Hypersonics and Aerothermodynamics for Atmospheric Entry

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15/10/2024, 3YP kick-off

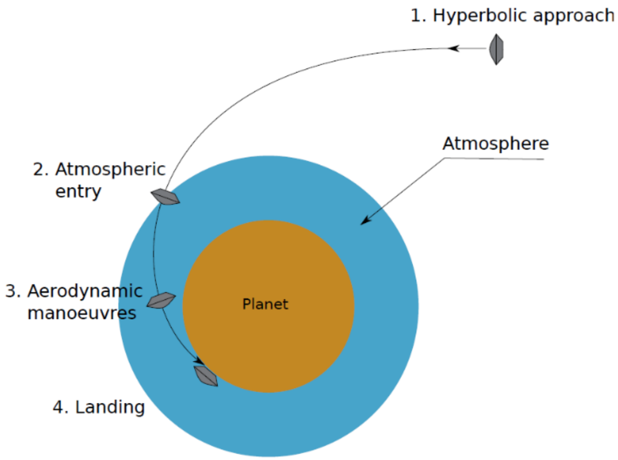
Atmospheric Re-entry

- Fast flying capsules heat up the gas in front of the vehicle
  - Gas temperatures up to two times the surface temperature of the sun
  - Extreme re-entry conditions lead to large heat load
  - Unprotected capsule would burn up (demise!)

- Heat loads aren’t well understood and difficult to predict. Experiments are needed to improve our understanding

Dragon V2 capsule [SpaceX].

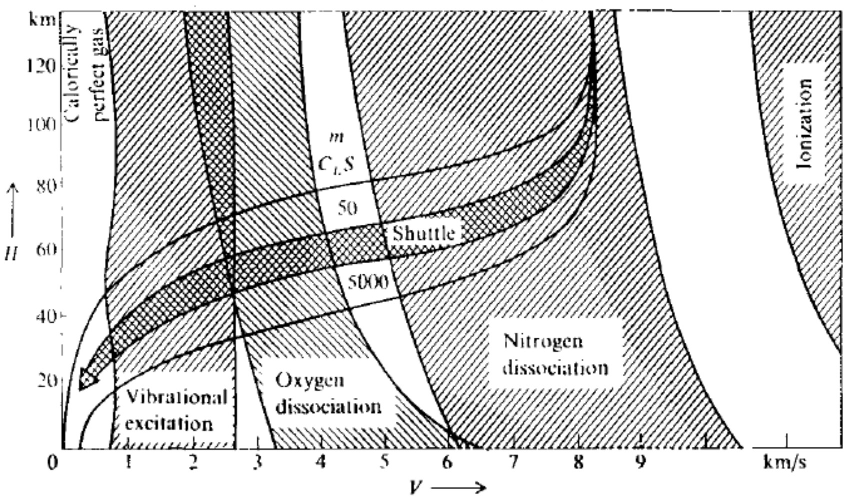
Hayabusa re-entry flight 2010, NASA.

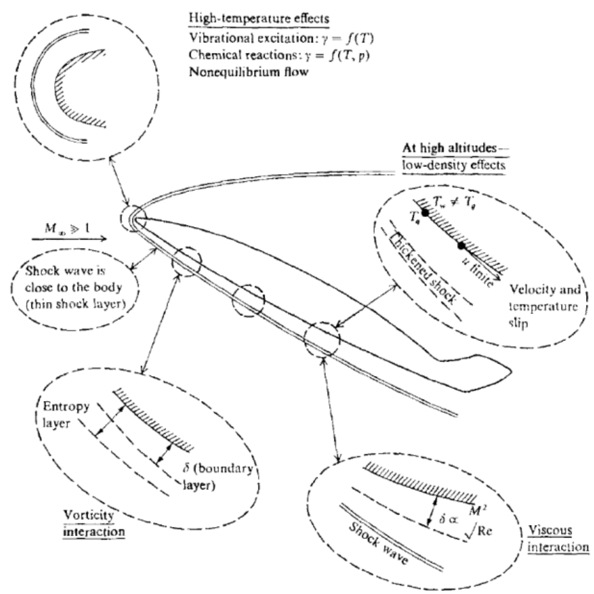


Potter, Ph.D. Dissertation, Univ. of Queensland, 2011.

