Using Statistical Risk Assessment to Optimize the Design of Inflatable Membrane Structures in Low Earth Orbit

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Inflatable Antenna - Motivation

- Large surface area
- Low storage volume
- High packing efficiency
- Low weight
- Low cost

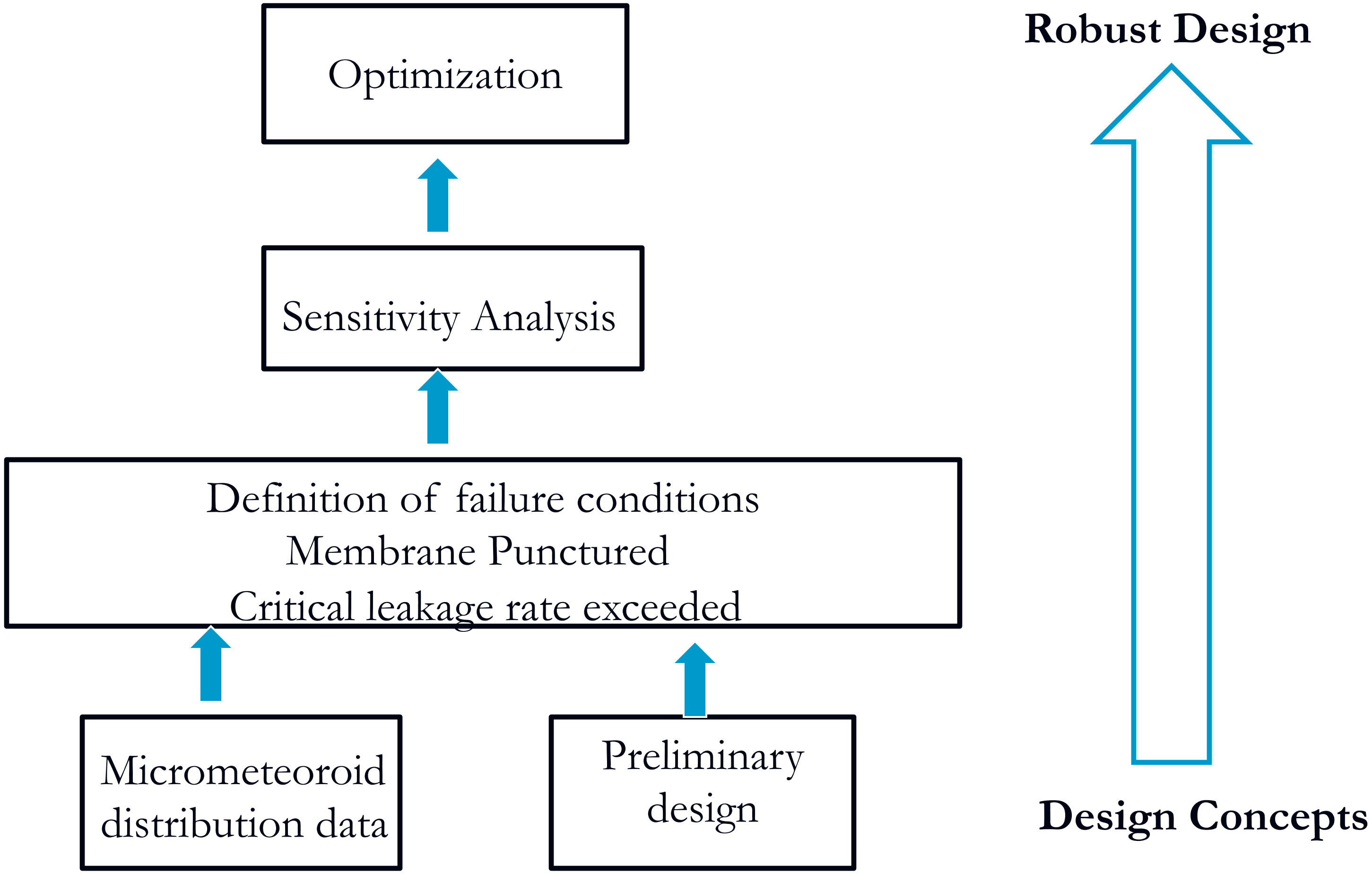
Challenges

- Large uncertainties in outer space environment.
- Complex interaction phenomenon.
- Lack of understanding of underlying physics.
- Robust inflatable design.
- Adequate shape control.

Objectives

- Use statistical methods to design robust inflatable structures.
  - Quantify the advantage of the design choices by assessing risk.
  - Comparison in terms of architecture, membrane layer, sublimate properties.

Objective



Robust Design

Optimization

Sensitivity Analysis

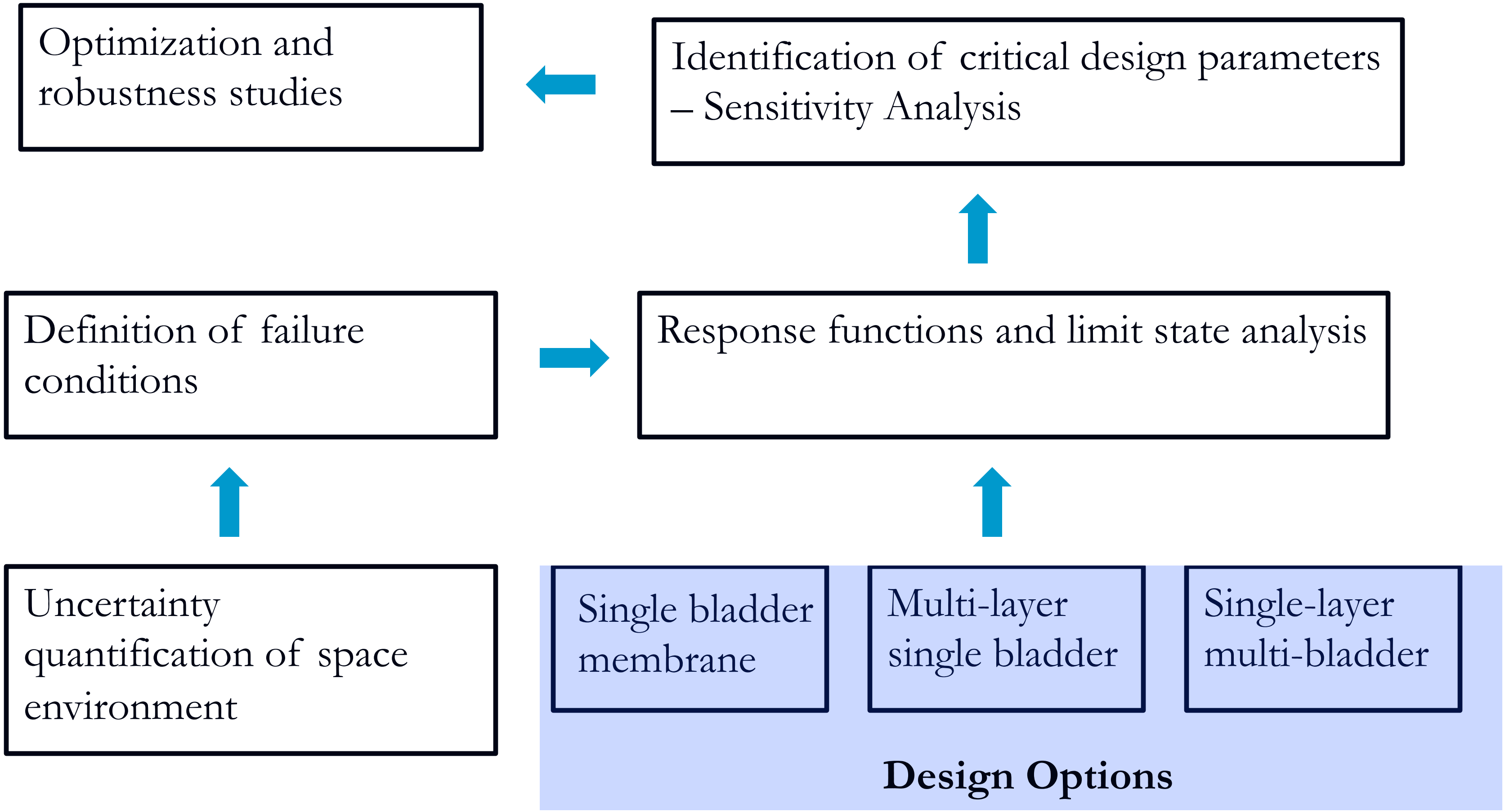
Definition of failure conditions
Membrane Punctured
Critical leakage rate exceeded

