INTERNATIONAL STANDARD

ISO 15388

Third edition
2022-10

Space systems — Contamination and cleanliness control

Systèmes spatiaux — Contrôle de la contamination et de la propreté

Reference number
ISO 15388:2022(E)

Contents

Page

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.

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).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of 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 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 third edition cancels and replaces the second edition (ISO 15388:2012), which has been technically revised.

The main changes are as follows:

— Annex B, which details guidelines for contamination analysis procedures, is added;

— Annex C, which indicates factors of combined uncertainty, is added;

— the latest international and national documents for planetary protection are referenced in 6.5.

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

This document addresses the preferred programme elements recommended for contamination and cleanliness control of space systems. This document is written in general terms as a baseline for developing and implementing the control programme. It can be cited as a baseline within a statement of work and/or used for assuring proposal precision and contractor performance. The users are responsible for integrating the elements of this document appropriately to their programme needs.

The purpose of contamination and cleanliness control is to prevent the degradation of the performance of space systems due to particulate and molecular contamination (including biocontamination), and to ensure that the mission objectives are achieved.

Space systems — Contamination and cleanliness control

1 Scope

This document establishes general requirements for contamination and cleanliness control that are applicable, at all tiers of supply, to the development of space systems, including ground processing facilities, ground support equipment, launch vehicles, spacecraft, payloads, and ground processing and on-orbit operations. It also provides guidelines for the establishment of a contamination and cleanliness control programme.

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 14624-3, *Space systems — Safety and compatibility of materials — Part 3: Determination of offgassed products from materials and assembled articles*

ISO 14644-1, *Cleanrooms and associated controlled environments — Part 1: Classification of air cleanliness by particle concentration*

ISO 14698-1, *Cleanrooms and associated controlled environments — Biocontamination control — Part 1: General principles and methods*

ISO 14698-2, *Cleanrooms and associated controlled environments — Biocontamination control — Part 2: Evaluation and interpretation of biocontamination data*

ISO 14952-2, *Space systems — Surface cleanliness of fluid systems — Part 2: Cleanliness levels*

ISO 14952-3, *Space systems — Surface cleanliness of fluid systems — Part 3: Analytical procedures for the determination of nonvolatile residues and particulate contamination*

ASTM E595, *Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment*

ECSS-Q-ST-70-02C, *Space product assurance — Thermal vacuum outgassing test for the screening of space materials*

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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

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

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

3.1.1
bakeout
activity of increasing the temperature of hardware to accelerate its *outgassing* (3.1.28) rates with the intent of reducing the content of molecular *contaminants* (3.1.11) within the hardware

Note 1 to entry: Bakeout is usually performed in a vacuum environment but may be done in a controlled atmosphere.

3.1.2
bioaerosol
dispersed biological agents [e.g. viable *particles* (3.1.29), allergens, toxins or biologically active compounds of microbial origin] in a gaseous environment

3.1.3
biocontamination
contamination of materials, devices, individuals, surfaces, liquids, gases or air with viable *particles* (3.1.29)

3.1.4
clean bench
table or bench-top working surface where a filtered airflow is concentrated across the bench top

Note 1 to entry: These bench tops have an established classification of maximum allowable airborne *contaminants* (3.1.11).

3.1.5
cleanliness level
established maximum allowable amount of contamination in a given area or volume, or on a component

Note 1 to entry: The term may also apply to the predicted or measured extent of contamination.

3.1.6
cleanliness requirement specification
CRS
document that defines and identifies the spacecraft items and the environmental areas which are sensitive to contamination, the acceptable contamination levels at beginning and end of life and the applicable contamination environment

3.1.7
cleanroom
room within which the number concentration of airborne *particles* (3.1.29) is controlled and classified, and which is designed, constructed and operated in a manner to control the introduction, generation and retention of particles inside the room

Note 1 to entry: The class of airborne *particle concentration* (3.1.30 and 3.1.31) is specified.

