Planetary Atmospheric EDL with Flexible and Inflatable Technologies

Courtesy of NASA

12th International Planetary Probe Workshop

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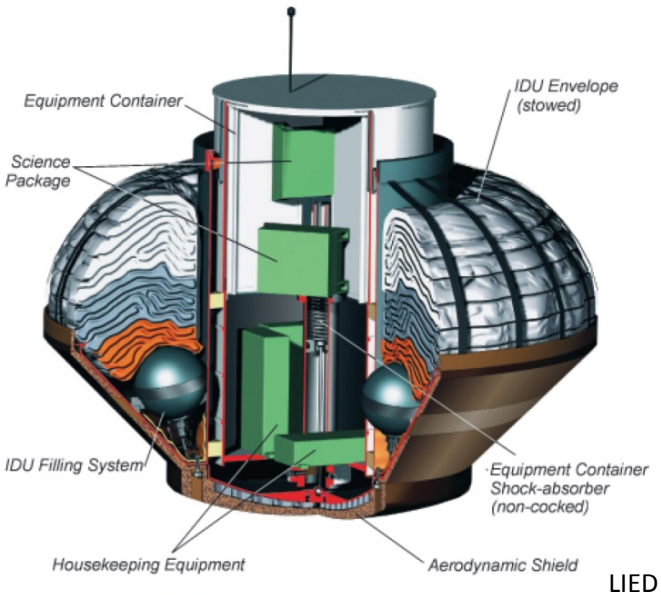
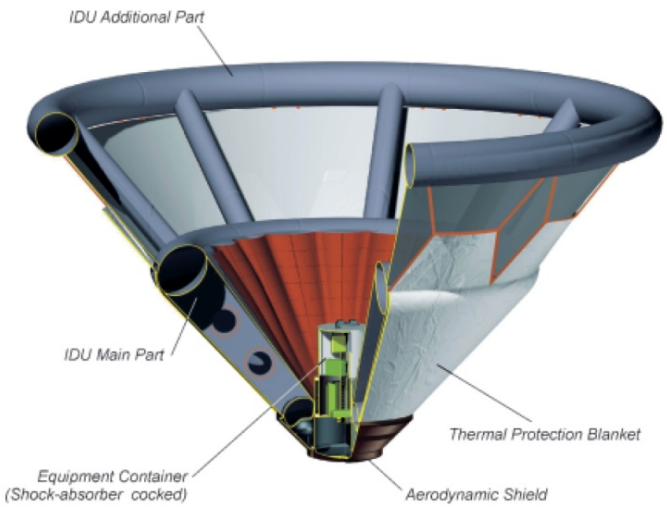
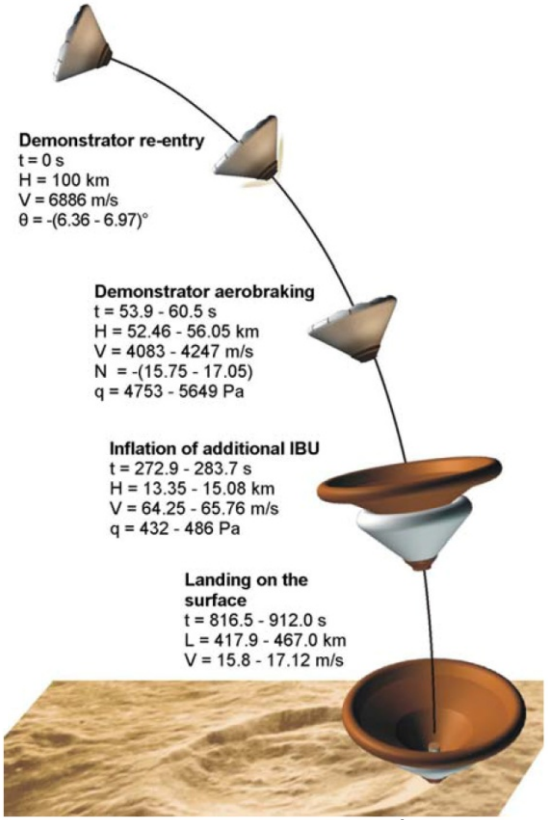
Large Inflatable Entry Decelerators (LIED)

