(Attachment to Guidelines on License Related to Control of Spacecraft)

Conditions and Methods for Calculating Expected Casualties (Spacecraft)

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Cabinet Office
National Space Policy Secretariat

History of revisions

Edition	Date of establishment	Detail of revisions
First Edition	March 30, 2018	New establishment

Table of Content

1. Introduction

This document provides examples of conditions and methods for calculating the expected casualties conducted as a risk assessment.

Risk assessment conducted under any conditions and methods not described in these Guidelines is also acceptable by showing evidence.

2. Target

As for spacecraft or components, etc. of the spacecraft that reenter the earth's atmosphere during or after the termination of the period of control of the spacecraft, an assessment using the expected casualties is required if it does not demise during reentry.

Confirm that the estimated expected casualties satisfy the international standard, and conduct a controlled reentry if necessary in order to reduce risk to the public.

The related items of the Guideline is as follows:

- Guidelines on License Related to Control of Spacecraft
  - ➢ 6.2.4 Prevention of damages to third parties upon reentry to the Earth
  - ➢ 6.4.1 Controlled reentry

3. Expected casualty (Ec) criteria

Expected casualties form one of the metrics that are internationally used for the risk assessment related to the launch and reentry of a launch vehicle. It is generally expressed as "Ec" (Expected Casualties), and the unit is a "person."

The comparison of criteria of expected casualties for the reentry of a spacecraft regulated by each state is shown in Table 3-1.

Table 3-1 Collective risk criteria for general public

No.	Organization	Title of document	Expected casualties (Ec)
1	NASA	NASA-STD-8719.14A Process for Limiting Orbital Debris	<Common items> - Spacecraft, etc. to be re-entered into the Earth atmosphere. - Consider fragments with a mean kinetic energy at impact larger than 15J. Uncontrolled Reentry - The risk of human casualty < 1×10^{-4} Controlled Reentry - The risk of human casualty < 1×10^{-4}

2	ESA	ESSB-HB-U-002 ESA Space Debris Mitigation Compliance Verification Guidelines	1×10^{-4}
3	CNES	French Space Operations Act Technical Regulation	Controlled reentry with recovery: 2×10^{-5} Controlled reentry with destruction: 2×10^{-5} Natural decay*: 1×10^{-4} * The appropriate means to the maximum extent possible are to be taken, in cases where the conduct of controlled reentry is reasonably proved to be impossible.

The failure probability based on FMEA (Failure Modes and Effects Analysis) may result in the underestimation of the probability of design fault or human error. The same trend is also applicable to the probability of anomaly caused by the degradation of propulsion performance, structural failure or environmental factors.
Due consideration must be paid so that the calculation would not be underestimated compared to the applicable criteria.

4. Expected casualties analysis procedure

In this Chapter, the typical calculation process of the expected casualties is described.
For the details of calculation methods, the following article may also be consulted.
FAA Flight Safety Analysis Handbook Version 1.0, September 2011

4.1 Hazard identification

Identify all modes of credible hazards including failures that may be the cause of the fall of spacecraft to the ground.
Upon the controlled reentry of a spacecraft, there are hazards that may cause loss of human life or long-term disability or loss of human function when it re-enters the atmosphere without sufficient ablation and the surviving debris impact the ground. The surviving objects may constitute spacecraft, residual propellant or capsules.
In the case of a controlled reentry, identify the failure modes that cause falling outside the planned reentry area and hazards above-mentioned. In identifying hazards, consider not only the case where a normal reentry cannot be executed due to a malfunction in maneuver during the controlled reentry, but also the case of natural decay as a result of failure in the execution of a controlled reentry due to the loss of a reentry function.

Also all credible hazard sources (impacting debris, blast, toxic release, etc.) that may cause damages when they fall onto ground must be taken into account in assessment for each mode.
In the case of a mode wherein liquid propellant or solid propellant impact the ground intact, it is assumed that a blast overpressure hazard by its explosion and a health hazard by toxic release may be caused.