Note 2 to entry: Levels of other cleanliness attributes such as chemical, viable or nanoscale concentrations in the air, and also *surface cleanliness* (3.1.39) in terms of particle, nanoscale, chemical and viable concentrations might also be specified and controlled.

Note 3 to entry: Other relevant physical parameters might also be controlled as required, e.g. temperature, humidity, pressure, vibration and electrostatic.

[SOURCE: ISO 14644-1:2015, 3.1.1]

3.1.8
cleanroom garment
clothing designed, manufactured and worn specifically to prevent contamination of hardware by personnel working in the *cleanroom* (3.1.7)

Note 1 to entry: Cleanroom garments include all items worn by personnel, such as coveralls, frocks, gloves, boots, finger cots and beard covers.

3.1.9
clean zone
defined space within which the number concentration of airborne *particles* (3.1.29) is controlled and classified, and which is constructed and operated in a manner to control the introduction, generation and retention of *contaminants* (3.1.11) inside the space

Note 1 to entry: The class of airborne *particle concentration* (3.1.30 and 3.1.31) is specified.

Note 2 to entry: Levels of other cleanliness attributes such as chemical, viable or nanoscale concentrations in the air, and also *surface cleanliness* (3.1.39) in terms of particle, nanoscale, chemical and viable concentrations might also be specified and controlled.

Note 3 to entry: A clean zone(s) can be a defined space within a *cleanroom* (3.1.7) or might be achieved by a separative device. Such a device can be located inside or outside a cleanroom.

Note 4 to entry: Other relevant physical parameters might also be controlled as required, e.g. temperature, humidity, pressure, vibration and electrostatic.

[SOURCE: ISO 14644-1:2015, 3.1.2]

3.1.10
collected volatile condensable material
CVCM
mass that outgasses from a material and subsequently condenses on a collector, expressed as a percentage of the initial specimen mass

3.1.11
contaminant
unwanted molecular or particulate matter that can affect or degrade the relevant performance or lifetime of the hardware to which it is attached

3.1.12
contamination
introduction of any undesirable molecular or particulate matter (including microbiological matter) into an item or into the environment of interest

[SOURCE: ISO 10795:2019, 3.62]

3.1.13
contamination and cleanliness control programme
organized effort to establish and achieve acceptable cleanliness and contamination levels during all phases of the space system project

3.1.14
contamination and cleanliness control plan
CCCP
document that describes how to implement a *contamination and cleanliness control programme* (3.1.13), as either an independent document or a part of the consolidated project plan

3.1.15
contamination budget
allowable levels of contamination of hardware at each phase of ground and flight operations

3.1.16
contamination profile
contamination-related conditions in each phase of ground and flight operations

Note 1 to entry: Conditions include airborne particulate cleanliness classes, pressure, humidity, temperature, number of personnel engaged in operations, cleaning activities, outlines of facilities and so on.

Note 2 to entry: The contamination profile is part of the *contamination and cleanliness control plan (CCCP)* (3.1.14).

3.1.17
cross-contamination
transfer of *contaminants* (3.1.11) from one surface or component to another

Note 1 to entry: Transfer can occur by migration along a surface, by physical contact, airborne as an aerosol, or as a gas or molecular matter.

3.1.18
debris
solid objects with their largest dimension greater than approximately 1 mm (1 000 µm) in size

3.1.19
electrostatic discharge
ESD
electrical breakdown of dielectric or gas or vacuum gaps, and also of surface interface of dissimilar materials, caused by differential charging of parts of dielectric materials and their interfaces

[SOURCE: ISO 11221:2011, 2.10, modified — The abbreviated term "ESD" has been added.]

3.1.20
generally clean
free from manufacturing residue, dirt, oil, grease, processing *debris* (3.1.18), or other extraneous contamination based on visual examination

Note 1 to entry: This level does not apply to hardware that is sensitive to contamination.

[SOURCE: ISO 14952-1:2003, 2.12, modified — The abbreviated term "GC" has been removed.]

