COMMITTEE DRAFT

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Space systems — Procedure for limiting risk of re-entering spacecraft and launch vehicle orbital stages

Systèmes spatiaux — Gestion du risque de la rentrée pour les étapes orbitales des véhicules spatiaux non habités et des lanceurs spatiaux

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 21095 was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Introduction

According to international treaties, the “launching state” is liable for damage or injuries caused by unmanned spacecraft and launch vehicle orbital stages that re-enter the Earth's atmosphere. In addition, commercial operators are subject to the national safety regulations or laws of the launching country that relate to re-entry of spacecraft and launch vehicle orbital stages. So as to minimize damage and injuries from re-entering spacecraft and launch vehicle orbital stages, all parties (developers, manufacturers, space service providers, satellite operators, and launch service providers) should take preventive measures during design and operations.

Space systems — Procedure for limiting risk of re-entering spacecraft and launch vehicle orbital stages

1 Scope

This International Standard provides a framework with which to assess, reduce, and control the potential risks that spacecraft and launch vehicle orbital stages (called “space vehicles” from now on) pose to people and the environment when those space vehicles re-enter the Earth's atmosphere and impact the Earth’s surface. It is intended to be applied to the planning, design, and review of space vehicle missions for which controlled or uncontrolled re-entry is possible.

This standard is applicable to following objects in assessing their ground hazard

a) objects re-entering from orbit in compliance with ISO 24113,

b) launch vehicles (including payloads, other objects separated during the ascent phase, etc.) that are mentioned in flight safety activities under sub-clause 6.2 in ISO 16420-2, and

c) interplanetary spacecraft returning to Earth, etc.

NOTE 1 Transportation systems which have wings are not applicable to this standard.

This International Standard complements ISO 14620-1, and ISO 17666.

This International Standard is not applicable to spacecraft containing nuclear power sources.

NOTE 2 Useful background information for this International Standard is available in ISO 24113.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 14620-1, *Space systems — Safety requirements — Part 1: System safety*

ISO 17666, *Space systems — Risk management*

ISO 10795, *Space systems — Programme management and quality — Vocabulary*

ISO 24113:2011, *Space Debris mitigation requirements*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 10795:2011 and the following apply.

3.1
controlled re-entry
type of re-entry where the time of re-entry is controlled and the impact of debris is confined to a designated ground zone

NOTE This International Standard does not cover specific design to be retrieved, such as the Space Transportation System.

3.2
expected number of casualty (Ec)
number of person who is killed or seriously injured by accident

4 Re-entry risk management

4.1 General

Re-entry risk management shall be conducted according to this standard, and also as a part of a system safety programme based on ISO 14620-1 / sub-clause 4.4 under the concept of risk management based on ISO 17666.

4.2 Re-entry safety programme

In addition to the safety activities required by ISO 14620-1 / sub-clause 4.4, a re-entry safety programme shall be established to ensure:

a) minimization of damage and injuries caused by re-entering spacecraft or launch vehicle orbital stages;

b) corrective action for risks assessed to exceed programme or mission thresholds.

4.3 Re-entry safety oversight and management

As required in ISO 14620-1 / sub-clause 4.3, the safety representatives should be appointed, and they should have responsibility for safety activities, have right to access to the related data, and authority to reject any project document, stop any project activities, or interrupt hazardous operations. And as required in ISO 14620-1 / sub-clause 4.4, at each design and operation phase, a review committee should review the result of the safety assessment and the plan for the next phase, and endorse the decision to proceed to the following phase. If there would be requirements that cannot be met, a request for deviation or waiver would be generated, and reviewed and disposed according to ISO 14620-1 / sub-clause 4. 10. 6.

4.4 Re-entry risk assessment and mitigation plan

A re-entry risk assessment and mitigation plan (RRAMP) through project life cycle shall be prepared as part of the safety data package specified in ISO 14620-1 / 4.10.5.

The RRAMP will define the work plan corresponding to each requirement in this International Standard and detailed schedules of critical activities (design, analysis and testing reviews) throughout the life of the programme. The required contents of the RRAMP are given in Annex A.

The RRAMP shall be approved by the safety representative, the head of project management and the customers. The RRAMP will change and evolve as the project proceeds.

