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高忠実な物理モデルによるリエントリ安全評価法 LS-DARC の開発 − 第 1 報

Development of High Fidelity Model-based Re-entry Safety Analysis Tool LS-DARC – Part 1

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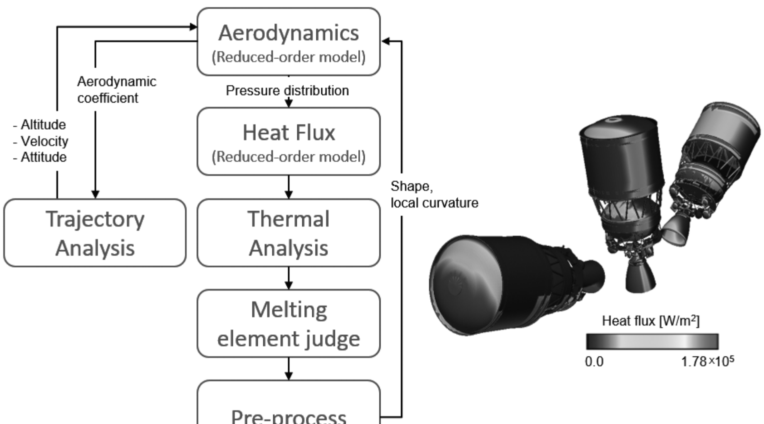
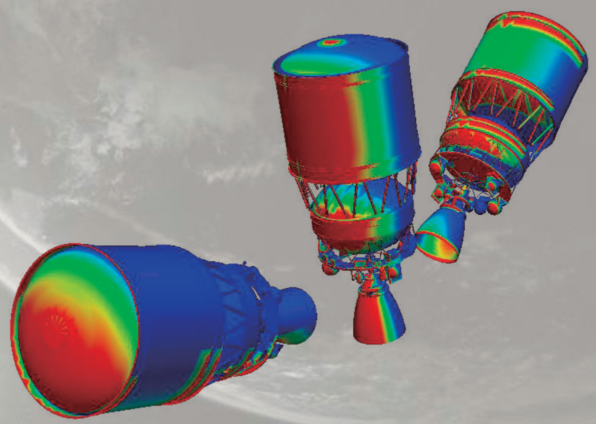
宇宙開発はこの半世紀において科学や工学の両面において飛躍的な発展を遂げてきた．一方，宇宙開発を今後も持続可能なものにするためにはスペースデブリ問題の対策が重要である．本研究は新たなデブリ発生を抑える非デブリ化対策として，ロケット上段や宇宙機の大気圏突入後の溶融残存物による地上被害リスクの最小化を目指している．とくに本研究では高忠実な物理モデルを採用した，複雑な実機形状の複合物理連成シミュレーションによるリエントリ安全評価法 LS-DARC（Destructive Atmospheric Re-entry Code）を開発している．設計パラメータ変更による安全性向上度を定量的に分析できるようにすることで，a) 上流設計段階からの溶融促進設計，b) 認知学的な不確かさの低減による高精度なリスク評価を実現することが目的である．LS-DARC を用いることで，下図に示すようにロケット上段や衛星などの複雑形状に対し，空力，6 自由度姿勢/軌道，熱流束，伝熱を連成解析し，溶融・破壊による形状変化も扱うことができる複合物理連成シミュレーションを行うことができる．本報告では，LS-DARC の開発状況と安全性評価法としての実用化に向けた研究課題を議論する．

Exponential progress in space exploration both for science and engineering have been made in a half century. Space debris problem is a growing concern to be tackled internationally to keep our space activity sustainable. For the improvement in the ground safety related to the survived debris after the destructive re-entry of the rocket upper stages and the spacecrafts, the comprehensive considerations on the design and the disposal operation should be made. High-fidelity model-based re-entry safety analysis tool LS-DARC is under the development in JAXA. Purpose of this study is an establishment of quantitative assessment of the design and disposal operation change effect on the re-entry risk. Consequently, a) design for demise from the initial development phase, and b) accurate risk prediction by reducing epistemic uncertainty are realized. LS-DARC is multi-physics coupling analysis code including the aerodynamic and 6DoF trajectory analysis, surface heat flux distribution analysis, three-dimensional thermal transfer analysis. Complicated real geometry can be considered including the small curvature effect on the heat flux increase and the shape change due to structure demise. Development status of LS-DARC is overviewed and the research needs are discussed.



2018.12.04 8th Space debris Workshop @ Chofu, Tokyo, Japan

Development of High Fidelity Model-based Re-entry Safety Analysis Tool LS-DARC – Part 1



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R&D Directorate, Research Unit III (JEDI)