3.1.21
ground support equipment
GSE
non-flight systems, equipment or devices necessary to support the operations of transporting, receiving, handling, assembly, inspection, test, checkout, servicing, launch and recovery of a space system at launch, landing or retrieval sites

[SOURCE: ISO 14625:2007, 3.1.5]

3.1.22
interface control document
ICD
specification that describes the characteristics that must be controlled at the boundaries between systems, subsystems and other elements

3.1.23
microorganism
microscopical individual constituted to carry out life functions

Note 1 to entry: Microorganisms include organisms such as bacteria, protozoa, yeasts, moulds, fungi, algae and organisms that depend upon other life forms for reproduction such as viruses and parasites.

Note 2 to entry: Multicellular organisms and agglomerations of microorganisms may be visible to the unaided eye.

3.1.24
molecular contamination
contamination due to deposition of molecules on surfaces or their presence in gases or liquids

3.1.25
at-rest
condition where the *cleanroom* (3.1.7) or *clean zone* (3.1.9) is complete with equipment installed and operating in a manner agreed upon, but with no personnel present

[SOURCE: ISO 14644-1:2015, 3.3.2]

3.1.26
operational
agreed condition where the *cleanroom* (3.1.7) or *clean zone* (3.1.9) is functioning in the specified manner, with equipment operating and with the specified number of personnel present

[SOURCE: ISO 14644-1:2015, 3.3.3]

3.1.27
offgassing
evolution of gaseous products from a liquid or solid material into an atmosphere

Note 1 to entry: This is for the application in habitable volume considering medical impact on human health.

3.1.28
outgassing
evolution of gaseous species from a material, usually in a vacuum

3.1.29
particle
unit of solid or liquid matter with observable size

[SOURCE: ISO 14952-1:2003, 2.20]

3.1.30
particle concentration
⟨on surface⟩ number of *particles* (3.1.29) per unit area

3.1.31
particle concentration
⟨by volume⟩ number of *particles* (3.1.29) per unit volume of fluid

3.1.32
responsible organization
organization that is responsible for the *contamination and cleanliness control programme* (3.1.13) and which is provided with the authority and resources needed to carry out the programme

3.1.33
recovered mass loss
RML
ratio of the *total mass loss* (3.1.40) of the specimen without the sorbed water to the initial mass:

$$w_{\mathrm{RML}} = w_{\mathrm{TML}} - w_{\mathrm{WVR}}$$

where

w_{RML} is the recovered mass loss, in per cent;

w_{TML} is the ratio of the total mass loss to the initial mass, in per cent;

w_{WVR} is the ratio of the *water vapour regained* (3.1.42) to the initial mass, in per cent.

Note 1 to entry: The quantity RML is introduced because water is not a critical *contaminant* (3.1.11) for some space systems (see 5.6.3). In most cases, the value of WVR is similar to that of the mass of outgassed water. However, WVR is not exactly the same as the water mass effused from the specimen. Therefore, RML is not equal to the real value of the mass loss other than water.

3.1.34
sensitive hardware
hardware that can be degraded by contamination

3.1.35
significant surface
surface of an item or product that is required to meet established *cleanliness level* (3.1.5) requirements

3.1.36
spacecraft charging
increase in electrostatic potential on spacecraft surfaces resulting from low-energy electron flux impinging on the surface

3.1.37
sterility
absence of viable *microorganisms* (3.1.23)

Note 1 to entry: Inactivated microbes can still represent an important form of *biocontamination* (3.1.3).

3.1.38
supplier
provider
organization that provides a product or a service

EXAMPLE Producer, distributor, retailer or vendor of a product or a service.

Note 1 to entry: A provider can be internal or external to the organization.

Note 2 to entry: In a contractual situation, a provider is sometimes called “contractor”.

[SOURCE: ISO 9000:2015, 3.2.5, modified —"provider" has been changed to an admitted term.]

3.1.39
surface cleanliness
level of contamination on a *significant surface* (3.1.35)

3.1.40
total mass loss
TML
total mass of material outgassed from a test specimen that is maintained at a specified constant temperature and operating pressure for a specified time and measured within the test chamber

Note 1 to entry: TML is expressed as a percentage of the initial specimen mass.

