Minimum-Mass Limit of Venus Atmospheric Probes

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Motivation

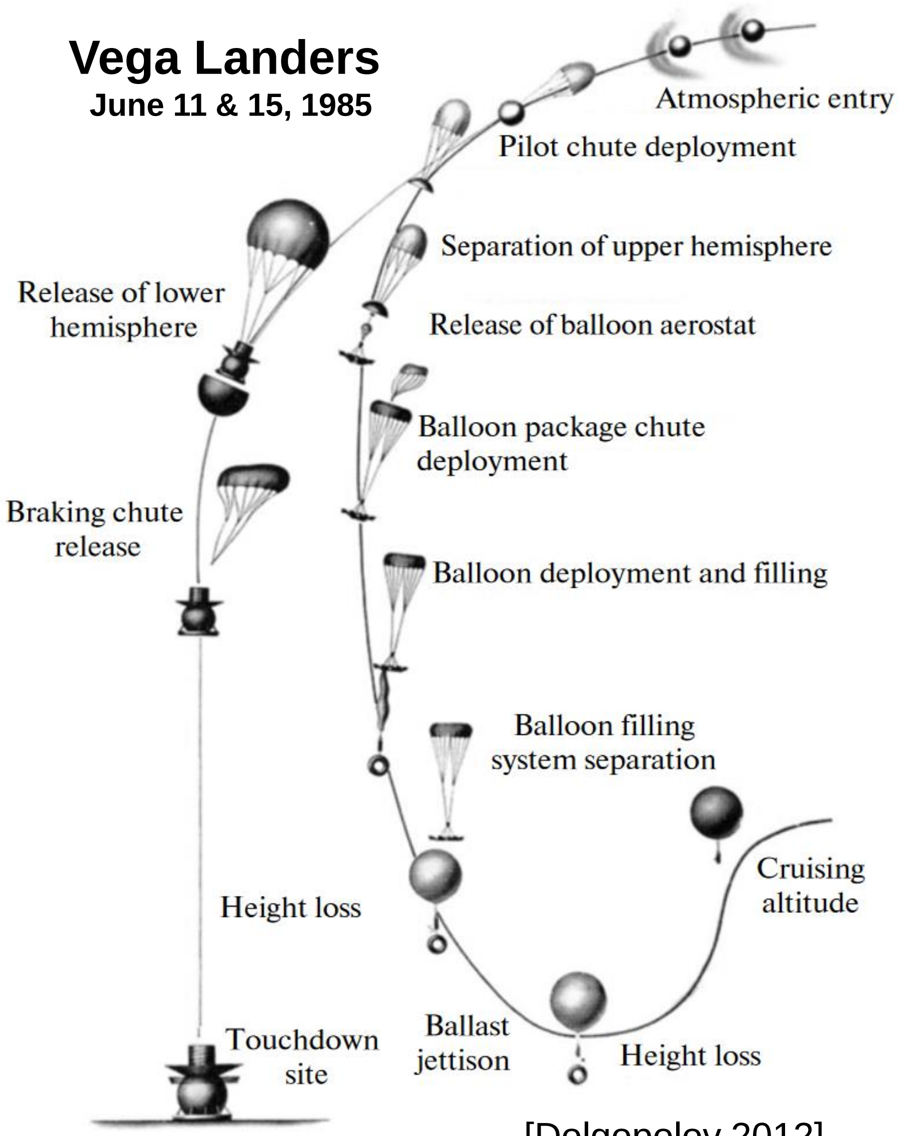
Over 30 years since any sensor has entered Venus atmosphere

- Venera 4 through 14, 1967-82
- Pioneer Multiprobe, 1978
- **Vega Landers 1985**

Science impact: the last **30 years of sensor development** has yet to be used on sampled Venusian gas!

Vega Landers

June 11 & 15, 1985



[Dolgopolov 2012]

Small Probes

But **flybys & orbiters** plentiful since 1985

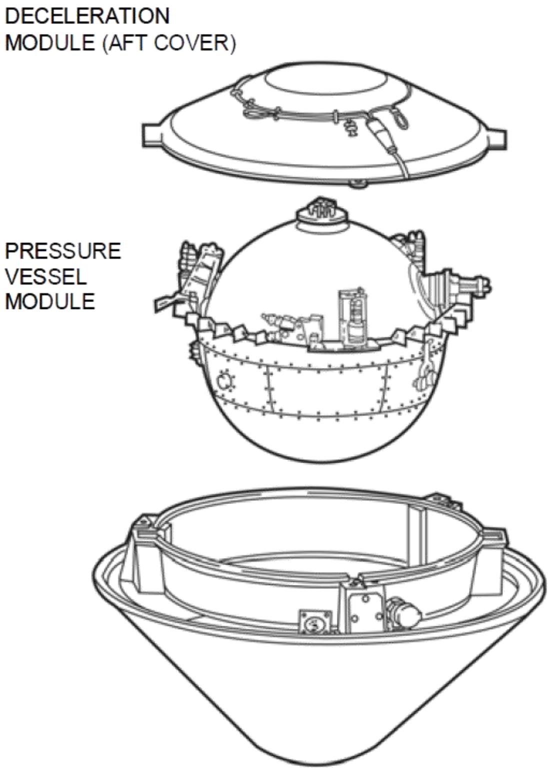
- Galileo 1990
- Magellan 1990 (orbit)
- Cassini-Huygens 1998 & 1999
- Messenger 2006 & 2007
- Venus express 2006 (orbit)
- Ikaros 2010
- Akatsuki 2015 (orbit)

Idea: Add a **small probe** to a larger mission

- Low mass (ideally)
- Low cost (ideally)

Pioneer Large Probe

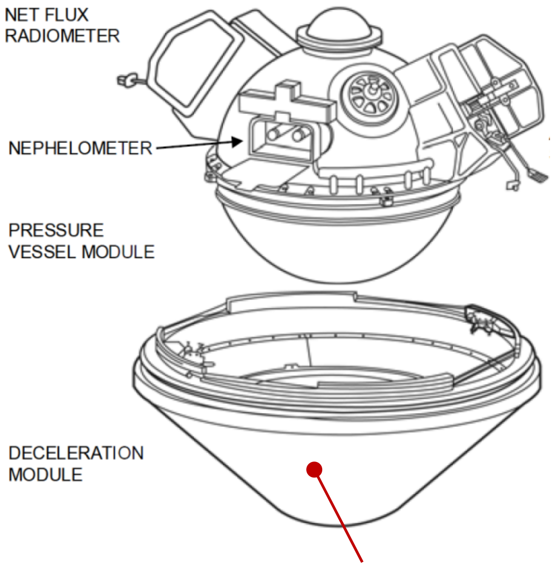
78cm sphere, 193kg (1978)



Pioneer Small Probe

47cm sphere, 61kg (1978)

No parachute



+ bonus 33kg landed

[Bienstock 2004]

Question: How "small" is small?

