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Technology Development toward Mars Aeroflyby Sample Collection

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Background

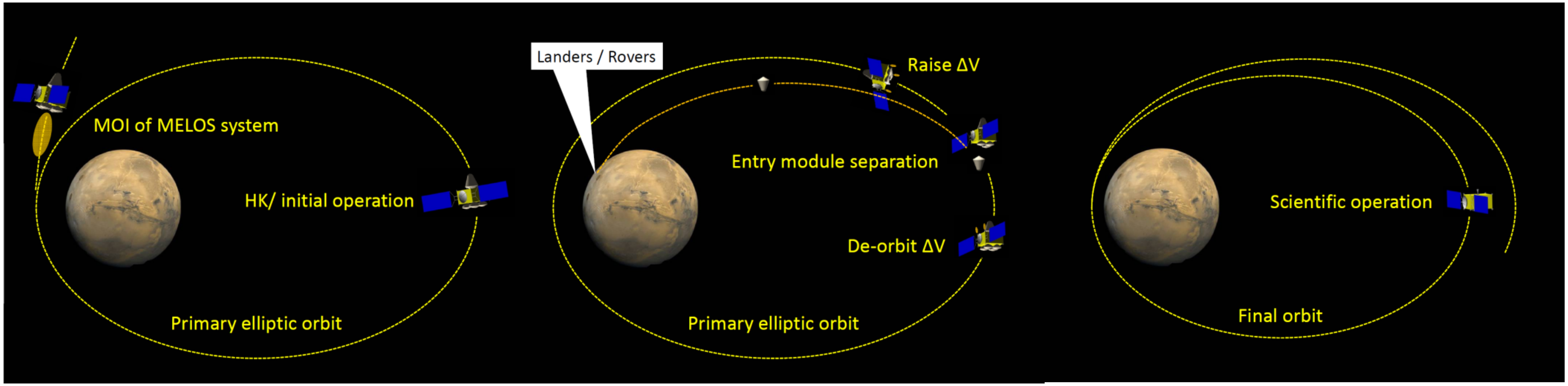
Mars Exploration with Landers & Orbiters Synergy (MELOS)

- Currently entertained in Japan (2020 launch)
- Conglomerate mission where orbiters, landers, rovers, and/or airplanes are used for aeronomical, meteorological, and geoscientific researches as well as life search
- To reveal *why Mars is now in red* – the fate of ancient water and carbon dioxide on the course of Martian history

Mission scenario

- MELOS system is first inserted into primary orbit altogether
- Entry systems are flown into Martian atmosphere using orbiter as a service module
- Orbiter is maneuvered to final orbit for scientific operation

→ Great potential for a variety of probe vehicles incorporated into MELOS

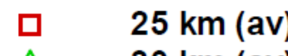


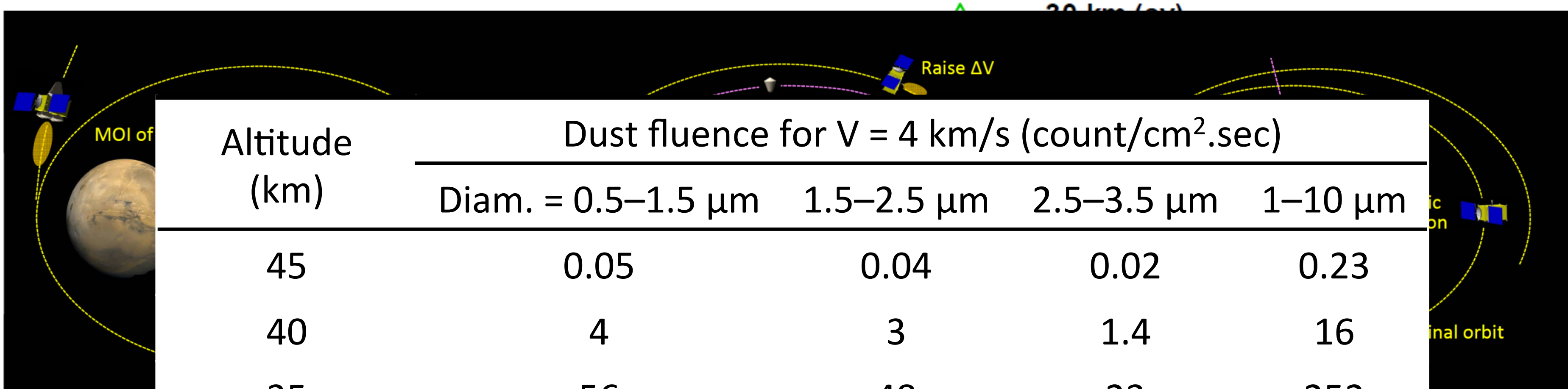
Mars Aeroflyby Sample Collection (MASC)

Mission concept

- Collection of Martian dust & gas samples during aeroflyby and return to Earth
- Originally proposed by Leshin et al. as a candidate for Mars Scout mission

Scenario

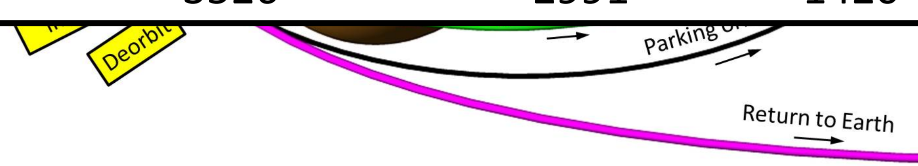




Altitude (km)	Dust fluence for V = 4 km/s (count/cm^2.sec)			
	Diam. = 0.5–1.5 μm	1.5–2.5 μm	2.5–3.5 μm	1–10 μm
45	0.05	0.04	0.02	0.23
40	4	3	1.4	16
35	56	48	23	252
30	367	312	148	1650
25	1331	1129	536	5984
20	3526	2991	1420	15849