3.1.41
visibly clean
absence of surface contamination when examined using a specified light source and angle of incidence, viewing distance and angle, and normal or magnified vision

Note 1 to entry: This level requires precision-cleaning methods but a *particle* (3.1.30) count may be optional.

Note 2 to entry: Fluorescence indicates possible contamination by, for example, a hydrocarbon.

Note 3 to entry: If recleaning fails to remove fluorescent indications, an investigation should be made to determine if the item material is naturally fluorescent or if the cleaning method is adequate.

[SOURCE: ISO 14952-1:2003, 2.35, modified — The abbreviated term "VC" has been removed.]

3.1.42
water vapour regained
WVR
mass of water vapour absorbed by a test specimen, after determination of *total mass loss (TML)* (3.1.40) and *collected volatile condensable material (CVCM)* (3.1.10), on exposure to a specified relative humidity atmosphere (usually 50 % at 23 °C or 65 % at 20 °C) for 24 h

Note 1 to entry: Some types of materials continue to absorb water for longer than 24 h. Repeated mass measurements after various time periods (e.g. 24 h, 48 h and 72 h) give a better understanding of the material's water absorbency.

3.2 Abbreviated terms

AIT	assembly, integration and test
AO	atomic oxygen
BOL	beginning of (operational or mission) life
CCCP	contamination and cleanliness control plan
CRS	cleanliness requirement specification
CVCM	collected volatile condensable material
ECSS	European Cooperation for Space Standardization
EOL	end of (operational or mission) life
ESA	European Space Agency
ESA	exposed surface area
ESD	electrostatic discharge
GSE	ground support equipment
GSFC	Goddard Space Flight Center (NASA)
ICD	interface control document
IEST	Institute of Environmental Sciences and Technology (USA)
JAXA	Japan Aerospace Exploration Agency
NASA	National Aeronautics and Space Administration (USA)
NPD	NASA policy directive
NPG	NASA procedures and guidelines
RML	recovered mass loss
TML	total mass loss
UV	ultra violet
WVR	water vapour regained

4 Management

4.1 Organization

The supplier shall establish a contamination and cleanliness control programme at the beginning of the project, for each level of configuration and item defined in the project. Performance requirements, defined by customer-supplier agreements, form the basis for cleanliness requirements.

4.2 Cleanliness requirement specification (CRS)

The supplier shall identify the hardware to be controlled, and specify the permissible cleanliness level in a quantitative manner. The hardware includes all items from component level to system level. The acceptable cleanliness levels of the hardware shall be specified at BOL and EOL, based on performance requirements and contamination analyses. The specification shall be established independently as a CRS or included in an overall project design specification. The cleanliness of hardware to be controlled at the boundary of systems, subsystems and other elements shall be stipulated in the ICD or its equivalent.

Cleanliness requirements that are more stringent than necessary to meet manufacturing and system performance requirements shall not be imposed at any level of assembly.

4.3 Contamination and cleanliness control plan (CCCP)

4.3.1 Specifying cleanliness necessitates the establishment of a budget for particulate and molecular contamination for all phases of the project and a clear methodology of how the required cleanliness levels can be achieved.

4.3.2 The supplier shall develop a contamination and cleanliness control plan that describes how to achieve and maintain the specified cleanliness level of the hardware during all the phases of the ground and flight operations. The plan may be an independent document or part of a consolidated project control plan.

4.3.3 The range of the plan and the level of detail shall be determined by the responsible organization with respect to the criticality of the hardware against contamination. This may require other tasks in addition to those described in this document or may lead to a reduction in the applicable requirements.

4.3.4 The CCCP shall

a) contain a contamination budget for all phases of the ground and flight operations,

b) provide methodology for achieving and maintaining the required cleanliness levels,

c) define how to deal with situations that may result in cleanliness specifications not being achieved,

NOTE 1 Possible situations include failures of facilities and launch delays for a spacecraft.

