analysis of flight data,[5-6] and Monte-Carlo TPS sizing uncertainty analyses.[7]

After the initial release of FIATv1 in 1998, a number of upgrades were incorporated into different versions of FIAT that were used for various applications. In the past year, for application to the Crew Exploration Vehicle (CEV) Program, most of these upgrades were combined into a single code named FIATv2. The FIATv2 application may be obtained by qualified individuals or organizations by completion of a Non-Disclosure and Software Usage Agreement with NASA Ames Research Center. Both ITAR and non-ITAR versions of the FIATv2 application and materials database are available. The ITAR version is subject to export-control and distribution restrictions and is available to NASA employees and contractors working on TPS analysis for CEV. Only the non-ITAR version is described in herein.

The purpose of this paper is to describe and demonstrate the expanded capabilities of FIATv2. The major improvements in FIATv2 (2006) compared with FIATv1 (1998) are as follows:

- A material database file is used to facilitate configuration management of material properties;
- The thickness of any material ply may be optimized to achieve a specified maximum temperature at a selected material interface;
- Output files contain header blocks with engineering or SI units as specified by the user;
- For multiple environments, output files are numbered sequentially;
- Some material properties may be input as a function of pressure;
- An air/radiation gap may be used;
- The default grid is improved, and the user-defined grid is still available;
- The FIATv2 application runs in a unix environment on Mac, PC, and Linux platforms.

The sections that follow provide a brief review of FIATv2 equations, a detailed look at input and output files, and a description of the sample problems.

FIATV2 EQUATIONS

An example of a FIATv2 grid is illustrated in Figure 2. Based on the material types and thicknesses, FIATv2 automatically generates a grid for each material ply. Each subsurface ply has a uniform grid. Typically, the top ply (material 1) has geometric stretching with finer resolution near the heated surface. In all plies, the maximum cell size never exceeds 0.1 inch. If the default grid is not satisfactory, the user may input a grid or specify how many cells to use in any subsurface ply. To account for surface recession, the grid is compressed in the top ply.

Density, pressure, and temperature are defined at cell centers, whereas heat and mass fluxes are defined at interfaces. Figure 3 provides a simple derivation of the equations for subsurface mass and energy conservation. A full nomenclature list is provided after the References section of this paper. The pyrolysis gas flow is assumed to be quasi-steady in the surface-normal direction. The equations are slightly more complicated in the top ply, because of the non-Lagrangian motion of the grid as it is compressed.

Most ablative TPS materials are organic resin composites. The composite solid is modeled as a general mixture of a two-component resin and a reinforcing material. The local density of the solid is given by the equation

$$\rho_s = (1-\phi)\left[\Gamma(\rho_A + \rho_B) + (1-\Gamma)\rho_C\right]$$

where A and B represent the organic resin, and C represents the reinforcing material. The porosity ϕ and resin volume fraction Γ are input quantities. Each of the three components may decompose independently. The decomposition is modeled as an Arrhenius-type reaction:

$$\frac{\partial}{\partial t}\left(\frac{\rho_i - \rho_{ri}}{\rho_{vi}}\right) = -A_i\left(\frac{\rho_i - \rho_{ri}}{\rho_{vi}}\right)^{\psi_i} \exp(-E_i/RT), \quad i = \text{A,B,C}$$

where ρ_{vi} and ρ_{ri} are the original (virgin) and the residual (char) density, respectively, of component i. The pyrolysis gas mass flux is calculated by the following approximation:

$$\dot{m}_g = \int_{\eta_0}^{\eta}\left(\frac{\partial \rho_s}{\partial t}\right) d\eta$$

The conditions at the ablating surface are determined by the aerothermal environment and by chemical interactions between the boundary layer gas, the pyrolysis gas, the ablation products, and the chemical constituents of the surface material. FIATv2 employs the following SEB:

$$\rho_e u_e C_{\text{H}}\left[H_r - h_w\right] + \dot{m}_c h_c + \dot{m}_c h_c + \alpha_w q_{\text{rad}} = (\dot{m}_c + \dot{m}_g)h_w + \sigma\varepsilon_w T_w^4 + q$$

Here $\rho_e u_e C_{\text{H}}$ is the convective heat transfer coefficient, H_r is the recovery enthalpy, q is the conduction heat flux, and all other quantities are defined at the ablating surface. Figure 4 illustrates the derivation of this equation as a sum of the various types of energy flux to and from the surface. This equation has been simplified from the general form presented in Reference 2 by assuming equal diffusion coefficients within the boundary layer and equal Stanton numbers for heat and mass transfer ($C_{\text{H}} = C_{\text{M}}$).

A blowing correction accounts for the reduction in heat transfer coefficient due to the injection of gases from pyrolysis and surface ablation into the boundary layer. The blowing correction equation used by FIATv2 is

$$\frac{C_H}{C_{H1}} = \frac{\ln(1 + 2\lambda B')}{2\lambda B'} = \frac{2\lambda B_1'}{\exp(2\lambda B_1') - 1} \quad \text{where} \quad B' = \frac{(\dot{m}_c + \dot{m}_g)}{\rho_e u_e C_{\text{M}}} \quad \text{or} \quad B_1' = \frac{(\dot{m}_c + \dot{m}_g)}{\rho_e u_e C_{\text{M1}}}$$

Here λ is the blowing reduction parameter and $C_{\text{H}}/C_{\text{H1}}$ is the ratio of the blown (ablating) to the unblown (nonablating) heat transfer coefficients. For laminar flow $\lambda = 0.5$, and for transitional or turbulent flow values between 0.2 and 0.4 are used. B' is a nondimensional mass blowing rate. Tables of B' (and h_w) for ablative materials can be generated using the ACE or MAT codes.[8-9]

In the equations above, H_r, $\rho_e u_e C_{\text{H1}}$, α_w, ε_w, λ and q_{rad} are input quantities, and $\dot{m}_g$, q and T_w are solution variables. Therefore, $\dot{m}_c$ and h_w are the only additional unknowns that are obtained using the B' tables of the TPS material. In general, for pyrolyzing ablators B'_c is a complex function of temperature, pressure, and B'_g.

Figure 5 is a plot of B'_c vs T_w with B'_g as a parameter for a carbon-phenolic material at one pressure. For numerical stability, these curves should be sufficiently smooth and well-resolved for interpolation. For a well-behaved model, B'_c should generally increase monotonically with temperature. The curves in the figure exhibit both attributes. For this material, a fine resolution for B'_g between 0.35 and 0.5 was needed. Solutions at low B'_g resemble carbon ablation with a diffusion-limited plateau for the production of CO at the surface. At large values of B'_g, this plateau is suppressed.

