Design of a Cubesat Re-entry Experiment for Satellite Demise

Luke Doherty, Tobias Hermann and Nafiz Chowdhury

Oxford Thermofluids Institute,
University of Oxford

3YP kick-off, Tue 15th Oct. 2024

Kick-off Overview

1. Course Overview (LD)
    - Timetable
    - Assessment
    - Submission / marking

2. Flight vehicle design & Group Allocations (LD)
    - Some brief thoughts…

3. Introduction to hypersonics and aerothermodynamics (TH)
    - Atmospheric re-entry
    - What is "hypersonics" / the heat transfer problem
    - Prediction of hypersonic flows
    - Flow similarity
    - Ground test capabilities
    - Oxford facilities
    - Thermal protection systems
    - The need for flight data…

4. Introduction to satellite demise (LD)
    - Why
    - Evolution of # objects
    - Concern
    - Aspects of the problem
    - Similarities/differences to re-entry capsules
    - Risk Estimation
    - Rarefied Flow & Bridging Functions

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Timetable

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Michaelmas 2023	
Week 1	Kick-off / group allocation
2	
3	
4	
5	
6	Guest lecture #1
7	Logbook review / feedback
8	Team presentations

Hilary 2024	
Week 1	Logbook review
2	
3	(Guest lecture #2 – tentative)
4	
5	~1/2hr lecture on report writing
6	
7	Logbook review / feedback
8	Team presentations

Trinity 2024	
Week 1	Review draft reports
2	Assessment presentations
3	
4	Report submission
5	
6	
7	
8	

Timetable and Assessment

- Regular meeting → Tues 1400 – 1600; Thom LR7
- Each team should have additional (regular) meetings outside of the formal contact hours
  - → This is a group project where progress will be dependent on both the individual and the group
  - Keep accurate meeting minutes, set clear tasks and timelines, create clear interfaces between sub-tasks
  - Communication is key!

- Logbook
  - Expected that you keep detailed notes as to your working / calculations / concept development / meeting minutes etc
  - Do not cut and paste (significant) content from the internet → this project is supposed to be *your* design

- Presentations
  - 25 – 30 mins per group (~5 mins per person, 5 – 10 mins for questions)
  - Each team to assess the other teams (in addition to TH/LD)

- Assessment
  - Reviews of logbook – submit week prior to feedback session i.e. submit in Wk 6 (MT)
  - Team Presentation – Wk 2 (TT) [opportunity for practice presentations in prior terms]
  - Final Report - submit Wk 4 (TT)

- Expectations
  - This is a “real-world” exercise
  - No tutorial sheets
  - Little formal teaching
  - No “text-book” answers – in fact, we fully expect you to ask us questions we don’t have the expertise to answer!
  - Self-directed learning and organisation → take ownership of your projects
  - The “final” design will not be mature, just a first draft, the first step towards a real system.

Flight Vehicle Design & Group Allocations

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The saying "it's not rocket science" exists for a reason

→ this is (close to) rocket science!

- Experimental flight vehicles require a multi-disciplinary team
- Aspects to consider –
  - Launch service provider (who, cost, restrictions, legislation/design guidelines)
  - Launch environment (vibrations, thermal cycling, certification)
  - Trajectory
  - Interfacing (communications/data acquisition)
  - Mechanical / structural design and manufacture, CAD
  - Electrical routing, power supply / consumption
  - Internal heat generation / cooling of electronics
  - Instrumentation (type, quantity, locations, data rates)
  - Re-entry aerothermal environment
  - Systems engineering / reliability / failure modes
  - … And don't forget the *science*!

Groups –

- 3 groups of 4 people
- Pick a sub-topic that interests you…

A Brief Introduction to Satellite Demise

Luke Doherty and Tobias Hermann

Oxford Thermofluids Institute,
University of Oxford

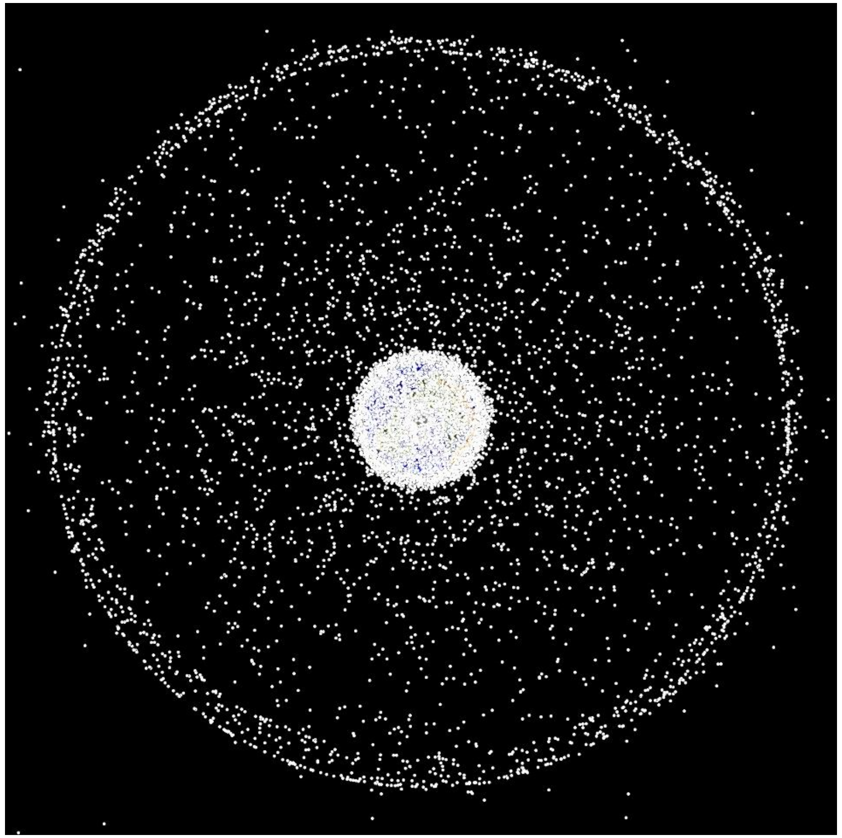
3YP kick-off, Tue 10th Oct. 2023

Why?

1. What do satellites provide to society? Are satellites important?
    - Communications & Internet
    - Navigation (GPS)
    - Earth observation / weather tracking & forecasting
    - Intelligence

→ Modern society is inextricably dependent on space-based services

2. What's the problem?
    - How much mass is in orbit?
    - How many objects are in orbit?
    - Collision (conjunction events)



Tracked objects (as of Jan. 1, 2019) viewed from GEO polar location [NASA ODPO].

