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Space systems — Re-entry risk management for unmanned 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

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

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

This second edition cancels and replaces the first edition (ISO 27875:2010) which has been technically revised. It also incorporates the Amendment ISO 27875/Amd1:2016. The main changes compared to the previous edition are as follows:

— revised 6.2;

— a Note 1 to entry was added to the definition of Ec;

— long sentences were divided into multiple sub-clauses with each sub-clause containing just one requirement.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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 the re-entry of spacecraft and launch vehicle orbital stages. To minimise damage and injuries from re-entering spacecraft and launch vehicle orbital stages, all parties (i.e., developers, manufacturers, space service providers, satellite operators, and launch service providers) should take preventive measures during design and operations.

Space systems — Re-entry risk management for unmanned spacecraft and launch vehicle orbital stages

1 Scope

This document provides a framework with which to assess, reduce, and control the potential risks that spacecraft and launch vehicle orbital stages (referred to hereinafter as "space vehicles") 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 inevitable.

This document is applicable to following objects in assessing their risk to the ground:

a) objects re-entering from orbit in conformance with ISO 24113;

b) launch vehicles (including payloads, other objects separated during the ascent phase, etc.) that are mentioned in flight safety activities under ISO 14620-2[1]; and

c) interplanetary spacecraft returning to Earth.

This document complements ISO 14620-1 and ISO 17666.

This document is not applicable to spacecraft containing nuclear power sources[2].

NOTE 1 This document does not apply to Space Transportation Systems with wings and control functions intended for targeted landing.

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

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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, *Space systems — Space Systems Space debris mitigation requirements*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 10795, ISO 24113 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at https://www.iso.org/obp

3.1
controlled re-entry
type of re-entry where the time of re-entry is sufficiently controlled so that the impact of any surviving debris on the surface of the Earth is confined to a designated area

Note 1 to entry: The designated area is usually an uninhabited region such as an ocean.

3.2
expected number of casualty
Ec
number of people who are predicted to be killed or seriously injured by an event

Note 1 to entry: The calculation of Ec is complex. Organizations use different processes to estimate Ec based on methods deemed applicable by the organizations. (see 5.5.1 and Annex C).

4 Re-entry risk management

4.1 General

Re-entry risk management shall be conducted according to ISO 17666, which is briefly explained in Annex B. This document mainly focuses on the estimation of the risk of casualty and partly on ground pollution. This document also presents requirements for when controlled re-entry would be conducted to reduce risk. This document acts as a part of a system safety programme based on ISO 14620-1.

4.2 Re-entry safety programme

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

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

b) suggestions for corrective actions regarding risks assessed as exceeding safety requirements.

4.3 Re-entry safety oversight and management

As required in ISO 14620-1, safety representatives shall be appointed. Safety representatives shall be responsible for safety activities, have the right to access related data, and be authorized to reject any project document, stop any project activities, or interrupt hazardous operations. As required in ISO 14620-1, at each design or operation phase, a review committee should review the result of the safety assessment, review the plan for the next phase, and endorse the decision to proceed to the following phase. If there are requirements that cannot be met, a request for deviation or waiver is generated and reviewed, and the space vehicle is disposed according to ISO 14620-1.

4.4 Re-entry risk assessment and mitigation plan

4.4.1 Preparation of the plan

A Re-entry Risk Assessment and Mitigation Plan (RRAMP) shall be prepared and updated throughout the project life cycle as part of the safety data package specified in ISO 14620-1.

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

4.4.2 Authorization of the plan

The RRAMP shall be approved by the safety representative, the head of project management, and the customers. The RRAMP will be changed and evolved as the project progresses.

4.5 Re-entry risk management concept

The scoring schemes for the severity of consequence of re-entry hazards are defined by the national authority. Based on ISO 17666, risk is assessed by the risk magnitude expressed as the combination of its severity and likelihood (see Annex B, and ISO 17666).

The scoring is typically related to the casualty area (see 5.5.1.2) in the case of casualty risk, damage of properties in the case of social risk, or pollution on the ground in the case of environmental risk (for example, see Table B.1, or ISO 17666). Generally, a risk index will be defined as a combination of severity and likelihood, and a risk magnitude will be defined for each risk index.

For assessing re-entry risk:

— In the case of natural re-entry, Ec is calculated as a function of the casualty area, orbital inclination, and population density. Since the re-entry cannot be avoided without control, likelihood is fixed as the probability of occurrence of 1,0, and the risk index is equivalent to the Ec. Sub-clause 5.5 describes assessment procedures for casualty risk in the case of natural re-entry. Sub-clause 5.6 for environmental risk.