FIATV2 FILE STRUCTURE

The FIATv2 file structure is illustrated in Figures 6-7 and summarized in Tables 1-2. FIATv2 reads input from three files. File *envir.inp* provides the time history of boundary condition data at the heated surface. Files *matdatabase.inp* or *matprp.inp* contain the material property data. File *main.inp* contains all other input quantities.

The default file names are used unless the user specifies alternative names in the unix command line: the command *fiatv2 file1 file2 file3* will run the executable file *fiatv2* with file names *file1* substituted for *main.inp*, etc. The material property file *matprp.inp* is selected if the user specifies IMATL ≠ 0 in the main input file. A complete description of all input quantities and units may be found in the FIATv2 User's Manual that is provided on the FIATv2 User's CD.

Table 1. FIATv2 Input Files

File Type	Default File Name	Alternative File Name
Main Input	*main.inp*	*file1* specified on command line
Surface Environments	*envir.inp*	*file2* specified on command line
Material Properties	*matdatabase.inp* or *matprp.inp*	*file3* specified on command line

FIATv2 writes five types of output files. Default file names are used unless the user specifies multiple environments in the environment input file. In this case, FIATv2 writes five output files for each environment, and these files are numbered sequentially as shown in Figure 7. In either case, if thickness optimization of a material ply is being performed, these files contain the output for the optimized ply thickness, with the exception of *thkrec.out*, which provides the iteration history for the sizing optimization.

Table 2. FIATv2 Output Files

File Type	Default File Name	Alternative File Name
Main Output	*fiat.out*	*fiat001.out, fiat002.out, …*
Thickness Iterations	*thkrec.out*	*thkrec001.out, threc002.out, …*
Pyrolysis and Ablation Data	*surf.out*	*surf001.out, surf002.out, …*
Thermal Data	*tc.out*	*tc001.out, tc002.out, …*
Interface Data	*interface.out*	*interface001.out, interface002.out, …*

INPUT FILE EXAMPLES

Sample *main.inp* files for cases with and without thickness optimization are presented in Figures 8 and 9, respectively. This file begins with a title line that is reproduced in the output files. The next few lines are various run parameters as described in the User's Manual. At the end of the file, the material ply data are tabulated. The ply information includes the ply number (sequential), the material name (from the database file), the initial temperature, the ply thickness, and the contact resistance, if any, at the bottom of the ply. In Figure 9, lines 5 and 6 specify that

the thickness of material one is to be optimized to reach a maximum temperature of 950 R at its lower surface.

Figure 10 is a sample *environment.inp* file for an arcjet case. The top line indicates that three environments are stacked in this file. These runs will be 90% of nominal heating, nominal heating (as tabulated in the file), and 110% of nominal heating. The intent of this case is to assess the effect of an estimated ±10% uncertainty in arcjet heating conditions on the ablation and thermal response of the TPS material. Each environment begins with a title line, followed by a second line that contains scaling factors that are applied to the convective and radiative heating table. For any environment, the active table may be re-used or a new table may be input. The five-line table in Figure 10 contains the time-dependent aerothermal boundary conditions for a nominal arcjet environment of 1000 W/cm^2 cold-wall heat flux and 0.75 atm for 30 seconds.

Figure 11 shows the top portion of the *matdatabase.inp* file. The first line is the title, and the next two lines are for information only. The fourth line gives the number of materials to be input (eight in this case) and the next eight lines provide, for each material, the character-string name, the version number, and the data type. There are five possible material types as noted on line 3; however, type 2 is not currently implemented in FIATv2. The material property data for each material sequentially follow this header block.

OUTPUT FILE EXAMPLES

FIATv2 output files have a common header followed by a file-specific header. The common header is shared by all five output files of any particular run. An example of the common output file header is shown in Figure 12. The common header includes the following information:

- The application name and version number
- The run title (from *main.inp*)
- The environment title (from *envir.inp*)
- The applicable convection and radiation scaling factors (from *envir.inp*)
- The database title (from *matdatabase.inp*)
- The material ply data (from *main.inp*)
- The thickness optimization being performed, if any (from *main.inp*)

File-specific headers are presented in Figures 13-17. All output quantities are labeled with SI or engineering units as specified by the user.

File *tc.out* (Figure 13) lists thermocouple temperatures and isotherm depths, at depths and thicknesses, respectively, specified in the main input file. Also tabulated are the surface temperature and, if thickness optimization is being performed, the temperature at the optimization location (under the header "bondloc"). Thermocouple columns "disappear" in the event a thermocouple is ablated.

File *fiat.out* (Figure 14) is the largest output file. For each print time, through-the-thickness profiles of solution quantities are tabulated. These quantities include depth (from the original surface), heat flux, temperature, density, and pyrolysis gas flux. The depth listed for point #1 is the surface recession at the specified time.

File *interface.out* (Figure 15) provides temperature and heat flux at inter-ply boundaries. To fit in 132 columns, the output is limited to the first five material interfaces. This information is useful for transfer of FIATv2 output to another thermal analysis tool.

File *surf.out* (Figure 16) tabulates surface temperature, surface blowing rates, total recession, char depth and virgin depth for each time step. The pyrolysis zone is defined as the region where the solid density is between 2% and 98% of the difference between ρ_v and ρ_c.

File *thkrec.out* (Figure 17) provides the iteration history for thickness, interface temperature, and recession. If sizing optimization is being performed, this file is the only record of the iterations performed by FIATv2. All other output files contain only the results for the optimized thickness, or for the final iteration if the optimization did not converge. This figure shows that eleven iterations were needed for FIATv2 to determine the thickness required to produce a maximum temperature of 950 R at the bond line. Convergence is typically achieved in 9 to 12 iterations.

SAMPLE PROBLEMS

The non-ITAR version of FIATv2 includes two sample problems. Complete input and output files are provided in the SampleProblems directory on the FIATv2 User's CD (Figure 18).

The first sample problem is the highest integrated heat load location on a CEV-like geometry for a lunar-return skipping trajectory. The second sample problem is an arcjet test condition with three environments (from Figure 10). For each problem, FIATv2 analyses are performed for two different TPS materials. The first material is the carbon phenolic used on the Pioneer Venus entry probes.[10] The second material is a reinforced carbon-carbon such as that used on the Shuttle Orbiter,[11] but without oxidation protection coatings that would be ineffective in these high heating environments.

The lunar skipping trajectory environment (Figure 19) has a high heating pulse, a cooldown period, then a second heat pulse of lower magnitude but long duration. In each pulse, the total surface blowing is greater for the pyrolyzing material (carbon phenolic) than for the non-pyrolyzing material (RCC). The solid ablation rate is higher for the RCC. For carbon phenolic, in the first heat pulse the pyrolysis gas blowing rate exceeds the char ablation rate. In the second heat pulse, as the phenolic has already been depleted near the surface of the composite, the char vaporization rate exceeds the pyrolysis gas blowing rate. The TPS thickness required to limit the bondline temperature to 950 R is much greater for RCC (7.7 inches) than for carbon phenolic (3.3 inches). This difference is attributed primarily to the higher thermal conductivity of RCC at lower temperatures.

