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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 2 報　熱流束モデル検証プロセス

Development of High-Fidelity Model-based Re-entry Safety Analysis Tool LS-DARC: Part 2 Uncertainty Quantification Process for Heat-flux Model

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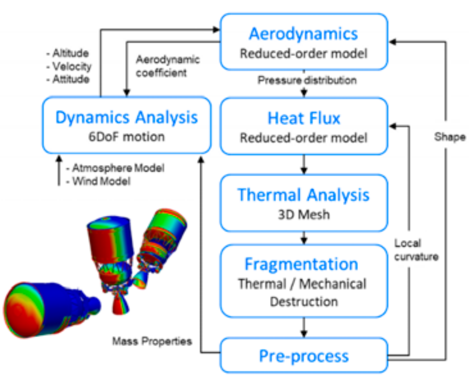
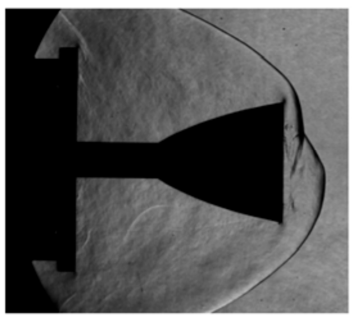
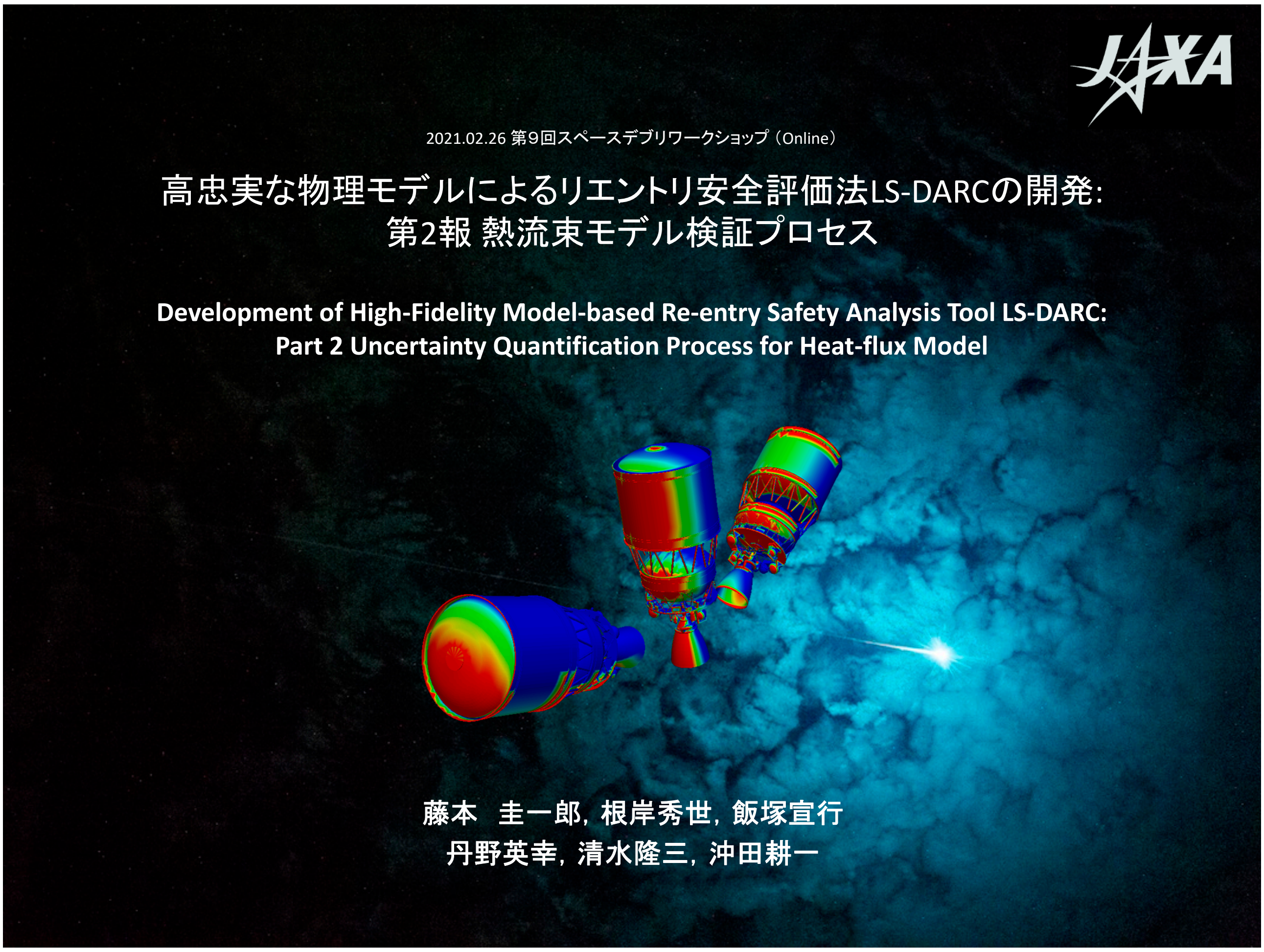
宇宙開発はこの半世紀において科学や工学の両面において飛躍的な発展を遂げてきた．一方，宇宙開発を今後も持続可能なものにするためにはスペースデブリ問題の対策が重要である．本研究は新たなデブリ発生を抑える非デブリ化対策として，ロケット上段や宇宙機の大気圏突入後の溶融残存物による地上被害リスクの最小化を目指している．本研究では，とくに高忠実な物理モデルをベースとした複合物理連成解析法であるリエントリ安全評価法 LS-DARC（Destructive Atmospheric Re-entry Code）の開発に取組んでいる．設計パラメータ変更による安全性向上度を定量的に分析できるようにすることで，a) 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 により下図に示すようなロケット上段や衛星などの複雑形状に対して溶融残存物が生じるかどうかを評価することができるが，安全評価法として実用化するためには物理モデルの検証プロセスの確立が不可欠である．本報告ではとくに熱流束モデル検証方法を提案し，高エンタルピー風洞試験による検証データ取得をはじめとした検証状況について述べる．

