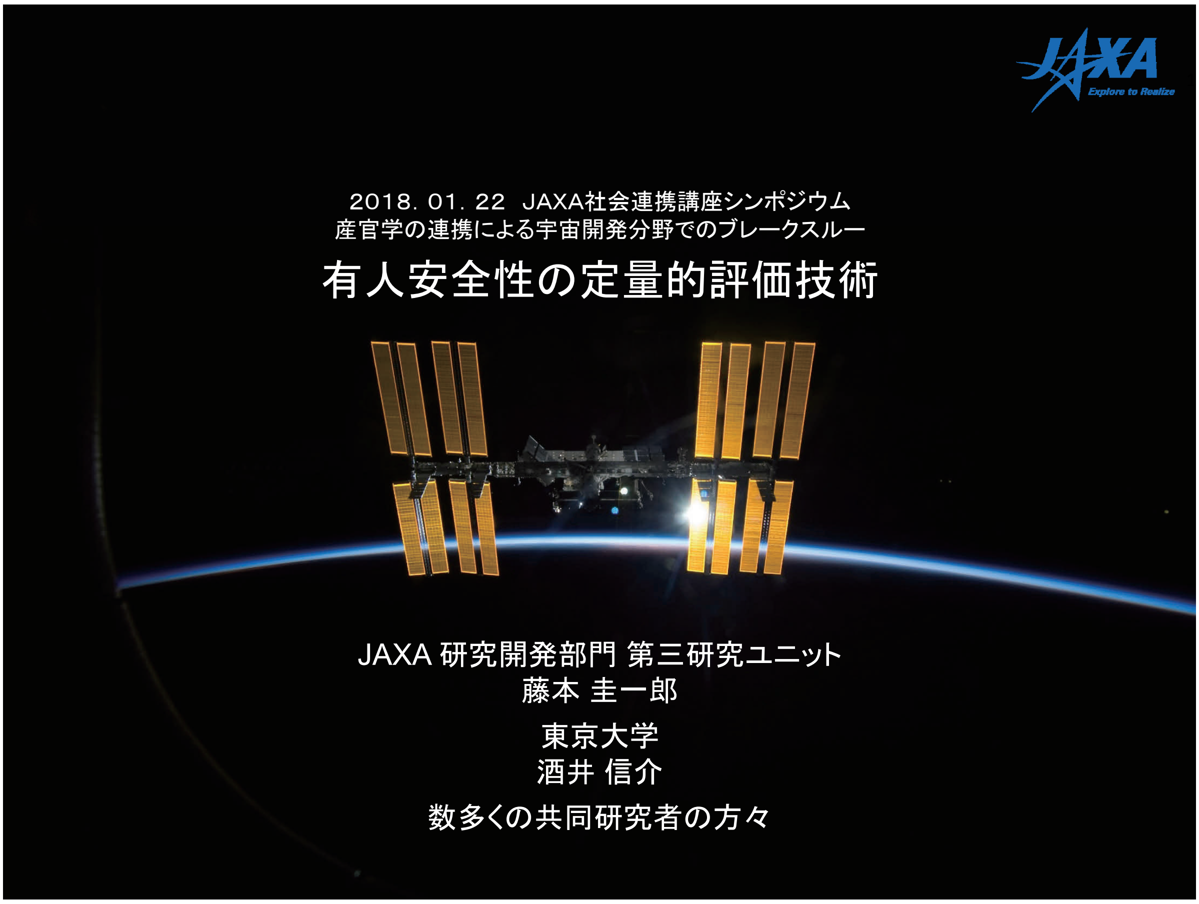
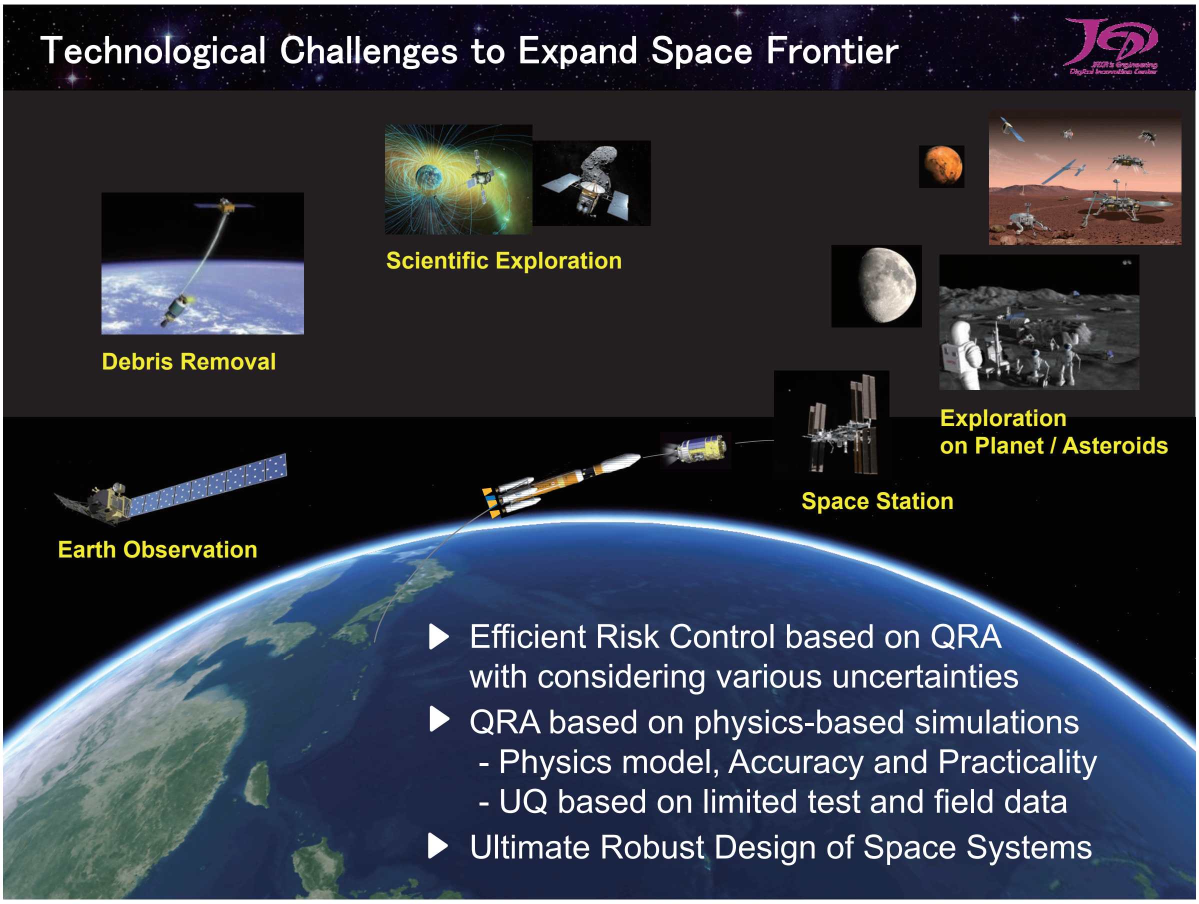

JAXA
Explore to Realize
2018. 01. 22　JAXA社会連携講座シンポジウム
産官学の連携による宇宙開発分野でのブレークスルー
有人安全性の定量的評価技術
JAXA 研究開発部門 第三研究ユニット
藤本 圭一郎
東京大学
酒井 信介
数多くの共同研究者の方々


Technological Challenges to Expand Space Frontier
Scientific Exploration
Debris Removal
Exploration
on Planet / Asteroids
Space Station
Earth Observation
▶ Efficient Risk Control based on QRA
with considering various uncertainties
▶ QRA based on physics-based simulations
- Physics model, Accuracy and Practicality
- UQ based on limited test and field data
▶ Ultimate Robust Design of Space Systems

Challenges to establish Risk Control based on QRA

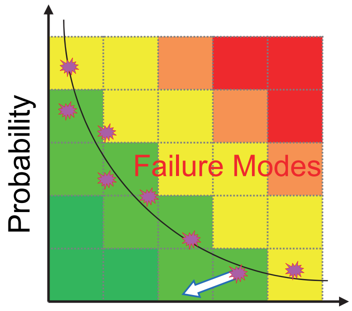
3

- Overcome difficulty of modeling complicated hazard physics to control risk by design and operation.