4.2. Development of failure probabilities

In the case of a controlled reentry, study the failure probability of each mode identified in 4.1. If the response to the failures in terms of predicted spacecraft behavior is the same, they can be grouped as one failure. Here, failure, etc. of the functions necessary for the execution of reentry (reliability of functions necessary for reentry at the starting point of reentry maneuver), in addition to anomaly of maneuver during the reentry maneuver (decrease of reliability during reentry maneuver), need to be considered. The decrease in reliability must be taken into account if it takes much time from launch or orbital insertion to the execution of reentry.
In case of the spacecraft to reenter by natural decay, calculation of failure probability is not necessary and the probability of impact on the earth equals 1.

4.3. Study on debris characteristics

Study the final conditions of impacting the earth by modeling each onboard component and fragments released as the result of break-up of a launch vehicle.
In the case of a controlled reentry, aerodynamic breakup during falling down is to be considered for each case of failure mode during reentry.
The following items must be taken into account for reentry survivability analysis:

- physical properties of reentry object (shape, size, mass, material, etc.)
- orbital properties at the start point of analysis (altitude, inclination, etc.)
- atmospheric model

4.4. Impact probability (*Pi*)

- In the case of uncontrolled reentry

The study may be implemented based on the assumption that a spacecraft can fall on any place within the range of orbital inclination. For simplicity, the impact probability can be calculated by assuming a homogeneous distribution or by allocating proportionally based on the local sun time of the orbit of each latitude band dividing the Earth by latitude within the orbital inclination range.

- Controlled reentry

Study the initial condition of the orbit, point and the velocity of spacecraft at the time of starting the reentry corresponding to the failure mode or flight phase identified in 4.1, and calculate the trajectory and impact point. Uncertainty must be taken into account for the calculation. Examples of causes of uncertainty are as follows:

- Cause of uncertainty in the initial condition of position and velocity of spacecraft.
- Causes of uncertainty in falling

Provide a reasonable estimate of the scope of potential impact on the ground by taking into account the uncertainty. For this purpose, due consideration must be paid so that the probability calculation will not become unsafe by extending the debris impact distribution.

When considering the worst case risk such as impacting urban area, the detailed study on the impact point may be omitted.

In addition, for a case where a controlled reentry cannot be executed due to the loss of a reentry function, thereby resulting in natural decay reentry, see the method of consideration in case of uncontrolled reentry described above.

4.5. Expected casualties (Ec)

Identify the fragments that survive and calculate the projected area to the ground. The expected casualties for each calculation point are obtained from the following equations. Sum up the values of casualty expectation obtained by multiplying the effective casualty area of each fragment, number of fragments and population density of the calculation point concerned by the impact probability of calculation point.

$$E_{C-Total} = \sum_i \sum_j E_{Cij}$$

$$E_{C_{ij}} = P_{I_{ij}} \left(\frac{N_{P_j}}{A_{P_j}} \right) (N_{F_i} A_{C_i})$$

P_{Iij}: the probability of a fragment from debris group "i" impacting on population center "j"

A_{Ci}: the effective casualty area for a fragment from debris group "i"

N_{Fi}: the number of fragments in debris group "i"

N_{Pj}: the number of people in of population center "j"

A_{Pj}: the area of the population center "j"

Source: FAA Flight Safety Analysis Handbook ver1.0, September 2011

(1) Exclusion of fragments to be considered

Calculate the expected casualties based on surviving objects that may cause serious damage to person involving the loss of human life or long-term disability or loss of human function by a collision or contact, etc. For the debris impact hazard at reentry phase, debris impact with a mean kinetic energy at impact not less than 15J (kg・m2/s2) must be considered. If other threshold are to be used for the calculation, submit the evidence.

Fragments with a mean kinetic energy not exceeding the threshold can be negligible for the purpose of calculation. When considering the ablation effect, fragments that can be considered demise during reentry can be excluded.

(2) Casualty area

A casualty area is a scope of potential hazard to human beings that may be caused by fragments as shown by square meters.

As for debris impact hazard, generally, the casualty area takes into account both the projected area of the debris fragment and the projected area of a human body from above, by assuming that a fragment vertically falls on a human standing up straight outside.

