Direct Simulation Monte Carlo Calculations in support of the Columbia Shuttle Orbiter Accident Investigation

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Mathematical models for gas dynamics

$$Kn=\lambda/L$$

λ : local mean free path
L: characteristic length

Euler Equations	Navier-Stokes Equations	Conservation Equations do not form a closed set

Boltzmann Equation	Collisionless Boltzmann Equation

0	0.01	1	100

Local Knudsen number

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The Boltzmann Equation

$$\frac{\partial}{\partial t}(nf) + \vec{v}\cdot\frac{\partial}{\partial \vec{r}}(nf) + \vec{F}\cdot\frac{\partial}{\partial \vec{v}}(nf) = \left[\frac{\partial}{\partial t}(nf)\right]_{collision}$$

f : distribution function
n : number density
F : external force

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Microscopic description of gases

- The rarefied regime is described by the Boltzmann equation
- Particulate nature of gas
- Gas is described by the position, velocity, energy of an ensemble of molecules in a statistical manner
- The microscopic description describes physical processes regardless of the mathematical complexity of the problem

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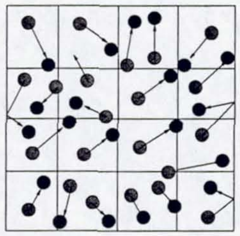
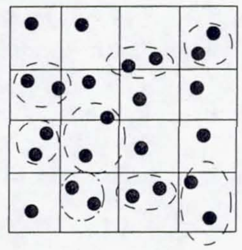
Direct Simulation Monte Carlo (DSMC)



Move phase (deterministic)



Collide phase (stochastic)

$$\frac{\partial}{\partial t}(nf) + \vec{v} \cdot \frac{\partial}{\partial \vec{r}}(nf) + \vec{F} \cdot \frac{\partial}{\partial \vec{v}}(nf) = 0$$

$$\frac{\partial}{\partial t}(nf) = \left[\frac{\partial}{\partial t}(nf)\right]_{collision}$$

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DSMC methodology

- Physical statistical simulation of real dilute gas flow
- Millions of molecules representing real gas molecules modify their velocities and positions as they interact with each other and the boundaries
- Discretization of time and physical space
- Decoupling of the move and the collide phase

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Features of DSMC

- The calculation is always unsteady. Steady state achieved as a long time state of the unsteady flow
- There are no *numerical instabilities*
- Fluctuations have the same physical characteristics as the real fluctuations
- Physics and chemistry models are mere additions to the molecular model *(surface interactions, energy exchange, chemical reactions)*

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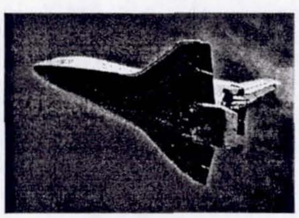
Application overview

- Ultimate goal: *to provide "piecewise integration" of key scenario events to determine the plausibility or implausibility of the candidate failure scenarios*
- Target of current analysis: Determine aerodynamic and heating behavior of the Shuttle Orbiter during aerobraking maneuvers
  - Provide an independent assessment of the internal plume engineering model developed by Steve Fitzgerald (NASA JSC)
- Methodology: Direct Simulation Monte Carlo method
  - DAC implementation by LeBeau (NASA JSC)
- Results: Flowfield simulations at representative re-entry trajectory points



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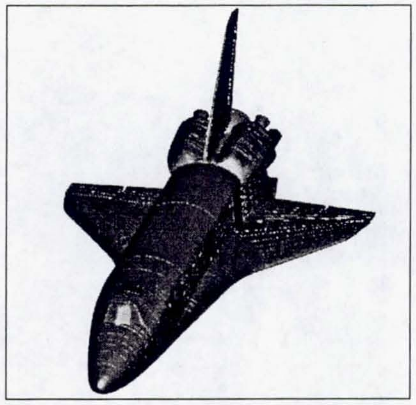
Modeling procedure

- Geometry Modeling
  - Surface grid: Triangulated unstructured constructed from Orbiter CAD model
  - Gas phase grid: Cartesian (adapted where large gradients are present)
- 3-D DSMC Analysis
  - Code used: DAC (version 97)
  - Thermal and chemical non-equilibrium included
  - Chemistry modeling : Finite rate chemistry model of Bird