Design — Operation

Design for Risk / Operation for Risk

Risk (Reliability/Safety)




Challenger (1986)


Concorde (2000)


Tsunami (2011)

4

Reliability

Reliability Challenges – Efficient Reliability Control

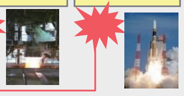
5

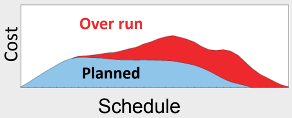
1: Overrun of development cost & schedule

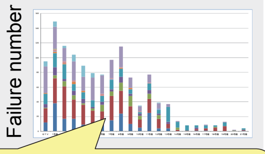
-Design is empirical deterministic MOS-based
-MOS is validated in later-phase tests
-Even after certification, failure occurs

Planning ⇨ Product Design ⇨ Prototype/ Test ⇨ Certification System Test ⇨ Operation

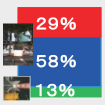
Failure







Main Cause
(1)Absence & poor accuracy of analysis
Less consideration of uncertainty of
(2)Product parameter variation
(3)Environmental parameter variation



System test (Over run)
System test
Component test

LE-7 Development cost

2: High cost reliability & life certification

-Large number of system firing test is performed and reliability is evaluated by failure numbers
-Efficient accelerated test is not established

→ Reliability = f(success count, failure count, level of confidence)

In H2A rocket development, 140 firing tests is performed in 10 years.
<Estimated human-rated engine certification cost>
3000 firing tests (few billion dollars) is required, means twice of whole cost of HII-A & HII-B development.

Elimination of failure modes

[A] Unknown failure modes
[B] Design consideration

Overrun of development cost & schedule

[C] Development rework by failure modes in later phases
[D] Efficient system reliability evaluation method is not established
[E] Strong dependency on high cost testing

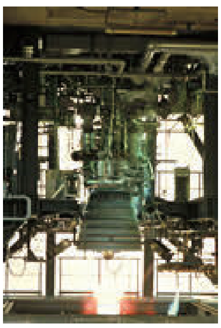
Reliability Challenges – Efficient Reliability Control

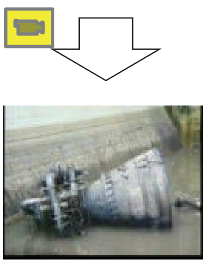
6

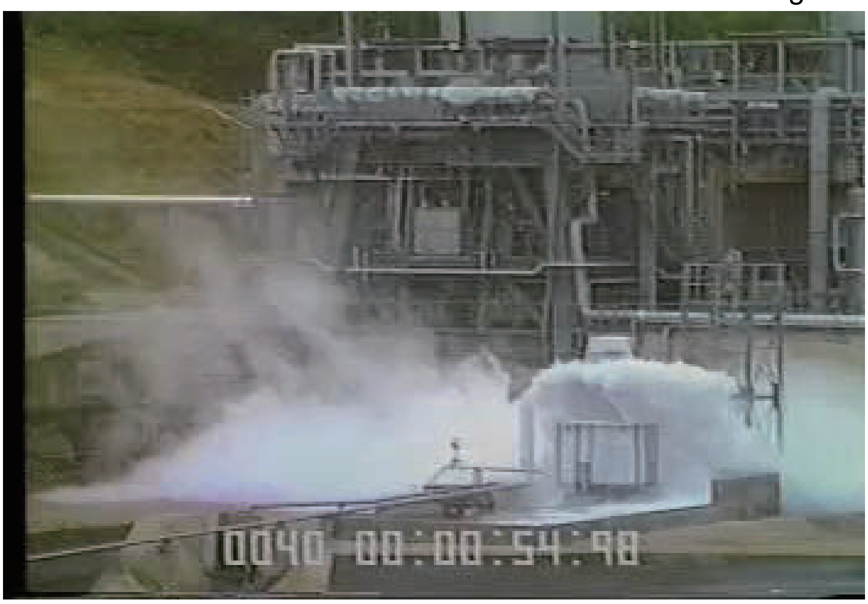
▷Even in later development phase, failure due to design can be happen.

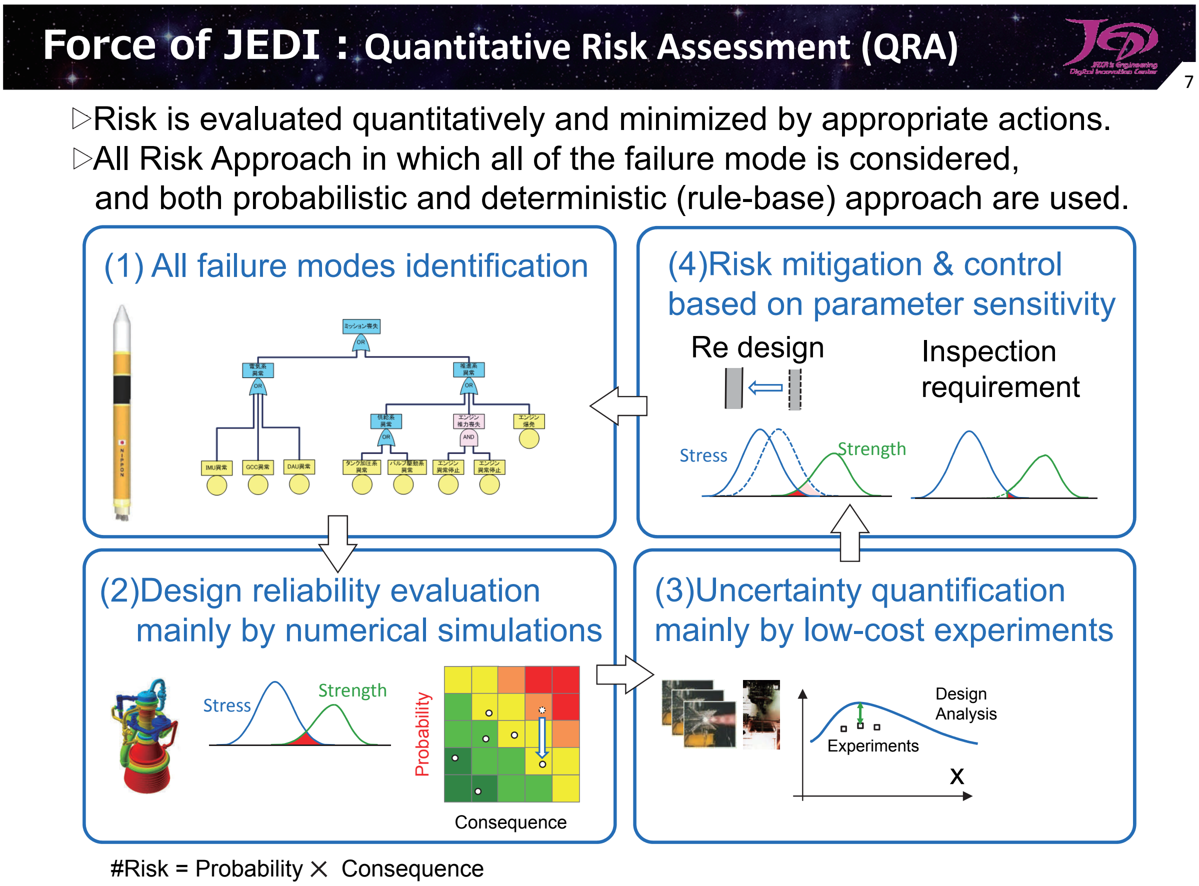
▷In the worst case, large amount of additional cost and time is required for the failure cause investigation, re-design, and re-certification.