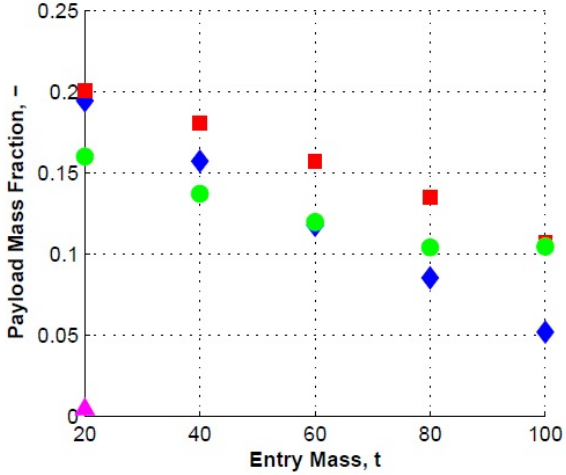


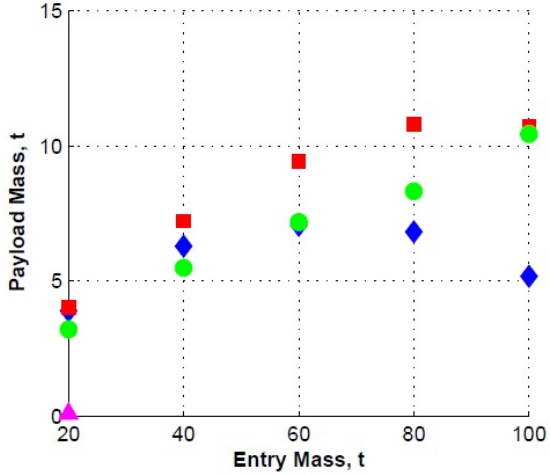


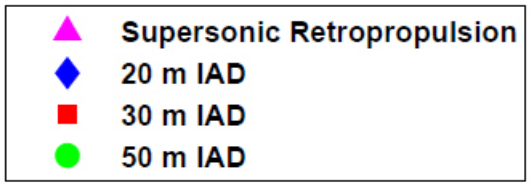
LIED technology – Courtesy of EASA



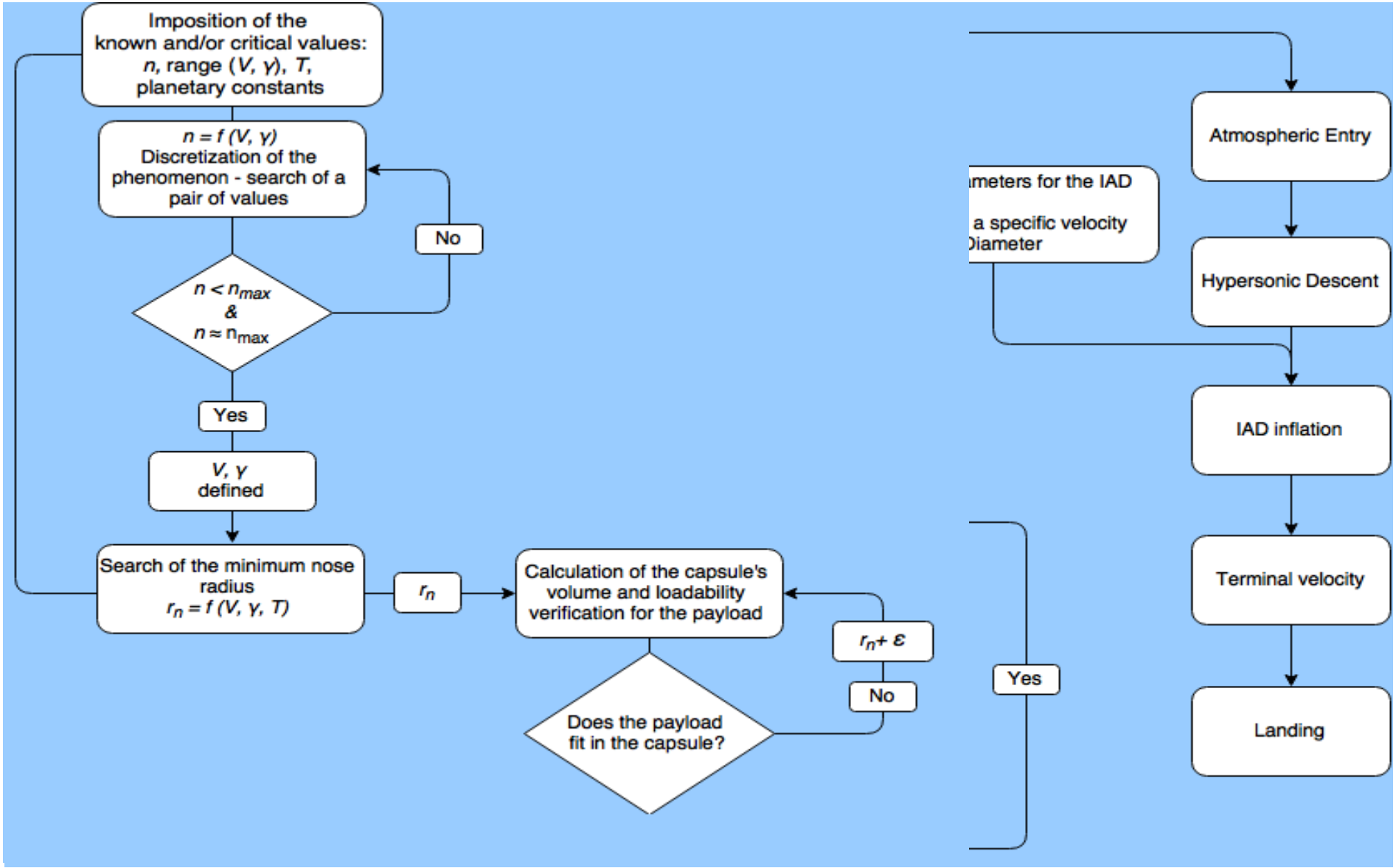
IRDT -2 mission – Courtesy of EASA







Courtesy of NASA


Imposition of the known and/or critical values: n, range (V, γ), T, planetary constants
$n = f(V, \gamma)$ Discretization of the phenomenon - search of a pair of values
No
$n < n_{max}$ & $n \approx n_{max}$
Yes
V, γ defined
Search of the minimum nose radius $r_n = f(V, \gamma, T)$
r_n
Calculation of the capsule's volume and loadability verification for the payload
$r_n + \varepsilon$
No
Does the payload fit in the capsule?
Yes
meters for the IAD
a specific velocity
Diameter
Atmospheric Entry
Hypersonic Descent
IAD inflation
Terminal velocity
Landing

Earth reentry mission - no crew on board

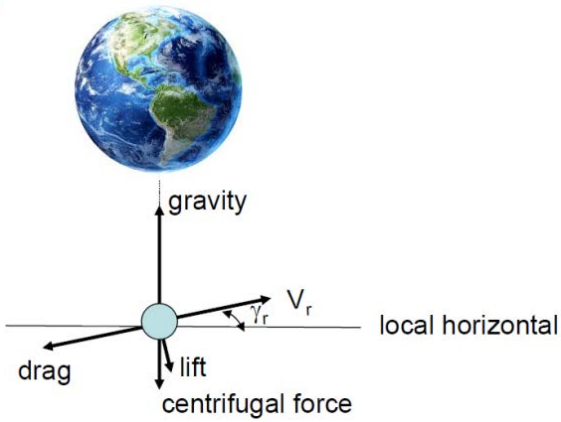
OBJECTIVES	REQUIREMENTS	VARIANTS
Low mass from ISS	150 kg	
Acceptable g values	Reentry velocity	Orbital $v = 5.5$ km/s Direct $v = 7.8$ km/s $\pm\Delta v$ provided by carrier
Adequate TPS	Reentry velocity Entry angle	As above Orbital $\gamma = -6.9°$ Direct $\gamma = -8.1°$ $\pm\Delta\gamma$ (carrier separation Δv)
Payload presence	Payload preservation	
LIED presence	Stages	Single LHIAD
Achieve soft landing	Landing velocity	Maximum $9 \div 11$ m/s

