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55^{th} FDC/41^{st} ANSS 「サブオービタルスペースプレーンの空気力学的な研究開発課題について」

Company Name	SPACE WALKER Inc. (https://space-walker.co.jp/corporate-profile)
Establishment	■ December, 25^{th}, 2017
Business Locations	■ HEAD QUARTER: Shimbashi 3-16-12 3Flr, Minato, 105-0004 Tokyo, Japan ■ SPACE TRANSPORTATION DEPT.: ・ Office in TOKYO UNIVERSITY OF SCIENCE Noda Campus, Building No.3, 2^{nd} Flr (Yamazaki 2641, Noda, 278-8510 Chiba, Japan) ■ Composite Materials Technology Dept.: ・ Office in KURE INDUSTRIAL PROMOTION CENTER KURE SUPPORT CORE (Agaminami 2-10-1, Kure, 737-0004 Hiroshima, Japan) ・ Manufacturing Plant in NIHON TAISHOKU Co., Ltd (Tashiromen 198, Tabira, Hirado, 859-4812 Nagasaki, Japan)
Capital	■ 1,116 Million ¥ (including CE Stock Acquisition Rights and CB as of June 30^{th}, 2022)
Activities	■ Design, Manufacturing and Operation of Reusable Suborbital Spaceplanes ■ Manufacturing and Sales of Space Development Related Components

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55^{th} FDC/41^{st} ANSS 「サブオービタルスペースプレーンの空気力学的な研究開発課題について」

Agenda

1. Suborbital Spaceplane Development
2. Experimental Winged Rocket
3. Aerodynamic R&D Issues

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55th FDC/41st ANSS 「サブオービタルスペースプレーンの空気力学的な研究開発課題について」

1. Suborbital Spaceplane Development

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- **Development of Suborbital Spaceplane**
  - ✓ Unmanned Dual Mission for Science and Small Satellite Launch
  - ✓ Common Shape for Space Tourism Service

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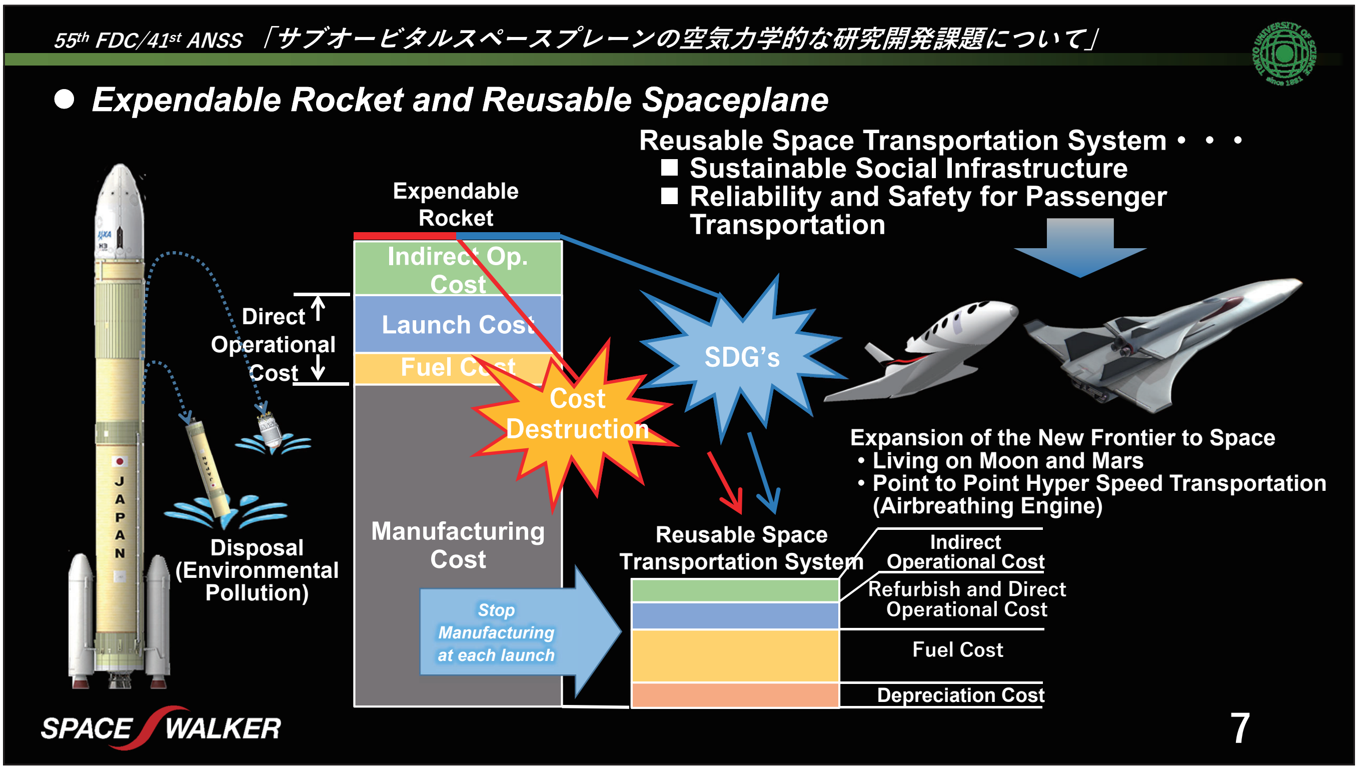

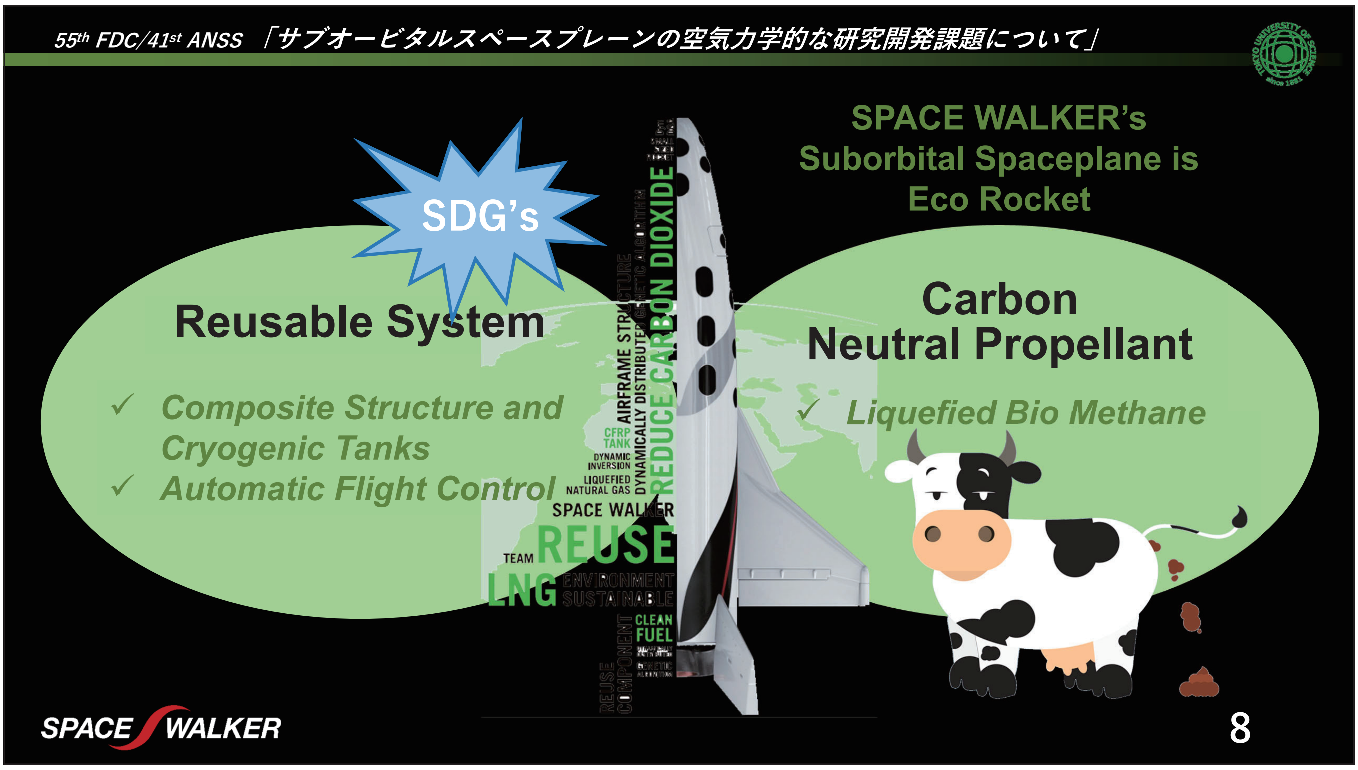

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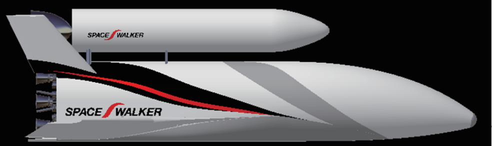
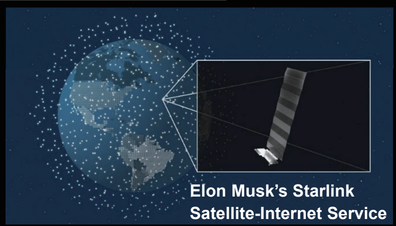
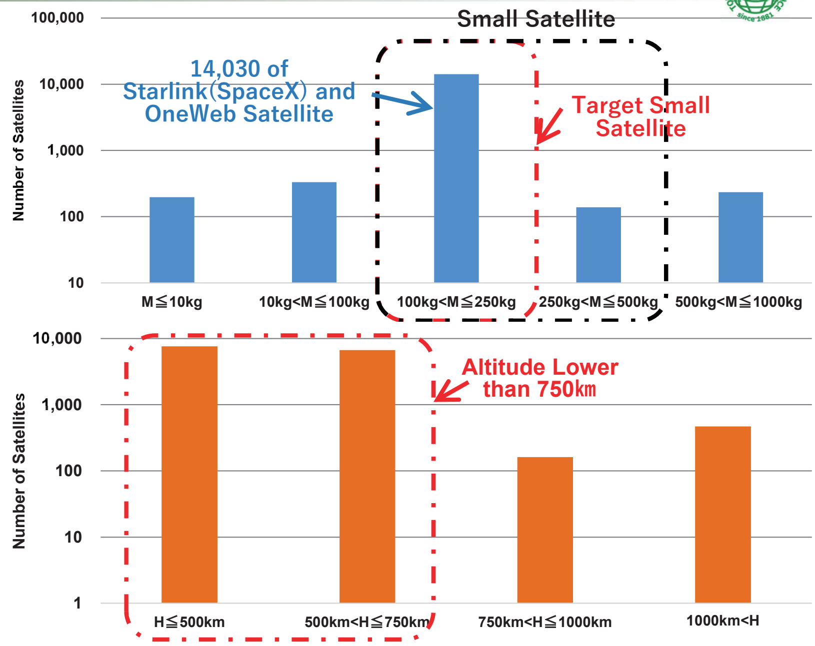
RaiJin (雷神) Mission

- Small Satellite of 200 [kg]
- Sun-synchronous Orbit of 700 [km] Altitude





https://www.wsj.com/articles/elon-musks-starlink-satellite-internet-service-battles-dish-over-airwaves-11657359181



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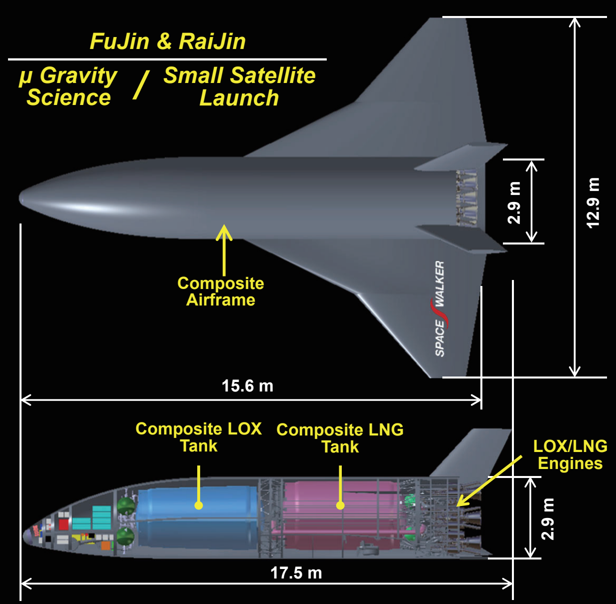

Mass [kg]		FuJin*1	RaiJin*2	NagaTomo*3
Dry			13,081	13,015
Propellant	LOX		24,687	16,844
	LNG*4		8,967	6,099
Propulsion Gas	He		4	2
	N2		95	68
RCS Gas	N2		176	176
Initial Mass			47,010	36,204
External Mass		500*5	6,999*6	-
Total Initial Mass		47,510	54,009	36,204
No. of Engines			7	5

Note: *1 100kg Payload to 150km Altitude
*2 200kg Satellite into Sun-synchronous Orbit of 700km Altitude
*3 6 Passengers with 2 Pilots/Crews
*4 Carbon Neutral Bio-methane Propellant
*5 Payload and External Carrier
*6 Expendable Upper Stage

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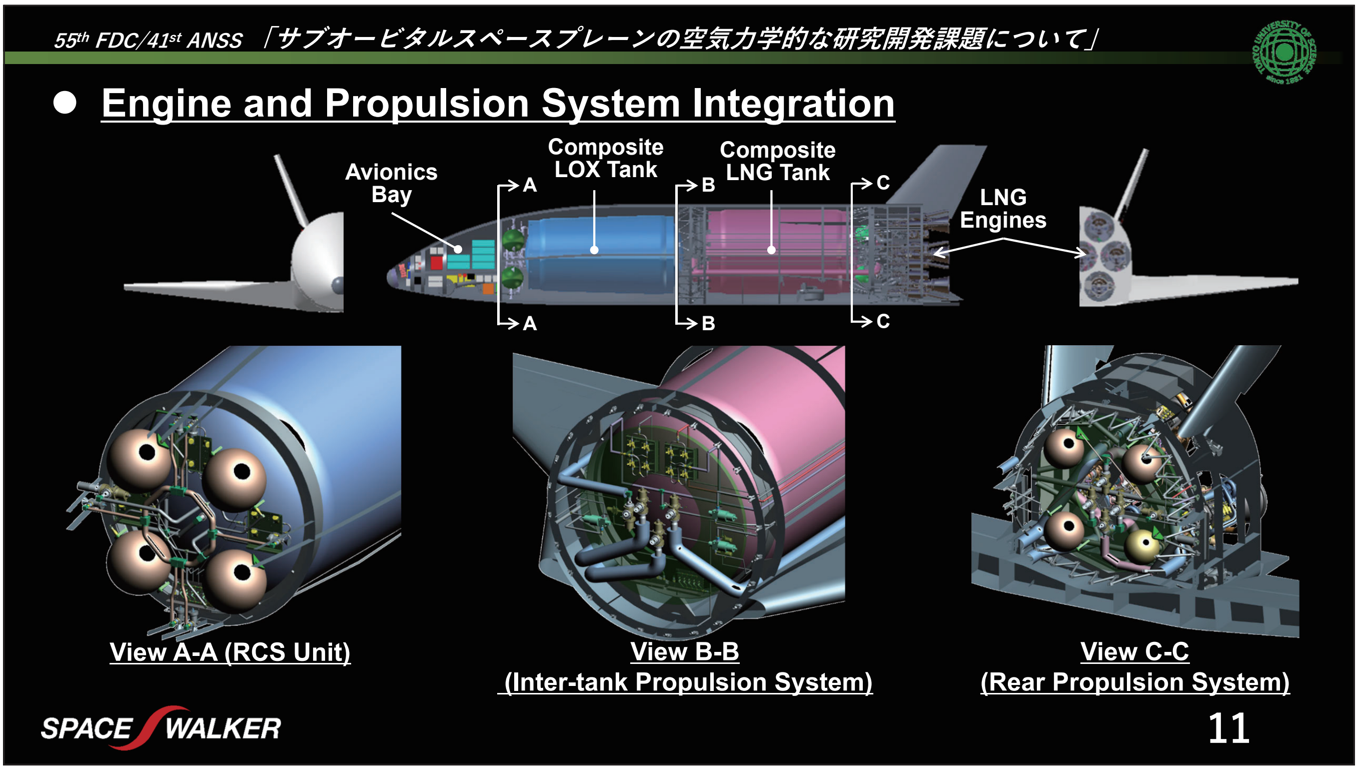