CAD model for the Orbiter

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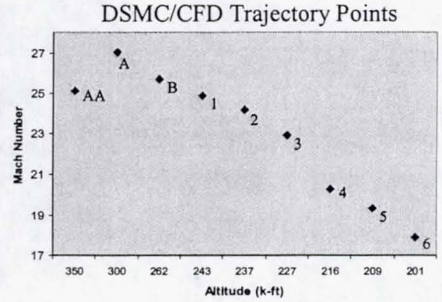
DSMC analysis of flight trajectory

- DSMC simulations were performed at two points of the entry trajectory

DSMC Point AA	DSMC Point A
EI + 91 seconds	EI + 197 seconds
Mach = 25.1	Mach = 27.0
Altitude = 350,274 ft	Altitude = 300,003 ft
AOA = 41 degrees	AOA = 40 degrees
Kn ~ 0.02	Kn ~ 0.001

DSMC/CFD Trajectory Points



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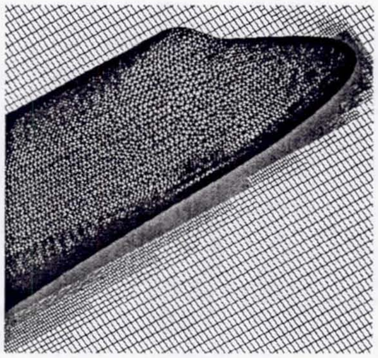
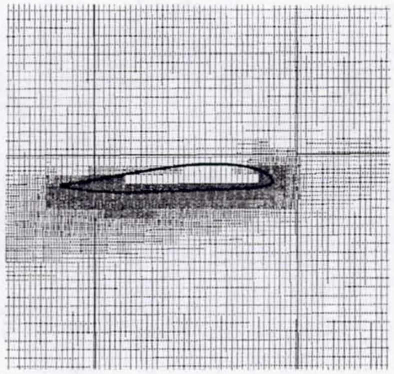
Grids used for the simulations



Adapted grid in the front part of the vehicle



Adapted grid around the wing

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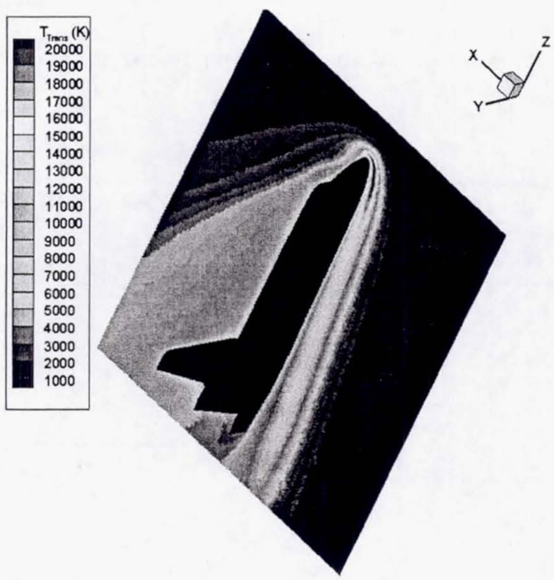
Flowfield temperature profile (350kft)