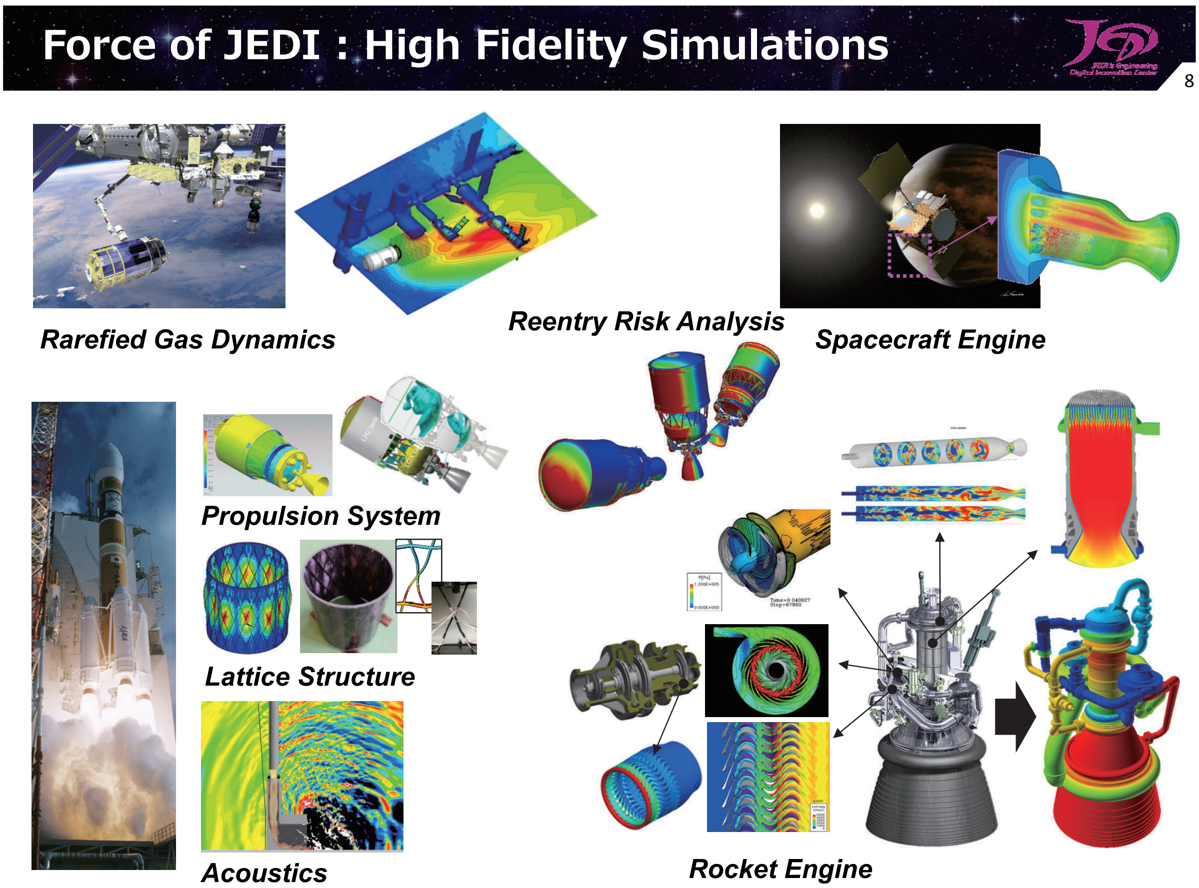
LE-7 Firing Test





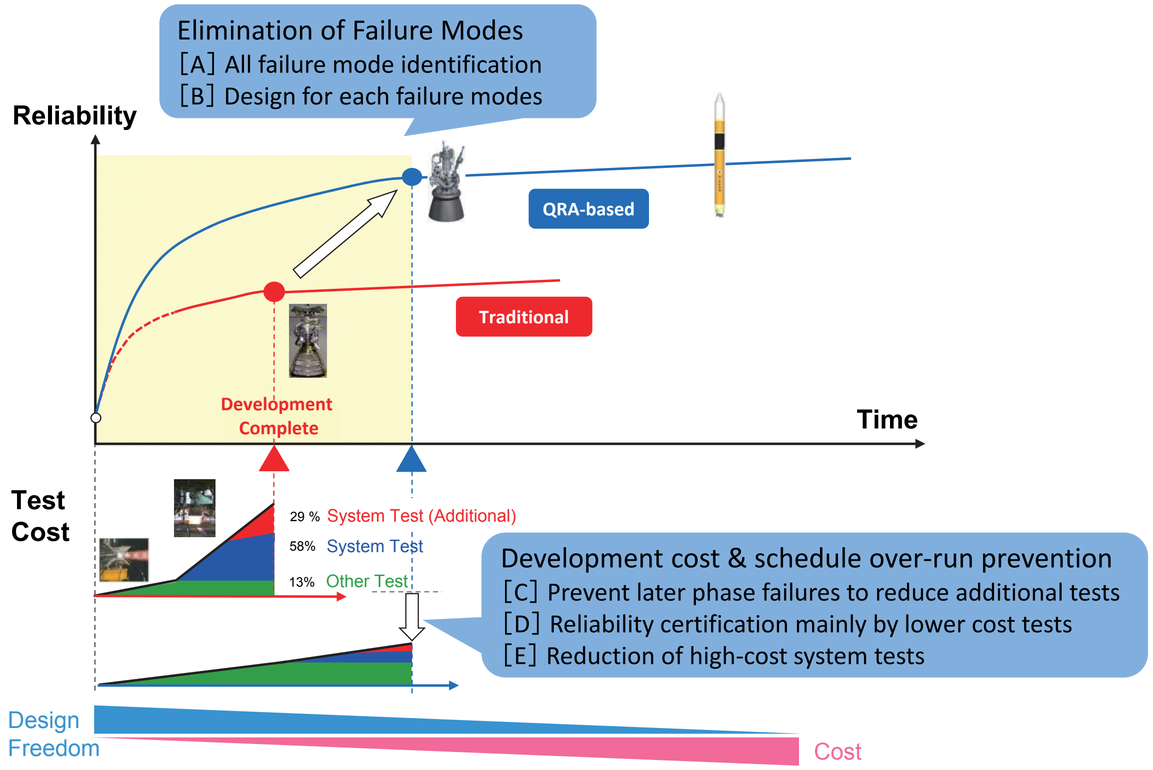



Force of JEDI : Quantitative Risk Assessment (QRA)
7
▷Risk is evaluated quantitatively and minimized by appropriate actions.
▷All Risk Approach in which all of the failure mode is considered,
and both probabilistic and deterministic (rule-base) approach are used.
(1) All failure modes identification
(4)Risk mitigation & control
based on parameter sensitivity
Re design
Inspection
requirement
Stress
Strength
(2)Design reliability evaluation
mainly by numerical simulations
Stress
Strength
Probability
Consequence
(3)Uncertainty quantification
mainly by low-cost experiments
Design
Analysis
Experiments
X
#Risk = Probability × Consequence


Force of JEDI : High Fidelity Simulations
8
Rarefied Gas Dynamics
Reentry Risk Analysis
Spacecraft Engine
Propulsion System
Lattice Structure
Acoustics
Rocket Engine