Adv

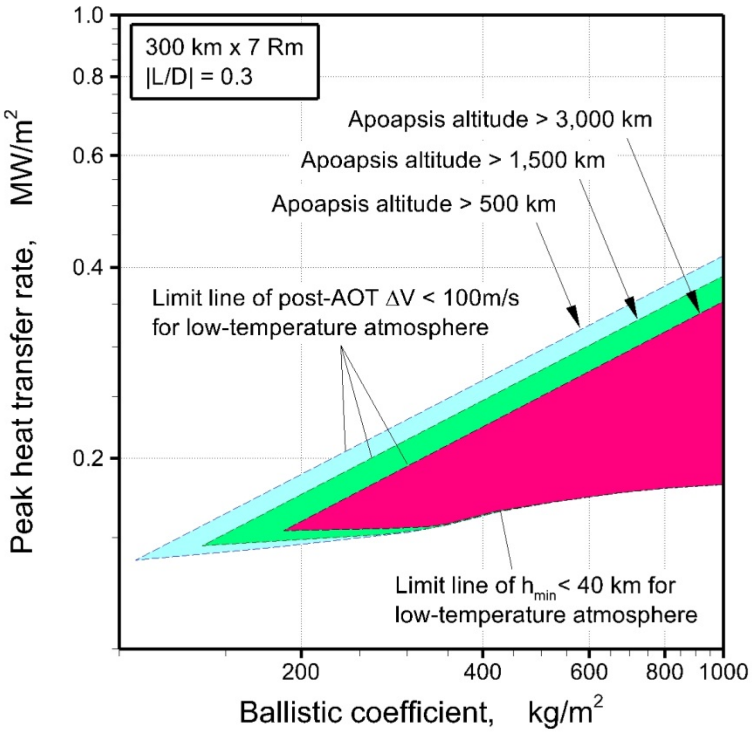
- V ... s may b ... m)
- C ... e
- Sample retu ... analysis
- Sample retu ... oved instruments

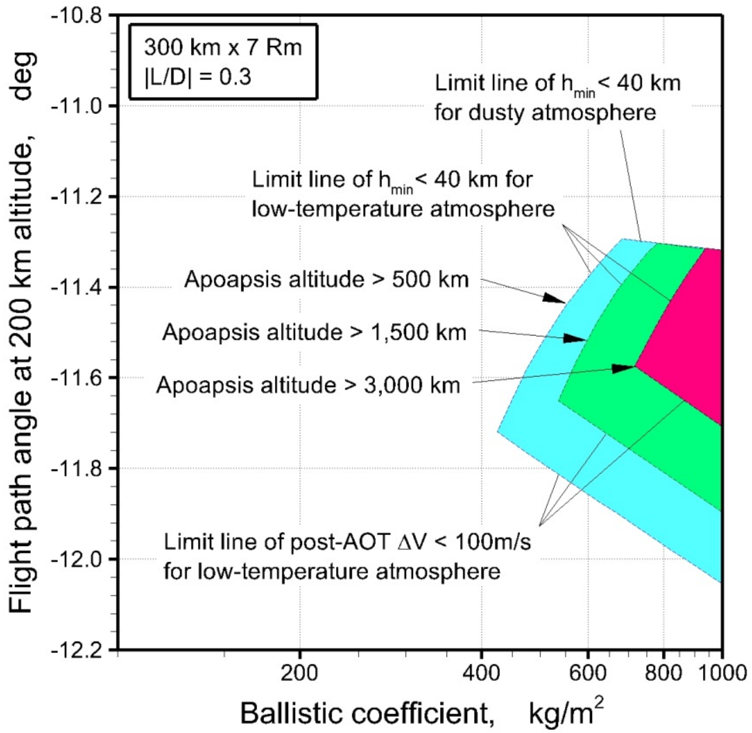


Fundamental Design Parameters for MASC

Critical keys

- Successful insertion to an orbit appropriate for earth return : precise GNC using lifting aeroshell is needed to cope with uncertainties in atmospheric density, aerodynamics of vehicle, & orbit/attitude determination
- Minimization of total ΔV required for AOT, post-AOT maneuver, and earth return
- Accessible lowest altitude < 40 km for sample collection
- Minimization of TPS for aerodynamic heating





Fundamental Mission Design

Design criteria

- Minimize total system mass (minimum dry mass of earth return subsystem may be almost determined by heritages of past systems)
- Decrease propellant mass for earth return to minimize mass of orbiter subsystem
- Increase apoapsis altitude of parking orbit to decrease ΔV for earth return
- Decrease β for reduction of TPS mass
- Increase β to enlarge ATO corridor

Orbit design	
Primary elliptic orbit (orb1)	300 × 7 R_m altitude
AOT target orbit (orb2)	150 × 500 km altitude
Theoretical ΔV for orb1 → orb2	−1.10 km/s
Nominal flight path angle	−11.54°
Allowed deviations	±0.20°
Expected lowest altitude	34.0±5.0 km
Post-AOT ΔV	< 60 m/s
Final parking orbit (orb3)	500 × 500 km altitude
ΔV required for orb2 → orb3	+ 79 m/s
ΔV required for orb3 → earth	+ 2.60 km/s (incl. margin)
Propulsion system (OME & RCS)	
Fuel / Oxidizer	Hydrazine / MON-3
O/F ratio	0.8
Specific impulse	315 sec
Structural factor	0.25