Micrometeoroid distribution data

Preliminary design

Design Concepts

Outline of procedure



Optimization and robustness studies

Identification of critical design parameters – Sensitivity Analysis

Definition of failure conditions

Response functions and limit state analysis

Uncertainty quantification of space environment

Single bladder membrane

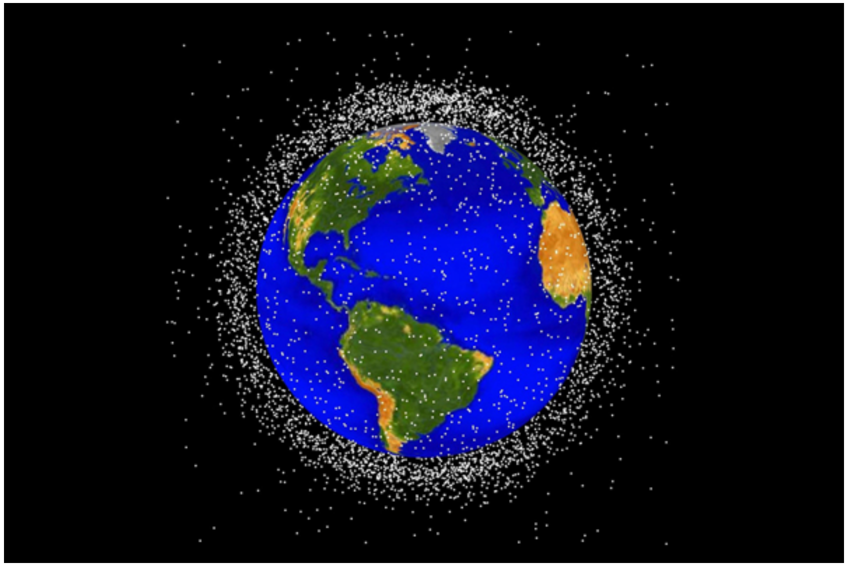
Multi-layer single bladder

Single-layer multi-bladder

Design Options

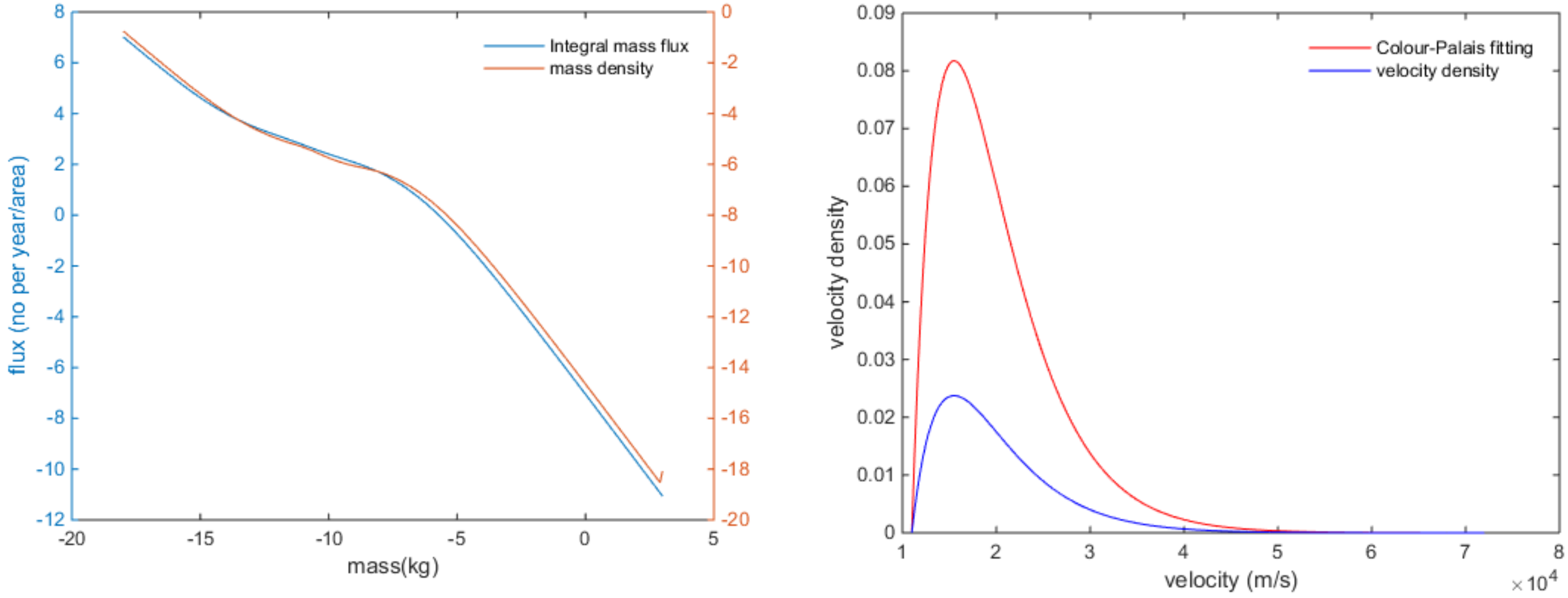
Space Environment

- Micro-meteoroids and space debris
- Mass and Velocity are the two parameters of primary interest