Can we beat a **61kg** sphere?

Study Goals and Method

Goal: Find **minimum mass probe** that can descend entire Venus atmosphere

Functional Requirements

- **Reach surface** before heat death (**750°K** temperature**, 90 atm** of pressure)
- **Bring payload**, which competes with thermal & pressure systems for mass

Methodology:

(1) Develop simple model of Venus atmosphere descent

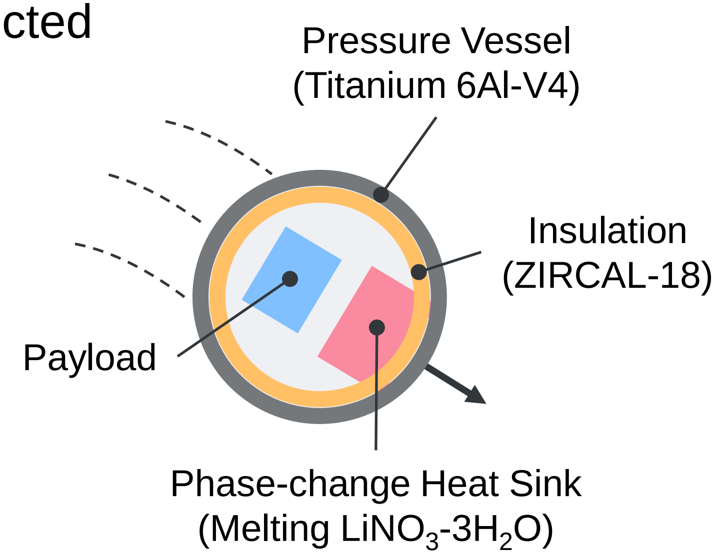
(2) Perform parametric study on probe mass

(3) Correlate pressure & thermal system mass to probe mass

(4) Find the minimum mass cutoff for a given payload

Descent Model

Entry completed, heat shield has already ejected



Deploy a Smooth Spherical Probe

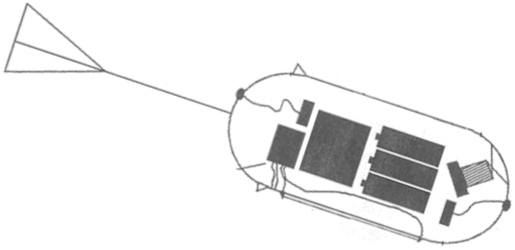
- **No Parachute**
- **65km** altitude
- **200m/s** velocity
- **30°** angle below horizon
- **30°C** internal temperature

Assumptions

- **Thermal capacity: Heat Sink <u>Only</u>** at FOS 1.3, assumes negligible capacity from pressure vessel, structure, & insulation
- **Internal Heating**: 50 watts from payload
- **Insulation Leakage**: 50% effectiveness
- **Pressure vessel**: buckling Roark's formula, FOS 1.3
- **Atmospheric data:** VIRA model, Schofield et. al. 1985
- **Heat convection:** from Achenbach 1978
- **Drag coefficients:** from Bailey 1972

Prior Study: Lorenz 1997

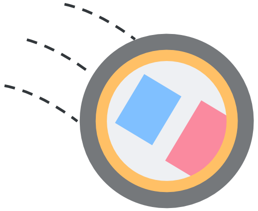
- **No Pressure Vessel**
- **Payload gains +100°C**