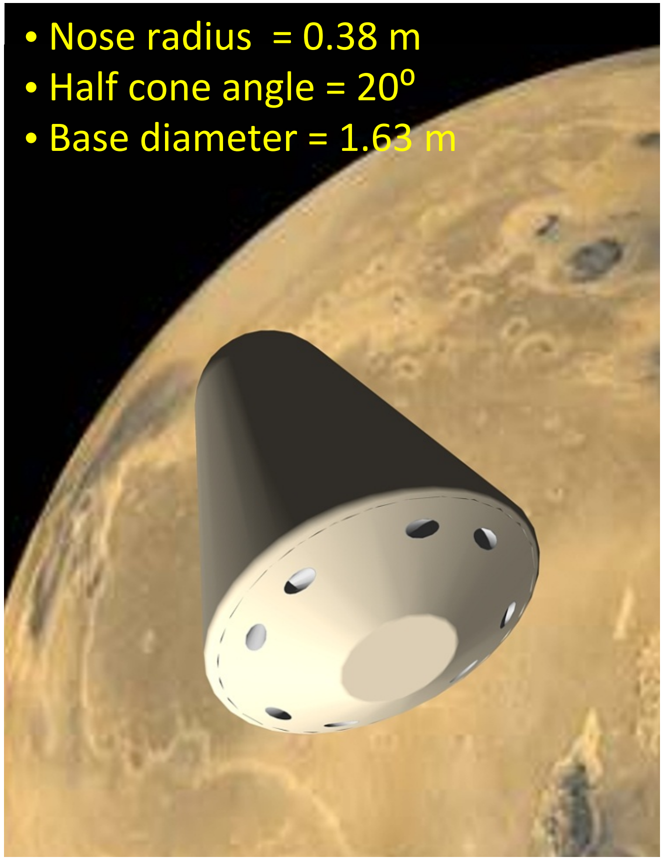
Ballistic coefficient, kg/m^2

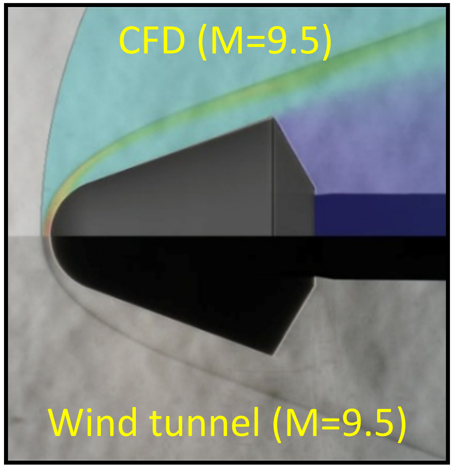
Aeroshell	
Structure	CFRP honeycomb with TPS
Area density	7.5 kg/m^2
TPS bulk density	0.25 g/cm^3
Aeroshell shape	Sphere-cone
Half-cone angle	20 deg
Base diameter, D_B	1.63 m
Nose radius, R_n	0.38 m
Aerodynamic characteristics	
Ballistic coefficient	700 kg/m^2
Lift-to-drag ratio, L/D	> 0.3
AOT guidance	
Guidance algorithm	APC + lateral control
Attitude control	PID yaw/pitch controller
L/D control method	Bank-angle modulation
Control device	bipropellant RCS

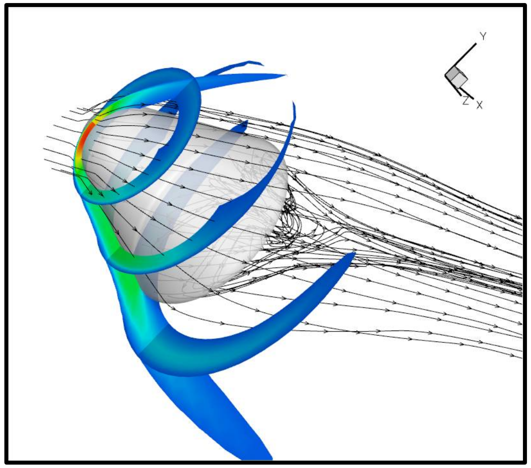
Aerodynamic Design

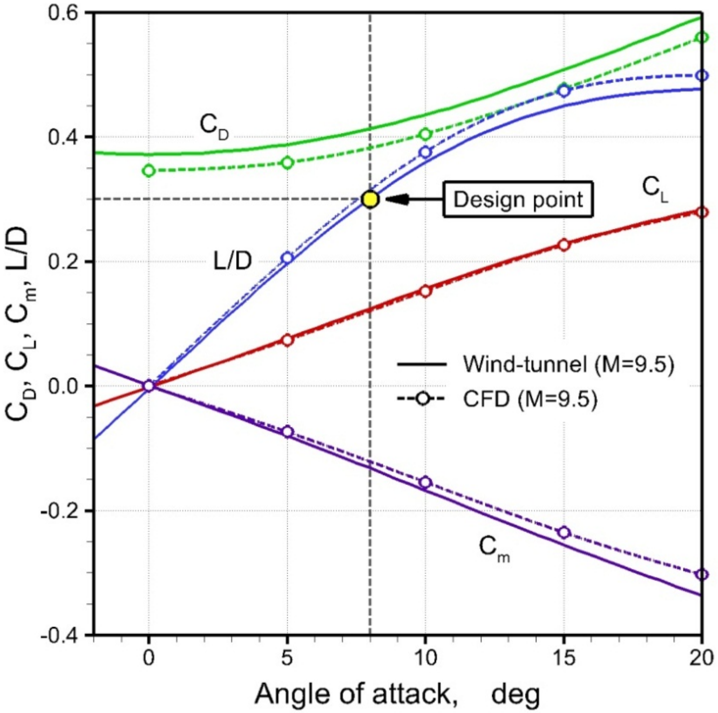
System requirements

- L/D > 0.3 (up to 0.4 for α < 12)
- $\beta \approx 700$ kg/m^2
- Equipped with light-weight TPS
- Equipped with RCS's









