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Conventional safety consideration for controlled reentry and measures for improvement

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運用を終了した宇宙機がそのまま軌道上に放置された場合、それ自体がスペースデブリとなるだけでなく他の物体との衝突等によってデブリ環境の悪化に寄与する恐れがある。また、特に低軌道で運用を終えた宇宙機においては、その後無制御で大気圏に再突入した際に溶け残った破片が地上に到達し、人命や財産等に危害を及ぼすリスクとなる。これらのリスクを総合的に低減する方策として、コントロールドリエントリは非常に好ましい運用終了処置と言える。一方で、そのために衛星の運用終了時期を早めなければならない可能性や、リエントリ制御が失敗した場合の社会的なリスク等、運用者から見ると明らかに不利益の方が多いため、促進には規制が必要と考えられる。ここでは、実際にコントロールドリエントリを行う際に考慮しなければならない事項や手続き等について紹介するとともに、規制化を検討する場合に特に議論が必要と認識される事項について整理する。

A spacecraft could be a space debris and its source while it stays on orbit after the mission. Moreover, a natural reentry of a spacecraft to the ground could be a potential risk to the people and assets because certain amount of the fragments may survive and reach to the ground. A controlled reentry would be quite preferable way to minimize both risks besides it gives less incentive to the mission provider because of no or less profit attempting to do so. Therefore, a regulation is one of the practical solution to promote controlled reentry. The conventional safety methodology and consideration for controlled reentry are introduced and some issues are addressed toward the future institutionalization.

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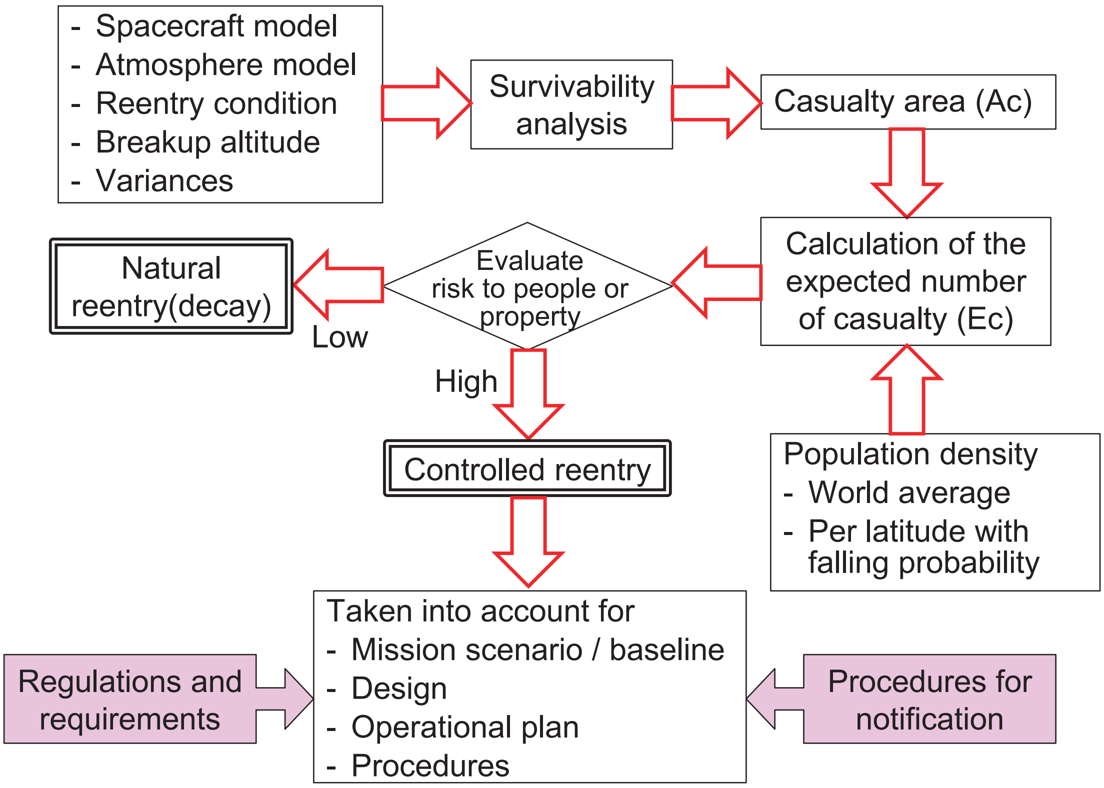
"If a spacecraft or orbital stage is to be disposed of by re-entry into the atmosphere, debris that survives to reach the surface of the Earth should not pose an undue risk to people or property."

