Revisiting ATD of Reentering Debris

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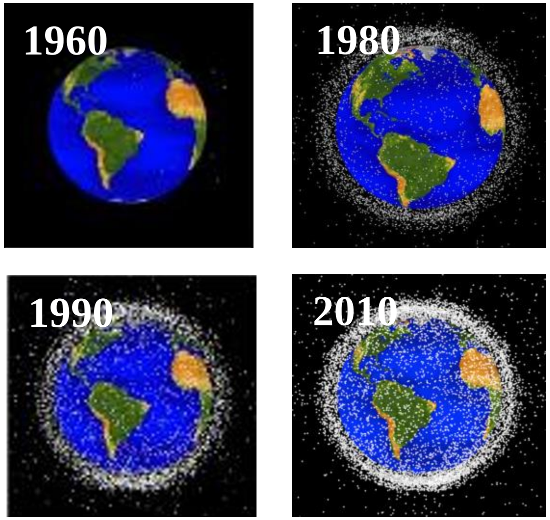
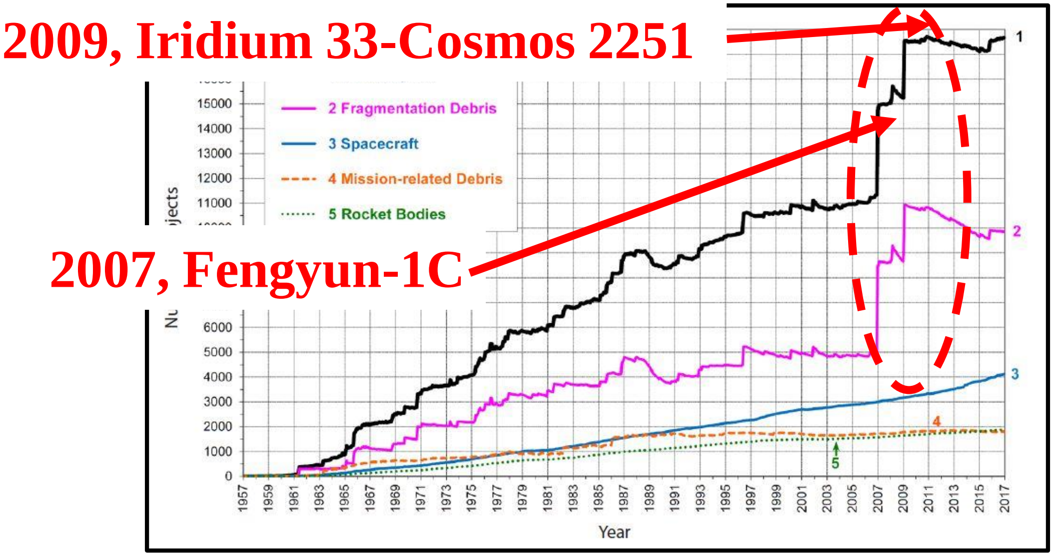
Research Background

Space debris

- Space debris is the man-made orbital debris that orbit Earth and represent a risk to spacecraft





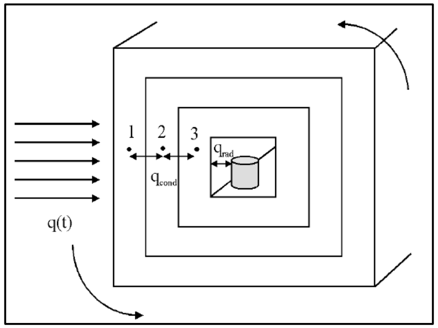
Ref) http://www.tulsaworld.com/news/local/her-eyes-return-to-the-skies/article_8c77d9fb-a4c6-5398-892a-7355df7ede2c.html

Ref) NASA, \Orbital Debris Quarterly News," in National Aeronautics and Space Administration Lyndon B. Johnson Space Center, vol. 21, Feb 2017.