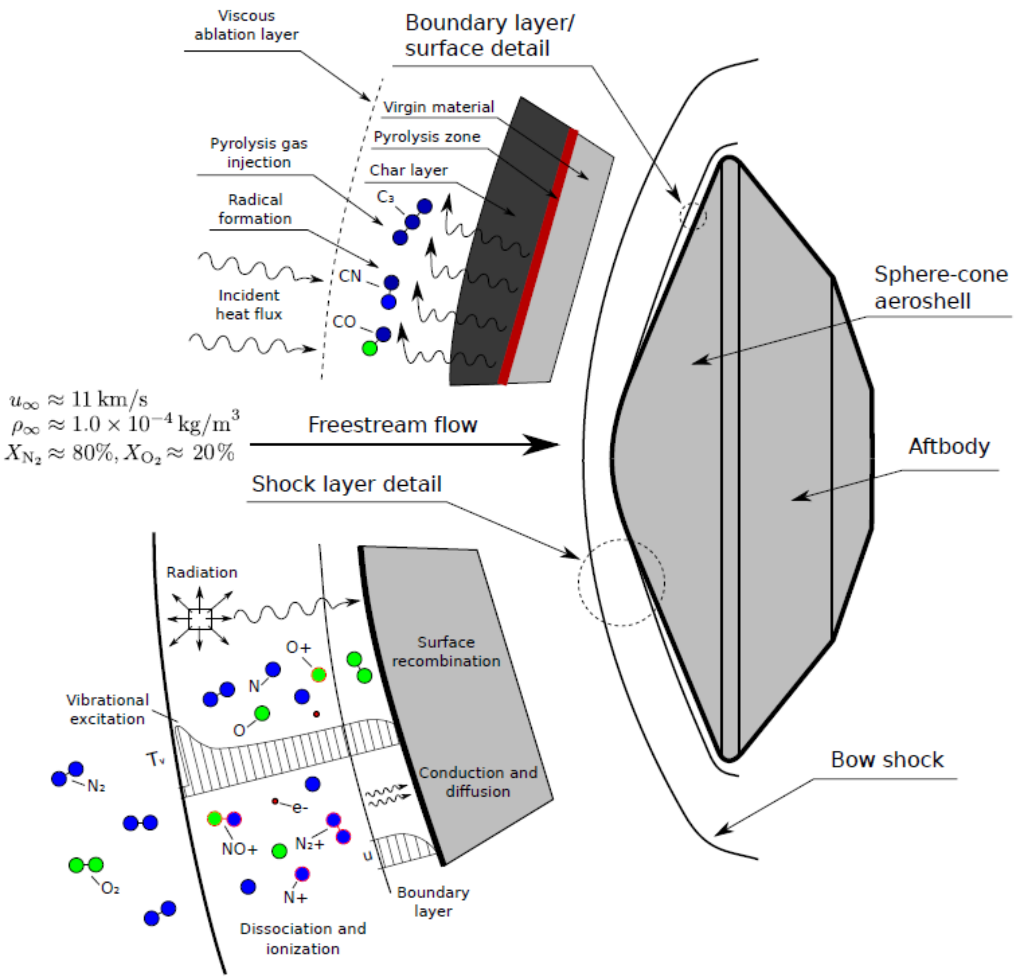
What is Hypersonics?