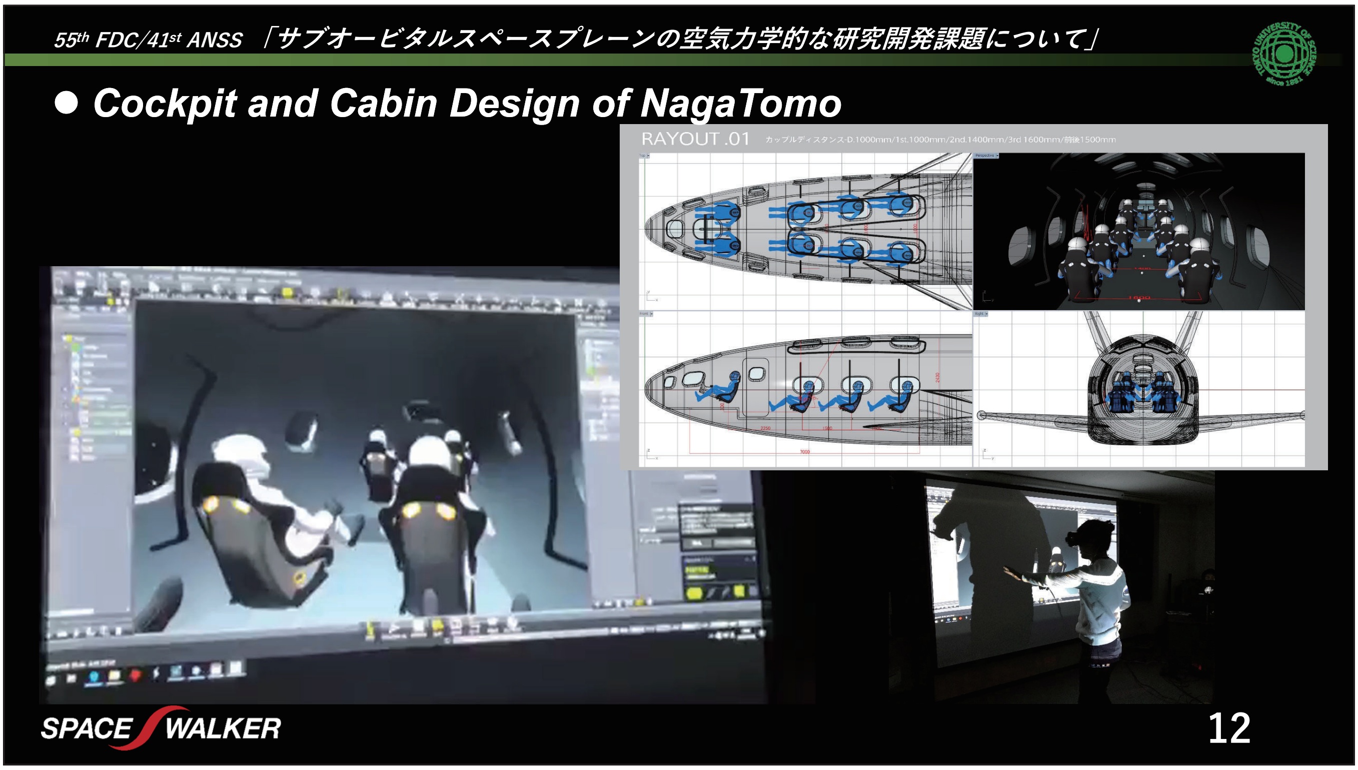

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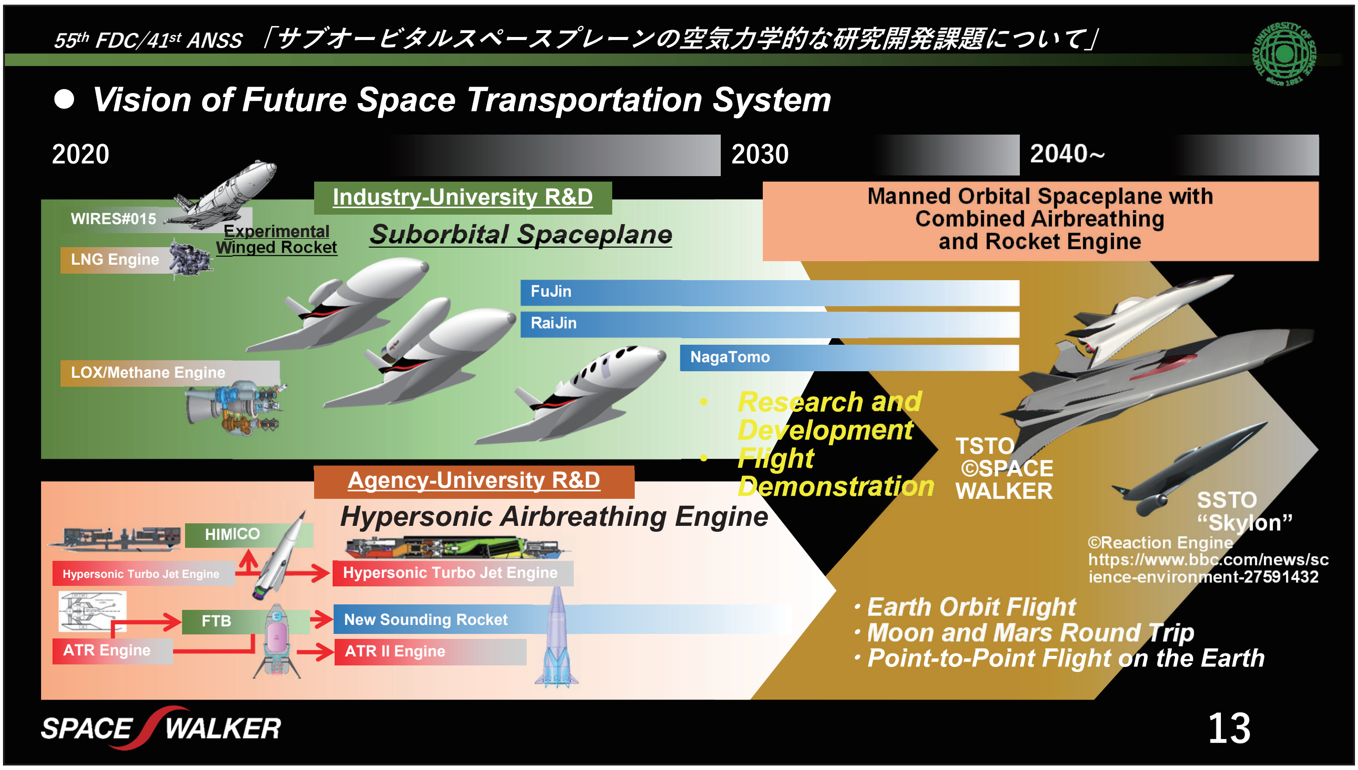

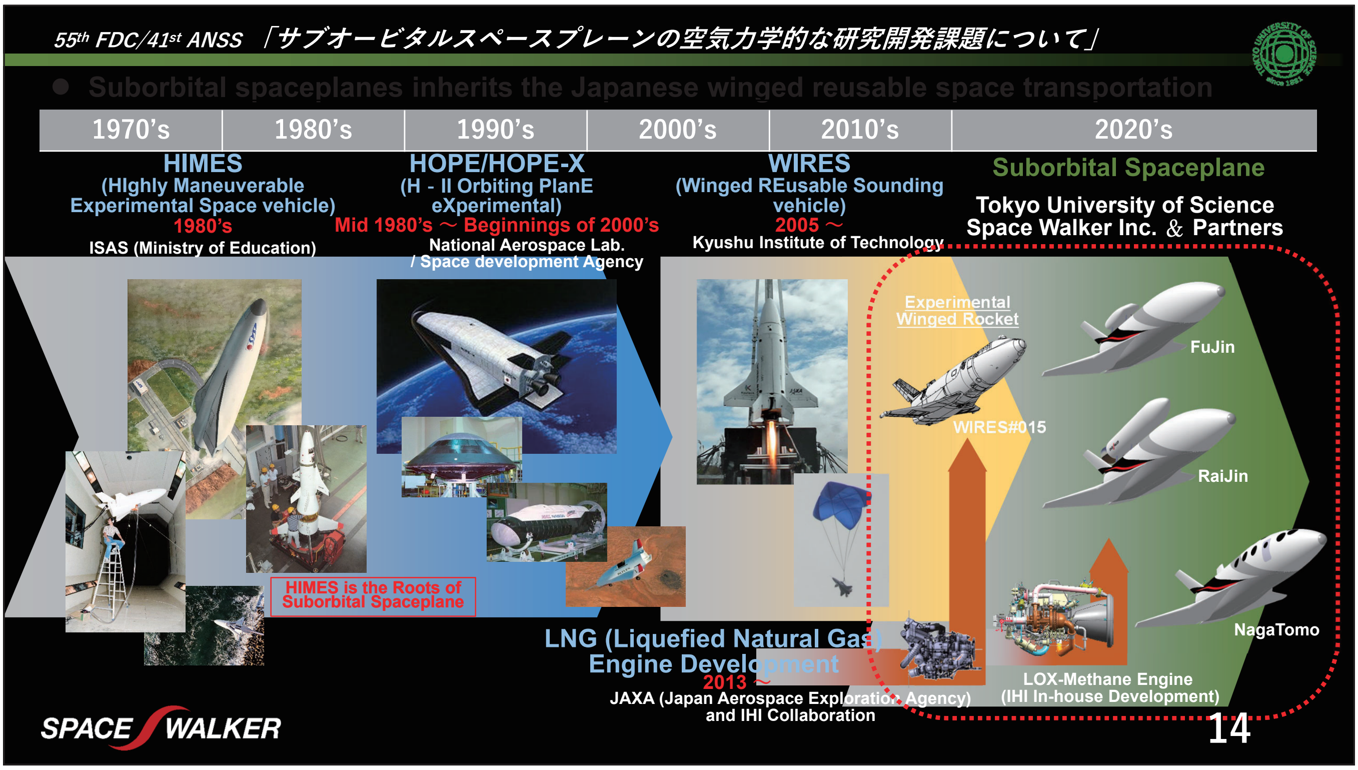

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55th FDC/41st ANSS 「サブオービタルスペースプレーンの空気力学的な研究開発課題について」

● Technology Issues and Challenges

	Technology	Issues	Partner’s Responsibility
1	Integration	・Airframe/System Integration & GSE’s, Operation	SPACE WALKER
2	System Design*	・System Optimization Methodologies (Vehicle/Propulsion System/Trajectory)	Tokyo University of Science, SPACE WALKER
3	Fault Tolerance System	・Manned/Unmanned Fault Tolerant System (NGC, Structure, Engine-Propulsion System, Mechanical & Electrical Equipment, Communication System)	SPACE WALKER, Kawasaki Powering your potential, IHI Realize your dreams, inet, TORAY Toray Carbon Magic, AIR WATER, JAXA
4	LOX/LNG Engine*	・Reusability (Reliability, Health Monitoring, Thrust Augmentation, Reignition), ・Clean Propellant	IHI Realize your dreams, AIR WATER
5	Autonomous Flight System*	・Failure Tolerant Navigation System ・Real-time Optimal Trajectory Generation and Guidance ・Adaptive Attitude Control Theory	Tokyo University of Science, Kawasaki Powering your potential
6	Composite Airframe & Propellant Tanks*	・Complex Airframe Composite Molding ・LOX Compatible Composite Tank (CFRTP-PC) ・Super-pressure Composite Gas Tanks	Kawasaki Powering your potential, TORAY Toray Carbon Magic, SPACE WALKER, Tokyo University of Science
7	Legalization	・Public-private council led by Cabinet Office/ Ministry of Land, Infrastructure, Transport and Tourism	SPACE WALKER, JAXA

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● Legalization

■ Commercial Manned Suborbital Space Transportation Research Group

（2018 Nov. – 2019 Mar.）

Organizer : SPACE WALKER, PD Aerospace
Secretariat : Japan Space Forum
Chair Person : Ms Naoko YAMASAKI (Former Female Astronaut)
Issues :
- Current overseas and domestic Development status of reusable space transportation
- Legal issues and legislation process

■ Political Survey Committee on Space and Ocean Development (Liberal Democratic Party, Special Committee)

Fifth Recommendation
(Issued on 2019, May 14)
"2.2 Expansion of space utilization in industry and science"

<Summary>
- In order to promote commercial sub-orbital flight, a public-private council is organized by the Cabinet Office, Ministry of Land, Infrastructure, Transport and Tourism, JAXA and other related ministries and agencies

■ Public-private council for
■ Commercial Suborbital Flight Legalization

- 2019, June 26 ： The 1st Committee Meeting
- 2020, May 28 ： The 1st WG Meeting on Future Issues
- 2021, July 14 ： The 2nd Committee Meeting
- 2021, May 27 ： The 2nd WG Meeting on Future Issues
- 2021, September 1 ： The 3rd Committee Meeting
- 2022, December 7 ： The 4th Committee Meeting

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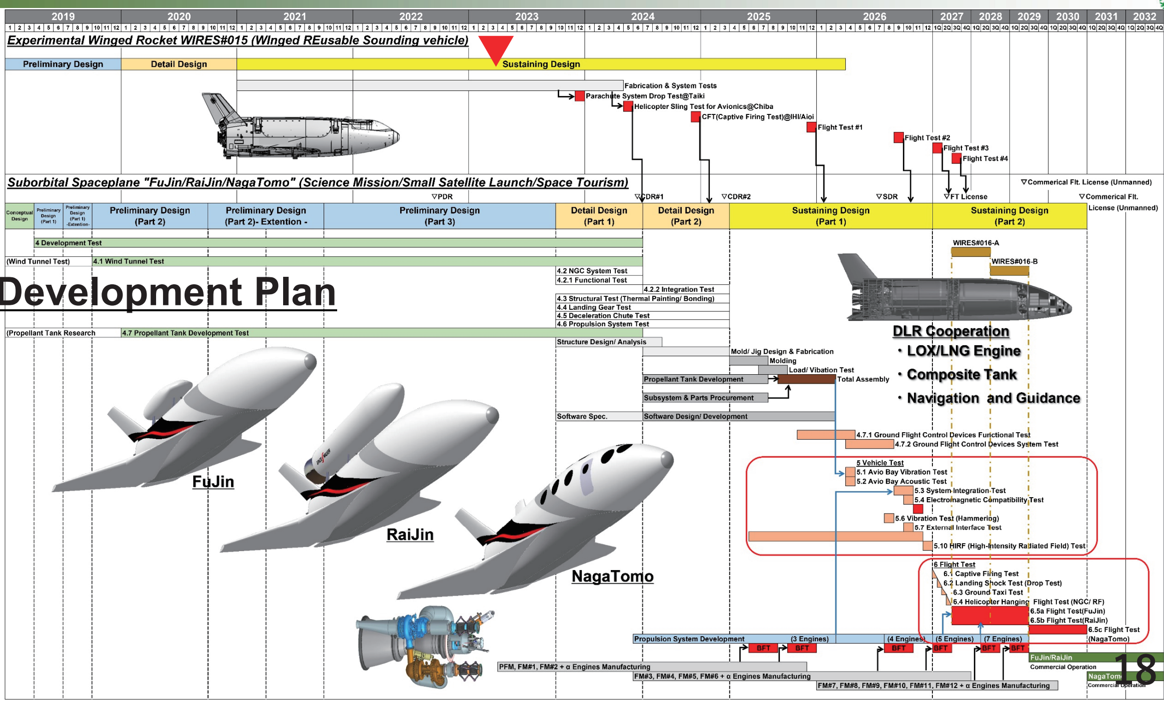
● Development Plan