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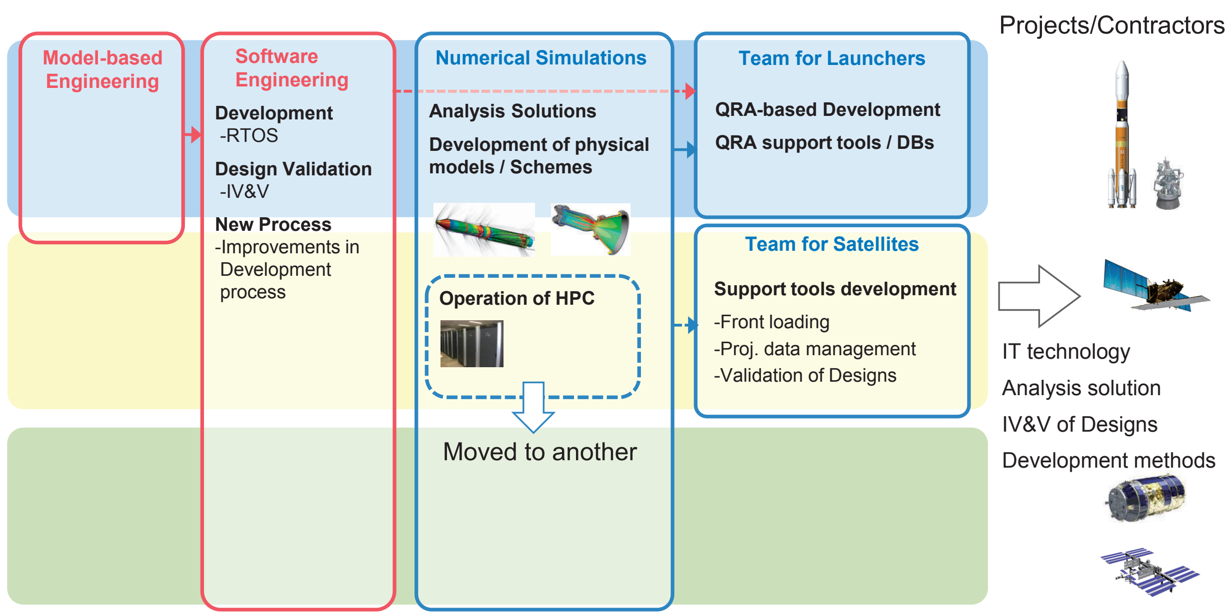
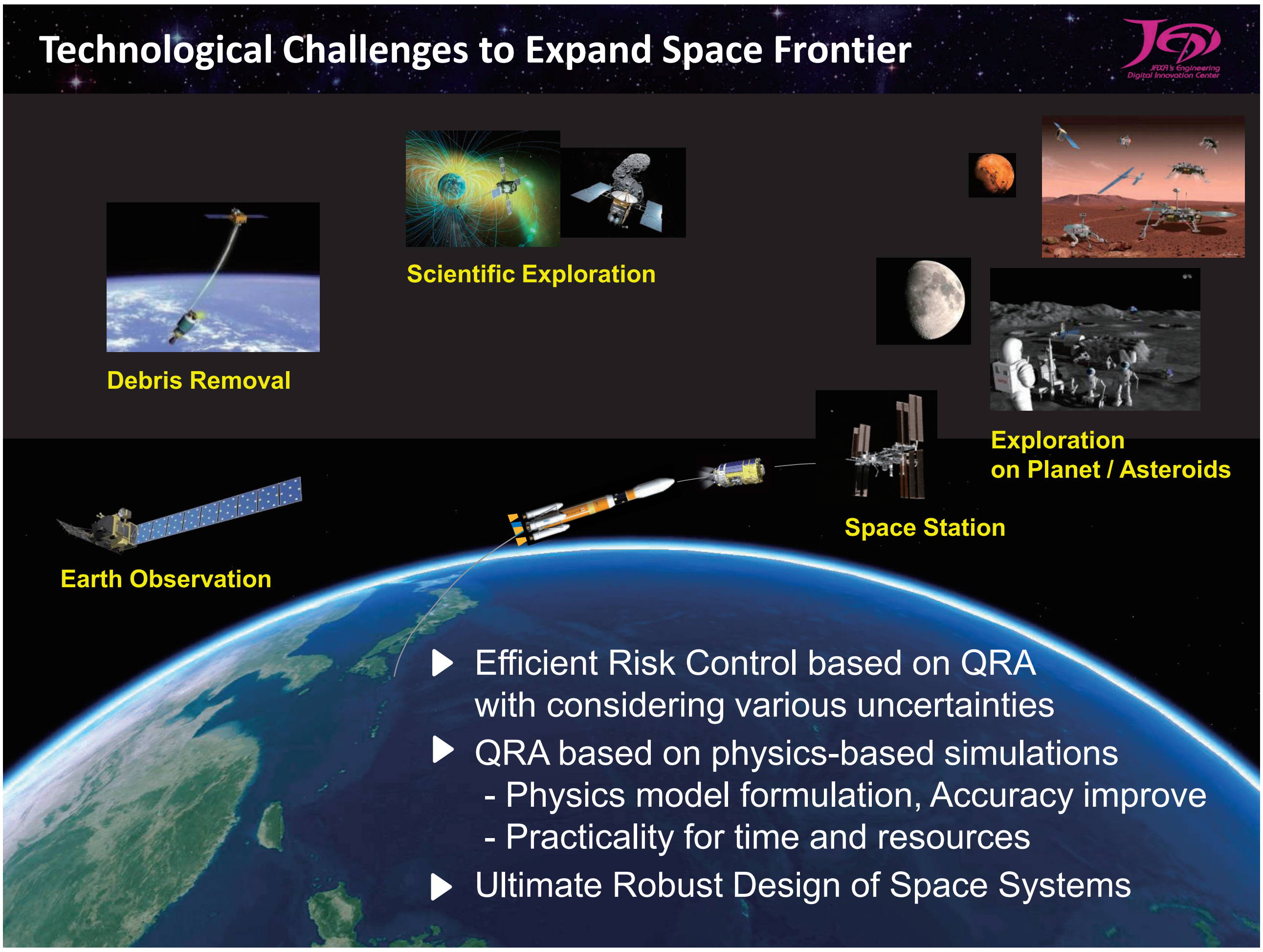
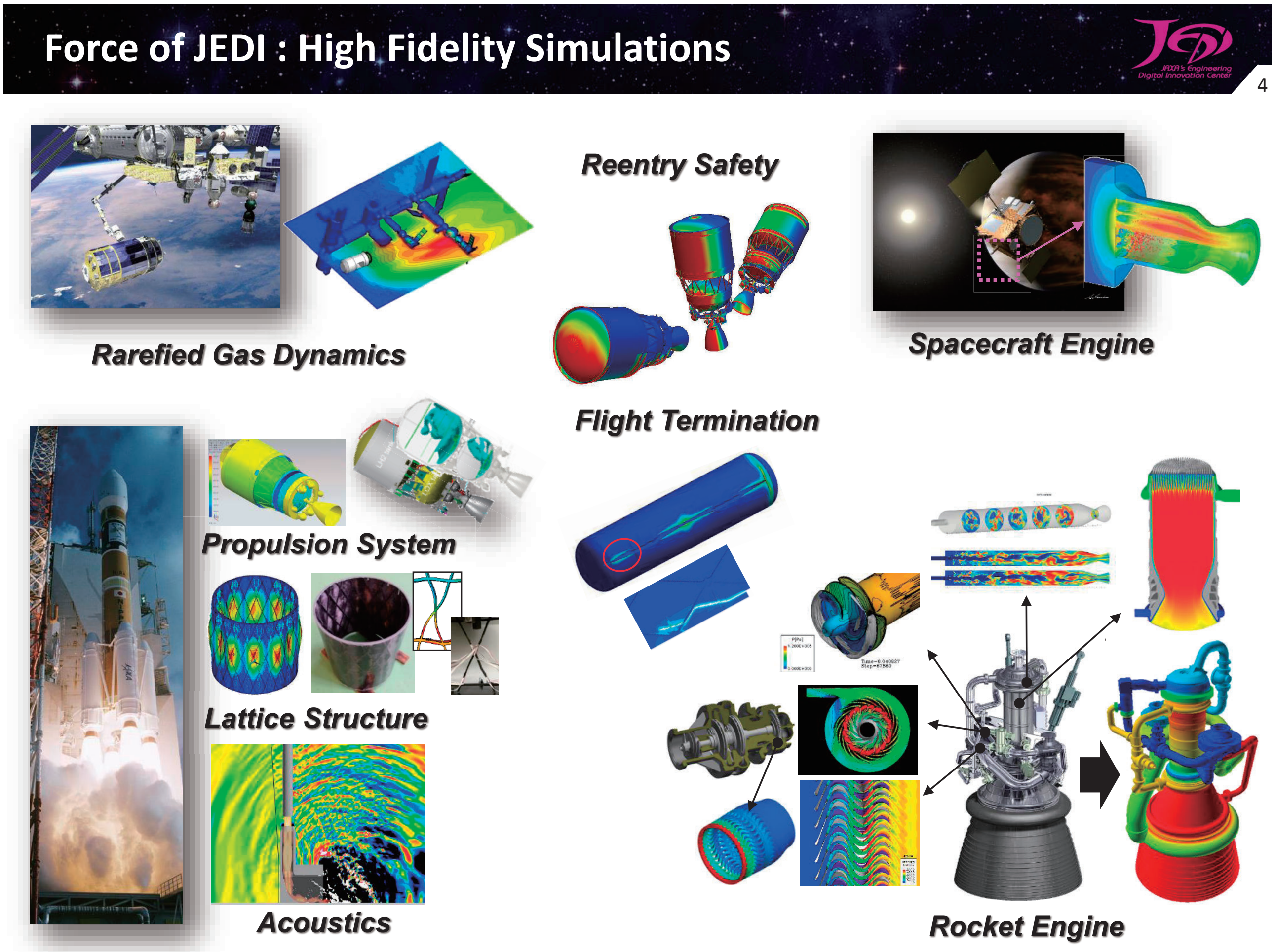
R&D Research Unit III (JAXA's Engineering Digital Innovation Center)

