Thermal Protection Systems

- Types of thermal protection systems (TPS)
- Ablation
- Thermal conductivity
- Still heavily using/adapting slides from 2012 NASA Thermal and Fluids Analysis Workshop: https://tfaws.nasa.gov/TFAWS12/Proceedings/ Aerothermodynamics%20Course.pdf
- Thermal protection slides in that package by John A. Dec/ NASA Langley

TPS Outline

- **Background Information**
  - What is TPS?
  - Selecting the Right Material for the Mission
- **Ablative TPS Modeling**
  - Ablator Characteristics
  - Surface Recession
  - In-Depth Models
- **TPS Sizing and Margin**
- **TPS Testing**
- **Look to the Future**

Types of Thermal Protection Systems

- Ablative (non-reusable)
  - Carries heat away by ablation processes and pyrolysis
  - Effectively passive transpiration cooling
  - Ideal for high heat flux/load entries
- Heat Sinks (reusable)
  - Entry heating is absorbed by surface material - high specific heat, low thermal conductivity
  - Heat is ultimately dissipated by surface cooling and/or jettisoning
- Active (reusable)
  - Active cooling via fluid injection through surface into flow
  - Complex; heavy; low technology readiness levels

1D Conduction

- Basic law of one-dimensional heat conduction (Fourier 1822)

$$Q = -KA\frac{dT}{dx}$$

where

K=thermal conductivity (W/m°K)

A=area

dT/dx=thermal gradient

3D Conduction

General differential equation for heat flow in a solid

$$\nabla^2 T(r,t) + \frac{g(r,t)}{K} = \frac{\rho c}{K}\frac{\partial T(r,t)}{\partial t}$$

where

g(r,t)=internally generated heat

ρ=density (kg/m^3)

c=specific heat (J/kg°K)

K/ρc=thermal diffusivity

Simple Analytical Conduction Model

- Heat flowing from (i-1) into (i)

...	T_{i-1}	T_i	T_{i+1}	...

$$Q_{in} = -KA\frac{T_i - T_{i-1}}{\Delta x}$$

- Heat flowing from (i) into (i+1)

$$Q_{out} = -KA\frac{T_{i+1} - T_i}{\Delta x}$$

- Heat remaining in cell

$$Q_{out} - Q_{in} = \frac{\rho c}{K}\frac{T_i(j+1) - T_i(j)}{\Delta t}$$

Finite Difference Formulation

- Time-marching solution

$$T_i^{n+1} = T_i^n + d(T_{i+1}^n - 2T_i^n + T_{i-1}^n)$$

where

$$d = \frac{\alpha \Delta t}{\Delta x^2} \qquad \alpha = \frac{k}{\rho C_v} = \text{thermal diffusivity}$$

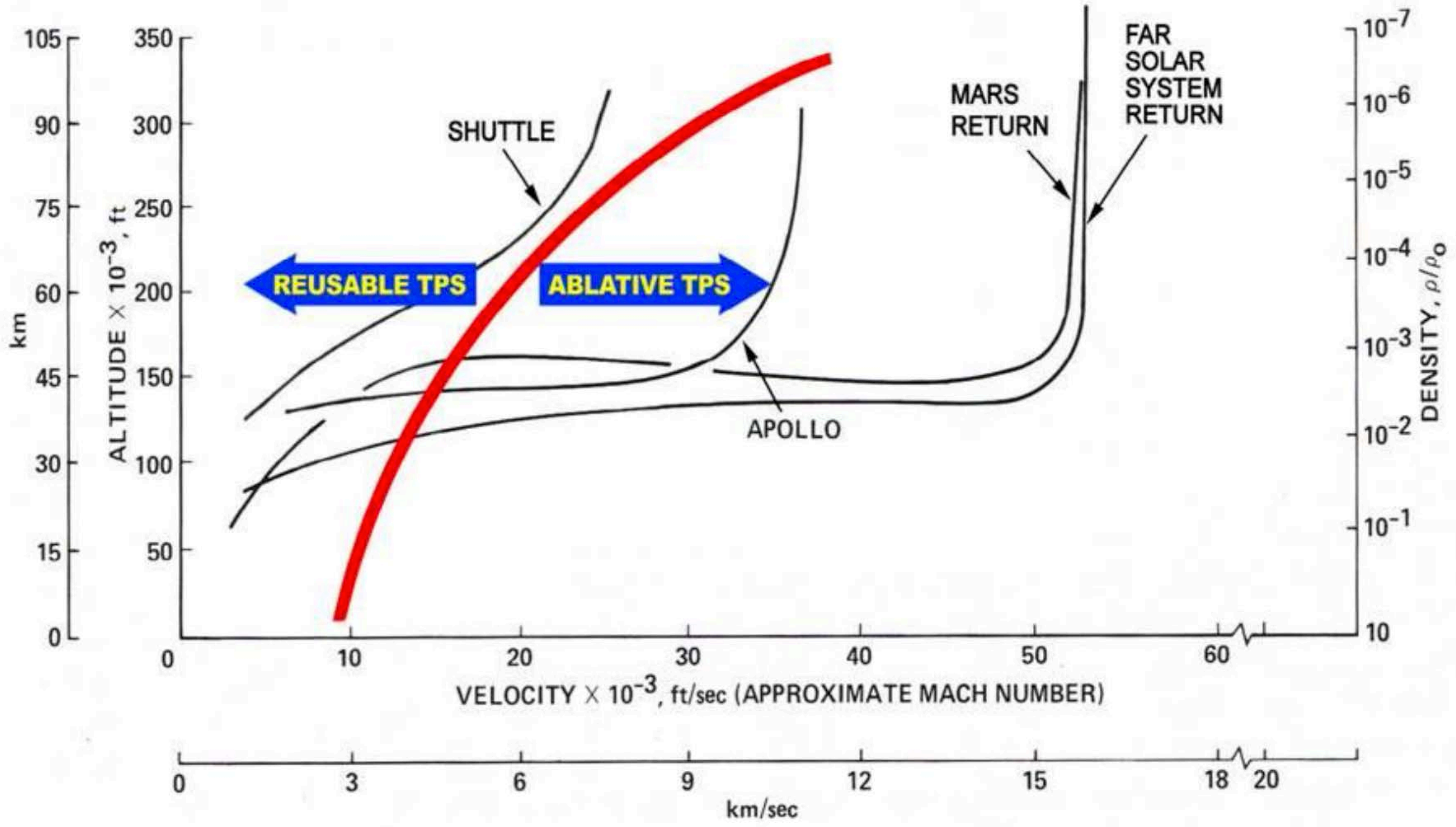
- For solution stability,

$$\Delta t < \frac{\Delta x^2}{2\alpha}$$

Ablation

- Definition:
  - The term ablation is encountered in many fields of science and engineering
    - In the medical field it refers to the surgical removal of a body part or tissue
    - In glaciology it refers to the removal of ice and snow from the surface of a glacier
  - In space physics, ablation is the process of absorbing energy by removal of surface material by melting, vaporization, sublimation, or chemical reaction

Why Ablative Materials?



Courtesy Bernie Laub, NASA Ames

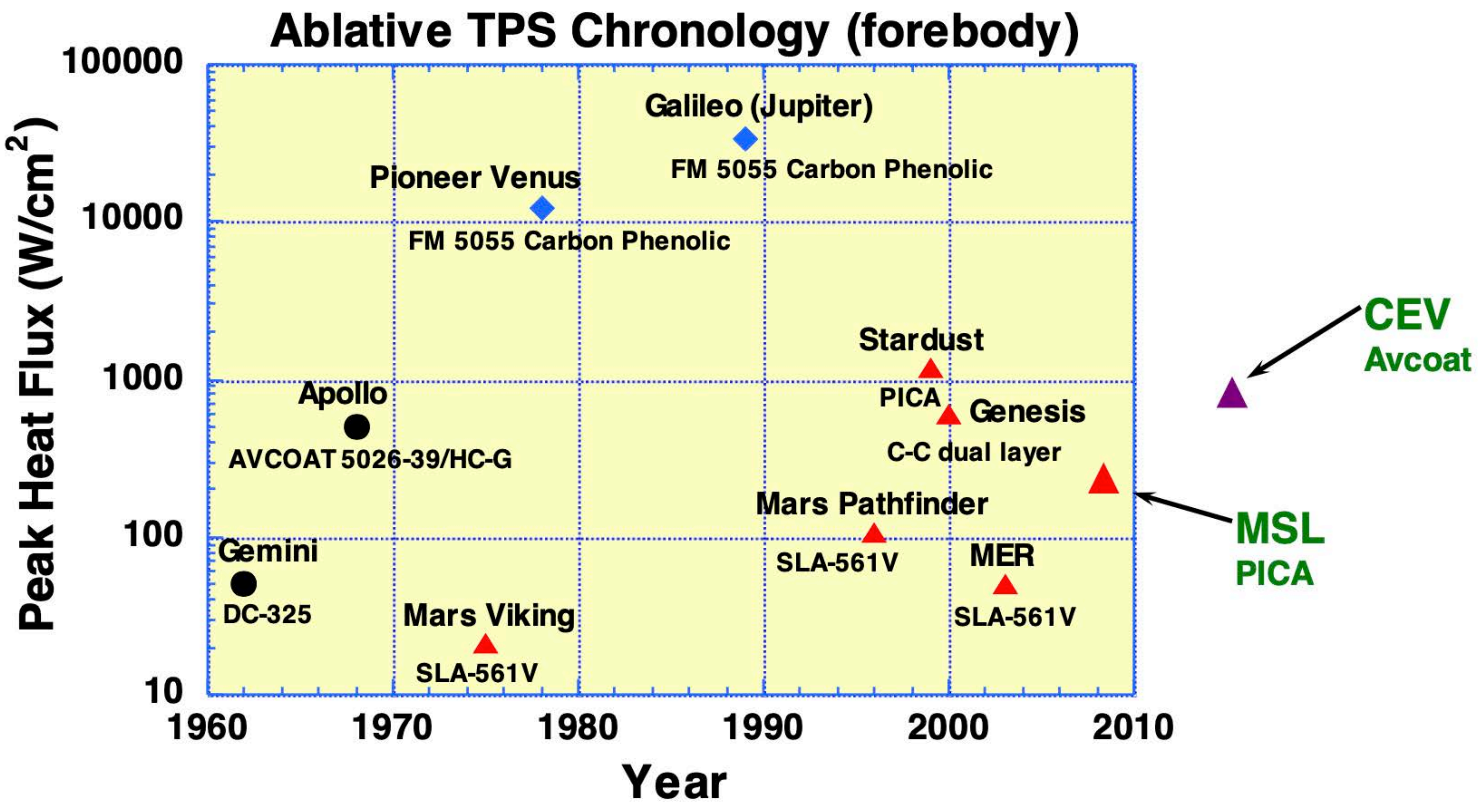
How is TPS Chosen/Designed?