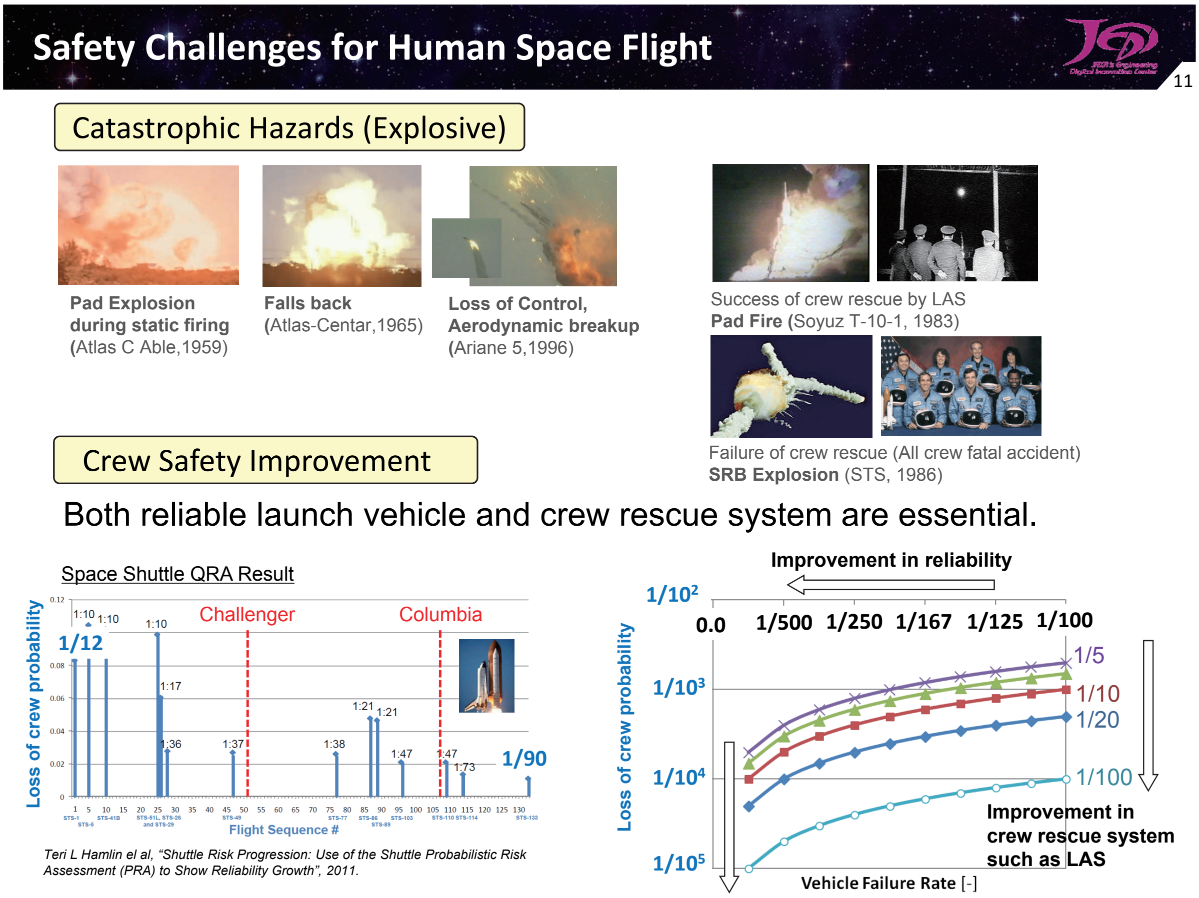
Quantitative Risk Assessment (QRA)

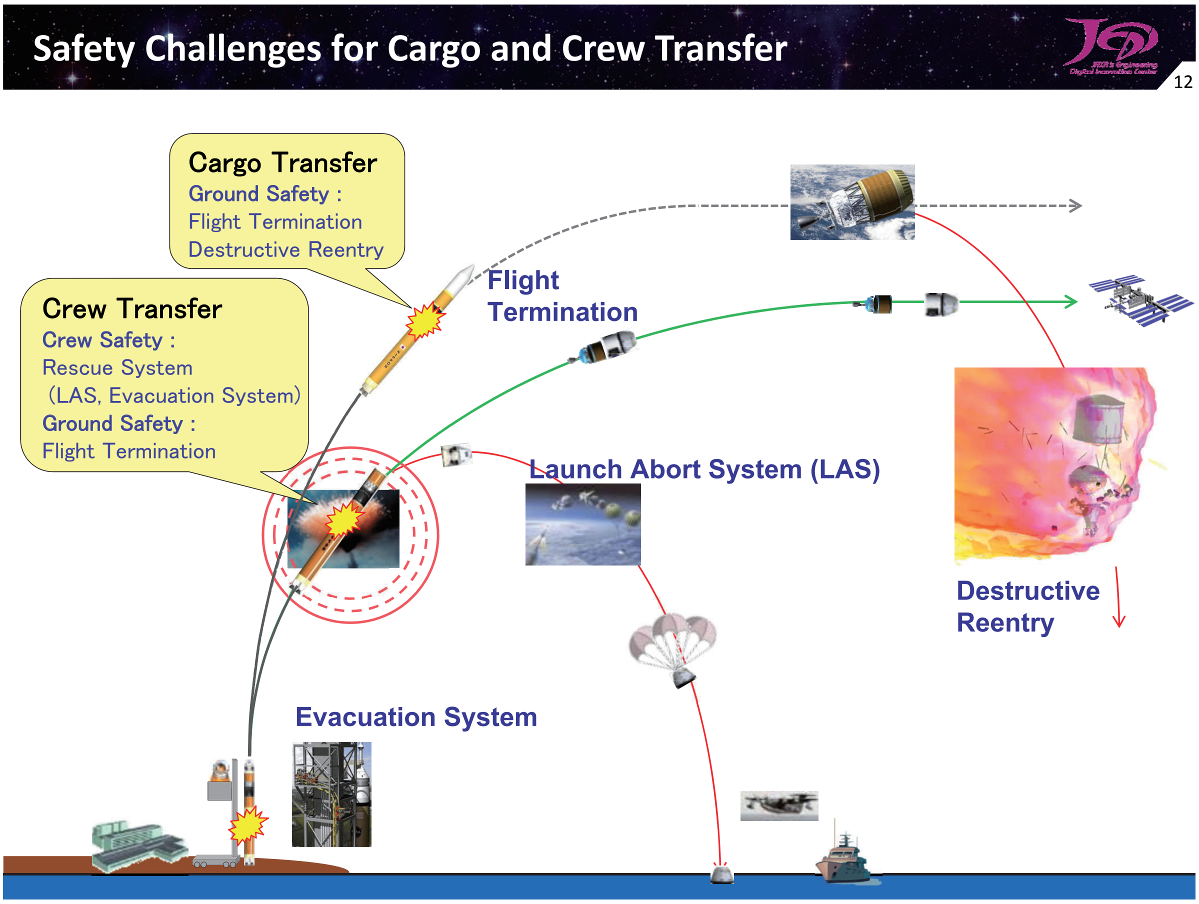
9



10

Safety


Safety Challenges for Human Space Flight
11
Catastrophic Hazards (Explosive)
Pad Explosion during static firing (Atlas C Able,1959)
Falls back (Atlas-Centar,1965)
Loss of Control, Aerodynamic breakup (Ariane 5,1996)
Success of crew rescue by LAS
Pad Fire (Soyuz T-10-1, 1983)
Failure of crew rescue (All crew fatal accident)
SRB Explosion (STS, 1986)
Crew Safety Improvement
Both reliable launch vehicle and crew rescue system are essential.
Space Shuttle QRA Result
Loss of crew probability
1/12
Challenger
Columbia
1/90
Flight Sequence #
Teri L Hamlin el al, "Shuttle Risk Progression: Use of the Shuttle Probabilistic Risk Assessment (PRA) to Show Reliability Growth", 2011.
Improvement in reliability
1/10²
0.0 1/500 1/250 1/167 1/125 1/100
1/10³
1/10⁴
1/10⁵
1/5
1/10
1/20
1/100
Improvement in crew rescue system such as LAS
Vehicle Failure Rate [-]


Safety Challenges for Cargo and Crew Transfer
12
Cargo Transfer
Ground Safety :
Flight Termination
Destructive Reentry
Crew Transfer
Crew Safety :
Rescue System
(LAS, Evacuation System)
Ground Safety :
Flight Termination
Flight Termination
Launch Abort System (LAS)
Destructive Reentry
Evacuation System

Quantitative Safety Assessment – Efficient Safety Control

13

[Objectives]

-Establishment of quantitative safety analysis method
(Safety design, TRL increase for future decision)

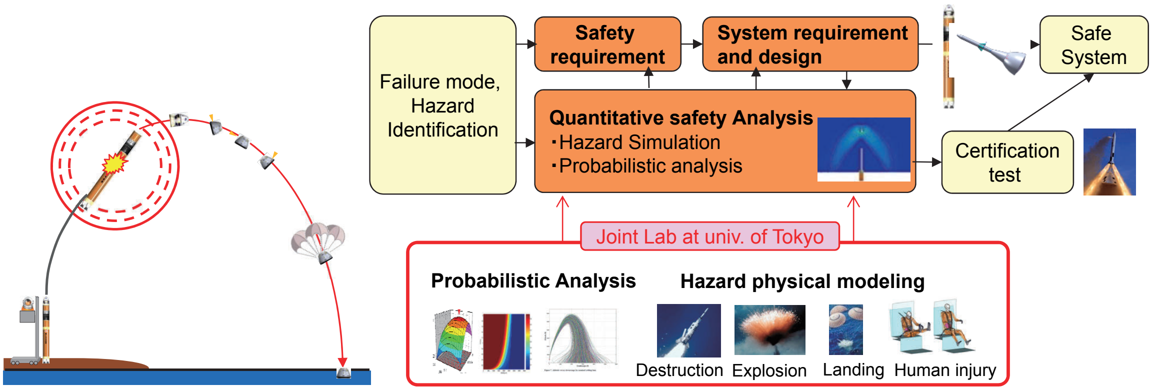
-Feasibility study of LAS (Conceptual design, safety requirement)