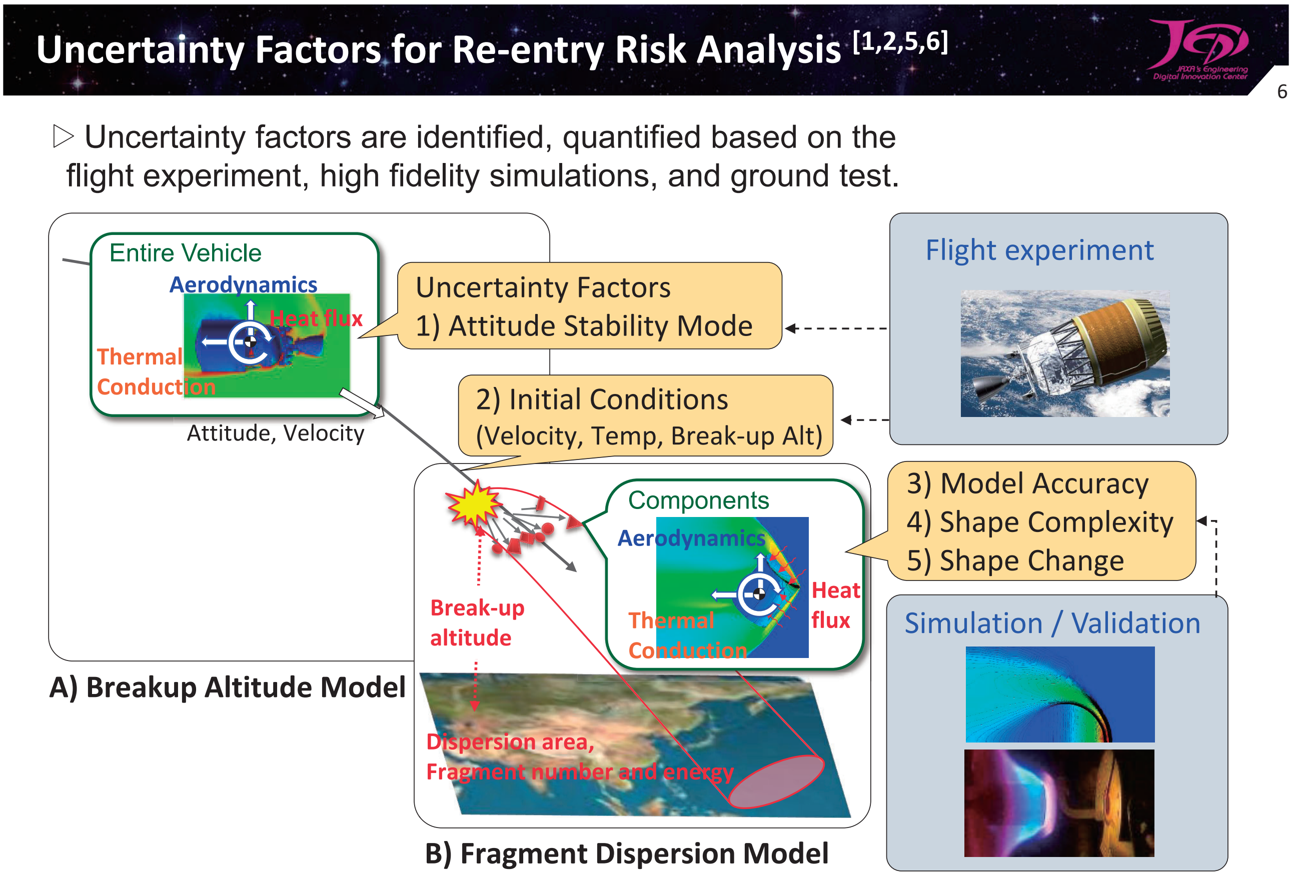
- Innovation of Engineering by using advanced IT technology
- IT technology professionals (About 40~50 people)




Technological Challenges to Expand Space Frontier
Debris Removal
Scientific Exploration
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 formulation, Accuracy improve
- Practicality for time and resources
Ultimate Robust Design of Space Systems


Force of JEDI : High Fidelity Simulations
4
Reentry Safety
Rarefied Gas Dynamics
Spacecraft Engine
Flight Termination
Propulsion System
Lattice Structure
Acoustics
Rocket Engine


Technological Challenges for our Sustainable Space Activity
Low cost active debris removal
(Risk control by removing existing objects)
Debris mitigation
(To prevent number increase,
design and operation improvement)
Debris situational awareness and defense
(Risk control for existing objects)
Formulating international standards and guidelines
(Rule-based risk control, sharing knowledge)


Uncertainty Factors for Re-entry Risk Analysis [1,2,5,6]
6
▷ Uncertainty factors are identified, quantified based on the flight experiment, high fidelity simulations, and ground test.
Entire Vehicle
Aerodynamics
Heat flux
Thermal Conduction
Attitude, Velocity
Uncertainty Factors
1) Attitude Stability Mode
2) Initial Conditions
(Velocity, Temp, Break-up Alt)
Flight experiment
Components
Aerodynamics
Heat flux
Thermal Conduction
Break-up altitude
Dispersion area,
Fragment number and energy
3) Model Accuracy
4) Shape Complexity
5) Shape Change
Simulation / Validation
A) Breakup Altitude Model
B) Fragment Dispersion Model