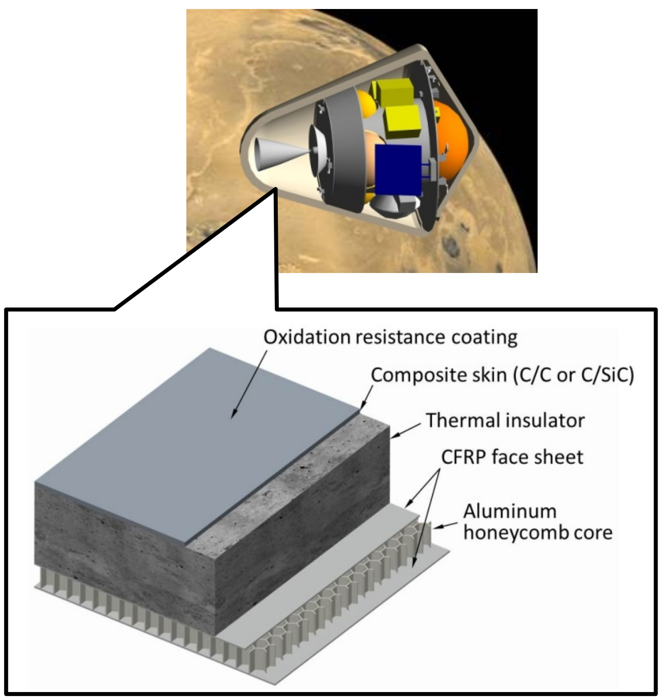
TPS Design

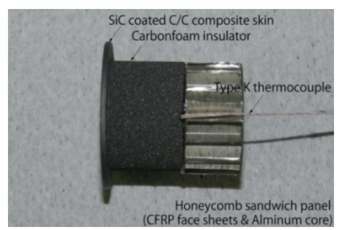
Development of non-ablative light-weight TPS (NALT)

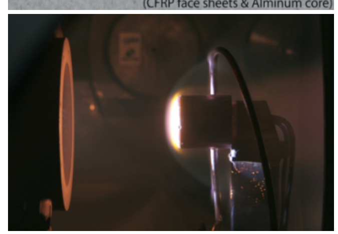
- Non-ablative TPS is favorable for dust sampling during hypersonic flight
- NALT consists of C/C skin, thermal insulator, and honeycomb structure

Conceptual design of MASC aeroshell

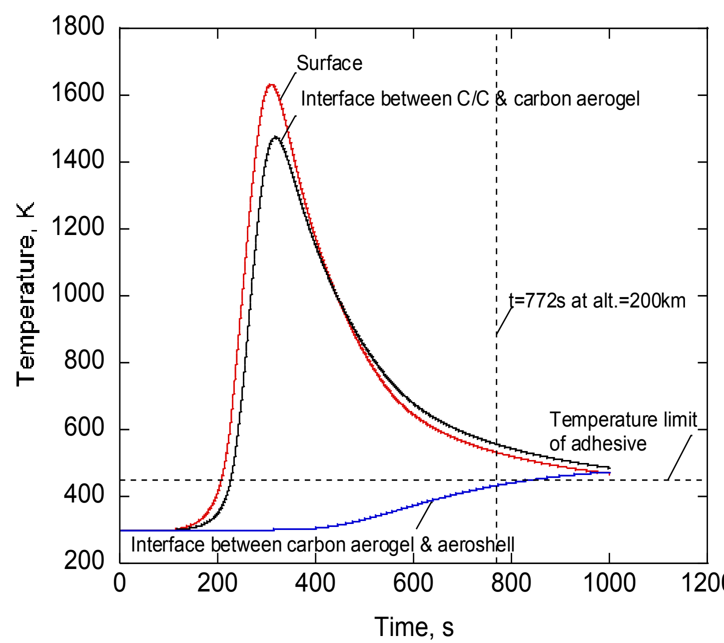
- 1D TPS analysis along a flight trajectory (search for solutions by trial-&-error method)
- Resulting in TPS area density of 9.0 kg/m^2 at stagnation point, 7.5 kg/m^2 in average, and total aeroshell mass of 133 kg







1D TPS analysis along flight trajectory



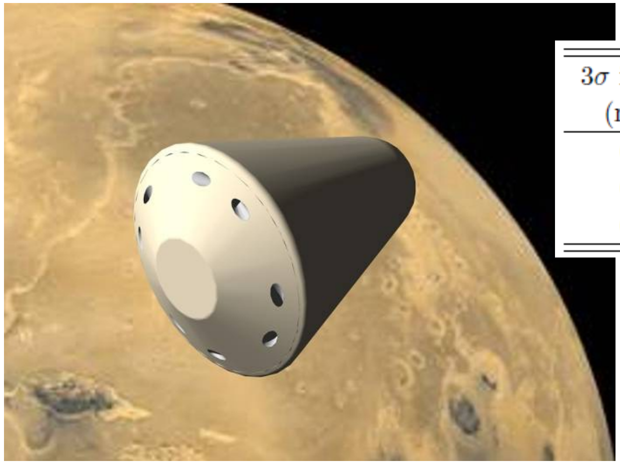
Design of GNC Subsystem

GNC subsystem configuration

- Effective descent/ascent rate control by bank-angle modulation using RCS's
- Analytic predictor-corrector (APC) controller for primary GNC architecture
- Lateral controller to minimize lateral deviation
- Proportional–integral–derivative (PID) controller for yawing/pitching stabilization

Assessment of designed GNC controller robustness

- Monte-Carlo simulation by taking into account uncertainties in atmospheric density, aerodynamics of vehicle, orbit determination, and guidance to entry I/F point
- Results have shown sufficient robustness of designed GNC controller
- Fuel used in bank-angle modulation is minimized by optimizing RCS's operation



3σ in ΔV	Apoapsis altitude (km)			Orbit inclination (deg)			Success rate
(m/s)	minimum	average	maximum	minimum	average	maximum	(%)
0.3	222.6	564.9	703.9	−0.404	0.135	1.632	99.8
0.5	232.1	561.9	782.42	−0.576	0.144	1.777	99.8
0.7	200.7	557.4	897.2	−0.899	0.149	1.813	99.8