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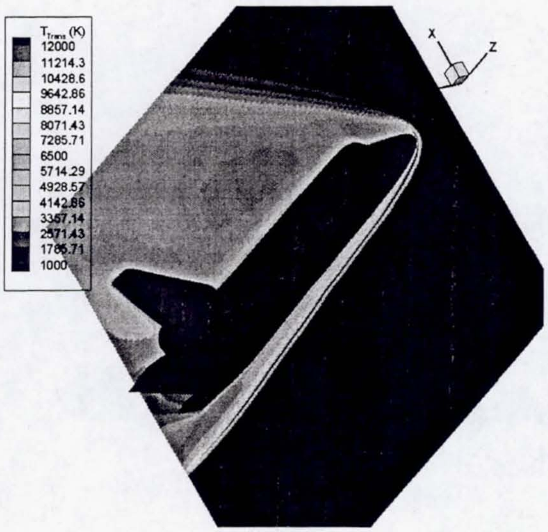
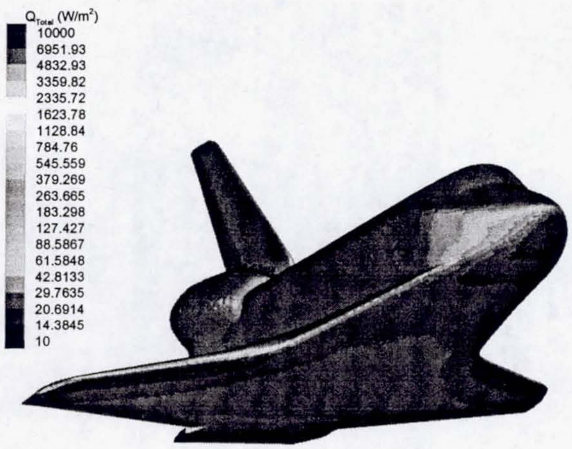
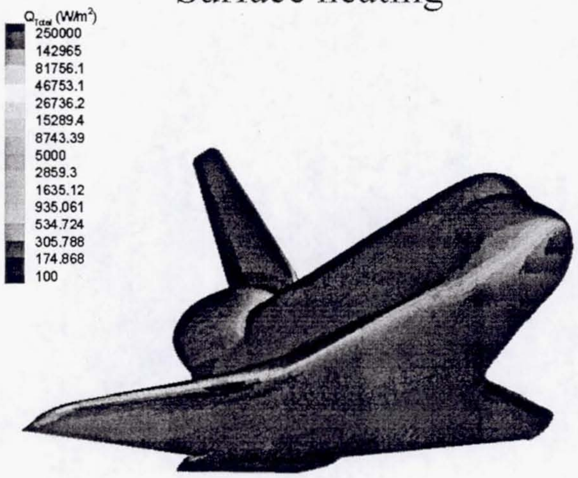
Flowfield temperature profile (300kft)



350 kft flowfield
Surface heating



300 kft flowfield
Surface heating



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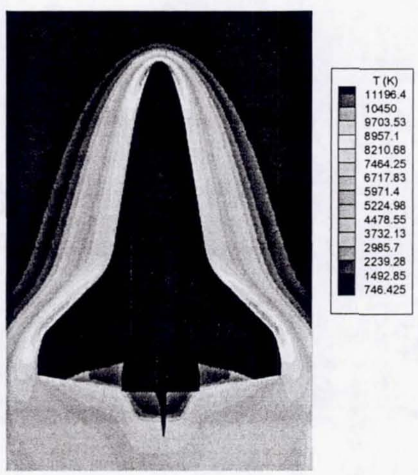
Temperature profile at wing level
(350 kft)



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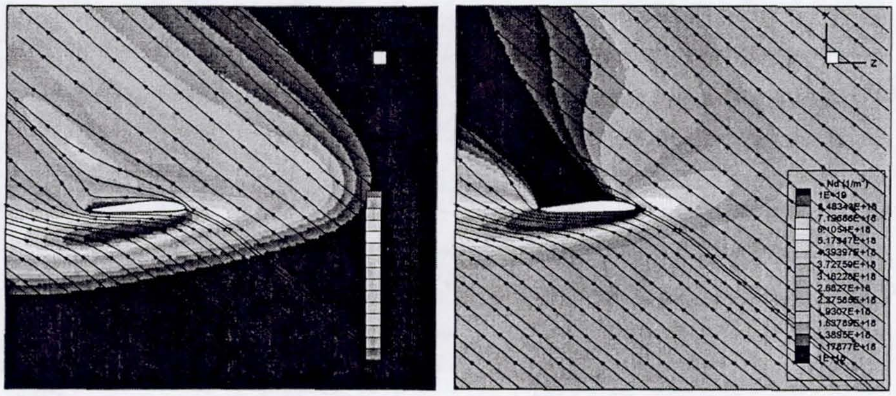
Temperature and density profiles 6m from centerline