Evolution of # of objects & mass

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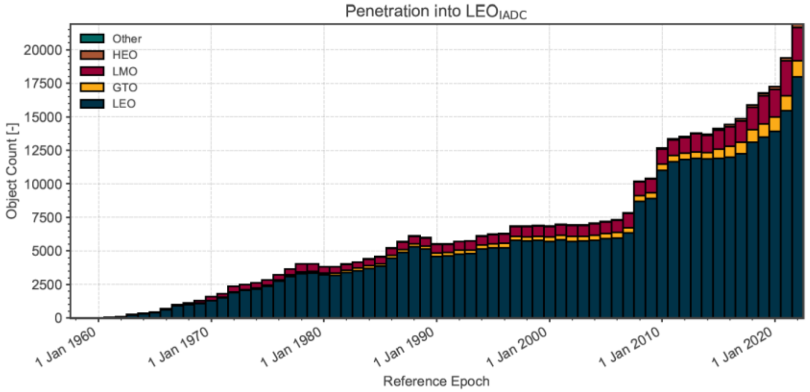
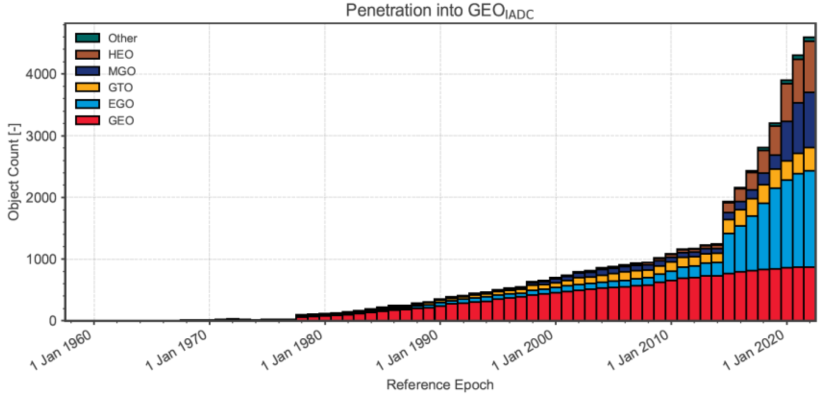


(a) Evolution of absolute number of objects.



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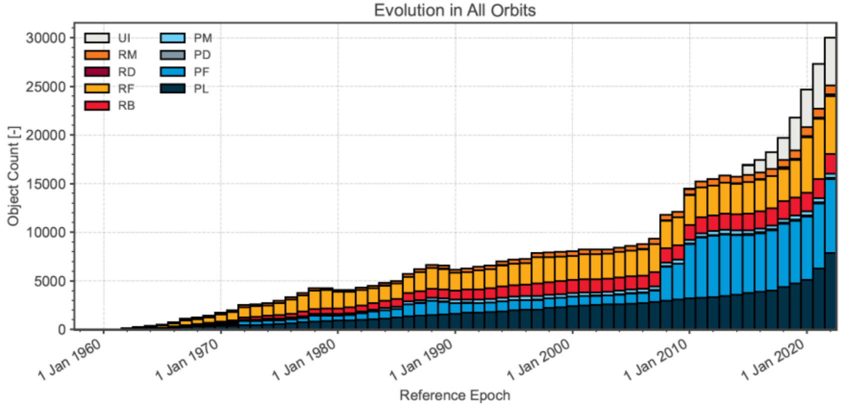

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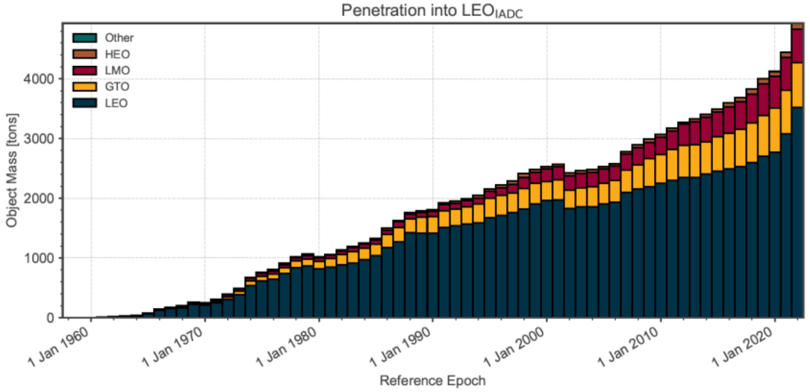
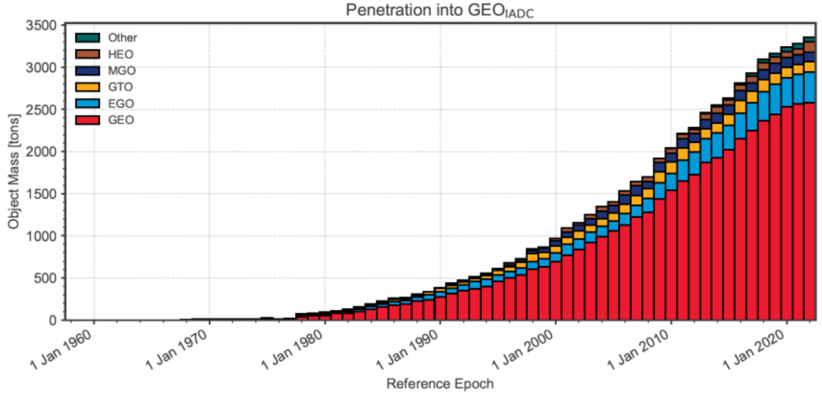


(b) Evolution of absolute mass.



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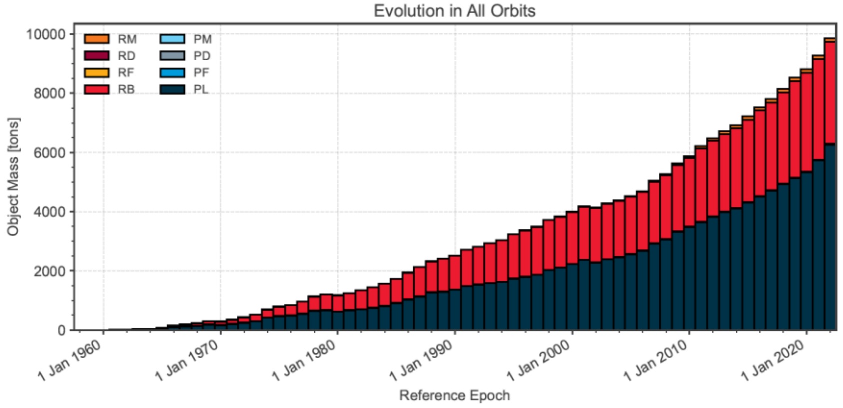

(b) Evolution of mass.

Source: ESA Space Environment Report, 2022. Figures 2.1, 2.4 and 2.6.

The concern…

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The **amount of objects**, their combined **mass**, and their combined **area** has been **steadily rising** since the beginning of the space age, leading to the appearance of involuntary collisions between operational payloads and space debris. Ever increasing **improvements in space surveillance sensor capabilities** during the last decades have brought down the size limits where debris can be reliably tracked and catalogued. This, in turn, implies that we know about significant amounts of space debris, but not all their originating events. The **space traffic** itself is also undergoing **notable changes** since 2015, particularly in Low Earth Orbits, fuelled by the **miniaturisation** of space systems and deployment of **large constellations**, with a shift towards **commercial operators**. These three elements (i.e. volume of traffic, type of spacecraft, type of operators) are all of relevance when one considers the adequacy of space debris mitigation guidelines and possible ways for sustainable space operations, especially when looking at the **Earth's orbital environment as a finite resource**, in line with the UN Long-Term Sustainability Guidelines [1].