Update Plan for Re-entry Safety Analysis Tools at JAXA

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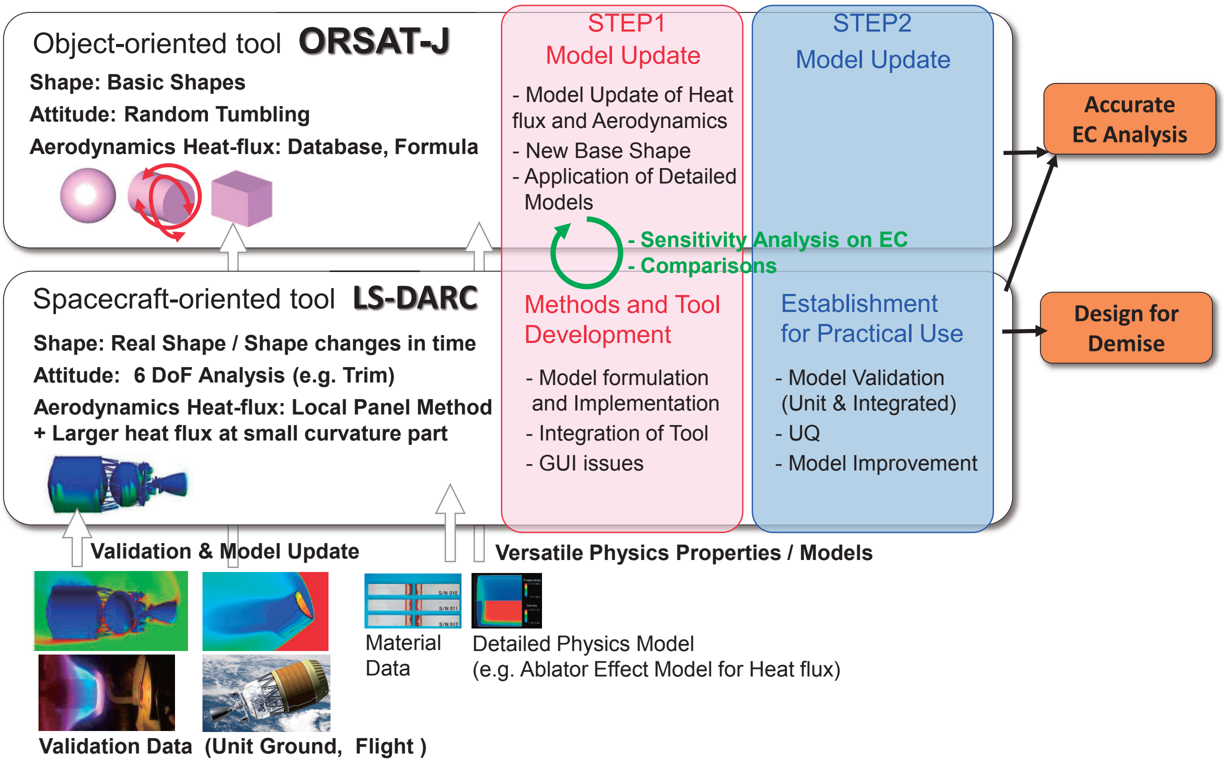
1) By improvement of re-entry safety analysis methods, accuracy improvement EC analysis and design for demise will be achieved.
2) By understanding physical mechanism, physics-based model and assumptions are re-considered.



Epistemic Uncertainty Quantification Strategy [1,2,5,6]

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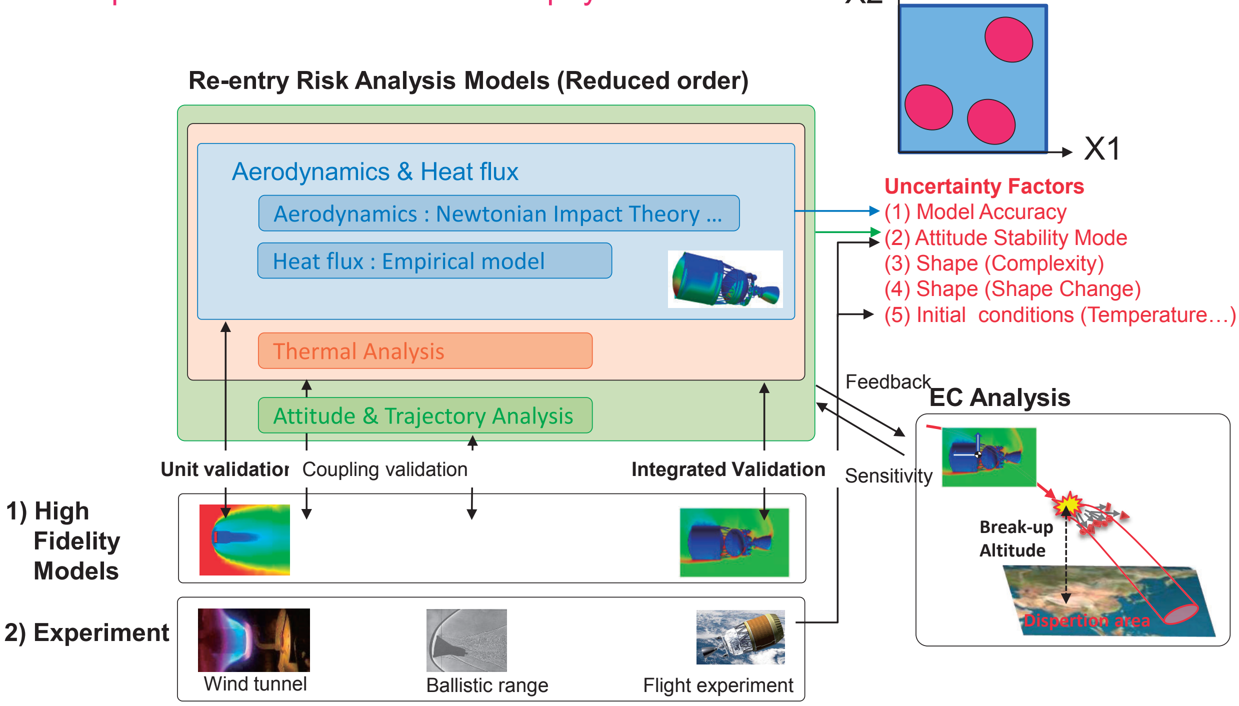
▷ Started from low cost Unit validation, then expensive Integrated validation.
▷ High fidelity simulation to understand physics and cover huge parameter space.
▷ Experiment not to miss unknown physics.



Spacecraft-oriented Re-entry Risk Analysis Tool : LS-DARC [3,4]