- Critical phase of re-entry: hypersonic flight
- Flow velocities above Mach numbers of approximately 5
- Flows for re-entry typically between 5 and 15 km/s
- Main characteristics compared to low-speed (or even low supersonic flow)
    - Compressible flow: Shock waves and expansion waves
    - Thin shock layers (distance from compression shock to vehicle wall)
    - High surface heat fluxes and surface shear stresses
    - Thermochemistry: gas radiation, chemical reactions, no calorically perfect gas (c_p and R are not constant)





The Hypersonic Heat Transfer Problem



Apollo Re-entry capsule [NASA]

Physical processes

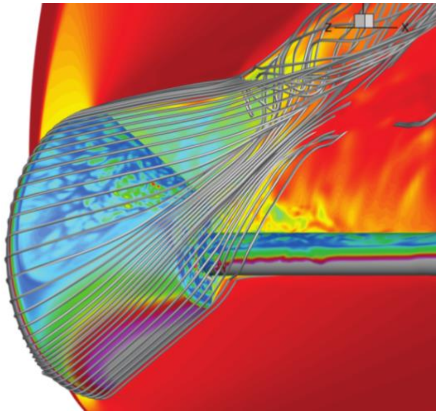
- Non-equilibrium thermochemistry
- Flow radiates
- Heat flux from gas
- Heat flux from radiation Interaction of burning heat shield and flow

Potter, Ph.D. Dissertation, Univ. of Queensland, 2011.

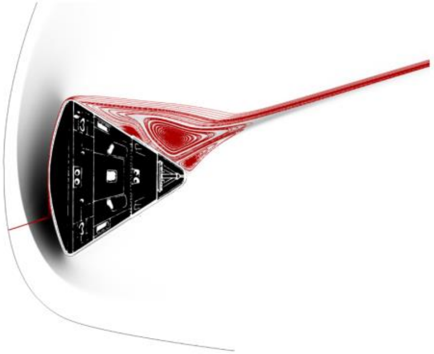
How to Predict/Test Hypersonic Flow Conditions?

- Flight test
  - Best possible testing method, very expensive and very rare

- Computational Fluid Dynamics
  - Simultaneous solution of mass, momentum, energy balance in the complete flowfield
  - Relies on thermochemical and fluid models (viscosity, reaction rates, thermal conductivity, diffusivity,…)
  - ANSYS Fluent, COMSOL Multiphysics (available via University licenses)
  - Eilmer4 (University of Queensland, open-source) https://gdtk.uqcloud.net/

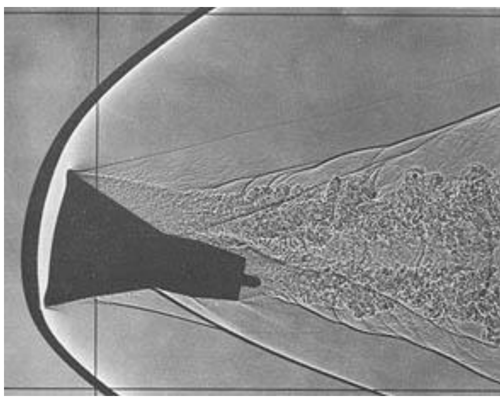


- Experimental ground testing facilities (wind tunnels)
  - Practically impossible to generate steady flows at entry-speeds for full-scale geometries
  - Various concessions need to be made: size of model, aerodynamic similarity, flow speed, flowfield/material region of interest