Research Background

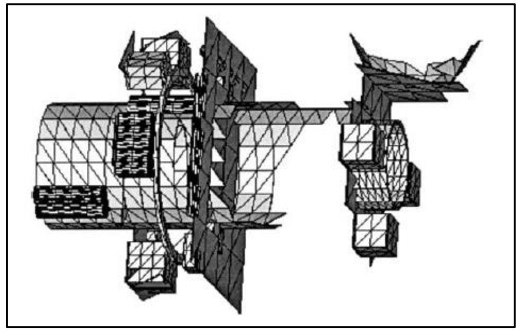
❖ Reentry tools

➢ ORSAT - USA

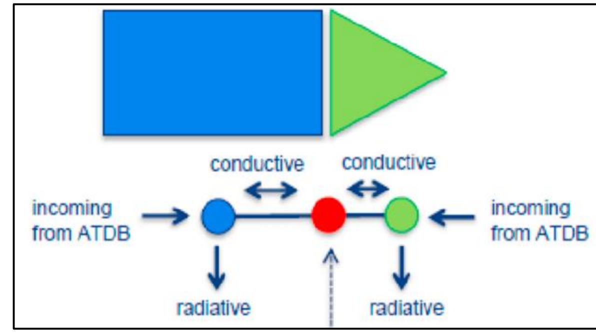


<One-dimension of box >

➢ SCARAB, DRAMA, SESAM, DEBRISK, FOSTRAD… - Europe

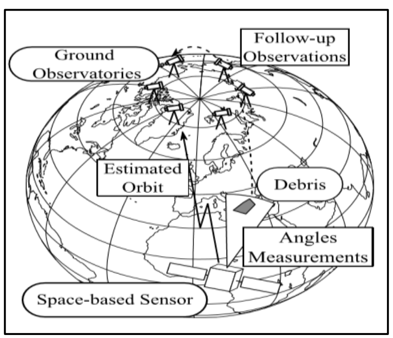


<Geometric Model>



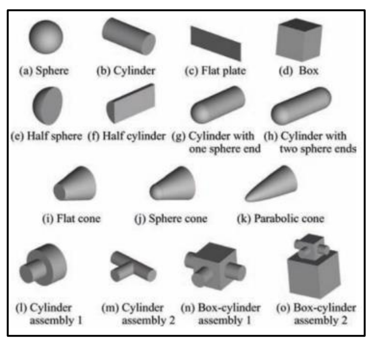
<'Connected-to' Relationship approach>

➢ ORSAT-J - Japan



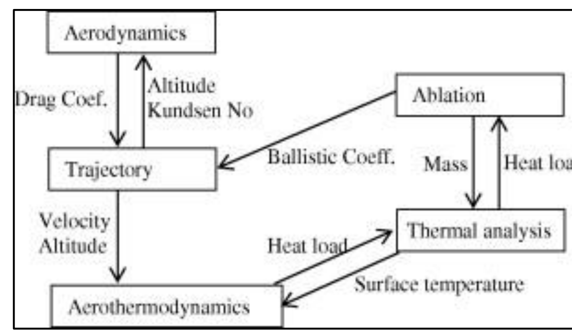
<Observation System>

➢ DRAPS - China



<Object shape types>

➢ SAPAR - Korea

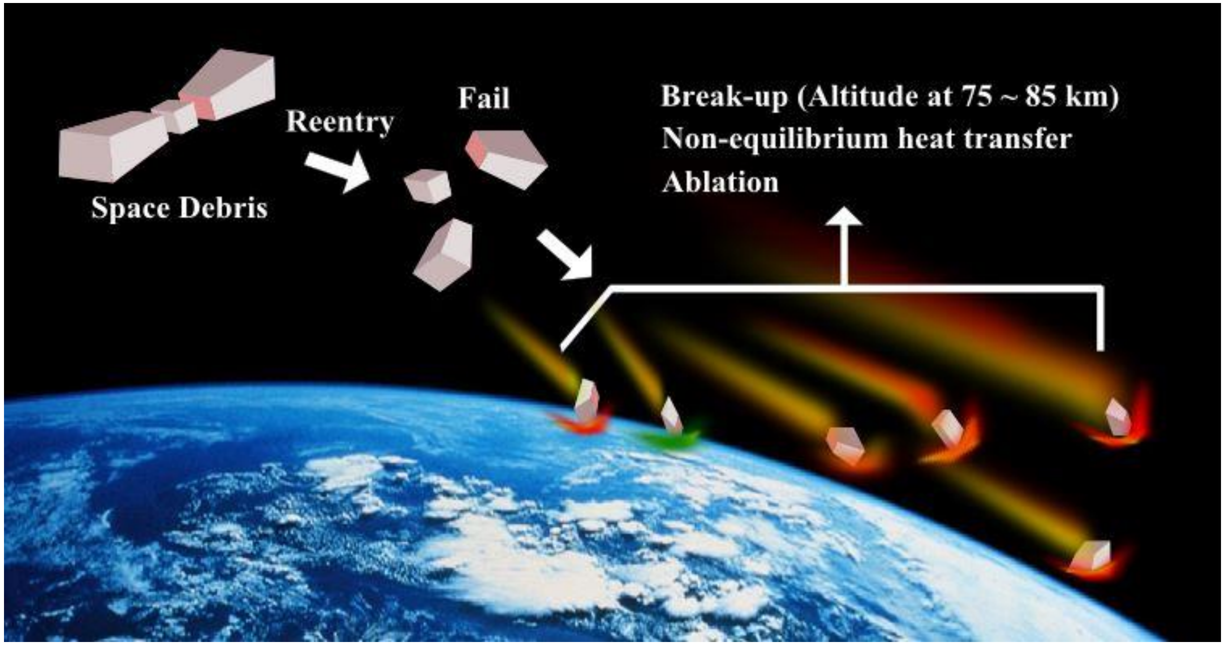


<Program Module of SAPAR>

Ref) H. S. Sim, "Flight Safety Analyses on the Upper Stage of a Space Launch Vehicle with Survivability Analyses of Debris Reentering the Earth's Atmosphere, A Doctoral Dissertation, Seoul National University, 2013.