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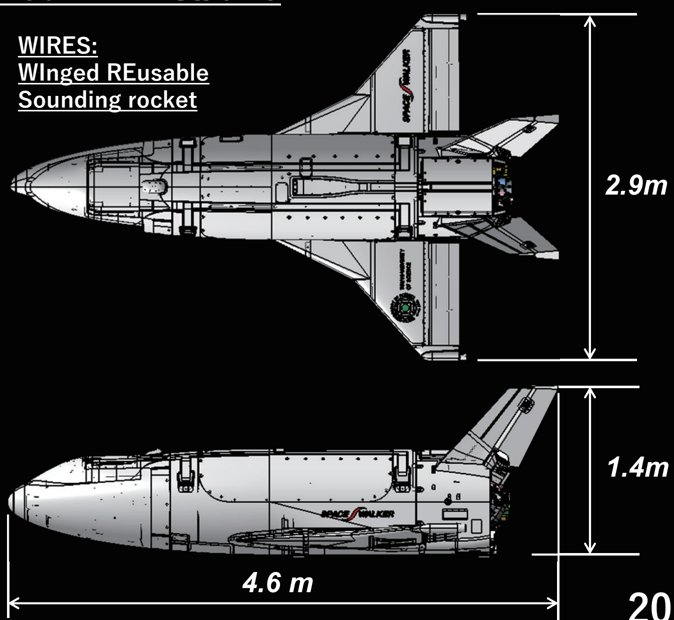
2. Experimental Winged Rocket

● Experimental Winged Rocket WIRES#015

Major Dimensions		
Initial Mass	1,000	[kg]
Max. Thrust	17.8	[kN]
Combustion Time	30	[s]
Max. Altitude	5.5	[km]

WIRES:
WInged REusable
Sounding rocket



Demonstration Issues
- LOX/LNG Engine (JAXA/IHI)
- Cryogenic Composite LOX and LNG Tanks
- Non-linear Attitude Control System Using DI Theory
- Real Time Guidance System Using Genetic Algorithm

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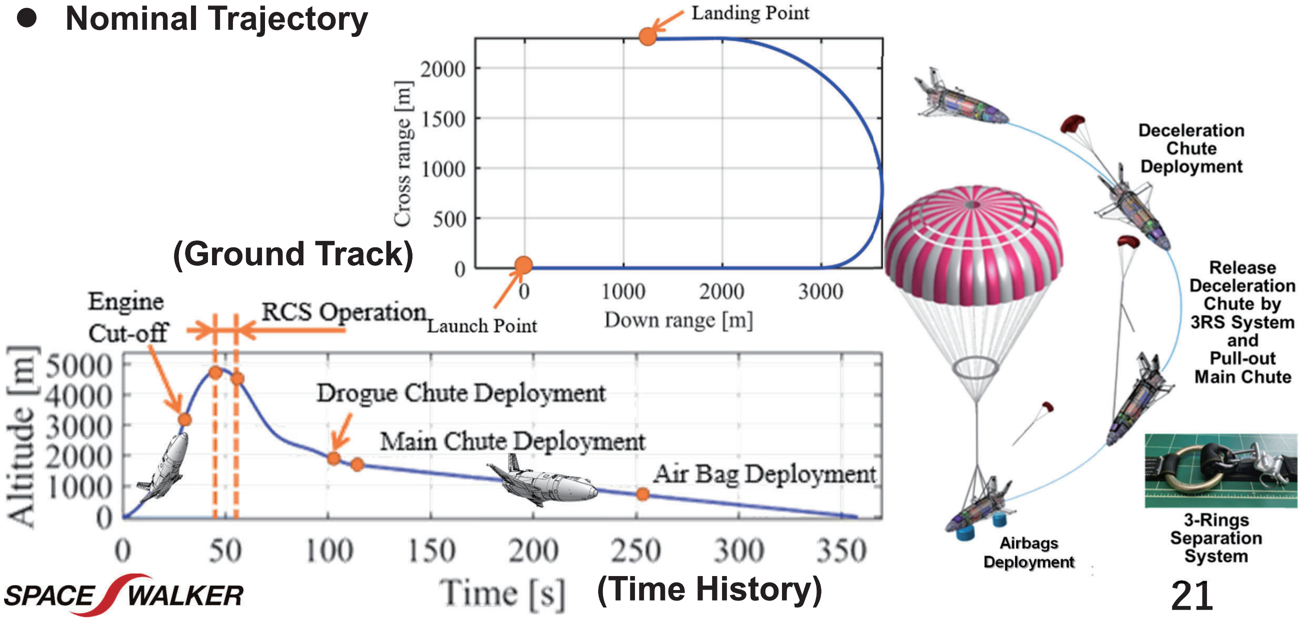
■ Experimental Winged Rocket WIRES#015 (2/6)

● Nominal Trajectory



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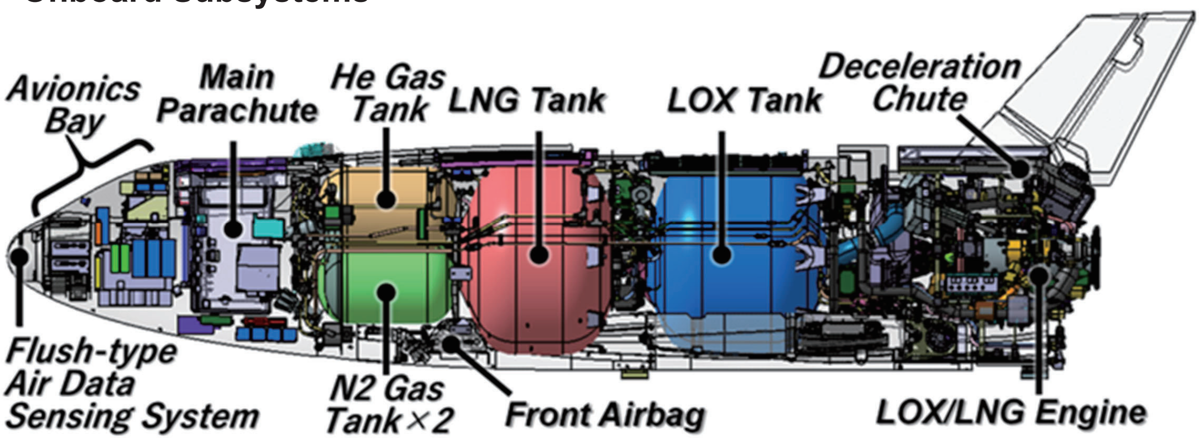
■ Experimental Winged Rocket WIRES#015 (3/6)

● Onboard Subsystems



✓ Composite Airframe and Tanks

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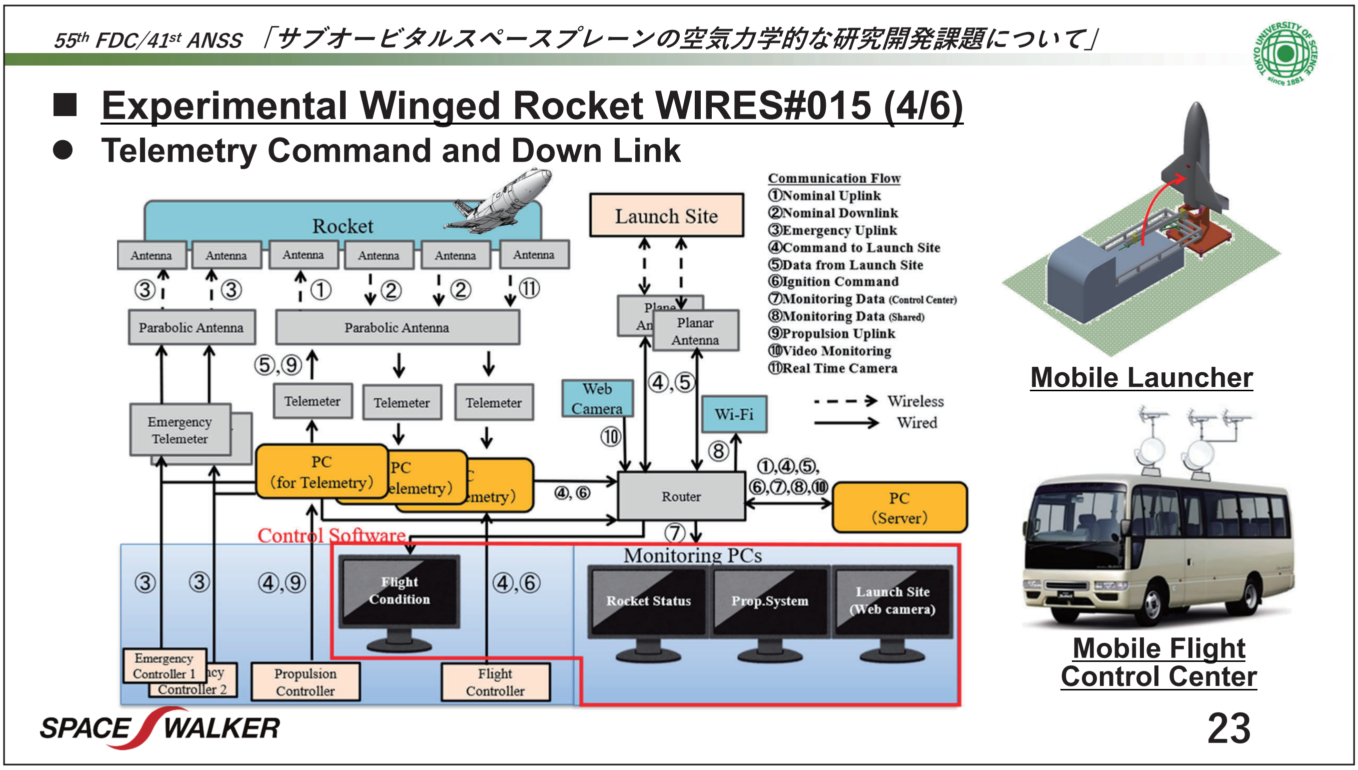
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■ Experimental Winged Rocket WIRES#015 (4/6)
● Telemetry Command and Down Link
Rocket
Antenna
Parabolic Antenna
Emergency Telemeter
Telemeter
PC (for Telemetry)
Launch Site
Planar Antenna
Web Camera
Wi-Fi
Router
PC (Server)
Control Software
Monitoring PCs
Flight Condition
Rocket Status
Prop.System
Launch Site (Web camera)
Emergency Controller 1
Emergency Controller 2
Propulsion Controller
Flight Controller
Communication Flow
①Nominal Uplink
②Nominal Downlink
③Emergency Uplink
④Command to Launch Site
⑤Data from Launch Site
⑥Ignition Command
⑦Monitoring Data (Control Center)
⑧Monitoring Data (Shared)
⑨Propulsion Uplink
⑩Video Monitoring
⑪Real Time Camera
Wireless
Wired
Mobile Launcher
Mobile Flight Control Center
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■ Experimental Winged Rocket WIRES#015 (5/6)
● Pre-flight Experiment Using Helicopter
東京理科大学 薬学部
東京理科大学 野田キャンパス 5号館
東京理科大学 野田図書館
野田市 島会館
運河散策の森
Google
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3. Aerodynamic R&D Issues

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3. Aerodynamic R&D Issues

3.1 Aerodynamic Characteristics Estimation Using CFD
3.2 Aerodynamic Interference and Separation Analysis
3.3 Highly Maneuverable Supersonic Airfoil
3.4 Multi-disciplinary Design Optimization (MDO)

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3.5 Differential-Pressure Type FADS (Flush Air Data Sensing) System with Two-stage Reference Pressure Chamber
3.6 Thermo-fluid Analysis of High Pressure Gas Tank
3.7 Release Behavior of Deceleration Chute in Wake Vortex
3.8 Landing Impact Mitigation Airbag with Multi-vent Holes

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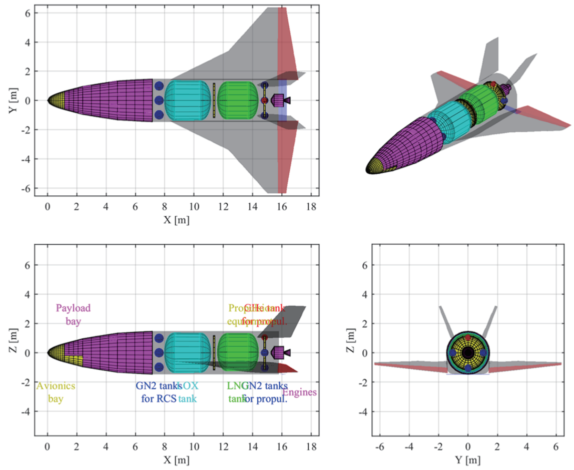
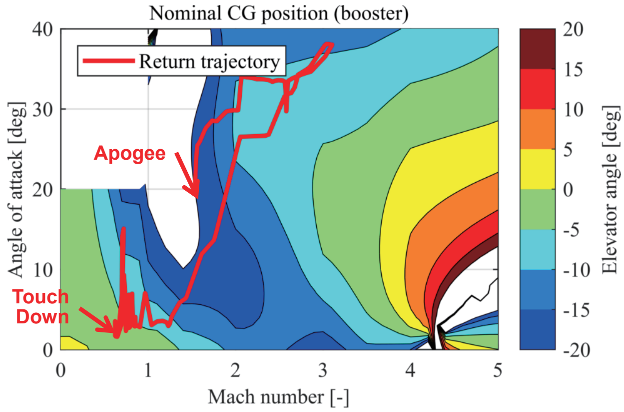
3.1 Aerodynamic Characteristics Estimation Using CFD

■ Trim Capability and Flight Profile (1/2)

Fujikawa, T., SW-R-SD-2021-001Fb 機体サイジング結果(レイアウト), Dec. 3rd, 2021.