For the arcjet environment (Figure 20), three heating conditions were run. These conditions were cold-wall heat fluxes of 900, 1000, and 1100 W/cm^2 at a stagnation pressure of 0.75 atm for 30 seconds, followed by a 30 minute cooldown at low pressure. The peak bondline temperature is relatively insensitive to the surface heat flux, presumably because most of the incident energy is being dissipated by ablation, pyrolysis, and reradiation. The total recession is strongly dependent on the heat flux. RCC recession is a fairly linear function of time.

SUMMARY

This paper described and demonstrated the expanded capabilities of FIATv2 (2006) compared with FIATv1 (1998). The major improvements in FIATv2 are:

- A material database file is used to facilitate configuration management of material properties;
- The thickness of any material ply may be optimized to achieve a specified maximum temperature at a selected material interface;
- Output files contain header blocks with engineering or SI units as specified by the user;
- For multiple environments, output files are numbered sequentially;
- Some material properties may be input as a function of pressure;
- An air/radiation gap may be used;
- The default grid is improved, and the user-defined grid is still available;
- The application runs in a unix environment on Mac, PC, and Linux platforms.

The FIATv2 application may be obtained by qualified individuals or organizations by completion of a Non-Disclosure and Software Usage Agreement with NASA Ames Research Center. Both ITAR and non-ITAR versions of the FIATv2 application and materials database are available.

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NOMENCLATURE

A_i	=	pre-exponential constant
B'	=	nondimensional mass flux
C_H	=	Stanton number for heat transfer
C_M	=	Stanton number for mass transfer
E_i	=	activation energy
H_r	=	recovery enthalpy
h	=	enthalpy
$\dot{m}$	=	mass flux
P	=	pressure
q	=	conduction heat flux
q_{rad}	=	radiative heat flux
R	=	universal gas constant
T	=	temperature
t	=	time
α	=	surface absorptance
ε	=	surface emissivity
Γ	=	volume fraction of resin
λ	=	blowing reduction parameter
ρ	=	density
$\rho_e u_e C_H$	=	heat transfer coefficient
σ	=	Stefan-Boltzmann constant
ψ	=	decomposition reaction order
η	=	surface-normal coordinate
ϕ	=	porosity

subscripts

c	=	char
e	=	boundary-layer edge
g	=	pyrolysis gas
i	=	density component A, B, and C
r	=	residual (char)
s	=	solid
v	=	virgin
w	=	surface (wall)
0	=	reference value
1	=	unblown value

- 1-D time-accurate solution of thermal diffusion with surface ablation and internal pyrolysis
  - Same equations as the Aerotherm CMA code
  - Greater stability
- Multilayer material stack
  - TPS, adhesive, insulation, structure, etc.

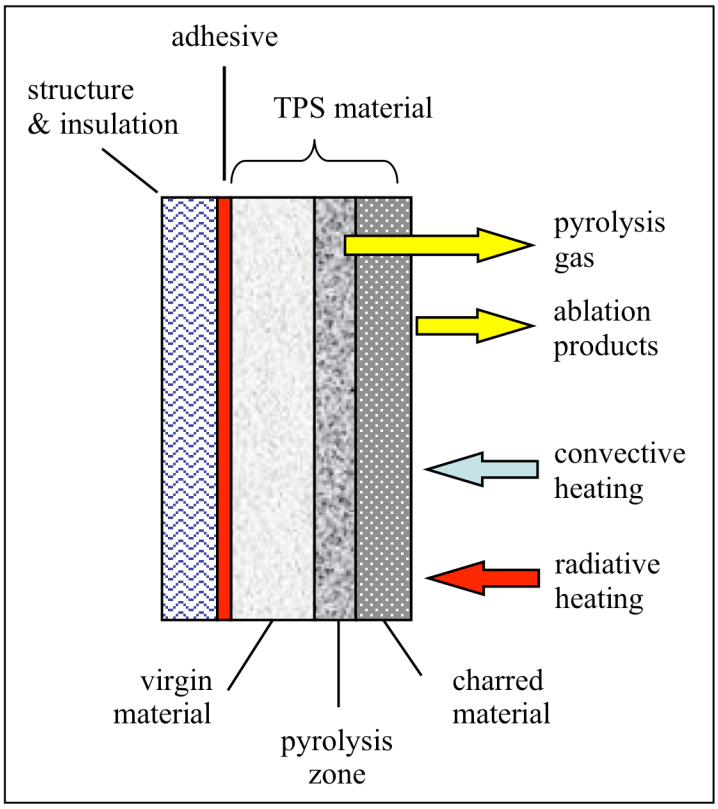


Figure 1. FIATv2 geometry.

- Based on the material type and thickness, FIATv2 automatically generates a grid for each material ply
  - Maximum of 10 plies
  - In most cases, the top ply has a geometrically-stretched grid
  - The maximum cell size never exceeds 0.1 inch
- If recession occurs, the grid in the top material is compressed
- Temperature, pressure, and density are defined at cell centers
- Fluxes are defined at cell interfaces

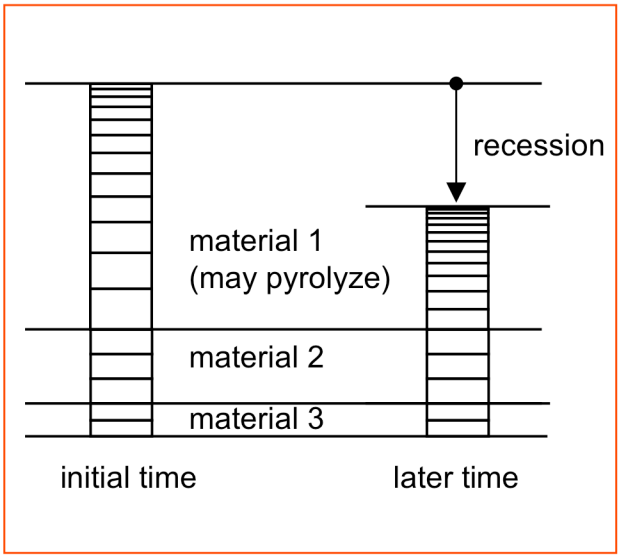
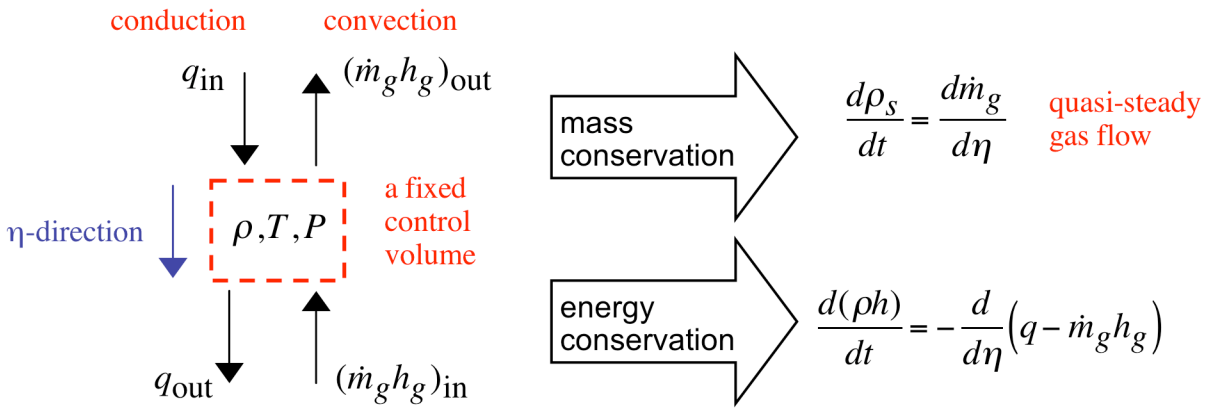