- **Heat rate, along with pressure and shear, determine type of TPS to employ**
  - Material classes have clear performance limits marked by poor performance/material failure

- **Heat load determines overall thickness of TPS material**

- **Other design features play a role**
  - Need for tiles, forebody penetrations, compression pads, structural loads, etc. can impact material selection and TPS design
  - RF transparency for materials that protect antennae

Ablative TPS Chronology



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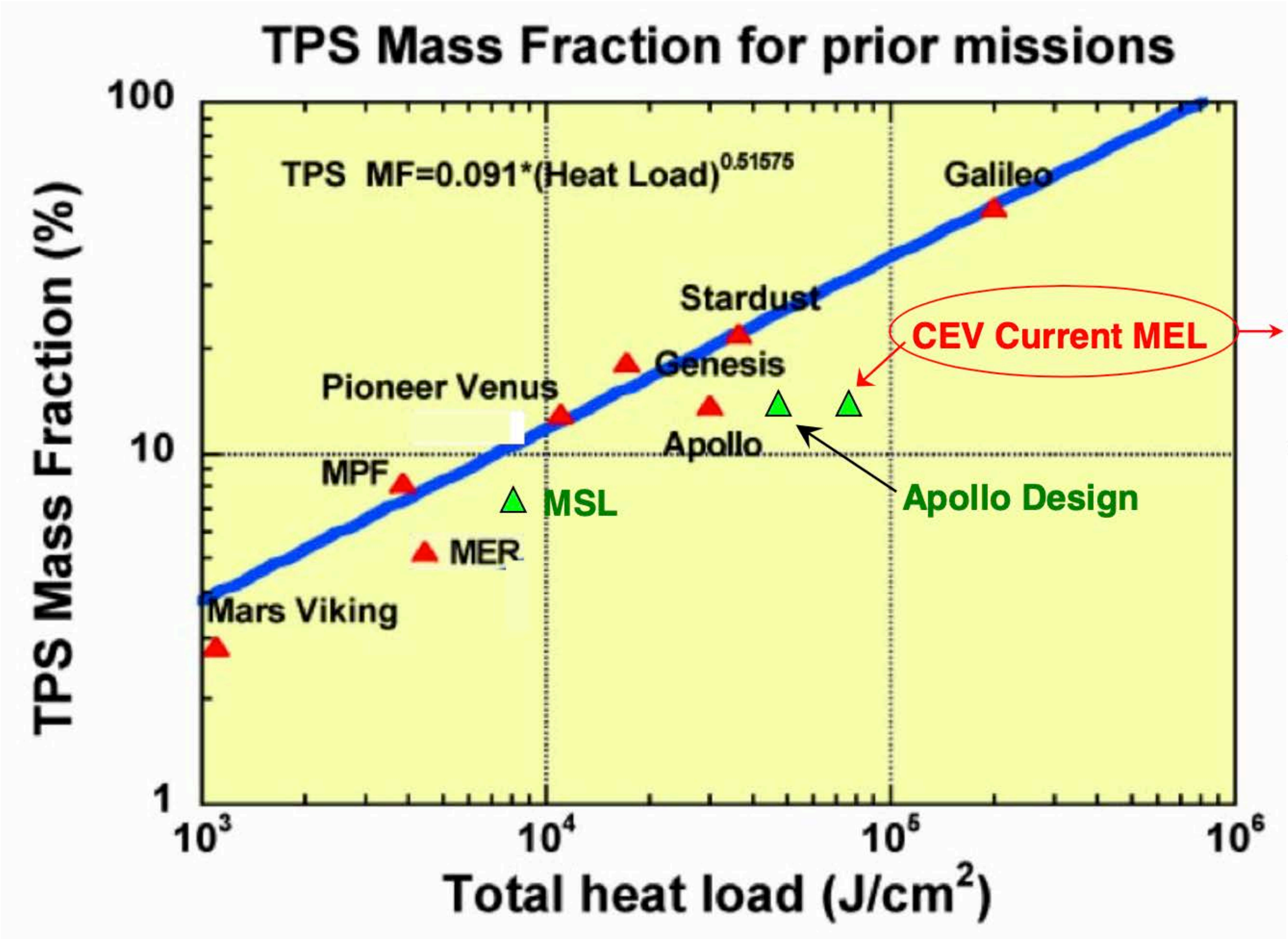
Some Available Ablatives

Material Name	Manufacturer	Density (kg/m^3)	Limit (W/cm^2)	
SLA-561V	Lockheed-Martin	256	~ 200	Not viable for high shear
FM 5055 Carbon Phenolic	Fibercote (formerly US Polymeric), Hitco Inc.	1450	> 10,000	No source of heritage Rayon
MX4926N Carbon Phenolic	Cytec (pre-preg), ATK, HITCO	1450	> 10,000	Flown on Shuttle SRM, never as a heat shield
PhenCarb-20,24,32	Applied Research Associates (ARA)	320-512	~ 750	Never flown
PICA (Phenolic Impregnated Carbon Ablator)	Fiber Materials, Inc. (FMI)	265	> 1500	Must be tiled above 1m diameter
Avcoat 5026 (Apollo)	Textron Systems	513	~1000	Recreated for CEV
ACC	Lockheed-Martin	1890	~ 1500	Heavy, not readily extendible above 2m

TPS Mass Fractions

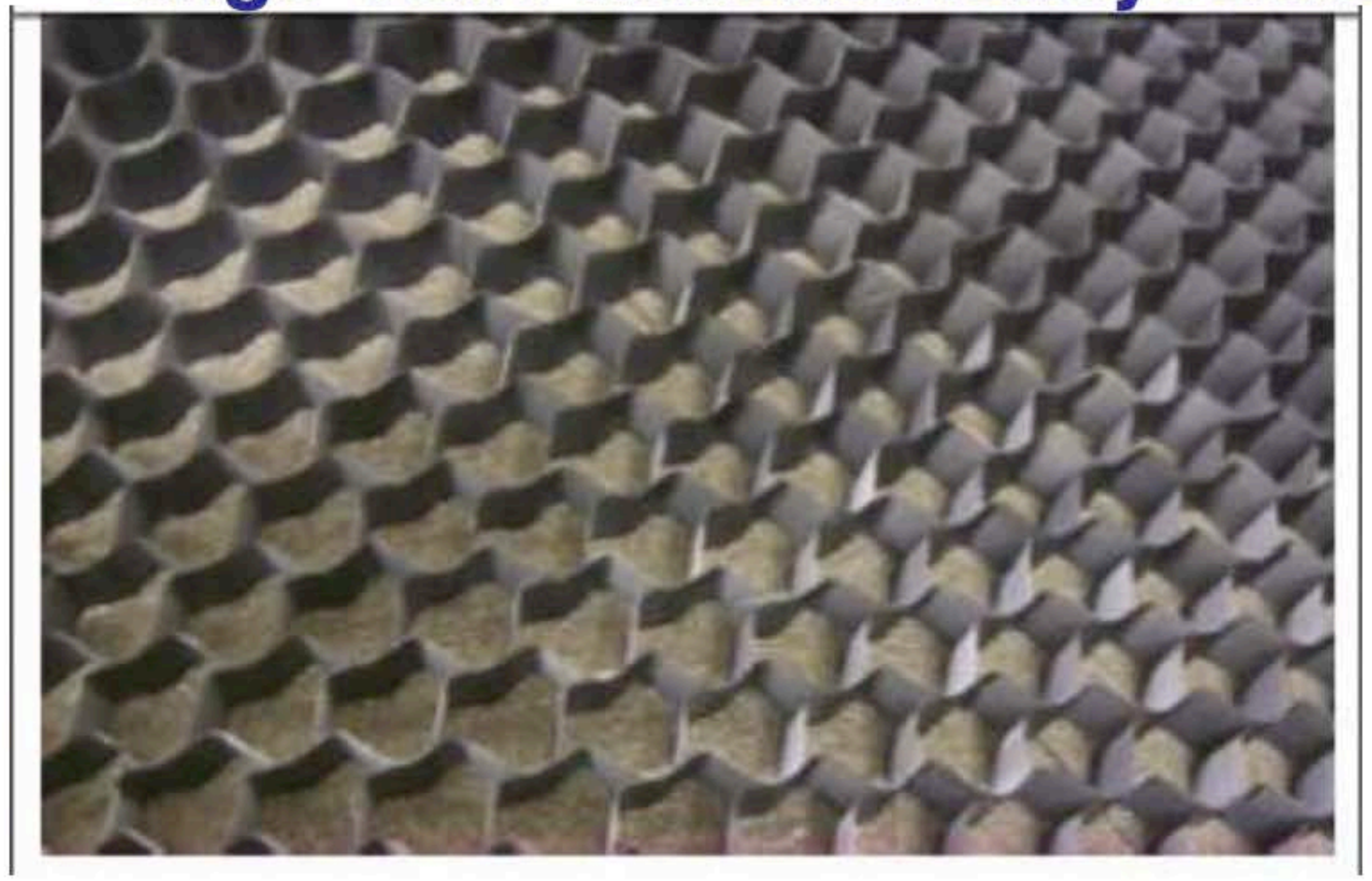


Wow! This is going to be hard w/o a significant improvement to the state of the art