— In the case of controlled re-entry, Ec is calculated in the same manner as for the natural re-entry (i.e., is a function of the casualty area, orbital inclination and population density), but the Ec is weighted by reliability of functions and sufficiency of propellants needed for controlling the re-entry. (See Annex B or ISO 17666). Sub-clause 7.4 describes assessment procedures for casualty risk in the case of controlled re-entry.

Proposed actions may be defined for each risk index (See Table B.3 and B.4, or ISO 17666.)

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 an uncontrolled re-entry and to 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) identification of a standardized process and resources for analysis;

c) identification of system/mission dependent parameters;

d) estimation of risk; and

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 using terms (risk scenario, risk magnitude, risk decision and actions, etc.) defined in ISO 17666.

5.2 Identification of safety requirements

5.2.1 Identification of requirements

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

5.2.2 Risk assessment plan

Re-entry risk assessment actions (analyses, reports, etc.) shall be defined and scheduled, and a compliance matrix that correlates safety requirements against the system design and operation plan, which includes achieved quantitative results, threshold values, consequences of violating 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 its associated mathematical parameters) and their thresholds, or the concept for risk decision and the actions according to the severity of consequences and the likelihood of occurrence.

NOTE 1 Several national governments and space agencies adopt 0,000 1 persons as an acceptable upper limit for 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.

5.3 Identification of standardized process and resources for analysis

A standardized process, to identify the safety requirements established by national or international authorities, shall be implemented by the entity which conducts the analysis. The standardized process shall designate methods, tools, models, and physical characteristics and properties of materials, as in the examples shown below.

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

   1) algorithms for trajectory, aerodynamic, aerothermodynamic, and thermal analyses for re-entry trajectory and thermal analyses;

   2) requisite physical characteristics, aerodynamic properties, and thermal properties for trajectory and thermal analyses;

   3) Earth model and atmospheric model;

   4) any constants or formulae for perturbations on the decaying trajectory;

   5) human population distribution model;

   6) definition of casualty area (see 5.5.1.2 for a typical definition of casualty area);

   7) reduction in mass and size, and deformation due to ablation during re-entry; and

   8) definition of the techniques and assumptions used to estimate the Ec (e.g., year of re-entry, population model, casualty area).

b) Analytic conditions, assumptions, or criteria for assessment

   Due to the complexity of re-entry physics and material responses, detailed analyses will be necessary to obtain accurate estimates of aerodynamic and thermal phenomena. If there are technical uncertainties or insufficient resources, then simplified models, analytic conditions, criteria, or assumptions may be applied.

   The following conditions may be assumed as given, for example:

   1) attitude mode (e.g., tumbling, side-on stable, etc.);

2) contribution of oxidation to the heating rate;

3) standard conditions of the break-up process and sequence (e.g., de-facto altitude of the aerodynamic break-up point where the space vehicle is assumed to be disjoined into a set of components, a specific value acquired from the analysis, etc.);

4) initial temperature when the analysis starts;

5) criteria for eliminating any components from the risk analyses due to their low survivability; and

6) threshold for minimum impact energy that causes casualty.

5.4 Identification of system/mission dependent parameters

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

a) the object's physical characteristics, aerodynamic properties, and thermal properties;

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

c) detailed characteristics of the space vehicle including its components (e.g., propellant tanks, pressurized vessels, major structural elements) and their architecture, mass, dimensions, shapes, connectivity, mutual shielding and nesting, and other factors (e.g., aerodynamic drag coefficient, coefficients for average heating); and

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

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

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

5.5 Estimation of risk in the case of natural re-entry

5.5.1 Estimation of the 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, and its result of the analysis shall include a list of objects that survive re-entry and impact on the ground.

5.5.1.2 Casualty area

5.5.1.2.1 Definition of casualty area

To estimate the risk of human casualty, a "casualty area" is typically defined as the average debris cross-sectional area plus a factor for the cross-sectional area of a standing individual which would have a "hazardous contact" with the "critical area of standing individual" ($A_{h\ critical}$). The total debris casualty area for a re-entry event is the sum of the debris casualty areas for all debris pieces surviving atmospheric re-entry. Here, "hazardous contact" is defined as contact that would cause casualty (injury or death); i.e., contact between an object which has an impact energy higher than the pre-defined threshold to prevent casualty and $A_{h\ critical}$ which is vulnerable to such a threshold for impact energy. Sub-clause C.2 shows one of the traditional methods for the calculation of casualty area.