Remarkable 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. Establishment of the uncertainty quantification process of the LS-DARC models is essential in order to make it practical re-entry safety analysis tool. In this report, the uncertainty quantification process especially on the heat flux model is proposed and discussed. Research activities on the validation data acquisition by the high-enthalpy wind tunnel and the model validations are discussed.






JAXA
2021.02.26 第9回スペースデブリワークショップ（Online）
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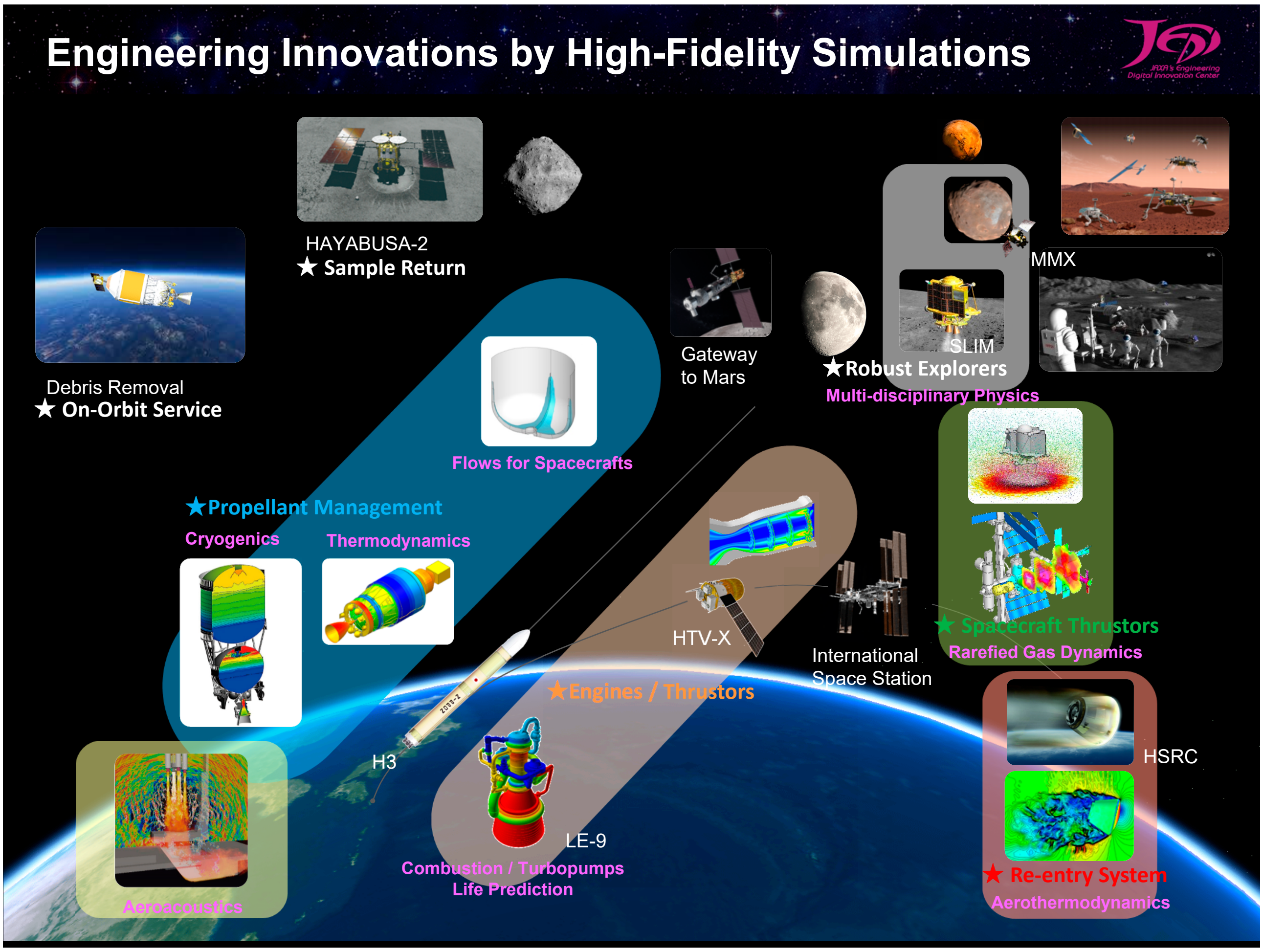
Engineering Innovations by High-Fidelity Simulations
HAYABUSA-2
★ Sample Return
Debris Removal
★ On-Orbit Service
Gateway
to Mars
MMX
SLIM
★Robust Explorers
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Flows for Spacecrafts
★Propellant Management
Cryogenics
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HTV-X
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Space Station
★ Spacecraft Thrustors
Rarefied Gas Dynamics
★Engines / Thrustors
H3
HSRC
LE-9
Combustion / Turbopumps
Life Prediction
★ Re-entry System
Aerothermodynamics
Aeroacoustics