EDL phases – from the ISS to the ground

Equations of motion

$$mg\sin\gamma = D + m\frac{V^2}{r}\sin\gamma + m\frac{dV}{dt}$$

$$mg\cos\gamma = L + m\frac{V^2}{r}\cos\gamma + mV\frac{d\gamma}{dt}$$



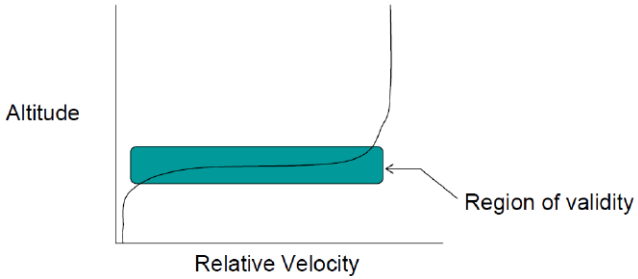
Ballistic entry

$L = 0$

$\gamma = const$

$\beta = const$

Exponential atmospheric density $\rho = \rho_0 e^{-xh}$



Allen and Eggers assumptions' region of validity
Courtesy of Georgia Institute of Technology

$$V = V_{atm} e^{Ce^{-xh}}$$

$$C = \frac{\rho_0}{2\beta x \sin\gamma} \qquad \beta = \frac{m}{C_D S}$$

LHIAD inflation

$$h_{infl} = -\frac{1}{x}\ln\left(\frac{\ln\frac{V_{infl}}{V_{atm}}}{C}\right)$$

$$\cancel{V = V_{atm} e^{Ce^{-xh}}} \xrightarrow{\text{transient}} V_{lift} = \sqrt{\frac{g \cdot r}{1 + \frac{(L/D)\rho \cdot r}{2\beta\cos\gamma}}}$$

Terminal speed

$$V_{lim} = \sqrt{\frac{2mg}{\rho C_p S}}$$

Capsule dimensioning

Structural limitations

$$n_{max} = \frac{x V_{atm}^2 \sin\gamma}{2ge}$$

$$h_{n_{max}} = \frac{1}{x}\ln(-2C)$$

$$V_{n_{max}} = V_{atm} e^{-1/2}$$

```
n_max_imp=-7.5;
%imposed maximum load factor
```

Thermal limitations

$$q_{conv} = k_q \sqrt{\frac{\rho}{r_n}} V_{atm}^3$$

$$q_{rad} = \sigma \epsilon T^4$$

At the thermodynamic equilibrium

$$T = \left(\frac{k_q \sqrt{\frac{\rho}{r_n}} V_{atm}^3}{\sigma \epsilon} \right)^{1/4}$$

$$h_{q_{max}} = -\frac{1}{x} \ln\left(\frac{\ln \frac{V_{q_{max}}}{V_{atm}}}{C} \right)$$

$$V_{q_{max}} = V_{atm} e^{-1/6}$$

```
T_lim_SLA=2000;
%imposed max operative temperature
```

Calculation of the nose radius so that the structural and thermal limitations are respected

$$r_n = \left(\frac{\ln\left(\frac{V_{q_{max}}}{V_{atm}}\right) k^2 V_{atm}^6 2mx\alpha^2 \sin\gamma}{\left(\sigma\epsilon T_{max}^4\right)^2 C_D \pi} \right)^{1/3}$$

```
Found base radius: 0.55
The found capsule is able
to bear the equivalent
heat load of 2000 K but
not to deliver 105 kg
Actually, it could contain
[kg]: 61.9004
```

```
The needed base radius is: 0.7
It can contain [kg]: 128.3589
```

Choosing the inflatable decelerator (IAD)

R Rigid Mid-L/D Aeroshells (Rigid Mid-L/D AS, *ellipsled chosen*)

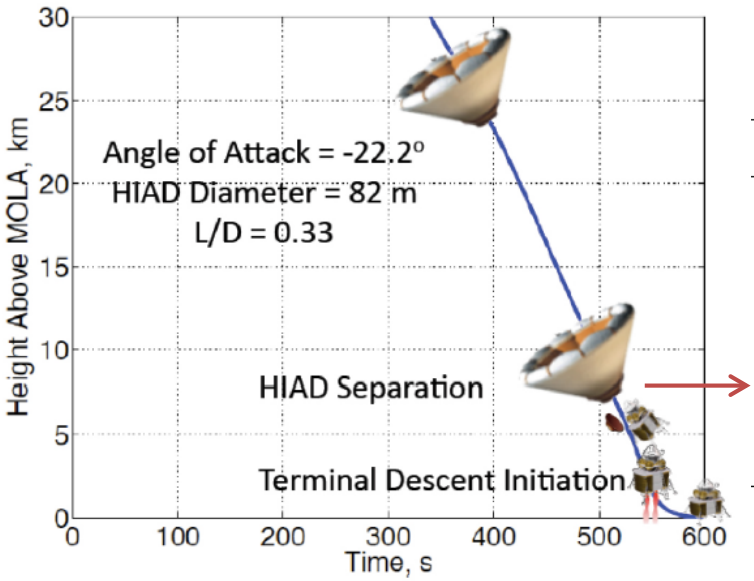
F Hypersonic Inflatable Aerodynamic Decelerators (HIAD)

R Supersonic Retro-Propulsion (SRP)

F Supersonic Inflatable Aerodynamic Decelerators (SIAD)

F Deployable Supersonic IADs With Skirt (SIAD-Skirt)

Baseline structure
NASA DRA5
(*Design Reference Architecture 5.0 for Mars*)