5.5.1.2.2 Additional study for practical casualty area

It should be noted that methods presented in Annex C use an average cross-sectional area of a standing individual. The resulting “casualty area” does not necessarily represent the critical area which leads to fatal or serious injury. As one possible method to acquire a more practical value, a set of $A_{h\ critical}$ and threshold impact energies which cause casualty should be defined first. Next, “hazardous fragments” shall be selected as those whose impact energy are beyond said thresholds, and $A_{h\ critical}$ (the area of a skull, for example) and the projected area of hazardous fragments will be used to obtain the casualty area. Not limited to such a method, a space system developing entity should prepare adequate methods accepted by the authorities, and apply them to their analysis.

NOTE For a known re-entry location, the accuracy of the calculation of the casualty area is improved by considering the following conditions:

a) elongation (caused by factors such as wind);

b) secondary impact effects by fragments generated by the impact on the ground, or enlargement of casualty areas by multiple bounces on the ground; and

c) other factors that can enlarge the effective casualty area.

5.5.1.3 Expected number of casualties

If the safety requirement is defined by the expected number of casualties (Ec), it shall be calculated from at least the following values, and confirm conformance 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; and

c) number of residents in the predicted landing area at the time of the predicted landing event.

Sub-clause C.4 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 regions, the probability is relatively high, and in low latitude band, the probability is low. See Figure C.3.

5.5.2 Estimation and assessment of casualty risk

The scoring schemes for the severity of consequence will be defined by the national authority in accordance with the casualty area or Ec. (see Annex B).

The likelihood shall be scored in accordance with the probability of occurrence. In the simple case of natural re-entry caused by disposal from the operation orbit, the probability of occurrence is always 1,0 so that the risk magnitude will be defined by the score of the severity of consequence (see B.4).

Proposed actions would be defined in accordance with risk magnitude.

5.6 Assessment of environmental risk

In cases where there are on-board radioactive substances, toxic substances or any other environmental pollutants, a risk assessment for the effects on the Earth's environment, including human health, shall be conducted.

The scoring scheme for the severity of consequence would be defined by the national authority depending on the hazard level of on-board materials.

The likelihood would be scored as a function of the probability of occurrence considering the strength of containers and the location of impact on the Earth, i.e., whether it is on landmass or ocean.

The risk index will be defined as a combination of severity and likelihood, and the risk magnitude will be defined for each risk index. Proposed actions would be defined corresponding to each risk magnitude. See Table B.6.

5.7 Risk decision and actions

5.7.1 Acceptance of risk or suggestion for risk reduction

According to the result of risk estimation conducted in 5.5 and 5.6, a decision shall be made to accept the design and operations, or to suggest additional risk reduction activities.

Decisions and actions for typical ground casualties and ground pollution are included in Figure 1.