Technological Challenges for our Sustainable Space Activity

Overview of Re-entry Safety Analysis

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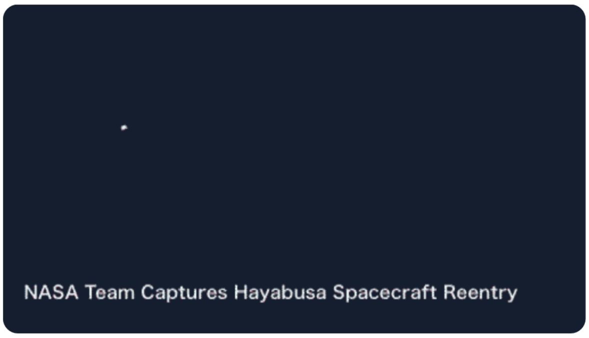
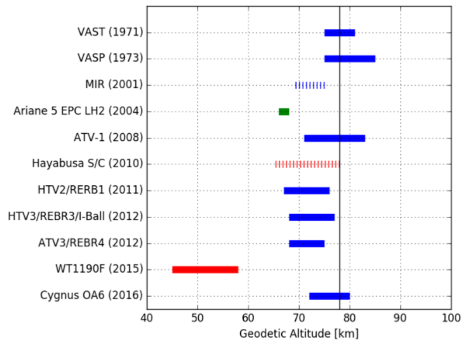
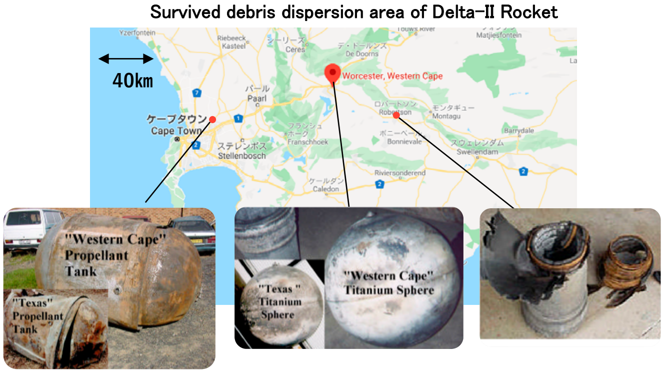
- Expected casualty (EC) value due to the survived debris of rocket upper stage and spacecrafts.
- If required, EC value is minimized by the controlled re-entry and the design-for-demise.
- Re-entry safety requirement is getting restricted internationally.





Survived debris dispersion area of Delta-II Rocket



AJ10 Engine(90~100kg)