Source: ESA Space Environment Report, 2022

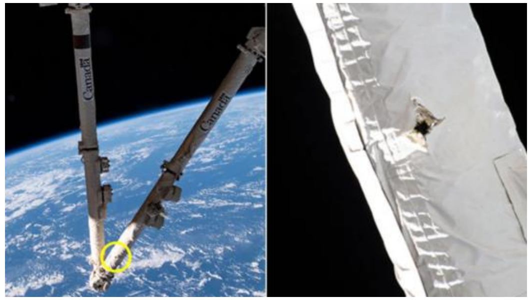
…August 2023, Starlink consists of over 5,000 mass-produced small satellites in low Earth orbit (LEO)…. nearly 12,000 satellites are planned … with a possible later extension to 42,000. [Wikipedia]

The concern…

Kessler Syndrome

→ uncontrollable cascade and growth of a debris

→ render access to orbit impossible



Source: https://edition.cnn.com/2021/06/01/world/iss-orbital-debris-robotic-arm-scn/index.html

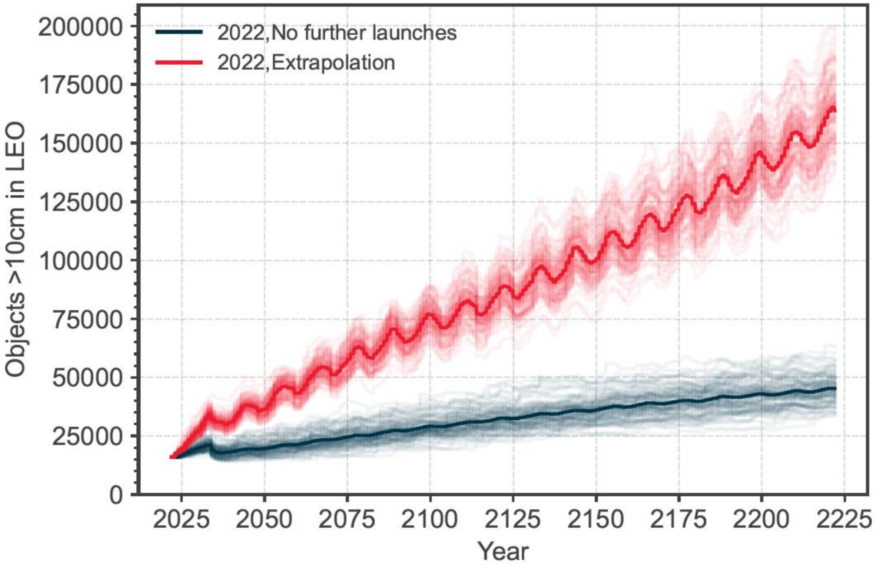


Figure 7.3: Number of objects in LEO_{IADC} in the simulated scenarios of long-term evolution of the environment.

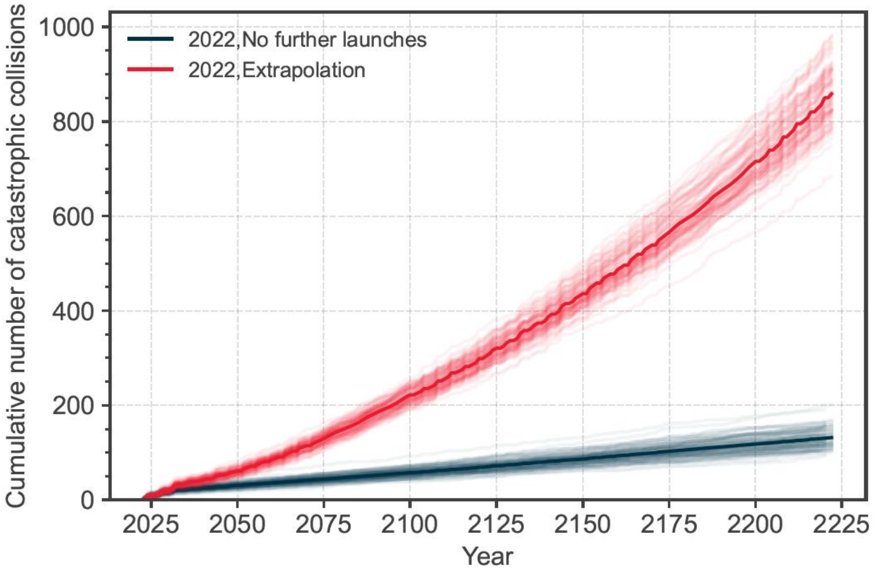


Figure 7.4: Number of cumulative collisions in LEO_{IADC} in the simulated scenarios of long-term evolution of the environment.

Source: ESA Space Environment Report, 2022

Aspects of the problem…

Active Debris Removal

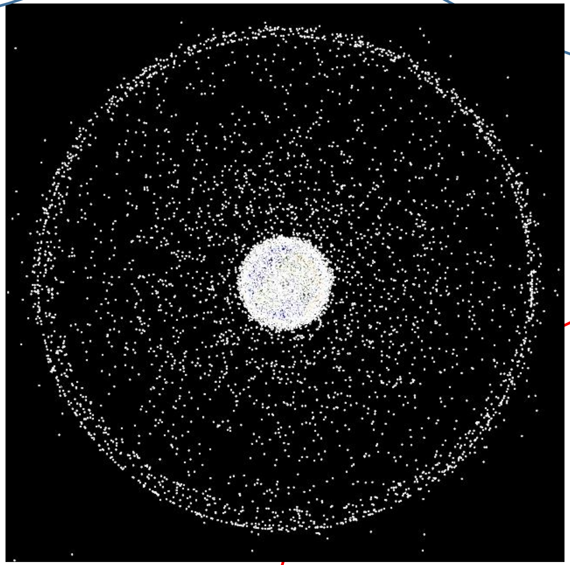
In-orbit servicing

RE-USE/RECYCLING
Sustainable in-orbit economy?

What is up there, where is it going

Remote sensing / detection

Orbital prediction / collision detection / avoidance



Uncontrolled vs controlled re-entry

Demise mechanisms/phenomenology

Satellite design-for-demise

DISPOSAL:
What happens when objects come back in?

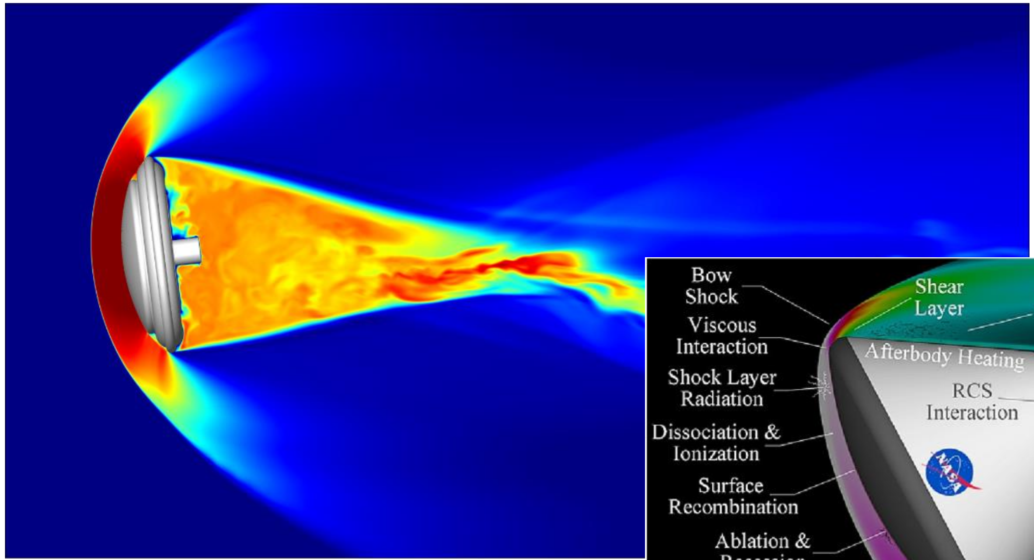
“Rules of the road” / laws or guidelines for conjunctions, debris removal/recovery

RESPONSIBILITIES/EXPECTATIONS:
Who moves first? Who owns what?