Example Probe Descent

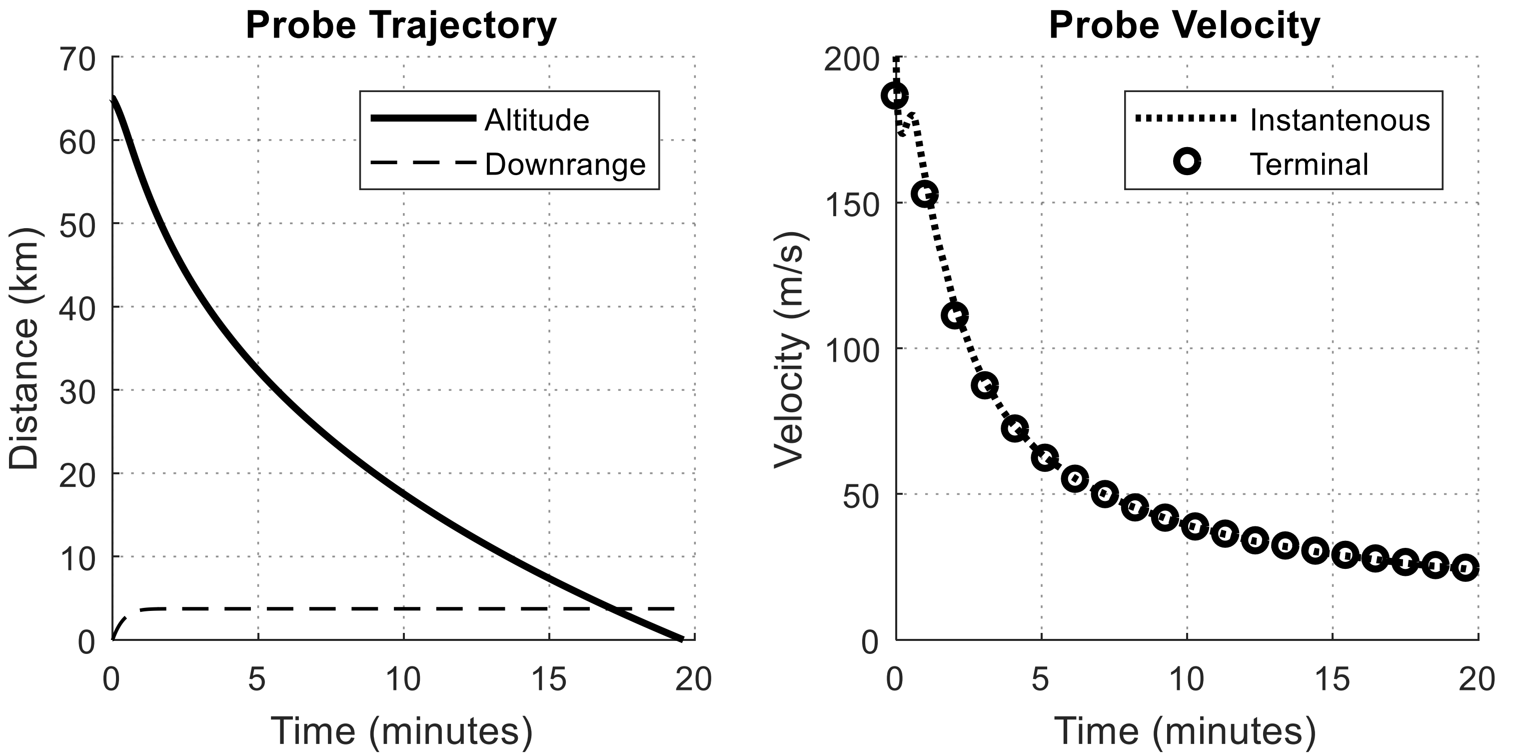
- **500mm** diameter sphere
- **0.8 bulk density***
- **52kg** total mass

- **17kg** pressure vessel (**5mm** thick)
- **5.5kg** of insulation (**30mm** thick)
- **4.5kg** of phase-change heat sink



~50% payload mass fraction

Reaches surface in **20 minutes**, impacts at **24 m/s**



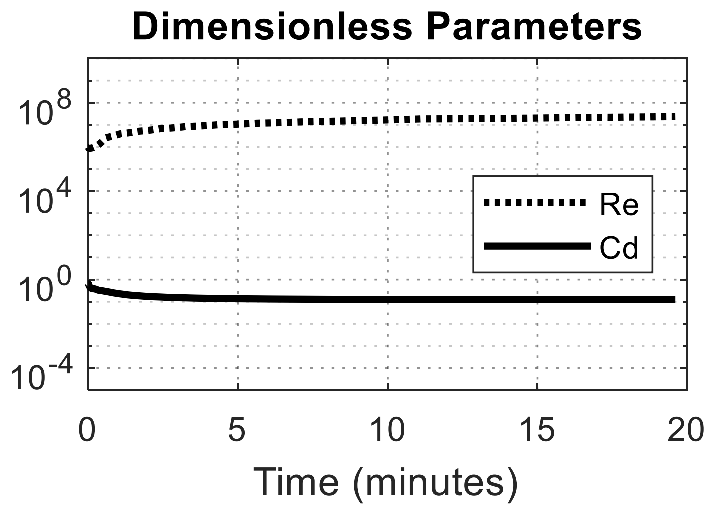
*bulk density normalized to water (1000kg/m^3): includes pressure vessel, insulation, payload, and heat sink

Lesson #1

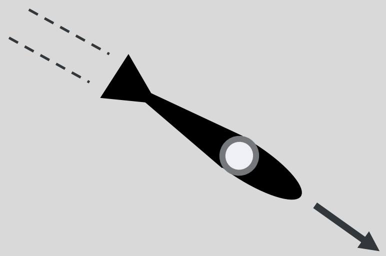
Reynolds number stays roughly constant (Re ≈ 10^7)

- Means **constant drag coefficient** (Cd ≈ 0.2 for a sphere)
- Lets allow **choosing Cd** as a design parameter