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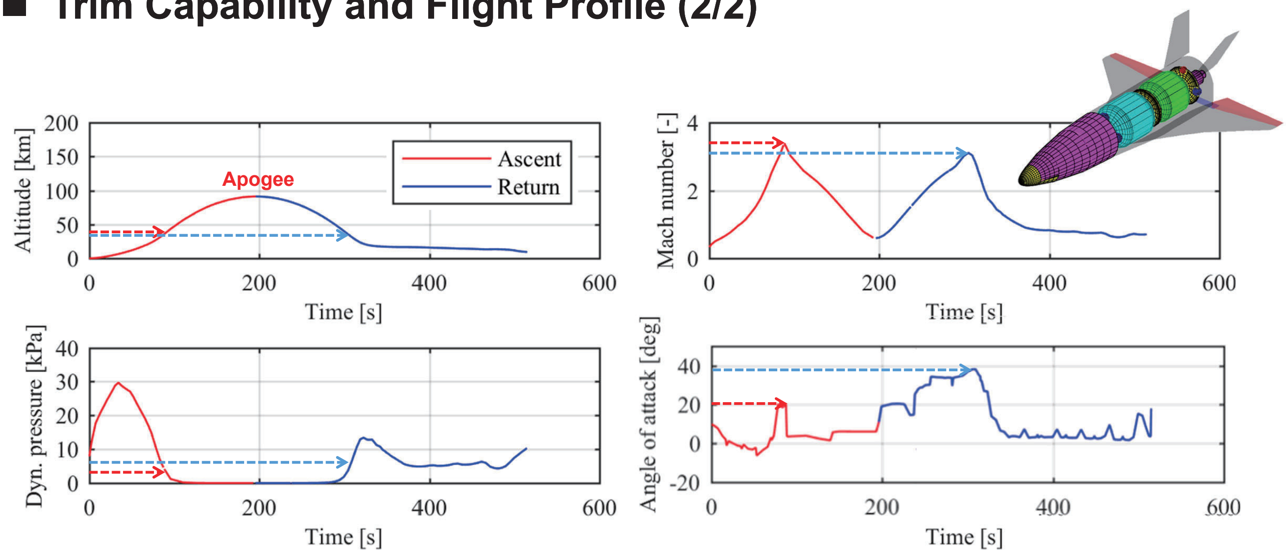
■ Trim Capability and Flight Profile (2/2)



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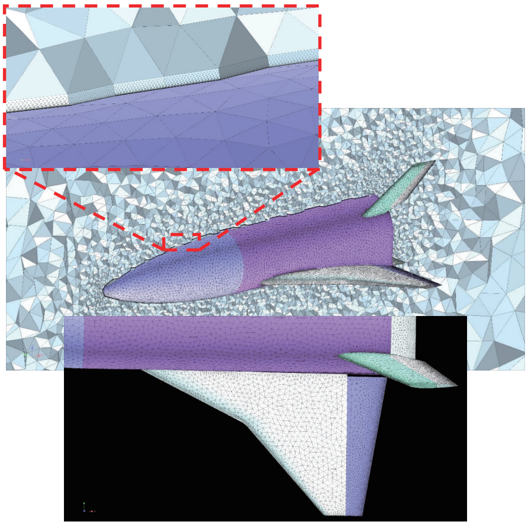
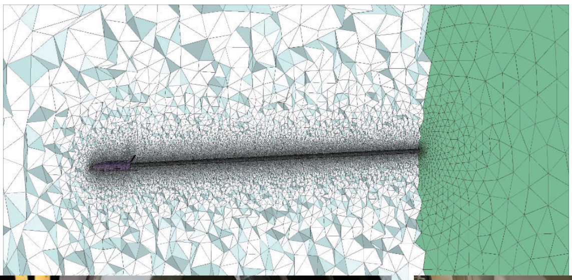
■ Comparison of WTT Results with CFD Analysis (1/6)

● WTT Model and CFD Mesh

Piran, A., et. al. “Comparison of Wind Tunnel Test Results of Suborbital Spaceplane FuJin with CFD Analysis,” IAC-22-D2.7.6, Sep. 21st, 2022.





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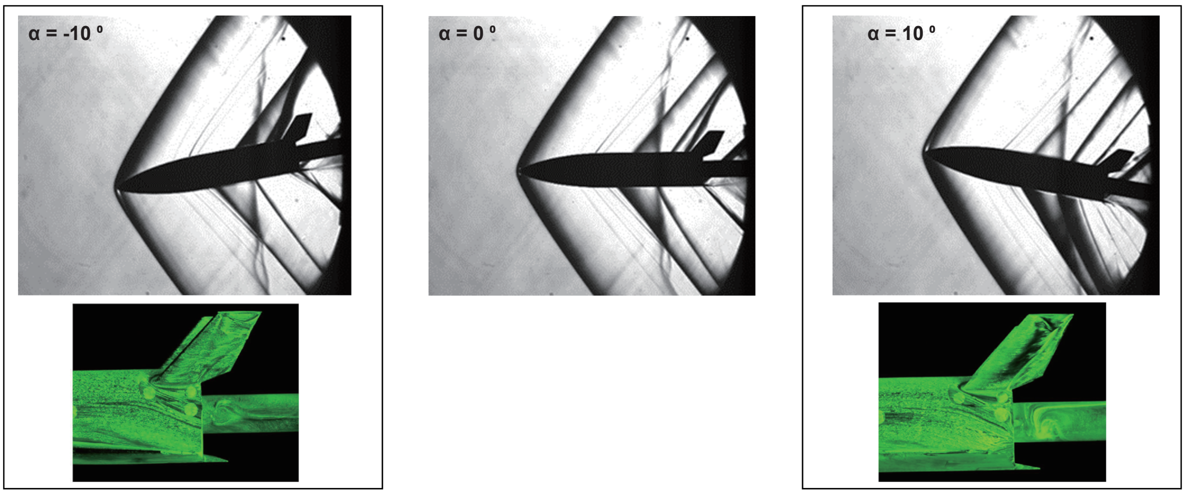
■ Comparison of WTT Results with CFD Analysis (2/6)

● WTT Flow Visualization



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■ Comparison of WTT Results with CFD Analysis (3/6)

● Flow Solver and Meshing

Flow solver : FaSTAR (unstructured CFD code)
Meshing : Mixed-Element Grid Generator in 3 Dimensions (MEGG3D)

CFD Parameters	Selection
Discretization	Cell-centered, finite volume
Accuracy	Unstructured Monotonic Upstream-Centered Scheme for Conservation laws (U-MUSCL, second order accuracy)
Time integration	Lower-Upper Symmetric Gauss-Seidel (LU-SGS)
Advection term scheme	Low-Dissipation Advection Upstream Splitting Method (SLAU, M<=1.3); Harten-Lax-van Leer-Einfeldt (HLLE, M>=1.6)
Turbulence model	SA-noft2

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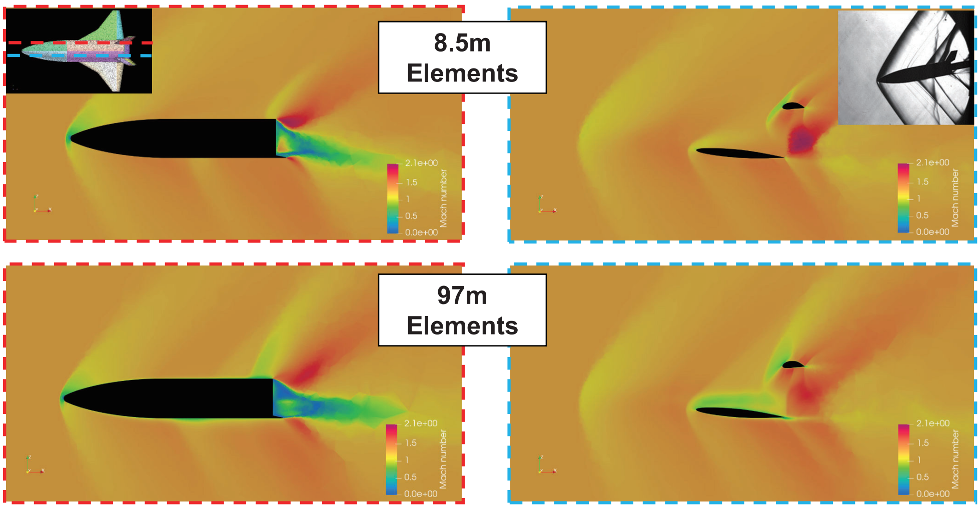
■ Comparison of WTT Results with CFD Analysis (4/6)

● CFD Flow Visualization



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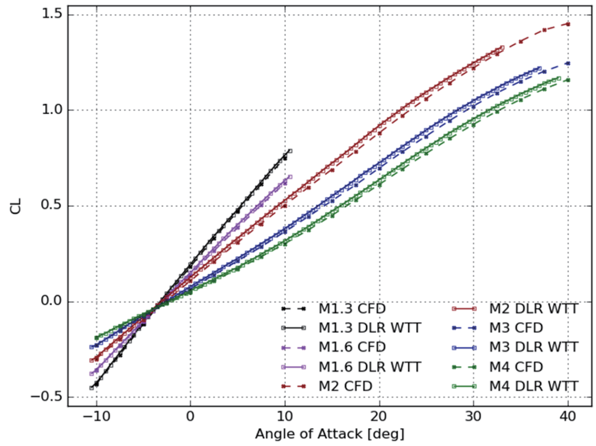
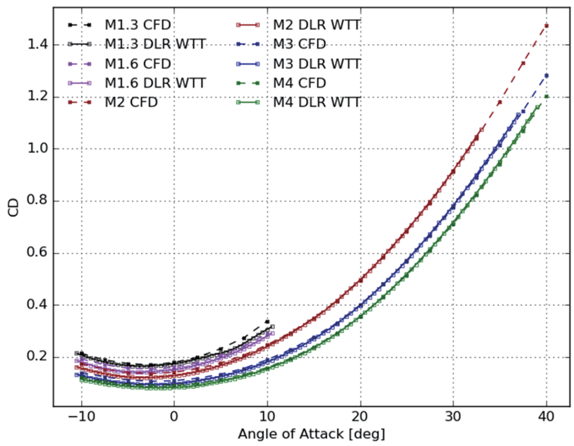
■ Comparison of WTT Results with CFD Analysis (5/6)

● Lift and Drag Characteristics



Clean



Clean

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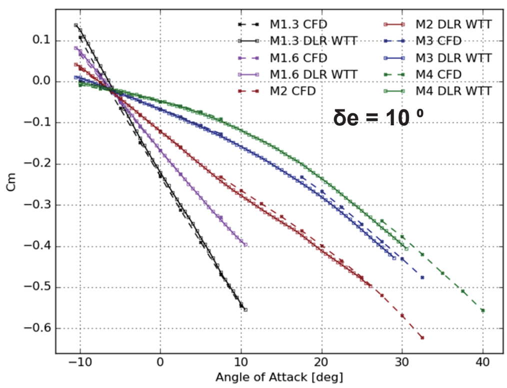
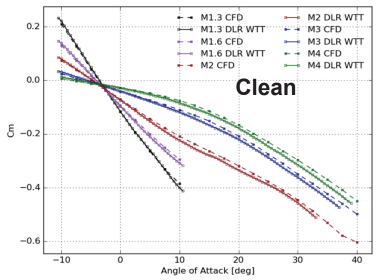
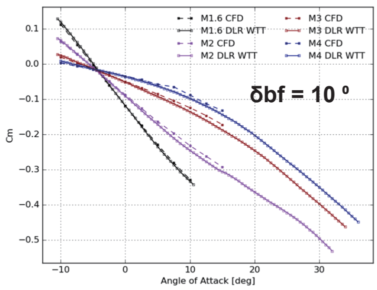
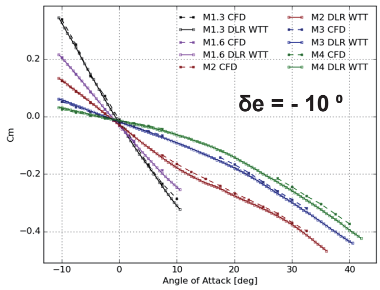
■ Comparison of WTT Results with CFD Analysis (6/6)

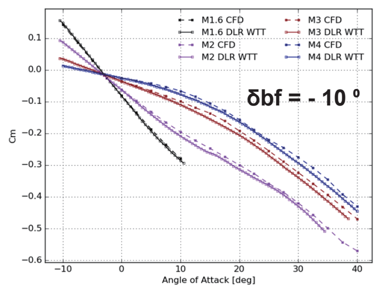
● Pitching Moment Characteristics











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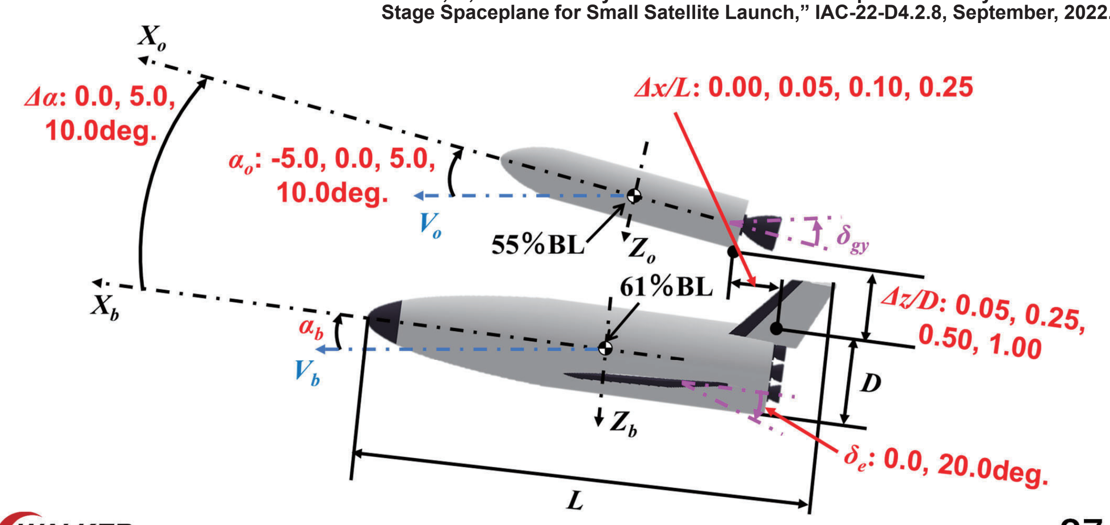
3.2 Aerodynamic Interference and Separation Analysis

■ Definition of Satellite Launch Configuration

Otsuki, T., et. al. "Aerodynamic Interference and Separation Analysis of a Two-Stage Spaceplane for Small Satellite Launch," IAC-22-D4.2.8, September, 2022.