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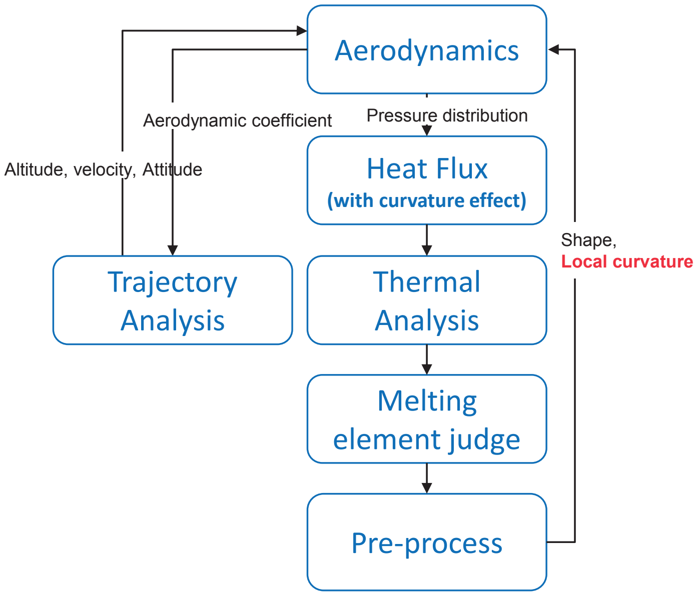
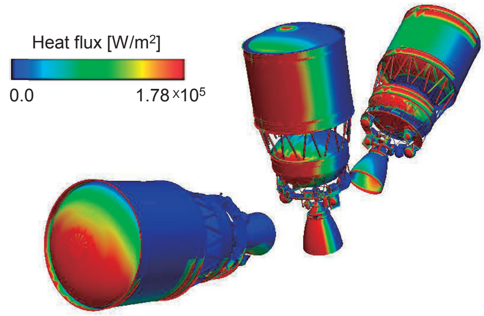
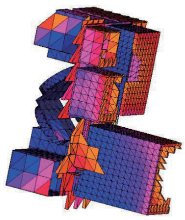
- **LS - Destructive Atmospheric Re-entry Code (LS-DARC)**
- Development start from FY2015, will be completed 1st ver. in this year.
- Heat flux model with considering local curvature effect !!
- Investigation on dynamic sampling[9], GPU-based shadowing.
- Model validation by wind tunnel and flight data is under the way for upper stages.







SCARAB (ESA) [7]

JAXA's CFD Tools for LS-DARC Model Validation [3,4]

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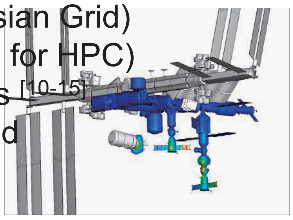
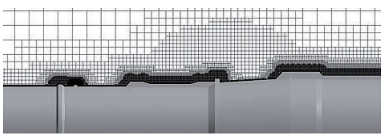
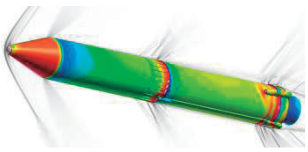
- High Altitude (Rarefied Flow) <UNITED>
  - Handling Complicated Geometry with 6DOF motion (Cartesian Grid)
  - Fast Computation (Tuned for HPC)
  - Various Numerical Models [10-15]
  - Validated & Widely Applied



Governing equations	Boltzmann equation of kinetic theory
Chemical reaction	No chemical reaction is considered
Collision model	Variable Soft Sphere model [11]
Internal energy relaxation model	LB model for internal energy relaxation [15] Constant (Zr=5, Zv=50) model for relaxation coefficient of rotational and vibrational energy
Wall reflection model	Diffusion reflection boundary at 300K (wall)
# of Particles	10^7 - 10^8

- Moderate/Low Altitude (Continuum Flow) <LS-GRID[16] / FLOW[17,18]>
  - Handling Complicated Geometry with 6DOF motion (Cartesian Grid-based)
  - Fast Computation (Tuned for HPC , Adaptive Mesh Refinement)
  - Various Numerical Models
  - Validated[19-21] & Applied to cryogenics[22] and combustion[23]





Governing equations	3D compressible Navier–Stokes eqs.
Chemical Reaction	Detailed chemical reaction, Fast time integration ERENA[34], Flamlet[36]
Spatial discretization	Cell-centered FVM
Spatial reconstruction	Green-Gauss[27,28,29] etc. Venkatakrishnan[30] limiter etc. (Wang's modification[31]) High-order FR method[32]
Inviscid Term	SLAU2[33] etc.
Viscous Term	Shima's Method
Turbulence Model	Baldwin-Lomax[24] Spalart-Allmaras[25] DES/DDES[26]
Time Integration	2nd order LU-SGS[34] with inner iterations
Grid	-Arbitrary unstructured grid -Body-fitted Cartesian grid[16]

High Fidelity Simulations - Random tumbling or Trim ?

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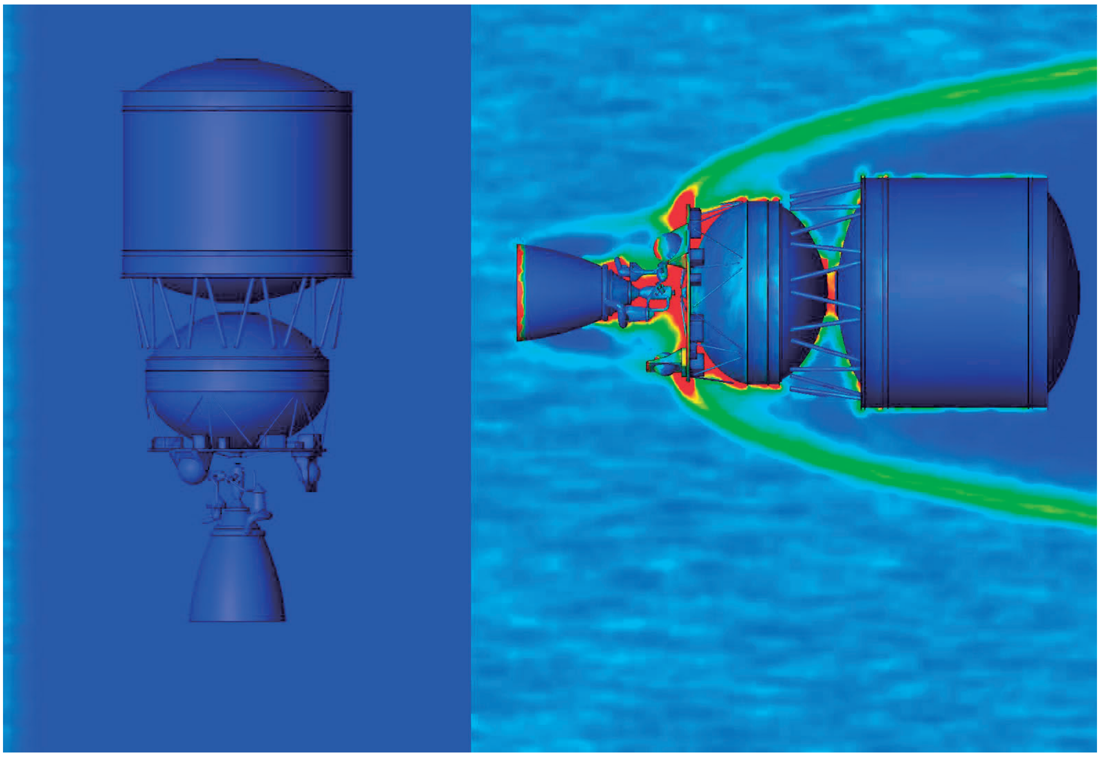
Demonstration 6DoF Analysis by DSMC code (UNITED)



High Fidelity Simulations - 1st Breakup Mechanism ?