$$Re = \rho U L/\mu$$

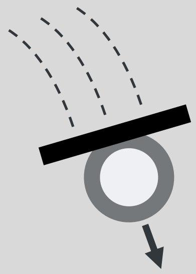


Strategy A: Fall Fast



- **Larger convection** coefficient
- **Less time to conduct** heat from skin

Strategy B: Fall Slow

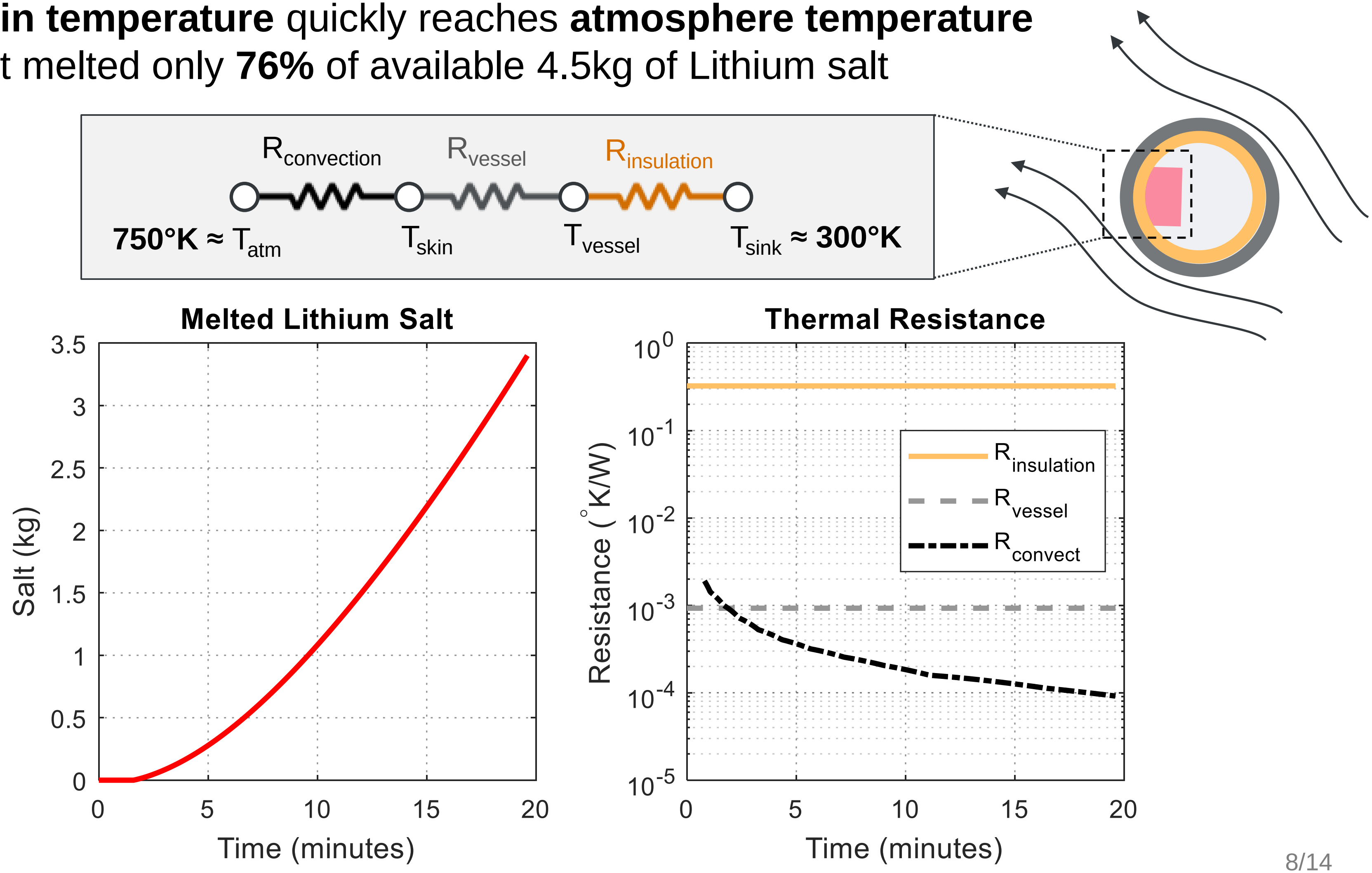


- **Smaller convection** coefficient
- **More time to conduct** heat from skin

Lesson #2

Conduction is the *dominant* constrictor of heat flow

- **Convection is very strong** (high velocity & Nu ≈ 10^4)
- **Skin temperature** quickly reaches **atmosphere temperature**
- But melted only **76%** of available 4.5kg of Lithium salt



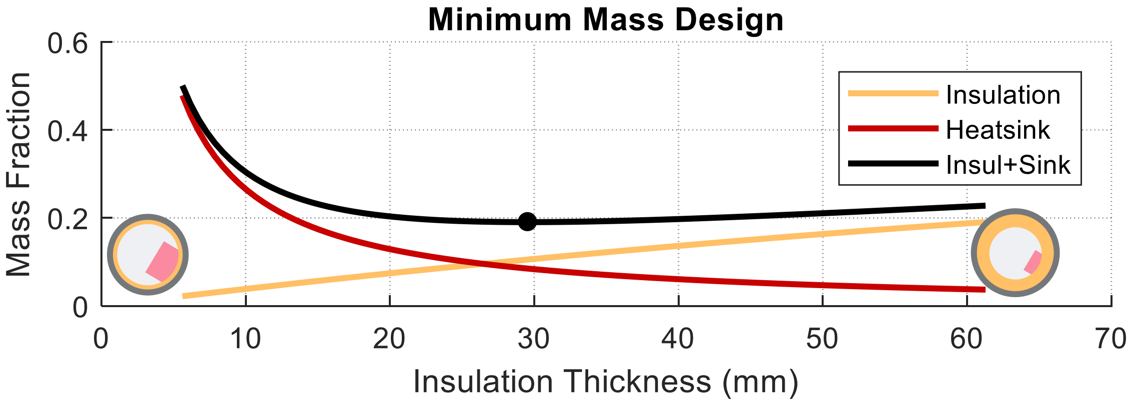
Lesson #3

Thermal design has an optimum

- **Time-to-impact** is only important input
- Instantaneous velocity does not matter

$$\text{Optimal Thickness} = \frac{1}{2}r - \frac{1}{2}r\sqrt{1 - 4\sqrt{C/r^2}}$$

$$C = \frac{FOS_{\text{thermal}}\, k_{\text{insulation}} \int T_{\text{skin}}\, dt}{\Delta h_{\text{sink}}\, \rho_{\text{insulation}}}$$