NOTE 2 Corrective actions can include additional cleaning operations.

d) define single-point failure modes that can affect cleanliness, including equipment failures and human errors,

e) define the risk of cross-contamination between hardware elements,

f) provide measurement and monitoring methods, procedures and requirements,

g) define the sequence of cleanliness activities,

h) define the roles and responsibilities of the organizations which will implement the requirements,

i) provide descriptions of when and how the cleanliness activities are to be reviewed,

j) provide information on how to implement design activities,

k) provide information on how to train personnel and assess them, and

l) provide references to procedures.

4.4 Interface control document (ICD)

4.4.1 The cleanliness of hardware to be controlled at the interfaces of different systems, subsystems and other elements shall be stipulated in the ICD or its equivalent.

4.4.2 The ICD may include the following types of information:

a) limitations on particles, gases, vapours and debris crossing the interface;

b) limitations on particles, gases, vapours and debris in the field of view of instruments and sensors;

c) limitations on energy (ultraviolet and ionizing radiation, thermal radiation, radio frequency radiation, etc.) that affect contaminant deposition and degrade performance.

4.5 Project reviews

The status of the contamination and cleanliness control programme shall be recorded and reported at the milestone project reviews where it shall be demonstrated that suitable activities are planned, are being implemented or have been successfully achieved.

5 Design activities

5.1 Identification of sensitive hardware

The supplier shall identify the sensitive hardware that may be degraded due to contamination during ground processing or flight and that shall be suitably protected. This hardware becomes the subject of detailed contamination and cleanliness control.

EXAMPLE Sensitive hardware includes optical detectors, optical assemblies and thermal control surfaces.

5.2 Nature of contaminants, their profile and their effects

5.2.1 General

The supplier shall identify:

a) the nature of the contaminants which may degrade the performance of sensitive hardware in any way, such as particulate, molecular or biocontaminants, during all phases of ground and flight operations;

b) the effects of contaminants on the sensitive hardware, using experience gained with similar spacecraft or similar operations in early phases of the project and, later, using data gained in realistic tests.

5.2.2 Typical contaminants

Typical contaminants are caused by factors such as outgassing (including re-emission of condensed contaminants, and return flux from collisions with the ambient atmosphere and spacecraft charging at high-Earth orbits); particles from materials, mechanisms or AIT facilities; grease from human handling, operation and AIT facilities; launch contaminants; leakage from pressurized units; microorganisms;

ESD; arcing-induced contaminants on solar cell coverglasses; exhaust products from thrusters; natural environments such as electron, proton and atomic oxygen fluxes; spacecraft charging; human waste dumps; and contamination from life support hardware.

5.2.3 Contamination profile

The supplier shall initiate the contamination profile that shows contamination-related issues, such as temperature, pressure, humidity and natural environments, in each phase of the life cycle and shall maintain it throughout development.

5.2.4 Effects of contamination on performance

The supplier shall develop a correlation between contamination levels and degradation in performance, and determine the allowable contamination limit for sensitive hardware. The cleanliness level requirements shall be estimated in the early phases and become more detailed through performance analysis.

5.3 Contamination prediction

The supplier shall perform an analysis of contaminant transport and deposition for all phases of ground and flight operations. If the level of contamination exceeds the specifications, protective measures shall be implemented. The parameters necessary to perform the analysis can include view factors; the outgassing kinetics of relevant materials; the condensation kinetics and temperatures of significant surfaces; temperatures of outgassing sources; the reflectance on the surfaces; the scattering interactions with the neutral space environment; the electrodynamic interactions with ambient space plasma; surface interactions with space radiation, particularly with the incident ultraviolet radiation; etc.

Annex B details guidelines for contamination analysis procedure.

Annex C indicates factors and relations of combined uncertainty that is contained in contamination analysis result.

5.4 Contamination budget

The supplier shall develop a contamination budget for both particulate and molecular species based on the contamination profile and design specification of hardware cleanliness. The contamination budget shall take into account the results of predictions, the probability of restoring cleanliness during ground and flight operations, as well as exposure times and the use of protective covers. Methods to be used for cleaning and maintaining cleanliness throughout all phases of the project shall be considered. Contamination levels for BOL and EOL shall be included in the budget.