An example of methods for considering the casualty area is as follows:

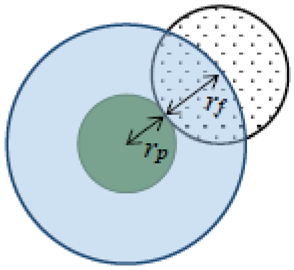
(i) Sphere

$A_c = \pi\ (\ r_p + r_f)^2$

A_c: casualty area (m^2)

r_p: radius of projection of human onto land surface (m)

r_f: radius of fragment (m)



(ii) Polygon

$A_c = A_f + (\ L_f \times r_p\ ) + A_p$

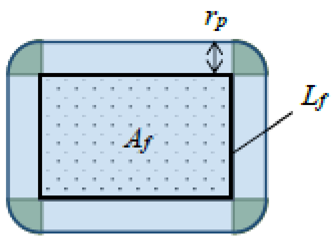
A_c: casualty area (m^2)

A_f: fragment area (m^2)

L_f: length of periphery of fragment (m)

r_p: radius of projection of human onto land surface (m)

A_p: projected area of human onto ground surface (m^2) = $\pi \times r_p^2$



(Reference 1) In the requirement related to the prevention of space debris generation stipulated by NASA, the projected human onto the ground surface is approximated as 0.36 m^2.

Source: Process for Limiting Orbital Debris, NASA-STD-8719.14A, NASA, 8 December 2011

(Reference 2) FAA typically represents a standing person by a 6 ft (1.829m) tall cylinder with a 1 ft (0.3048m) radius.

Source: FAA Flight Safety Analysis Handbook Version 1.0, September 2011

When indirect effect such as blast caused by secondary explosion, scattering or toxic release can be considered as potential hazard sources, its impact area must be estimated according to the following thresholds:

- blast wave: peak overpressure not less than 6.9 kPa (1.0 psi)
- toxic concentration: equivalent to the level stipulated in the international standard or by the space agency of each state for each material.

Presently, as described above, the concerned area at vertical falling onto a human standing up straight outside is generally applied for the purpose of computation of a casualty area of debris impact; whereas some space agencies consider the case of a human laying on the ground or a fragment flown by wind and colliding with a standing person on the side of the body. Meanwhile, some space agencies consider persons inside the building and exclude small fragments to a significant degree, and also collapse of a building due to a large fragment.
As these points are still under discussion among international agencies, note that the standards concerning these points may be changed. And it is desirable to discuss the appropriate assumption for the safety according to the properties of spacecraft to be operated.

(3) Setting of calculation areas and population data

In order to obtain a world population distribution, it is recommended to use GPW (Gridded Population of the World), the population distribution data [Version 4 as of January 2018] NASA Socioeconomic Data and Applications Center (SEDAC):
<http://sedac.ciesin.columbia.edu/data/collection/gpw-v4>

This data has a function of predicting a population increase, and has been properly maintained and updated.
More detailed data is necessary as a specific, limited area is at high risk of being posed to hazards in cases of anomaly situations upon the controlled reentry.
Especially in an urban area, due consideration must be paid so that population density may not be inappropriately reduced and it is necessary to prepare population data using data of population census (Census etc.)

5. Reentry risk assessment on microsatellite

As for microsatellites, an applicant is recommended to consult with National Space Policy Secretariat of the Cabinet Office of Japan (hereafter the "NSPS") as early as possible because detailed study may be omitted as the hazard that may be caused by reentry is small as long as its design is not extreme (for example, a microsatellite constituted by many parts made of titanium or a microsatellite loaded with radioactive materials or toxins).

6. Example of analysis tools

Examples of tools for reentry risk assessment open to public are as follows.

Note that these are not the tools recommended by the NSPS. Further, as a risk assessment largely depends on input parameters, a prior consultation with the NSPS is recommended.

- NASA
  - DAS (Debris Assessment Software):
    This is a debris estimation supporting tool. It is open to public, though a user is required to execute a Software Usage Agreement with NASA. The creation of an account with NASA Software Catalog is also required.
    <https://orbitaldebris.jsc.nasa.gov/mitigation/das.html>