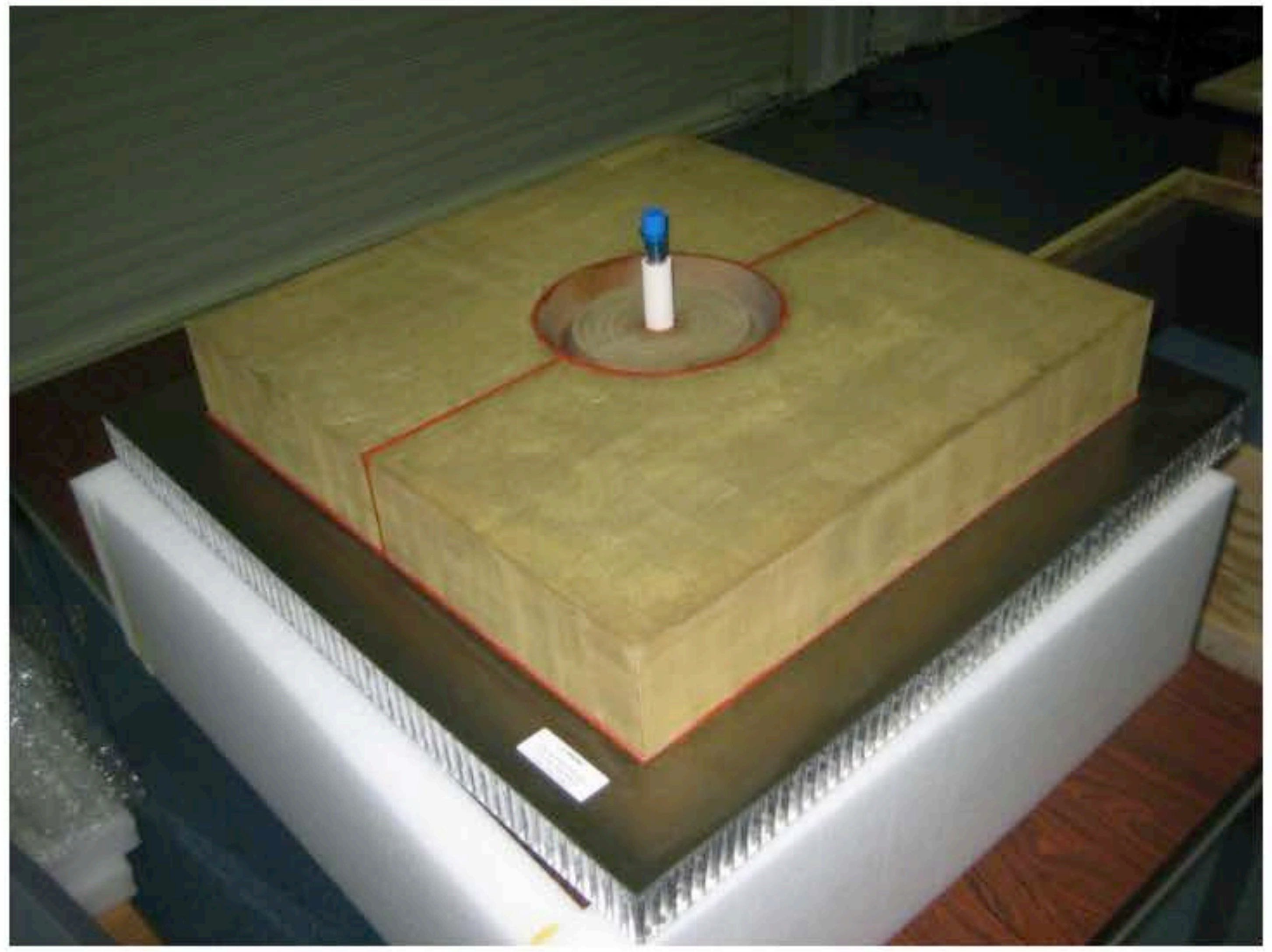
Courtesy Bernie Laub, NASA Ames

Ablative Composition

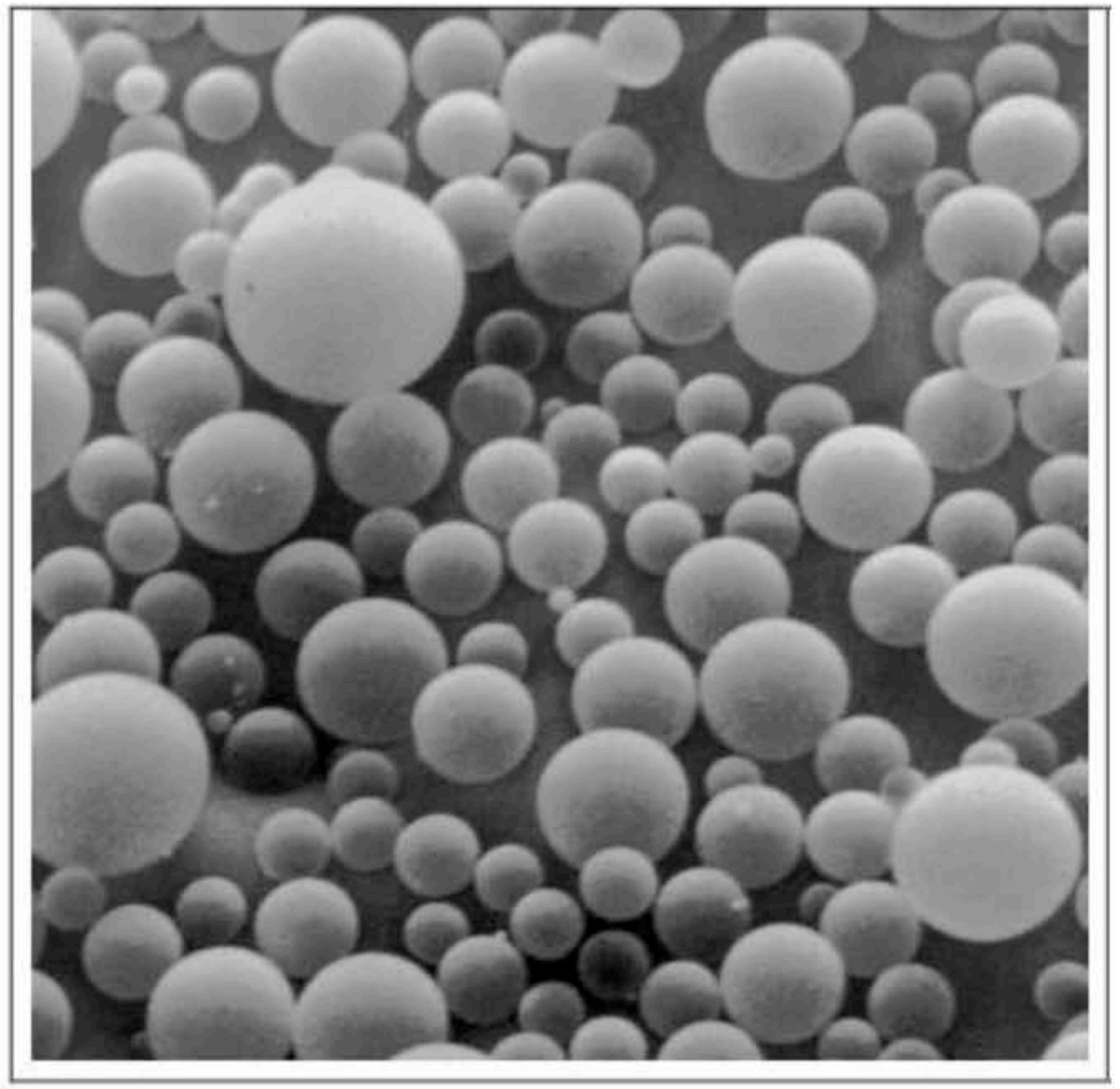
Large Cell Phenolic Honeycomb



Organic Fiber Reinforced Phenolic



Silica Microballoons



Largest ~100 Microns

Pyrolyzing Ablators

Substrate Material (e.g. fibers, cloth)

- **Desire ability to withstand high temperatures (reradiation)**
- **Carbon is best; glass also good (heat of vaporization)**

Organic Resins (e.g. phenolics)

- **Pyrolyzing ablators only**
- **When heated resin generates gas and leaves carbon residue**
- **What are they good for?**
  - in-depth and surface transpiration
  - endothermic reactions absorb energy
  - carbon char for reradiation