[Development of Technology]

Quantitative safety analysis technology based on high-fidelity numerical simulations
1) Safety design in early design phases, 2) Appropriate reliability/safety requirements,
3) Decrease in validation test cost

[Success Criterion]

-Realization of full phase abort feasibility (as conceptual design)

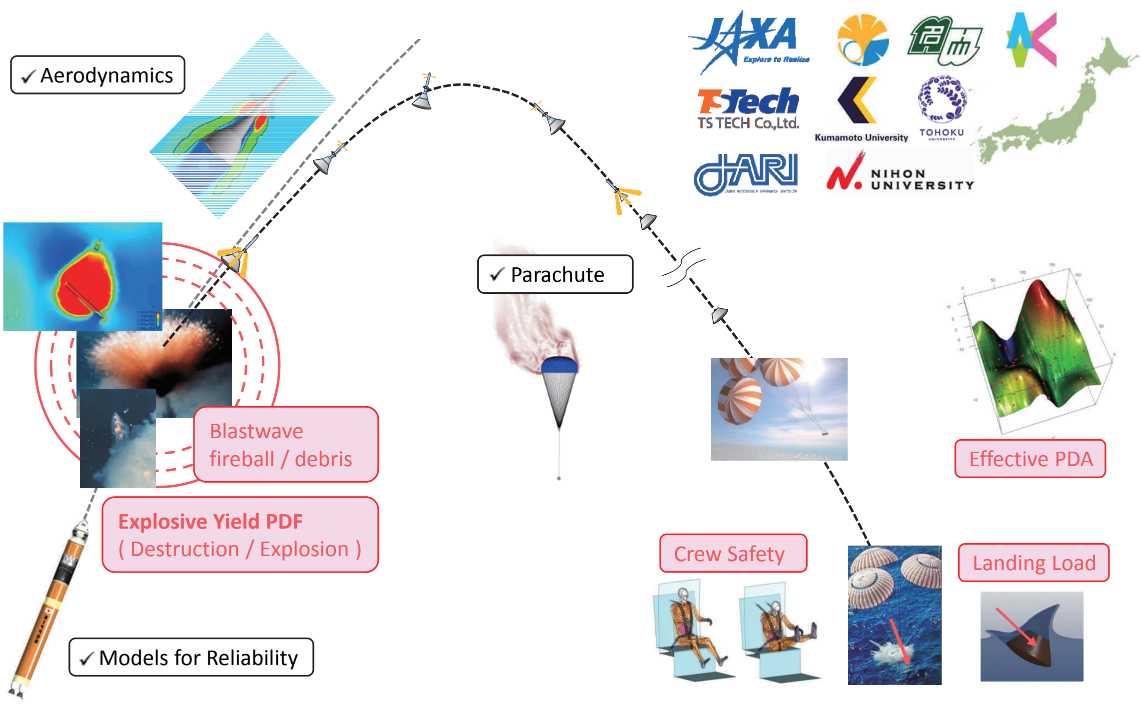


High Fidelity Simulations for Safety

14

▷ Models for Failure Mode Physics.

▷ Joint research with univs and automobile fields.

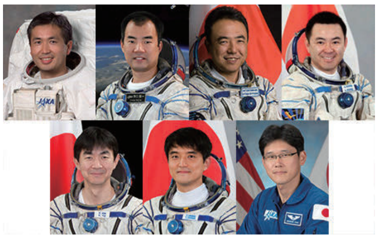


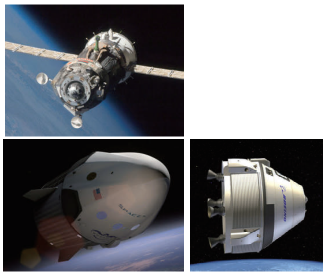
Objective - High Fidelity Simulations for Safety

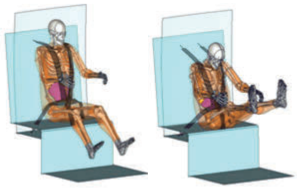
15

[Crew Injury]

- Japanese decision making for JAXA's astronaut missions.
- Establish physics-based injury risk model and investigate mechanism.

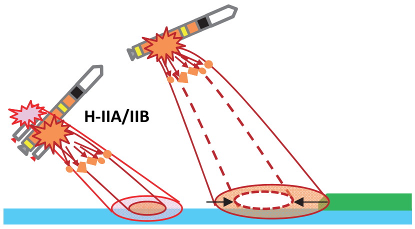






[Explosion Process]

- Possibility to ease trajectory restriction by accurate safety analysis. Additional performance, etc...



High Fidelity Hazard Simulations – Contribution to Engineering

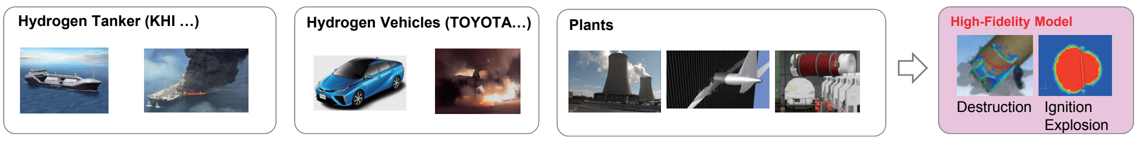
16

<Contribution to other fields>

Establish serious research communities and improve high-fidelity simulation capability.

Destruction and explosion

-In the fields of hydrogen automobile, fuel cell, LH2 storage tanks, transportation of nuclear waste, investigation of the hazard mechanism & QSA for rare event is essential.
-Demands for the QSA getting significant.
-Since hazard simulation technology is key to keep the quality of Japanese products, the investigation to establish QSA is meaningful.



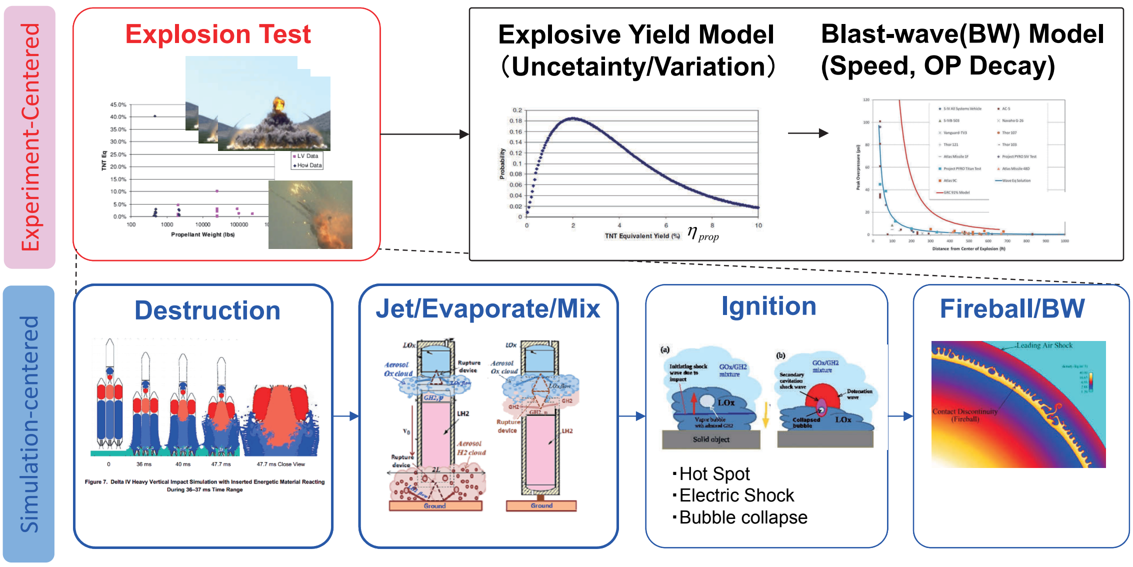
Occupant Safety

-Safety is the key for the international competitiveness for the automobile and trains.
Open collaboration framework is employed in this research project to achieve the goal !