- Section 5.3.2, IADC Space Debris Mitigation Guidelines -

Typical evaluation process



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Regulations and requirements related to controlled reentry

JAPAN

Regulation of GOJ

- Standard for safety evaluation on launching satellites.

Regulation of JAXA

- Safety standard for controlled reentry.[JERG-0-047] (Applied to HTV)

Europe

-European Code of Conduct for Space Debris Mitigation, 28/06/2004

Regulation of ESA

-Space Debris Mitigation Policy for Agency Projects [ESA/ADMIN/IPOL(2014)2]

-Space Debris Mitigation for Agency Projects Annex1 [ESA/ADMIN/IPOL(2008)2]

Regulation of the other countries.

e.g.

-Flight safety code (Australia) (Applied to Hayabusa)

Requirements for controlled reentry are enrolled or tied with space debris mitigation requirements.

United States

-U.S. Government Orbital Debris Mitigation Standard Practices, December 2000.

-United States Space Command Policy Directive 10-39, "Satellite Disposal Procedures", 1 May 2001.

-United States Space Command Policy Directive 13-4, Minimization and Mitigation of Space Debris", 1 February 2001.

Regulation of NASA

- NASA Procedural Requirements for Limiting Orbital Debris [NPR8715.6]
- Process for Limiting Orbital Debris [NASA-STD-8719.14]
- Range Flight Safety Program [NPR8715.5]

Regulation of USAF

- (the United States Air Force's) Space and Missile System Center (SMC) Orbital/Sub-orbital Debris Mitigation User's Handbook, Version 1.0, July 2002.

Regulation of FAA

- Reentry of a reentry vehicle other than a reusable launch vehicle, CFR Title14, Vol.4 chapter III Part 435 (2008.5), U.S.A.

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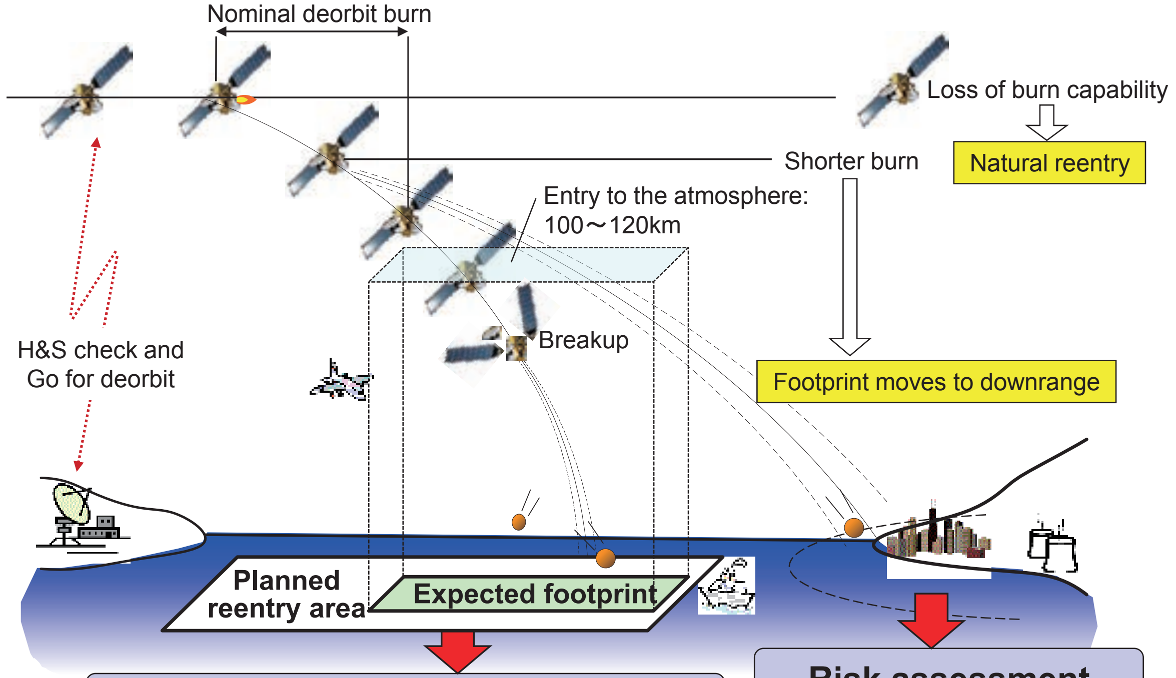
Typical event flow during controlled reentry