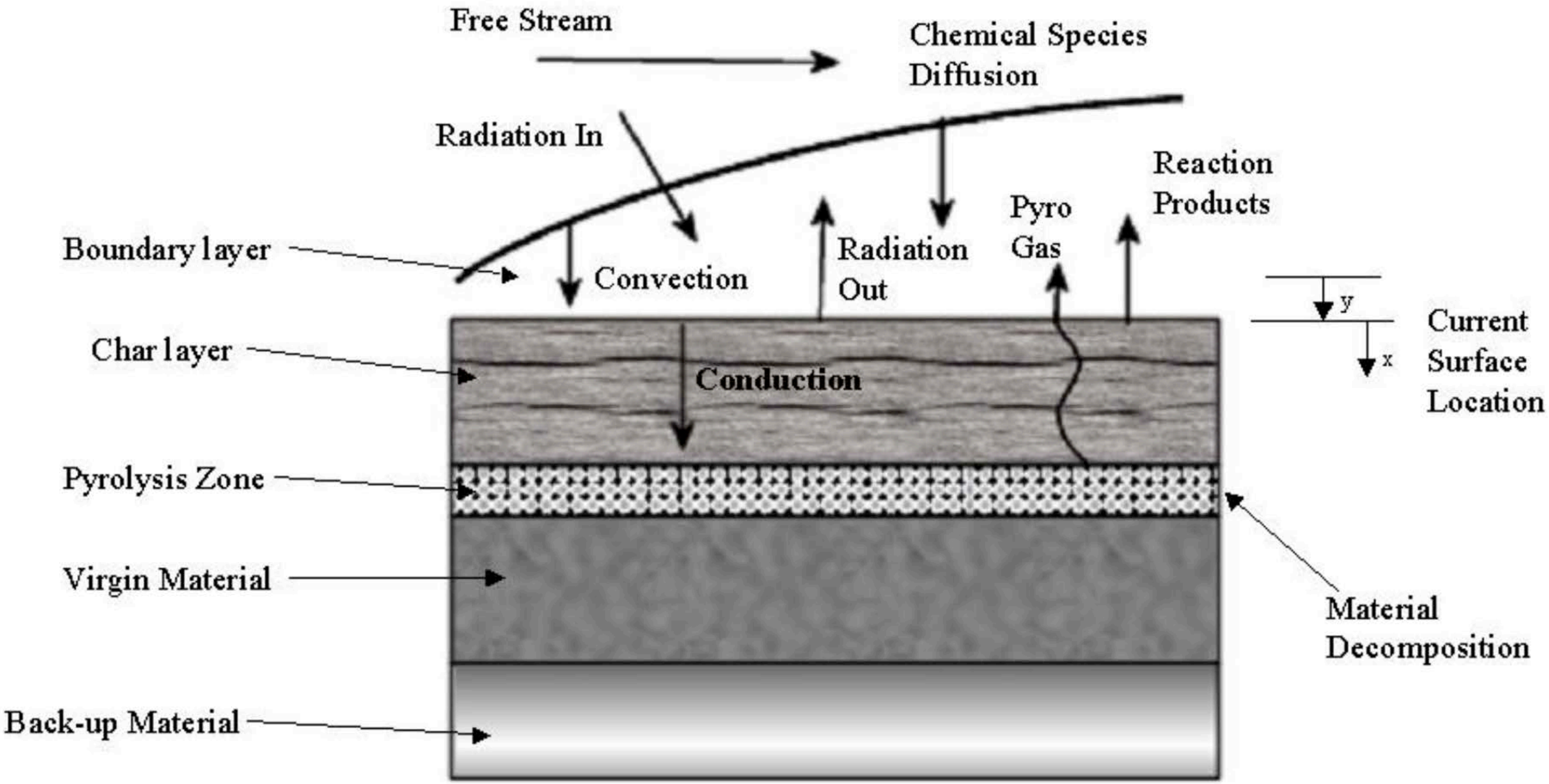
Additives (e.g. microballoons, cork)

- **Density & thermal conductivity control**

Added Reinforcement (e.g. honeycomb)

- **Structural integrity, bond verification (adds mass)**

How Do Ablators Work?



Surface Ablation Mechanisms

- Melting – common ablation mechanism, but doesn't absorb much energy
- Vaporization – absorbs significant amount of energy
- Oxidation – exothermic process that adds energy
- Sublimation – Can be significant energy absorber
- Spallation – Mass loss with minimal energy absorption (Thermostructural Failure – HIGHLY UNDESIRABLE)

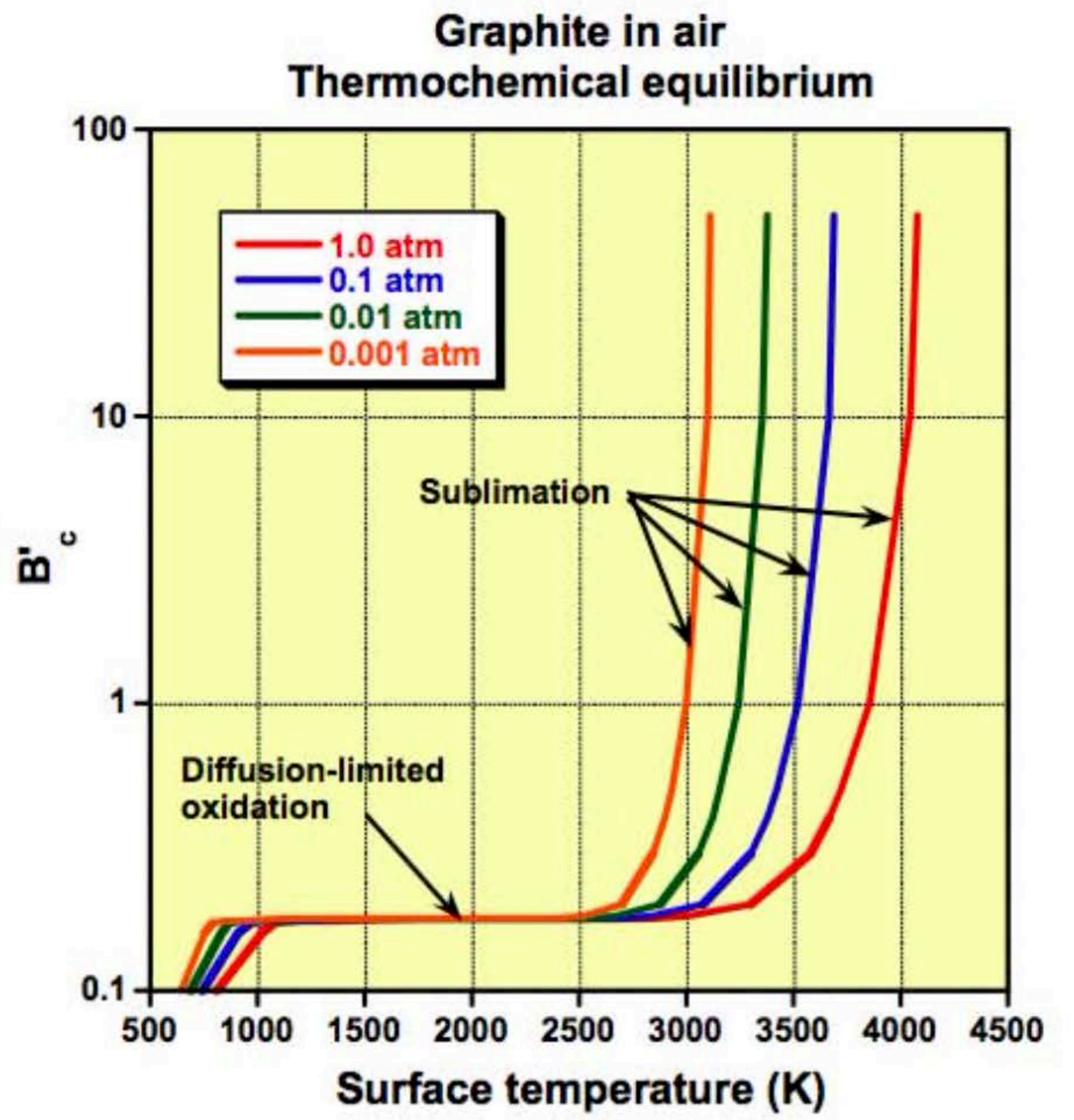
Oxidation

- Oxidation is an *exothermic* process
- Example:

$$2C(s)+O_2(g)\rightarrow 2CO(g)$$

$$\Delta H_{comb} \approx -4170 \;\; kJ/g_{carbon}$$

- Note: the B' curve for carbon in air was generated with assumptions of thermochemical equilibrium, equal diffusion coefficients, etc.
- The "equilibrium" assumption allows the diffusion-limited plateau to extend to *unrealistically low* surface temperatures



Other exothermic surface chemistry is possible ("nitridation" and "hydridation") but these are not typically significant players

Courtesy Bernie Laub, NASA Ames

Other Mechanisms at Play

- Material decomposition …aka pyrolysis
  - Endothermic reactions absorb energy
  - Convection of pyrolysis gas through the char
- Conduction through the material
  - Transfer energy to structure or heat sink
- Re-radiation from the surface
  - Largest percentage of energy is dissipated through this mechanism

TPS Modeling Approach

- In the mid to late 1960's, Kendall, Rindal, and Bartlett, and Moyer and Rindal extended the work by Kratsch et. al.
  - Included unequal heat and mass transfer coefficients
  - Non-unity Lewis and Prandtl numbers
  - Corrected in-depth energy equation:
    - to account for the energy of the pyrolysis gas convection and generation within the solid
    - to account for grid motion due to a coordinate system that is attached to the receding surface

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x_S}\left(k \frac{\partial T}{\partial x_S}\right) + \left(h_g - \bar{h}\right)\frac{\partial \rho}{\partial t}\bigg|_x + \dot{S}\rho c_p \frac{\partial T}{\partial x_S} + \dot{m}_g \frac{\partial h_g}{\partial x_S} \qquad (12)$$