Motivation to Develop High-fidelity Re-entry Safety Model

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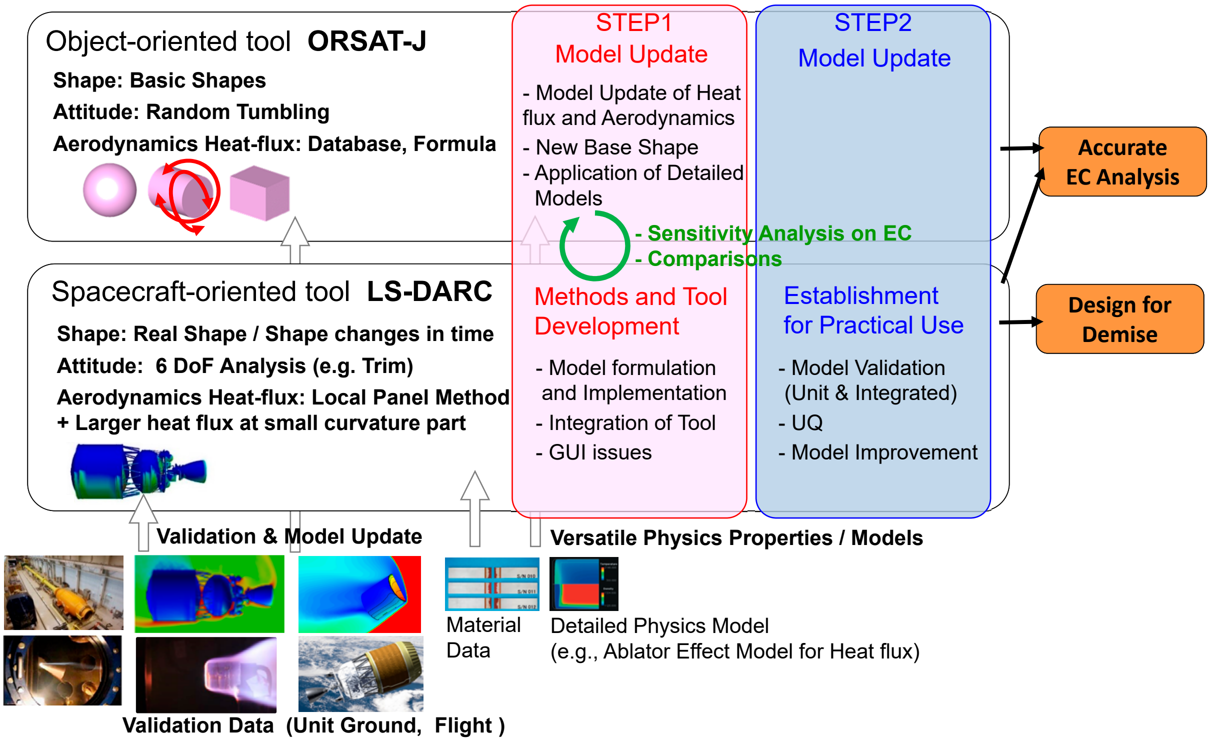
▹ Accurate EC analysis becomes available by reducing epistemic uncertainties.
(e.g.) Heating surface area can be increased by considering the detailed geometries.

▹ Design-for-Demise becomes available by evaluating the design parameter sensitivity.



Spacecraft-oriented Re-entry Risk Analysis Tool : LS-DARC

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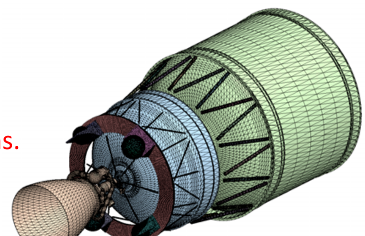
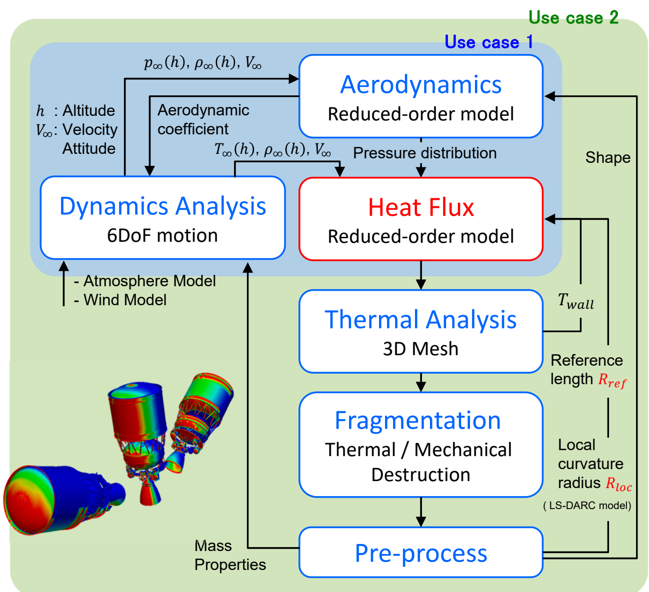
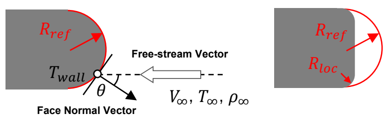
LS - Destructive Atmospheric Re-entry Code (LS-DARC)

▹ Development start from FY2015, completed 1st version in this fiscal year.
▹ Easy-to-use multi-disciplinary physics analysis.
▹ Heat flux models are originally formulated for the basic shape predictions.
▹ Heat flux model with considering local curvature effect.
▹ Fast MPI runs by super-computers.



Arbitrary Polyhedral Mesh





Trajectory	6DoF equations of motion – 4th order Runge–Kutta / Higher–order
Atmospheric properties	– US62/76 – NRL MSISE–00 / Earth GRAM
Aerodynamics	– Modified Newton Impact Theory – Nocilla correlation model
Heat flux	– LSDARC model – SCARAB 3.1 model (Radiative dissipation, oxidization, hot wall effect modification)
Thermal analysis	3D Thermal transfer equation
Destruction	– Thermal destruction – Mechanical destruction * under the development

Spacecraft-oriented Re-entry Risk Analysis Tool : LS-DARC

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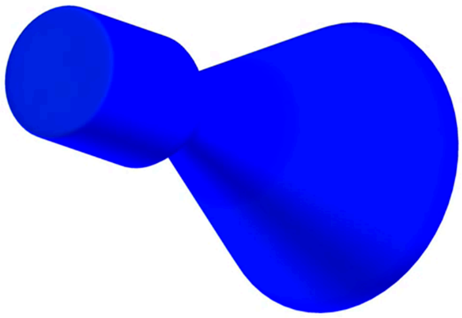
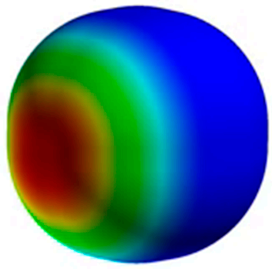
High-fidelity multidisciplinary analysis including 6-DoF motion and shape change effects.