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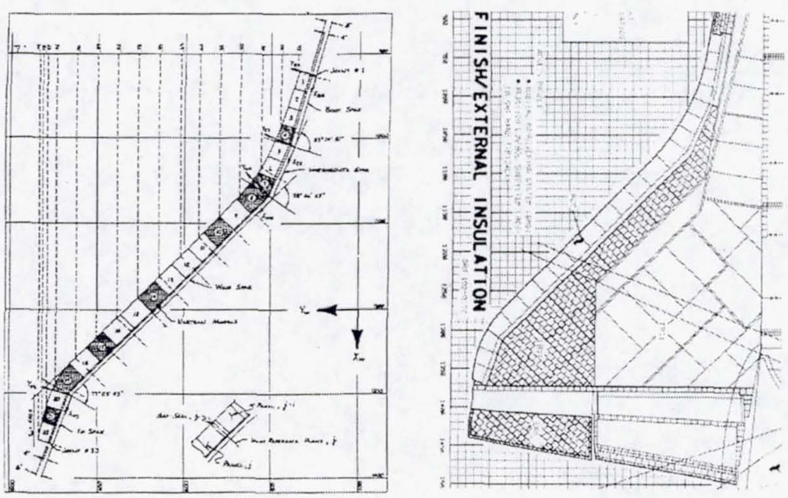
Wing geometry



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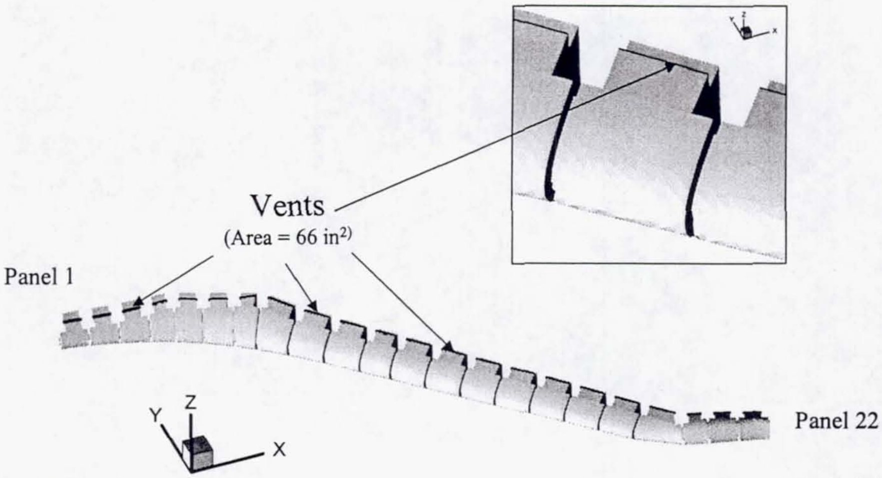
Wing leading edge geometry



Damage scenarios investigated

- What size plume can burn though wire(s) in 530 seconds from EI?:
  - Scenario A: Breach between RCC panels 9 and 10
  - Scenario B: 10 inch hole in RCC panel 8

Damage scenarios simulations

Goal: Model the effects of a damage to the leading edge

- 3-D representation of critical parts of wing leading edge
- Boundary conditions from undisturbed geometry simulations
- DSMC simulations performed with full chemical and thermal non-equilibrium included

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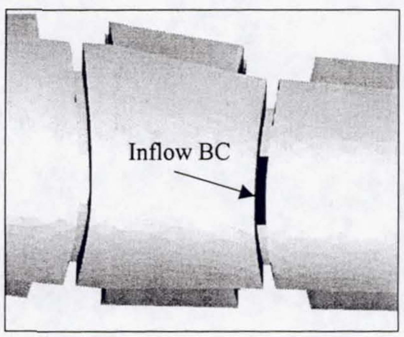
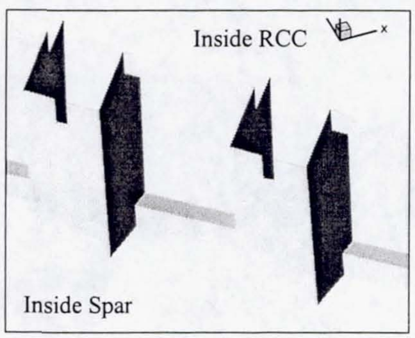
Damage scenario A
Flow through a slit