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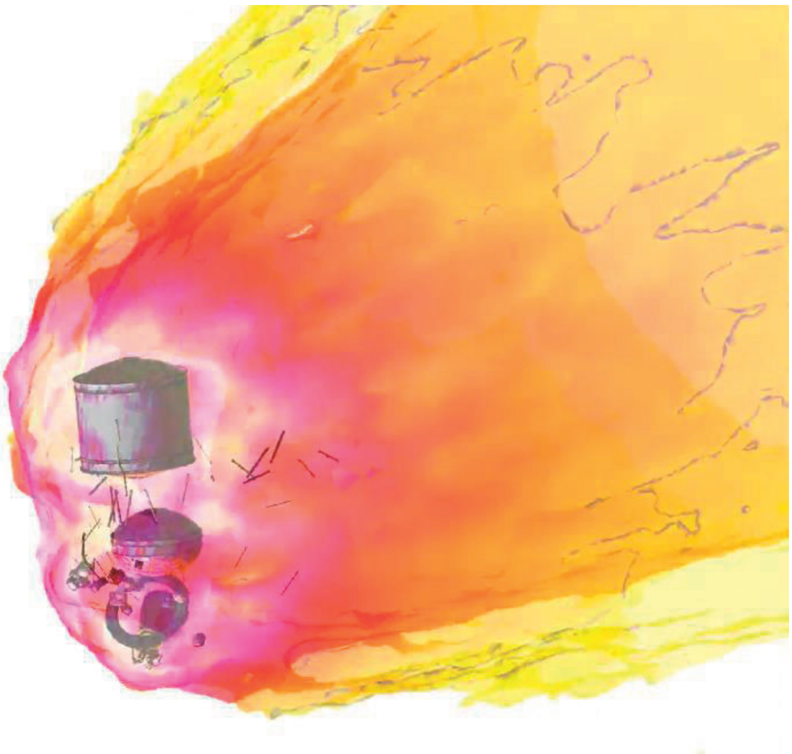
Demonstration 6DoF Analysis by DSMC code (UNITED)



Re-entry Flight Test – Model Validation and Understand Physics

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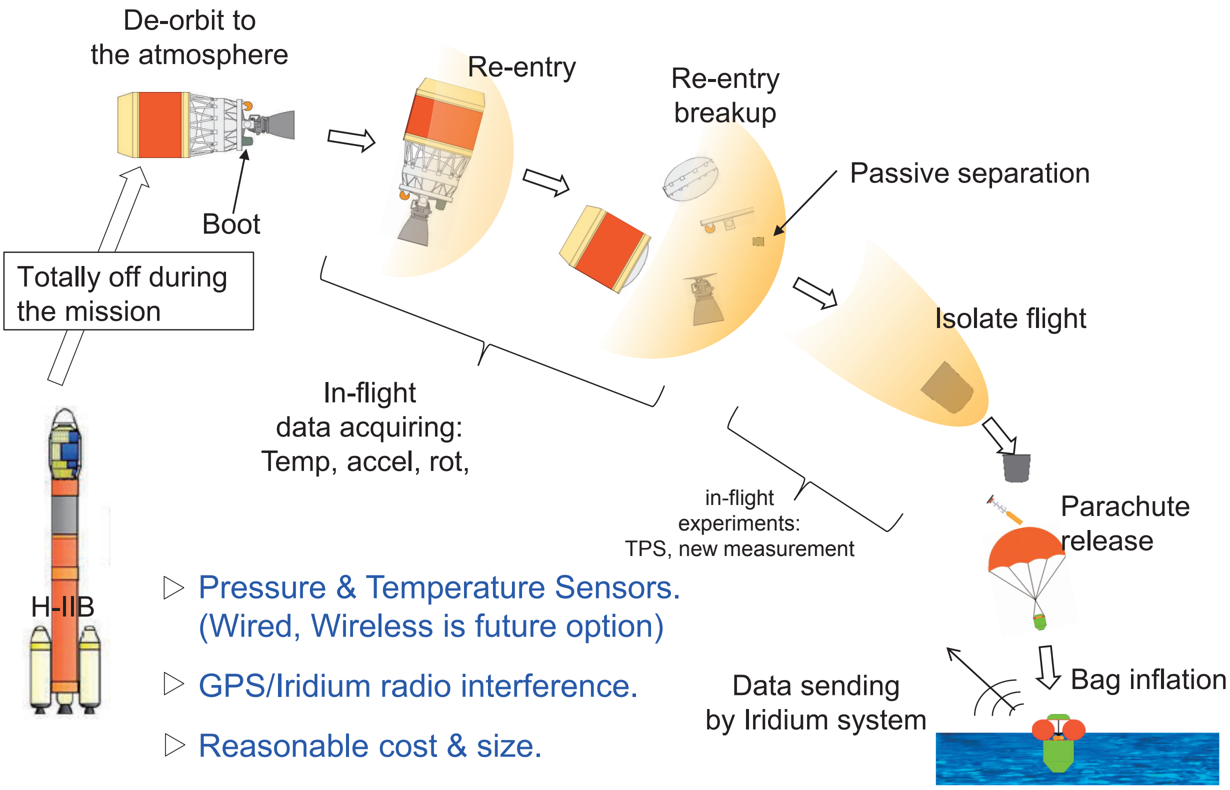

- ▷ Pressure & Temperature Sensors.
  (Wired, Wireless is future option)
- ▷ GPS/Iridium radio interference.
- ▷ Reasonable cost & size.
- ▷ Currently under the certification.

Object of benchmark study between JAXA and CNES [4]

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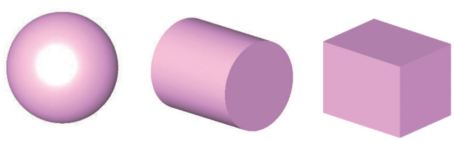
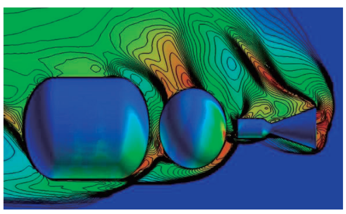
- ▷ Understanding of the flow mechanism during the re-entry.
- ▷ Uncertainty quantification especially for the aerodynamic characteristics and the heat flux models.
- ▷ Further accuracy improvement based on the detailed understanding of the physics and the bits from the high-fidelity numerical simulation fields.
- ▷ JAXA wants to develop spacecraft-oriented re-entry risk analysis, and CNES wants to compare CFD and the local surface method results.

STEP1 : Basics (FY2015~2017)
- Well studied and much experiments
- Less uncertainty factors
  and known I.C. and B.C.