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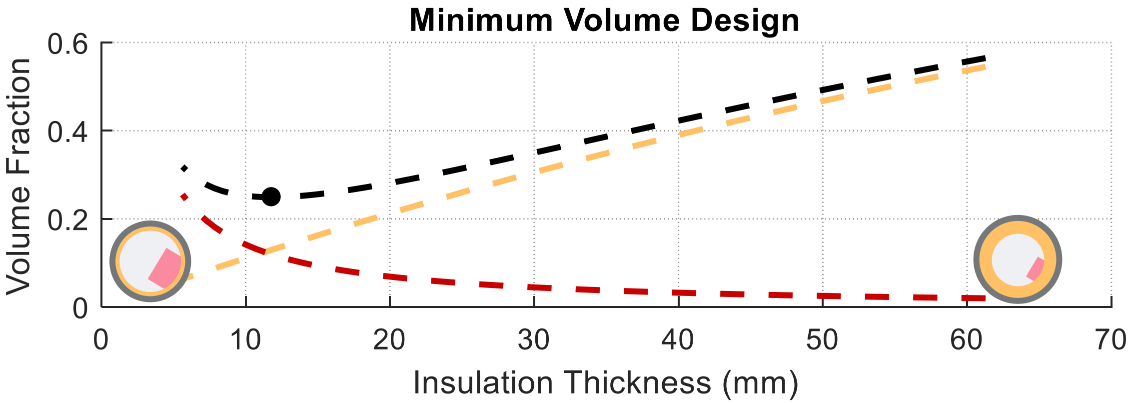
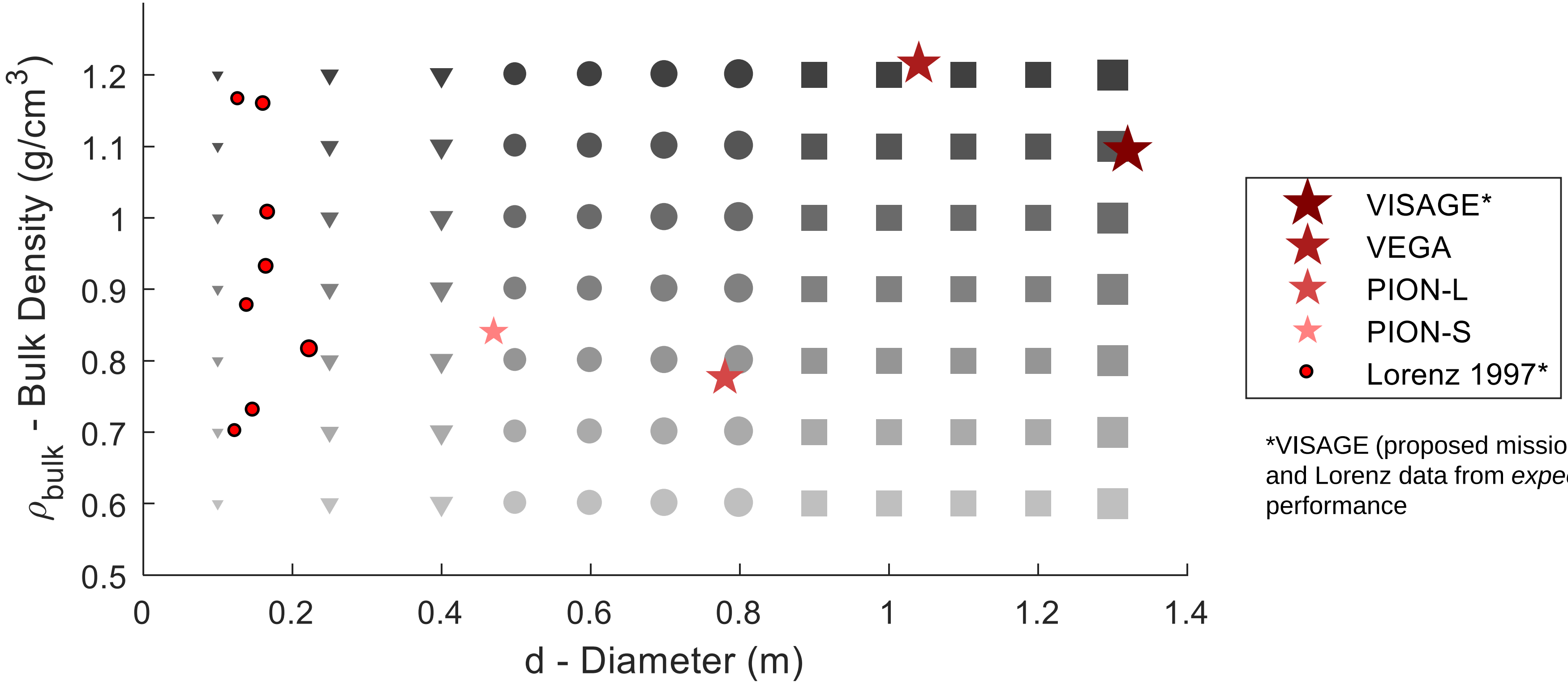
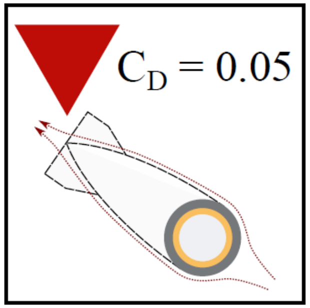
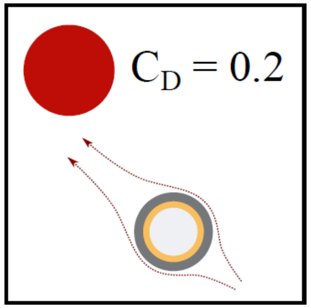