Reentry plan / Dispersion analysis

- Designation of the reentry area
- Evaluation of the debris dispersion

Risk assessment

- Debris survivability analysis
- Expected number of casualties

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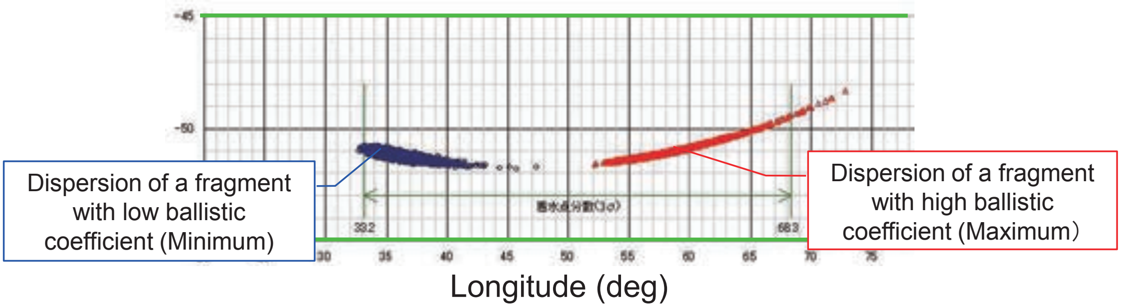
Evaluation of the footprint

Expected footprint

- Dispersion analysis is implemented to evaluate the design of the footprint.
- Survivability of the actual flight hardware may or may not be considered for dispersion analysis. It basically depends on program or mission owner.

- The following example is a kind of “worst case” evaluation. That includes the following assumption, errors and uncertainties into account.
  - ✓ Sample fragments are assumed to envelope logically maximum ballistic coefficient regardless actual survivability of the system.
  - ✓ Error of the initial condition such as velocity and trajectory of the vehicle at the reentry interface point.
  - ✓ Dispersion of the atmospheric concentration.
  - ✓ Dispersion of each sample fragment is calculated by Monte-carlo simulation.



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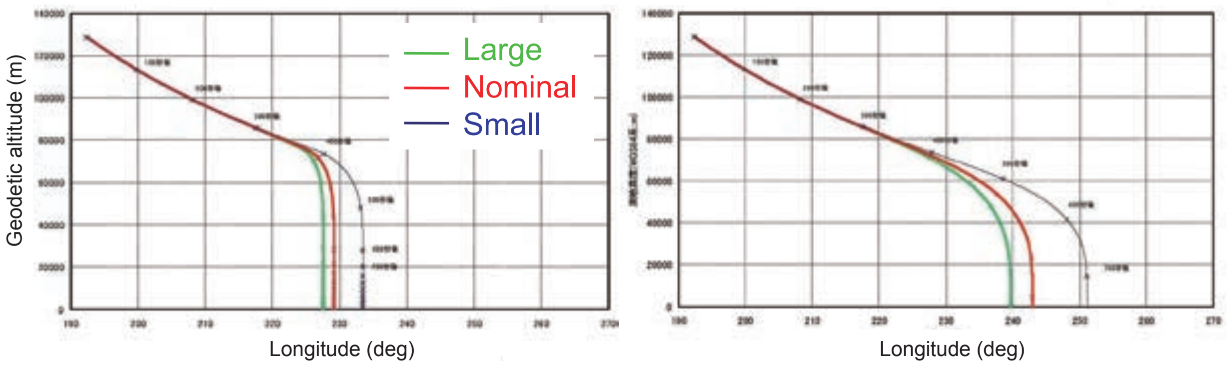
Evaluation of the footprint



Altitude profile for a fragment with low ballistic coefficient

Altitude profile for a fragment with high ballistic coefficient

The effect of the atmospheric concentration

It is also evaluated that,

- the effect by the wind can be considered negligible to this result.
- the acceleration by the typical explosion could only create a negligible effect comparing to the other factors.