3σ in L/D (%)	Success rate (%)
5.0	99.8
10.0	99.8
20.0	98.2

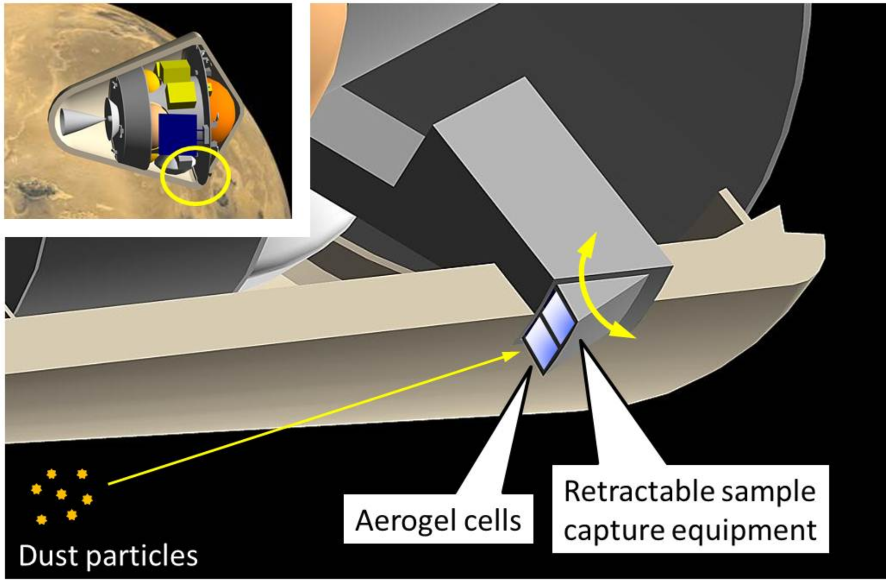
Dust Sampler Design

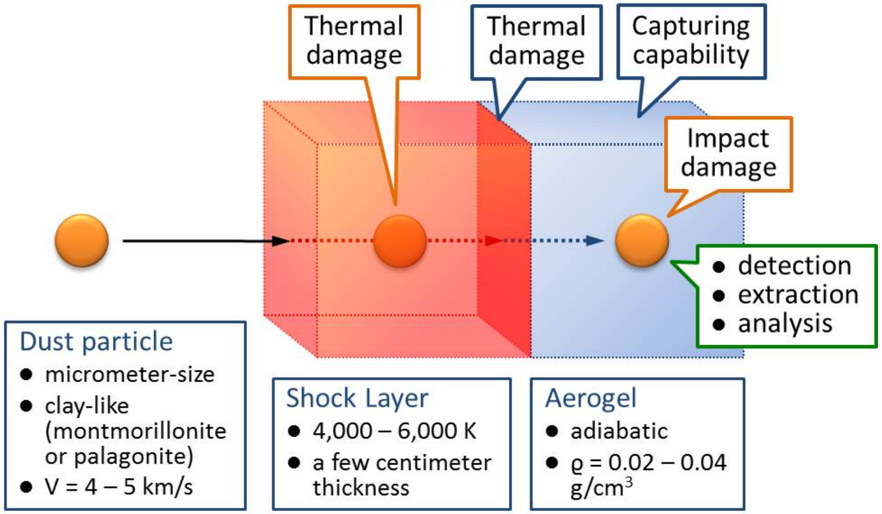
■ Approach

- Retractable samplers (currently 2) are exposed for a few seconds
- Samplers are located near aeroshell base to reduce heat transfer rate
- Silica aerogel is used for capturing sample particles (like STARDUST)
- Aerogel cells are transported to the reentry capsule inside MASC

■ Key issues

1. Damages inflicted on dust particles by high-temperature shock layer
2. Damages inflicted on aerogel exposed to high-temperature shock layer
3. Dust capturing capabilities of aerogel
4. damages inflicted on dust particles by impingement
5. capabilities of detecting & extracting dust samples stuck in the aerogel