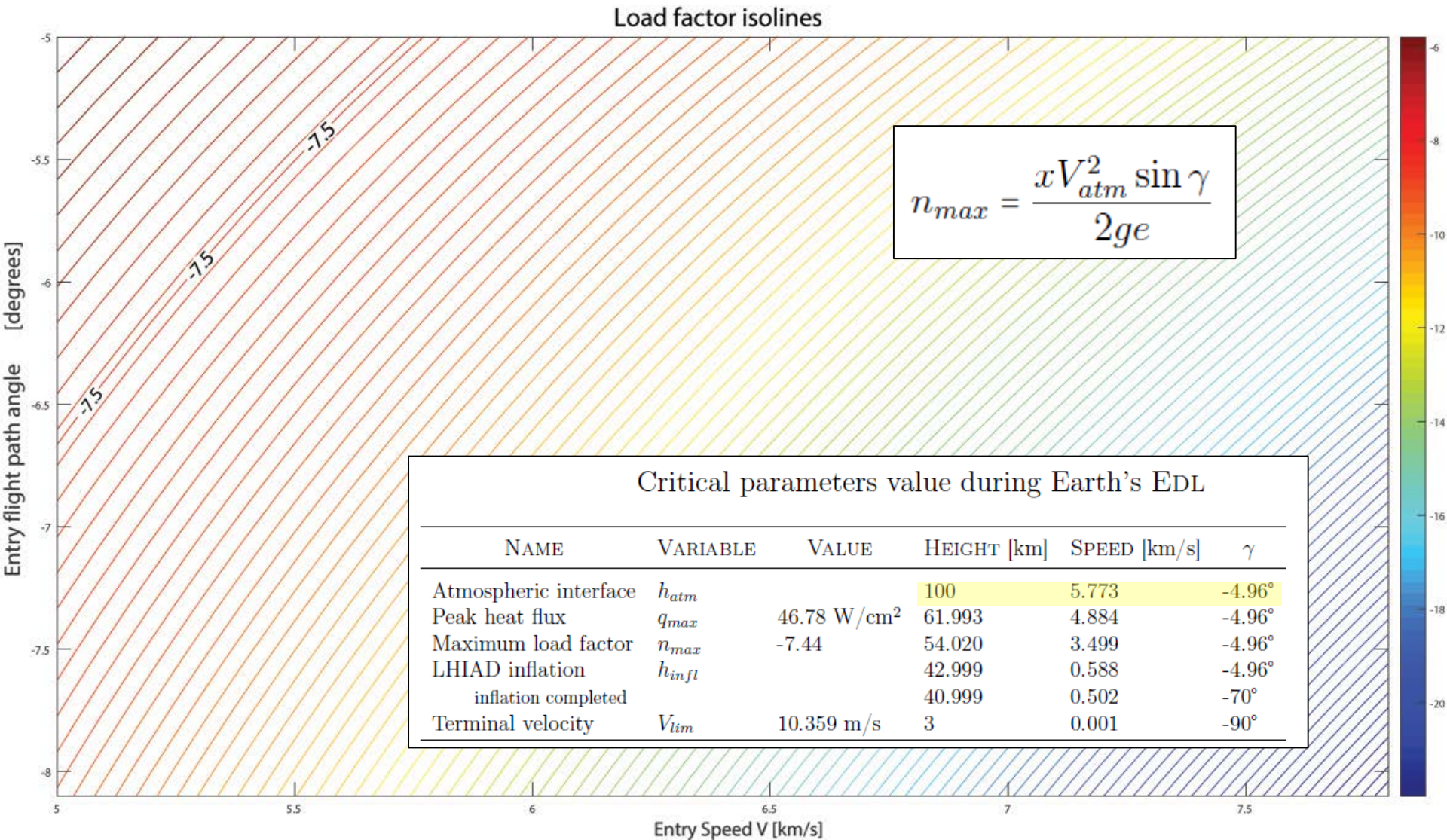


Architecture 6 EDL phase – courtesy of NASA

	Aerocapture	Hypersonic	Supersonic	Subsonic
DRA5 [Arch. 1]	Rigid Mid-L/D AS	Rigid Mid-L/D AS	Propulsion	Propulsion
Architecture 2	LHIAD	LHIAD	Propulsion	Propulsion
Architecture 3	*n/a*	Propulsion	Propulsion	Propulsion
Architecture 4	Rigid Mid-L/D AS	LHIAD	Propulsion	Propulsion
Architecture 5	Rigid Mid-L/D AS	LHIAD	LHIAD	Propulsion
Architecture 6	LHIAD	LHIAD	LHIAD	Propulsion
Architecture 7	Rigid Mid-L/D AS	Rigid Mid-L/D AS	DSIAD	Propulsion
Architecture 8	LHIAD	LHIAD	LSIAD-Skirt	Propulsion

From a trade-off of completed missions and an iterative calculation, for the 150 kg of the Earth mission, it has been chosen a single Lifted Hypersonic IAD (LHIAD) with a **diameter of 5 m**.