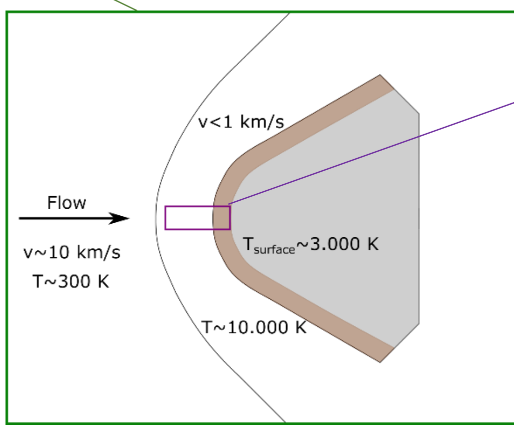


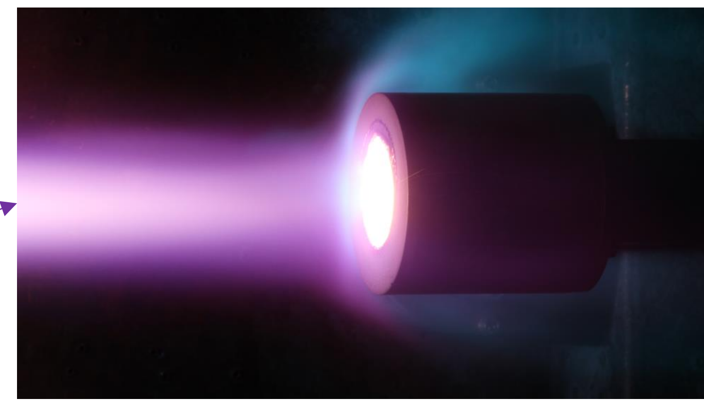
The State of the Art in Ground Testing Facilities

- Impulse facilities
  - Replication of hypervelocity flows
  - Extremely short test times
  - Limitation: Cold models
- Plasma wind tunnels
  - Continuous high temperature flow
  - Qualification of heat shield materials
  - Limitation: Restricted aerodynamic similarity



Gemini capsule in a hypersonic flow [NASA].





Ablative material probe in radiating plasma flow [Uni Stuttgart].

Similarity in High Enthalpy Flows

- Impulse facilities:
  - Scaling of non-equilibrium flowfield
  - Parameters: gas, geometry, h, ρL
  - Based on chemical reaction rate equation

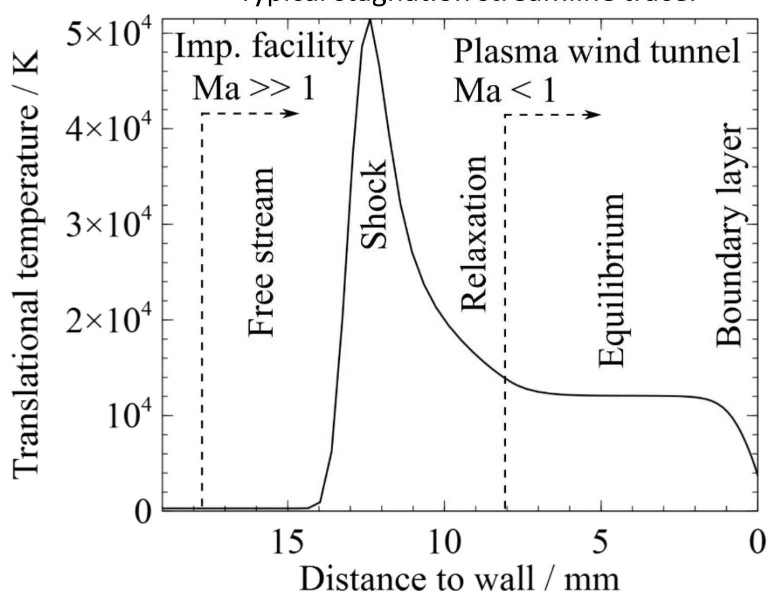
$$\frac{u}{V_\infty}\frac{\partial c_O}{\partial(x/R)}\left[\frac{V_\infty}{R}\right] + \frac{v}{V_\infty}\frac{\partial c_O}{\partial(y/R)}\left[\frac{V_\infty}{R}\right] = K_1\left(\frac{\rho}{\rho_\infty}\right) c_{O_2} c_M$$

$$u'\frac{\partial c_O}{\partial x'} + v'\frac{\partial c_O}{\partial y'} = K_1 \frac{(\rho_\infty R)}{V_\infty}\rho' c_{O_2} c_M$$

- Plasma wind tunnels
  - Scaling of stagnation streamline boundary layer
  - Parameters: gas, h, p_{stag}, β
  - Based on Fay-Riddell heat flux correlation

$$q_w = 0.76\, \mathrm{Pr}^{-0.6}(\rho_e\mu_e)^{0.4}(\rho_w\mu_w)^{0.1}\sqrt{\left(\frac{du_e}{dx}\right)_s}\,(h_{0_e}-h_w)\left[1+(\mathrm{Le}^{0.52}-1)\left(\frac{h_D}{h_{0_e}}\right)\right]$$

Typical stagnation streamline trace.