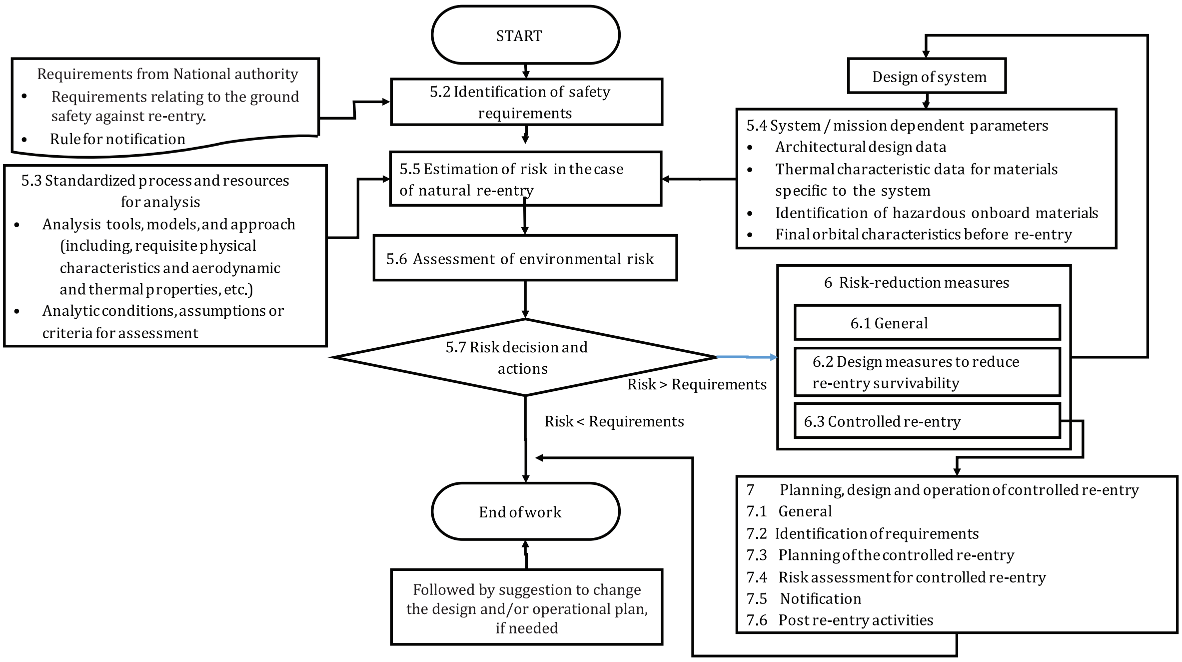


Figure 1 — Flow for risk assessment and disposal planning

5.7.2 Consideration with other risk, if required

If the safety requirements include a risk scenario other than ground casualty and environmental effects, an adequate process shall be added to the above set. For each risk scenario, the risk decisions and actions corresponding to the risk magnitude estimated in 5.5.2 shall be determined, documented, and approved by a safety representative.

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

6 Risk-reduction measures

6.1 General

Typical measures to reduce re-entry risks are defined in 6.2 and 6.3.

The mission design or other measures designed to reduce re-entry survivability shall be documented in the RRAMP.

NOTE 1 Other measures (e.g., assisted natural re-entry, launch at a different inclination to minimise population at risk, intentional break-up just prior to re-entry or reduced orbital lifetime to avoid increased population growth) are being discussed for the cases that the mission objective or mission cost-benefit metrics allows them.

NOTE 2 If the intentional break-up would be planned, ISO 24113 specifies that the intentional break-up of a spacecraft or launch vehicle orbital stage in Earth orbit shall be avoided. An intentional break-up which is planned to take place just prior to re-entry does not contravene ISO 24113 if the break-up occurs at a sub-orbital altitude that is low enough to prevent the resulting debris from entering into orbit. It is normal procedure to document the risks associated with such an action in the RRAMP.

6.2 Design measures to reduce re-entry survivability

If the expected number of casualties does not meet safety requirements, the use of structural design and materials that minimise the survivability or debris casualty area of fragments are encouraged for all hardware that survives re-entry.

If the environmental effects or other risks do not meet the requirements specified in the national regulations, the design, operations or disposal method shall be modified.

6.3 Controlled re-entry

If the survivability analysis shows that risk of human casualty on the ground in the case of an uncontrolled re-entry is greater than safety requirements, control measures shall be developed to reduce the risk below the threshold by aiming the fragments to uninhabited regions, such as broad ocean areas.

This method is also encouraged to minimise the risk to the public regardless of conformance. See Clause 7.

NOTE 1 Controlled re-entry is the most efficient disposal method with respect to lifetime reduction and human casualty risk control. However, since it requires a propulsion subsystem powerful enough to perform the last re-entry burn, it is not feasible for spacecraft with low-thrust propulsion. For such a case, there is another option called “assisted natural re-entry” or “semi-controlled re-entry”. In this option, manoeuvres are performed until the vehicle is left very close to its effective re-entry point. A study suggests that, with proper phasing of the final argument of perigee and longitude, it is possible to reduce the casualty risk to an acceptable value even when using low-thrust propulsion.

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 vehicle so that all surviving fragments impact a designated area on the surface of the Earth, such as over an ocean, with the required probability.

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

The details shall be documented in the safety data package specified in ISO 14620-1, and should be reviewed in the Safety Review.

7.2 Identification of requirements

Applicable requirements for controlled re-entry shall be identified in accordance with the related countries or regulators.

7.3 Planning of the controlled re-entry

7.3.1 Landing location and area

7.3.1.1 Determination of landing location and area

Landing location and area shall be defined on the basis of each specific controlled re-entry.

7.3.1.2 Planning of landing area

The planned landing area shall be sufficiently wider than the "envelope of predicted impact points of surviving objects" (referred to as "footprint") to give flexibility for operation and margin for uncertainty of the actual footprint.

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

Permission shall be obtained from governments having jurisdiction over a territory when a vehicle or any other re-entering object is intended to land or could land as per the plan.