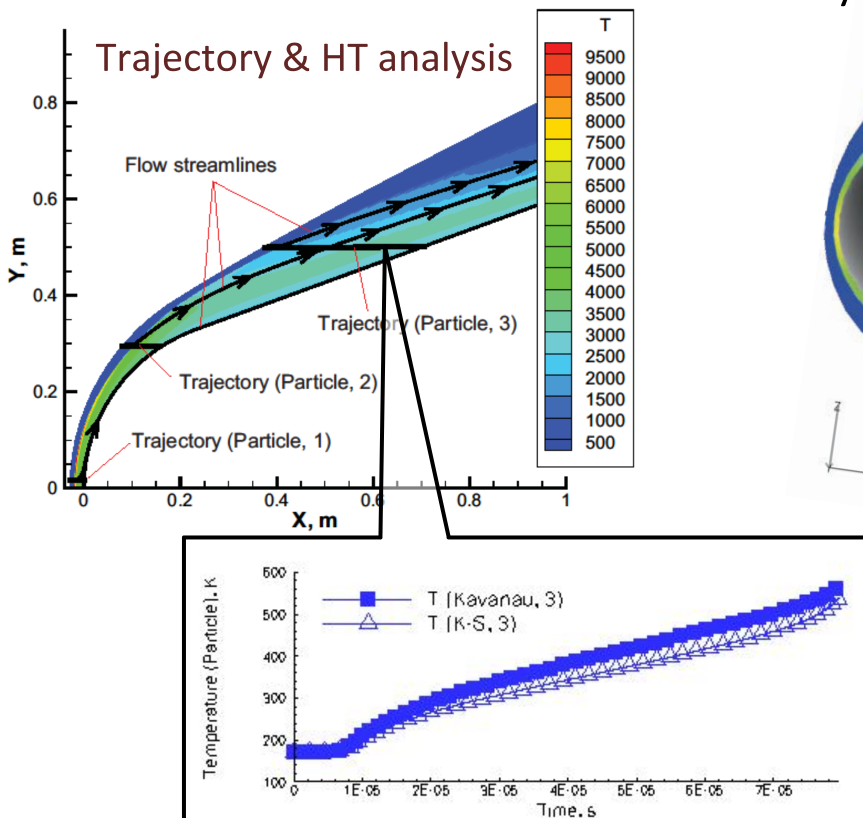


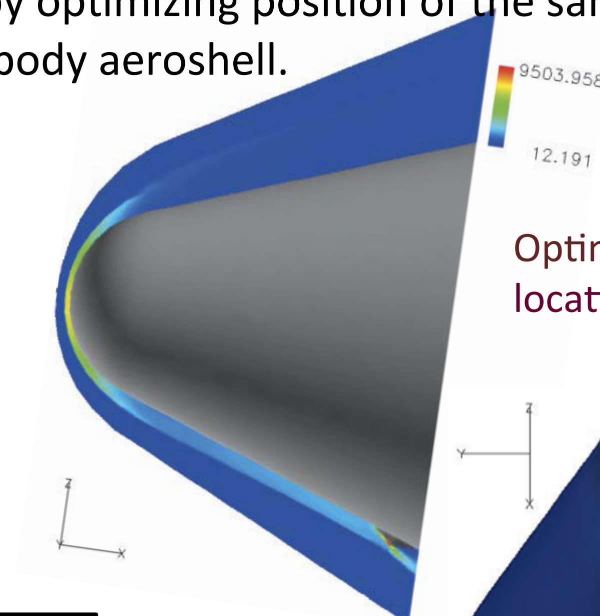


Assessment of Sample Damages

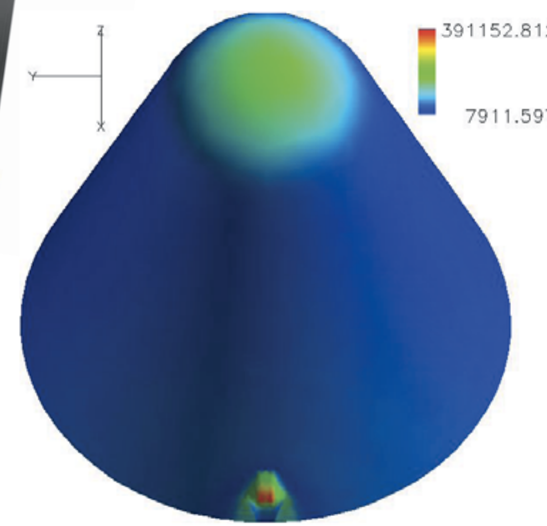
Trajectory & heat transfer analysis of sample dust particles

- Particles rush almost straightly across the shock layer and reach the aeroshell surface.
- Particle temperature remains below the critical temperature since flight time < 5 μs.
- Temperature raise can be reduced by optimizing position of the sample collector in relation to the flow around the forebody aeroshell.





Optimization of collector location by means of CFD

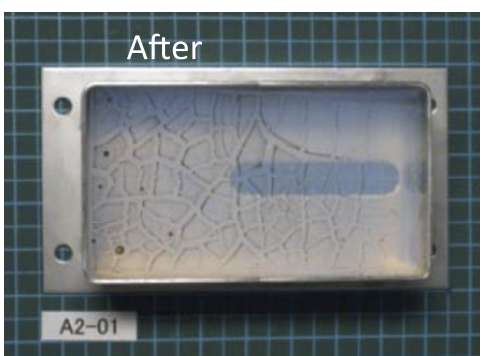


Assessment of Aerogel Damages

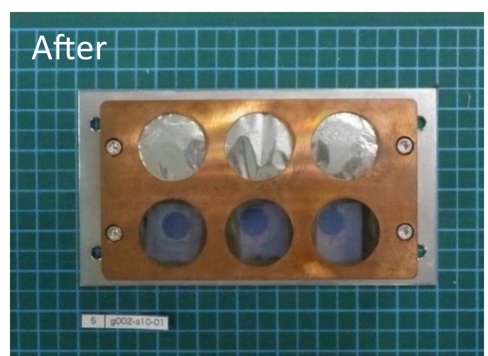
Arcjet heating test campaign

- 1st circular : aerogel surface was vitrified to the depth of several μm & charred materials were formed on the surface by oxidation of hydrophobizing agents
- 2nd circular : an aerogel cell to shore up structural strength as well as to reduce heat transfer rate was successfully demonstrated with non-hydrophobic aerogel
- 3rd circular : non-silica aerogel specimens are tested to improve heat resistance