5 Risk assessment for the case of natural re-entry

5.1 General

A safety assessment shall be conducted to evaluate the risks associated with uncontrolled re-entry, and determine the need for design improvements or a controlled re-entry. The safety assessment should include the following:

a) Identification of the safety requirements

b) standardized process and resources for analysis

c) system / mission dependent parameters

d) Estimation of risk

e) Risk decision and actions

NOTE Because the general concept for risk assessment is given in ISO 17666, this clause supplements specific requirements related to re-entry matter using terms (risk scenario, risk magnitude, risk decision and actions, etc.) defined in ISO 17666.

5.2 Identification of safety requirements

Specific re-entry safety requirements imposed contractually, voluntarily or by national or international authorities shall be identified and applied, and where possible, quantified with threshold parameters.

Re-entry risk assessment actions (analyses, reports, etc.) shall be defined and scheduled. A compliance matrix between safety requirements and system design and operation plan, which includes achieved quantitative results, threshold values, consequences of not meeting thresholds and the probability that those consequences would be realized, shall be maintained.

The expected output is the assessment parameters (e.g. risk to people on the ground and the associated mathematical parameters) and the thresholds for them or the concept for risk decision and actions according to the probability and severity of consequences.

NOTE 1 Several national governments and space agencies adopt 0.0001 persons as an acceptable upper limit for the “expected number of casualties (Ec) “

NOTE 2 Generally, on-board radioactive substances, toxic substances and any other hazardous materials are considered when evaluating and limiting the potentially adverse effects of re-entry on the Earth’s environment.

NOTE 3 Although there are a number of risks associated with re-entry, currently most national authorities require the assessment of only two risks - casualty expectation and adverse effects on the Earth’s environment.

5.3 Standardized process and resources for analysis

A standardized process, complied with the safety requirements posed by national or international authorities, if there are, shall be authorized by the entity which conduct analysis. The standardized process should designate methods, tools, models, and physical characteristics and properties, as shown the examples below

a) Analysis tools, models, and approach, including:

1) algorithms for trajectory, aerodynamic, aerothermodynamic and thermal analyses for re-entry trajectory and heating analysis,
2) requisite physical characteristics and aerodynamic and thermal properties for trajectory and thermal analyses,
3) treatment of component thermal shielding and vehicle disassembly during the break-up process,
4) atmosphere model,
5) human population distribution model and definition of casualty area, and

   [See 5.5.1.2 for typical definition of casualty area.]
6) criteria for eliminating any vehicle components from the risk analyses, and
7) any other criteria or assumptions that affect the assessment of casualty; (Including below b).)

b) Analytic conditions, assumptions or criteria for assessment
Because of the complexity of space vehicle re-entry physics and material responses, detailed analysis will be necessary to obtain accurate aerodynamic and thermal phenomena. If there are technical uncertainties or insufficient resources, then simplified models, analytic conditions, criteria or assumptions may be applied. If there are technical uncertainties or lack of resources, general and simple models, analytic conditions, and criteria or assumptions may be applied.

The following conditions may be given, for example:

1) attitude mode (e.g. tumbling, side-on stable),
2) contribution of oxidation to the heating rate, and
3) conditions of the break-up process and sequence; (de-facto value for aerodynamic break-up point where the space vehicle is assumed to be disassembled into a set of components.)
4) initial temperature.
5) threshold for minimum impact energy that must be considered as a cause of casualty

NOTE 1 An object whose impact energy is less than 15 Joules is exempt from casualty assessment in some agencies.

6) models for reduction of mass and size, and deformation of shape due to ablation.

NOTE 2 If the safety requirements identify a risk scenario other than ground casualty, an adequate process is added to the above set.

5.4 System / mission dependent parameters

The following shall be obtained from those organizations that are responsible for the design and operation of a space vehicle.

a) The object physical characteristics and aerodynamic and thermal properties shall be obtained from those organizations that are responsible for the design and operation of a space vehicle.

b) orbital characteristics which defines the initial point of re-entry analysis

c) detailed identification of the spacecraft or launch vehicle orbital stage including its components (e.g. propellant tanks, pressurized vessels, major structural elements) and their architecture, mass, dimensions, shapes, material properties (e.g. melting point, density), connectivity, mutual shielding and nesting and other factors (e.g. aerodynamic drag coefficient, coefficients for average heating), and

NOTE 1 Design data of deployment devices will enable better estimation of the break-up point.