Explosion Process Modeling - Motivations

17

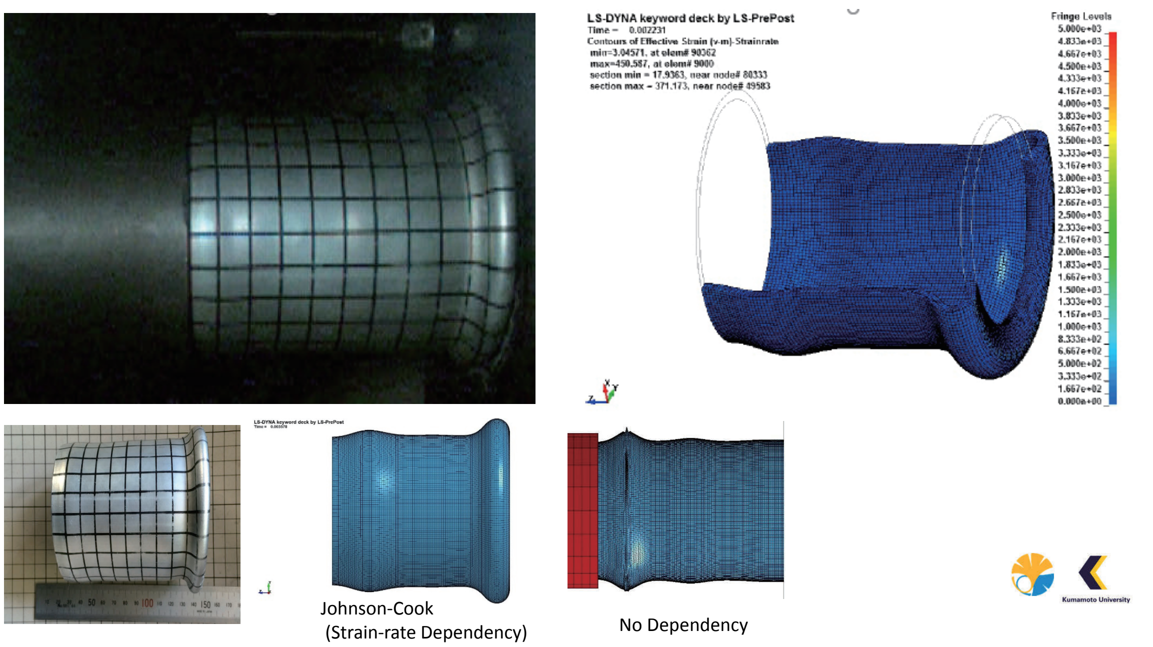
- ▷ Motivation to establish explosion process model are
  (1) Understand hazard physics
  (2) Cost reduction of uncertainty quantification test (= Less uncertainty)
- ▷ In order to achieve goal above, numerical model for destruction and explosion process & efficient risk assessment technique are essential



Explosion Process Modeling - Destruction

18

- ▷ Constitutive eq. and failure criterion for liquid rocket tank (Al-alloy) were developed.
- ▷ Strain-rate and temperature dependencies are modeled to predict destruction process.



Ref: 中井佑, 波多英寛, 藤本圭一郎, 泉聡志, 酒井信介, "アルミ合金円管の高ひずみ速度大変形に関する動的有限要素法解析," 第48期定時社員総会および年会講演会, 2017.

Explosion Process Modeling - Destruction

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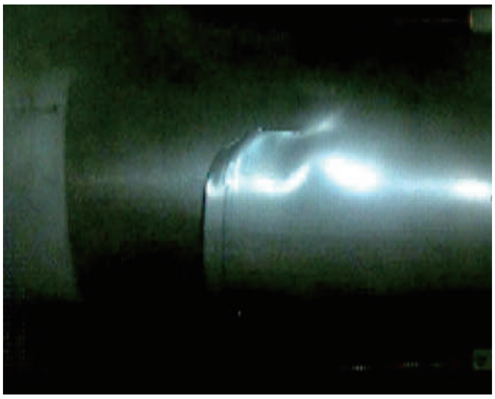

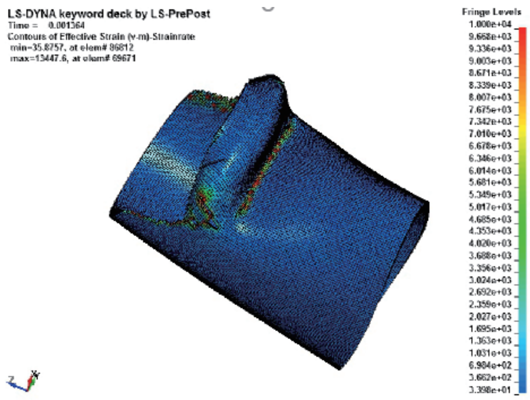

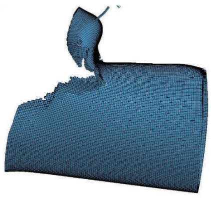

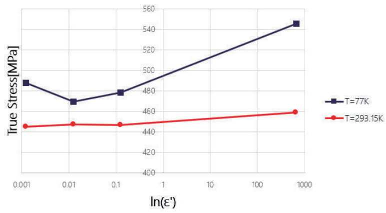

Explosion Process Modeling - Destruction

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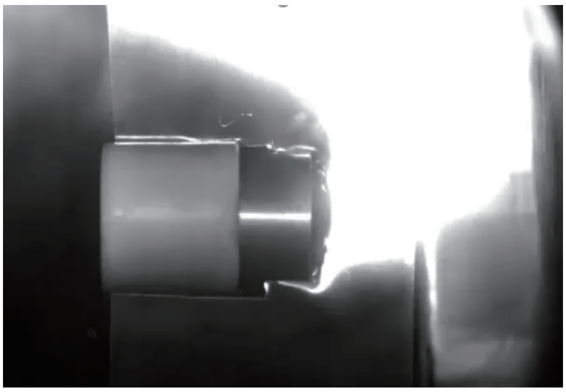
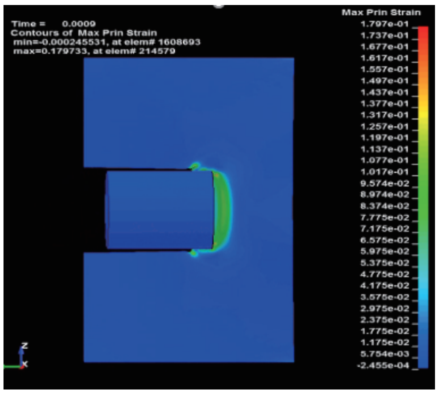
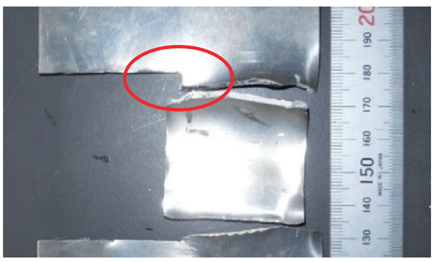
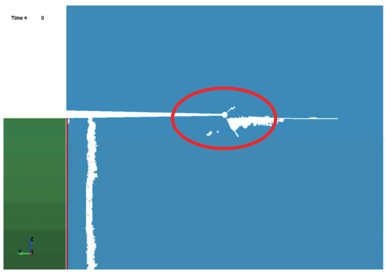






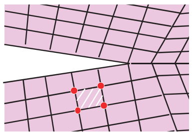


Explosion Process Modeling - Destruction

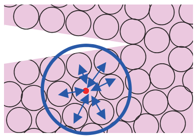
21

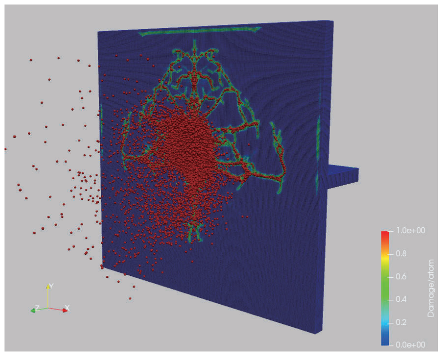
1) Multi-Physics Analysis
   - Structure / Fluid / Heat transfer of Multiple Shape in 6-DoF motion
2) Deforming Complicated Shape
3) Coupling analysis with Fluid Dynamics
   - Condition dependent flow structure
   - Evaporation
   - Reactive Flow (Combustion)

FEM



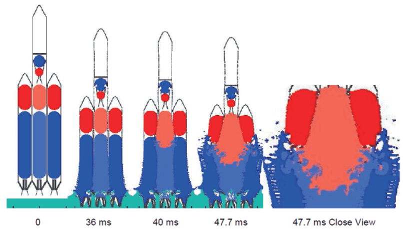
Peridynamics





Destructive Reentry

Flight Termination / Fall back failure



[1] Lambert, R. R., "Liquid Propellant Blast Yields For Delta IV Heavy Vehicles," 34th Department of Defense Explosives Safety Board Seminar, National Technical Information Service, ADA532286, July 2010.