5.5 Cleanliness-oriented design

The supplier shall develop methods to maintain the cleanliness of sensitive hardware, to reduce its sensitivity to contamination and to ease cleaning, and shall describe the outline of the cleanliness-oriented design in the CCCP. Typical preventive measures include ensuring suitable location and orientation of sensitive hardware; de-contamination heater on sensitive surfaces; minimizing the usage of outgassing materials; using venting holes, baffles and shields; using protective covers on the ground; controlling the temperature of outgassing hardware; designing cleaning processes; enclosing contamination sources; baking; processing human wastes; using molecular adsorbers, etc. The measures shall be chosen based on the cleanliness specification and the contamination budget.

The design of ground support equipment that is in the same room as, in close proximity to or in contact with, flight hardware shall also be similarly considered.

5.6 Selection of materials and processes

5.6.1 General

Materials and processes shall be selected to minimize contamination as well as to meet other functional requirements. The primary screening items for materials are outgassing, offgassing, particle generation, fungus growth and fragility.

5.6.2 Outgassing

The initial screening of materials shall be in accordance with ASTM E595 or ECSS-Q-ST-70-02C. Materials having TML of less than 1,0 %, RML of less than 1,0 % and CVCM of less than 0,1 % are generally considered as low-outgassing materials. The figures do not represent the acceptance criteria. Materials should be selected considering also temperature, mass and surface area in use.

A material is considered as a possible contamination source under the following conditions. In these cases, even a low-outgassing material can cause contamination problems.

a) The material is used nearby, or in direct view of, the contamination-sensitive surfaces.

b) The material is used nearby, or in direct view of, the cryogenic surfaces.

c) The material is used in large amounts.

d) The material is expected to be at a higher temperature than other surfaces.

A material is considered to pose less of a risk of contaminating other surfaces under the following conditions. In these cases, materials not considered as low-outgassing material can be applied with no or small contamination impact.

— The material is used far from, or is not in direct view of, the contamination-sensitive surfaces.

— The material is used far from, or is not in direct view of, the cryogenic surfaces.

— The material is used in small amounts.

— The material is expected to be at a lower temperature than other surfaces.

The requirements for the use of TML and RML depend on the performance requirements for the space system and specific uses of materials in the system (see 5.6.3).

Materials that pass the standard screening tests may nevertheless cause degradation of sensitive hardware and may require further characterization. The customer and supplier shall establish materials selection guidelines, with requirements that are more stringent, using other test methods, if justified by mission and performance requirements.

Material selection adequacy is verified by contamination prediction (see 5.3). Even materials which do not meet the materials selection guidelines may be used as long as the predicted level of contamination meets the contamination budget (see 5.3 and 5.4).

NOTE 1 Properties such as TML, RML, CVCM and WVR of often used materials are publicly available on the electronic databases listed in Annex A.

NOTE 2 Long-term outgassing estimation using ASTM E1559 (see Reference [34]) and other, similar test methods are applicable for establishing guidelines for the selection of materials.

5.6.3 Absorbed water vapour

Some materials contain large quantities of absorbed water that contribute to the TML. If the outgassing of water vapour is not critical to the application, the outgassed water may be subtracted from the TML to provide an RML to meet the requirements. The adjusted mass loss value is given by the RML.

5.6.4 Offgassing

Materials shall be screened, in accordance with ISO 14624-3, for their offgassing characteristics, carrying out a toxicological assessment of the risks to personnel when the materials are used in habitable areas during flight.

5.6.5 Quality control

Suitable quality control processes to verify the performance of materials shall be maintained. Processes and compositions of commercial materials are possible to be not controlled sufficiently to meet the requirements of space systems. The specification of quality control processes shall be determined on a case-by-case basis.

ASTM E595 or ECSS-Q-ST-70-02C may be used as a quality control test for the outgassing characteristics of materials.