NOTE 2 It is important to list all of the components which could be released when the space vehicle fragments during re-entry. This is particularly the case for any components possibly surviving re-entry, and whose impact energy on the ground may be beyond the criteria defined in sub-clause 5.3.b)-5)

NOTE 3 Several organizations define the minimum total mass of components to avoid underestimation of the potential risk. For example, components will be listed-up until the total mass of the components would reach to 70 % of the vehicle mass, on the condition that the rest of 30 % will be cables, small sensors, or other parts which demise during re-entry.

d) properties of small but potentially surviving and hazardous objects that are likely to be released during re-entry.

5.5 Estimation of risk

5.5.1. Estimation of number of casualties

5.5.1.1 Survivability analysis

A survivability analysis shall be conducted according to 5.3 and 5.4 to confirm compliance with the requirements in 5.2. The result of the analysis shall include a list of the objects that are expected to survive re-entry and impact on the ground, and the associated characteristics of those objects such as their mass and projected area.

NOTE It is encouraged that, according to the risk defined in 5.2, the risks of re-entry (probability of occurrence and severity of consequences) are estimated and reported as follows:

a) critical components with their characteristics, in enough detail to conduct trajectory and thermal analyses (e.g. mass, shape, dimensions);

b) results of analyses including an estimate of the characteristics of the fragments likely to survive re-entry (e.g. mass, shape, dimensions, velocity, kinetic energy at impact);

c) probability of hazard and severity of consequence estimated according to the risk scenario identified by safety requirements.

5.5.1.2 Casualty area

To estimate the risk to human beings, typically “casualty area” is defined as an envelope covering all the locations of the geometric centre of maximum projected area of a surviving object which would have “critical contact” with “critical area of human being in a static standing position” ($A_{h\ critical}$). Here, “critical contact” is defined that would cause casualty, and defined by the contact between object which has higher impact energy than pre-defined threshold to prevent casualty and $A_{h\ critical}$ which is vulnerable to such threshold of impact energy.

The casualty area of a space vehicle shall be calculated by summing the casualty areas of all constituent objects that are expected to survive re-entry.

Sub-clause B.2 in Annex-B shows one of traditional method for the calculation of casualty area.

NOTE 1 It should be noted that methods presented in Annex-B uses an average area of standing human being. So that the result of “casualty area” doesn’t necessarily present the critical area which bring about fatality or serious injury. As one of possible methods to acquire more practical value, a set of $A_{h\ critical}$ and threshold of impact energy which causes casualty should be defined firstly. Then the “critical fragments” are to be selected as those whose impact energy are beyond the threshold, and $A_{h\ critical}$ (an area of skull, for example) and the projected area of critical fragments will be used to obtain casualty area.

Not limited to such method, a space system developing entity should prepare adequate methods accepted by the authority, and apply them to analysis.

NOTE 2 For more effective evaluation of the casualty area, the following conditions may be considered.

a) Elongation.
b) Secondary impact effects such as break-ups and bounce.
c) Other factors that may enlarge the effective casualty area.

5.5.1.3 Expected number of casualties

Expected number of casualties (Ec) shall be calculated from at least the following values, and be confirmed to be compliant with the requirement.

a) Sum of casualty areas of all the surviving objects

b) Predicted landing area defined by the latitude band corresponding to orbital inclination

c) Number of human beings resident in the predicted landing area at the time of the predicted landing event

Sub-clause B.4 in Annex-B shows typical methods for calculation of Ec.

NOTE The probability of impact on the limited latitude band differs according to the latitude. In high latitude region, the probability is relatively high, and in low latitude band, the probability is low. (See Figure B.3 in Annex B.)

5.5.2. Assessment for Environmental effects

In the case of on-board radioactive substances, toxic substances or any other environmental pollutants, an assessment of the effects that they have on the Earth's environment, including human health, shall be done.

5.6 Risk decision and actions

According to the result of the estimation of risk conducted in sub-clause 5.5, a decision shall be made to accept the design and operation, or initiate risk reduction activities.

Decision and actions for typical ground casualties and ground pollution is shown in Figure 1.

If the safety requirements identify a risk scenario other than ground casualty and environmental effects, an adequate process is added to the above set. If applicable, the risk magnitude shall be determined by the severity and probability of a hazard. For each risk scenario the risk decision and actions corresponding to the risk magnitude ~~estimated in 5.4~~ shall be determined, documented and approved by a safety representative.