1st test campaign

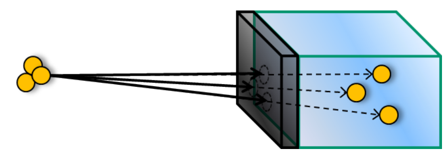


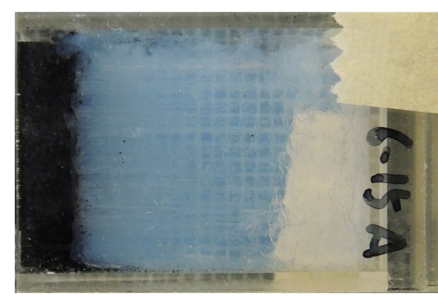
2nd test campaign



3rd test campaign

- Carbon aerogel (CA)
- CASA: CA/SA 2-layer aero-gel for higher heat-resistance





Assessment of Dust Capturing Capabilities

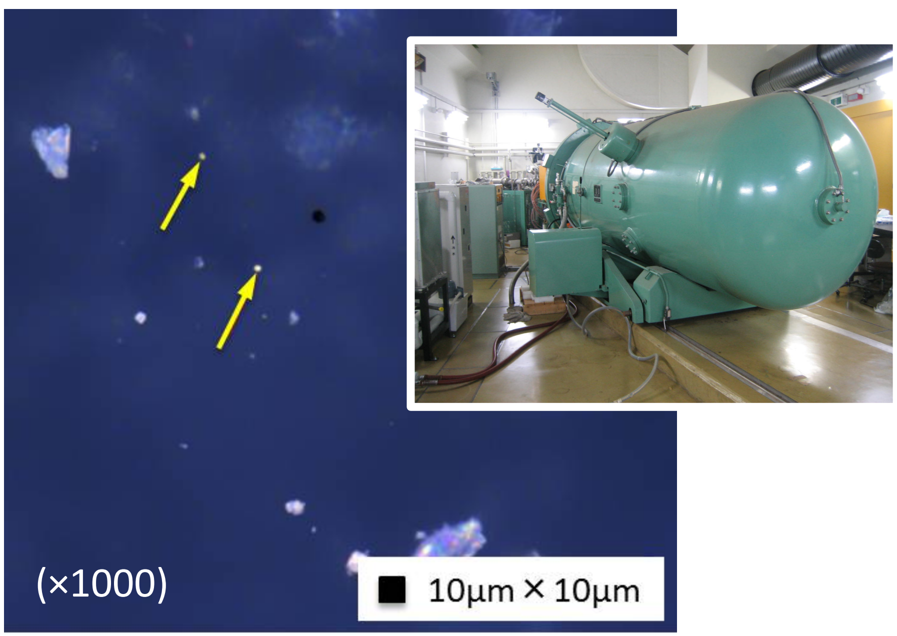
■ LGG dust capture tests (at Space Plasma Lab., ISAS)

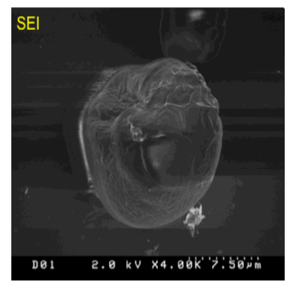
- Alumina/montmorillonite particles of 10-30 μm in diameter were successfully captured by aerogel cells before/after arcjet-heating
- Scan, extraction, & SEM/EDS analysis of samples has been successfully demonstrated

■ VdG dust capture tests (at HIT)

- Argental particles of 1 μm in diameter were successfully captured by aerogel cells both before/after arcjet-heating.

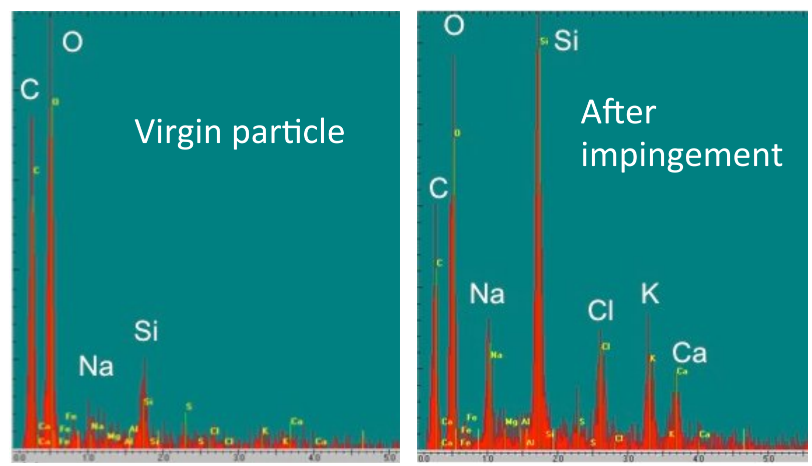
VdG dust capture tests





SEM/EDS Analysis (montmorillonite, 10 μm)

Particle surface is seen to somehow contaminated by melted aerogel.