6 Biocontamination

6.1 General

The organisms that cause biocontamination are fungi, yeast, viruses and bacteria. They are contaminants by virtue of their biomass and also generate contaminants by virtue of their biological processes, thriving both on the ground and in flight. They are introduced on the ground during manufacturing, integrating and testing, transporting and operating processes. Human waste and metabolic by-products accelerate the growth of microorganisms associated with water or nutrients. Hardware cleanliness can include requirements for viable organisms as well as dead organisms, chemical and particulate by-products, and metabolic products from the organisms.

6.2 Contamination of hardware by microorganisms

6.2.1 Microorganisms produce substances that result from their metabolic and/or biological processes. These materials can cause contamination or corrosion.

6.2.2 A preventive measure is to eliminate or reduce moisture and nutrients. The prevention of the propagation of microorganisms, especially in rooms with recirculating-air systems, is difficult. Effective countermeasures include installing high-performance filters and implementing effective cleaning processes. Designing hardware so that it is easily cleanable is also an important countermeasure.

6.3 Sterile hardware

6.3.1 Sterility requirements may be imposed on hardware for use in habitable systems, biological experiments and interplanetary missions. These requirements may be in addition to other contamination control requirements imposed on the system.

6.3.2 Sterile processing procedures include, but are not limited to, eliminating contact with contaminated objects, with bioaerosols in air and purge gases, and with personnel.

6.3.3 Ground-handling processes shall be designed to fulfil the sterility requirements on hardware. This includes keeping the hardware in sterile environments, such as sterile packaging, sterile isolators and sterile rooms, in accordance with the procedures described in ISO 14698-1. The CCCP shall include, or reference, the procedures required to meet hardware requirements.

6.3.4 Ground operations shall be monitored to verify that hardware cleanliness and environments meet the requirements. Evaluation and interpretation of biocontamination data shall be in accordance with ISO 14698-2.

6.3.5 Personnel shall be provided with proper garments, as required, to prevent exposure to hazardous contaminants and to protect hardware from contamination.

6.4 Habitable space systems

6.4.1 Habitable spacecraft

Specific measures shall be taken to protect onboard personnel from harmful contaminants, including biocontaminants and toxic materials. The measures shall include the control of outgassing (offgassing) from materials and hardware and control of the flammability of materials. Objectionable odours should also be controlled to maintain a comfortable environment within the habitable spacecraft if this is required for the particular space programme. Special atmospheres, such as pure oxygen, shall also be considered in defining the requirements.

6.4.2 Offgassing

Materials used in habitable locations of spacecraft shall be screened for offgassing in accordance with ISO 14624-3.

6.5 Planetary protection

6.5.1 Planetary protection activities shall be included in the CCCP; in particular studies of outer space and exploration shall be conducted so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extra-terrestrial matter and, where necessary, shall adopt appropriate measures for this purpose (see e.g. United Nations Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, Article IX, 10 October 1967).

Planetary protection shall be planned and performed according to the latest international and national documents such as References [16],[17],[43],[44].

6.5.2 Protection of other planets requires limits on the quantities of viable organisms that may be transported to a planet that can have life forms currently, or had been able to have them in the past. The level of protection required depends upon scientific judgement of the probability of life on the planet.

6.5.3 Protection of the Earth requires procedures that prevent possibly harmful organisms from other planets damaging the inhabitants and the environment of the Earth when vehicles and samples are transported back to the Earth.

6.6 Sample protection

Biological samples from scientific studies and routine monitoring shall be protected from contamination as necessary to meet system performance requirements. The protection methods shall be included in the CCCP.

7 Contamination and cleanliness control for ground operations

7.1 Training of personnel

Personnel shall be trained in accordance with the CCCP and shall comply with it, according to their assigned tasks. Additional information relating to personnel in cleanrooms can be found in ISO 14644-5:2004, 4.3 and Annex C.

7.2 Cleanroom selection and cleanliness control

7.2.1 General

7.2.1.1 The supplier shall select, based on the contamination budget (see 5.4), suitable environments for the manufacture, assembly, transportation, integration and testing of hardware. This includes launch site processing.