Figure 2. FIATv2 grid example with recession.



- In the top ply only:
  - The grid is compressed to account for recession
  - Extra terms appear in the equations owing to the "non-Lagrangian" movement of the control volume

Figure 3. Internal mass and energy balances derived from a finite control volume.

- Assume equal diffusion coefficients and $C_M = C_H$
- Balance the energy fluxes at the ablating surface (at temperature T_w)

$$\rho_e u_e C_H [H_r - h_w] + \dot{m}_c h_c + \dot{m}_c h_c + \alpha_w q_{rad} = (\dot{m}_c + \dot{m}_g) h_w + \sigma \varepsilon_w T_w^4 + q$$

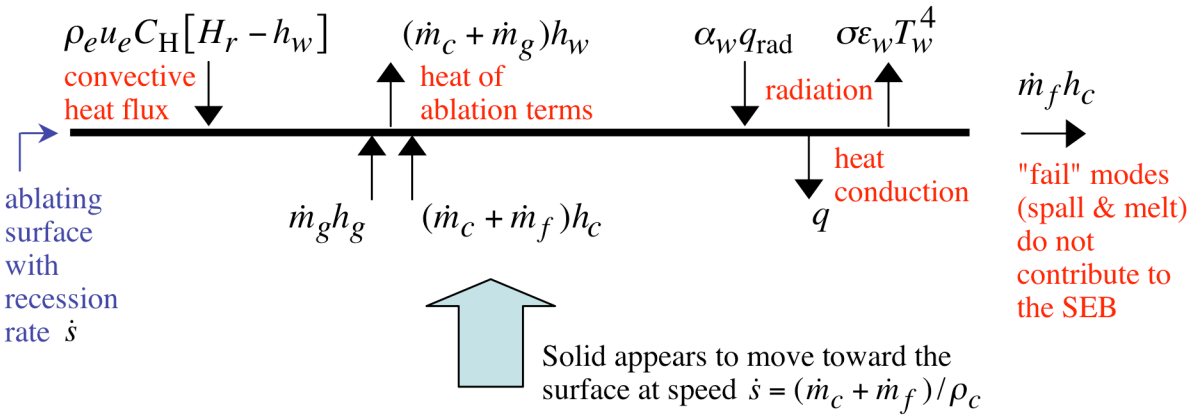


Figure 4. The surface energy balance.

- This set of solutions works well with FIATv2
- B' solutions for organic resin composites are complex
  - Plotting the solutions should be a prerequisite!
  - After plotting, some $B'g$ may be eliminated or added, as needed
  - For this composition, fine resolution for $B'g$ from 0.35 to 0.50 is needed
- The shape of the solutions depends on the elemental and species compositions in the gas mixture at the surface

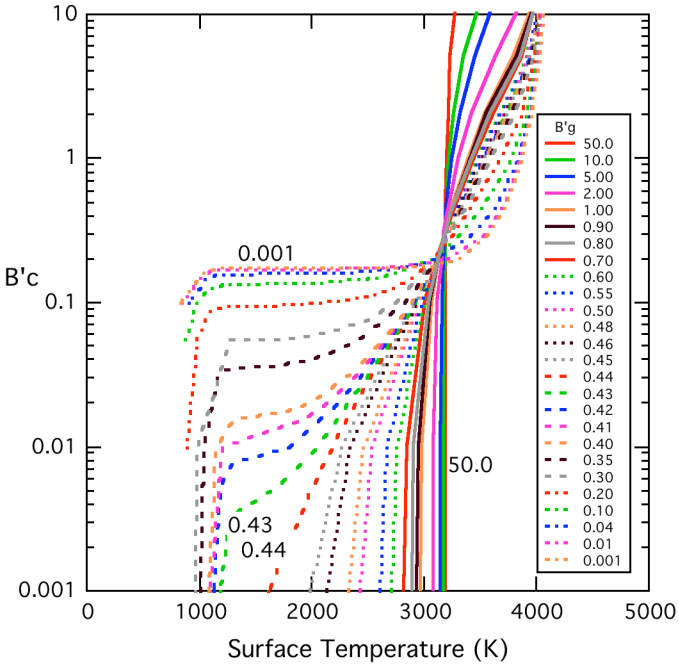


Figure 5. B' curves for carbon phenolic at one pressure.