7.3.1.3 Predicted footprint

The predicted footprint shall be calculated by dispersion analysis that is based on the actual manoeuvre plan and condition, tied with a specific date and time, and shall be a source of the notification described in 7.5. The manoeuvre plan shall be established so that the predicted footprint will be well within the notified area with the required probability.

NOTE 1 It is customary to respect the Protocol on Environmental Protection to the Antarctic Treaty.

NOTE 2 The accuracy of the calculation is improved by considering as many influencing factors as possible, such as: effects due to the dispersion of the initial condition of orbital characteristics at the end of a re-entry manoeuvre, aerodynamic characteristics of the vehicle, atmospheric instability, and wind.

7.3.2 Design features for controlled re-entry

7.3.2.1 Space vehicles

In the vehicle design, the functions and performance required for controlled re-entry shall be incorporated in addition to the capability for nominal mission operation.

NOTE 1 It is important that some functions continue to work at altitudes lower than those of mission operations. These include:

a) Functions for orbit determination and attitude control;

b) Functions for monitoring essential parameters for controlled re-entry;

c) Functions to execute or to interrupt execution of re-entry manoeuvres by ground commands followed by passivation, if required, etc.

7.3.2.2 Ground systems

The following functions shall be provided:

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

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

7.4 Risk assessment for controlled re-entry

7.4.1 Risk assessment method

The risk assessment shall be conducted with the method defined by the relevant authority, and it shall be confirmed that the risk does not surpass the threshold.

Typically, the severity will be scored by the casualty area, impact energy, hazardous pollution, etc. See Table B.1.

The likelihood will be scored by the probability of occurrence of casualty, ground pollution, etc. See Table B.2.

The expected value of the number of casualties is represented by Ec, from which the probability of one or more casualties can be computed as 1- Exp(-Ec). The probability can be approximated as Ec if Ec is much less than 1,0. In the case of controlled re-entry, Ec is a function not only of the casualty area, orbital inclination, and population density but also of the reliability of operational functions, the reliability of re-entry control functions, the sufficiency of propellants, etc. Details will be given by the relevant authorities. See B.5.

NOTE In the case of controlled re-entry, there are three possible scenarios for the definition of Ec:

a) a failure causes loss of control during normal operations and results in a natural re-entry;

b) a failure of essential functions for controlled re-entry or insufficient propellant prevents successful control and causes natural re-entry as a result; and

c) a successful controlled re-entry is conducted as planned.

7.4.2 In case of non-conformance

If the risk magnitude would not satisfy the safety requirement, the design of surviving objects or the reliability of operational and disposal functions shall be re-arranged.

7.5 Notification

7.5.1 Normal plan

International civil aviation and maritime organizations require the notification of the potential users of the area that covers the predicted footprint and can additionally require a specific authorization process to ensure that the notified area does not interfere with the territory of a nation.

The notification shall be up-to-date as required by each stakeholder, and changes to the identified area shall be re-authorized prior to execution of the re-entry manoeuvres.

7.5.2 Contingency plan

A contingency notification process shall be prepared if the re-entry deviates significantly from the original plan or any safety concern is in place due to the following concerns.

a) Airline

   ICAO Annex 15 “Aeronautical Information Services” such as NOTAM (Notice to Airmen) and AIP (Aeronautical Information Package) define procedures for notification.

b) Maritime routes

   “Notice to Mariners” and “Navigational Warnings (NAVAREA/NAVTEX, etc.)” define procedures for notification.

7.6 Post re-entry activities

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

NOTE Assumed hazardous conditions include:

— a large floating object left on the area; or

— propellant tanks landing or floating containing toxic materials.

Annex A
(informative)

Contents 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 risk of re-entry, and process of work, mainly given by the relevant authorities.

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

EXAMPLE 2 Technical and management standards 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 reference documents and tools 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 risk 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.

This sub-clause describes the details of tailoring with a compliance matrix. The rationale and justification for tailoring 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.

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. If 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 to.

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, debris casualty area, and risk to people and property. Included are the expected results of these modifications on re-entry risk.

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

Per 7.5, 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 are 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 also contains 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 hazardous materials, details of the process required to mitigate risk associated with the hazardous materials are provided to every nation that might be affected by the re-entry.

Annex B
(informative)

The risk management process

B.1 General

The risk management process is defined in ISO 17666. The work may partly include the following tasks.

(1) Definition of the risk management policy. One of the works is establishment of scoring schemes for the severity of consequences and likelihood of occurrence for the tradable resources. Another is a risk index scheme to denote the magnitudes of the various risk scenarios.