STEP2 : Rocket Upper Stage (FY2017)
- Less studies
- To know current model accuracy
  for realistic problems
  (e.g.) Shock interaction, concave shape





Basic Shape: Analysis Conditions and Grid

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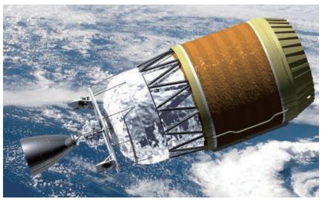
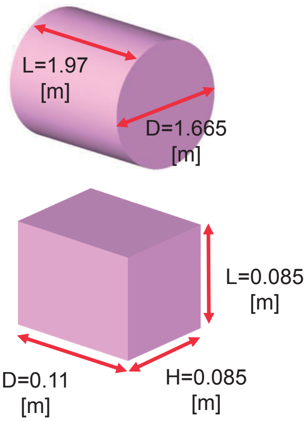
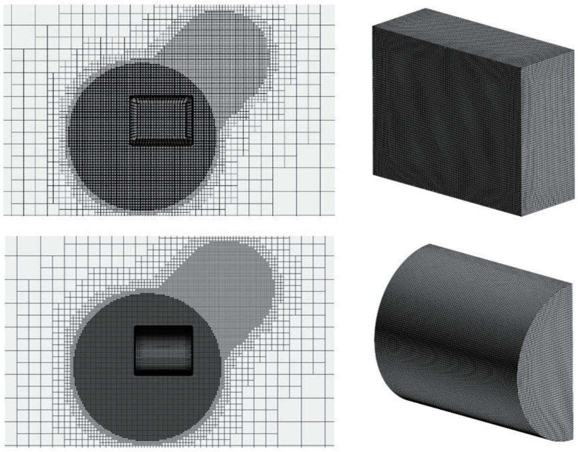
- ▷ Geometries are cylinder and box (Sub-systems of rocket upper stage).
- ▷ $M_\infty = 11.72$ for box, $M_\infty = 14.35$ for cylinder.
- ▷ Laminar flow, 2nd order Green-Gauss with Venkatakrishnan limiter, SLAU2 for Euler flux, 2nd order time accuracy by LU-SGS with inner iteration.







Total : 2.64 million cells
Minimum grid size:
3.36 × 10^{-6} Cell Reynolds number=0.5 for box
1.39 × 10^{-5} Cell Reynolds number=0.5 for cylinder

Basic Shape: Comparison of CFD and Correlation Models [4]

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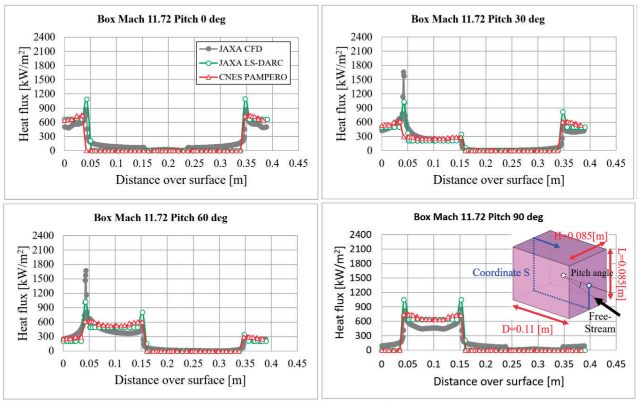
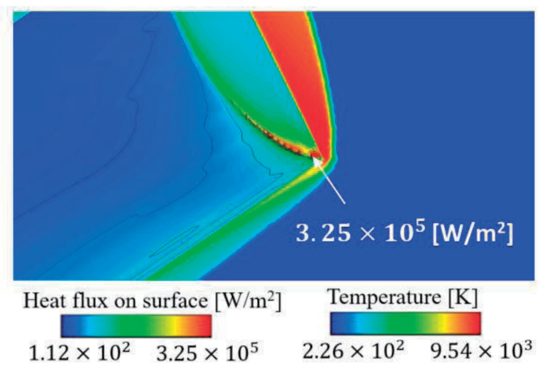
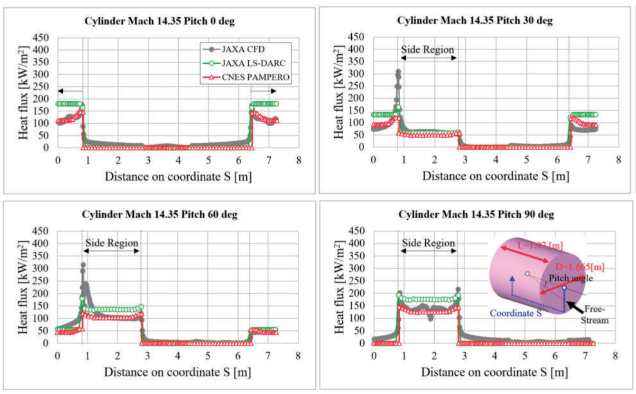
- ▷ LS-DARC and PAMPERO[8] can quantitatively predict even at corners with same model parameter value.
- ▷ Shadowed lee-ward surface may have non-zero heat flux. → Next research topic.







Upper Stage: Analysis Conditions and Grid

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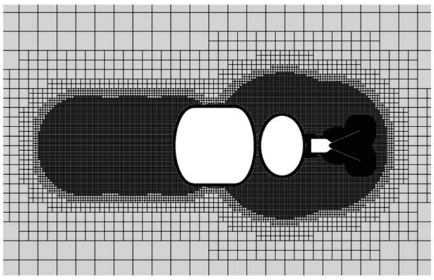
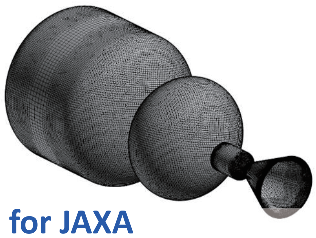
- ▷ Geometries are simplified rocket upper stage.
- ▷ $M_\infty = 10.64$ at 45 km.
- ▷ Baldwin-Lomax model, 2nd order Green-Gauss with Barth-Jespersen limiter, SLAU for Euler flux, 2nd order time accuracy by LU-SGS with inner iteration.





Grid for JAXA
Total : 3.97 million cells
Minimum grid size:
1.85 × 10^{-6} Cell Reynolds number=5.0

Grid for CNES
Total : 7.94 million cells
Minimum grid size:
1.0 × 10^{-6}

Upper Stage: Comparison of CFD and Correlation Models [4]