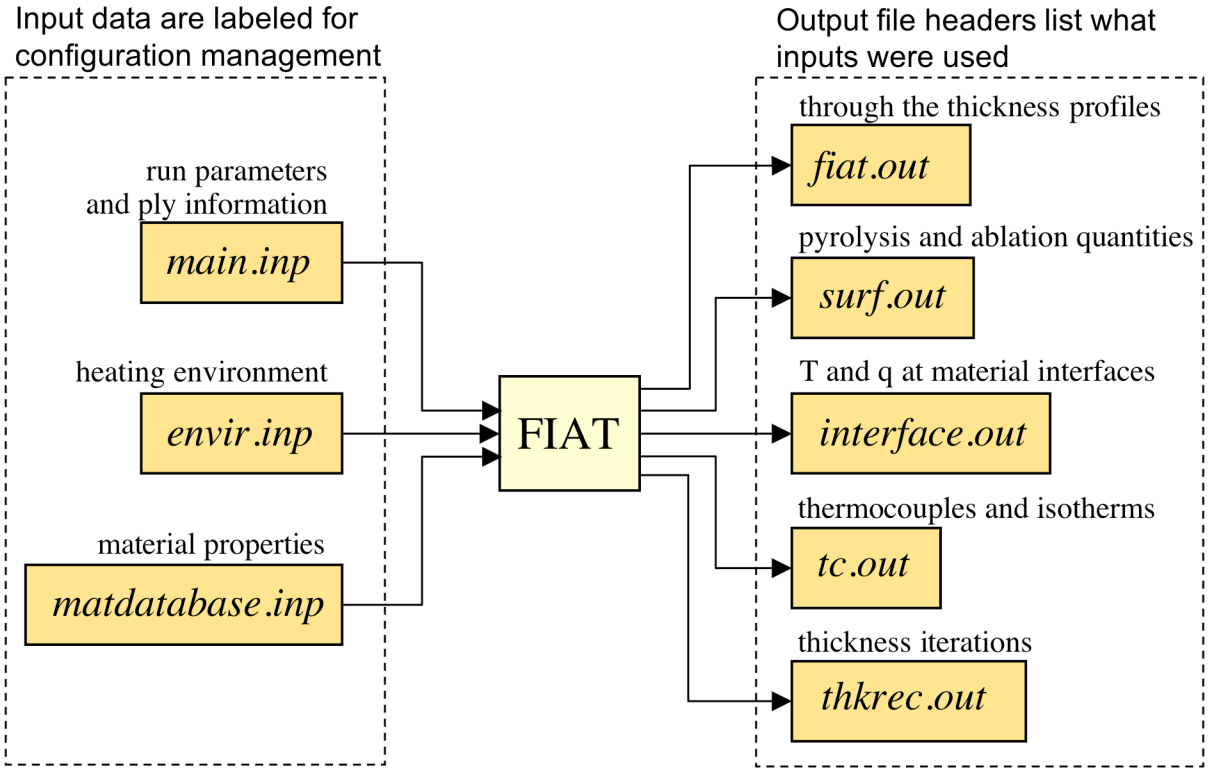
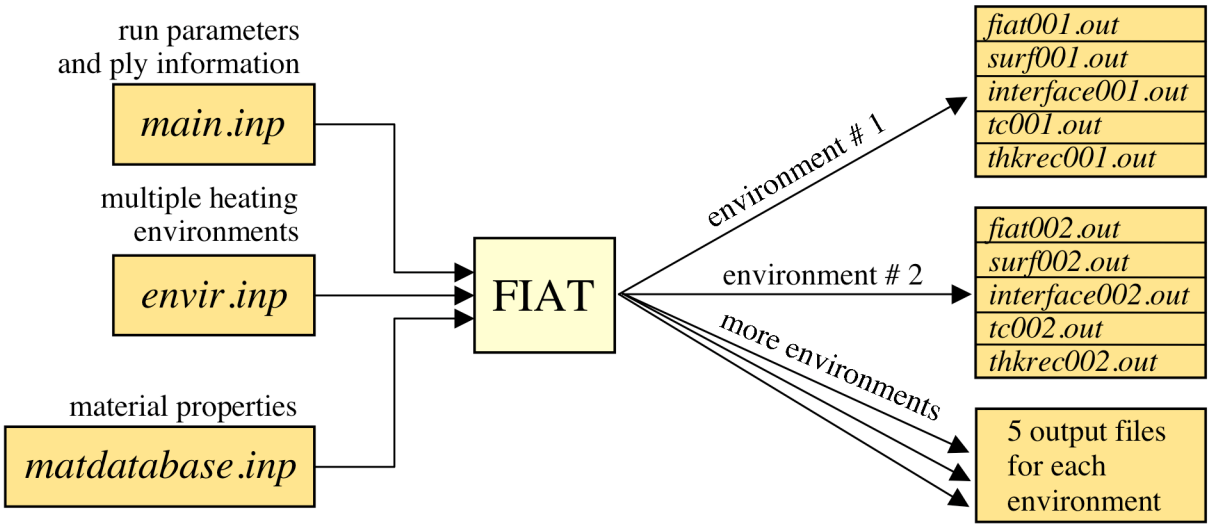
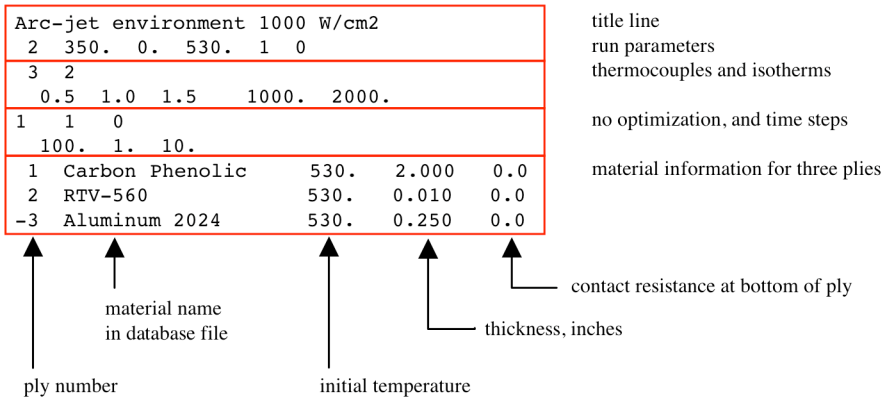


Figure 6. FIATv2 file structure.



- Five output files per environment
- Current limit is 999 environments (4995 output files)

Figure 7. Alternate output files.



- The title line is printed in all output files
- All input quantities and units are listed in the FIATv2 User's Manual

Figure 8. Main input file (*main.inp*) for arcjet case. No thickness optimization.

```
DAC2 worst integrated heatload
 2  350.  0.  0.  1  0
 6  0
  0.2  0.5  1.0  1.5  2.0  2.5
1   0  -1
  950.  6.   1.
  100.  1.  10.
 1  Carbon Phenolic    500.    3.500     0.0
 2  RTV-560            500.    0.020     0.0
 3  Ti-6Al-4V          500.    0.032     0.0
 4  Ti 64 HC           500.    2.000     0.0
-5  Ti-6Al-4V          500.    0.032     0.0
```

title line
run parameters
thermocouples and isotherms

optimization and time steps

material information for five plies

- Ply 1 is to be optimized for a maximum temperature of 950 R at it's lower surface
- The initial guess for thickness is 3.5"
- The optimized thickness is estimated to be between 1" and 6"

Figure 9. Main input file (*main.inp*) for flight case, with thickness optimization.

```
3
Run 1: scaled 90% heating
5   0.9   0.9
   0.     12519.   0.   0.0704     0.75   0.5
  30.     12519.   0.   0.0704     0.75   0.5
  30.2    12519.   0.   0.000001   0.75   0.5
  30.5    12519.   0.   0.000001   0.001  0.5
2000.0    12519.   0.   0.000001   0.001  0.5
Run 2: unscaled (100%) heating
0   1.0   1.0
Run 3: scaled 110% heating
0   1.1   1.1
```

number of environments
first environment title
table size and scaling factors

five table lines
$t, H_r, q_{\text{rad}}, \rho_e u_e C_{\text{H1}}, P, \lambda$

second environment title
reuse table with new scaling
third environment title
reuse table with new scaling