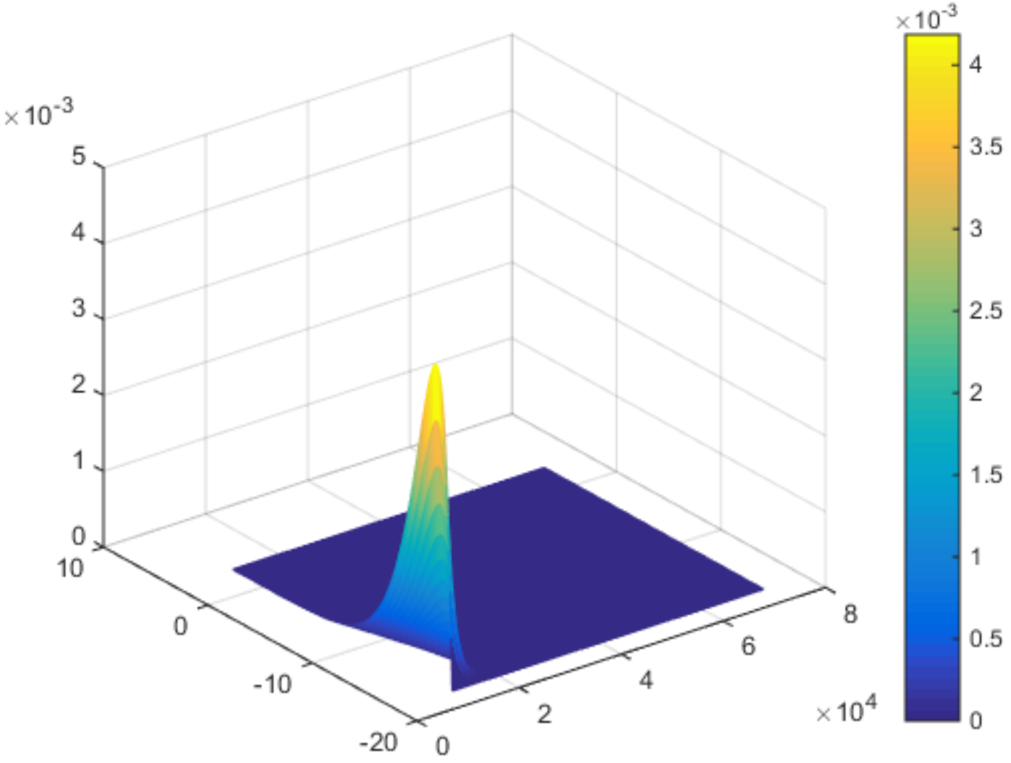


Micrometeoroid mass and velocity distribution

Probability density function for micro-meteoroid mass and velocity



Joint Probability distribution

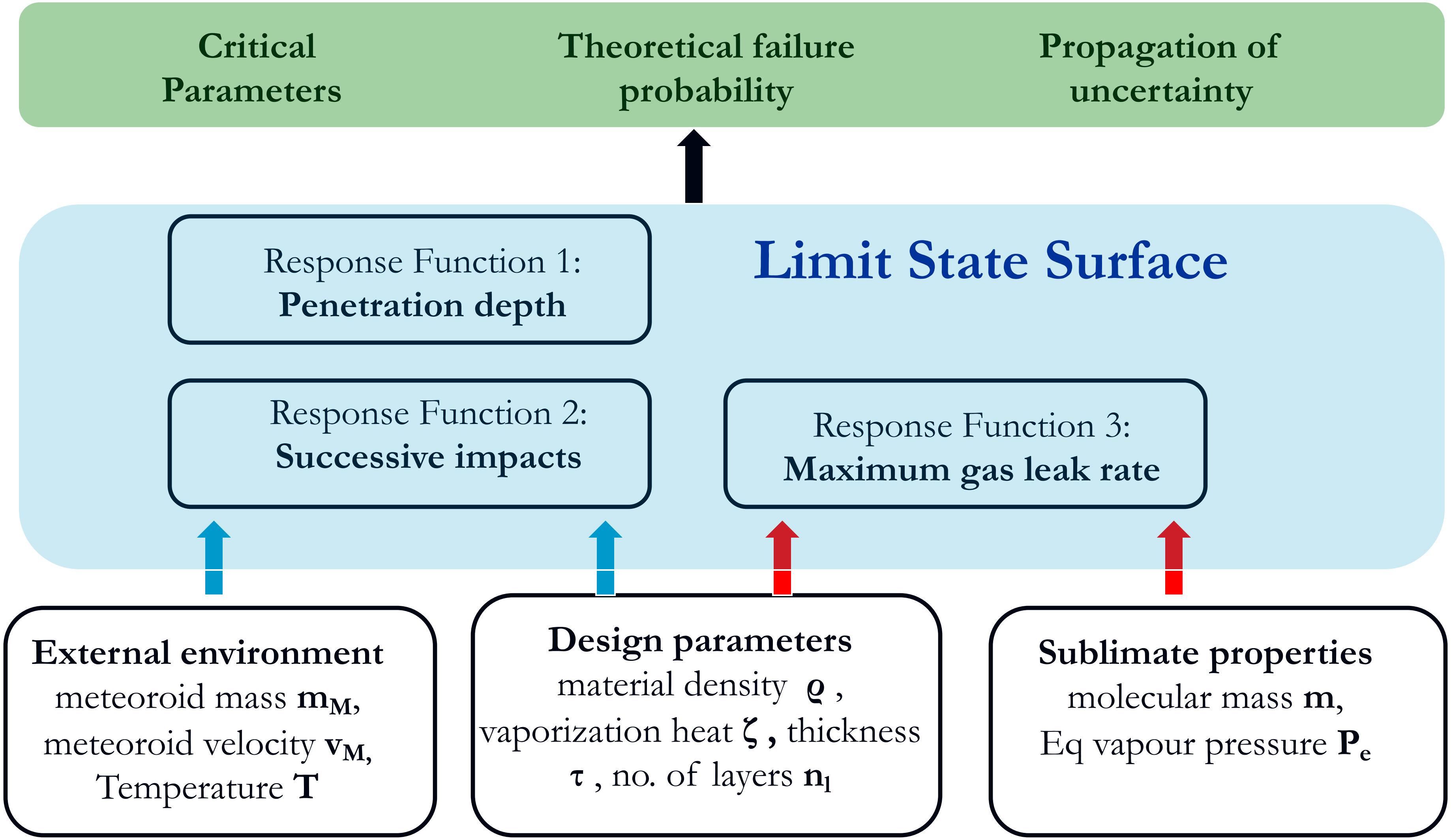


Joint mass and velocity probability distribution

- **Mass and velocity distributions assumed independent events**

$$\phi_{m,v}(m,v) = f_m(m) \times f_v(v)$$

Outline of Analysis



Critical Parameters

Theoretical failure probability

Propagation of uncertainty

Limit State Surface

Response Function 1: **Penetration depth**

Response Function 2: **Successive impacts**