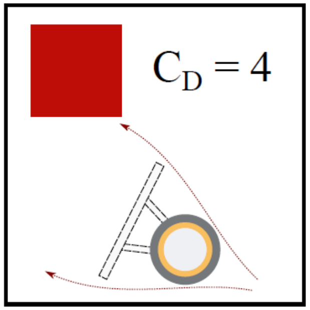
Parameter Sweep



*VISAGE (proposed mission) and Lorenz data from *expected* performance





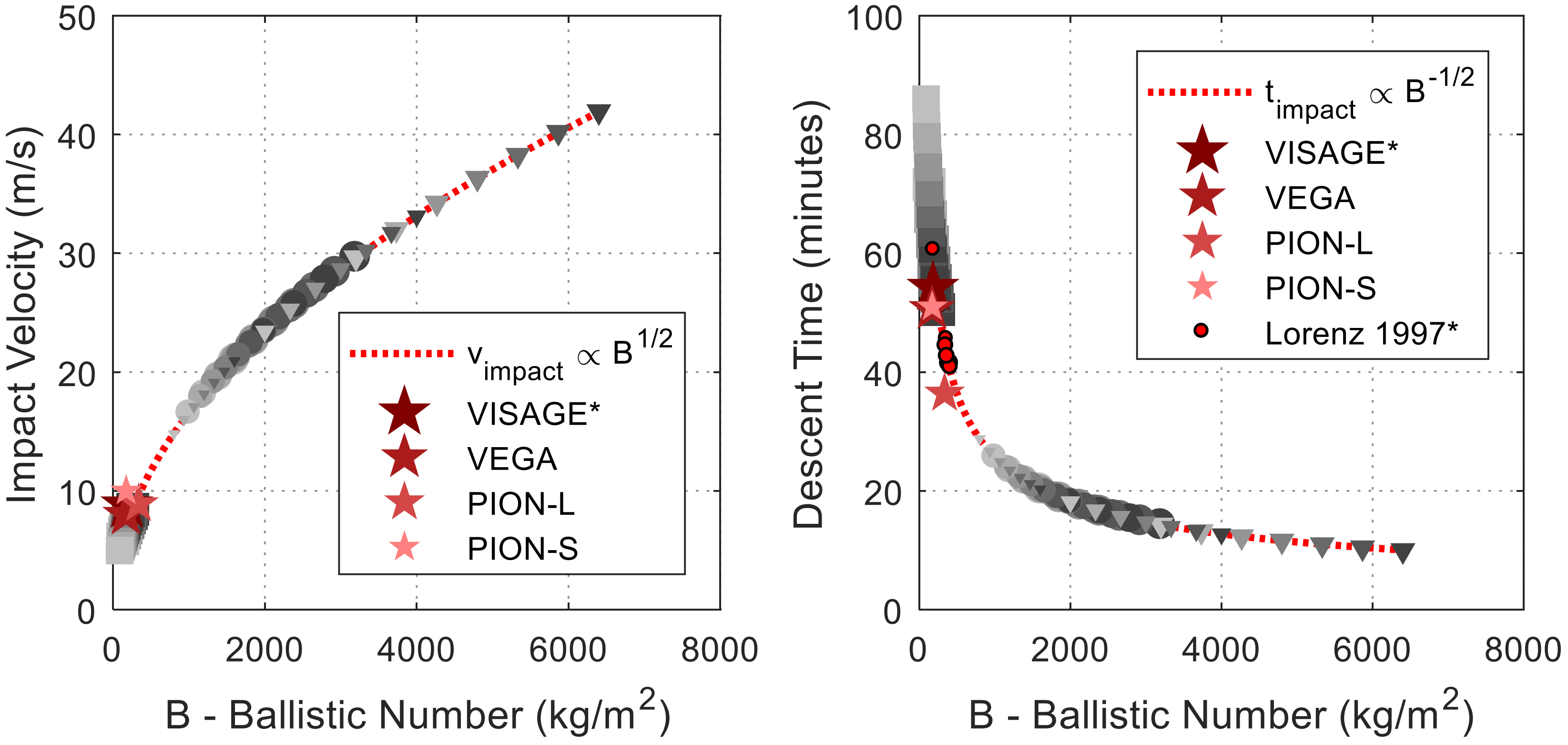


Assumes **streamlining adds negligible mass**

Trajectory Correlations

Impact velocity and time correlate with Ballistic number B

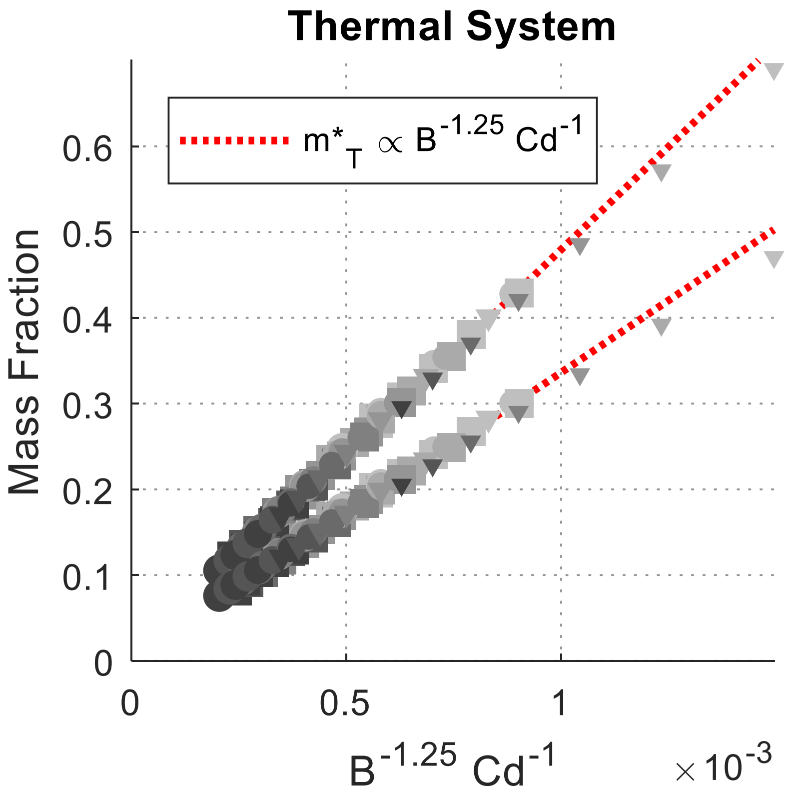
$$B = \frac{m}{\pi r^2 C_d}$$

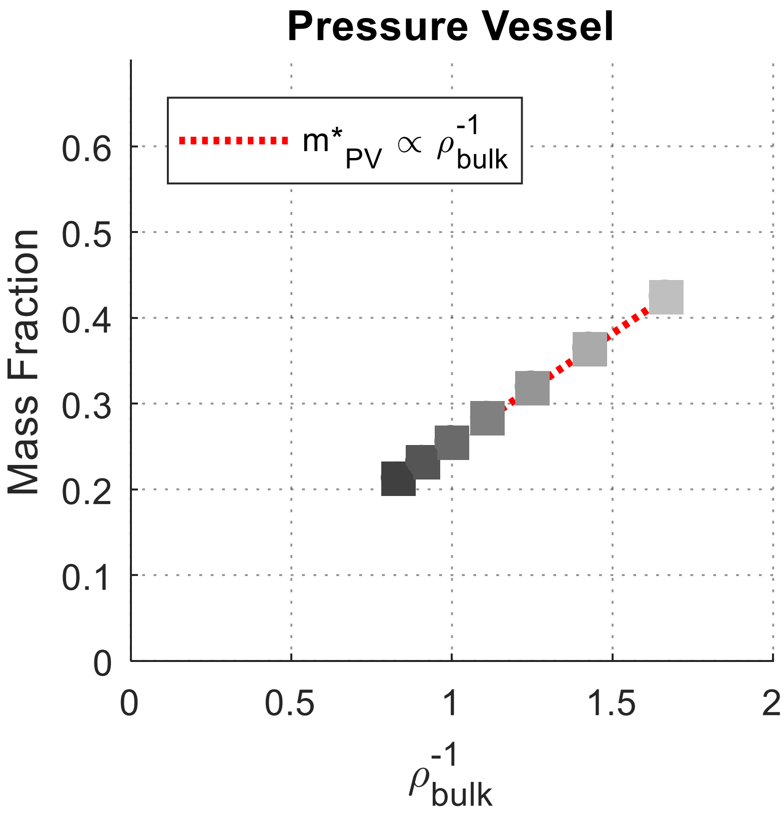


Note: Data for VISAGE*, VEGA, PION-L, & PION-S probes assumes separated flow (**Cd=1.2**), and impact time measured from **parachute cut at 45-55km,** or **50km if no parachute**

Mass Fractions of Subsystems

- **Thermal system:** dependent on both **ballistic number** and **drag coefficient**
- **Pressure vessel:** dependent only on **bulk density**


Thermal System