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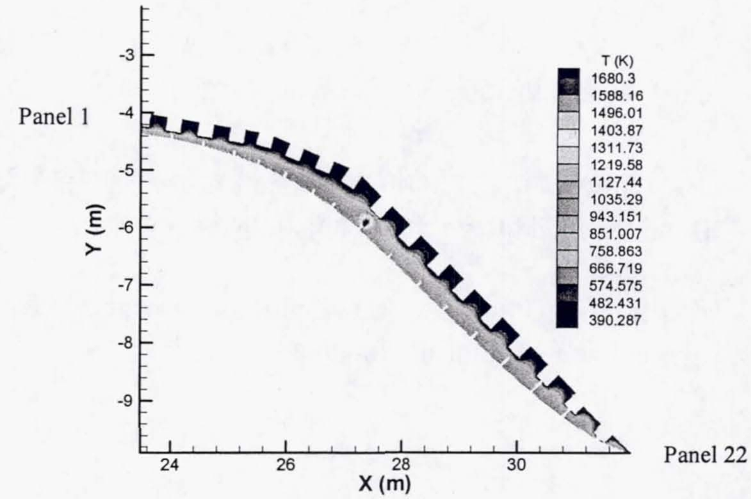
Representative internal wing leading edge flow field



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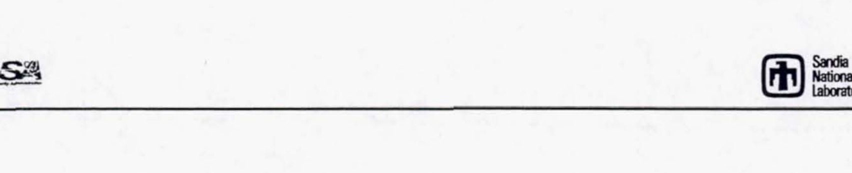
Representative internal wing leading edge spar heating



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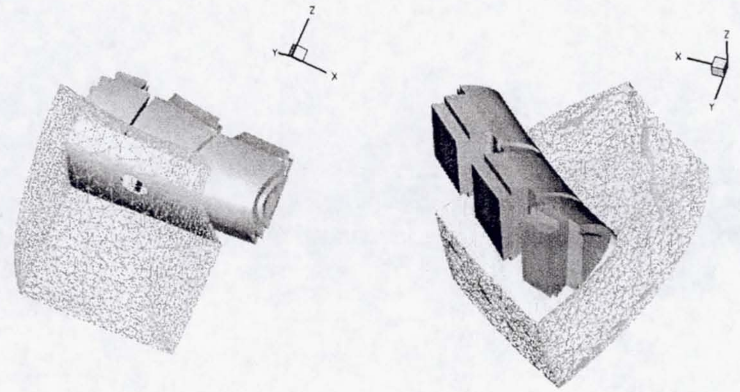
Damage scenario B
Panel 8, 10" hole



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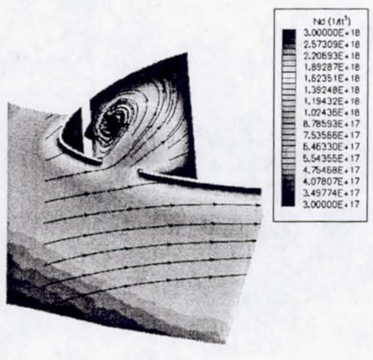
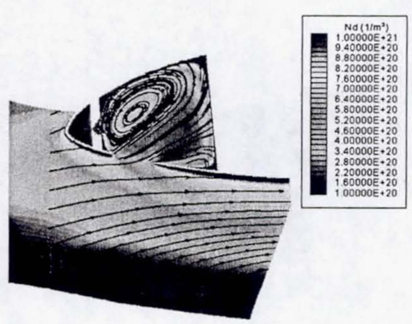
Number density in flowfield with streamlines



350kft



300kft

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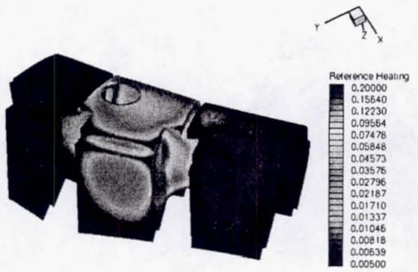
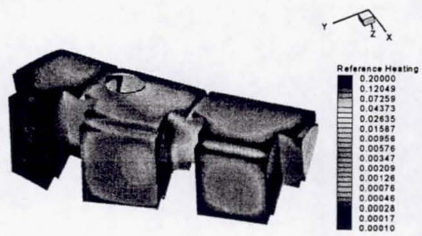
Reference heating distribution in RCC cavity