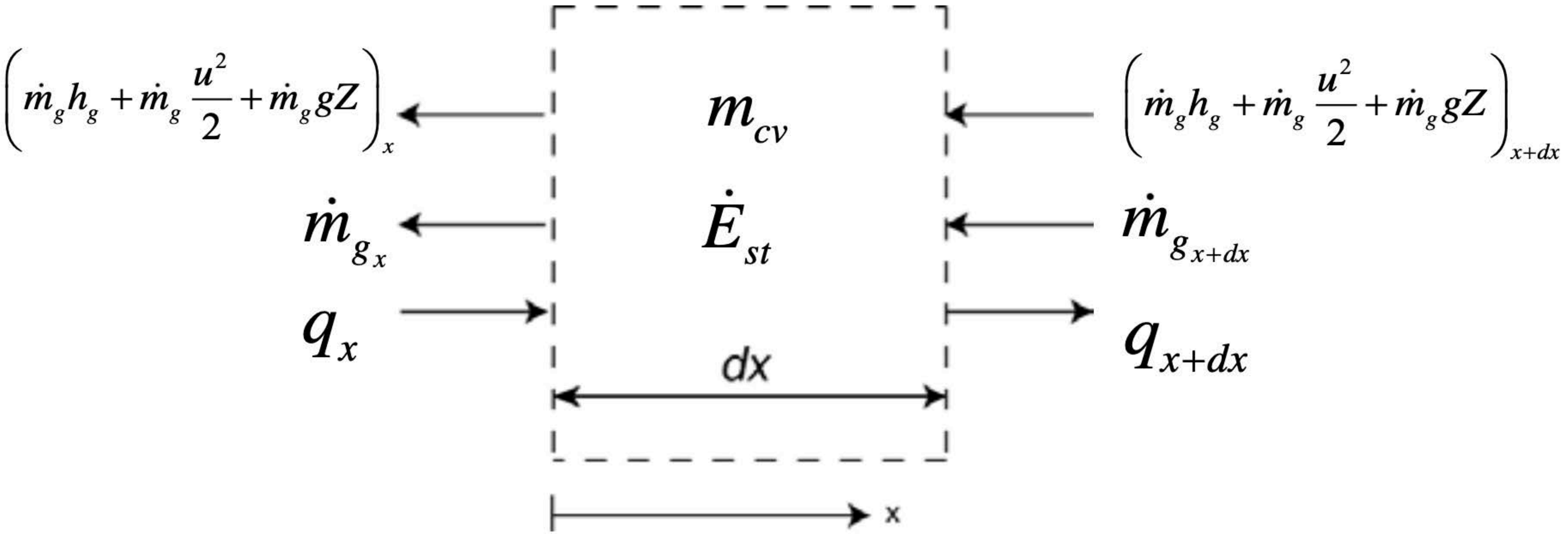
$$-k\frac{dT}{dx} = \rho_e U_e C_H \left(H_{sr} - h_{sw}\right) + \rho_e U_e C_M \left(\sum_i \left(Z_{ie}^* - Z_{iw}^*\right) h_i^0 + B_c' h_c + B_g' h_g - B' h_w\right) - q^* + q_{\substack{rad \\ out}} - \alpha q_{\substack{rad \\ in}} \qquad (13)$$

- If the diffusion coefficients are assumed equal and the Le=Pr=1.0, the surface energy balance simplifies to

$$-k\frac{dT}{dx} = \rho_e U_e C_H \left(H_{sr} - h_{sw} + B_c' h_c + B_g' h_g - B' h_w\right) - q^* + q_{\substack{rad \\ out}} - \alpha q_{\substack{rad \\ in}} \qquad (14)$$

Governing Differential Equations Derivation

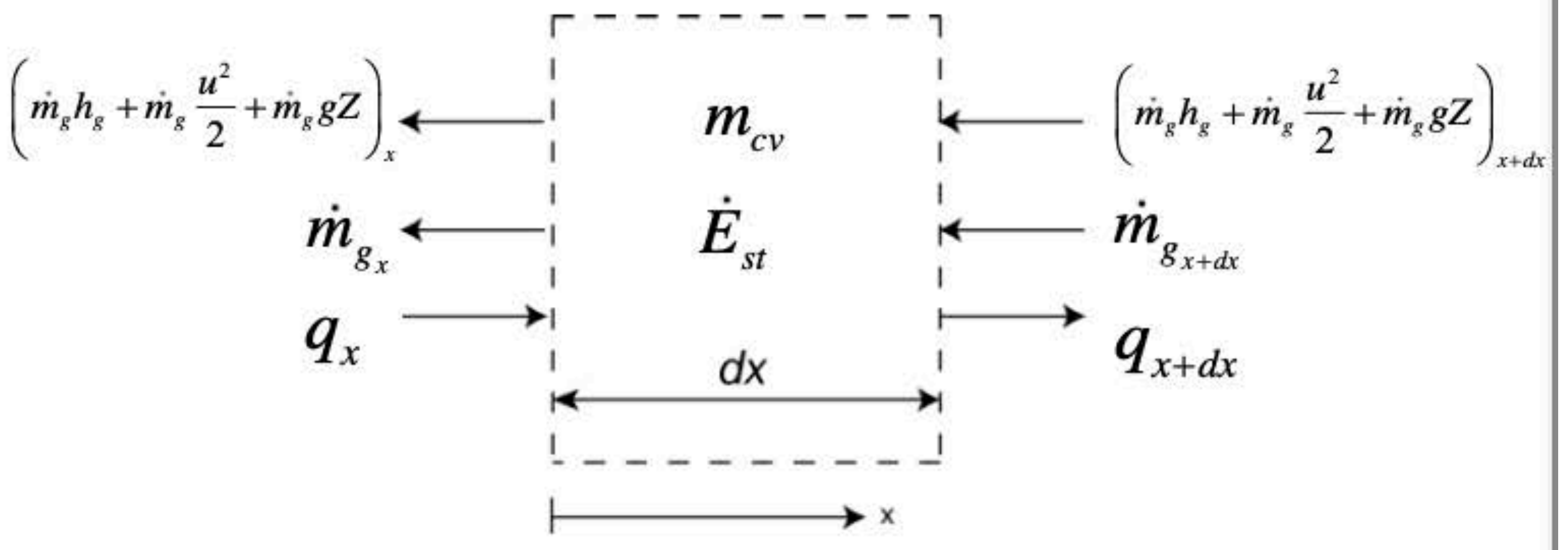
1-dimensional control volume



Conservation of Mass

Pyrolysis gas flows from the pyrolysis zone through the porous char to the heated surface

- Assume gas flow is 1-D and normal to the heated surface
- Assume dp~0 across the char (neglect the momentum eqn)



$$\frac{\partial m_{cv}}{\partial t} = \dot{m}_{in} - \dot{m}_{out} \qquad (15)$$

Where $m_{cv} = \rho A dx$ (16) $\dot{m}_{g_{x+dx}} = \dot{m}_{g_x} + \frac{\partial \dot{m}_{g_x}}{\partial x} dx$ (17)

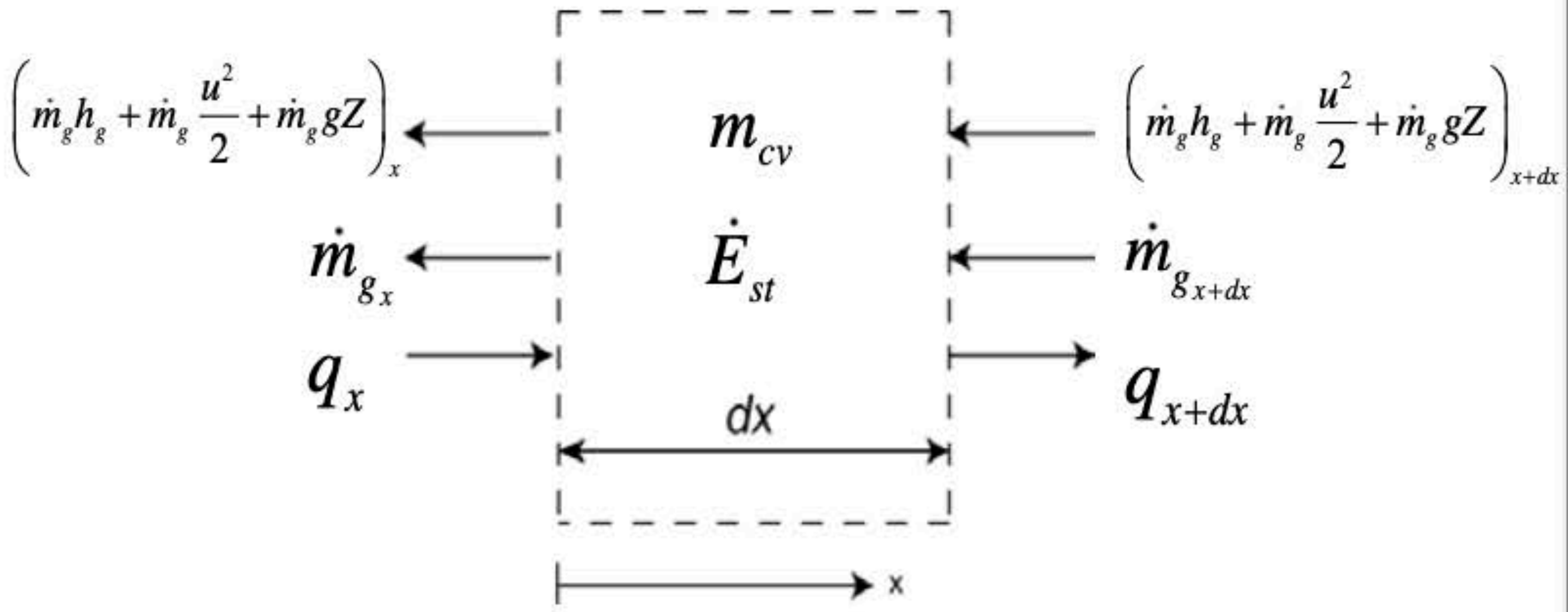
$$A \frac{\partial \rho}{\partial t} dx = \left(\dot{m}_{g_x} + \frac{\partial \dot{m}_{g_x}}{\partial x} dx \right) - \dot{m}_{g_x} \Rightarrow \boxed{\frac{\partial \rho}{\partial t} = -\frac{\partial \dot{m}''_{g_x}}{\partial x}} \qquad (18)$$