(2) Preparation of the risk management plan.

(3) Identification of the risk scenario. Typical risk scenario may include human casualty caused by impact of surviving objects, ground pollution by hazardous objects, hazardous damage of critical facilities by impact of heavy surviving objects, etc.

(4) Assessment of the risk. [Typical methods for assessment of casualty is introduced in Clause 5 and 6.]

(5) Decision of risk acceptance or risk reduction.

(6) Action for risk reduction, recommendation for acceptance, or acceptance of risk.

This Annex focuses on providing an example of scoring schemes for the severity, the likelihood, and the risk magnitude.

B.2 Example of scoring schemes for severity and likelihood

Examples of the scoring schemes for the severity of consequences, and likelihood of occurrence for the tradable resources is presented in following Table B.1 and B.2.

Table B.1 — Example of a severity-of-consequence scoring scheme for re-entry event

Score	Severity	Assessed impact	Severity of consequence: Impact on safety
5	Catastrophic	Total casualty area of surviving objects is far larger than threshold, and some of them have large impact energy for critical facilities, or the hazardous ground pollution will not be avoidable.	Non-allowable impact
4	Critical	Total casualty area of surviving objects is far larger than threshold, and some of them have fatal impact energy, or there is potential hazardous pollution.	Hazardous impact
3	Major	Total casualty area of surviving objects is slightly larger than threshold, and some of them have large impact energy, or there is slight potential of hazardous pollution.	Non-negligible impact
2	Significant	Total casualty area of surviving objects is slightly larger than threshold, but none of them have large impact energy, and there is no potential hazardous pollution.	Needs managemental decision
1	Negligible	Total casualty area of surviving objects is smaller than threshold, none of them have large impact energy, and there is no potential hazardous pollution.	Minimal or no impact

NOTE

(1) Number of categories or designations are subject to change. Above score and designations are just examples.

(2) Critical casualty area will be given by the authority, or calculated from the given Ec, orbital inclination, etc.

(3) Critical impact energy will be given by the authority.

Table B.2 — Example of a likelihood scoring scheme for re-entry event

Score	Likelihood	Probability of occurrence
E	Maximum	Larger than 10^{-2} as example
D	High	Larger than 10^{-3} as example
C	Medium	Smaller than 10^{-3} as example
B	Low	Smaller than 10^{-4} as example
A	Minimum	Smaller than 10^{-6} as example

NOTE

(1) Number of categories or designations are subject to change. Above score and designations are just examples.

(2) Likelihood is probability.

B.3 Risk index and magnitude scheme

A risk index scheme to denote the magnitudes of the various risk scenarios will be established; example shown in Table B.3. An example of risk magnitude designations and proposed actions for individual risks is shown in Table B.4.

Table B.3 — Example of risk index and magnitude scheme

			Severity				
			1	**2**	**3**	**4**	**5**
			Negligible	**Significant**	**Major**	**Critical**	**Catastrophic**
Likelihood	**E**	**Maximum**	Very Low	Low	Medium	High	Very high
	D	**High**	Very Low	Low	Medium	High	Very high
	C	**Medium**	Very Low	Low	Medium	Medium	High
	B	**Low**	Very Low	Very Low	Low	Low	Low
	A	**Minimum**	Very Low	Very Low	Very Low	Very Low	Very Low

NOTE Officially, risk index and magnitude are defined in coordination with relevant authorities.

Table B.4 — Example of risk magnitude designations and proposed actions for individual risks

Risk index	Risk magnitude	Proposed actions (as indicated in ISO 17666)
E4, E5, D5	Very high risk	Unacceptable risk: implement new team process or change baseline — seek project management attention at appropriate high management level as defined in the risk management plan.
E4, D4, C5	High risk	Unacceptable risk: see above
E3, D3, C3, C4	Medium risk	Unacceptable risk: aggressively manage, consider alternative team process or baseline — seek attention at appropriate management level as defined in the risk management plan.
E2, D2, C2, B3, B4, B5	Low risk	Acceptable risk: control, monitor — seek responsible work package management attention.
E1, D1, C1, B1, B2, A1, A2, A3, A4, A5	Very Low risk	Acceptable risk: see above

NOTE

(1) In the example, risk magnitude designation, acceptability, and proposed actions are used for illustration only. Project-specific definitions can be different.

(2) Re-entry safety requirement given by the relevant authorities is expected to give the baseline to define above matrix.