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■ CFD Solver

Calculation method of FaSTAR

Governing equation	Compressible Navier-Stokes equation
Turbulence model	RANS Spalart–Allmaras-noft2-R
Spatial discretization method	Cell center method Harten–Lax–van Leer–Einfeld
Time integration method	Lower Upper Symmetric Gauss–Seidel Implicit method
Grid generation	HexaGRID
Calculator	JAXA Supercomputer System generations 2 and 3

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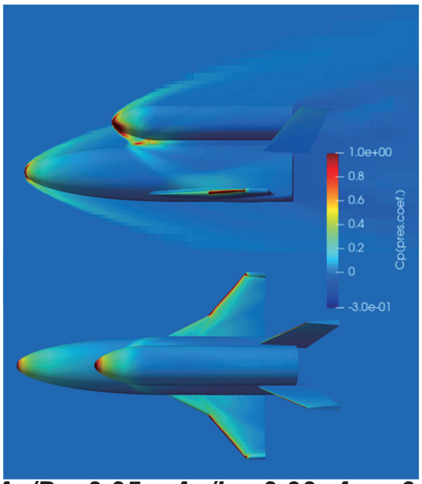
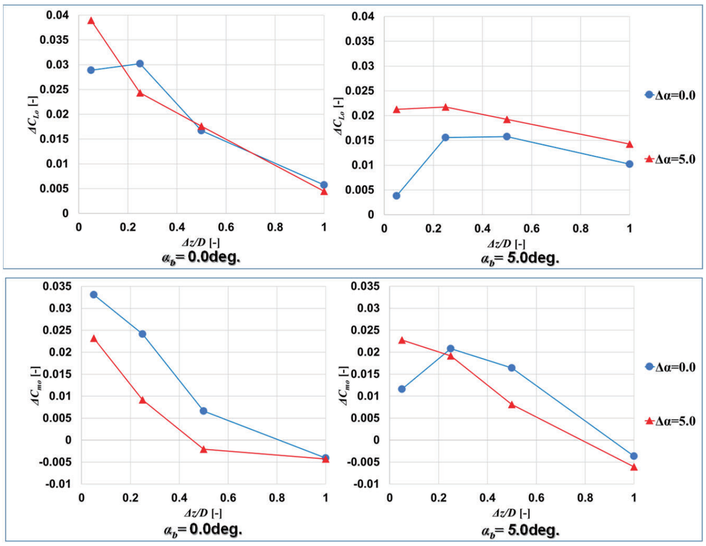
■ Pressure Distribution and Aerodynamic Characteristics



$\Delta z/D$ = 0.05, $\Delta x/L$ = 0.00, $\Delta\alpha$ = 0.0,
$\alpha_o = \alpha_b$ = 0.0, and δ_e = 0.0



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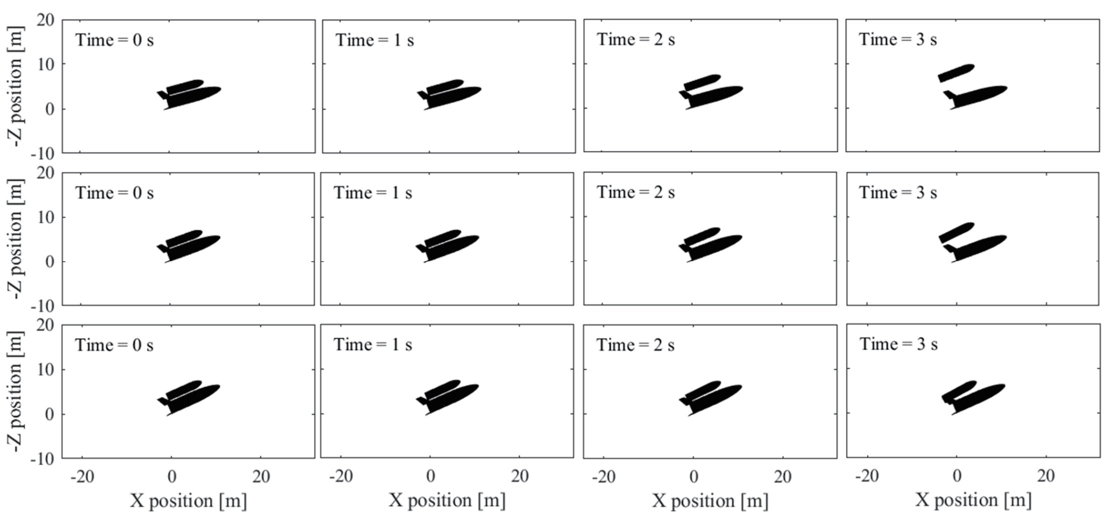
■ Longitudinal 3DoF Flight Simulation

Initial AoA 1.0deg.

Initial AoA 6.0deg.

Initial AoA 10.0deg.



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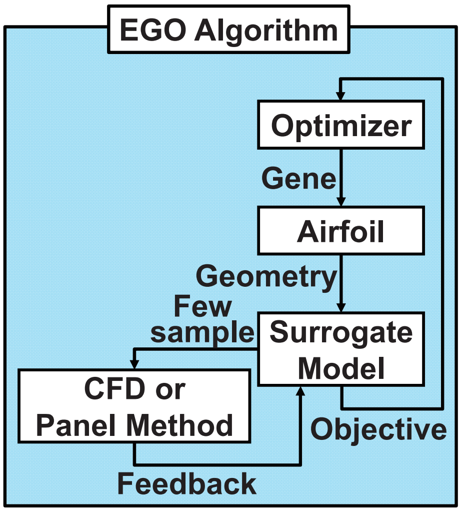
3.3 Highly Maneuverable Supersonic Airfoil

■ Multi-Objective Optimization by Multi-Fidelity EGO

Watanabe, T, et. al. "Multi-Objective Optimization of Highly Maneuverable Supersonic Airfoil Using Multi-Fidelity EGO," The 2022 Asia-Pacific International Symposium on Aerospace Technology, Oct. 12-14, 2022.

- Supersonic Airfoil Optimization by Expansion/Compression Waves Adjustment
  - ✓ A.C. (Aerodynamic Center) Forward Shifting
  - ✓ Maximizes Lift to Drag Ratio
- EGO (Efficient Global Optimization) Algorithm



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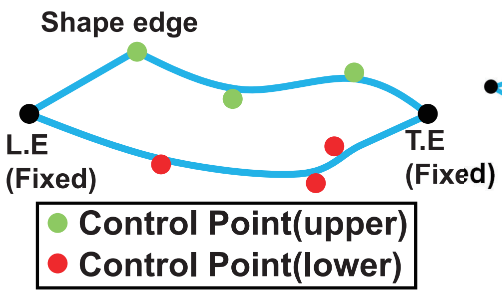
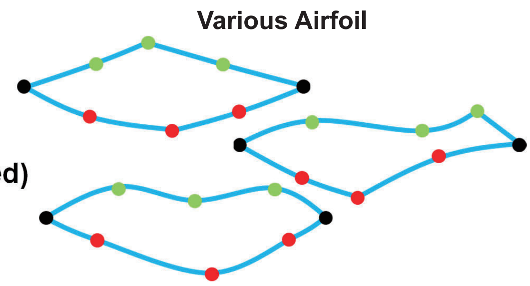
■ Definition of Airfoil





■ CFD Solver

CFD Analysis Parameter

Software	FaSTAR
Meshing	Construct 2D(O-Grid)
Governing Equation	Navier-Stokes Equation
Turbulence Model	SA-noft2
Analysis AoA	0~20 deg. 4 step

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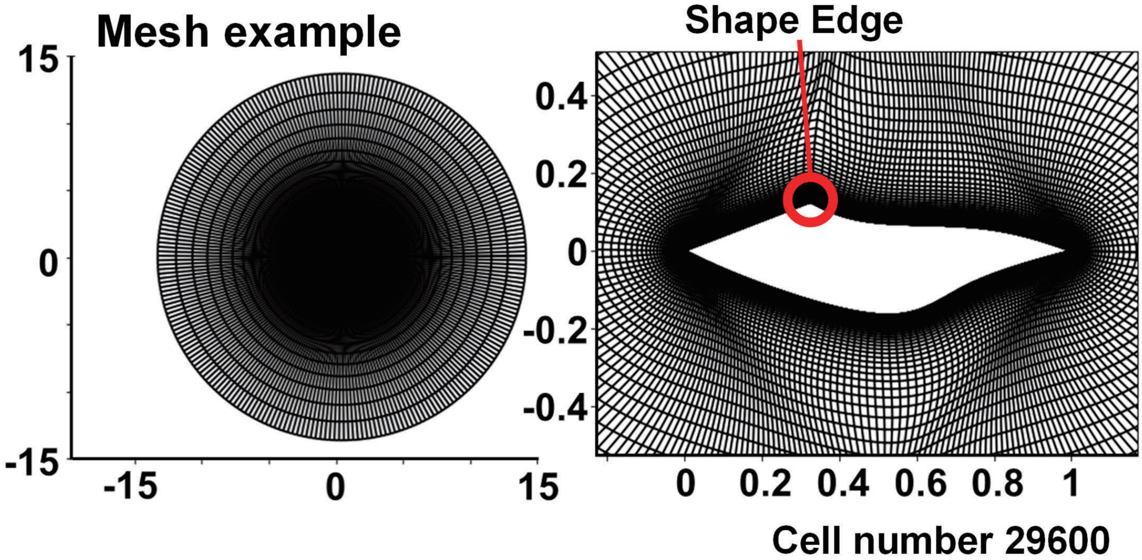
■ Optimization Results (1/x)



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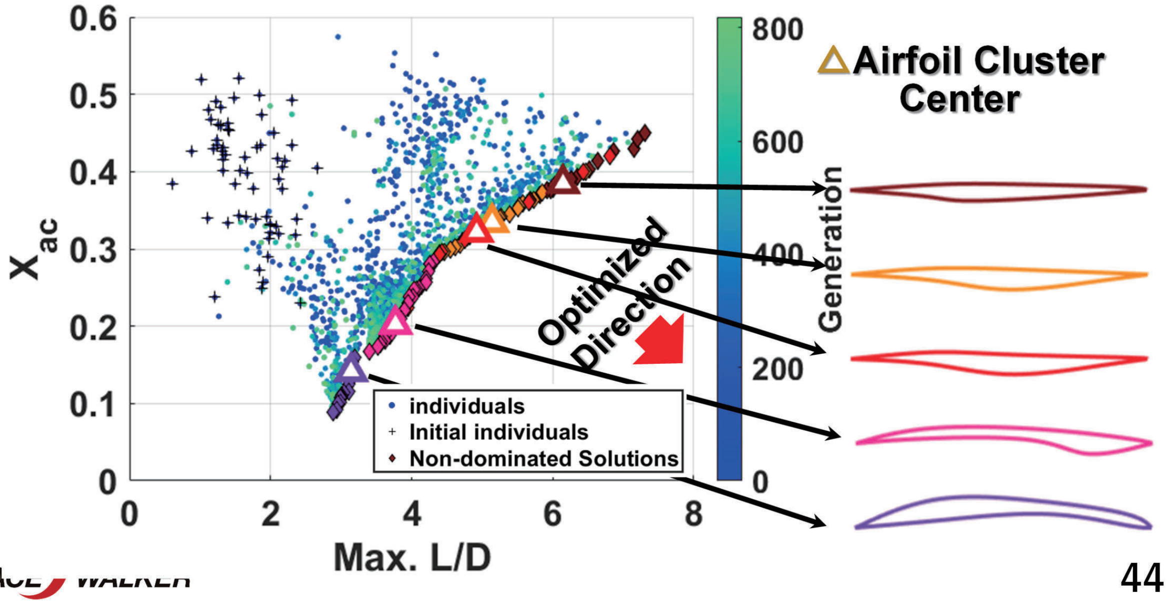
■ Optimization Results (2/3)



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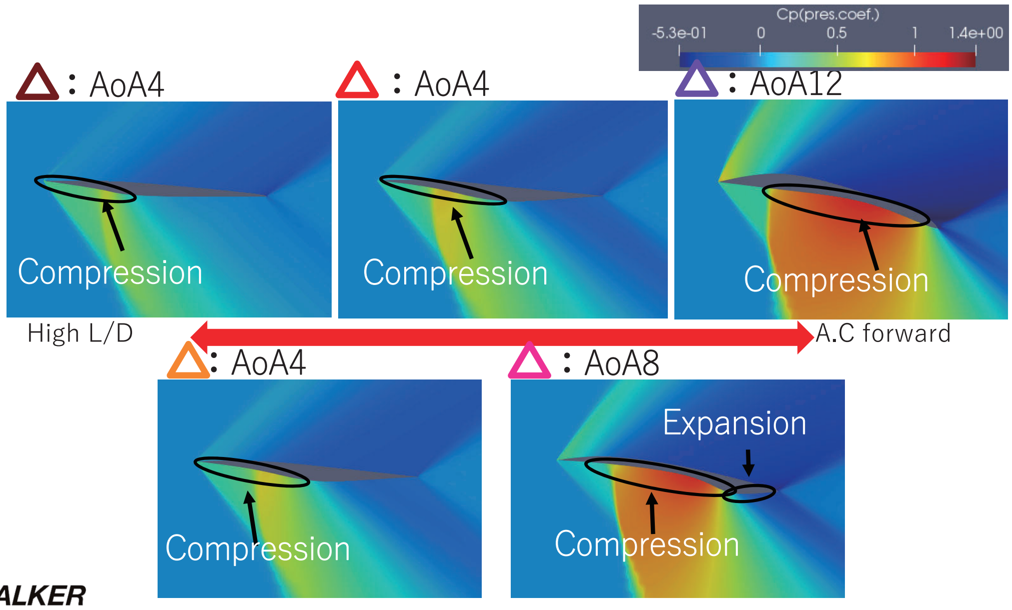
■ Optimization Results (3/3)



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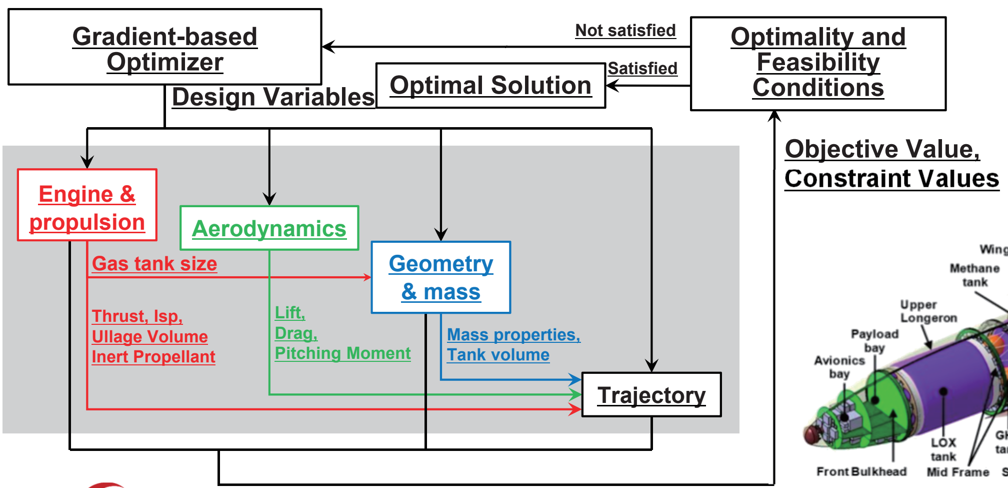
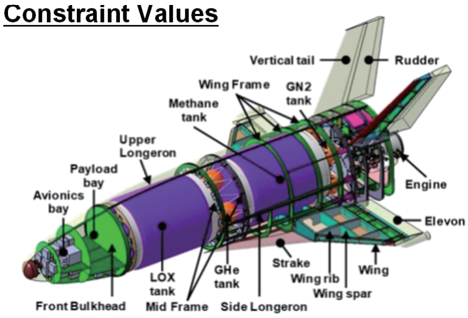
3.4 Multi-disciplinary Design Optimization (MDO)

■ Gradient-based Optimization

Fujikawa, T., et. al. "Application of Multidisciplinary Design Optimization to the Development of an Unmanned Suborbital Spaceplane by Industry-Government-Academia Collaboration," IAC-22-D2.7.9,x71209, Sep. 21st, 2022.