Pressure Vessel

Example Probes (at $\rho_{payload} = 0.7 kg/m^3$)

A: Spherical 500mm Diameter

- **Total:** 52kg mass, 0.8 bulk density
- **Payload**: 25kg mass (47%), 0.7 density
- **Trajectory**: 22min descent, 19m/s impact

B: Streamlined 400mm Diameter

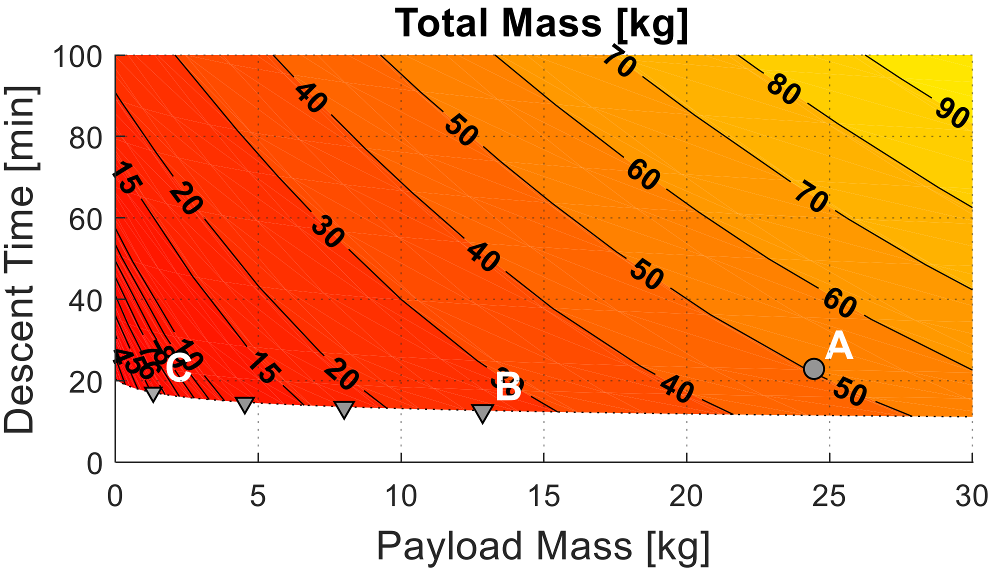
- **Total:** 27kg mass, 0.8 bulk density
- **Payload**: 13kg mass (48%), 0.7 density
- **Trajectory**: 12min descent, 34m/s impact

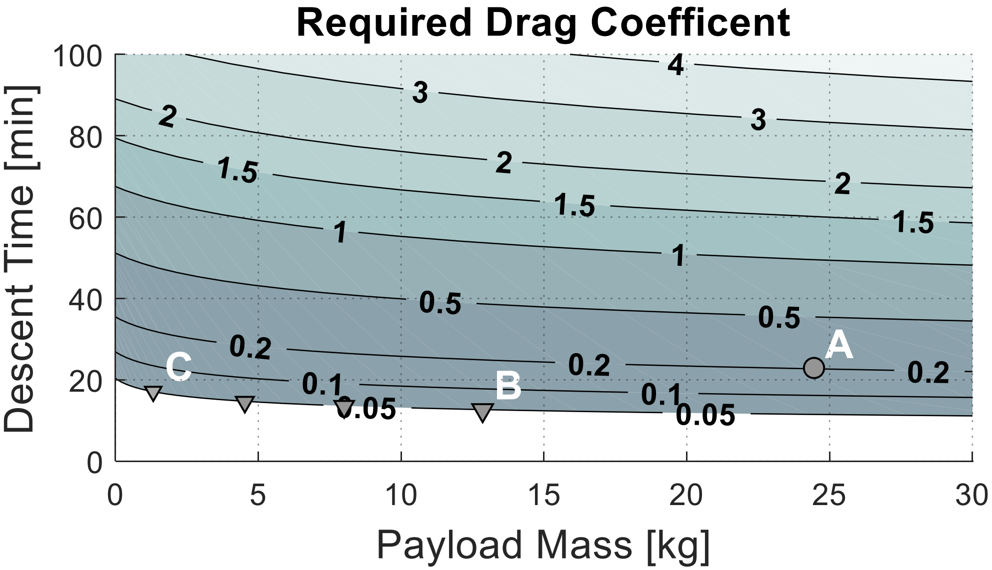
C: Streamlined 250mm Diameter

- **Total:** 5.7kg mass, 0.7 bulk density
- **Payload**: 1.4kg mass (24%), 0.7 density
- **Trajectory**: 17min descent, 25m/s impact

Cutoff around 2kg, as thermal & pressure systems take all the mass

Small probes (5-10kg range) with 30°C payload can plausibly survive Venus atmosphere