B.4 Risk assessment for natural re-entry

In the case of natural re-entry, since the probability of occurrence is 1,0 in Table B.2, the score of likelihood is always “E”. The risk index and risk magnitude are determined by severity, then Table B.3 and B.4 can be simplified as Table B.5 and B.6.

Table B.5 — Example of risk index and magnitude scheme for the case of natural re-entry

			Severity				
			1	**2**	**3**	**4**	**5**
			Negligible	**Significant**	**Major**	**Critical**	**Catastrophic**
Likelihood	**E**	**Maximum**	Very Low	Low	High	Very high	Very high

Table B.6 — Example of risk magnitude designations and proposed actions for individual risks

Risk index	Risk magnitude	Proposed actions (as just indicated in ISO 17666)
E5	Very high risk	Unacceptable risk: implement new team process or change baseline — seek project management attention at appropriate high management level as defined in the risk management plan
E4	High risk	Unacceptable risk: see above
E3	Medium risk	Unacceptable risk: aggressively manage, consider alternative team process or baseline — seek attention at appropriate management level as defined in the risk management plan.
E2	Low risk	Acceptable risk: control, monitor — seek responsible work package management attention.
E1	Very Low risk	Acceptable risk: see above

B.5 Risk assessment for controlled re-entry

In the case of controlled re-entry, likelihood depends on the requirement of relevant authorities as well as:

(1) reliability of control system;

(2) sufficiency of propellant needed for control re-entry; and

(3) reliability of mission completion, etc.

The idea of "risk index and magnitude scheme" and "risk magnitude designations and proposed actions for individual risks" are same as Table B.2 and Table B.3.

Annex C
(informative)

Calculation of expected number of casualties

C.1 General

Re-entry survivability analysis will generate the list of objects predicted to 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.

C.2 Calculation of casualty area[3]

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 physical contact (which cause casualty) with an average cross-sectional area of a standing individual.

The sum of the casualty areas of all the surviving objects will present the 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 cross-sectional area of a standing individual assumed to be a circle (radius of a standing individual (r_h) = 0,34 m, cross-sectional area of a standing individual (A_h) = 0,36 m^2, as example) as shown below. For the simplified assumption of circular debris, Ac can be calculated for a spherical object by the following equation. (See Figure C.1 and C.2)

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

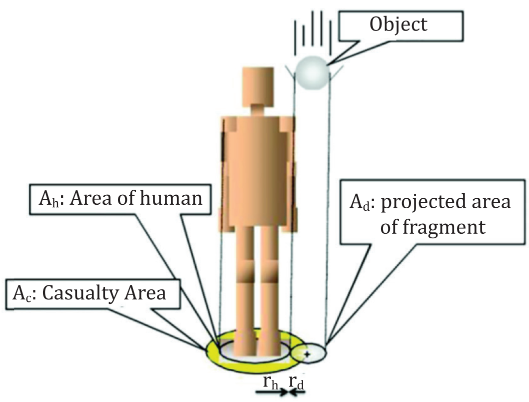


Figure C.1 — Typical concept of Casualty Area presented by A_h and A_d

For other shapes, as shown in Figure C.2,

$$A_C = A_d + \left(\text{perimeter of impact object} \times r_h\right) + A_h$$

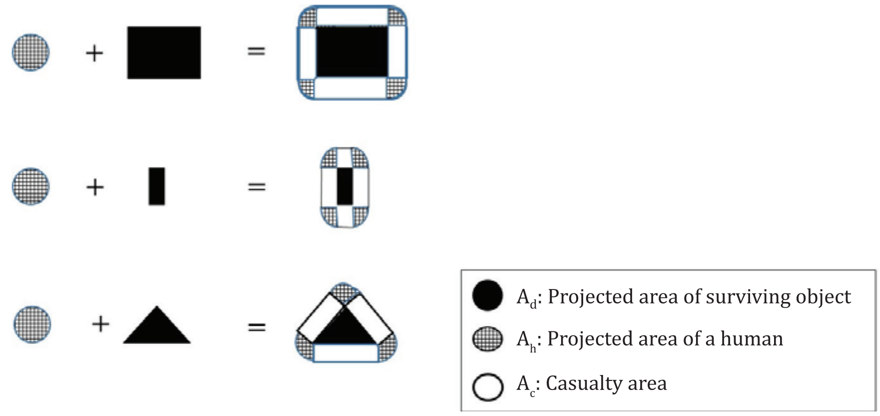


Figure C.2 — Casualty Area in the case of polygonal shapes

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

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

C.4 Calculation of Ec

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

$$Ec = AcN/Ai \tag{1}$$

where

Ac is the casualty area as a sum of all the surviving objects;

Ai is the area of potential impact zone on the ground limited by latitude band corresponding to the orbital inclination;

N is the population in the potential impact zone (Ai), given by the population model.