Important considerations for the accurate EC predictions are,

- ▷ Fragment is aerodynamically stable or not ?
- ▷ How much attitude behavior and the deceleration rate are varied by the shape change ?
- ▷ How much are the heat flux level and the temperature increase rate changed during the re-entry ?



Melting Rocket Engines



Gas Tanks

Ref (1): Fujimoto, K., Negishi, H., Shimizu, R., Daibo, T., Iizuka, N., Okita, K., "High-Fidelity Spacecraft-oriented Re-entry Safety Analysis Code of JAXA: LS-DARC", Proceedings of the 9th IAASS Conference, 2019.

Uncertainty Quantification Process – Key Uncertainty Factors

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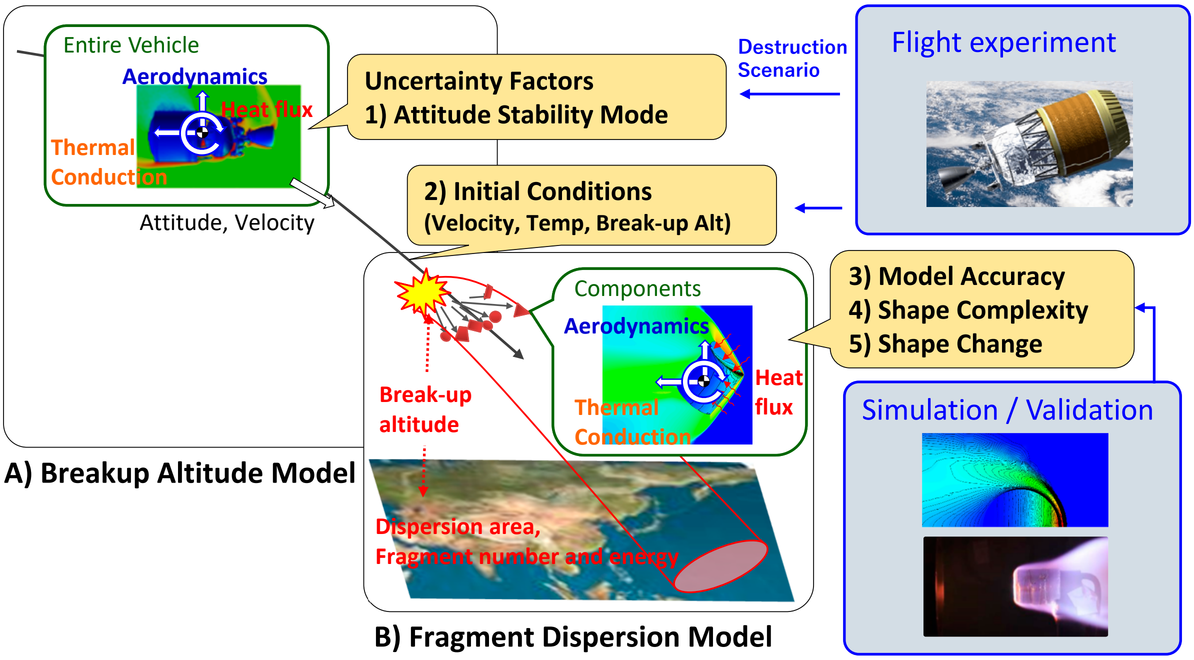
▷ Key uncertainty factors for re-entry risk analysis are identified, and the related uncertainties are quantified based on the flight experiment, high fidelity simulations, and ground test.



Ref (2): Fujimoto, K., Tani, H., Negishi, H., Saito, Y., Iizuka, N., Okita, K., Kato, A., "Uncertainty Quantification for Destructive Re-Entry Risk Analysis: JAXA Perspective," Stardust Final Conference, Conference, Springer book, pp.283-300, 2018.