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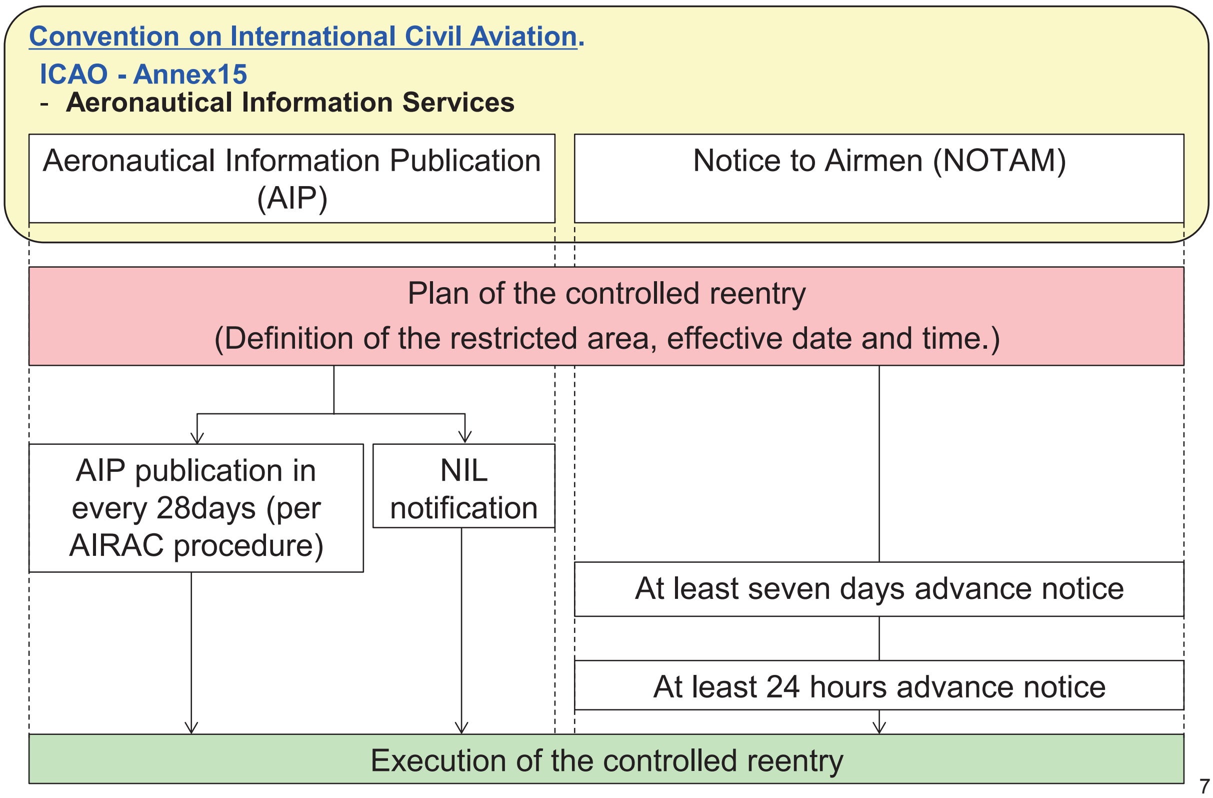
Procedures for notification upon controlled reentry