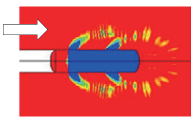
Explosion Process Modeling - Ignition

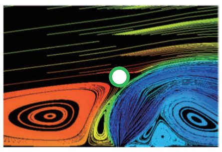
22

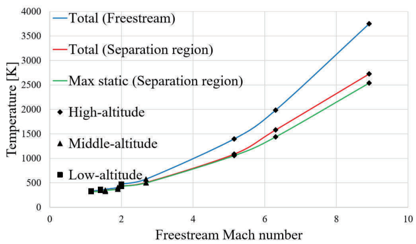
▷ Ignition delay, its location and energy are key driver of the explosive yield.

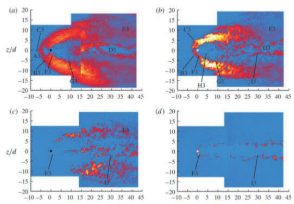
▷ Ignition mechanisms and conditions at which ignition and flame hold were investigated.

Freestream Stagnation





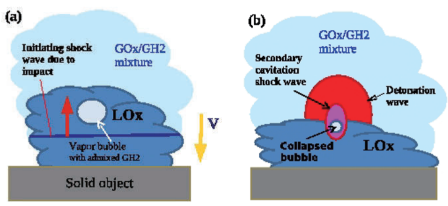




Experiment by Stanford

Ref: I. Toshihiro, F. Keiichiro, M. Daiki, and T. Nobuyuki, "Numerical Simulations of Transverse Jet in Supersonic Crossflow toward an Understanding of Interaction Mechanism," in 31st International Conference on Shock Waves, 2017.

Collision of LH2 and LOX



Landing Acceleration – Validation study

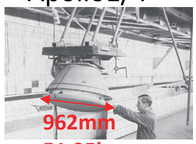
23

Analysis : LS-DYNA ALE, CIP-LSM
Approach : Analytical, HTV-R6.8%, Apollo1/4
Condition : Velocity and pitch angle
(incl. off-nominal)

HTV-R6.8%

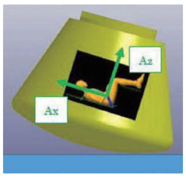
1.5kg

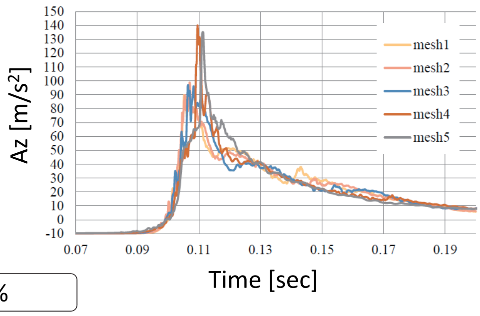
Apollo1/4



51.95kg

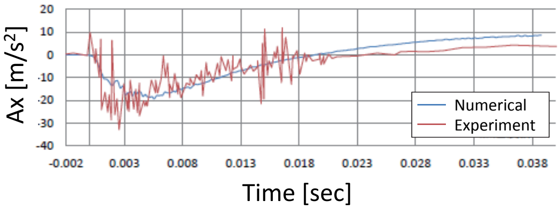
Grid Resolution Study

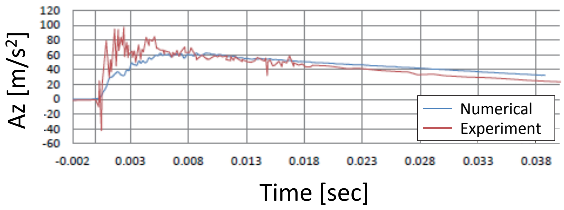




Case Name	Cell Size [m]	Az Max [G]
Mesh1	0.065	9.381
Mesh2	0.070	10.065
Mesh3	0.080	9.881
Mesh4	0.100	14.276
Mesh5	0.150	13.766

HTV-R 6.8%

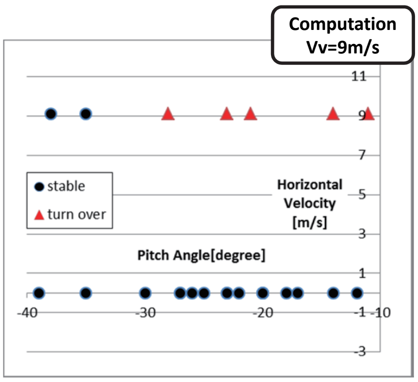


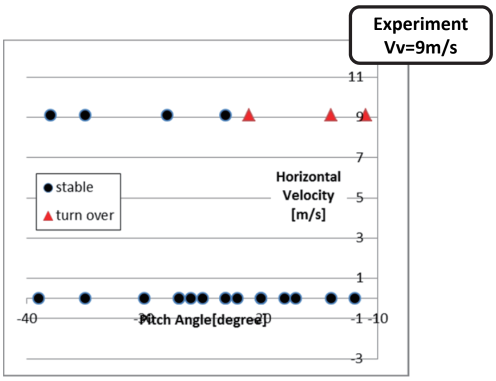


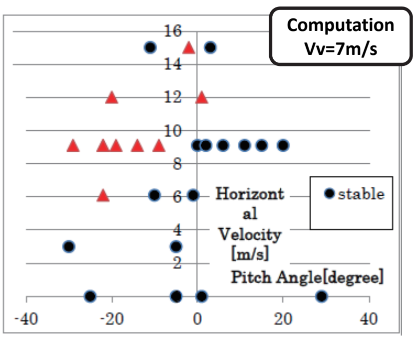
Work by Shunnosuke Inoue, Shinsuke Sakai (Univ. of Tokyo)

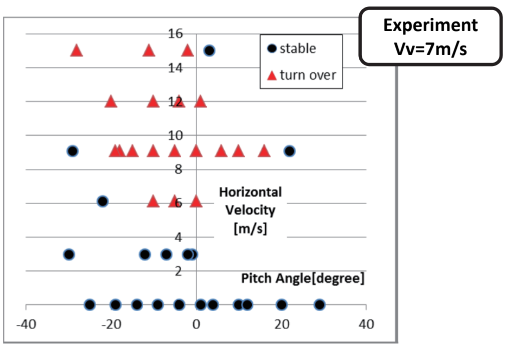
Landing Acceleration – Validation study

24







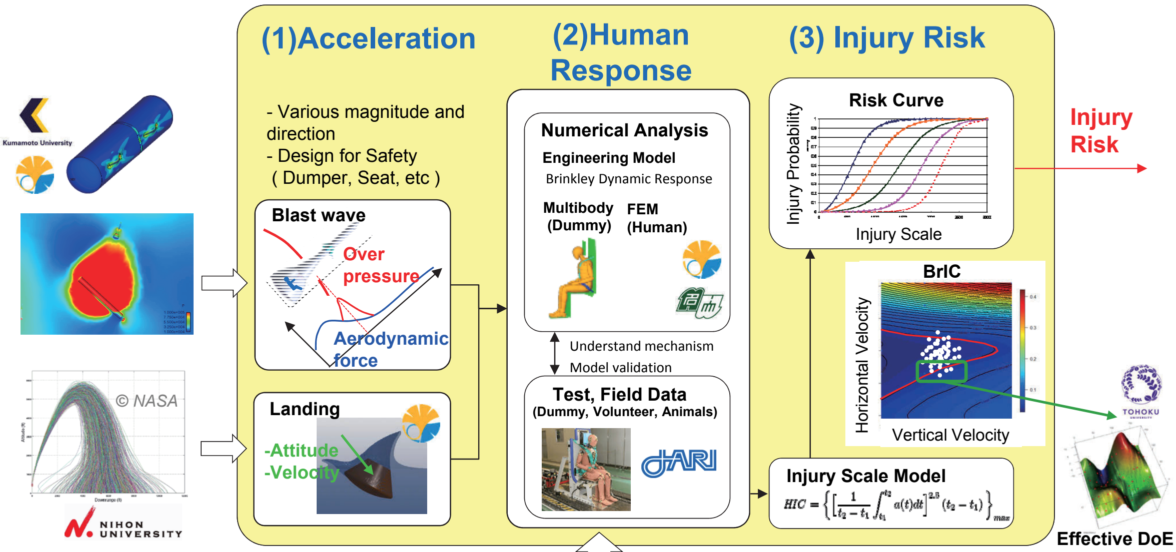


Work by Takuya Furumoto, Takehiro Himeno (Univ. of Tokyo)

Quantitative Crew Safety Analysis

25

▷ Physical models have been developed with joint research with universities.