Uncertainty Quantification Process – Overview

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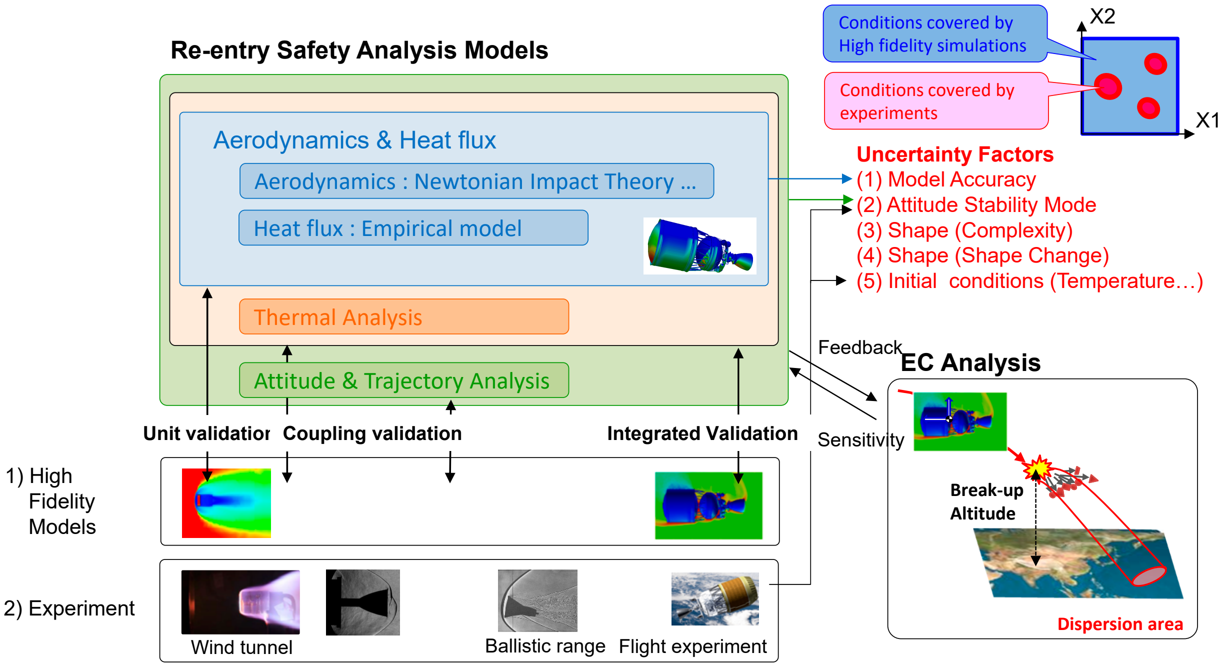
- ▹ Destruction scenario investigation and key uncertainty factor identification by flight test in early phases.
- ▹ Started from low-cost unit validation, then expensive Integrated validation.
- ▹ Comparison with high-fidelity simulations to understand physics and cover parameter space globally.
- ▹ Comparison with experiments not to miss unknown physics under the carefully selected conditions.



Strategy for Heat-flux Model Validations

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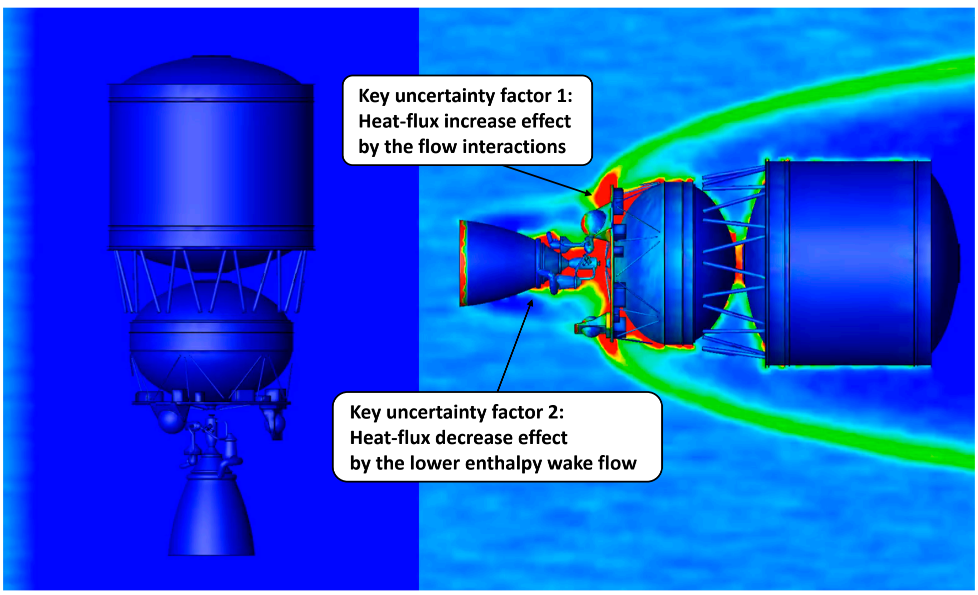
- ▹ Perfect prediction accuracy is not pursued, but its result should be the worst-case (e.g., lower heat-flux).
- ▹ Destruction scenario investigation and key uncertainty factor identification by flight test in early phases.
- ▹ Higher heat-flux area is always on the windward, thus the accurate prediction can be achieved even by the simple formulation of the heat-flux model.
- ▹ Heat-flux validations for basic shapes were carried out, then those for the realistic shape.