Ref) Z. N. Wu, R. F. Hu, X. Qu, Wang, and Z. Wu, "Space Debris Reentry Analysis Methods and Tools," Chinese Journal of Aeronautics, vol. 24, no. 4, pp. 387-395, 2011.
Ref) I. P. Fuentes, D. Bonetti, F. Letterio, G. V. de Miguel, G. B. Arnao, P. Palomo, C. Parigini, S. Lemmens, T. Lips, R. Kanzler, Upgrade of esa's debris risk assessment and mitigation analysis (drama) tool: spacecraft entry survival analysis module, Acta Astronautica 158 (2019) 148-160.

Research Background

❖ Limitations



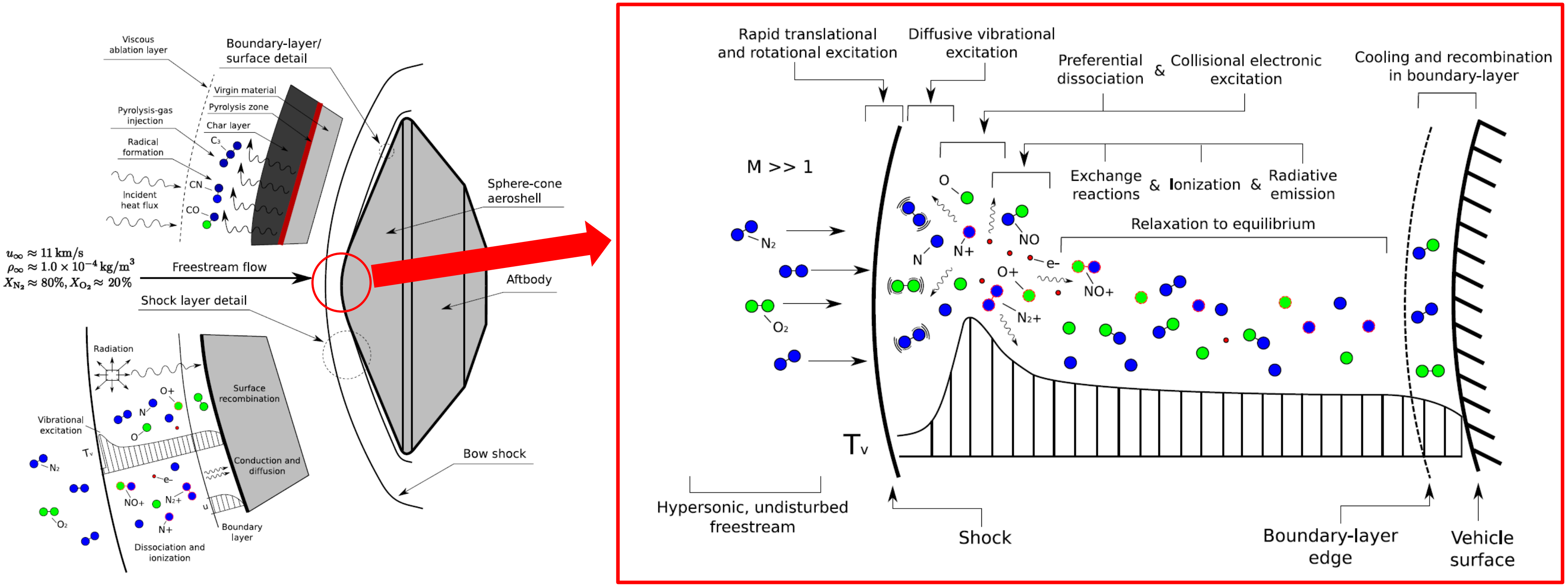
- **Break-up process**
- **Heat transfer** → **Strongly related to ablation and thermal break-up**
- **Ablation**

Ref) S. H. Park and G. Park, "Reentry Trajectory and Survivability Estimation of Small Space Debris with Catalytic Recombination," Advances in Space Research, vol. 60, no. 5, pp. 893-906, 2017.