350kft



300kft

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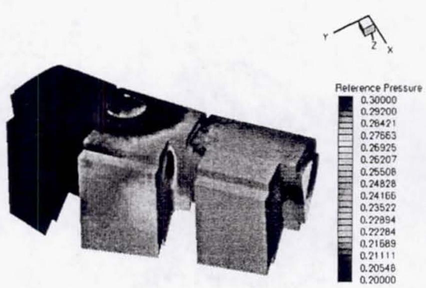
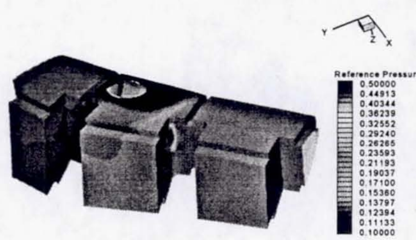
Reference pressure distribution in RCC cavity



350kft



300kft

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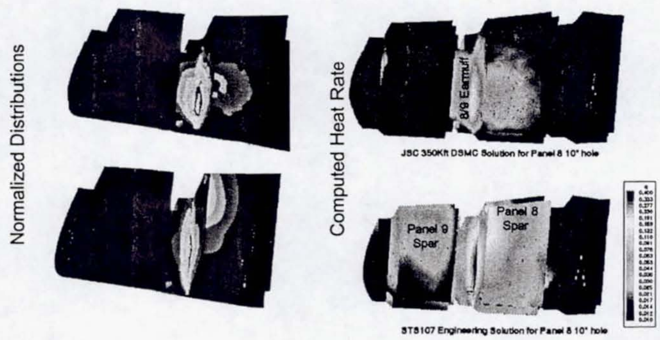
Heating Distribution and Engineering Model Comparisons

- Plume heating model was developed based on continuum flow assumptions, leading to slightly less diffuse plume structures
- Results are favorable
  - Heating predictions within factor of 2
  - Similar predicted impingement location



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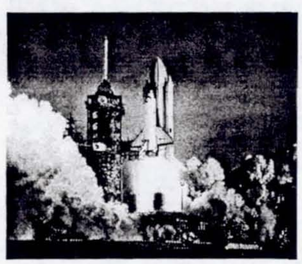
Conclusions

- The Direct Simulation Monte Carlo method was used to provide 3-D simulations of the early entry phase of the Shuttle Orbiter
- Undamaged and damaged scenarios were modeled to provide calibration points for engineering "*bridging function*" type of analysis
- Currently the simulation technology *(software and hardware)* are mature enough to allow realistic simulations of three dimensional vehicles



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Extras

Applications of DSMC and typical length-scales

- Hypersonics (m)
- Microelectronics manufacturing processes (cm)
- Physical, Chemical vapor deposition (cm)
- MEMS (microns)
- Non-equilibrium chemistry (atomic level)

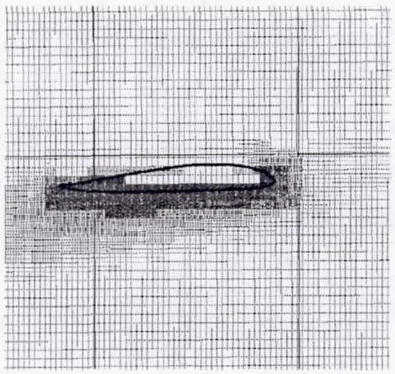
The limitations of DSMC

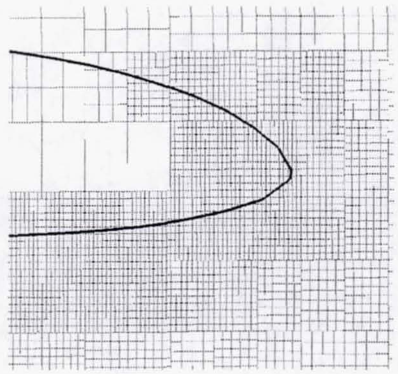
- The computational load increases with the density of the flow
- Statistical error decreases as a function of the *square root* of the number of samples
- DSMC can carry more information than actually needed for some applications
- DSMC is an MMP empowered technology

Calculations performed

- 350 kft
  - 2 levels of adaptation
    - 1st level of adaptation: mean free path wide subcells
    - 2nd level of adaptation: 0.5 mean free path subcells
- 300 kft
  - 2 levels of adaptation
    - 2nd level of 350kft adaptation
    - 3rd level of adaptation:(0.1 mean free path subcells)

Grid 6 meters from the centerline





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