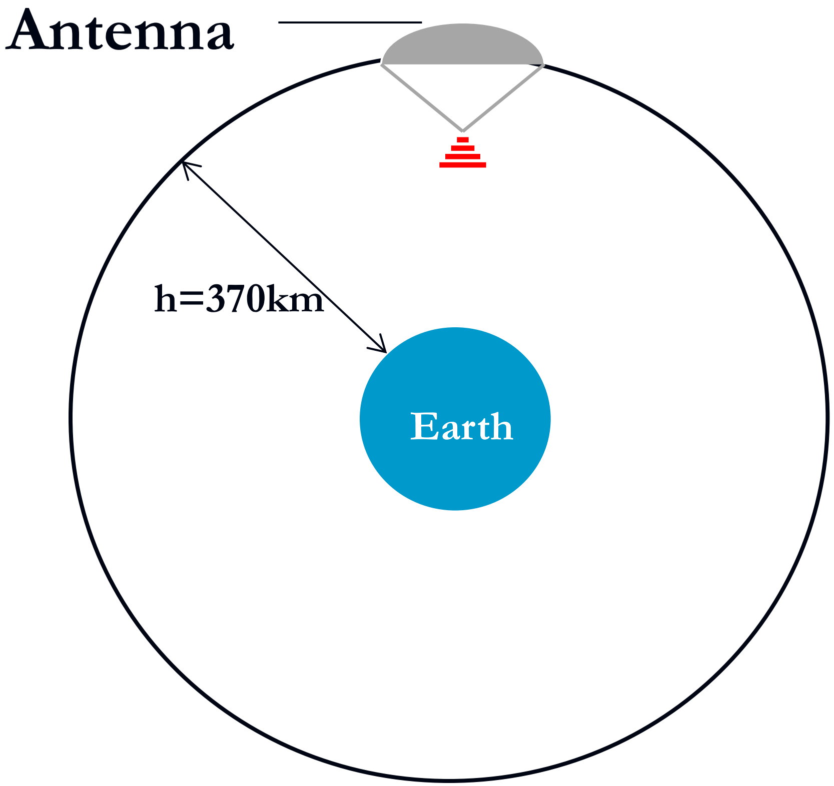
Response Function 3: **Maximum gas leak rate**

External environment
meteoroid mass $\mathbf{m_M}$,
meteoroid velocity $\mathbf{v_M}$,
Temperature **T**

Design parameters
material density ϱ ,
vaporization heat ζ , thickness
τ , no. of layers $\mathbf{n_l}$

Sublimate properties
molecular mass **m**,
Eq vapour pressure $\mathbf{P_e}$

Membrane Analysis – Definition of problem

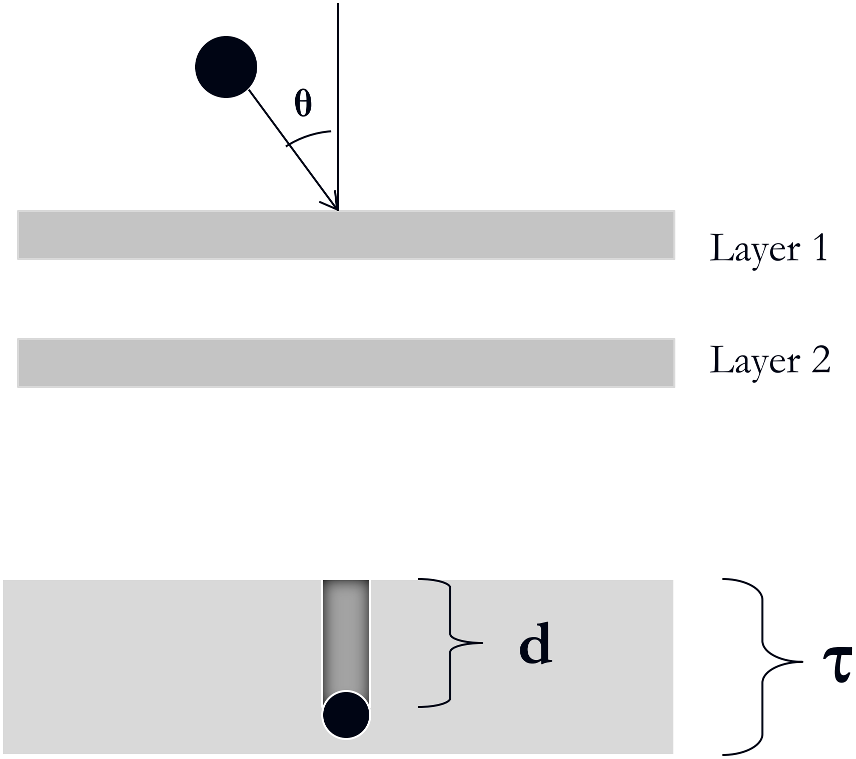


- Cross sectional area facing earth is 1 m^2
- T_{avg} in LEO = 394K

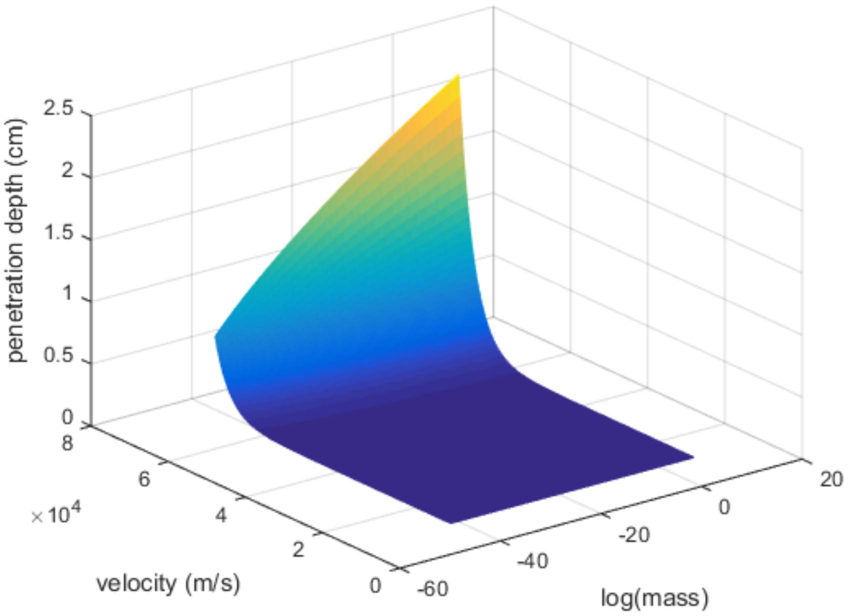
Penetration depth

Successful penetration condition (Babuscia, 2013)