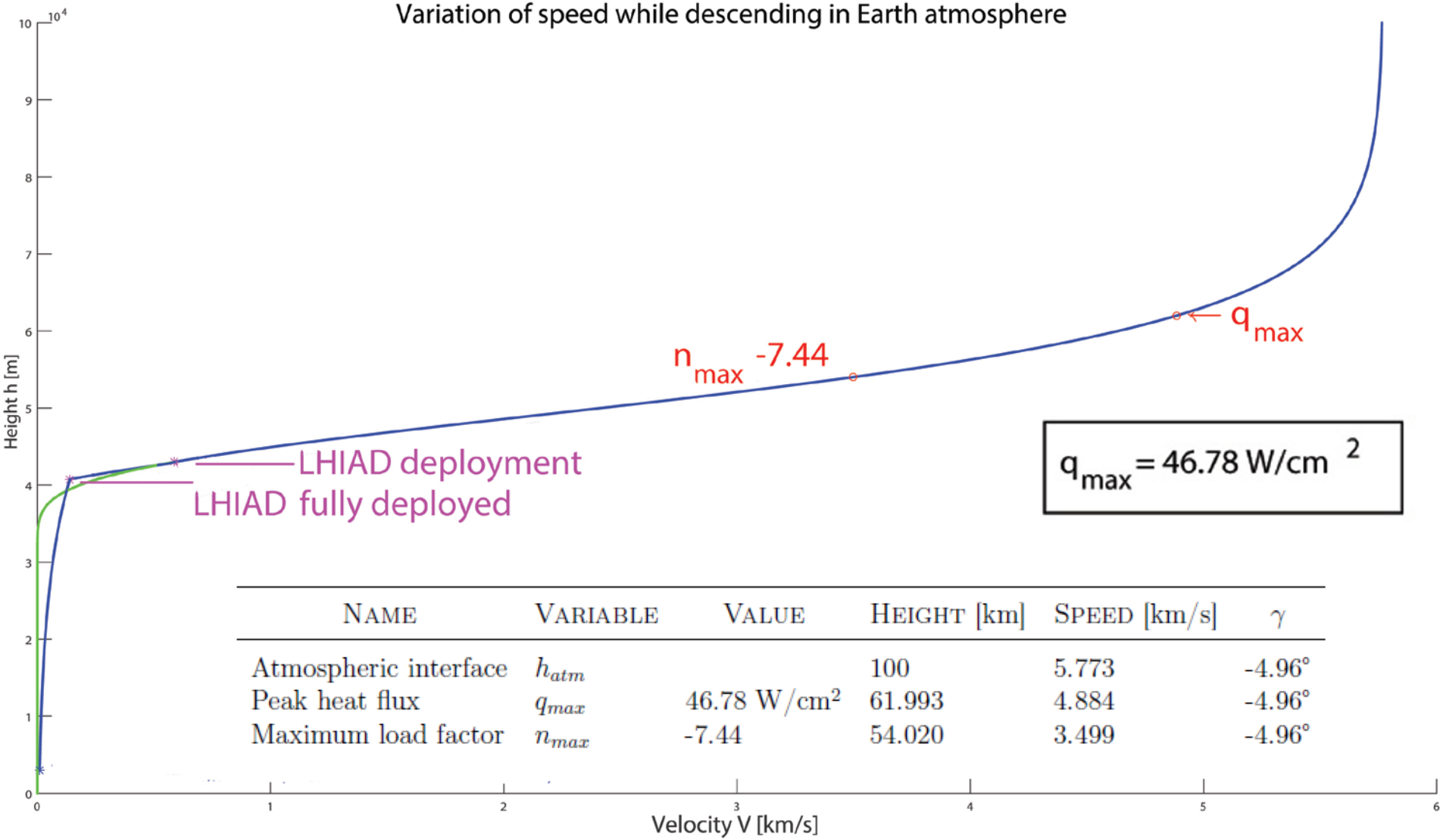
Analysis results



$$n_{max} = \frac{x V_{atm}^2 \sin\gamma}{2ge}$$

Critical parameters value during Earth's EDL

NAME	VARIABLE	VALUE	HEIGHT [km]	SPEED [km/s]	γ
Atmospheric interface	h_{atm}		100	5.773	-4.96°
Peak heat flux	q_{max}	46.78 W/cm^2	61.993	4.884	-4.96°
Maximum load factor	n_{max}	-7.44	54.020	3.499	-4.96°
LHIAD inflation	h_{infl}		42.999	0.588	-4.96°
inflation completed			40.999	0.502	-70°
Terminal velocity	V_{lim}	10.359 m/s	3	0.001	-90°



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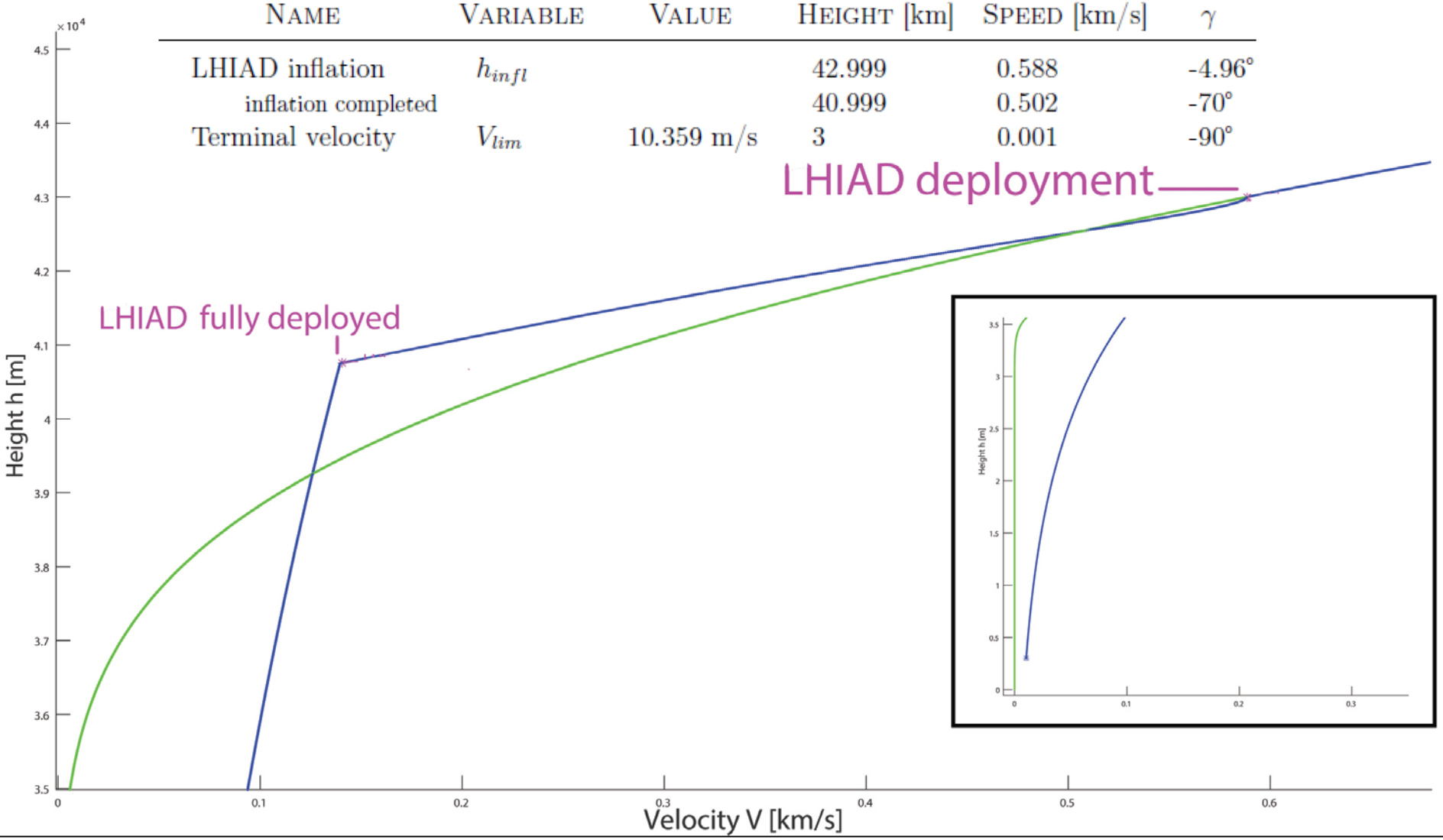