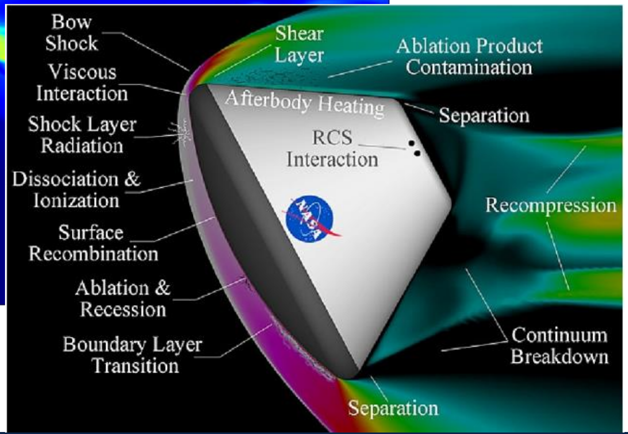
Similarities/differences to Re-entry Capsules

Satellite demise takes all the re-entry aero-capsule phenomena and adds complexity due to →

1. Geometry
2. Motion (tumbling)
3. Failure mechanisms



[NASA Entry Systems Modelling]; Scanlon et al. (2015), AIAA Journal, DOI: 10.2514/1.J053370;



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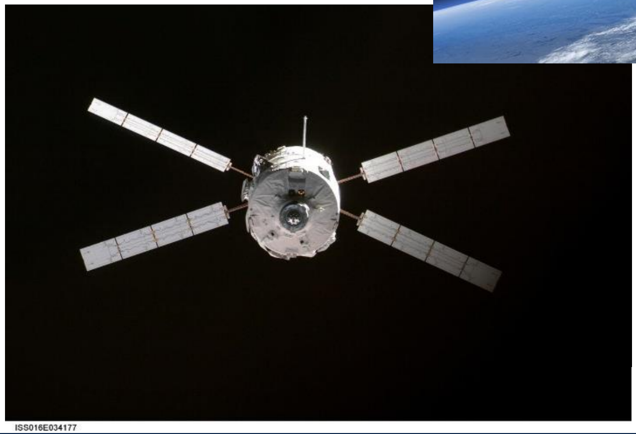
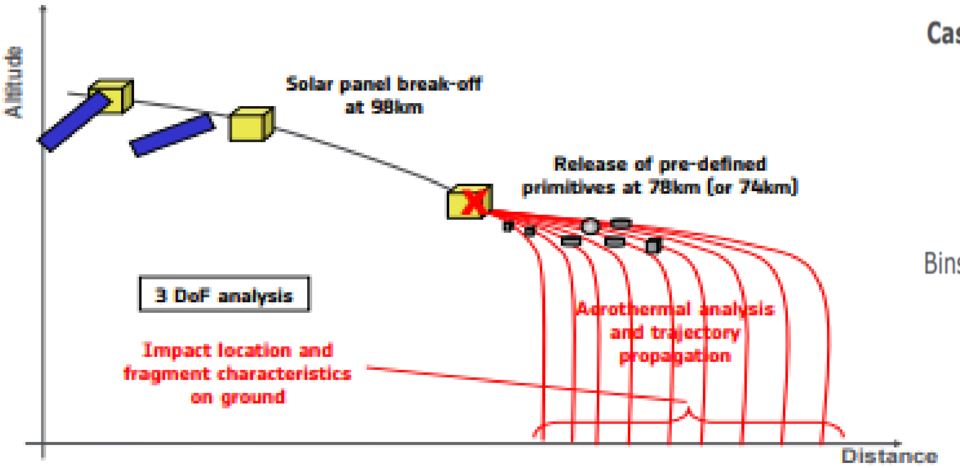
60 Starlink Satellites abord a Falcon 9 [Source: SpaceX/Wikipedia]

Sentinel 1A [Source: ESA]



Jules Verne ATV [Source: NASA]

Risk Estimation



Casualty expectancy

Fatality expectancy

$$E_{f,i} = \sum_{n} \sum_{m} (P_i)_{n,m} \cdot (\rho_p)_{n,m} \cdot (A_C)_{n,m} \cdot (\eta_f)_{n,m}$$

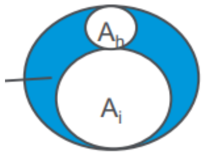
Bins on Earth surface

Impact probability

Population density

Casualty cross-section

Fatality index



$$A_c = \sum_{i=1}^{n} \left(\sqrt{A_h} + \sqrt{A_i} \right)^2$$

A_h – average human cross-section
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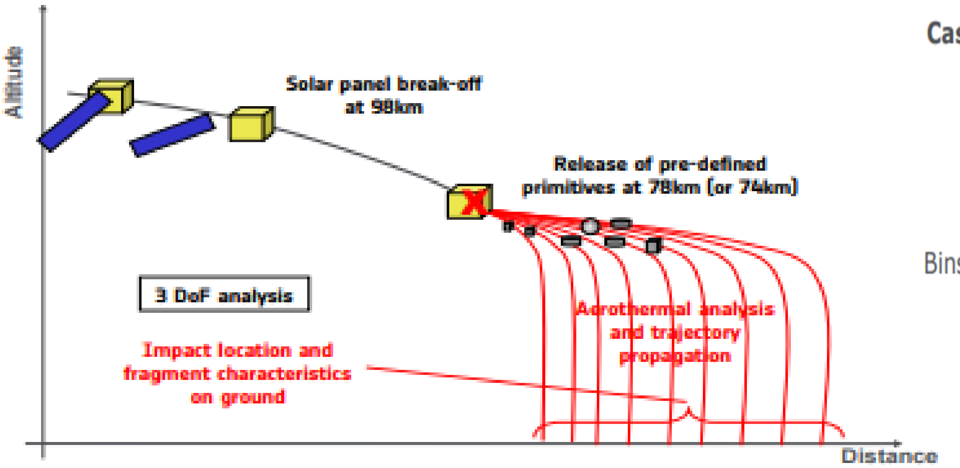

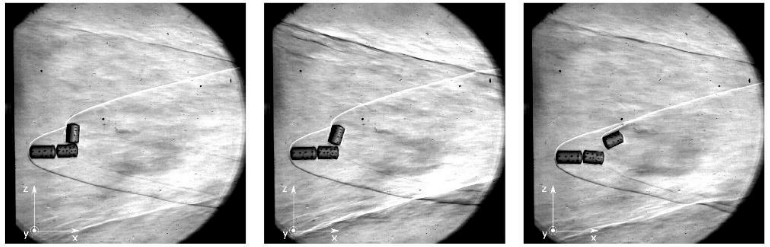

d) $t = 3$ ms e) $t = 5$ ms f) $t = 10$ ms

Separation of ISS modules in TUSQ facility [Leiser et al 2022]

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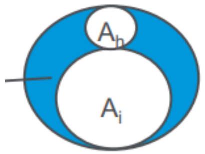

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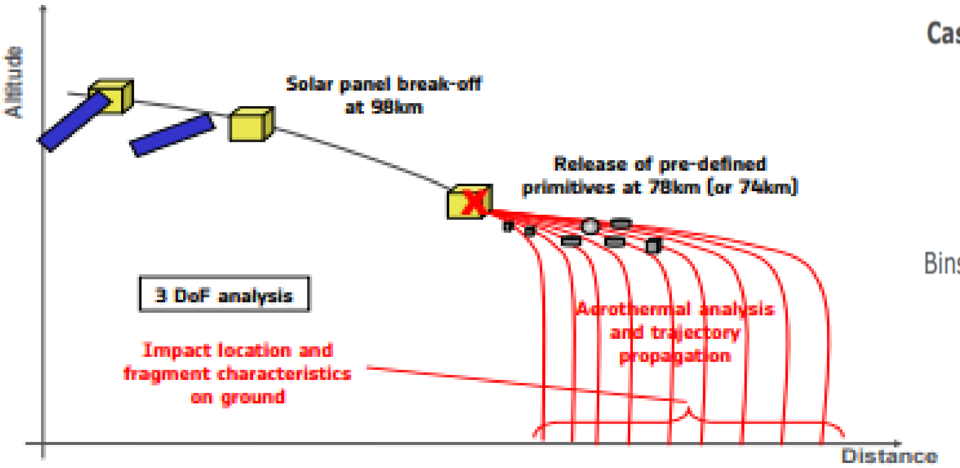