Research Background

❖ Post-shock relaxation

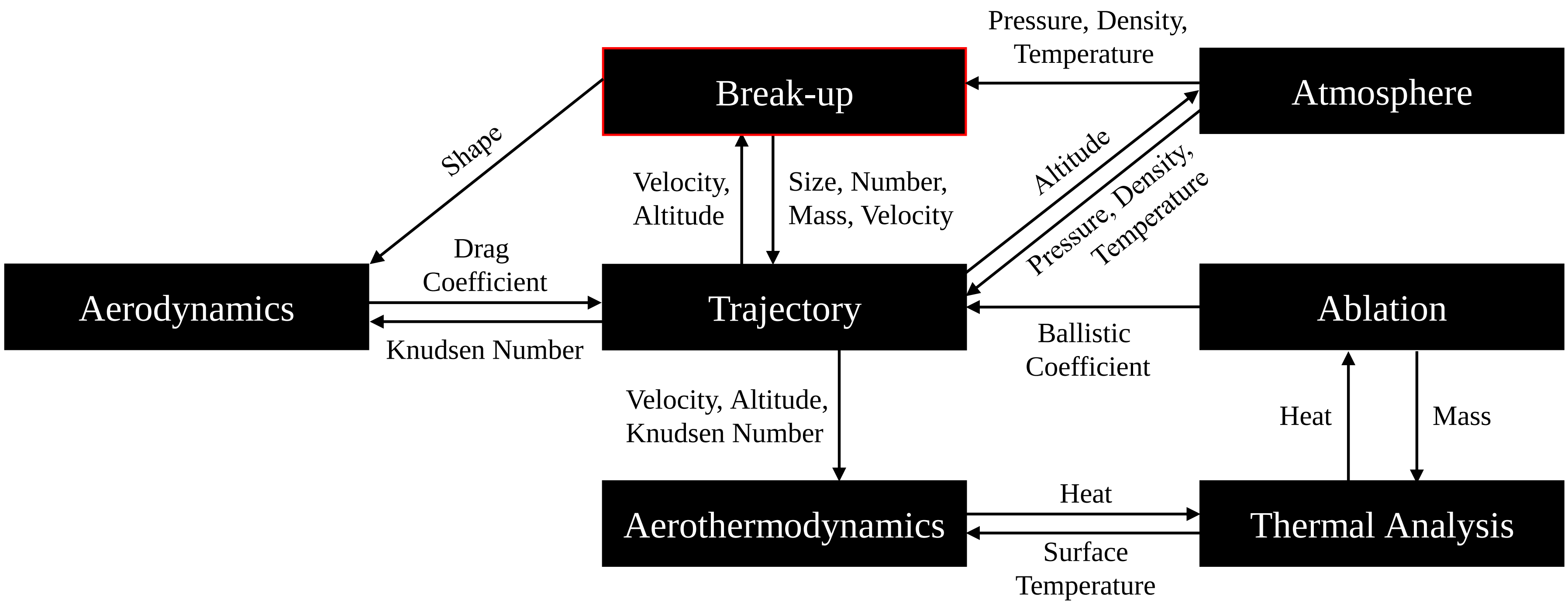
Ref) D. F. Potter, Modelling of radiating shock layers for atmospheric entry at earth and mars, Ph.D. Thesis. University of Queensland (2010).



<Chemical kinetic processes along the stagnation streamline>

- Across the shock wave, most of the freestream kinetic energy is rapidly transformed into translational energy as they collide with the more dense shock-layer gas.
- Inter-particle collisions then excite the rotational, vibrational, ionization, and electronic modes of the molecules, and translational energy begins to relax.
- Rotational and translational energy modes quickly equalize due to efficient energy transfer, while vibrational excitation is considerably slower.
- Sufficiently far behind the shock, after many collisions have occurred, the flow reaches a state of local thermodynamic equilibrium. But, if the relaxation time is far too short, non-equilibrium effect should be considered.