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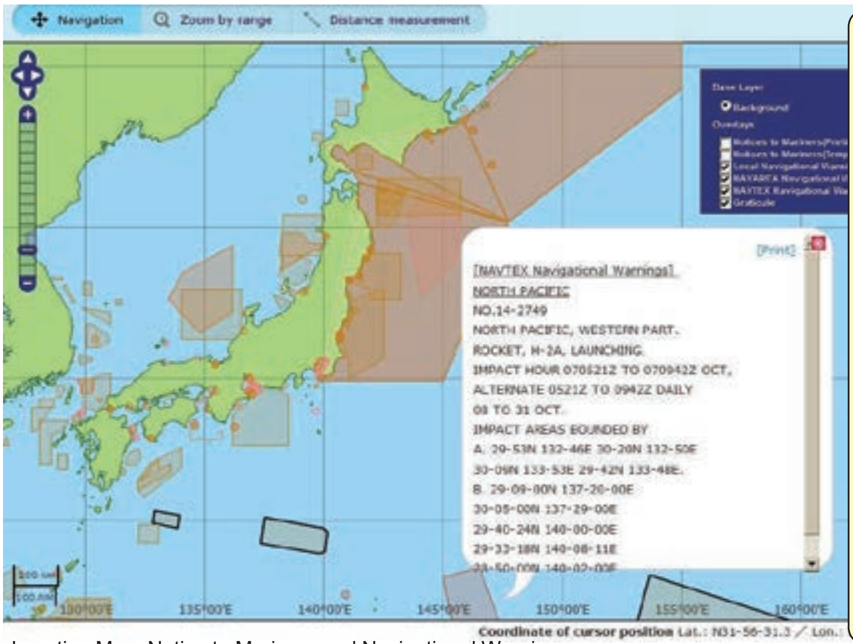
Procedures for notification upon controlled reentry



Location Map, Notice to Mariners and Navigational Warnings:
http://www1.kaiho.mlit.go.jp/TUHO/vpage/visualpage_en.html

Navigational Warnings

NAVAREA warnings
- Warnings that are provided via satellite, inmalsat is used for NAVAREA XI, by the responsible government on each NAVAREA.

NAVTEX warnings
- Warnings that are provided via Medium Frequency from each NAVTEX station on the coast. 518kHz is commonly used in the world.

Local navigational warnings
- Additional warnings are locally given by a related government officials.

Notices to Mariners
- Information via publication and internet for updating the latest status on any events affecting a ship route. Updated in weekly basis.

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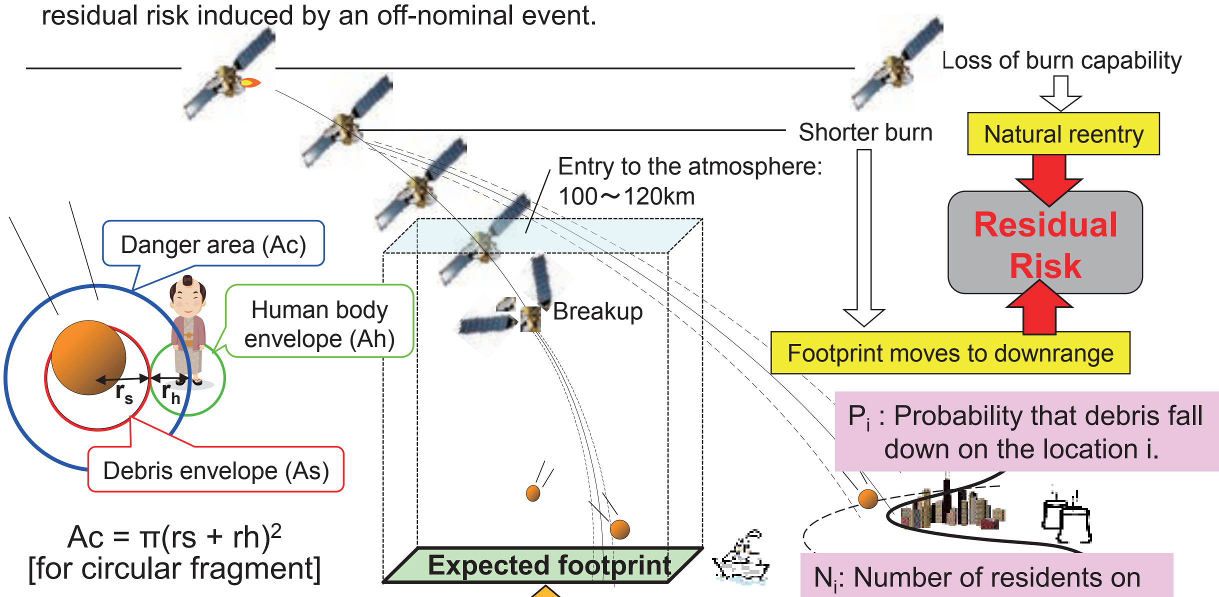
Expected number of casualty (Ec)

- Ec is the value to express the casualty risk associated with reentry.
- It is widely utilized for both natural and controlled reentry.
- Because nominal controlled reentry is arranged not to create casualty, Ec basically express residual risk induced by an off-nominal event.