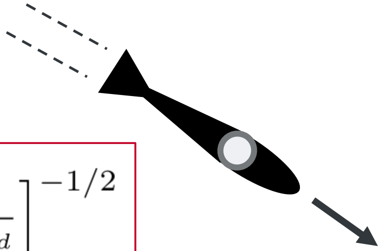




Conclusions

Aerodynamics: Streamlining is highly enabling

- **Mitigates** conduction timeline
- **Negligibly** increases convection
- **Tradeoff** shorter measurement time (~15 minutes) for a colder payload



$$t_{\text{impact}} \propto \left[\frac{m}{\pi r^2 C_d}\right]^{-1/2}$$

Thermal: Tradeoff between insulation and sink mass

- **Optimums exists** for both minimum mass and volume
- **Analytic solution** for optimum point

$$\text{Optimal Thickness} = \tfrac{1}{2}r - \tfrac{1}{2}r\sqrt{1 - 4\sqrt{C/r^2}}$$

Small probes are plausible

- **Range 5-10kg** have payload fractions above 20%
- **Pressure vessel** takes ~20% to 40% of mass (**denser is better**)
- **Thermal system** takes ~10% to 40% of mass (**denser & streamlined is better**)

$$m^*_{\text{pressure vessel}} \propto \frac{1}{\rho_{\text{bulk}}}$$

$$m^*_{\text{thermal}} \propto B^{-5/4} C_d^{-1} \approx \frac{C_d^{1/4}}{m^{5/12}\rho_{\text{bulk}}^{5/6}}$$

[in-prep] Izraelevitz, J.S. & Hall, J. Minimum-Mass Limits for Streamlined Venus Atmospheric Probes. AIAA Journal of Spacecraft and Rockets, 2018

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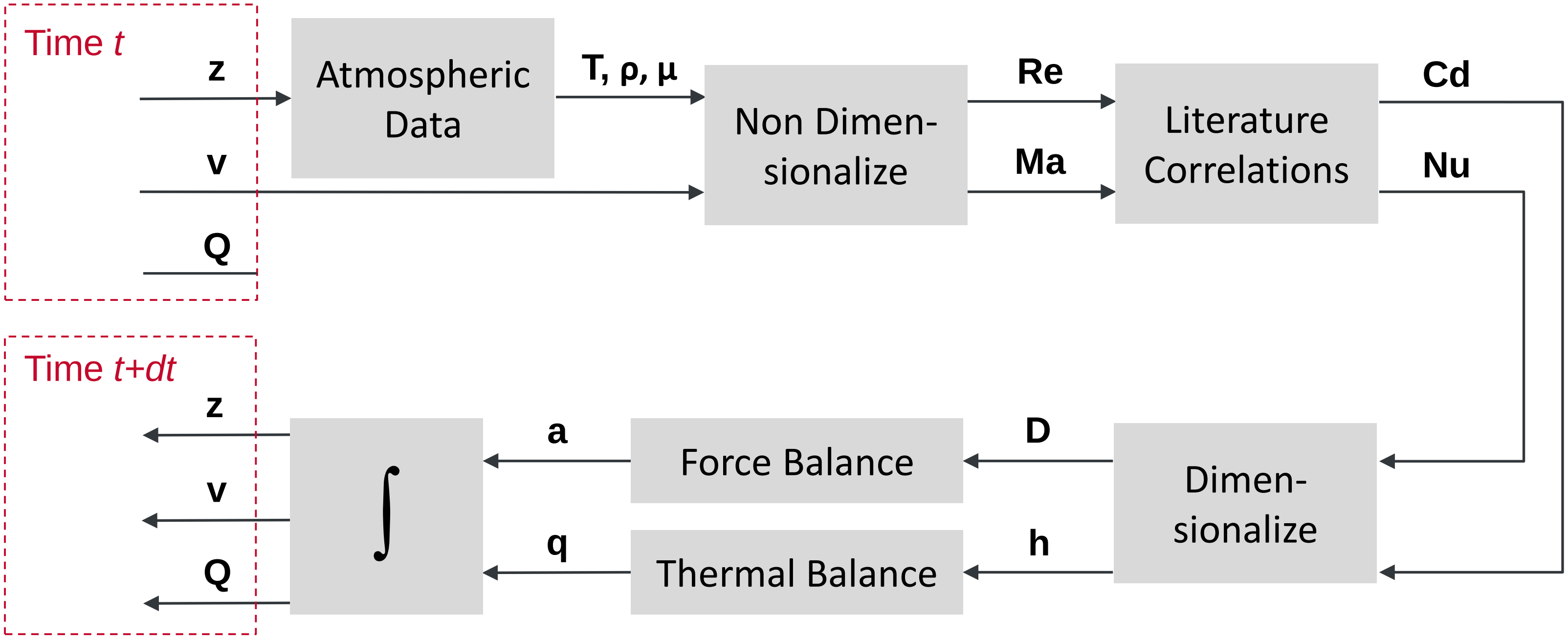
Backup Slides

Computation Method

ODE solver (Runga-Kutta), combined with **known correlations** for spheres



z - altitude
v - velocity
Q - heat energy sunk
T, ρ, μ - atmosphere properties
Re - Reynolds number
Ma - Mach number

Cd - drag coefficient
Nu - Nusselt number
D - drag force
h - convection coefficient
a - acceleration
q - heat flow rate

Example Probes

Probe Number	Diameter (m)	Bulk Density (vs water)	Drag Coefficient	Mass (kg)	Ballistic number (kg/m^2)	Impact Velocity (m/s)	Impact Time from 50km (s)	Payload Mass (kg)	Payload Mass Fraction	Payload Bulk Density (vs water)
1	0.5	0.8	0.2	52.35988	1333.333	19.11983	22.24201	24.67644	0.471285	0.679686
2	0.4	0.8	0.05	26.80826	4266.667	34.2394	12.29557	12.95176	0.483126	0.665883
3	0.25	0.7	0.05	5.726862	2333.333	25.28088	16.75017	1.400331	0.24452	0.643993