Reentry Analysis Tool



<Reentry Tool>

Ref) S. H. Park, H. D. Kim, and G. Park, "Orbit, orbital lifetime, and reentry survivability estimation for orbiting objects," Advances in Space Research, vol. 62, no. 11, pp. 3012-3032, 2018.

Aerothermodynamics

❖ Post-shock relaxation

- Post-shock conditions are numerically calculated using the Poshax3 (developed at UQ). Fully Navier-Stokes equations are solved (conservation equations for mass, momentum, energy, chemical species).

- 1-D, inviscid flow, chemical reactions, thermal energy exchange and radiative cooling can be considered.

$$\frac{\partial \rho_s}{\partial t} + \frac{\partial}{\partial x}(\rho_s u) = \dot{\omega}_s$$
$$\frac{\partial \rho u}{\partial t} + \frac{\partial}{\partial x}(\rho u^2 + p) = 0$$
$$\frac{\partial \rho E}{\partial t} + \frac{\partial}{\partial x}(u(\rho E + p)) = -\frac{\partial q_{rad}}{\partial x}$$
$$\frac{\partial \rho e_{ve}}{\partial t} + \frac{\partial}{\partial x}(u(\rho e_{ve} + p_e)) = -\frac{\partial q_{rad}}{\partial x} + \dot{\Omega}_{VT} + \dot{\Omega}_{ET} + \dot{\Omega}_{VC} + \dot{\Omega}_{EC}$$

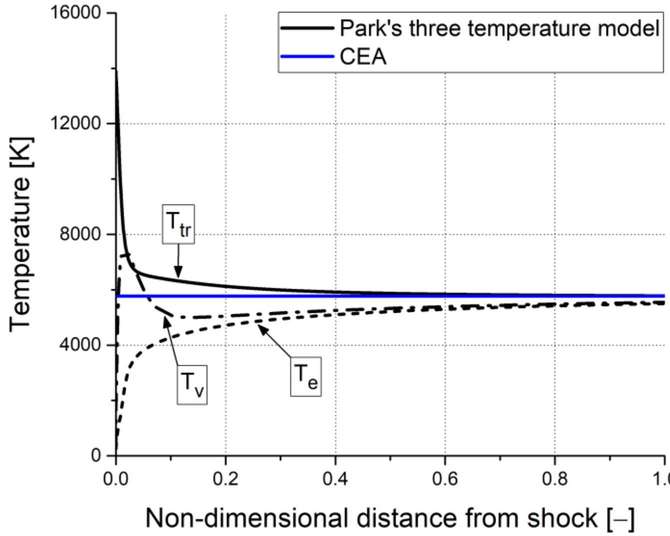
$$\frac{\partial}{\partial x}(u e_v) = \dot{\Omega}_{VT} + \dot{\Omega}_{VE} + \dot{\Omega}_{VC}$$
$$\frac{\partial}{\partial x}(u(e_e + p_e)) = -\frac{\partial q_{rad}}{\partial x} + \dot{\Omega}_{ET} + \dot{\Omega}_{EV} + \dot{\Omega}_{EC}$$

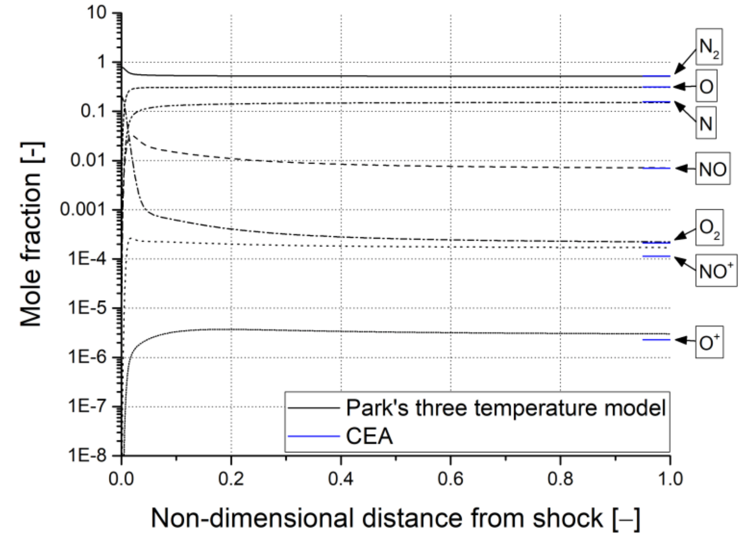
- ✓ Two or **Three temperature** models
- ✓ Air (O_2=22% & N_2=78%)
- ✓ 11 species air model (O, N, O_2, N_2, NO, O^+, N^+, O_2^+, N_2^+, NO^+, e^-)
- ✓ Chemical-kinetic and Vibration-electron energy exchange model by Park
- ✓ Translation-electron energy exchange model by Gnoff
- ✓ Gupta-Yos's mixture rule
- ✓ Serbin's theory for shock stand-off distance

Ref) D. F. Potter, Modelling of radiating shock layers for atmospheric entry at earth and mars, Ph.D. Thesis. University of Queensland (2010).