Demonstration 6DoF analysis by JAXA DSMC code (UNITED)

Unit Validation of Heat-flux Model for Basic Shapes

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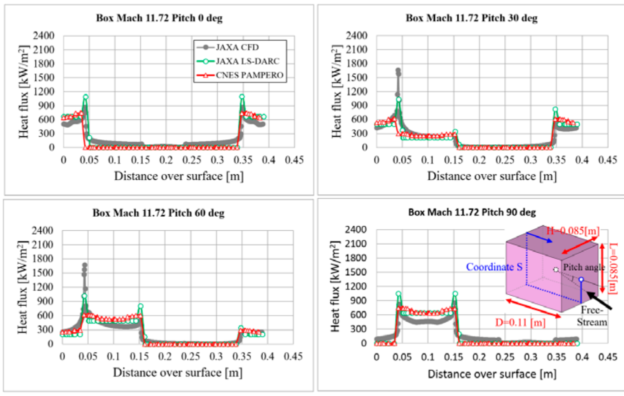
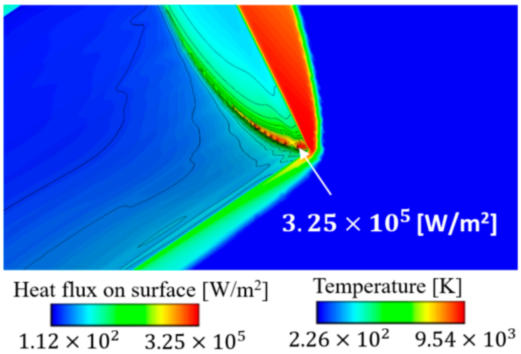
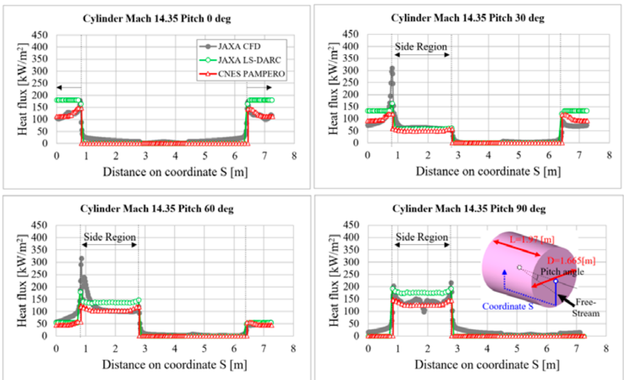
- ▹ Heat-flux model of LS-DARC were validated for basic shapes by the comparison with the results by CNES's PAMPERO under the joint research.
- ▹ LS-DARC and PAMPERO can quantitatively predict even at corners without changing the model parameter value.







Ref (3): Fujimoto, K., Negishi, H., Saito, Spel, M., Prigent, G., "Benchmark of JAXA and CNES Re-entry Safety Analysis Tools for Accurate Heat-flux Prediction ", Proceedings of the 9th IAASS Conference, 2017.

Unit Validation for Each Heat-flux Model Terms

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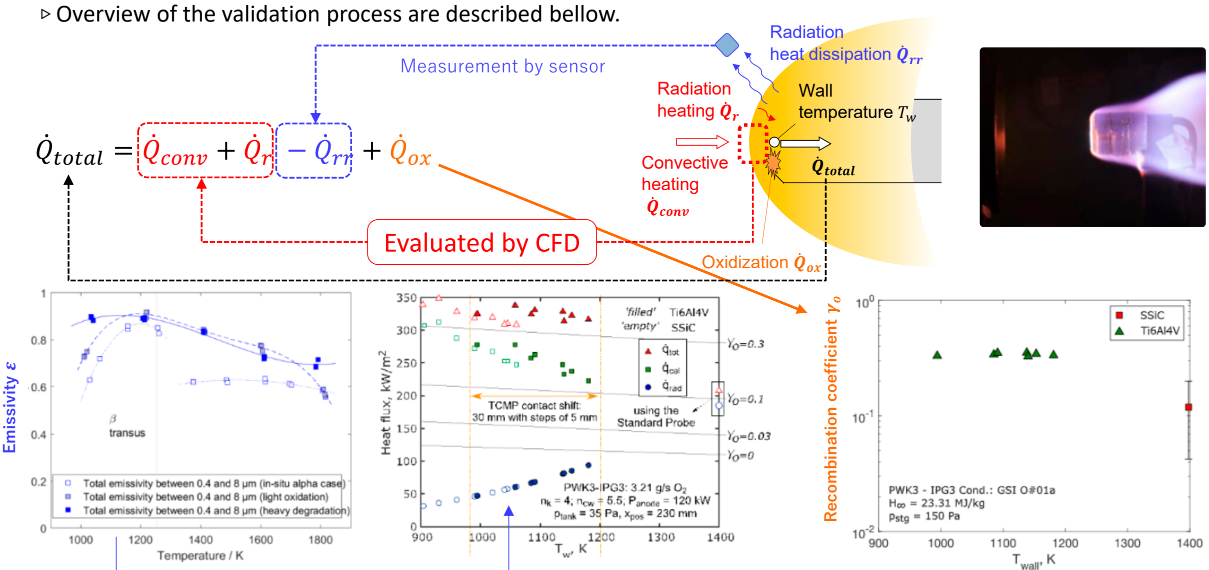
- ▹ Uncertainty quantifications for each heat flux model terms are essential.
- ▹ Unit validation process was proposed based on the previous works, the heat flux formulations and the related material properties will be validated.
- ▹ Heat-flux induced by the recombination $\dot{Q}_{ox}$, the convective heating $\dot{Q}_{conv}$, the radiation heating $\dot{Q}_r$, and the radiation heat dissipation $\dot{Q}_{rr}$ can be obtained. It significantly contribute to the efficient uncertainty quantification and the model accuracy improvement.
- ▹ Overview of the validation process are described bellow.