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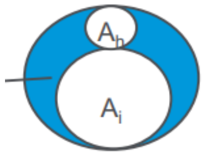

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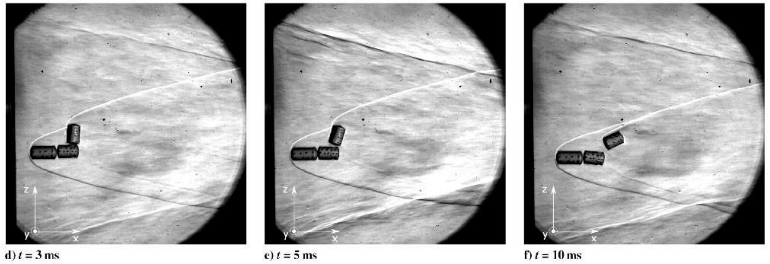

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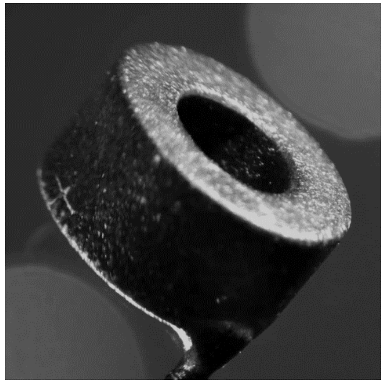

Liquid crystal heat transfer in Oxford LDT [Berry et al 2023]

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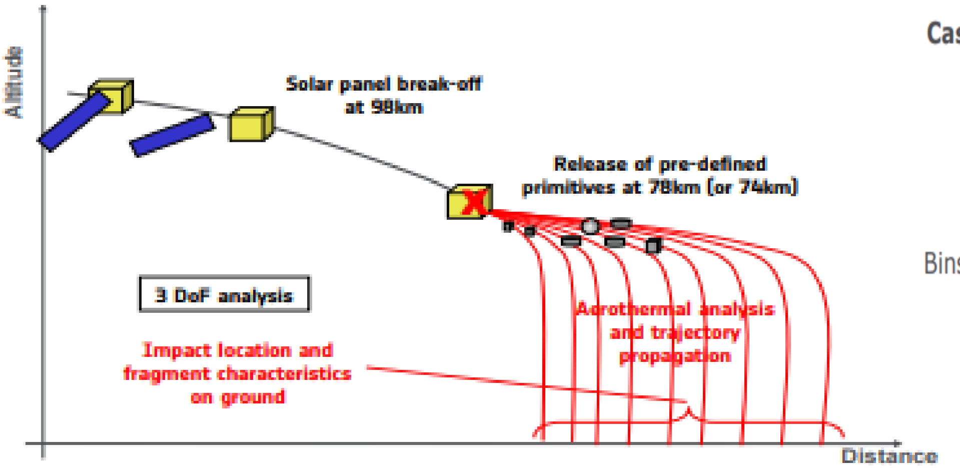

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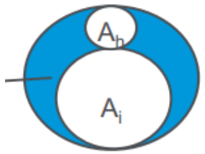

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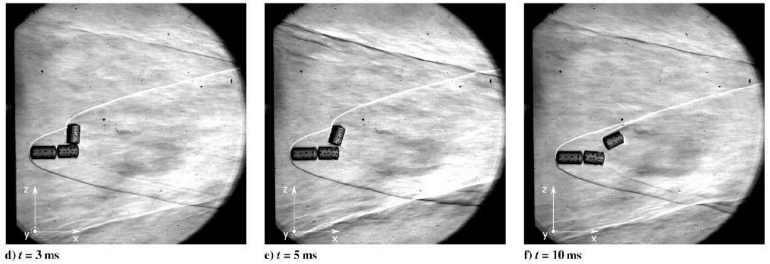

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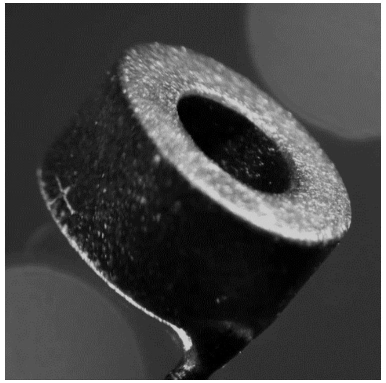

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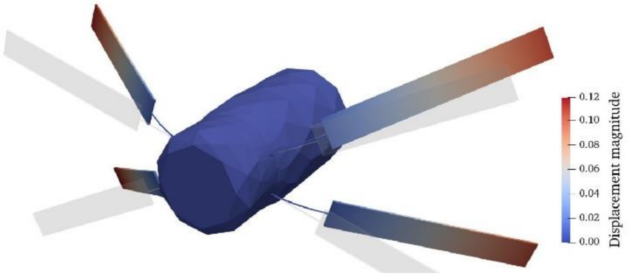
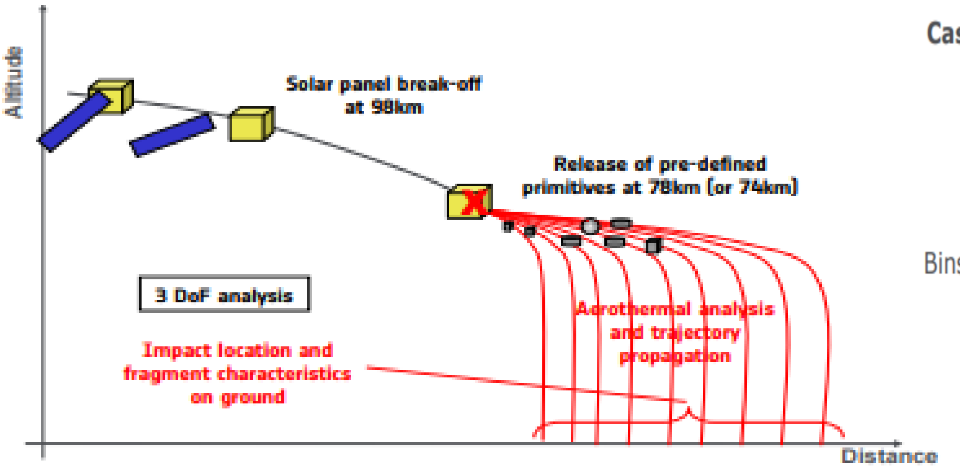


Structural deformation computed for an ATV using a coupled aero-structural solver [Morgado et al 2022]

Risk Estimation



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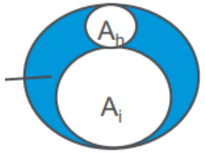

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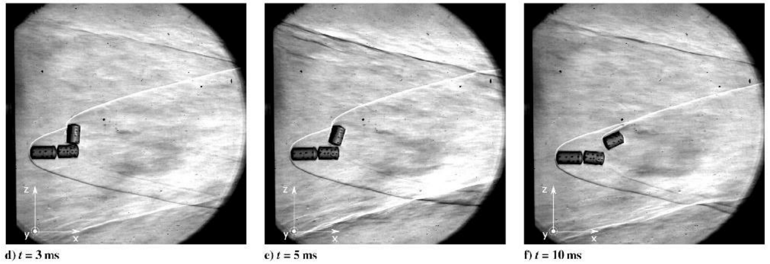