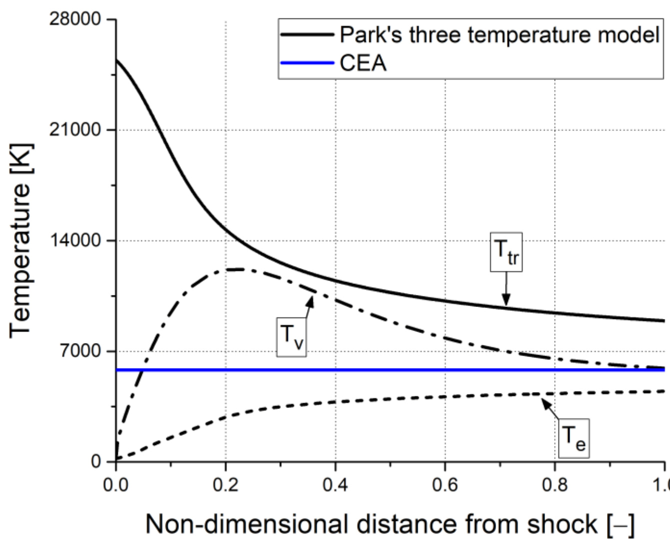
Post-shock Relaxation Data

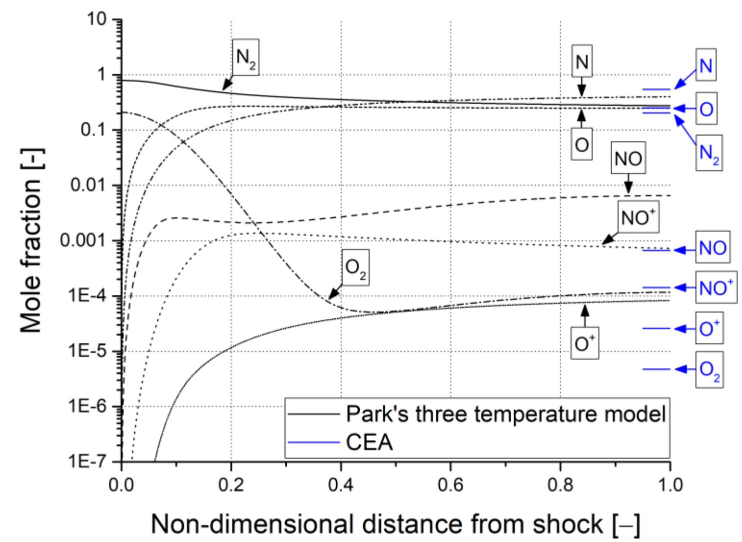
At 45 km





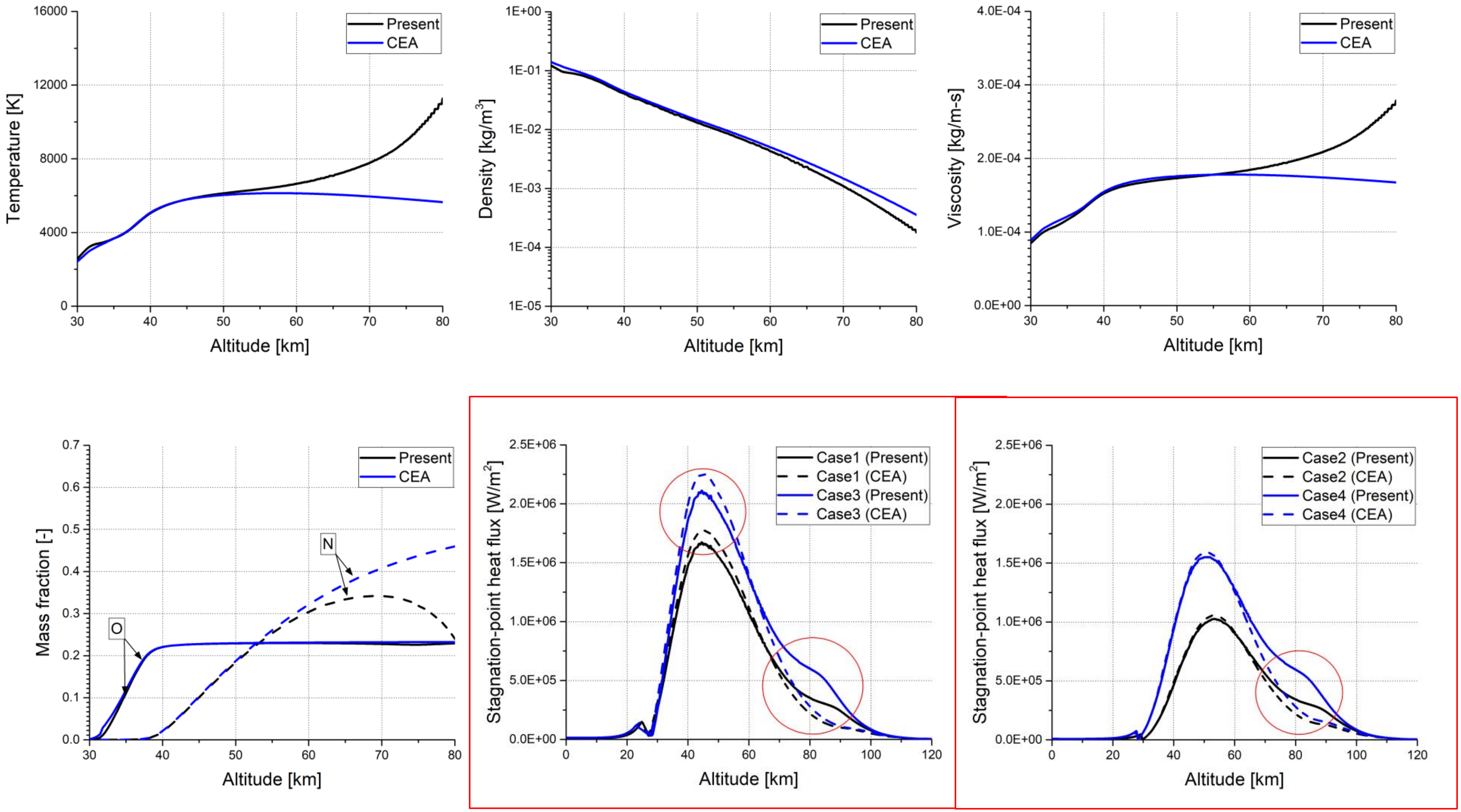
At 75 km