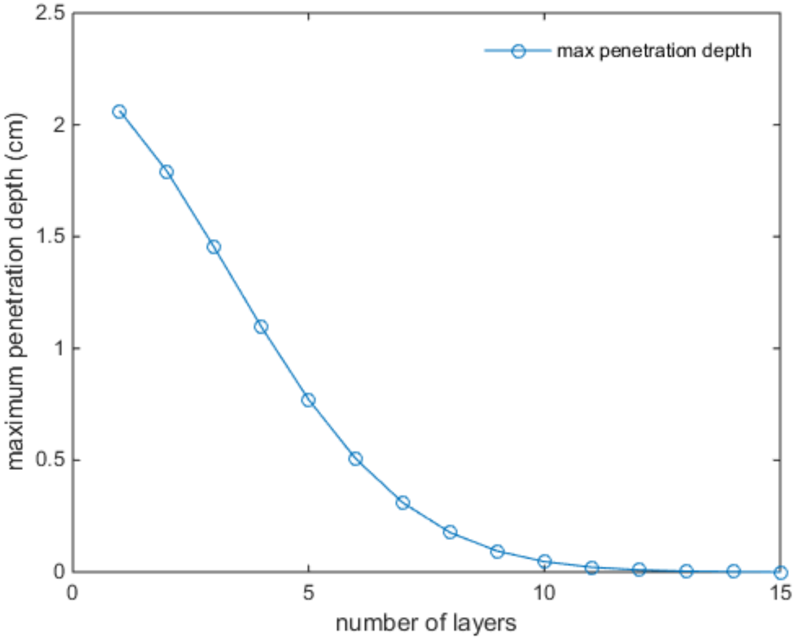
$$0.9^{\frac{2(nL-1)}{3}} \underbrace{\left(\frac{9 m_M v_M^{2}}{\left(2\pi\rho_{mylar}\zeta_{mylar}\right)}\right)^{1/3}}_{\mathbf{d}} \geq \tau$$