$\frac{\partial \rho}{\partial t}$ Determined experimentally and modeled with an Arrhenius fit

$\dot{m}''_{g_x}$ = Mass flow rate per unit area

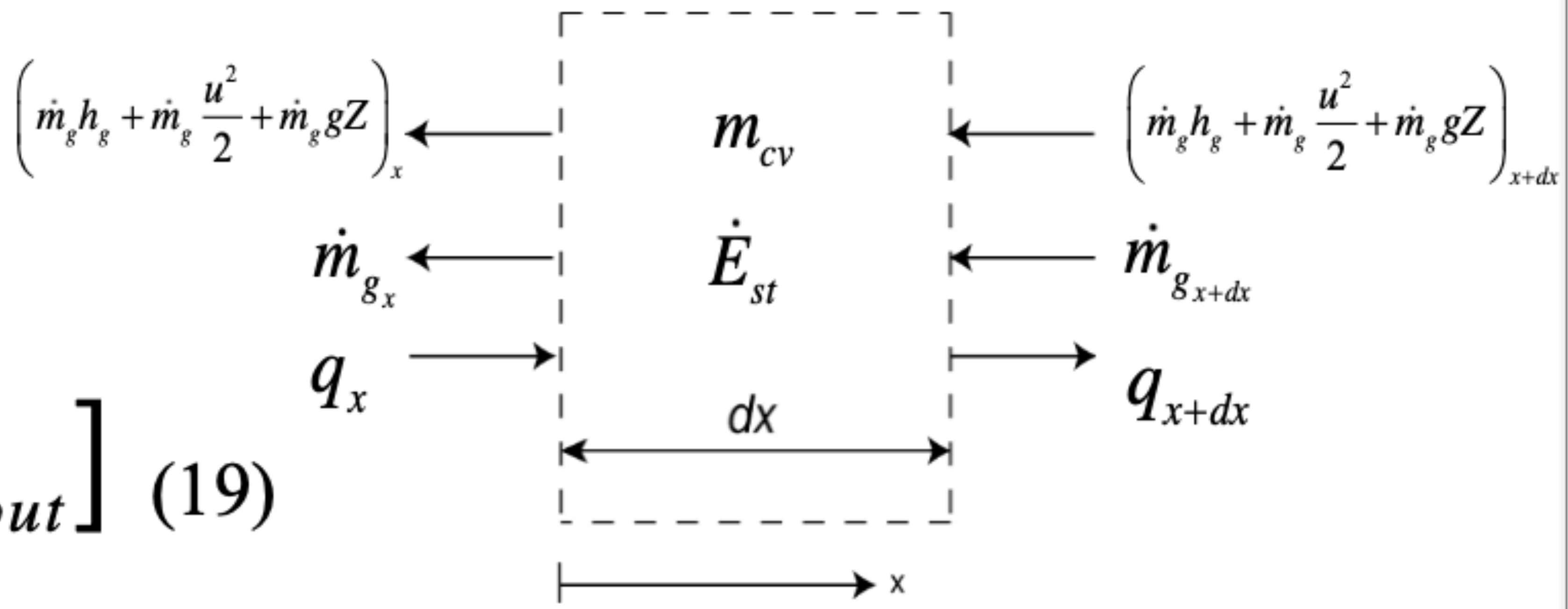
Conservation of Energy

- Two energies associated with this control volume
  - Pyrolysis gas flow
  - Heat conduction.



- Pyrolysis gas flow assumptions
  - Pyrolysis gas is in thermal equilibrium with the charred material within the control volume
  - Pyrolysis gas residence time within the control volume is small.
  - Potential energy of the pyrolysis gas may be neglected since the change in height across the control volume is negligible.
  - The kinetic energy of the pyrolysis gas may be neglected since it is of small magnitude relative to its enthalpy

Conservation of Energy (2)



- 1st Law of Thermodynamics

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \left[\dot{m}_{in}(e+Pv)_{in} - \dot{m}_{out}(e+Pv)_{out}\right] \quad (19)$$

Where *e* is the total energy per unit mass and includes kinetic, potential, and internal energy

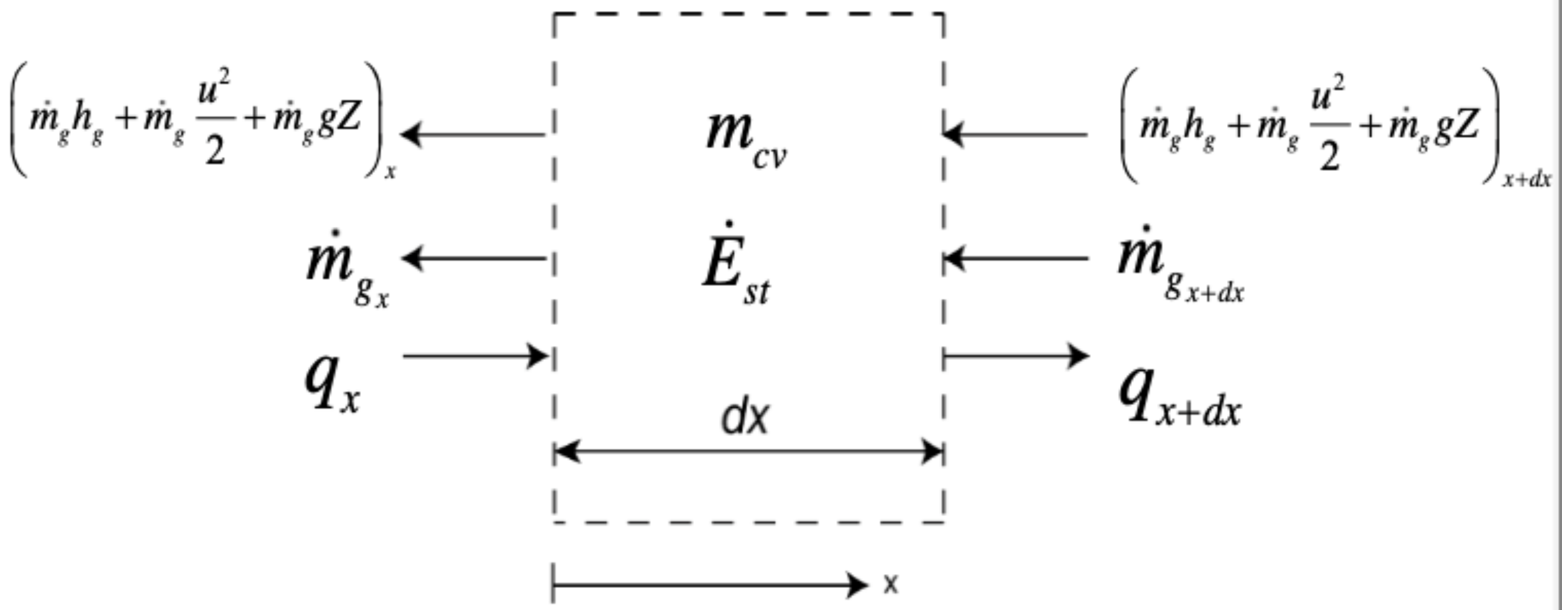
The internal energy and flow work may be expressed in terms of the enthalpy by, $h = u + Pv$

Rewriting equation 19 in a simplified form gives,

$$\frac{dE_{cv}}{dt} = \dot{E}_{in} - \dot{E}_{out} \qquad (20)$$

Conservation of Energy (3)