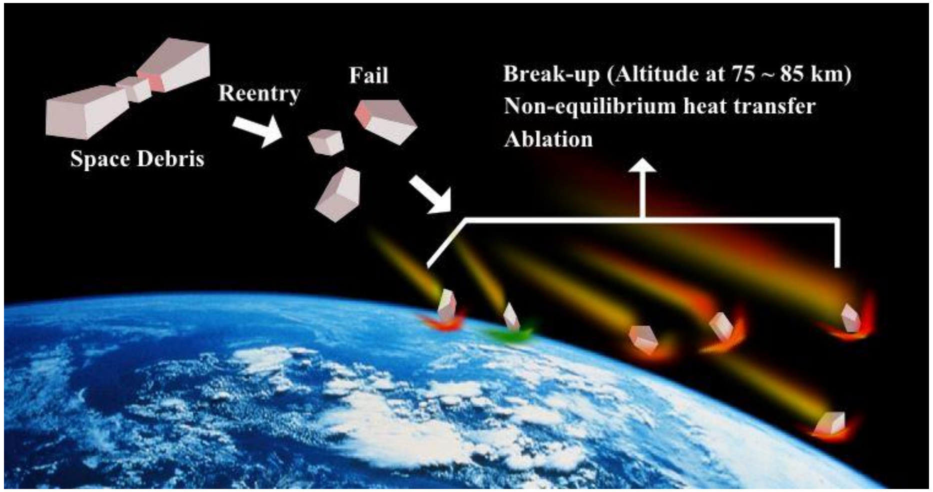
Ref) S.-H. Park et al., "Re-entry survival analysis and ground risk assessment of space debris considering by-products generation," Acta Astronautica, 2020 (accepted).