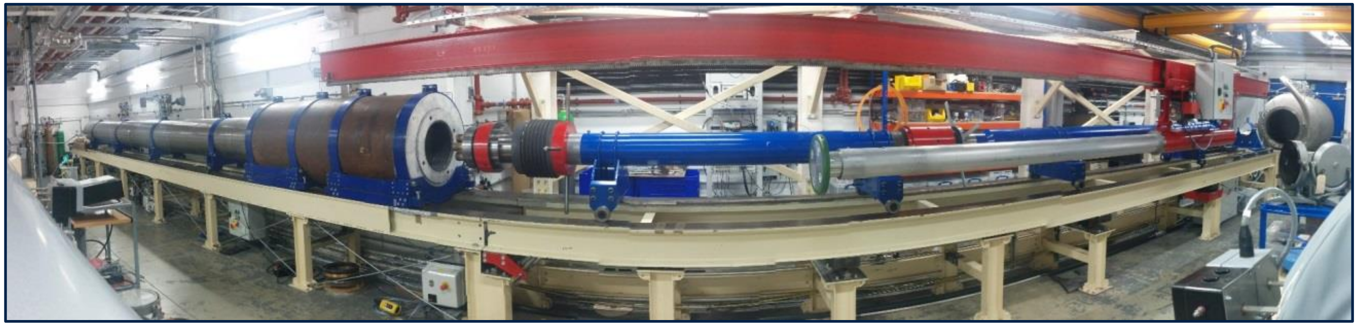
Anderson “Hypersonic and High Temperature Gas Dynamics”

Impulse/Hypersonic Facilities at Oxford

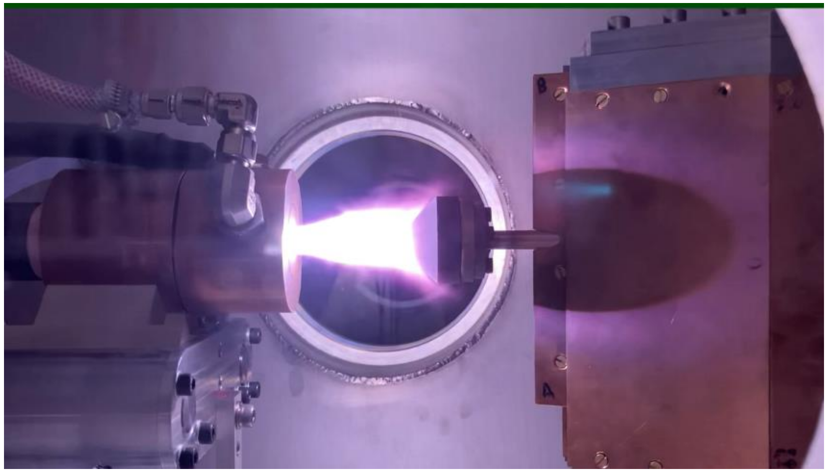
- High Density Tunnel: High speed cold flow
  - Space planes, hypersonic propulsion

- Low Density Tunnel: High altitude flows
  - Aero-braking manoeuvres

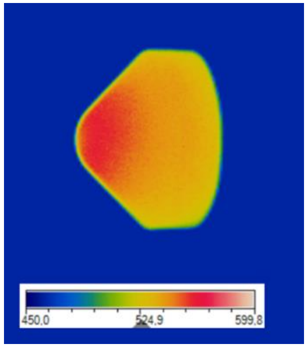
- T6 Stalker Tunnel: Fastest flows in Europe
  - Re-entry of spacecraft from asteroids or other planets