- An environment table may be reused with different scaling factors
- Alternatively, a new table may be input for any environment
- Here we are considering heat fluxes of 900, 1000, and 1100 W/cm^2

Figure 10. Environment input file (*envir.inp*) for arcjet case, with three environments.

```
FIAT Material Database File, Non-ITAR Version 1.00 May 2006 NASA Ames
Material specification: sequence number, character name, version number, type
Type: 0=subsurface, 1=reusable, 2=pyro only, 3=abl only, 4=pyro+abl
   8  number of materials to follow, format i4,2x,a16,2x,a5,2x,i1
   1  Aluminum 2024       1.00  0
   2  BMI graphite        1.00  1
   3  Carbon Phenolic     1.00  4    Peterson & Nicolet, JSR 1974
   4  RTV-560             1.00  0    C-TPSA-A-DOC-000,  Ver. 01 (Rev. 0)
   5  Shuttle RCC         1.00  3    TPSX
   6  SIP                 1.00  0    C-TPSA-A-DOC-000,  Ver. 01 (Rev. 0)
   7  Ti-6Al-4V           1.00  0    C-TPSA-A-DOC-000,  Ver. 01 (Rev. 0)
   8  Ti 64 HC            1.00  0
...material data sets, in the sequence given above, follow this line
```

this area may be used to indicate the source of the data

- First line is the title, to be reprinted in all output files
- Second and third lines are for information only
  - There are five material types, as noted
- Fourth line lists the number of materials to be input
- Then the main header block lists, in order, the names, version number, and type for each material
- The property models sequentially follow this header block

Figure 11. Material database file header.

```
FIAT version 2.01 May 2006 NASA Ames
Title: DAC2 worst integrated heatload
Environment: DAC2 lunar skipping margined (1.822  conv, 2.7 rad)
     convection scaling factor =    1.822
     radiation  scaling factor =    2.700
FIAT Material Database File, Non-ITAR Version 1.00 May 2006 NASA Ames
     Matl.  1 = Carbon Phenolic   version  1.00  thick= 3.29248 inches
     Matl.  2 = RTV-560           version  1.00  thick= 0.02000 inches
     Matl.  3 = Ti-6Al-4V         version  1.00  thick= 0.03200 inches
     Matl.  4 = Ti 64 HC          version  1.00  thick= 2.00000 inches
     Matl.  5 = Ti-6Al-4V         version  1.00  thick= 0.03200 inches
Thickness optimization of material  1 based on temperature at bottom of material 1.
```

optimized thickness for this case

- For each run, the five output files share a common header
  - Code name and version number
  - Run title (from *main.inp*)
  - Environment title (from *envir.inp*)
  - Convection and radiation scaling factors applied to the environment table
  - Material data file and version number
  - Material ply data
  - Thickness optimization being performed, if any

Figure 12. Common header block for output files.

```
Unit 36: Isotherm depths; surface, TC and optional  bondloc temperatures vs time.
         Bondloc is the depth used for thickness optimization.

                    isotherm temperature (R) or TC depth (inches) measured from initial surface
                    3.29248   0.20000   0.50000   1.00000   1.50000   2.00000   2.50000
                    -------   -------   -------   -------   -------   -------   -------
     time        Tw  bondloc      tc01      tc02      tc03      tc04      tc05      tc06
      sec         R         R         R         R         R         R         R         R

    0.000    500.00    500.00    500.00    500.00    500.00    500.00    500.00    500.00
    1.000    601.08    500.00    500.13    500.00    500.00    500.00    500.00    500.00
    2.000    648.97    500.00    501.39    500.00    500.00    500.00    500.00    500.00
    3.000    685.62    500.00    504.33    500.00    500.00    500.00    500.00    500.00
    4.000    719.03    500.00    508.97    500.01    500.00    500.00    500.00    500.00
    5.000    752.06    500.00    514.93    500.03    500.00    500.00    500.00    500.00
    6.000 ... one line of output for each print time
```

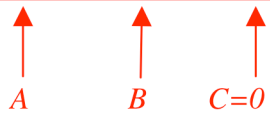
- Each output file has a file-specific header
- All quantities are labeled with SI or engineering units
- This example is the file *tc.out*
  - TC columns "disappear" when a thermocouple is ablated

Figure 13. File specific header example, for output file *tc.out*.

```
time(sec) =    52.00000

pt  material              depth       q cond      temp      density      m dot g   <---- partial densities
 #  name                    in    btu/ft^2-s     deg r      lb/ft^3     lb/ft^2-s          (dimensionless)

 1  Carbon Phenolic   1.7850E-05  159.0236206   3731.80   7.2804E+01   1.2751E-02   0.020269   0.000920   0.
 2  Carbon Phenolic   2.5887E-02  149.5080872   3451.48   7.2854E+01   1.2733E-02   0.025679   0.001484   0.
 3  Carbon Phenolic   5.2200E-02  134.4288330   3155.51   7.2937E+01   1.2676E-02   0.034079   0.002669   0.
 4  Carbon Phenolic   7.9416E-02  118.4277115   2838.45   7.3096E+01   1.2576E-02   0.048180   0.005582   0.
 5  Carbon Phenolic   1.0757E-01   98.8939743   2513.65   7.3450E+01   1.2377E-02   0.073571   0.013998   0.
 6  Carbon Phenolic   1.3668E-01   77.3291779   2192.08   7.4442E+01   1.1905E-02   0.123901   0.044589   0.
 7  Carbon Phenolic   1.6680E-01   55.3079796   1877.85   7.8040E+01   1.0444E-02   0.232599   0.180053   0.
 8  Carbon Phenolic   1.9795E-01   34.9508781   1591.47   8.4838E+01   5.2545E-03   0.453399   0.430924   0.
 9  Carbon Phenolic   2.3016E-01   22.4820614   1355.56   8.7695E+01   1.9461E-03   0.757994   0.465833   0.
10  Carbon Phenolic   2.6349E-01   15.4723940   1174.91   8.9012E+01   5.5881E-04   0.944518   0.466567   0.
11  Carbon Phenolic   2.9796E-01   11.4383144   1029.54   8.9374E+01   8.9340E-05   0.996291   0.466579   0.
12  Carbon Phenolic   3.3361E-01    8.5213213    913.14   8.9400E+01   9.2614E-11   1.000000   0.466579   0.
    ...there are 53 nodes of Carbon Phenolic, and 78 total.
74  Ti 64 HC          5.1778E+00    0.0000000    500.00   6.0150E+00   0.0000E+00   0.000000   0.000000   0.
75  Ti 64 HC          5.2889E+00    0.0000000    500.00   6.0150E+00   0.0000E+00   0.000000   0.000000   0.
76  Ti-6Al-4V         5.3525E+00    0.0000000    500.00   2.7650E+02   0.0000E+00   0.000000   0.000000   0.
77  Ti-6Al-4V         5.3685E+00    0.0000000    500.00   2.7650E+02   0.0000E+00   0.000000   0.000000   0.
78                    5.3765E+00    0.0000000    500.00                0.0000E+00 <-- back face values
```