- The energy entering and leaving the control volume can be expressed as



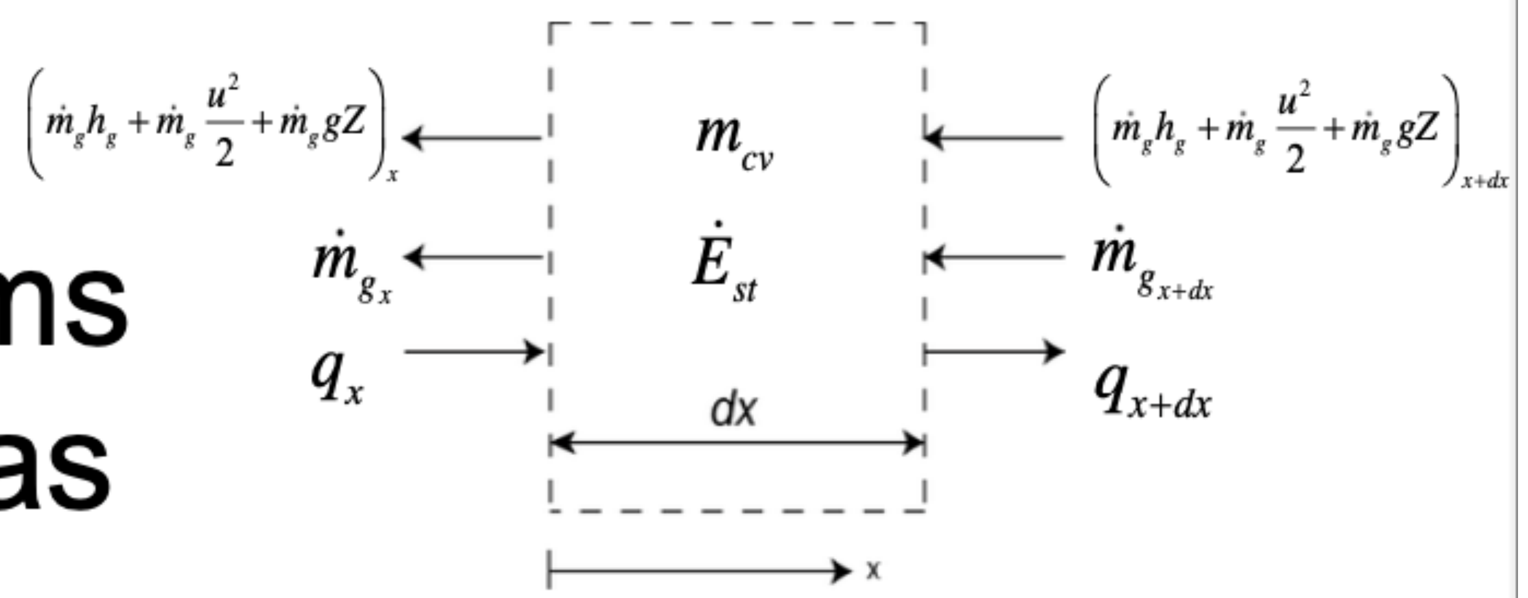
$$\dot{E}_{in} = q_x + \left(\dot{m}_g h_g\right)_{x+dx}$$
$$\dot{E}_{out} = q_{x+dx} + \left(\dot{m}_g h_g\right)_x \qquad (21)$$

- Expressing the incremental heat conduction leaving and the convection of energy by the pyrolysis gas entering the control volume as Taylor series expansions gives, dropping H.O.T

$$q_{x+dx} = q_x + \frac{\partial q_x}{\partial x}dx$$
$$\left(\dot{m}_g h_g\right)_{x+dx} = \left(\dot{m}_g h_g\right)_x + \frac{\partial}{\partial x}\left(\dot{m}_g h_g\right)_x dx \qquad (22)$$

Conservation of Energy (4)

- The rate of energy storage within the control volume can be expressed in terms of the density and enthalpy of the solid as



$$\frac{dE_{cv}}{dt} = \frac{\partial}{\partial t}(\rho h)Adx \qquad (23)$$

- Substituting eq 21 into eq 20, and using the definitions in eqns 22 and 23 gives

$$\frac{\partial}{\partial t}(\rho h)Adx = \left[q_x + (\dot{m}_g h_g)_x + \frac{\partial}{\partial x}(\dot{m}_g h_g)_x dx\right] - \left[q_x + \frac{\partial q_x}{\partial x}dx + (\dot{m}_g h_g)_x\right] \qquad (24)$$

Conservation of Energy (5)

- Canceling like terms, dividing by *Adx*, and using Fourier's law of heat conduction eqn 24 reduces to,

$$\underbrace{\frac{\partial}{\partial t}(\rho h)}_{\mathrm{I}} = \underbrace{\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right)}_{\mathrm{II}} + \underbrace{\frac{\partial}{\partial x}\left(\dot{m}''_{g_x} h_g\right)}_{\mathrm{III}} \qquad (25)$$

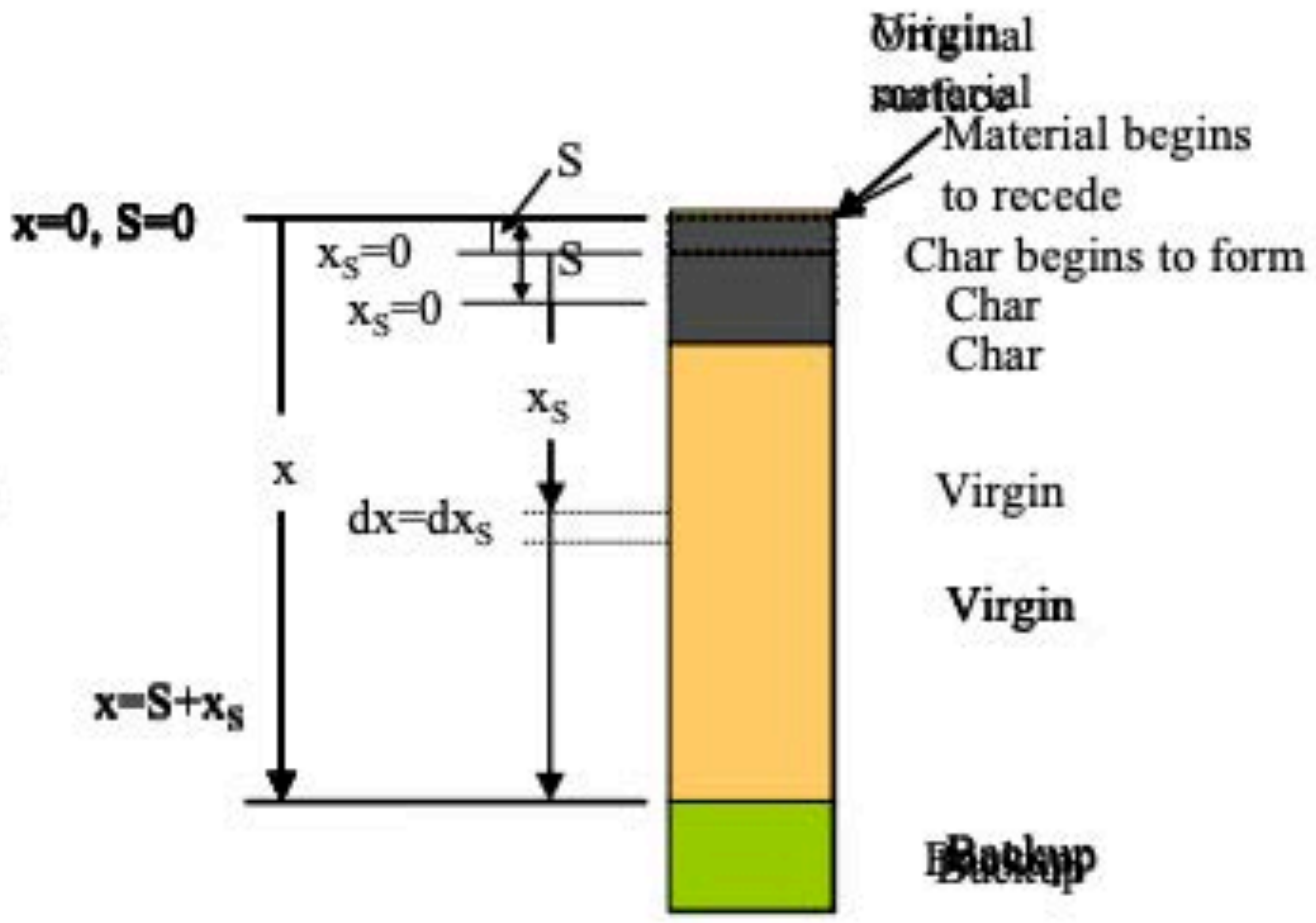
Where,

ρ	: density of the solid
h	: enthalpy of the solid
h_g	: pyrolysis gas enthalpy
k_x	: thermal conductivity in the x-direction
T	: temperature
$\dot{m}_{g_x}$	: local gas flow rate in the x-direction
x	: coordinate direction

- Physically,
  - Term I represents energy storage
  - Term II represents conduction through the material
  - Term III represents convection due to pyrolysis gas flow

Adapting to a Moving Coordinate Frame

- The control volume is not fixed in space, it is tied to the receding surface
  - Requires transforming eqns 18 and 25 into a moving coordinate system
  - After some elaborate calculus and algebraic manipulation we arrive at,



Conservation of mass in a moving coordinate system

$$\left.\frac{\partial \rho}{\partial t}\right|_{x_S} = \dot{S}\left.\frac{\partial \rho}{\partial x_S}\right|_t + \left.\frac{\partial \rho}{\partial t}\right|_x \qquad (26)$$

Conservation of energy in a moving coordinate system

$$\underbrace{\left.\frac{\partial}{\partial t}(\rho h)\right|_{x_S}}_{I} = \underbrace{\left.\frac{\partial}{\partial x_S}\left(k_x \frac{\partial T}{\partial x_S}\right)\right|_t}_{II} + \underbrace{\left.\frac{\partial}{\partial x_S}\left(\dot{m}''_{g_x} h_g\right)\right|_t}_{III} + \underbrace{\dot{S}\left.\frac{\partial}{\partial x_S}(\rho h)\right|_t}_{IV} \qquad (27)$$

Where terms I-III are the same as in eqn 25 and term IV is the convection of energy due to coordinate system movement