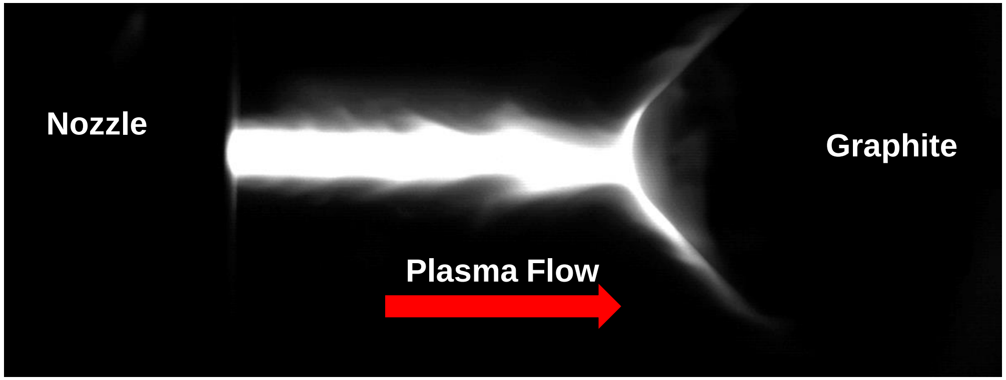
Plasma Facility at Oxford: OPG



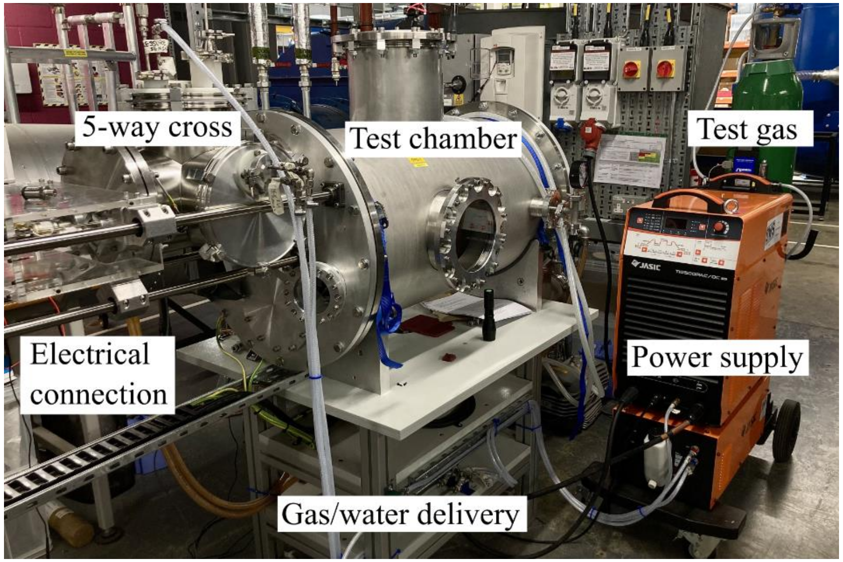
Material sample testing



Infrared Thermography image

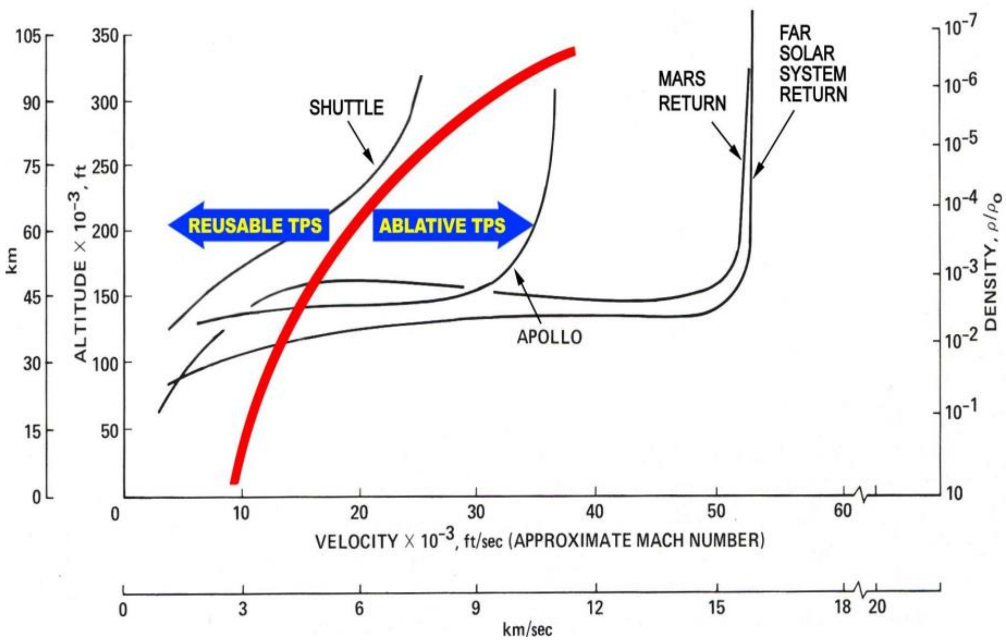


High-speed imaging

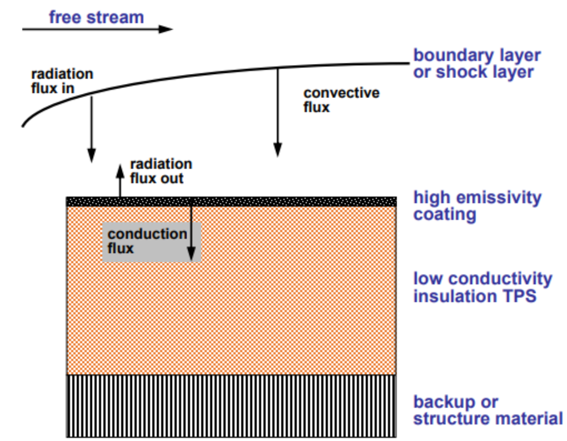


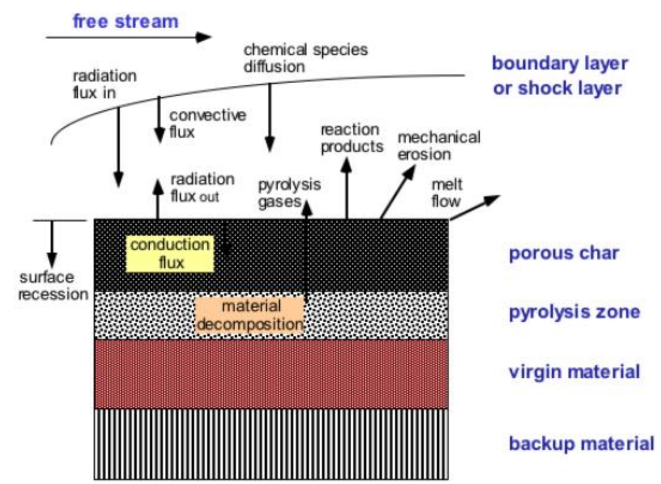
Thermal protection systems

- Re-usable system: Heat rejection through re-radiation and internal heat storage



- Ablative system: continuous burning up of heat shield. Heat rejection through re-radiation, endothermic internal chemical reactions, blowing of pyrolysis gas





Johnson “Thermal Protection Materials and Systems: Past and Future “, 40th International Conference and Exposition on Advanced Ceramics and Composites, 2015

References:

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- Compressible flow equations: NACA 1135 table
  - https://www.nasa.gov/sites/default/files/734673main_Equations-Tables-Charts-CompressibleFlow-Report-1135.pdf

- Heat transfer correlations:
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  - Aaron Brandis and Christopher Johnston, *Characterization of Stagnation-Point Heat Flux for Earth Entry* *https://arc.aiaa.org/doi/10.2514/6.2014-2374*

- Thermal protection systems and design architecture:
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  - https://www.nasa.gov/centers/ames/entry-systems-vehicle-development/tps-materials.html
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  - https://core.ac.uk/download/pdf/42700645.pdf

- Ground testing facilities: Dan Marren and Frank Lu *Advanced Hypersonic Test Facilities*

- Heat transfer: Theodore Bergman, Adrienne Lavine, Frank Incropera, David Dewitt *Fundamentals of Heat and Mass Transfer*