The result of the assessment is expressed in a risk assessment matrix, if applicable.

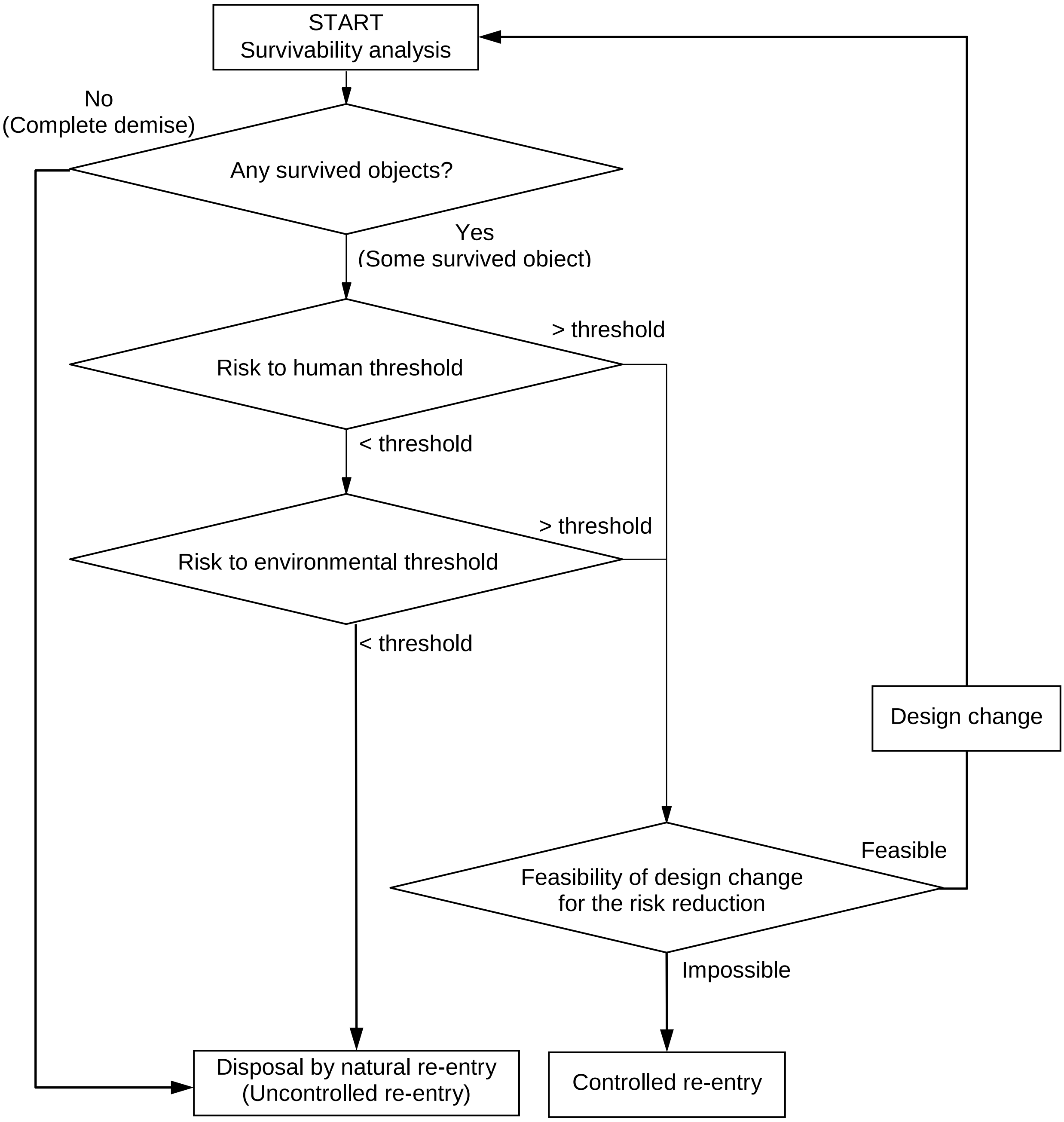

Figure 1 — Flow for risk assessment and disposal planning

6 Risk-reduction measures

6.1 General

The following typical measures to reduce re-entry risks are defined in 6.2, 6.3 and 6.4. Other measures (e.g. launch at different inclination to minimize population at risk, intentional break-up just prior to re-entry or reduced orbital lifetime to avoid increased population growth) may be taken if the mission objective or mission cost-benefit metrics allow(s) them. The measures, namely:

a) design measures to reduce re-entry survivability, and

b) controlled re-entry shall be planned, designed and documented in the safety data package specified in ISO 14620-1, and should be reviewed in the Safety Review.