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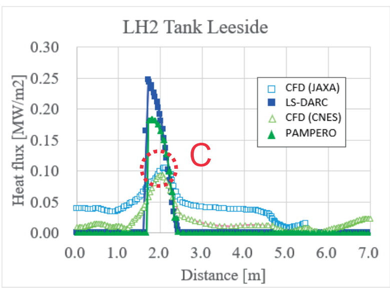
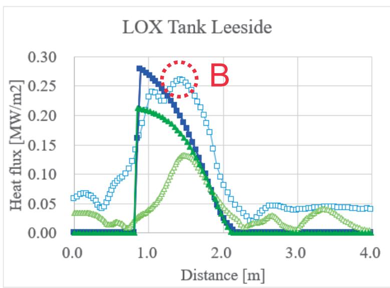
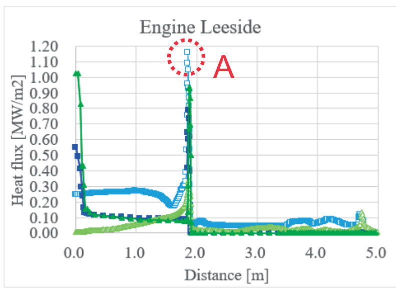
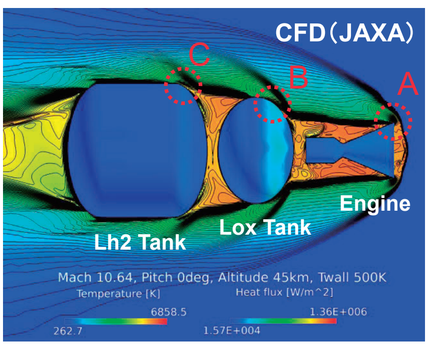
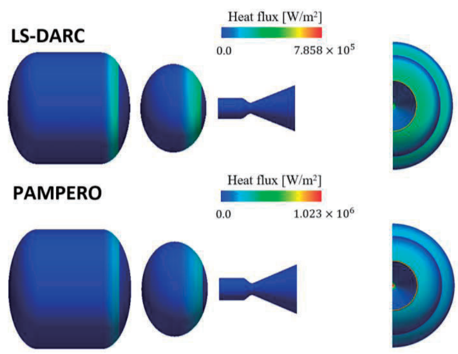
- ▷ Results by CFD and correlation models are in good agreement. Large local peak at nozzle rip can also quantitatively predicted.
- ▷ Larger heat flux by correlation models over tanks in wake flow.











Upper Stage: Comparison of CFD and Correlation Models [4]

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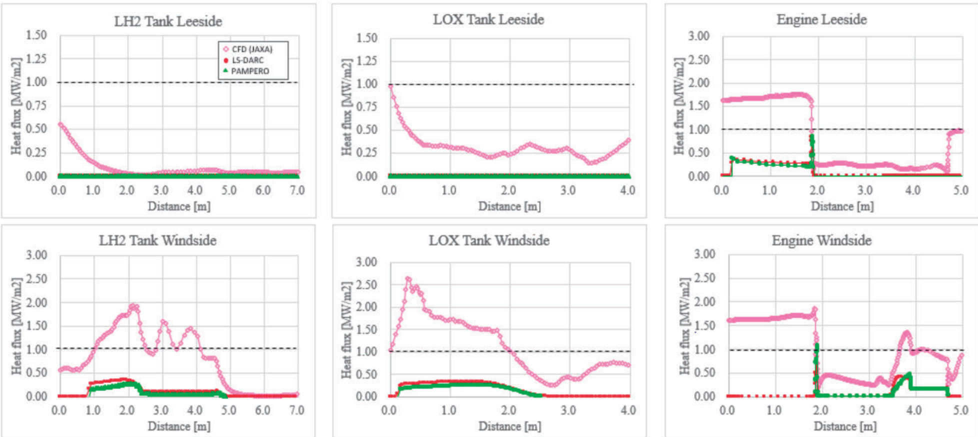
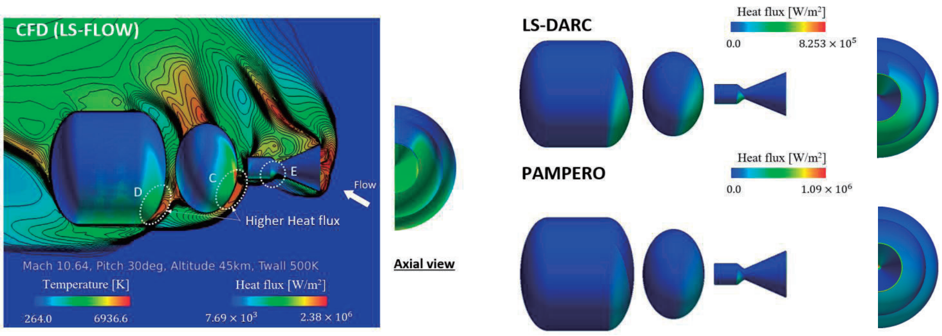
▷ Much smaller for correlation model than CFD result.





LS-DARC Demonstration for Rocket Upper Stage

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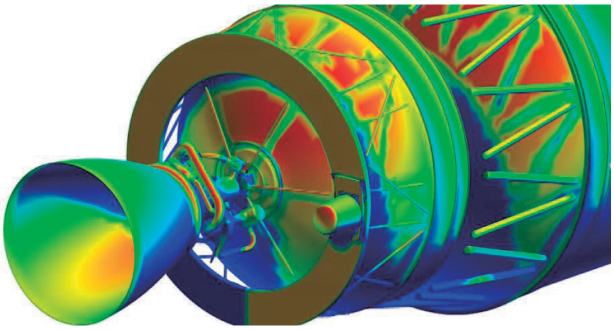
▷ Real shape effect can be considered.
- Possibility of trim
- Increased aerodynamic heating area
- Rapture due to local heating spot
  (by heat flux model with considering local curvature effect)

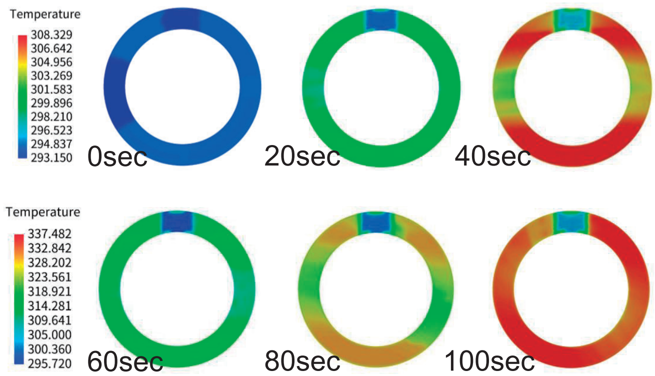
▷ Easy-to-Use, Just prepare 3D mesh for thermal analysis.
- Fully automated analysis can be realized.

▷ LS-DARC can be applied to
- Natural decay prediction
- Conceptual design studies
  (Minimum dV for re-entry, etc…)

▷ Model validation work is under the way.



Heat flux distribution



Conclusion and Future Works

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▷ Uncertainty quantification strategy was proposed.

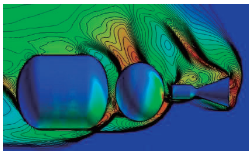
▷ Benchmark study for basic shapes and rocket upper stage were carried out between JAXA and CNES.

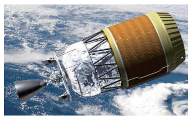
- Key flow mechanism such as significant larger heat flux at sharp edges, and the shock interaction and low dynamic pressure wake effect for multiple bodies were clarified.
- Heat flux predicted by correlation models are in good agreement with CFD even for significant large heat flux peak at sharp corners.

▷ Further research should be done for aerodynamics and heat flux models

Formulation for
1) Concave shapes
2) Wake effect (low dynamic pressure)
3) Shock interactions
4) Turbulent boundary layer effect
5) Non-zero hidden leeward surfaces

Validation for
1) Heat flux with small curvature effect





Flight tests

▷ Further research also for destruction modeling at high temperatures

▷ Validation and detailed analysis for upper stage are currently under the way.

High-fidelity Analysis Wind-tunnel tests

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22

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