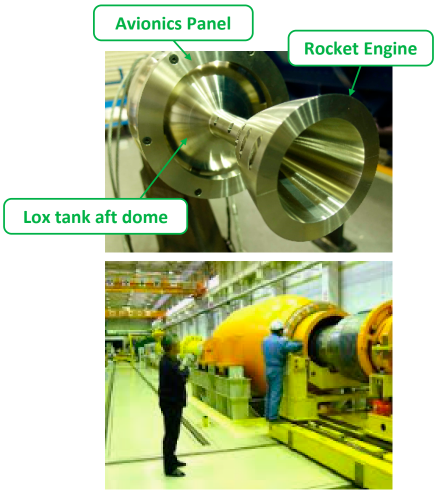


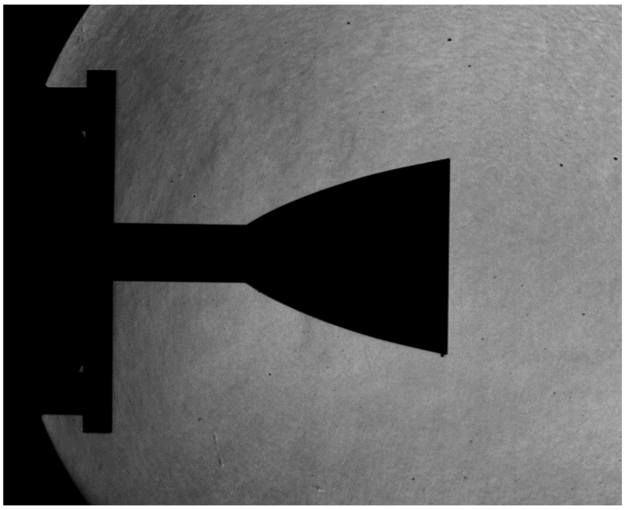
$$\dot{Q}_{rr} = \varepsilon \cdot \sigma \cdot T_w^4$$

**All plots are taken from the following literature.*
Ref (4): Massuti-Ballester, B., Pagan, A., Herdrich, G., "Oxidation and heterogeneous catalysis on titanium Ti-6Al-4V in high-enthalpy flows," IAC-18,C2,4,8,x46403, 2018.

Integrated Validation of Heat-flux Model for Realistic Shapes

▹ Integrated validation of the heat-flux model for the engine of rocket upper stage is under the way.
▹ Complicated flow interactions such as the shock wave interactions and the unsteady wake flow were observed, those effects are not considered in the heat-flux model formulations.
▹ Unsteady recirculation and shock wave motions are observed, which is resulting in the unsteady aerodynamic heating.
▹ Measured heat-flux distributions are compared with the predictions, and the model parameter sensitivity study is under the way to achieve the lower predicted heat-flux level as comparing with the measurement.





High enthalpy shock tunnel : HIEST Max enthalpy 25MJ/kg, Max stagnation pressure 150MPa, 0.5m test article

Conclusion

▹ High-fidelity spacecraft-oriented re-entry safety analysis code LS-DARC (Destructive Atmospheric Re-entry Code) has been developed for the epistemic uncertainty reduction on the expected casualty (EC) predictions and the design-for-demise to minimize the ground risk related to the survived debris.

▹ LS-DARC is the high-fidelity multidisciplinary coupling analysis code to predict the complicated off-nominal physics during the destructive re-entry of the rocket upper stages and the spacecrafts.

▹ Trajectory and attitude of the multiple complicated fragments, and those demising processes due to the severe aerodynamic heating can be predicted. Reduced-order models of the aerodynamic characteristics and the heat flux distributions are keys to handle complicated fragment shapes and to maximize analysis speed for the practical probabilistic analysis.

▹ Analysis capabilities and the current development status were shown. Uncertainty quantification strategies were discussed especially for the heat flux model.

▹ [Previous study] Predicted heat flux distributions were agreed well with the CFD result, and the prediction capability of the LS-DARC has been reached the same level with the ESA's SCARAB and the CNES's PAMPERO.

▹ Unit validation process was proposed by following same approach with the previous studies.

▹ Current status of the integrated validation for the rocket upper stage was summarized.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