6.2 Design measures to reduce re-entry survivability

If the expected number of casualties does not meet the requirement, the use of structural designs and materials that minimize the survivability of fragments shall be encouraged for all hardware that might re-enter the Earth's atmosphere, whether by uncontrolled or controlled means.

NOTE 1 Possible solutions may be the selection of materials that are easily demisable, the replacement of single materials with multi-layered materials, and changing the location of items for better exposure to the ablation environment, etc.]

NOTE 2 The risk reduction measures should not degrade the reliability or safety of the systems during operation.

For example, a composite tank may be superior to the titanium tank in terms of easy demise, but not of reliability and safety due to its vulnerability to cryogenic or radiation environment if it would be applied to cryogenic fluids or installed on the place exposed to outer space for long years.

If the environmental effects or other risks specified in the national regulations do not meet the requirement, then the design, operation and/or disposal method shall be modified.

6.3 Controlled re-entry

If the survivability analysis for an uncontrolled re-entry shows that risk to humans on the ground will be greater than safety requirements allow, control measures should be developed to reduce the risk below the threshold by confining the fragments to uninhabited regions, such as broad ocean areas.

This method is also encouraged to minimise the risk to the public regardless of compliance. [See Clause 7 in detail.]

7 Planning, design and operation of controlled re-entry

7.1 General

Controlled re-entry is one of the best practices, upon mission completion, to mitigate both orbital debris and public risk on the ground. It involves the planned re-entry of a space vehicle so that any surviving fragments impact a designated area on the surface of the Earth, such as an ocean.

The responsible organization shall confirm that all the intent of the following requirements for planning, design and operation will be met.

7.2 Identification of requirements

Identify applicable requirements for the controlled re-entry with respect to the related countries or regulators.

NOTE 1 Related requirements may be found in the documents associated with orbital debris mitigation and/or range safety regulation.

NOTE 2 Typical requirements are:

a) Allowable distance from the impact points of any surviving objects to landmasses, traffic conditions and interference with oceanic plants.

b) Allowable Ec presented by the product of the probability of failure of the re-entry control maneuvers and the risk of human casualty assuming uncontrolled re-entry.

7.3 Planning of the controlled re-entry

7.3.1. Landing location and area

Landing location and area shall be defined for the basis of the specific controlled re-entry. The planned landing area shall be sufficiently wider than the “envelope of predicted impact points of surviving objects” (referred to “footprint”) so as to give flexibility for operation and margin for uncertainty of the actual footprint.

The planned landing area is to be subjected for survey to ensure if any restrictions or undesirable conditions exist.

When spacecraft or any other re-entering objects are intended to land, or could land per the plan, on the territory of a certain nation, there must be a permission of the government having a jurisdiction over the territory.

NOTE 1 Protocol on Environmental Protection to the Antarctic Treaty must be respected.

The predicted footprint will be calculated by dispersion analysis that is based on the actual maneuver plan and condition, tied with specific date and time, and will be a source of the notification described in Sub-clause 6.4. The maneuver plan must be established so that the predicted footprint will be well within the notified area.

NOTE 2 The calculation can include consideration of the dispersions of the initial condition of orbital characteristics at the end of re-entry maneuver, aerodynamic characteristics of vehicle, atmospheric instability, wind effects, and other effects.

7.3.2. Design features for controlled re-entry

7.3.2.1. Vehicles

The vehicle design must take into account the functions and performance required for controlled re-entry in addition to the capability for nominal mission operation.

NOTE 1 As examples, following functions will be required to work in lower altitude than that of mission operation.

a) Functions needed for orbit determination and attitude control.

b) Functions needed for monitoring essential functions for controlled re-entry.

c) Functions to interrupt execution of re-entry maneuvers per ground commanding, if required, etc.

NOTE 2 Appropriate levels of radiation hardness will be required in the design of a launch vehicle orbital stage performing a controlled re-entry.