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■ Aerodynamic Characteristics Estimation by Multi-fidelity Method

$$C_{\mathrm{mod}}(x, M, \alpha) = C_{\mathrm{baseline}}(M, \alpha) + \tilde{C}_2(x, M)\alpha^2 + \tilde{C}_1(x, M)\alpha + \tilde{C}_0(x, M)$$

- $C_{\mathrm{mod}}(x, M, \alpha)$: Aero coefficient of modified shape or mated vehicle
- $C_{\mathrm{baseline}}(M, \alpha)$: Aero coefficient of baseline shape from wind-tunnel test
- Modification (quadratic function of α)

x : Vehicle design variables
M : Mach number
α : Angle of attack

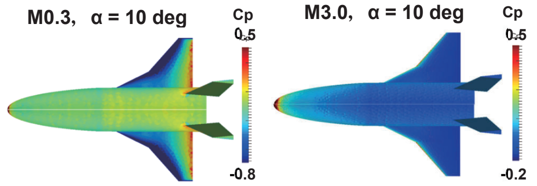
Aerodynamic analysis using panel method is applied to 300 different shapes before optimization

$\tilde{C}_2, \tilde{C}_1, \tilde{C}_0$ are constructed

Panel methods

Subsonic : Linear potential flow theory with compressibility correction

Supersonic : Modified Newtonian for windward Prandtl-Meyer expansion for leeward



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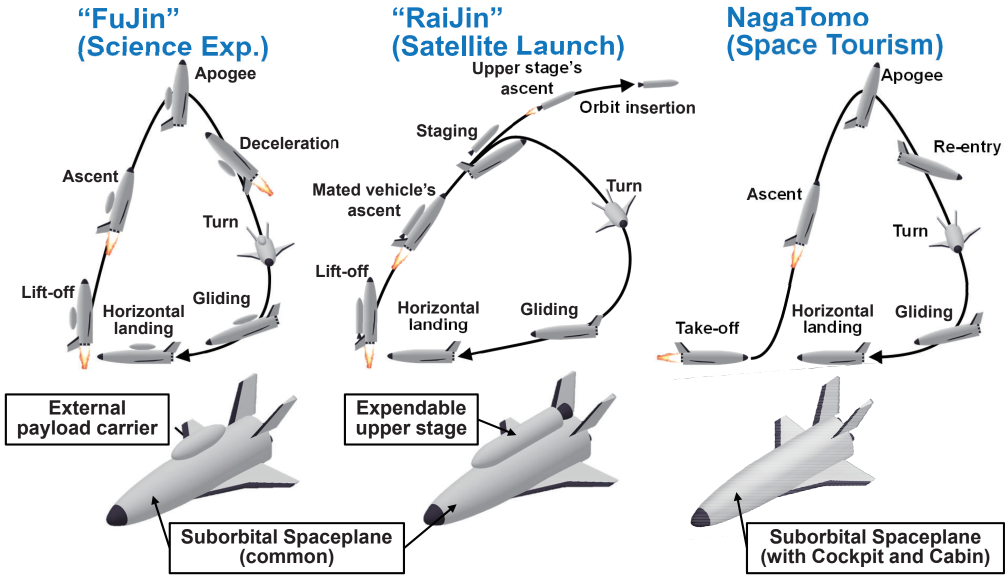
■ Mission Profiles



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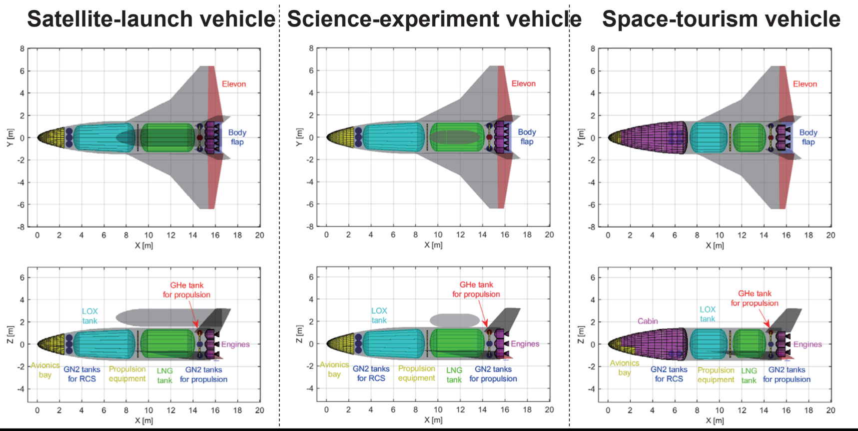
■ MDO Results



	Satellite-launch vehicle	Science-experiment vehicle	Space-tourism vehicle
Initial mass	54 t	48 t	36 t
Payload	200 kg	500 kg	Two pilots and six passengers
Orbit	SSO 700 km	Suborbital 164 km	Suborbital 115 km
No. of engines	7	7	5
Exp. ratio	13.6 (upper stage: 87.3)	13.6	13.6

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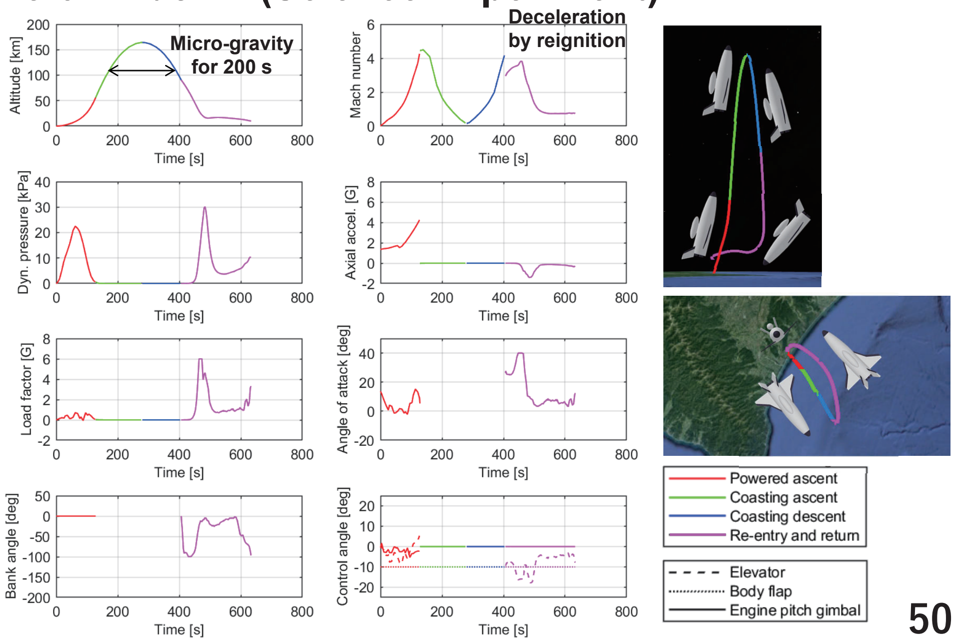
■ Flight Profile of "FuJin" (Science Experiment)



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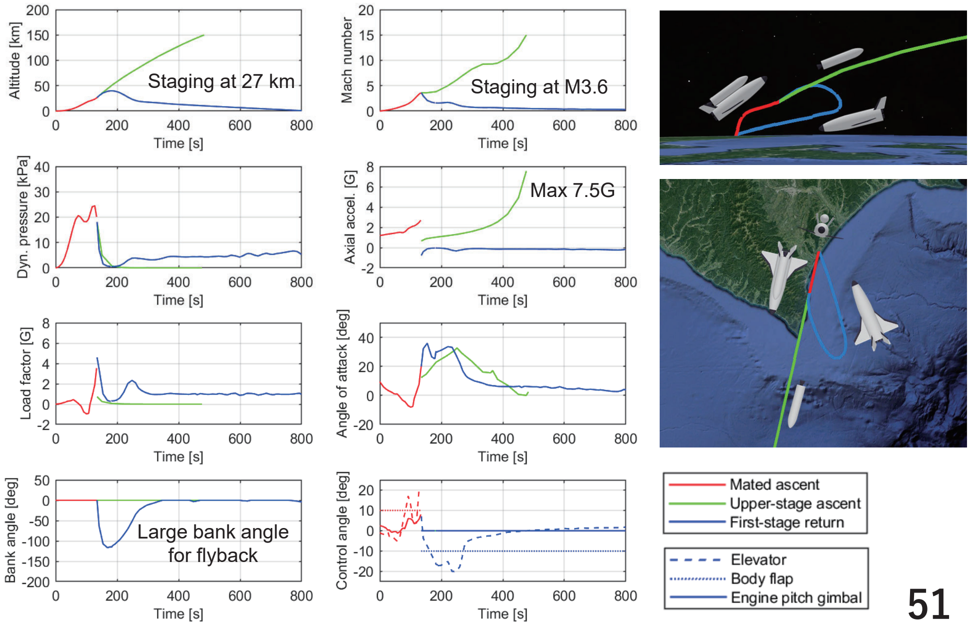
■ Flight Profile of "RaiJin" (Satellite Launch)



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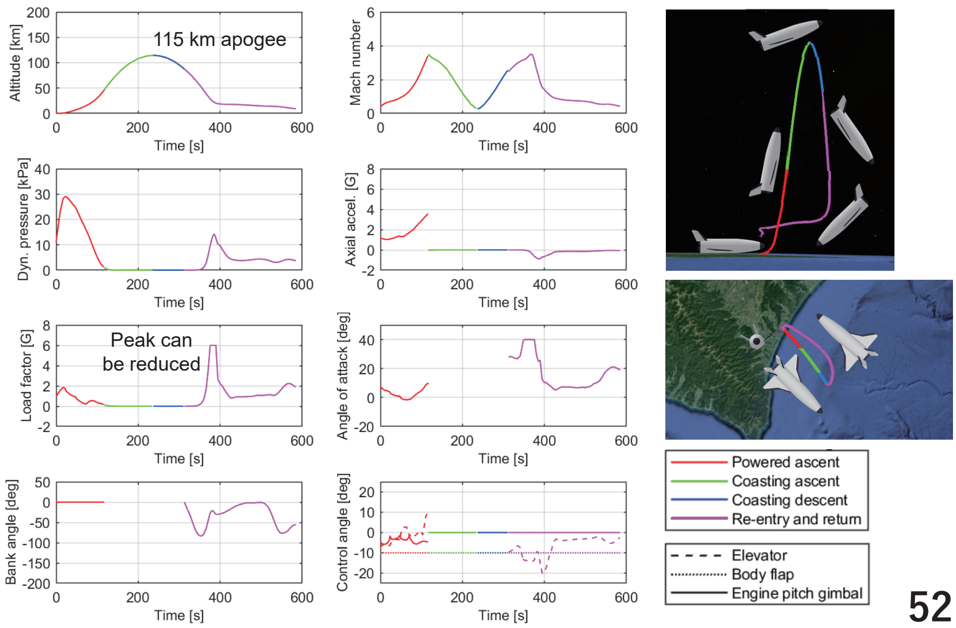
■ Flight Profile of "NagaTomo" (Space Tourism)



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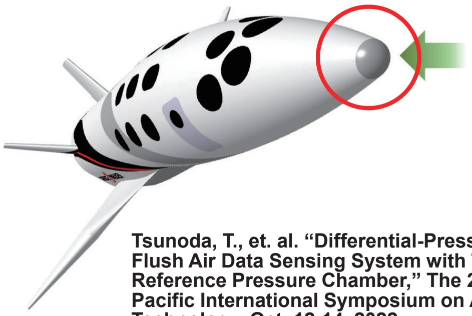
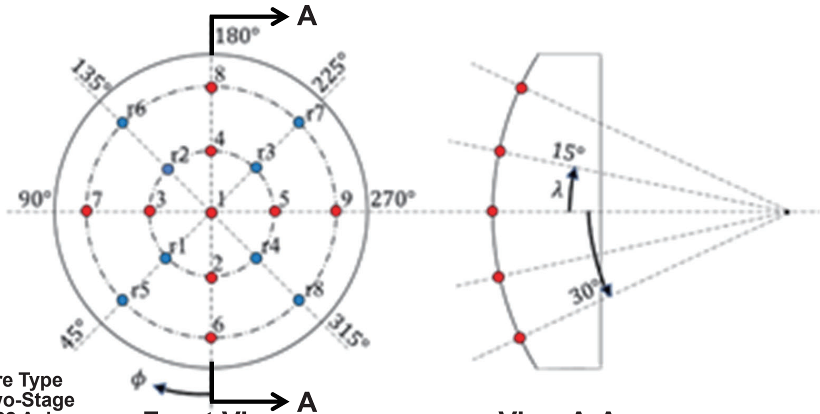
3.5 Differential-Pressure Type FADS (Flush Air Data Sensing) System with Two-stage Reference Pressure Chamber

■ Pressure Ports (1/3)





Tsunoda, T., et. al. "Differential-Pressure Type Flush Air Data Sensing System with Two-Stage Reference Pressure Chamber," The 2022 Asia-Pacific International Symposium on Aerospace Technology, Oct. 12-14, 2022.

● Air Data Pressure Ports	9 Ports
● Reference Pressure Ports	8 Ports
Total	17 Ports

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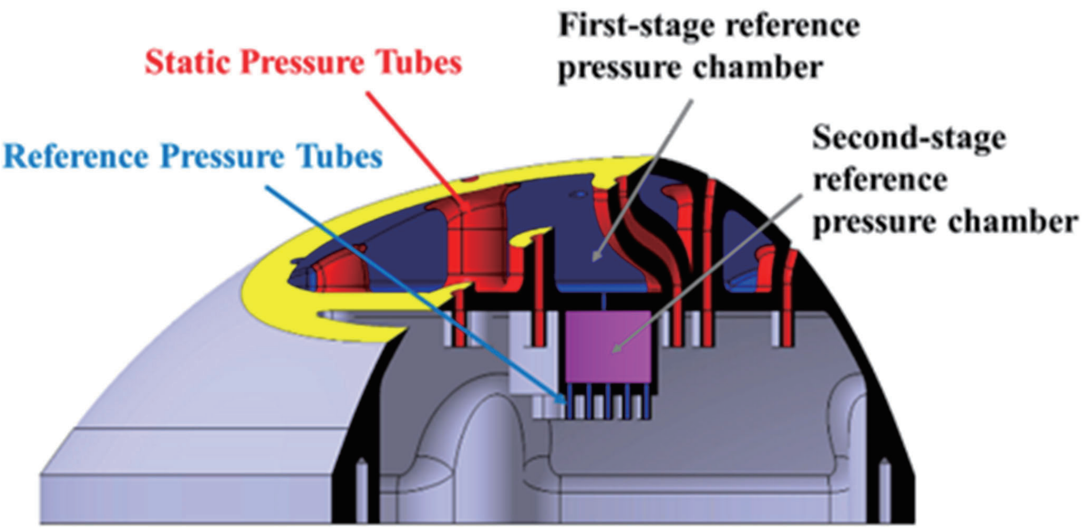
■ Pressure Ports (2/3)



FADS Manufactured by 3D Printing

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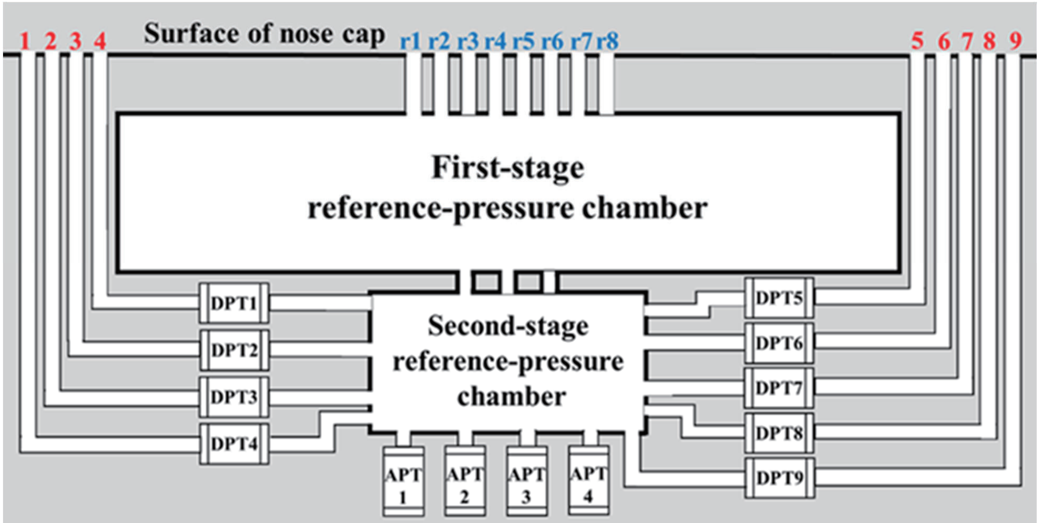
■ Pressure Ports (3/3)



FADS Manufactured by 3D Printing

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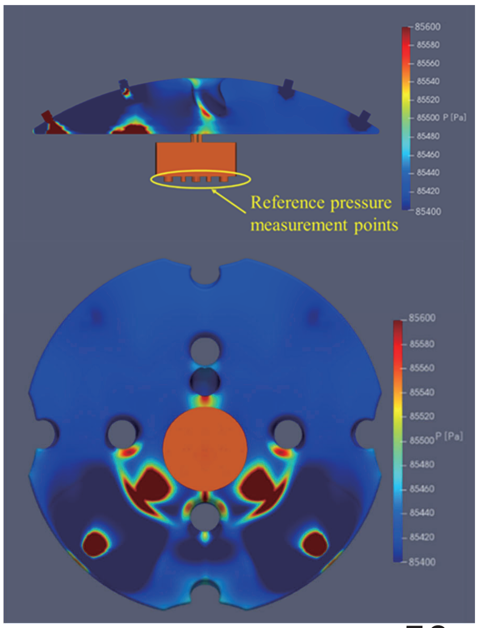
■ CFD Analysis of Reference Pressure Chamber

CFD analysis conditions.