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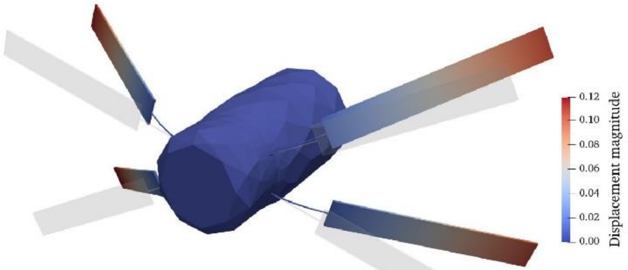

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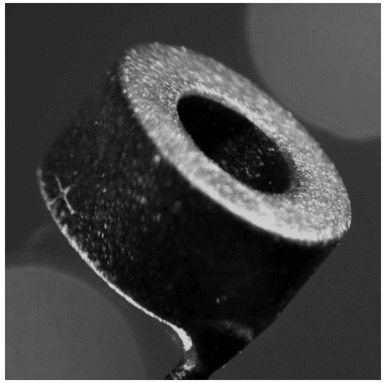

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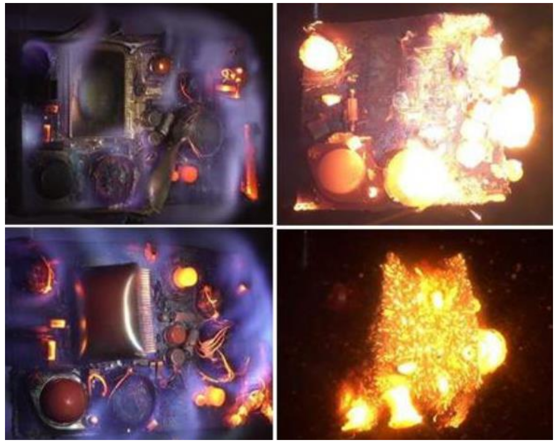

Electronics board demise in DLR L2K facility [Beck et al 2019]

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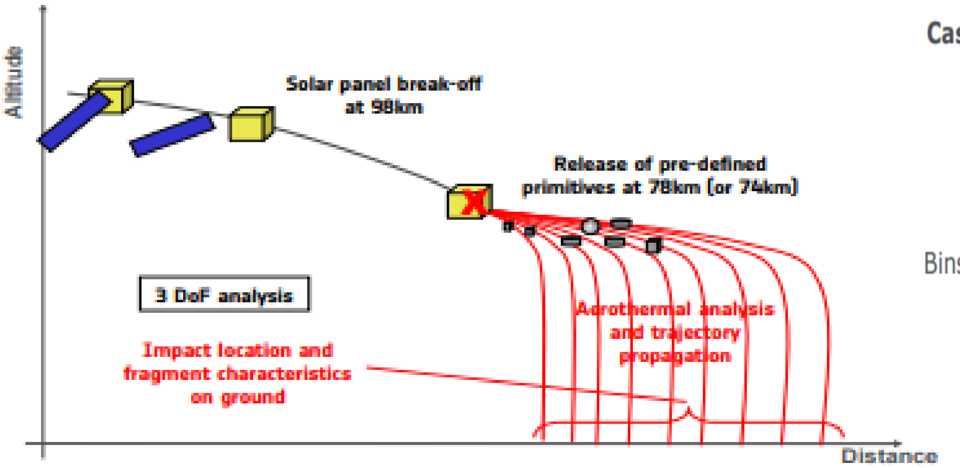
Risk Estimation



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Bins on Earth surface

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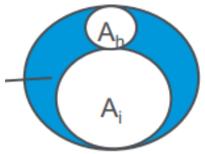
Fatality index



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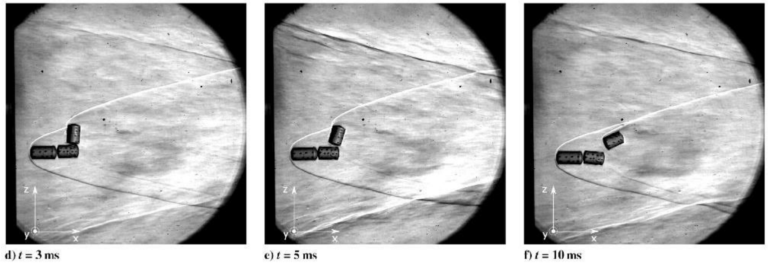

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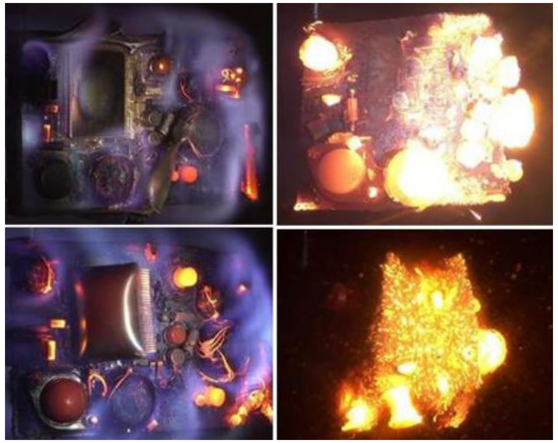

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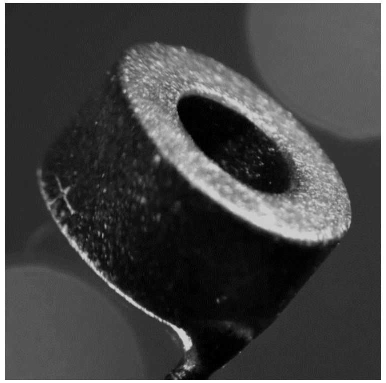

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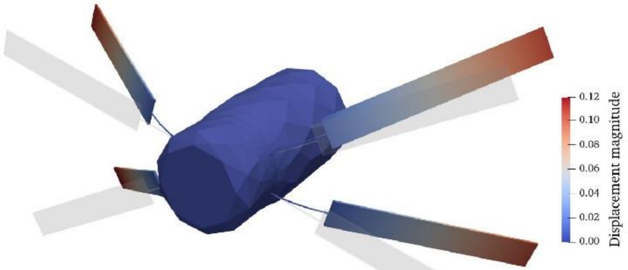

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Co_3O_4/Al#1 Co_3O_4/Al#2 Co_3O_4/Al#3 Co_3O_4/Al#4

Effect of Al-based thermites on titanium plate [Monogarov et al 2017]

Risk Estimation

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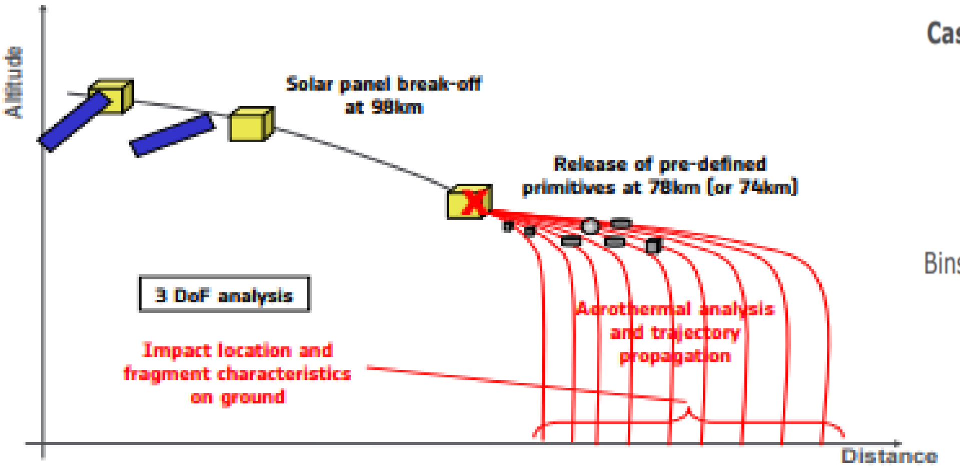