7.3.2.2. Ground systems

Following functions shall be provided:

a) Functions to support ground operators to ensure the re-entry sequence is in progress within allowable state, and the predicted footprint will be within notified area.

b) Functions to allow ground operators to interrupt execution of re-entry maneuvers, if required.

7.4 Notification

The area that envelopes predicted footprint must be notified per the procedures defined by international civil aviation and maritime organizations. Specific authorization process may be additionally required by a relevant government in the case that the notified area is within or interfere with territory of a nation.

Notification must be up-to-date as required by each stakeholder and any changes for notified area must be reauthorized prior to execution of the re-entry maneuvers.
Contingency notification process must be prepared in the event that the re-entry was far deviated from original plan and/or any safety concern is in place due to subsequent situation.

NOTE
a) Airline
The notification should be provided according to the procedures defined in ICAO Annex 15 “Aeronautical Information Services” such as NOTAM (Notice to Airmen) and AIP (Aeronautical Information Package).

b) Maritime routes
The notification should be provided according to the procedure relating to “Notice to Mariners” and “Maritime safety information” (NAVAREA / NAVTEX, etc.)

7.5 Post re-entry activities

If a hazardous condition induced by the controlled re-entry is expected or found, it must be secured immediately.
Related officials shall be notified with the detail of the problem.

NOTE Assumed Hazardous conditions

- a large floating object left on the area.
- propellant tanks landing or floating with toxic materials.

Annex A
(Informative)

Content of the re-entry risk assessment and mitigation plan

A.1. Scope of the RRAMP

This clause defines the project to be managed, the name of the contract under which the document is produced, the name of organizations related to the contract, the applicable phase of this document and other general information related to the management activities.

A.2. Related documents

A.2.1. Normative references

This sub-clause defines normative references (e.g. ISO 14620-1).

A.2.2. Applicable regulations and rules

This sub-clause defines regulations, rules and standards which control the re-entry risk and process of work.

EXAMPLE 1 Domestic rules and guidelines which impose requirements for safety.

EXAMPLE 2 Technical and management standard applied in the organization (e.g. system safety standard, question and answer programme standard, design standard and operation standard).

A.2.3. Reference

This sub-clause defines references that provide additional details, which may be either cited or referred to.

EXAMPLE 1 Details of the methodology, tools (e.g. trajectory model, atmosphere model, heating model, material database, re-entry break-up model, environmental assessment model) and assumptions (e.g. population model, break-up and demise conditions) used to develop the re-entry and environmental hazard estimates.

EXAMPLE 2 Mission description, including initial conditions for the re-entry analysis or including the initial state of the space vehicle (initial altitude, eccentricity, latitude, longitude, velocity and flight-path angle, and other parameters at the beginning of re-entry).

EXAMPLE 3 Applicable company standards that define assumptions (initial temperature, structural strength of deployed parts, effect of oxidation, tumbling pattern, aerodynamic drag coefficients, break-up altitude, etc.).

EXAMPLE 4 Technical documentation or input package for review, which includes plans and reports for design, analyses, tests and operations.

A.3. Re-entry risk management

A.3.1. Re-entry safety programme

This sub-clause defines the safety programme, mentioning the relation to the system safety programme.

A.3.2. Re-entry safety oversight and management

This sub-clause describes the organizational structure of the project and identifies the functions and responsibilities of the safety organization, which is assigned to ensure the risk management activities for this project.

This sub-clause also describes the review system to manage the re-entry risk for a project, including types and methods of reviews, members of the review board, contents of input data package, responsibility and frequency.

Next, this sub-clause describes the details of tailoring with a compliance matrix. The rationale and justification are clarified.

A.3.3. Re-entry risk assessment and mitigation plan

This sub-clause describes the process to produce, approve and modify a programme plan. Annex B describes the compliance between this International Standard and the RRAMP.

A.3.4. Schedule

This sub-clause describes detailed schedules of critical activities (design, analysis and testing reviews) throughout the life of the programme.

A.4. Risk assessment

A.4.1. Concept for assessment

This sub-clause explains the concept of assessment, design and operation philosophy, applicable technology, etc.

A.4.2. Mission description

This sub-clause provides a detailed description of the space vehicle's mission and its planned end-of-mission orbit or refers to the documents which define them. This includes a full description of the orbit parameters (inclination, apogee, perigee, argument of perigee) and the initial conditions used in the re-entry analysis, including altitude, latitude, longitude, velocity, flight-path angle and time epoch. Also included are

— a physical description of the re-entering vehicle, including a detailed breakdown of the vehicle construction, material properties, mass, dimensions and shapes of major components, and

— a list and description of radioactive or other materials which are likely to affect the Earth's environment.