- For each print time, through-the-thickness profiles are tabulated
- The last point (#78 in this example) lists the back-face values
- For pyrolyzing materials, "partial densities" are $(\rho_i - \rho_{ri})/\rho_{vi}$ for $i = A, B, C$

Figure 14. Sample output from file *fiat.out*.

```
Unit 45: Material interface data (T and Q)  vs time.
         Interface depth (inches) measured from initial surface.

              bottom of matl.   1    bottom of matl.   2    bottom of matl.   3
              depth =      3.2925    depth =      3.3125    depth =      3.3445
              -------------------    -------------------    -------------------
      time         T             Q         T             Q         T             Q
       sec         R     btu/ft2-s         R     btu/ft2-s         R     btu/ft2-s

     0.000    500.00     0.0000000    500.00     0.0000000    500.00     0.0000000
     1.000    500.00     0.0000023    500.00     0.0000006    500.00     0.0000000
     2.000    500.00     0.0000027    500.00     0.0000026    500.00     0.0000000
     3.000    500.00     0.0000038    500.00     0.0000022    500.00     0.0000001
     4.000    500.00     0.0000036    500.00     0.0000029    500.00     0.0000001
     5.000 ... one line of output for each print time
```

- This file contains temperature and heat flux at material interfaces
- Output limited to first 5 interfaces (to fit in 132 columns)
- These data may be useful as input to another analysis tool

Figure 15. File specific header for output file *interface.out*.

```
Unit 27: Pyrolysis and ablation quantities  vs time.
         Depths measured from initial surface.

                                                                                                  pyrolysis  zone range
 time        Tw       mdotg       mdotc       mdotf   mdottotal   recession    char(2%)   virgin(98%)
  sec         R    lb/ft2-s    lb/ft2-s    lb/ft2-s    lb/ft2-s      inches      inches      inches

0.000    500.00   0.000E+00   0.000E+00               0.000E+00    0.000000    0.000000    0.000000
1.000    601.08   2.683E-20   2.532E-07               2.532E-07    0.000000    0.000000    0.000000
2.000    648.97   2.457E-18   2.660E-07               2.660E-07    0.000000    0.000000    0.000000
3.000    685.62   5.156E-17   2.769E-07               2.769E-07    0.000000    0.000000    0.000000
4.000    719.03   6.254E-16   2.933E-07               2.933E-07    0.000000    0.000000    0.000000
5.000    752.06   5.927E-15   3.133E-07               3.133E-07    0.000000    0.000000    0.000000
6.000 ... one line of output for each print time
```

- Last three columns provide the recession and the locations of top and bottom of the pyrolysis zone
  - Pyrolysis zone is defined as the region 2% to 98% pyrolyzed based on density (same definitions used in the CMA code)
  - Depths are measured from original (unablated) surface

Figure 16. File specific header for output file *surf.out*.

```
Unit 19: Sizing iteration history

 iteration    thickness temperature   recession
                  inch           R        inch

         1  2.2500E+00  8.7302E+02  2.2090E-01
         2  2.8750E+00  1.5536E+03  2.1660E-01
         3  3.1875E+00  1.1576E+03  2.1571E-01
         4  3.3437E+00  9.9346E+02  2.1981E-01
         5  3.2656E+00  9.2955E+02  2.2112E-01
         6  3.3047E+00  9.6066E+02  2.2039E-01
         7  3.2852E+00  9.4496E+02  2.2021E-01
         8  3.2949E+00  9.5269E+02  2.2045E-01
         9  3.2900E+00  9.4892E+02  2.1977E-01
        10  3.2925E+00  9.5078E+02  2.2008E-01
        11  3.2925E+00  9.4989E+02  2.1978E-01
```

- Thickness was optimized, in 11 iterations, for 950 R at the user-specified location
- FIATv2 finds a thickness that produces a temperature slightly lower than the value specified

Figure 17. File specific header for output file *thkrec.out*.

- Two sample problems with different environments
  - Case 1 is the highest integrated heat load point for a lunar-skipping trajectory
  - Case 2 is an arc-jet test condition with three sub-cases
- Each case has two subdirectories for different TPS materials
- Each subdirectory contains the three input files and all output files
  - Old output files are labeled "-old"
  - FIATv2 output should be reproduced to about 4 digits

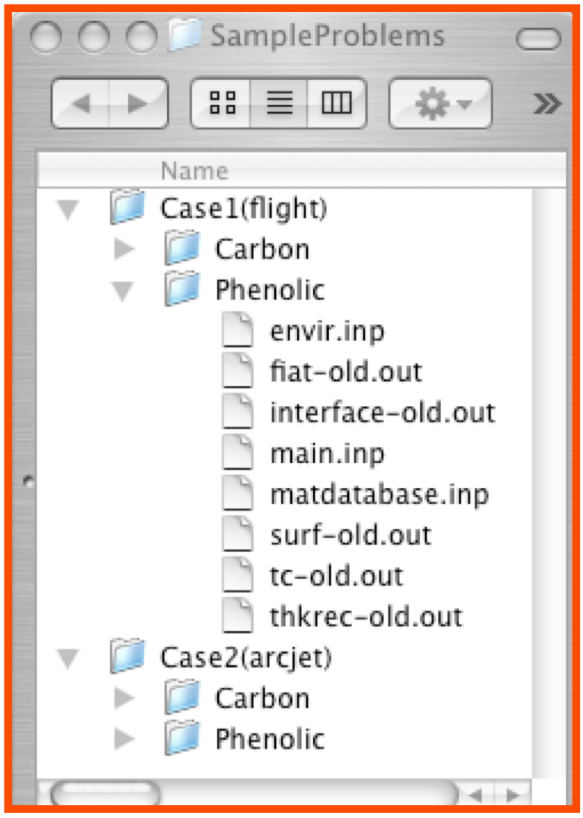


Figure 18. FIATv2 sample problems.