Penetration depth

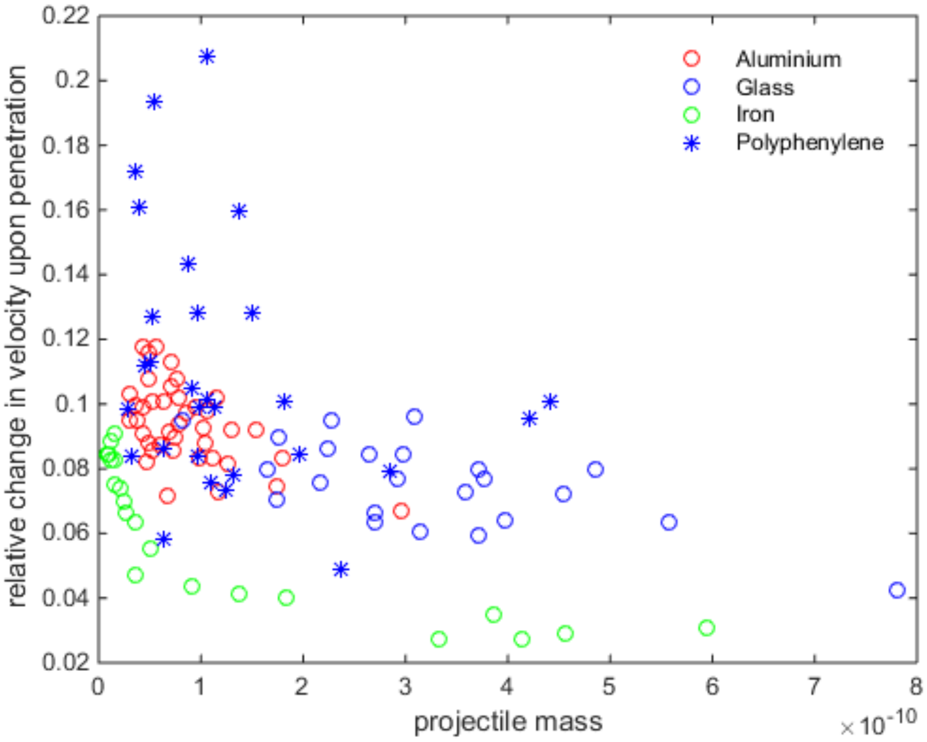


P-depth as a function of mass and velocity



P-depth as a function of no. of layers

Successive Impact Deceleration

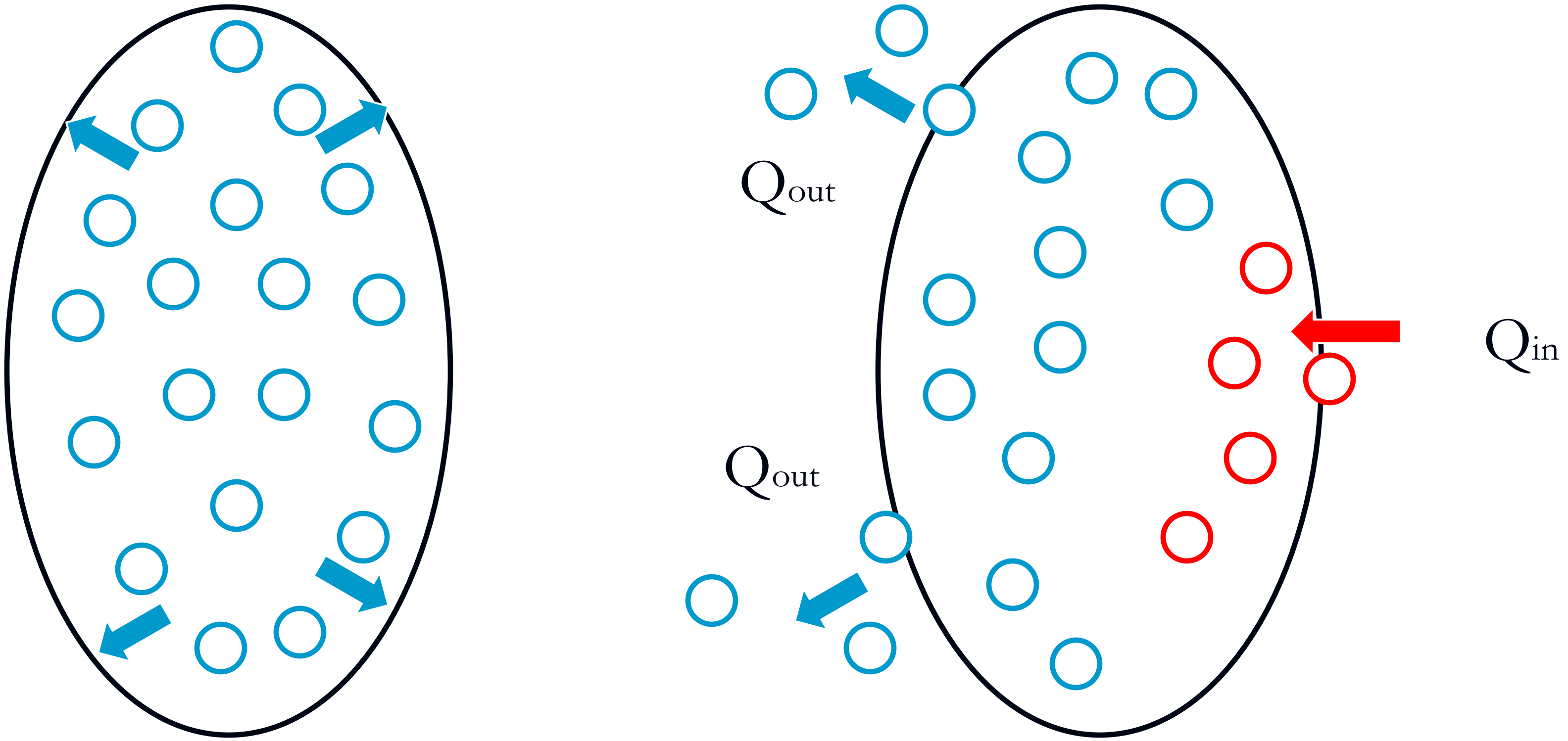


Hyper-velocity projectile deceleration (Pailer, 1980)

Correlation between deceleration, projectile mass and density

$$\left(\Delta V / V\right)_{avg} \approx 0.089$$

Maximum Gas Leak Rate



Before Impact

After Repeated Impacts

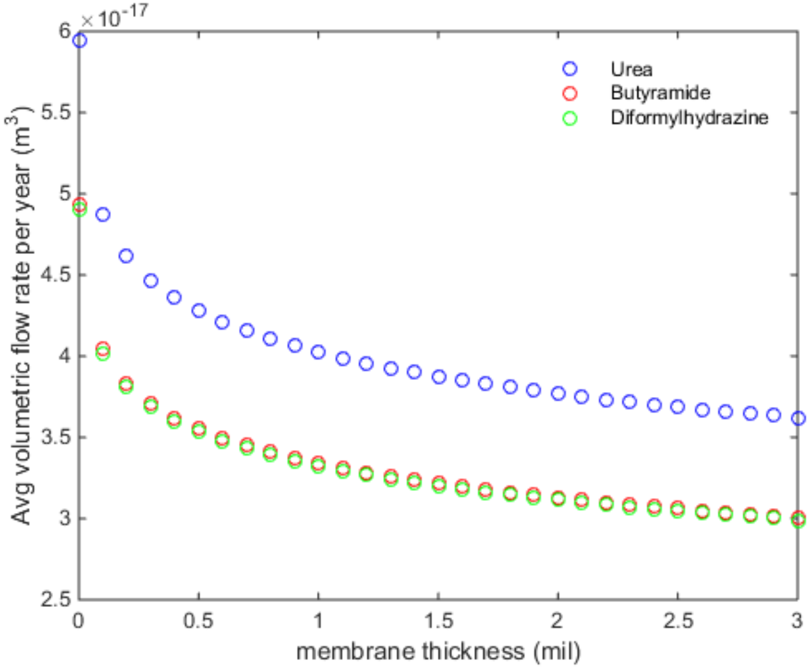
Maximum Gas Leak Rate

$$\dot{Q}_{out} = \underbrace{\left(\frac{\sum A_i p_i M_{tot}}{time} \right)}_{\text{Max total leak area}} \underbrace{\sqrt{\frac{kT}{2\pi m}}}_{\text{Sublimate mobility}}$$

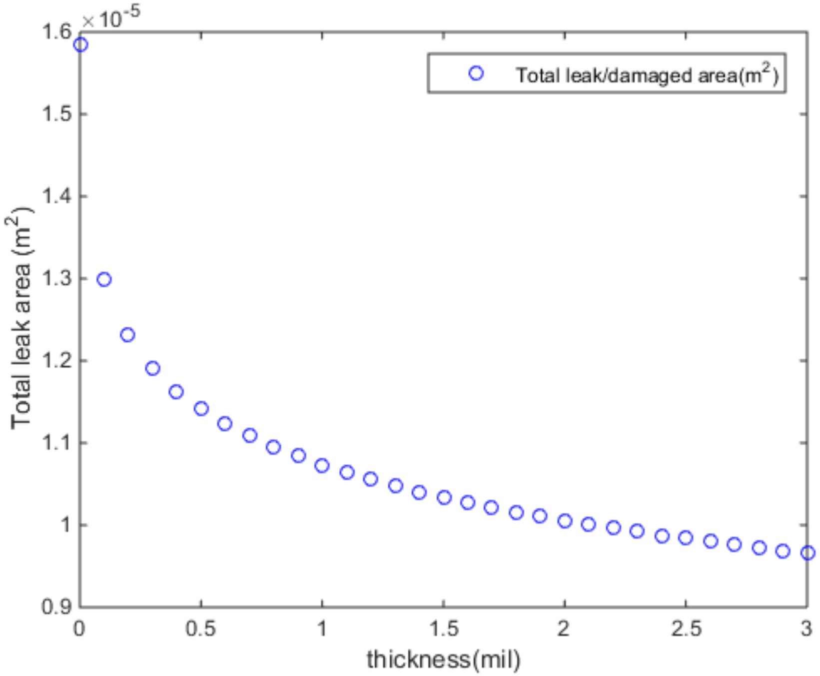
$$\dot{Q}_{in} = \frac{\dot{M}RT}{mP_{eq}}$$