Solver		ρ Simple Foam
Turbulence Model		RANS (k − ε)
Pressure-velocity Coupling Method		SIMPLE method
Kinematic Viscosity Coefficient ν	$[m^2/s]$	1.0×10^{-5}
Density ρ	$[kg/m^3]$	1.25



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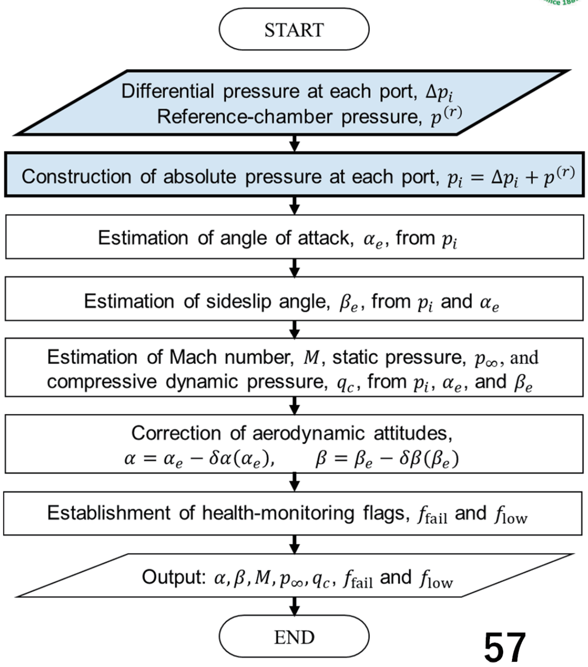
■ Air Data Estimation Algorithm

$$\frac{p - p_\infty}{q_\infty} = \varepsilon(\alpha, \beta, M)\sin^2\theta + \cos^2\theta$$

ε : Calibration Coefficient

Ref. Whitmore, S. A., Cobleigh, B. R. and Hearing, E. A., Design and Calibration of the X-33 Flush Airdata Sensing (FADS) System, NASA/TM-1998-206540, 1998.



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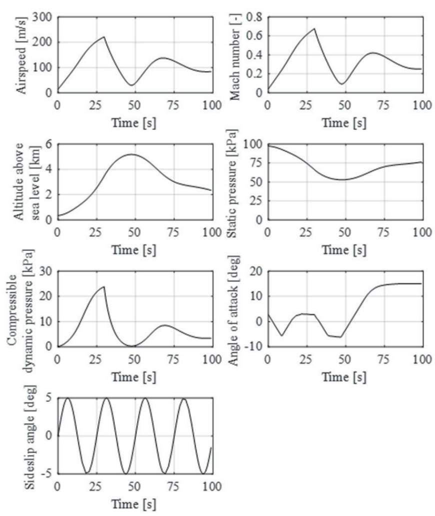
■ Nominal Flight Profile and Pressure Error Model



Item		Value		
		APT A	APT B	DPT
Range	[kPa]	[0, 30]	[0, 120]	[-10, 10]
Full scale (FS)	[kPa]	30	120	20
Error (3σ)	[Pa]	30 (=0.1%FS)	120 (=0.1%FS)	20 (=0.1%FS)

ATP : Absolute Pressure Tube
DPT : Differential Pressure Tube

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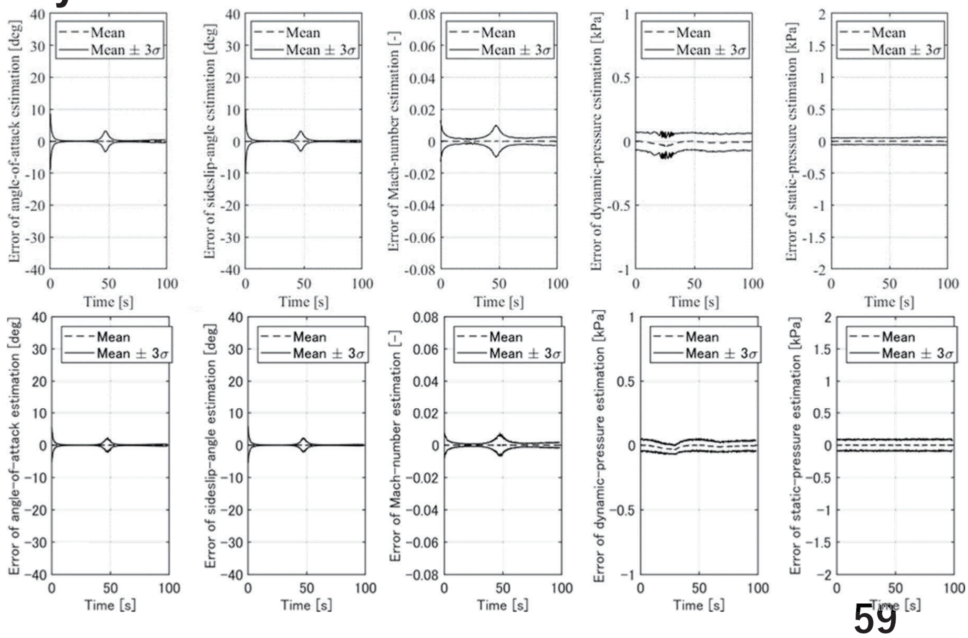
■ FADS Error Analysis

APTs A only

APTs B and DPTs



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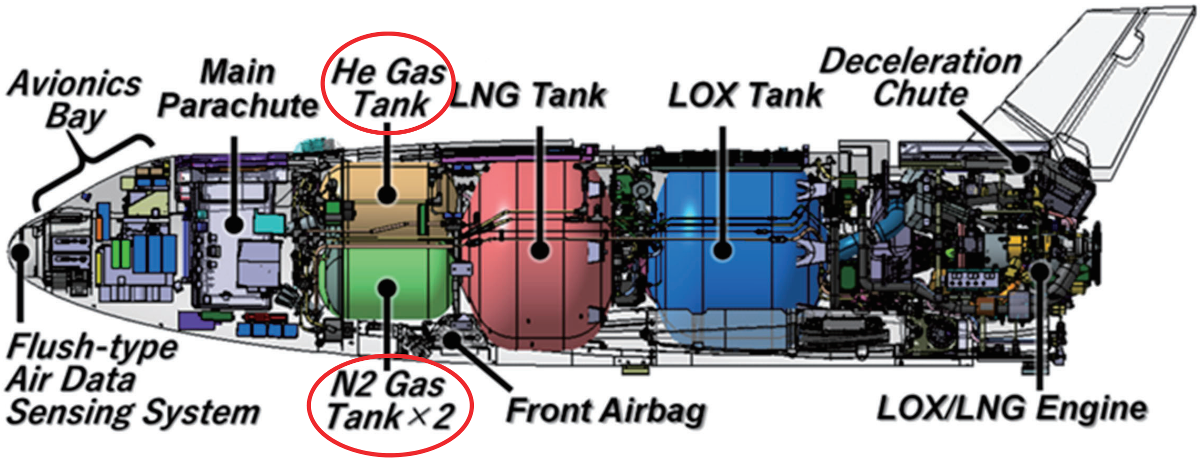
3.6 Thermo-fluid Analysis of High Pressure Gas Tank

■ Experimental Winged Rocket WIRES#015



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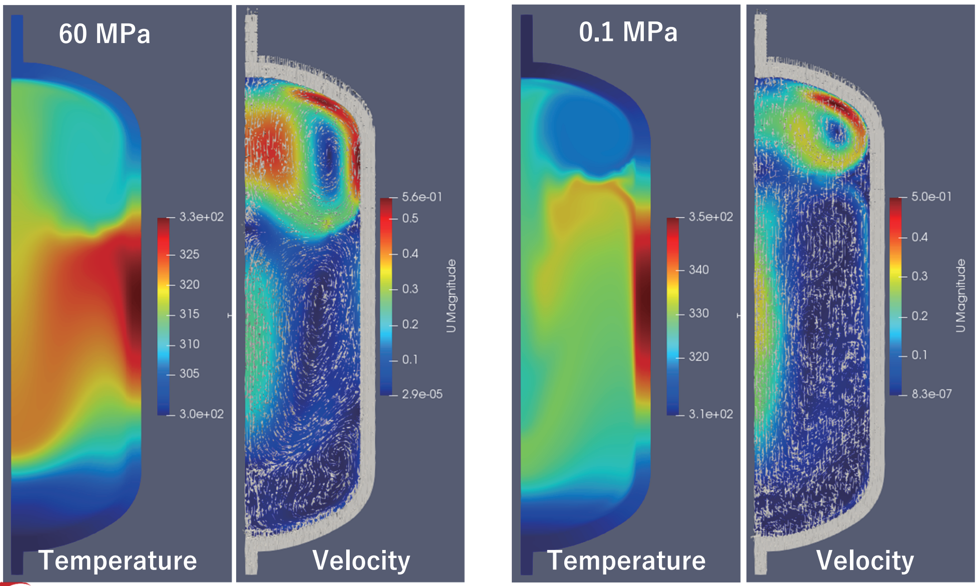
■ High Pressure Gas Behavior at Exhaust/Adiabatic Expansion



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3.7 Release Behavior of Deceleration Chute in Wake Vortex

■ Parachute System Deployment Test of Experimental Winged Rocket WIRES#015

Parachute System Deployment Test
(December 15, 2021)

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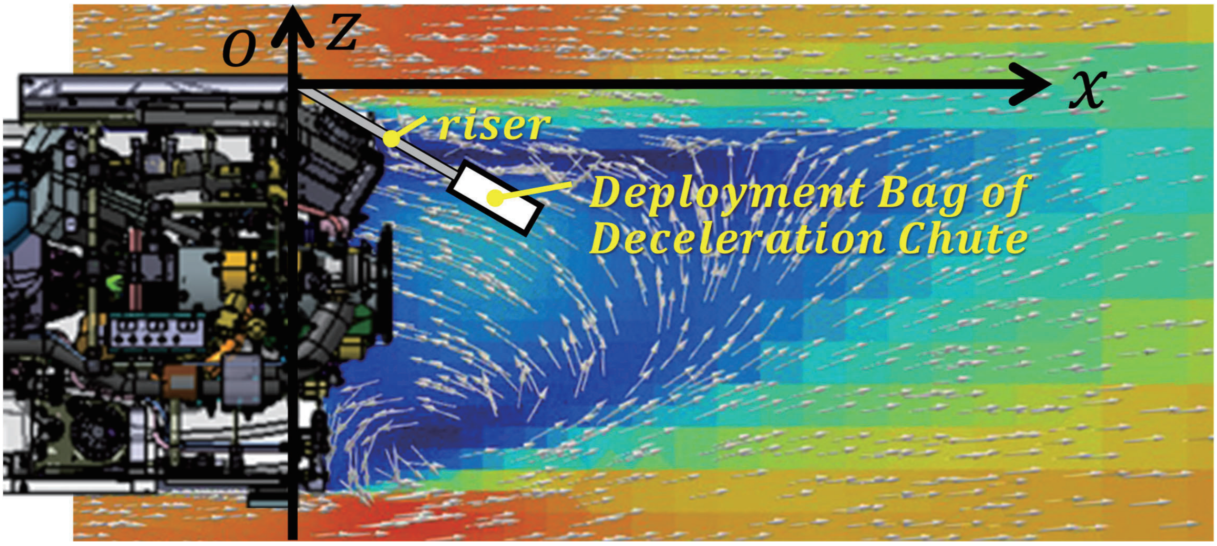
■ Kinematic Model of Deceleration Chute (1/2)



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■ Kinematic Model of Deceleration Chute (2/2)

$$m_c \frac{d^2 r_c}{dt^2} = F_c + F_{rc} - m_c g \quad (3.1)$$

$$m_r \frac{d^2 r_r}{dt^2} = F_r + F_{cr} - m_r g \quad (3.2)$$

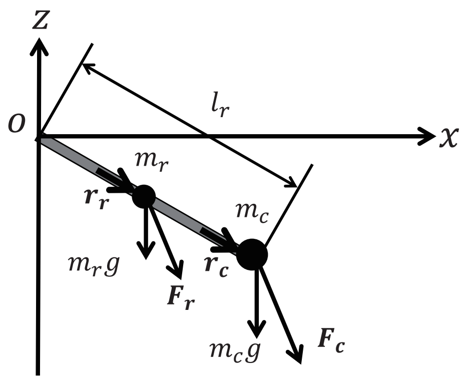
$$F_{rc} = -F_{cr} \quad (3.3)$$

$$r_c = 2 r_r \quad (3.4)$$

$$l_r = |r_c| \quad (3.5)$$

$$m_r = \mu l_r \quad (3.6)$$

$$\left(m_c + \frac{m_r}{2}\right) \frac{d^2 r_c}{dt^2} = F_c + F_r - (m_c + m_r) g \quad (3.7)$$



Kinematic Model

m_c, m_r : mass of chute and riser
r_c, r_r : position of chute and riser

F_c, F_r : force of chute and riser
F_{rc}, F_{cr} : internal forces
g : gravity acceleration
l_r : riser length
μ : line density