- TPS sizing details
  - Lunar skipping trajectory (two heat pulses)
  - Highest heat load location on surface
  - Margins applied to convective and radiative heating
  - Sized for 950 R at TPS/RTV interface
- Material stackup and optimized thickness (inches) for two TPS materials
  - Higher thickness for Shuttle RCC is attributed to its higher conductivity at low temperatures

Carbon Phenolic	3.29248
RTV-560	0.02000
Ti-6Al-4V	0.03200
Ti 64 HC	2.00000
Ti-6Al-4V	0.03200
Shuttle RCC	7.69580
RTV-560	0.02000
Ti-6Al-4V	0.03200
Ti 64 HC	2.00000
Ti-6Al-4V	0.03200

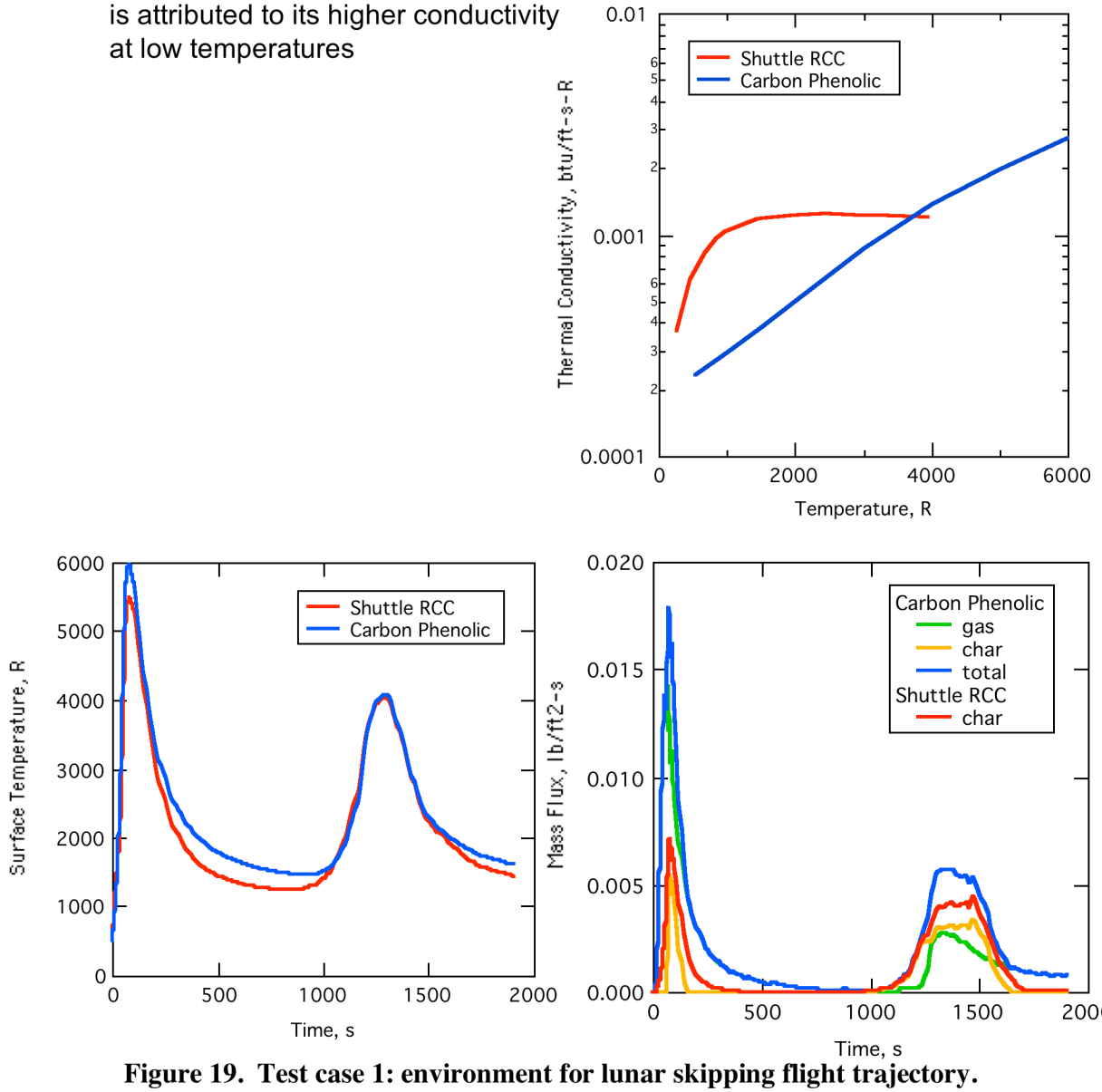


Figure 19. Test case 1: environment for lunar skipping flight trajectory.

- Case details
  - Nominal 1000 W/cm^2 heating and ±10%
  - Stagnation pressure of 0.75 atm
  - 30 second exposure, followed by 30 minute cooldown
  - Sample thickness is 2 inches
- Peak bondline temperature (°R) is relatively insensitive to heat flux

Material	90% heating	100% heating	110% heating
Shuttle RCC	1352	1361	1368
Carbon Phenolic	831	836	839

- Recession (mils) is a strong function of heat flux

Material	90% heating	100% heating	110% heating
Shuttle RCC	41	49	57
Carbon Phenolic	34	46	61

  - Shuttle RCC recession is relatively linear
  - Carbon Phenolic has greater curvature

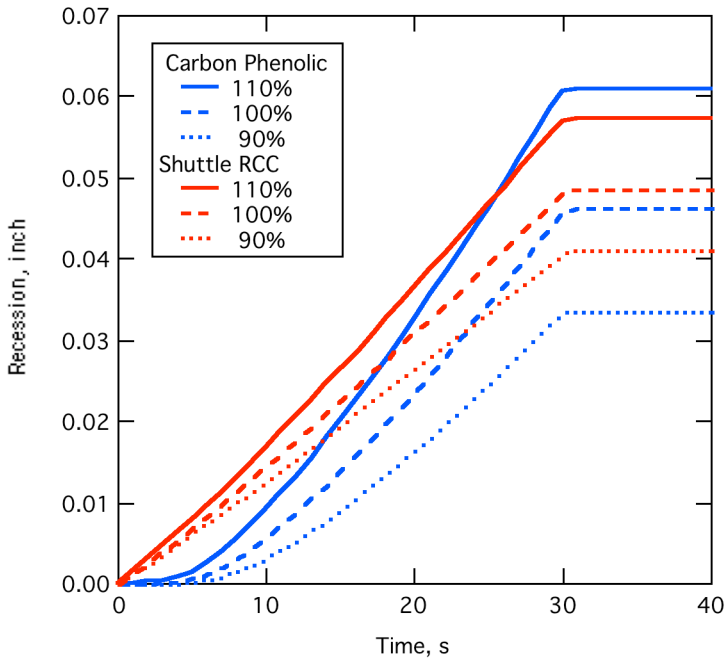


Figure 20. Test case 2: arcjet environment.