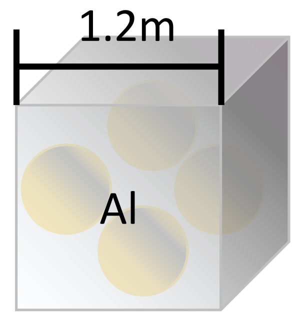
Surface Heat Transfer Data



Ref) S.-H. Park et al., "Re-entry survival analysis and ground risk assessment of space debris considering by-products generation," Acta Astronautica, 2020 (accepted).

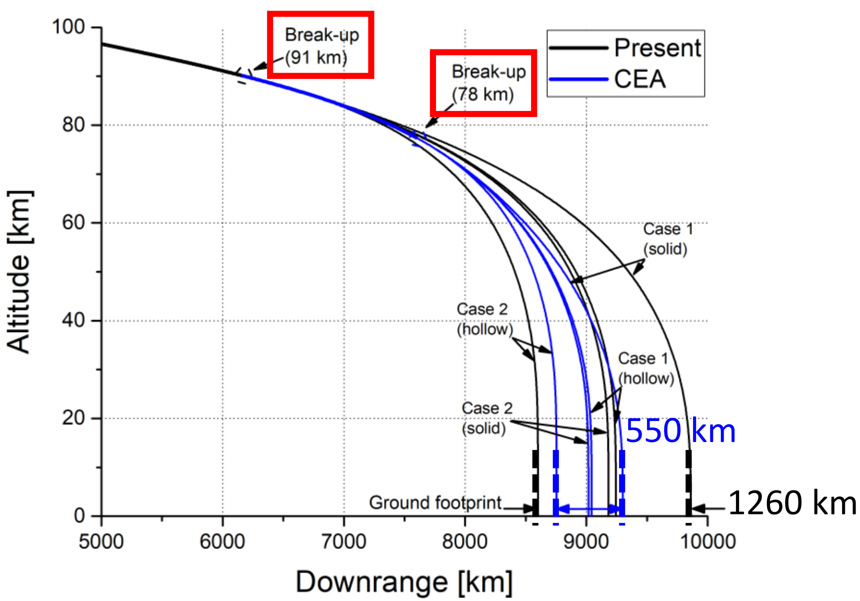
Ground Risk Assessment

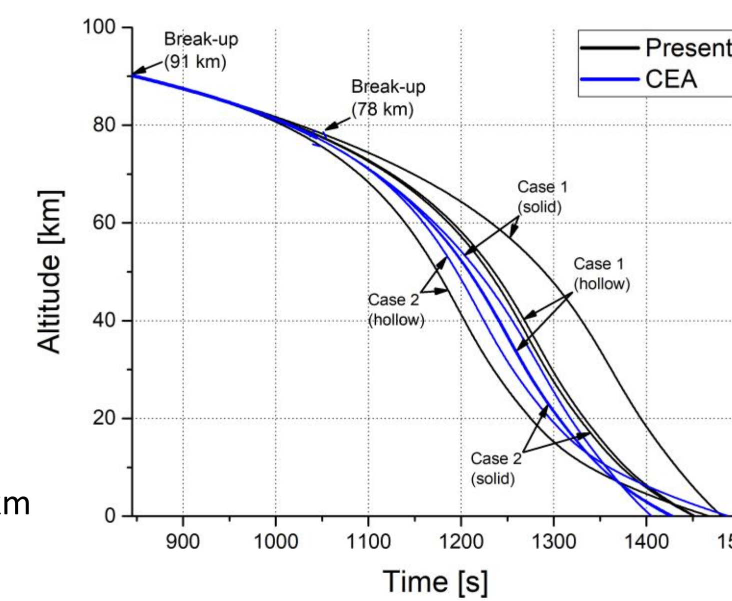




<Test case>

- ✓ Mass of external panel ≈ 60 kg
- ✓ 4 child cases are included (Cases 1 and 2 (hollow and solid))
- ✓ Total mass ≈ 600 kg





Ref) S.-H. Park et al., "Re-entry survival analysis and ground risk assessment of space debris considering by-products generation," Acta Astronautica, 2020 (accepted).

Conclusions

- ✓ Non-equilibrium flow effect was considered in reentry ATD tool.
- ✓ There was a large discrepancy between equilibrium and non-equilibrium flow for post shock conditions, especially at high altitudes
- ✓ Consequently, there were large discrepancies in the ground footprint as well as downrange of re-entry objects, implying the importance of the implementation of the non-equilibrium approach to the re-entry analysis.

Thank you