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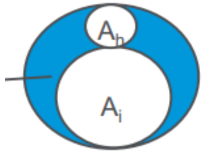
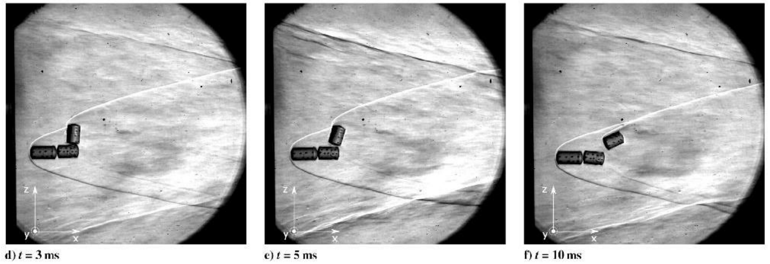
Fatality index

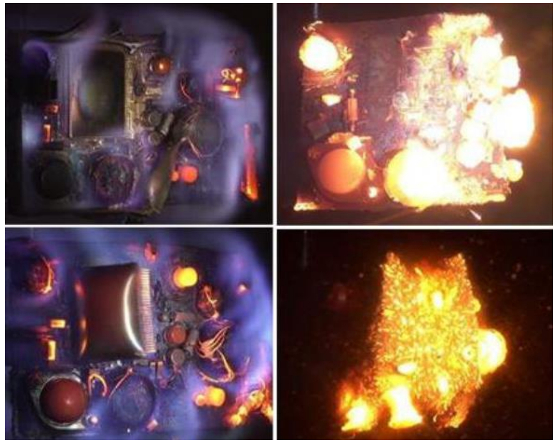


$$A_c = \sum_{i=1}^{n}\left(\sqrt{A_h} + \sqrt{A_i}\right)^2$$

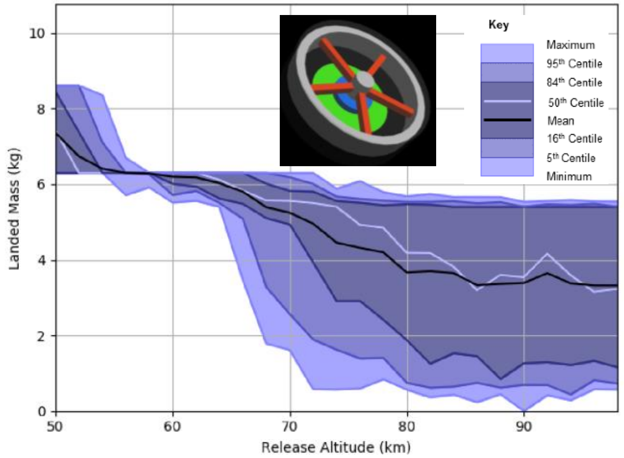
A_h – average human cross-section
A_i – surviving debris cross-section
n – number of surviving pieces



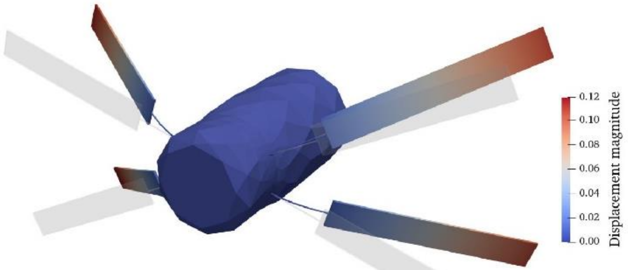
Separation of ISS modules in TUSQ facility [Leiser et al 2022]



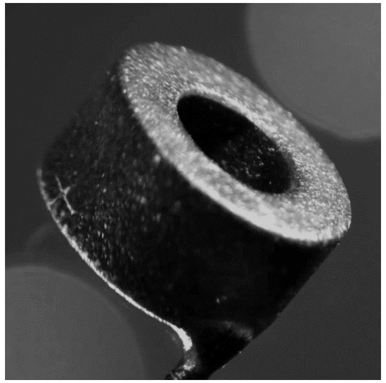
Electronics board demise in DLR L2K facility [Beck et al 2019]



Probabilistic assessment of landed mass of reaction wheel [Beck and Holbrough 2022]



Structural deformation computed for an ATV using a coupled aero-structural solver [Morgado et al 2022]



Liquid crystal heat transfer in Oxford LDT [Berry et al 2023]

Co_3O_4/Al#1 Co_3O_4/Al#2 Co_3O_4/Al#3 Co_3O_4/Al#4

Effect of Al-based thermites on titanium plate [Monogarov et al 2017]

Risk Estimation

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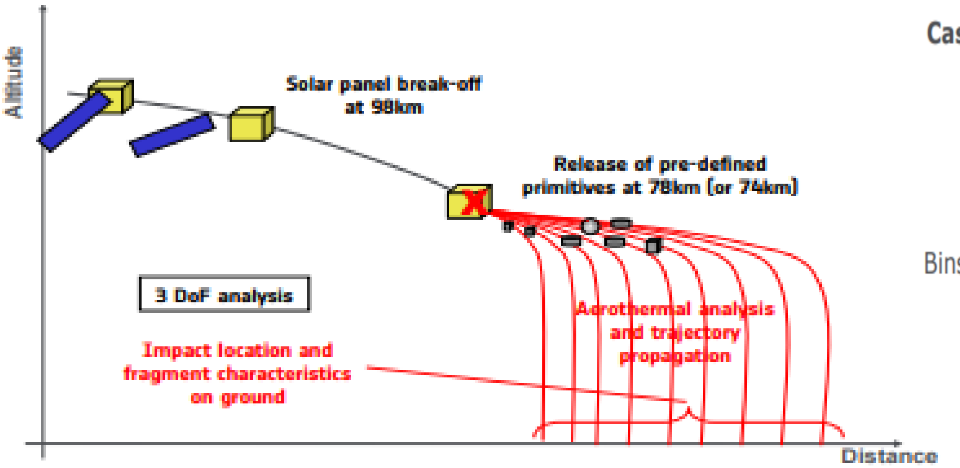
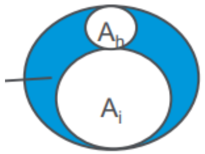


Casualty expectancy — Fatality expectancy

$$E_{f,i} = \underbrace{\sum_{n}\sum_{m}}_{\text{Bins on Earth surface}} \boxed{(P_i)_{n,m}} \cdot \boxed{(\rho_p)_{n,m}} \cdot \boxed{(A_C)_{n,m}} \cdot \boxed{(\eta_f)_{n,m}}$$

Bins on Earth surface; Impact probability; Population density; Casualty cross-section; Fatality index



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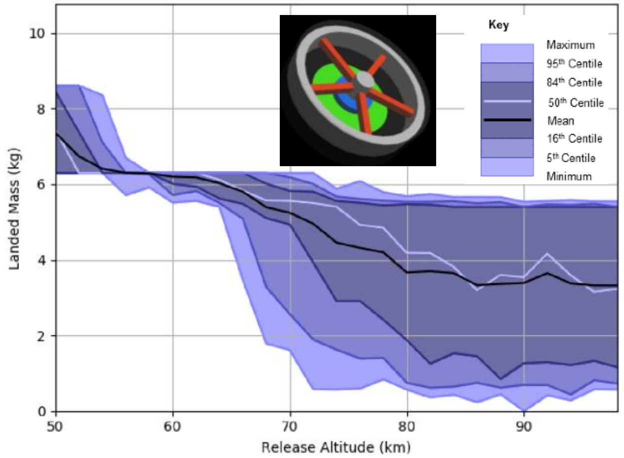