A.4.3. Safety requirements

This sub-clause describes or cites safety requirements induced from the rules or regulations imposed by a government or other entity that ensures ground safety.

A.4.4. Process and resources for analyses

This sub-clause identifies and describes the procedures, methods, tools, models, assumptions and parameters used to assess risks. In the event that details related to the vehicle's design specifications, components and orbit inclination are not yet known, the above-required information based on assumptions and parameters of a worst-case scenario is provided.

A.4.5. Estimation of risk

This sub-clause identifies the result of estimation. Detailed reports are referred.

A.5. Risk-reduction measures

A.5.1. Structural design measures to reduce re-entry survivability

This sub-clause describes specific features that have been incorporated in the design of the spacecraft or launch vehicle orbital stage to reduce re-entry survivability and hazards to people and property. Included are the expected results of these modifications on re-entry hazards.

A.5.2. Controlled re-entry

This sub-clause describes or cites the design specifications that enable controlled re-entry for the space vehicle, the operation plans from mission termination to the final manoeuvring for re-entry and the ground support plans to monitor re-entry. It identifies the nominal geographic region within which surviving fragments will impact, provides the rationale for selecting the region for disposal and includes plans and schedules for timely warnings of fragment impact. Estimation of the fragment impact zones for a controlled re-entry includes the effect of uncertainties pertaining to re-entry, atmospheric conditions and other factors.

A.5.3. Notification

According to 6.4, any nation or organizations that could potentially be affected by the impact on aircraft, ships or land are identified. This sub-clause includes a list of such nations or organizations which is notified of plans for controlled re-entry, contact information and a notification schedule for each nation or organization.

For a controlled re-entry into a safe area, this sub-clause shall also contain a plan for the timely notification of responsible agencies of the time and location of expected fragment impact [e.g., in order that a Notice to Airmen (NOTAM) and Notice to Mariners can be sent].

For both uncontrolled and controlled re-entry, when the re-entering spacecraft or launch vehicle orbital stage contains a hazardous material, details of the process required to mitigate hazards associated with the hazardous material shall be provided to every nation that might be affected by the re-entry.

Annex B
(Informative)

Calculation of expected number of casualty

B.1. General

Re-entry survivability analysis will generate the list of objects survive re-entry and impact on the ground. The list will include their projected areas to calculate casualty area, and mass and impact velocity to calculate impact energy, at least.

B.2. Calculation of casualty area

Casualty area (Ac) is an envelope covering all the positions of centre of projected area of a surviving object where it would impact on the ground with having interference with an average standing static human being.

The sum of the casualty areas of all the surviving objects will present vehicle's casualty area.

NOTE Typically, casualty Area (A_c) is defined by projected area of fallen objects (radius (r_d), projected area (A_d)) and average area of standing human assumed to be circle (human radius (r_h) = 0.34 m, human area (A_h) = 0.36 m^{2,} as example) as shown below. For the simplified assumption of circular debris, Ac can be calculated for sphere object by the following equation. (See Figure B.1 and B.2)

$$A_C = \pi(r_h + r_d)^2$$

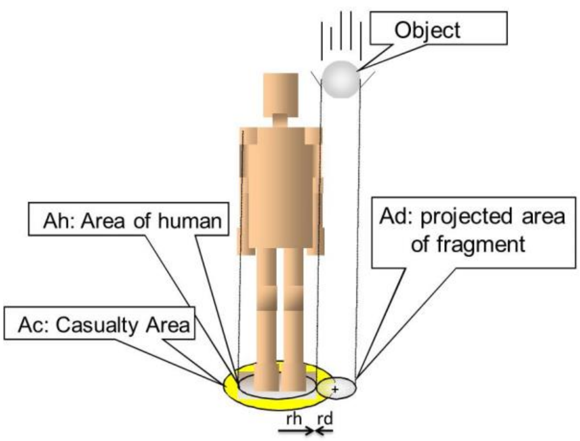

Figure B.1 — Typical concept of Casualty Area presented by A_h and A_d

For other shapes, as shown in Figure B.2,
$A_C = A_d +$ (perimeter of impact object × r_h) + A_h

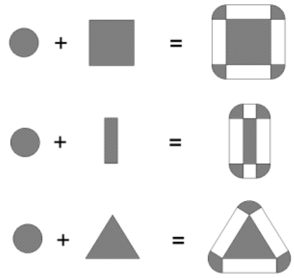

Figure B.2 — Casualty Area in the case of polygonal shapes

B.3. Potential impact zone in the case of uncontrolled re-entry

Potential impact zone is defined by surface of the Earth and latitude defined by the orbital inclination of vehicles in the case of natural re-entry.