Mars atmospheric entry mission with human crew on board

OBJECTIVES	REQUIREMENTS	VALUES
Very high mass from LMO	40000 kg entry 20000 kg landed	
Acceptable g values	Reentry velocity *Human survivability*	Orbital $v = 4km/s$
Adequate TPS	Entry angle	Orbital $\gamma = -11.5 \div -13.5°$
Adequate deceleration	Proper $\beta = {}^{m}/_{C_D A}$	
Huge payload presence	*Payload mass fraction* Payload preservation Adequate capsule	
LIED presence	Stages	
Achieve soft landing	Landing velocity	Maximum $4.5 \div 5$ m/s

EDL phases

HIAD inflation

$$h_{HIAD_{infl}} = -\frac{1}{x}\ln\left(\frac{\ln\frac{V_{HIAD_{infl}}}{V_{atm}}}{C}\right)$$

transient

SIAD inflation

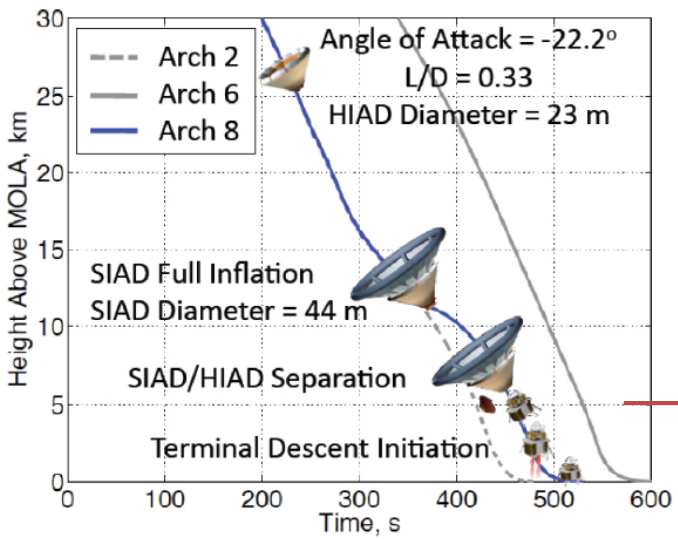
$$h_{SIAD_{infl}} = -\frac{1}{x}\ln\left(\frac{\ln\frac{V_{SIAD_{infl}}}{V_{atm}}}{C}\right)$$

transient

$$V_{lift} = \sqrt{\frac{g\cdot r}{1+\frac{(L/D)\rho\cdot r}{2\beta\cos\gamma}}}$$

transient

Choosing the inflatable decelerator (IAD)



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Architecture 7	Rigid Mid-L/D AS	Rigid Mid-L/D AS	DSIAD	Propulsion
Architecture 8	LHIAD	LHIAD	LSIAD-Skirt	Propulsion

Architecture 8 EDL phase – courtesy of NASA

It was decided to entrust the hypersonic deceleration to a Lifted Hypersonic IAD (LHIAD) with a **diameter of 20 m**, followed by a Lifted Supersonic IAD (LSIAD) which slows down the capsule to the subsonic regime with a **diameter of 40 m**.

Capsule dimensioning

Structural and human limitations

$$n_{max} = \frac{x V_{atm}^2 \sin\gamma}{2ge}$$

$$V_{n_{max}} = V_{atm} e^{-1/2}$$

n_max_imp=-5.5;

%imposed maximum load factor

Thermal limitations

$$T = \left(\frac{k_q \sqrt{\frac{\rho}{r_n}} V_{atm}^3}{\sigma \epsilon} \right)^{1/4}$$

$$V_{q_{max}} = V_{atm} e^{-1/6}$$

T_lim_SLA=2000;