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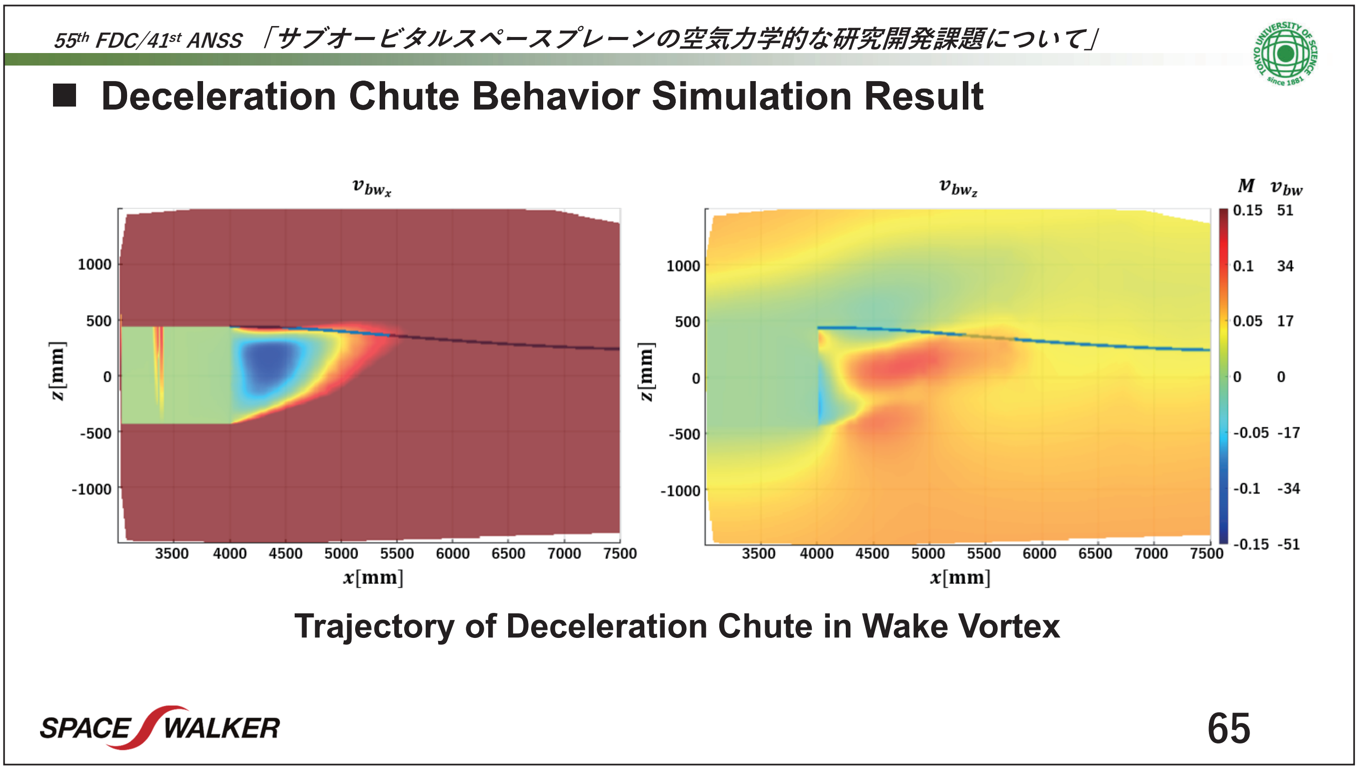

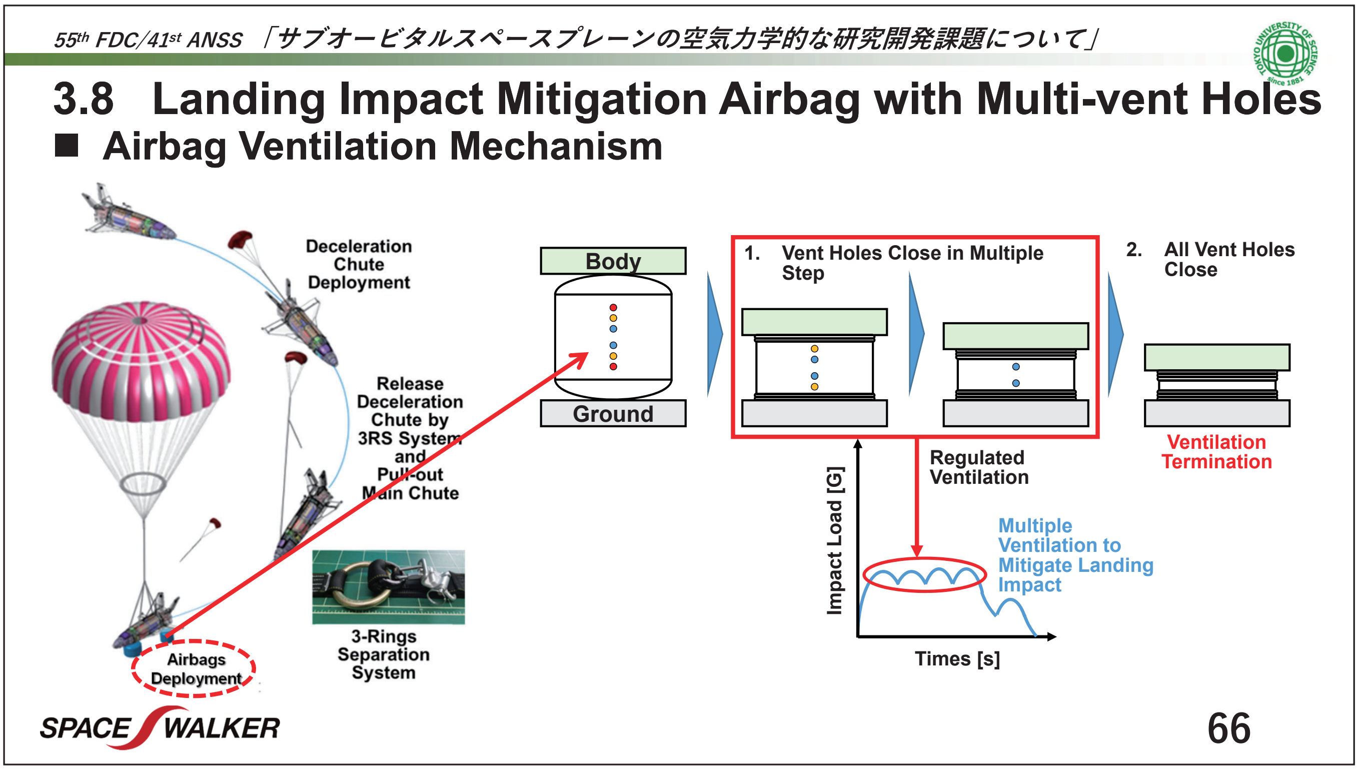

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■ Equations of Motion (1/3)

- ***Vehicle Equation of Motion:***

$$-Mg + (P - P_a)SM\frac{dv}{dt} = -Mg + (P - P_a)S \qquad (1)$$

- ***Gas Differential Equation:***

$$PV = mRT \qquad (2)$$

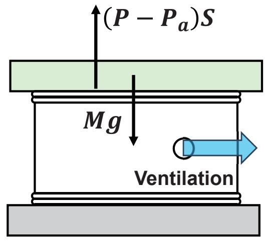
$$\frac{dP}{dt} = -\frac{P}{V}\frac{dV}{dt} + \frac{RT}{V}\frac{dm}{dt} + \frac{mR}{V}\frac{dT}{dt} \qquad (3)$$

- ***Gas Adiabatic Expansion:***

$$dU = -PdV + dH_e + \frac{1}{2}dmU_e^2 \qquad (4)$$

$$mC_v dT + dmC_v T = -PdV + dmC_p T_e + \frac{1}{2}dmU_e^2 \qquad (5)$$

$$\frac{dT}{dt} = \frac{-PSv(\kappa - 1) + \left\{(\kappa T_e - T)R + \frac{1}{2}(\kappa - 1)U_e^2\right\}\frac{m}{dt}}{mR} \qquad (6)$$



P: Airbag Pressure
S: Airbag Cross Section
P_∞: Atmospheric Pressure Area
V: Gas Volume
m: Gas Mass
T: Gas Temperature
C_v: Specific Heat (Volume Const)
C_p: Specific Heat (Volume Const)
P_e: Exit Pressure
H_e: Exit Entropy
T_e: Exit Temperature
ρ_e: Exit Gas Density
S_e: Exit Area
U_e: Exit Velocity
M_e: Exit Mach No.
a_e: Exit Gas Sonic Velocity

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■ Equations of Motion (2/3)

- ***Gas Ventilation Equation:***

$$\frac{dm}{dt} = -\rho_e S_e U_e \qquad (7)$$

- ***Compressible Bernoulli Equations:***

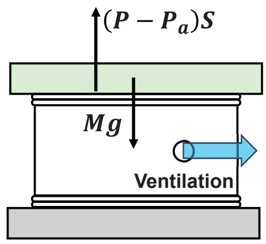
$$P_e = P_\infty \qquad (8)$$

$$M_e = \sqrt{\frac{2}{\kappa - 1}\left[\left(\frac{P}{P_e}\right)^{\frac{\kappa-1}{\kappa}} - 1\right]} \qquad (9)$$

$$\rho_e = \rho\left(1 + \frac{\kappa - 1}{2}M_e^2\right)^{\frac{1}{\kappa-1}} \qquad (10)$$

$$a_e = \sqrt{\kappa\frac{P_e}{\rho_e}} \qquad (11)$$

$$U_e = a_e M_e \qquad (12)$$



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P_e: Exit Pressure
H_e: Exit Entropy
T_e: Exit Temperature
ρ_e: Exit Gas Density
S_e: Exit Area
U_e: Exit Velocity
M_e: Exit Mach No.
a_e: Exit Gas Sonic Velocity

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■ Equations of Motion (3/3)

● ***Choke Condition*** $M_e \geq 1$:

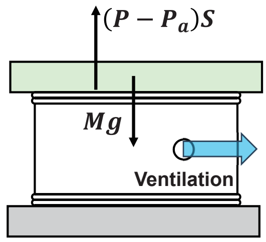
$$M_e = 1 \quad (13)$$

$$P_e = P\left(\frac{2}{\kappa+1}\right)^{\frac{\kappa}{\kappa-1}} \quad (14)$$

$$\rho_e = \rho\left(\frac{2}{\kappa+1}\right)^{\frac{1}{\kappa-1}} \quad (15)$$

$$a_e = \sqrt{\kappa\frac{P_e}{\rho_e}} \quad (16)$$

$$U_e = a_e \quad (17)$$



P: *Airbag Pressure*
S: *Airbag Cross Section*
P_∞: *Atmospheric Pressure Area*
V: *Gas Volume*
m: *Gas Mass*
T: *Gas Temperature*
C_v: *Specific Heat (Volume Const)*
C_p: *Specific Heat (Volume Const)*

P_e: *Exit Pressure*
H_e: *Exit Entropy*
T_e: *Exit Temperature*
ρ_e: *Exit Gas Density*
S_e: *Exit Area*
U_e: *Exit Velocity*
M_e: *Exit Mach No.*
a_e: *Exit Gas Sonic Velocity*

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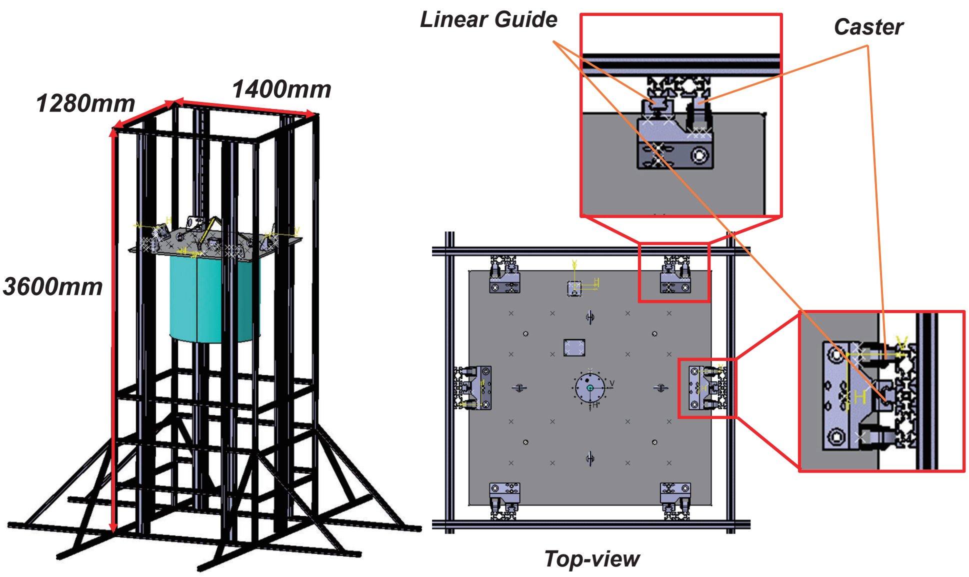
■ Test Stand



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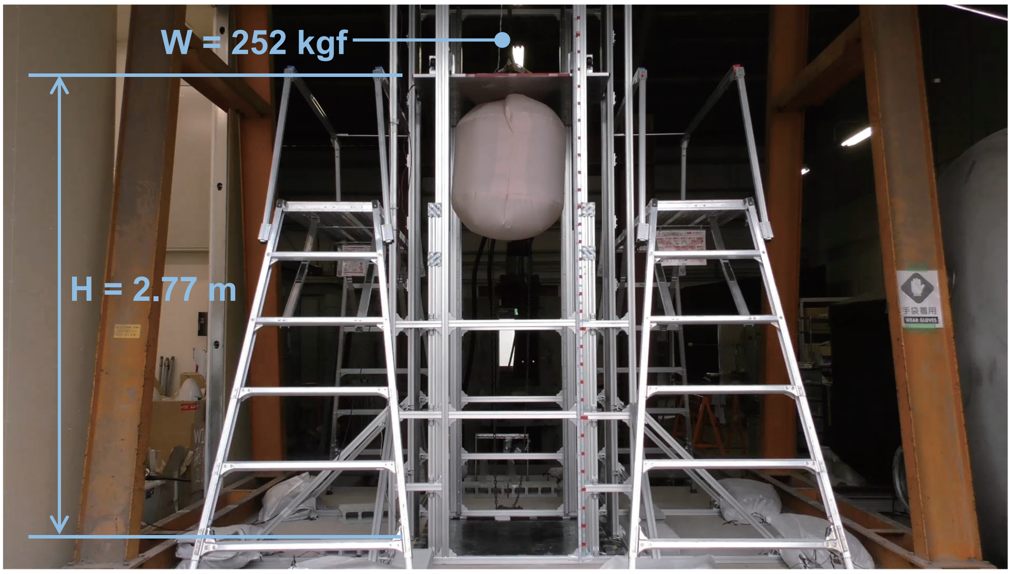
■ Drop Test



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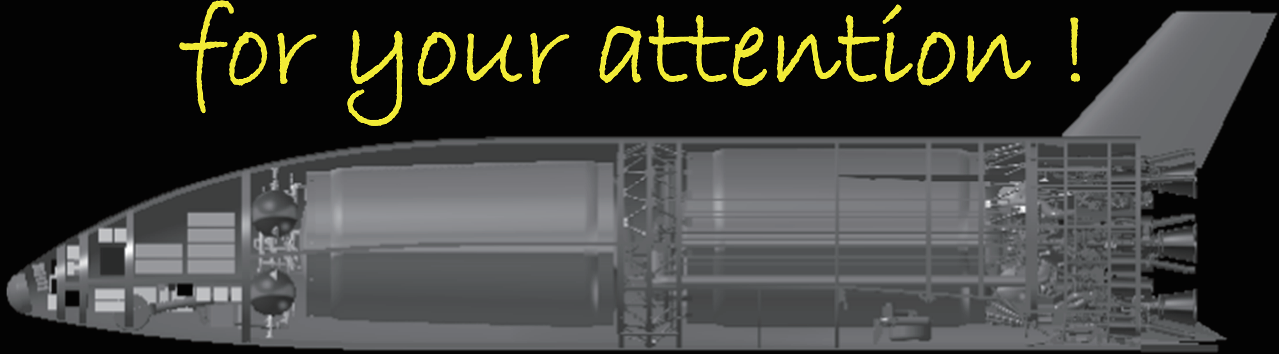
Thanks

for your attention !



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