B.4. Calculation of Ec

In rough estimation, Ec will be calculated by the following formula without considering the difference of impact probability depending on the latitude.

$$Ec = Ac\, N / Ai \qquad (1)$$

Here,
Ac: Casualty area as a sum of all the surviving objects.
Ai: Area of potential impact zone on the ground limited by latitude band corresponding to the orbital inclination
N: number of peoples being resident in the potential impact zone (Ai)
N shall be given by the population model

If the Earth is modeled as a perfect sphere;

$$Ec = Ac\, N / (4\ \pi\, Re^2 \sin(i)) \qquad (2)$$

Here,
Re: radius of the Earth (6,378,145 m)
i : orbital inclination
N: population within a latitude band bounded by +/- Inc.

To get more exact value, the difference of provability of impact on the specific latitude bands may be taken into considerations. Ec will be obtained by the product of the probability of impact on specific latitude band and number of human being resident in the latitude band, and integration of them within the latitude range covered by orbital inclination.

$$Ec = \sum_{i=\mathrm{minlatitude}}^{\mathrm{maxlatitude}} Pi\, Ni / Ai \qquad (3)$$

Here,
Ai : ground area in i-th latitude band
Ni : population within Ai

Pi : probability of impact in i-th latitude band

NOTE Probability of impact for each latitude band is shown for several cases of orbital inclination (form 5 degree to 88 degree) in Figure B.3.

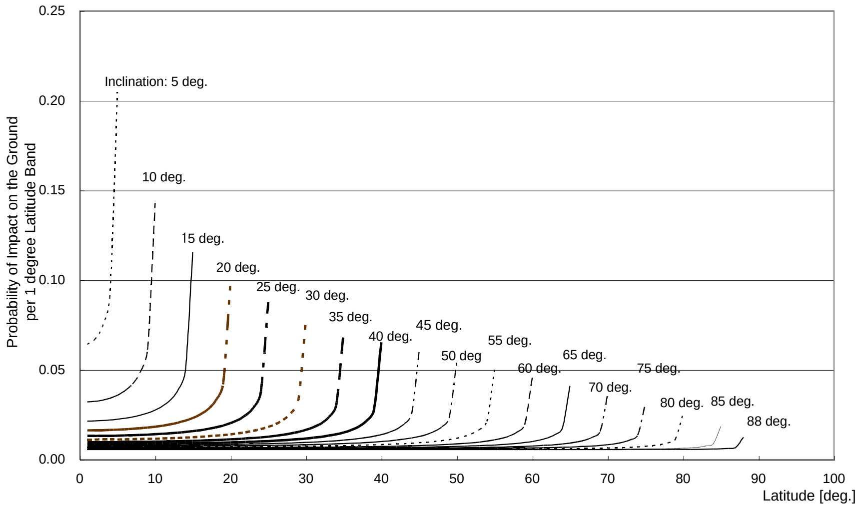

Figure B.3 — Probability of Impact on the Earth in Each One-Degree Latitude Band Depending on the Inclination

B.5. Population distribution models of human being

The “population distribution models of human being” is selected as authorized in subsection 4.3.

NOTE Followings are typical models. The Gridded Population of the World are used in several world space agencies.

a) GPW2: Gridded Population of the World, version 2 (produced by the Center for International Earth Science Information Network :CIESIN) [See: http://sedac.ciesin.org/gpw/global.jsp]
b) UNESCO: UNESCO model
c) DP: Demography Project 1994 Data (provided by the Social Science Information System based at the University of Amsterdam) [See: http://www.sociosite.net/topics/population.php]
d) GGP: Gridded Global Population Distribution of the World (provided by the United Nations Environment Programme) [See: http://na.unep.net/datasets/datalist.php]
e) IDB: Census Bureau’s International Programs Center International Data Base (IDB).

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