Final Form of the Energy Equation

- It is convenient to express the (ρh) terms in equation 27 in terms of material properties rather than the thermodynamic quantity of enthalpy
- Performing some algebra and defining a new quantity, $\bar{h}$, the energy equation takes the following form

$$\underbrace{\rho c_p \frac{\partial T}{\partial t}}_{I} = \underbrace{\frac{\partial}{\partial x_S}\left(k_x \frac{\partial T}{\partial x_S}\right)}_{II} + \underbrace{\left(h_g - \bar{h}\right)\frac{\partial \rho}{\partial t}\bigg|_x}_{III} + \underbrace{\dot{S}\rho c_p \frac{\partial T}{\partial x_S}}_{IV} + \underbrace{\dot{m}''_{g_x} \frac{\partial h_g}{\partial x_S}}_{V} \qquad (28)$$

where

$$\bar{h} = \left[\frac{\rho_v H_v - \rho_c H_c}{\rho_v - \rho_c}\right]$$

$$H_v = h_v^0 + \int_0^T c_{p_v} dT$$

$$H_c = h_c^0 + \int_0^T c_{p_c} dT$$

ρ_v : virgin material density

ρ_c : charred material density

H_v : total enthalpy of the virgin material

H_c : total enthalpy of the charred material

Final Form of the Energy Equation (2)

$$\underbrace{\rho c_p \frac{\partial T}{\partial t}}_{I} = \underbrace{\frac{\partial}{\partial x_S}\left(k_x \frac{\partial T}{\partial x_S}\right)}_{II} + \underbrace{\left(h_g - \bar{h}\right)\frac{\partial \rho}{\partial t}\bigg|_x}_{III} + \underbrace{\dot{S}\rho c_p \frac{\partial T}{\partial x_S}}_{IV} + \underbrace{\dot{m}_{g_x} \frac{\partial h_g}{\partial x_S}}_{V} \quad (28)$$

- Each term in equation 28 has physical significance
  - Term I
    - rate of sensible energy storage
  - Term II
    - net conduction through the material
  - Term III
    - creation of sensible energy due to pyrolysis (ie the heat of decomposition)
  - Term IV
    - energy convected due to coordinate system movement
  - Term V
    - energy convected away due to pyrolysis gas generation at that point

Thermal Protection System Sizing Approach

- **Baseline (zero-margin) sizing computed assuming nominal environments and response model to hit given bondline temperature limit**
- **Margin process then applied to account for various sources of uncertainty**
- **Appropriate factors of safety be applied to trajectory dispersions, aerothermal loads, initial conditions, and material variabilities**
- **Primary (thermal) margin is applied directly to the TPS design criterion (e.g. maximum bondline temperature)**
  - The impact of this margin on TPS thickness is material-dependent since the sensitivity of bondline temperature to thickness is material-dependent
- **Secondary (recession) margin is also employed**
  - Bondline is insensitive to excessive recession until it is too late
- **Various independent sources of error are RSS'ed to avoid stacked conservatism**
- **Additional program imposed thickness factor of safety is recommended to account for unknown unknowns**
- **Other factors (e.g. thermal stress, CTE mismatch, adhesive failure) should also be tracked as possible limiting cases**
  - Adhesive failure accounted for by maintaining conservative bondline temperature limit

Simplified Sizing Approach

- Using the semi-infinite solid approximation, closed-form analytical solutions to the in-depth energy equation can be derived.
- For a thick slab which has a constant surface temperature at any instant in time, the temperature at a depth ***x*** within the solid at time ***t*** is given by,

$$T(x,t) = erf\left(\frac{x}{2\sqrt{\alpha t}}\right)(T_i - T_s) + T_s \qquad (29)$$

where,

T_i *is the initial temperature*

T_s *is the surface temperature*

erf is the gaussian error function

α *is the thermal diffusivity* $= \dfrac{k}{\rho c_p}$

k = *thermal conductivity*

c_p = *specific heat*

ρ = *density*

Simplified Sizing Approach (2)

- In this simplified approach, the amount of material required for insulation and the amount of material required for recession are calculated separately
- To calculate the recession in an approximate way, use the data correlation parameter known as the heat of ablation (Q^*) and solve for recession rate

$$\dot{s} = \frac{\dot{q}_{cw}\left(\frac{H_r - H_{air}^{T_w}}{H_r}\right) - \sigma\varepsilon T_w^4}{\rho Q^*} \qquad (5)$$

Simple Finite Difference Approach

- To increase the fidelity, a finite difference approximation of equation 1 can be written incorporating a simplified surface energy balance

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) \qquad (1)$$

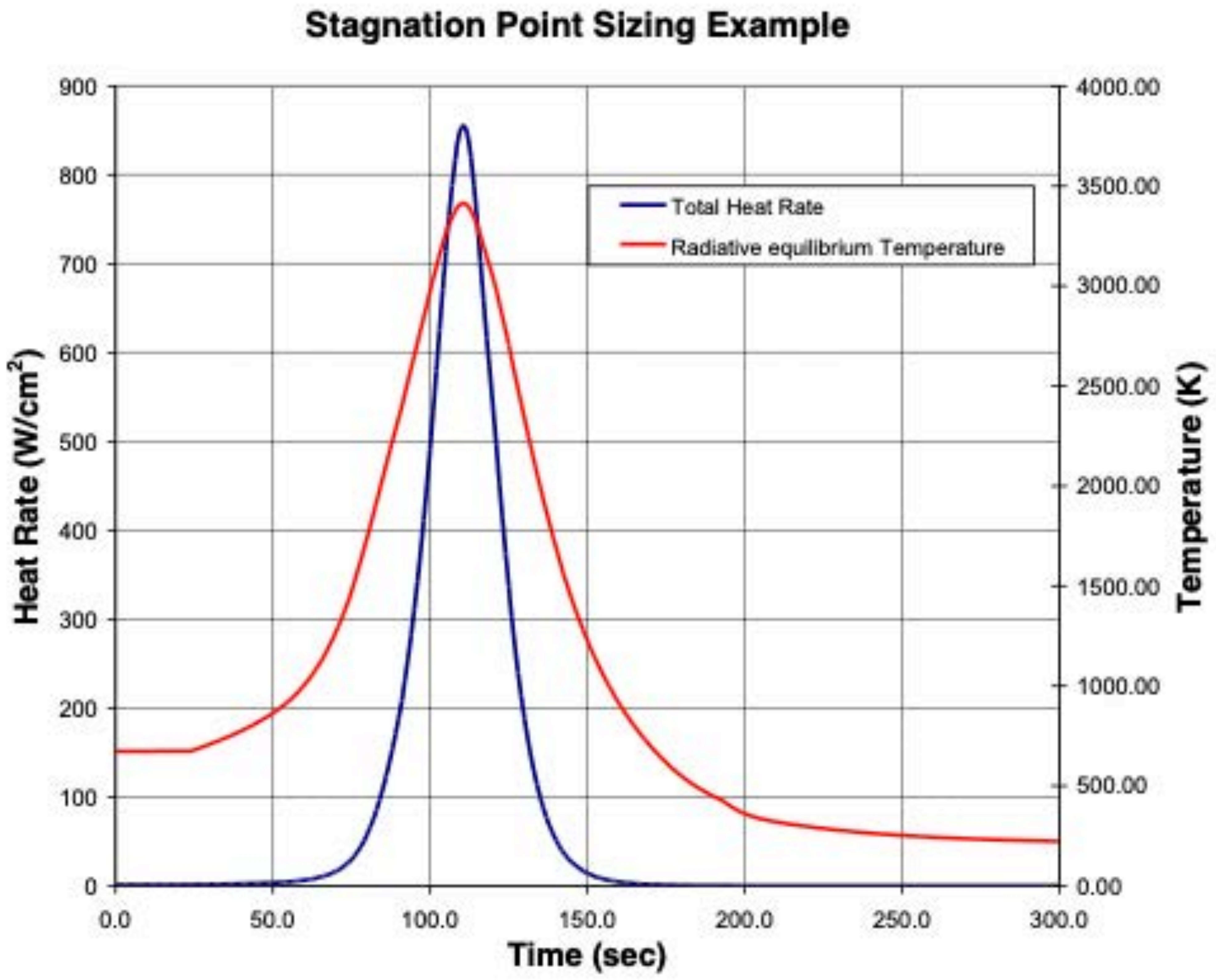
$$\dot{q}_{conv} + \alpha \dot{q}_{rad} - \dot{q}_{cond} - \varepsilon \sigma T_w^4 = 0 \qquad (30)$$

$$\left(1 + \frac{2k\Delta t}{\rho c_p \Delta x_i^{\,2}}\right) T_i^{n+1} - \frac{2k\Delta t}{\rho c_p \Delta x_i^{\,2}} T_{i+1}^{n+1} = T_i^n + \alpha \dot{q}_{rad} \frac{2\Delta t}{\rho c_p \Delta x_i} + \dot{q}_{conv} \frac{2\Delta t}{\rho c_p \Delta x_i} - \varepsilon \sigma T_i^{n4} \frac{2\Delta t}{\rho c_p \Delta x_i} \qquad (31a)$$

$$T_i^n = -\frac{k\Delta t}{\rho c_p \Delta x_i^{\,2}} T_{i-1}^{n+1} + \left(1 + \frac{2k\Delta t}{\rho c_p \Delta x_i^{\,2}}\right) T_i^{n+1} - \frac{k\Delta t}{\rho c_p \Delta x_i^{\,2}} T_{i+1}^{n+1} \qquad (31b)$$

Stagnation Point Sizing Example

- Ballistic Earth entry
  - Ballistic coefficient = 60 kg/m^2 , entry velocity = 12.6 km/s
  - 60° sphere cone, 0.8 m diameter, r_n= 0.23 m
  - At the stagnation point, H_r can be approximated by $\frac{V^2}{2}$



- PICA heat shield

$$\rho = 265.0 \frac{kg}{m^3}$$

$$k = 1.6 \frac{W}{m \cdot K}$$

$$C_p = 1592.0 \frac{J}{kg \cdot K}$$

- Radiative equilibrium temperature

$$T_w = \sqrt[4]{\left(\frac{\dot{q}_{cw}}{\varepsilon \sigma} + T_{surr}^4 \right)}$$

Stagnation Point Sizing Example (2)

- Comparing the simplified approach, the simple FD approach, and the high fidelity code CMA