Condition for normal operation: $\dot{Q}_{in} \geq \dot{Q}_{out}$

Maximum Gas Leak Rate

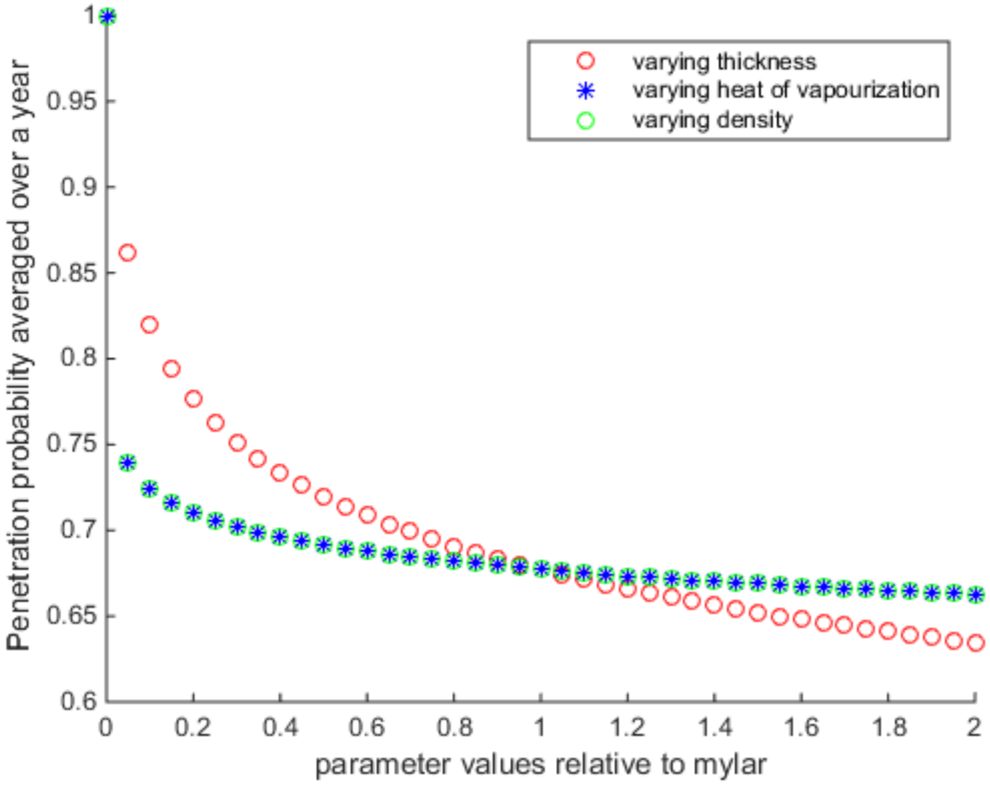


Avg. exit flow-rate vs. membrane thickness



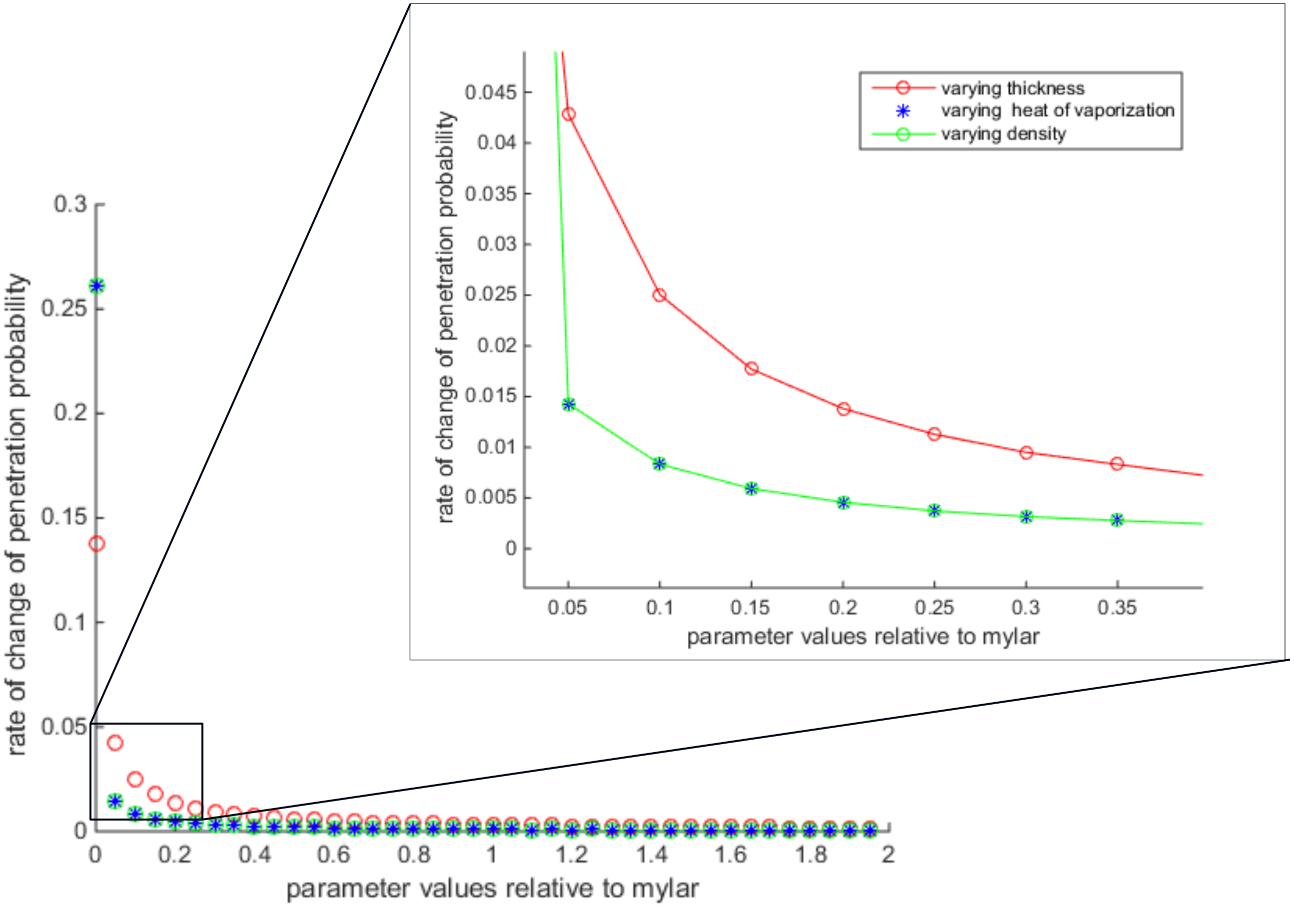
Total leak area vs. membrane thickness

Theoretical probability of successful penetration



Probability of successful meteoroid penetration.