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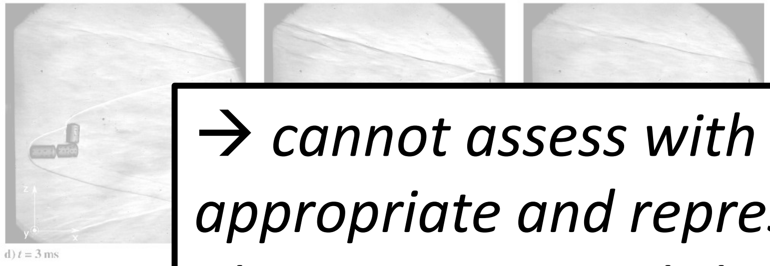
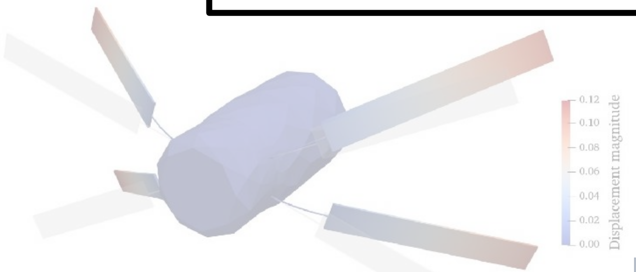


Separation of

Electronics board demise in DLR L2K facility [Beck et al 2019]

→ cannot assess with these methods if current models are appropriate and representative of reality [Van Hauwaert et al, ESA ATD 3 Workshop 2021]



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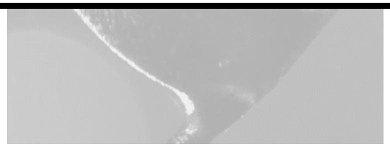

Liquid crystal heat transfer in Oxford LDT [Berry et al 2023]

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Effect of Al-based thermites on titanium plate [Monogarov et al 2017]

Rarefied Flow & Bridging Functions

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Continuum Flow

- Molecule-to-molecule interactions occur most frequently
- Modelled with Euler (inviscid) or Navier-Stokes Equations (viscous)

Free Molecular Flow

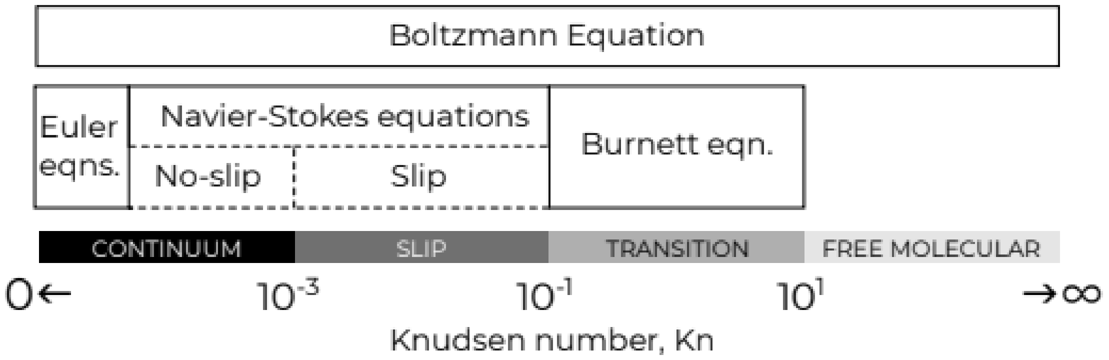
- Molecule-to-surface interactions occur most frequently
- Modelled with (collision-less) Boltzmann Equation

Knudsen Number

- Ratio of mean-free-path to a reference length
- Dimensionless number that indicates degree of rarefaction i.e. how far along the axis we are towards free-molecular flow

Bridging Functions

- Region between continuum and free-molecular is ill-defined → cannot be described (in general) analytically
  - NS equations can be extended, but is still limited
  - DSMC numerical method is most successful method
- At engineering level → reliance on bridging functions
  - Essentially a curve fit to data or correlations at each extreme
  - Depend on the configuration/conditions at which the data or correlations were generated i.e. limited accuracy



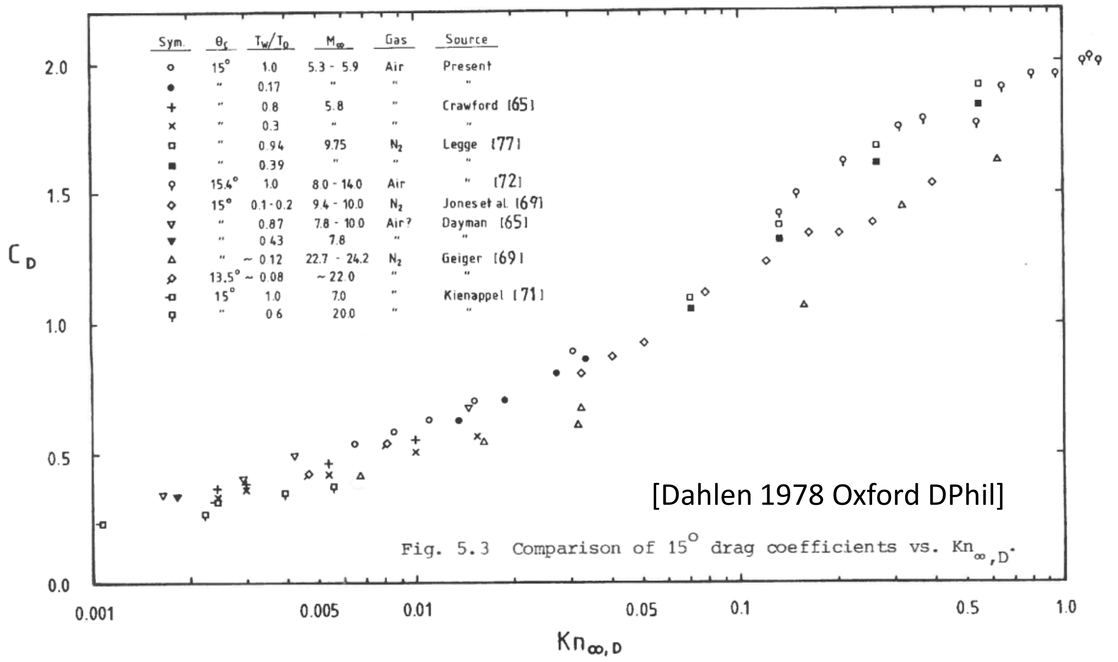


Fig. 5.3 Comparison of 15° drag coefficients vs. $Kn_{\infty,D}$.

[Dahlen 1978 Oxford DPhil]

Now what?

Team Management… (discussion within groups)

- Meeting schedules
- Shared document/teams channel set up
- Allocation of meeting chair/secretary (minute taker) etc

Timelines

- Rough scheduling → when should the scientific question be finalised? Initial concept review? Design Review?
- Sync with assessment schedule
- Start with early drafts of final report to catch gaps

Task Allocations

- Who is responsible for each aspect of the project?
- Where are the interfaces between different aspects?
- Define scope of each task

Remember

→ Work hard, but have fun!

→ There is no pre-defined answer…

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