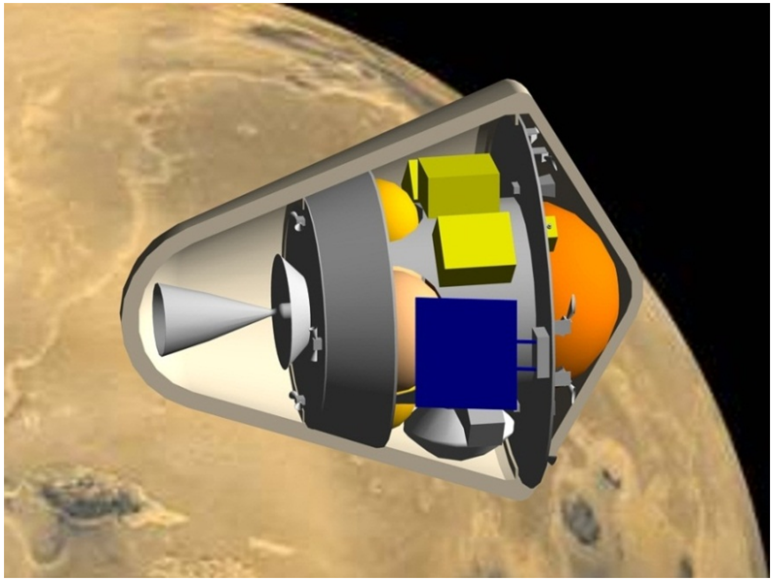


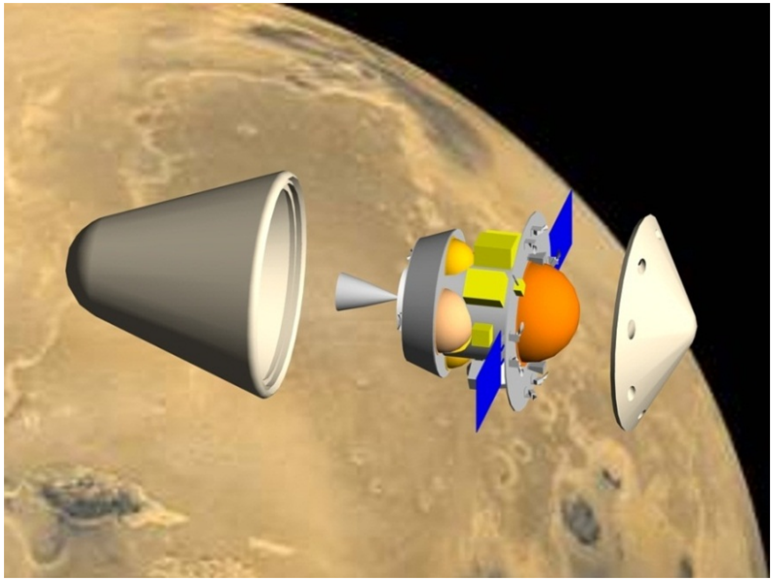
System Configuration

Conceptual system design

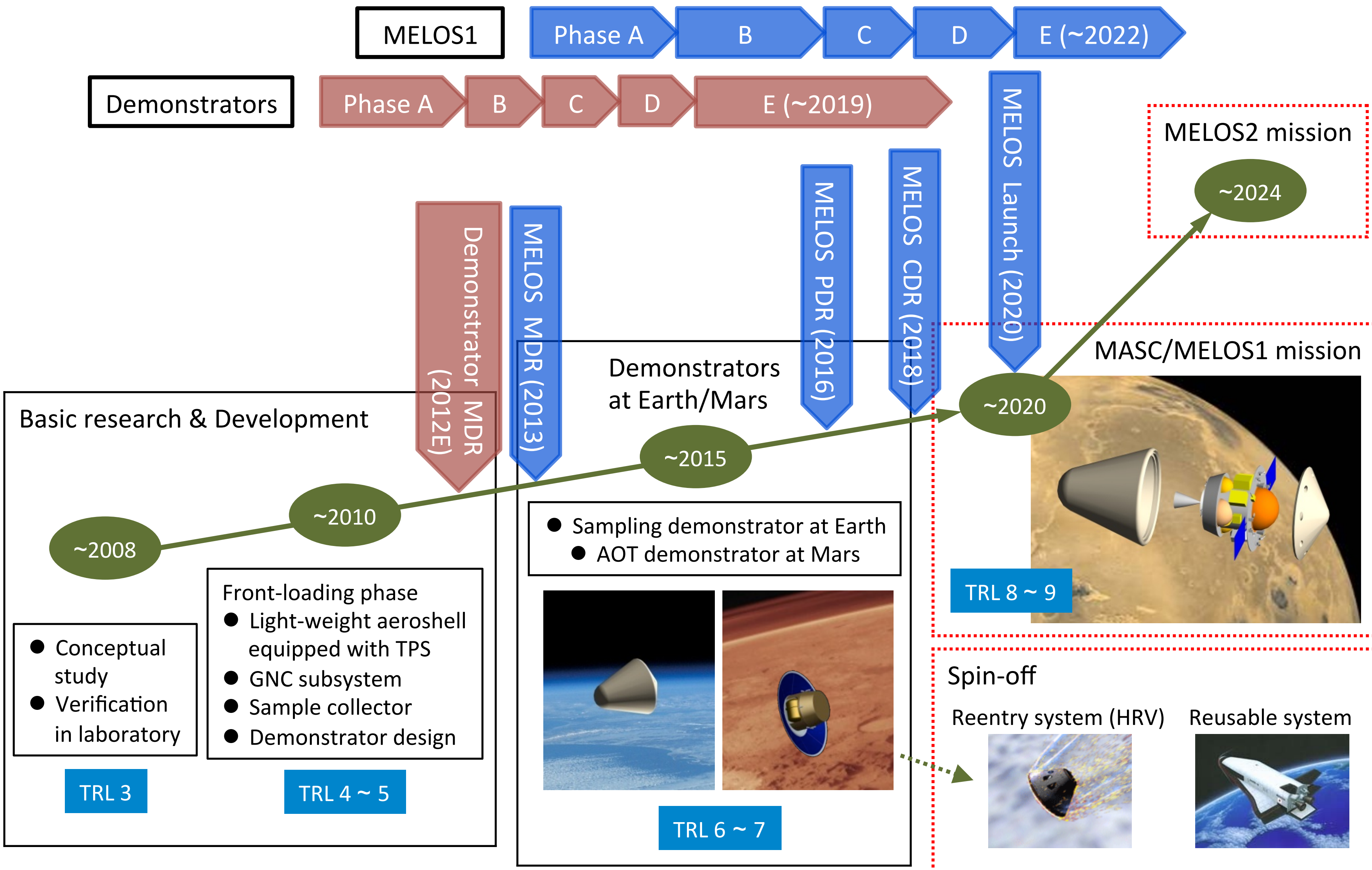
- Conducted based on the latest status of subsystem development, and on heritages of HAYABUSA sample return system
- Further reduction of system mass may be realized by introducing new instruments

Total mass	593			
Orbit insertion subsystem		175		
Aeroshell			133	
RCS (dry)			15	
Hydrazine (fuel)			15	
MON-3 (oxidizer)			12	
Orbiter subsystem		358		
OME propellant for departure			190	
Hydrazine (fuel)				105
MON-3 (oxidizer)				85
Earth return subsystem			168	
OME (dry)				48
Hydrazine (fuel)				15
Structure				35
Sampler				10
Electronics				44
Earth reentry capsule				16
Margin		60		





Development Plan (if applied to MELOS1)



Conclusion

- Mars Aeroflyby Sample Collection (MASC) using AOT technologies is proposed as a part of MELOS mission
- Feasibility study of MASC has been conducted
  - The trajectory calculations have shown that a wide AOT corridor acceptable for the state-of-the-art GNC technologies in planetary explorations can be achieved by use of a lifting aeroshell with L/D > 0.3.
- Preliminary R & D of the MASC subsystems are in progress
  - The integrated aeroshell with the TPS is designed to have a 7.5 kg/m^2 area density
  - Robustness of developed GNC controller has been demonstrated
  - Overall examinations of dust sampling & analyzing techniques have been conducted
  - The dust particles are expected to reach the collector across the shock layer without fatal damages
  - Silica aerogel cell is found to capture dust samples of sub-µm in diameter, regardless of heat transfer from the high-temperature gases
- MASC system is feasible with a minimum total mass of 600 kg
- MASC is also applicable to other missions, or even solely