%imposed max operative temperature

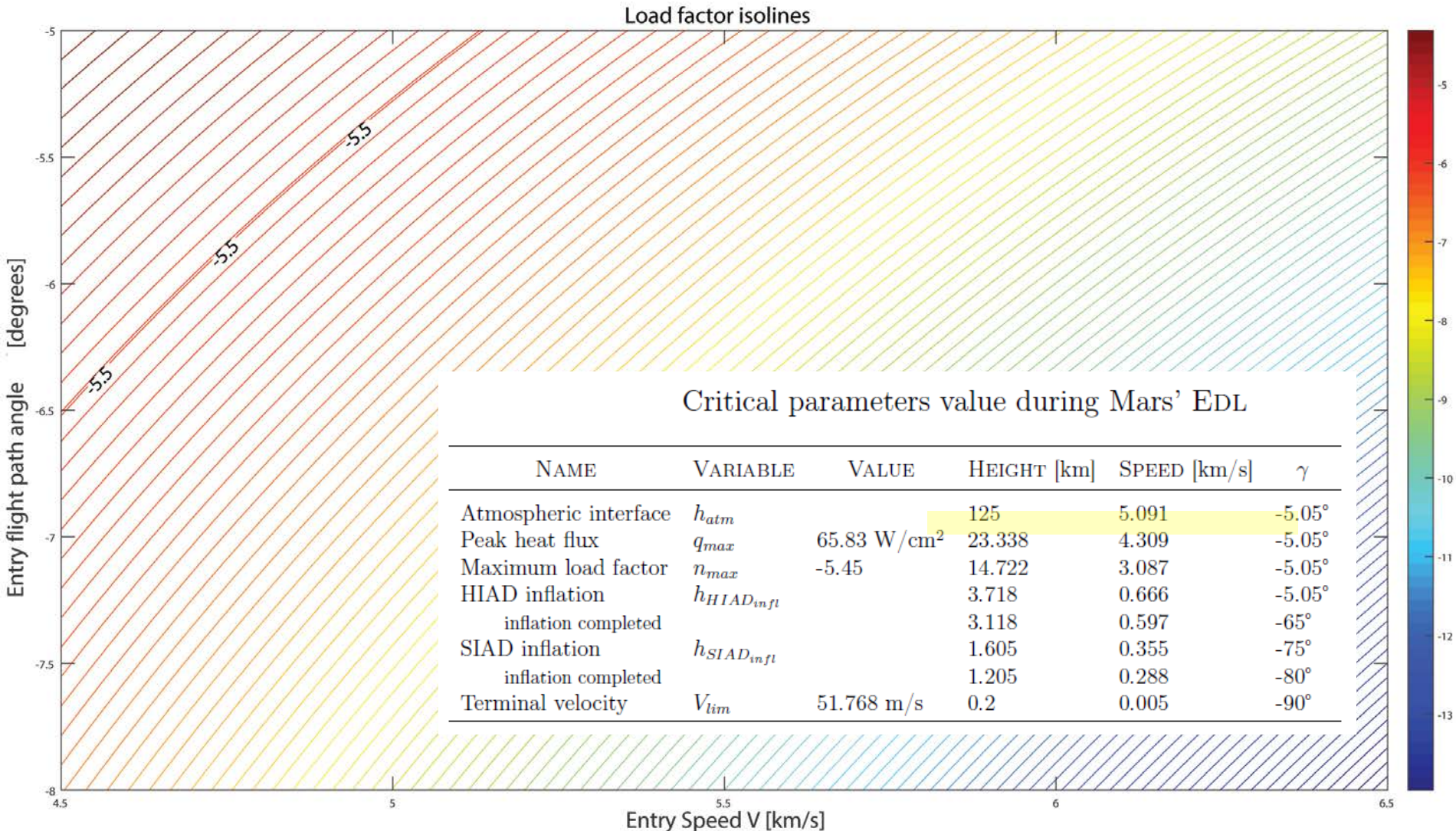
Calculation of the nose radius so that the structural and thermal limitations are respected and the survival of the human crew is ensured

$$r_n = \left(\frac{\ln\left(\frac{V_{q_{max}}}{V_{atm}}\right) k^2 V_{atm}^6 2mx\alpha^2 \sin\gamma}{\left(\sigma\epsilon T_{max}^4\right)^2 C_D \pi} \right)^{1/3}$$

```
Found base radius: 3
The found capsule is able to bear the equivalent
heat load of 2000 K but not to deliver 20000 kg
Actually, it could contain [kg]: 15563.1657

The needed base radius is: 3.15
It can contain [kg]: 21550.6223
```

Analysis results



Critical parameters value during Mars' EDL

NAME	VARIABLE	VALUE	HEIGHT [km]	SPEED [km/s]	γ
Atmospheric interface	h_{atm}		125	5.091	-5.05°
Peak heat flux	q_{max}	65.83 W/cm^2	23.338	4.309	-5.05°
Maximum load factor	n_{max}	-5.45	14.722	3.087	-5.05°
HIAD inflation	$h_{HIAD_{infl}}$		3.718	0.666	-5.05°
inflation completed			3.118	0.597	-65°
SIAD inflation	$h_{SIAD_{infl}}$		1.605	0.355	-75°
inflation completed			1.205	0.288	-80°
Terminal velocity	V_{lim}	51.768 m/s	0.2	0.005	-90°