If the Earth is modelled as a perfect sphere;

$$Ec = AcN/(4\pi \mathrm{Re}^2 \sin(i)) \tag{2}$$

where

Re is the radius of the Earth (6 378 145 m);

i is the orbital inclination;

N is the population within a latitude band bounded by ± Inc.

To get a more exact value, the difference of probability of impact on specific latitude bands may be taken into consideration. Ec will be obtained by the product of the probability of impact on a specific latitude band and the population within the band, which is integrated over the latitude range covered by the orbital inclination.

$$Ec = \sum_{i=\text{minimum altitude}}^{\text{max imum altitude}} PiNi / Ai \quad (3)$$

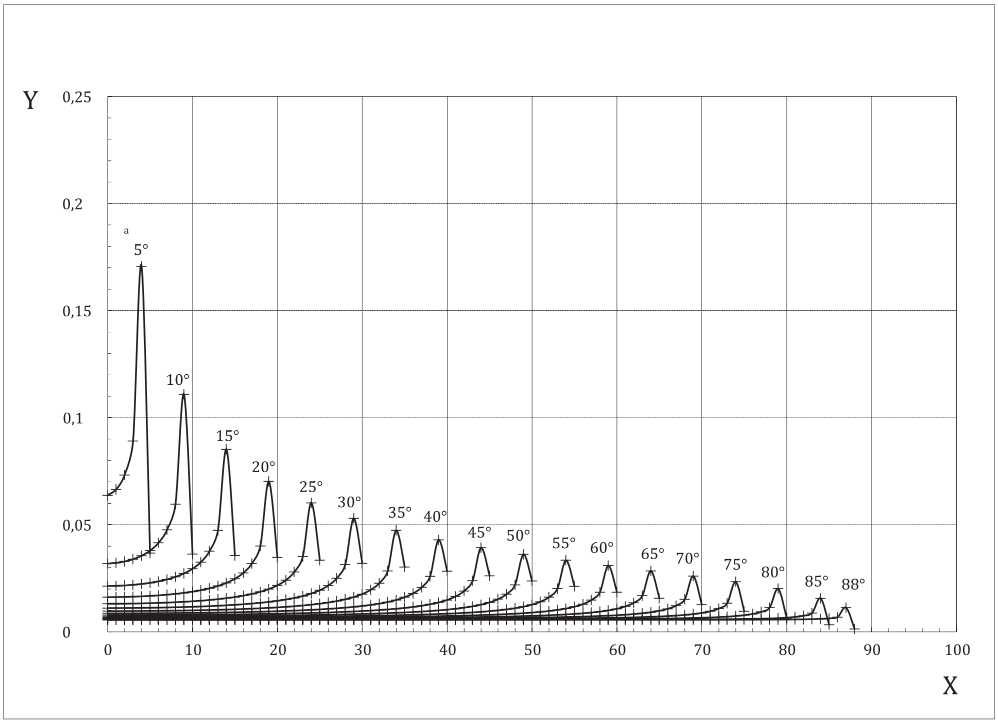
where

Ai is the ground area in i-th latitude band;

Ni is the population within Ai;

Pi is the probability of impact in i-th latitude band.

NOTE Probability of impact for each latitude band is shown for several cases of orbital inclination (from 5 degrees to 88 degrees) in Figure C.3.



Key

X geographical latitude bands (degrees)

Y probability of impact one degree latitude band

a Orbit inclination angle.

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

C.5 Population distribution models

The "population distribution models" is selected as indicated in 5.3.

NOTE The following are typical models. The Gridded Population of the World is used in several national space agencies.

a) GPW4: Gridded Population of the World, version 4 (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);

d) GGP: Gridded Global Population Distribution of the World (provided by the United Nations Environment Programme);

e) IDB: Census Bureau's International Programs Center International Data Base (IDB).

Bibliography

[1] ISO 14620-2, *Space systems — Safety requirements — Part 2: Launch site operations*

[2] United Nations, *Principles Relevant to the Use of Nuclear Power Sources in Outer Space*, (General Assembly resolution 47/68 of 14 December 1992), A/RES/47/

[3] NASA-STD-8719.14A, 2011-12-08

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