Design for Safety

1. Fujimoto, K. Wada, E. Sakai, S. et. al, "Development of Spaceship Crew Injury Risk Analysis Method for Impact Load," 2017 NASA HRP Workshop, 2017.
2. 藤本圭一郎, 酒井信介泉聡志ら, "有人宇宙船における衝撃加速度に対する乗員安全評価法の構築-第1報," 第60回宇宙科学技術連合講演会,2016.
3. F. Keiichiro et al., "Investigation on the Crew Injury Biomechanics at Water Landing for Human Space Flight," IRCOBI 2017, Short Communication, 2017.

Work by Kazuki Kuriyama, Akihiro Ueda, Shunsuke Imaizumi, Naoki Saito, Kodai Nakagawa, Akira Tkahashi (Univ. of Tokyo)

Quantitative Crew Safety Analysis – Design for Safety

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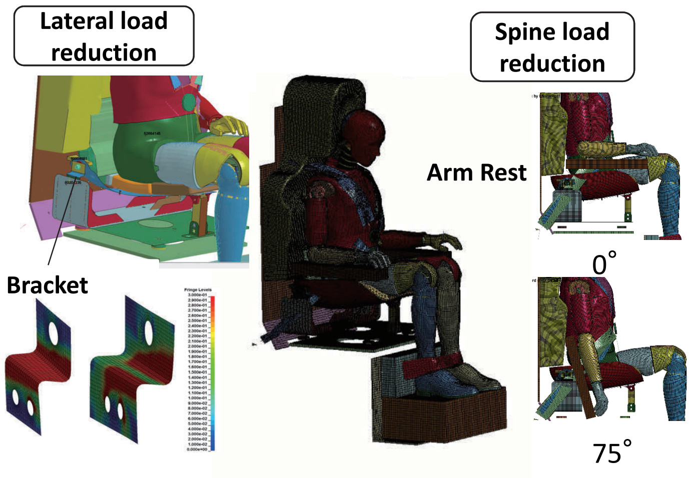
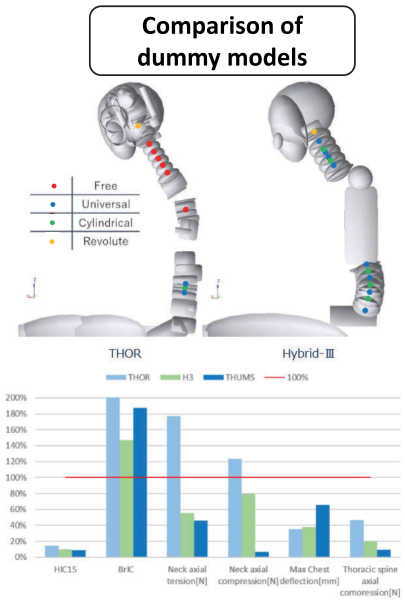
▷ FEM-based dummy model has been validated for the design spacecraft seat.

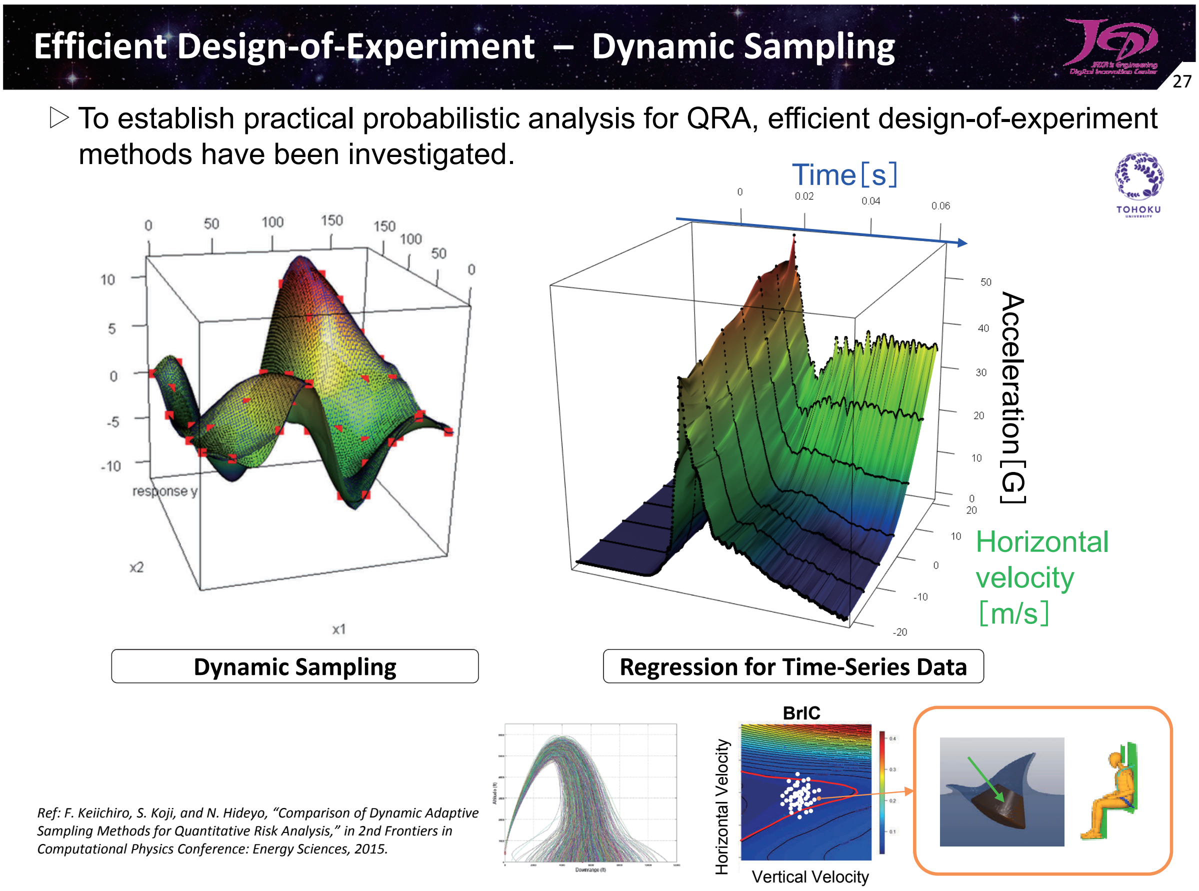
▷ Further crew safety improvements have been achieved by the comprehensive consideration on the design for safety.





Work by Kodai Nakagawa (Univ. of Tokyo)

Work by Akira Takahashi (Univ. of Tokyo)


Efficient Design-of-Experiment – Dynamic Sampling
27
▷ To establish practical probabilistic analysis for QRA, efficient design-of-experiment methods have been investigated.
response y
x2
x1
Time[s]
Acceleration[G]
Horizontal velocity [m/s]
Dynamic Sampling
Regression for Time-Series Data
BrIC
Horizontal Velocity
Vertical Velocity
TOHOKU
Ref: F. Keiichiro, S. Koji, and N. Hideyo, "Comparison of Dynamic Adaptive Sampling Methods for Quantitative Risk Analysis," in 2nd Frontiers in Computational Physics Conference: Energy Sciences, 2015.