$Ac = \pi(rs + rh)^2$
[for circular fragment]

$Ec = Ac \times \sum(P_i N_i/A_i)$ [persons]

Ec ≒ 0
(Nominal)

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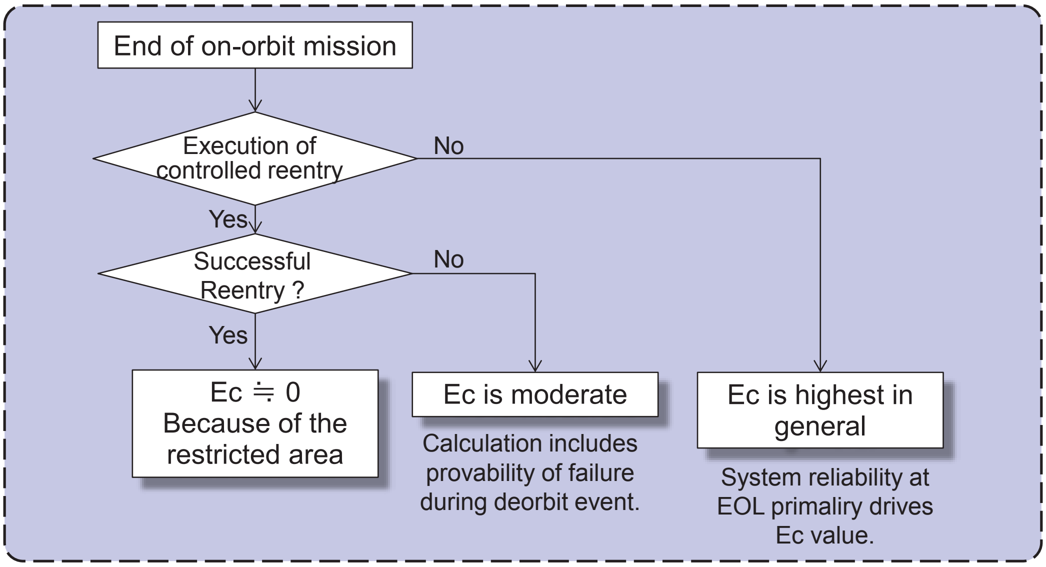
Expected number of casualty (Ec)



- The following population data are applied to the calculation of Ec, as an example in JAXA .
  - ✓ Global average --- The case fragments fall down on the sea.
  - ✓ National average --- The case fragments fall down on the land.
  - ✓ City average --- The case fragments fall down on the congested city.
  - ✓ Average on each latitude --- Natural (Uncontrolled) reentry.

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Benefits vs. Disadvantages of the controlled reentry

- ➢ Controlled reentry is quite preferable deorbit method for both orbiter debris mitigation and public safety.
  - ✓ Unnecessary object such as a satellite at EOL is immediately removed from orbit.
  - ✓ Public risk induced by fallen space object is minimized.
- ➢ Besides, spacecraft owners are not motivated to plan controlled reentry because of,
  - ✓ No profit.
  - ✓ Risk of mishap due to unsuccessful reentry.
  - ✓ Additional works to do.
  - ✓ Potential early retirement of a satellite to support reentry.

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Suggestions for future

- Controlled reentry is the best option for deorbiting satellite at EOL, if feasible. However a satellite owner would not be motivated to take this option because of disadvantages rather than their profit.
- Regulation may be a practical solution to promote controlled reentry however there must be fair rules and guidelines as a common scale.
- It is also necessary to simplify and standardize risk evaluation techniques and related analysis to support fire judge, while scientists continue searching for real phenomena.