Variation of speed while descending in Mars atmosphere

Name	Variable	Value	Height [km]	Speed [km/s]	γ
Atmospheric interface	h_{atm}		125	5.091	-5.05°
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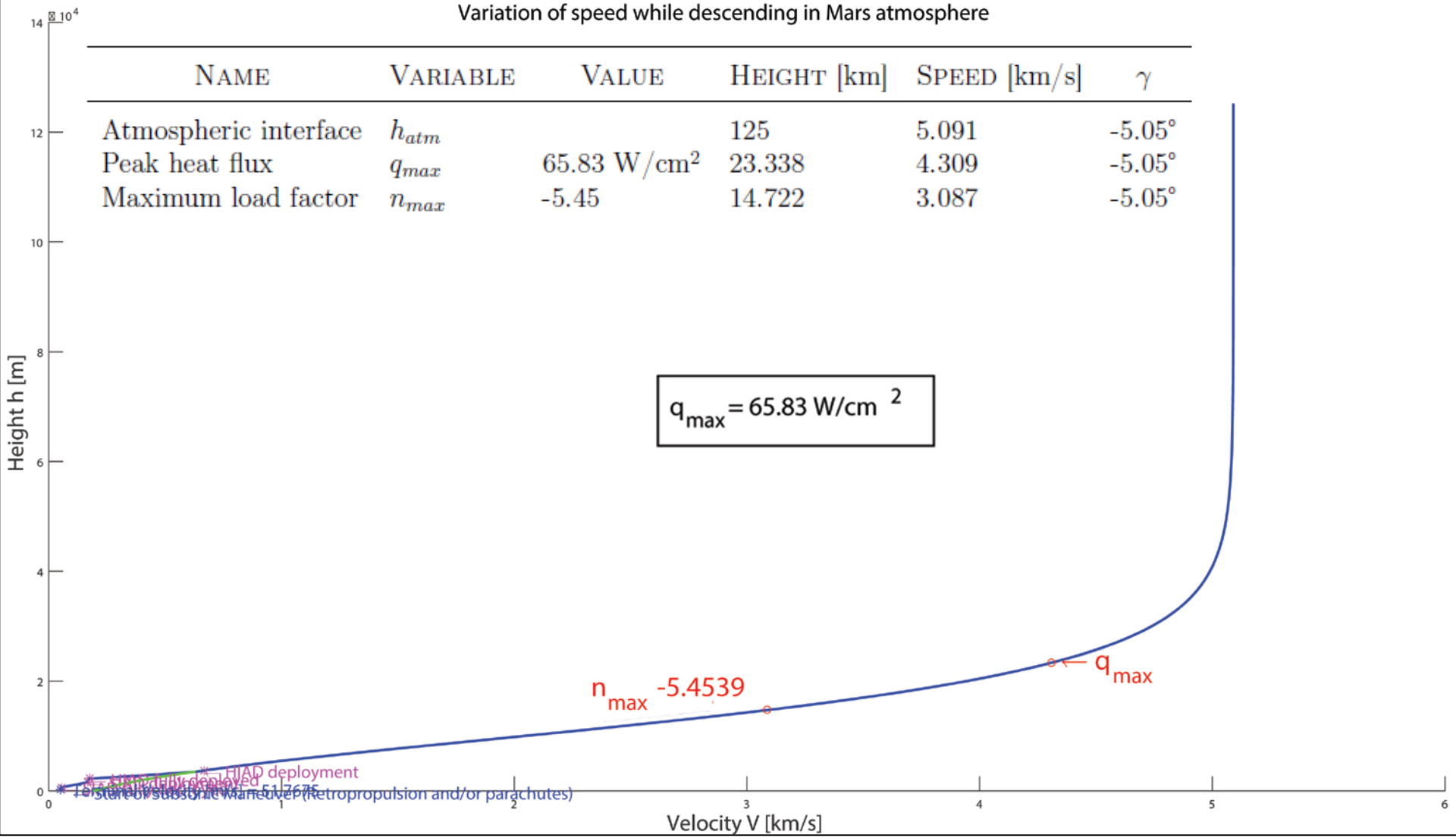

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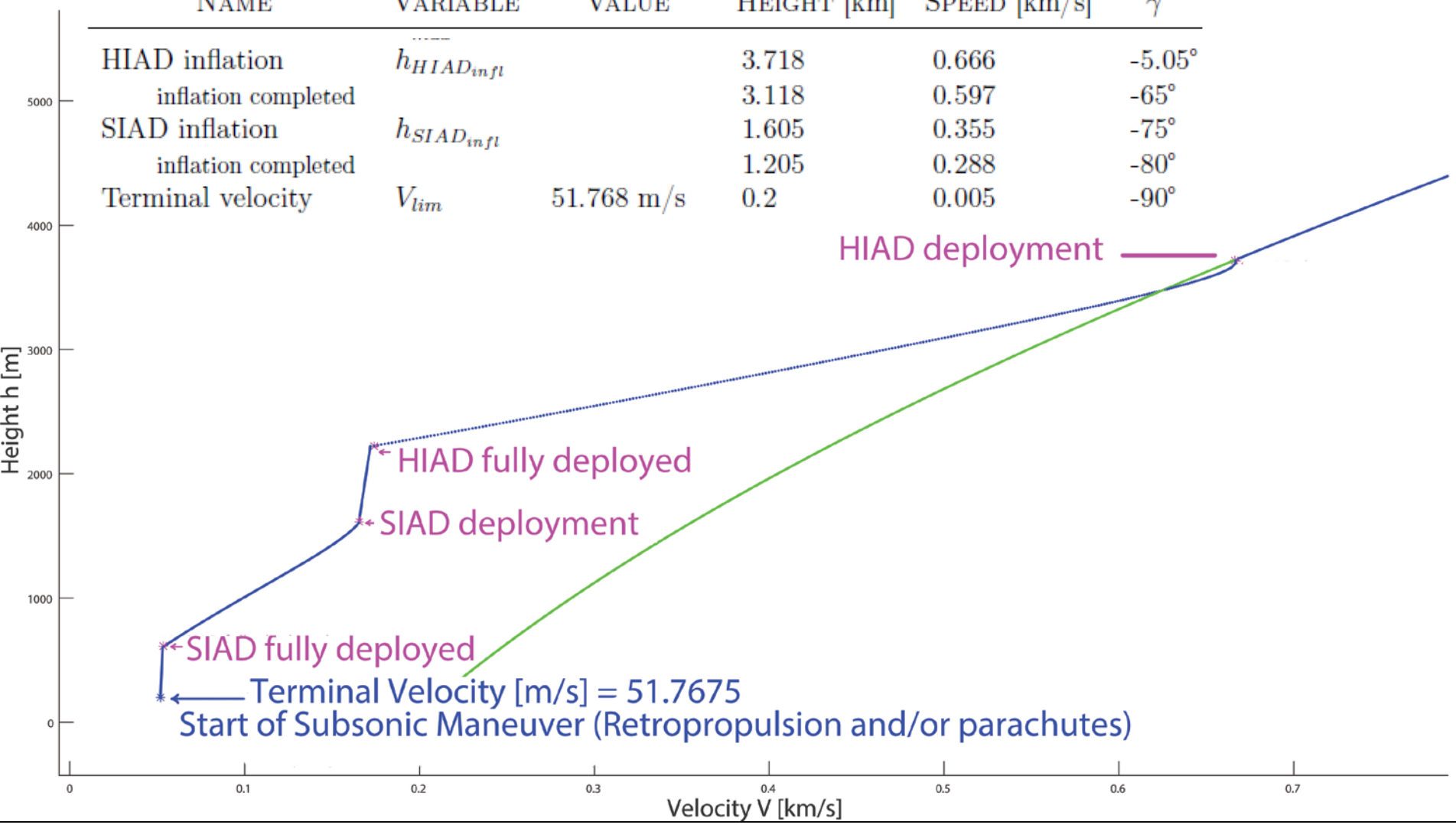

Thank you!