Sensitivity Analysis

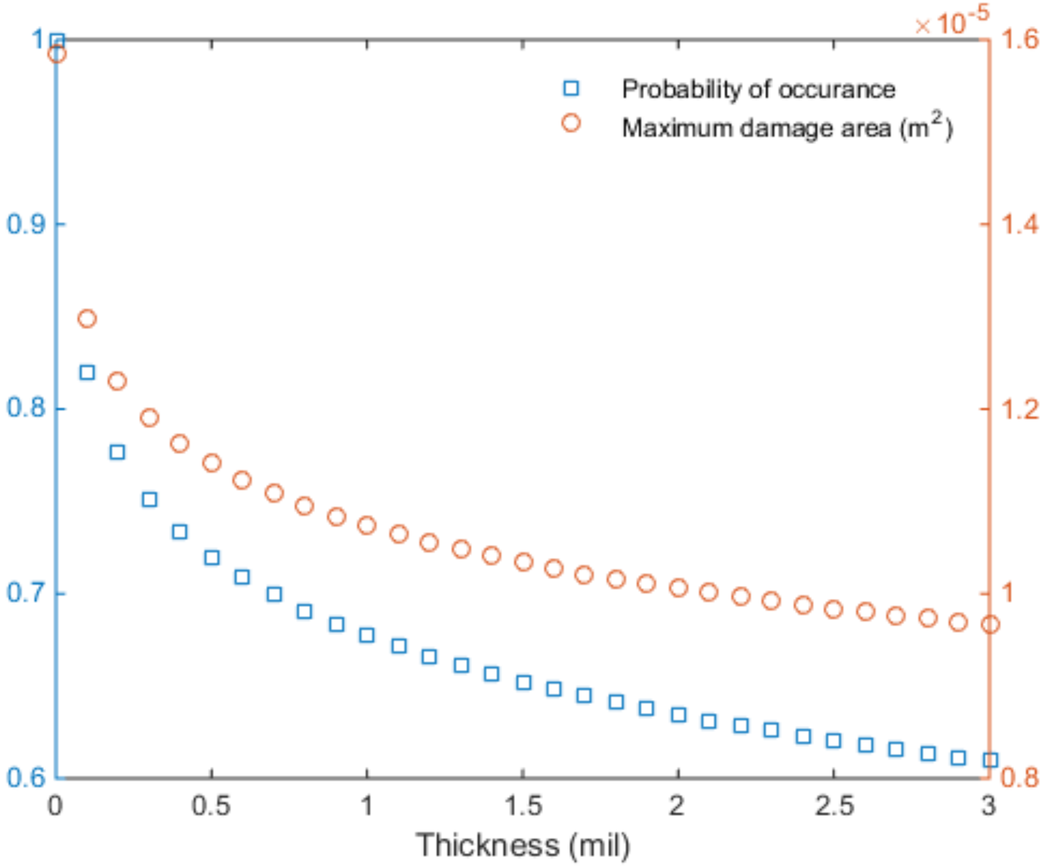


Sensitivity analysis of material properties

Discussion

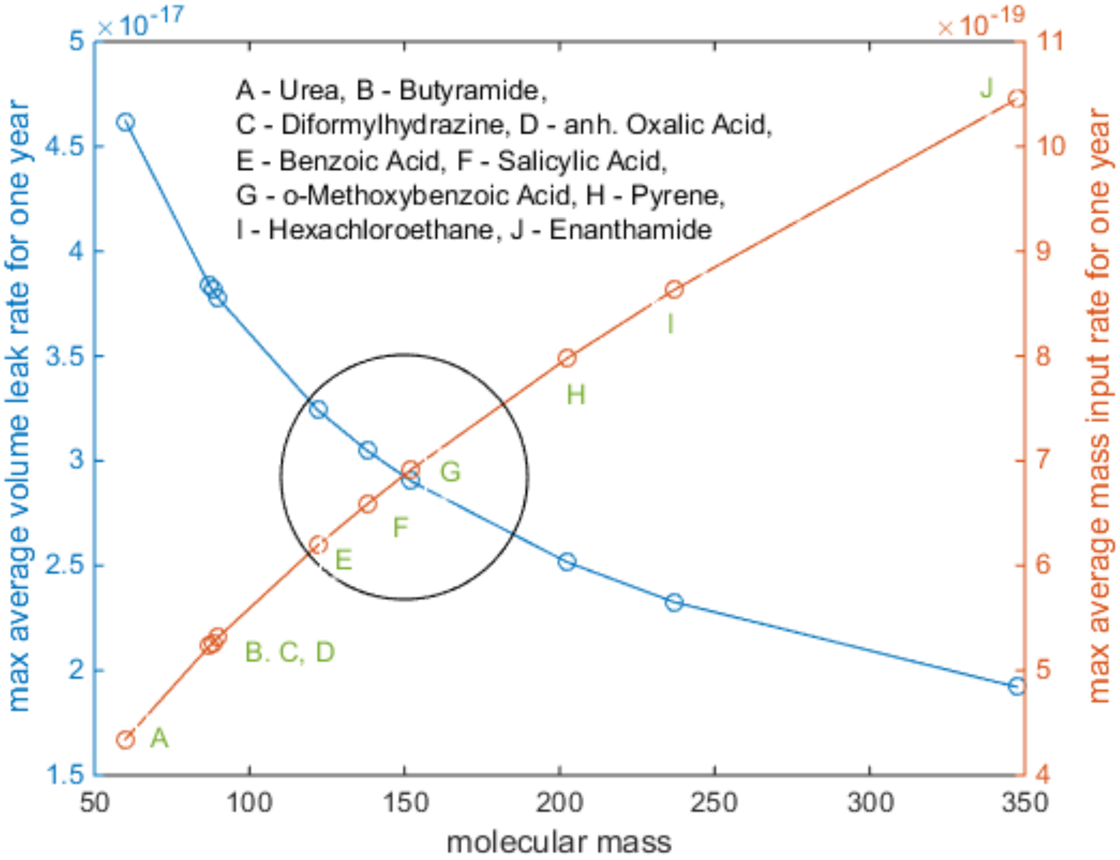
- **Yearly penetration probability converges to 65% above a membrane thickness of 2 mil**
- **Penetration probability shows much higher sensitivity (about three times) to membrane thickness as compared to density and heat of vaporization**

Theoretical probability for max damage area



Probability of failure and total leakage area vs. thickness

Volumetric Leak Rate



Volume and mass flow-rates for different sublimates

Conclusions

- Multilayer membrane better than multi-bladder system.
- Volume rate of leak shows stronger sensitivity to molecular mobility than molecular mass
- At Tavg= 394K, the following studied sublimates were found to perform the best:

1. benzoic acid
2. salicylic acid
3. o-methoxybenzoic acid

Ongoing/further work

- Inclusion of pre-stress into model
- Promising areas: Diaphragm based actuation, Rigidization on command

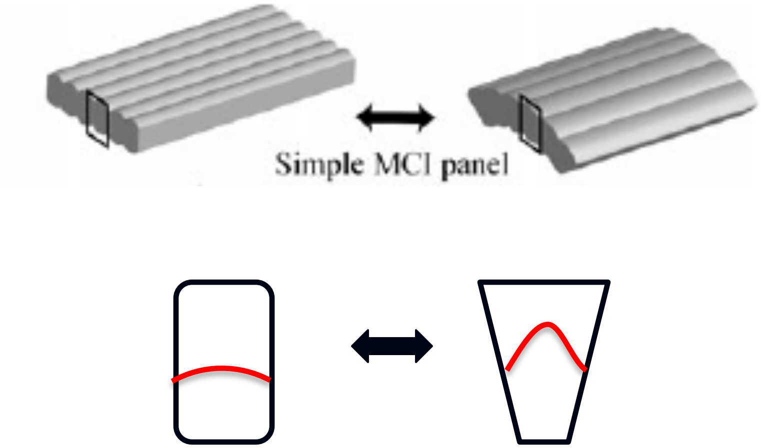


Fig 12. Diaphragm based actuation (Ishimura, 2013)

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