7.2.1.2 Cleanroom selection shall be based on hardware cleanliness requirements, required operating procedures and exposure times.

7.2.1.3 Allowable airborne particle concentrations shall be specified as a class of air for the operational occupancy state, in accordance with ISO 14644-1.

7.2.1.4 Procedures for operational and at-rest conditions shall be specified to the extent necessary to meet hardware cleanliness requirements.

7.2.1.5 Special clean zones may be established to meet special hardware cleanliness requirements in a local area.

7.2.1.6 Operational monitoring of airborne and surface contaminants shall be specified to the extent required to meet project performance requirements and risk/cost benefits.

7.2.1.7 Materials, parts, hardware and test equipment that are authorized to be taken into cleanrooms shall be compatible with the cleanliness requirements of the area. An approved list of materials for use in cleanroom areas is recommended. The cognizant contamination control or systems engineer shall approve materials for use in cleanrooms.

7.2.2 Failure of facilities

7.2.2.1 Failures of facilities, such as electrical power and cooling water, and equipment breakdown shall be considered in the CCCP and in relevant operating procedures that are defined so as to prevent damage to flight hardware.

7.2.2.2 Single-point failure mechanisms, including human error, shall be analysed and measures shall be taken to avoid them, with special consideration given to risk/cost benefits.

7.2.3 Facility operating procedures

Facility operating procedures include overall cleaning and control of the cleanroom, monitoring of facility cleanliness and maintaining facilities. When flight hardware is present, cleaning of the cleanroom shall be limited to the extent necessary to meet hardware cleanliness requirements.

7.2.4 Additional information

7.2.4.1 Additional information on the design, construction and start-up of cleanrooms can be found in ISO 14644-4.

7.2.4.2 Additional information on the operation of cleanrooms can be found in ISO 14644-5.

7.3 Cleanroom garments

7.3.1 General

One purpose of a cleanroom garment is to prevent contaminants generated by people from getting to the product. For some applications, the garment is also used to protect personnel from hazardous materials.

7.3.2 Considerations for garment selection

7.3.2.1 Garments shall be selected based on hardware cleanliness requirements, the type of airflow in the cleanroom and the location of the personnel relative to the hardware. The usual garment choices for aerospace use include a full coverall with a hood and shoe coverings or a frock and partial head cover with some type of shoe cover.

7.3.2.2 The garment shall have good ESD protection, high permeability to air and water vapour, low particle transmission capacity, low particle generation capacity, good cleanability and good wear properties, including resistance to laundering and dry cleaning.

7.3.2.3 Personnel should not wear frocks when personnel are working above hardware or when product cleanliness levels are stringent.

The rationale is that a frock does not retain the particles generated by the wearer of the garment because the bottom is open. Studies have shown that airborne-particle concentrations increase when frocks are worn as compared to coveralls. The open bottom allows large particles and debris to fall out. These will not become airborne but will deposit on the cleanroom floor or on product surfaces near the wearer. Frocks are suitable for the processing of hardware in clean benches where coveralls are not needed.

7.3.3 Additional information

Additional information on the selection and use of cleanroom garments can be found in ISO 14644-5:2004, 4.2 and Annex B.

7.4 Ground support equipment (GSE)

For the selection and operation of ground support equipment in the same room as, or near, flight hardware, the cleanliness requirements of the flight hardware, and contamination sources such as outgassing and lubricants, shall be taken into consideration. Particle-generating materials or fragile surfaces shall be sealed or covered as well as possible.

Equipment-cooling fans can generate a flow of molecular or particulate matter. The exclusion of such fans or the re-direction of their airflow away from flight hardware shall be considered.

7.5 Monitoring cleanliness of flight hardware and its near surroundings

Contamination shall be monitored to the predetermined levels and time intervals as per the procedures defined in the CCCP. Monitoring equipment shall be located at suitable places and under specified conditions.

The cleanliness shall be monitored and recorded as per test plans and operating procedures, as required. Monitoring may include the following: concentrations of airborne particulate and molecular contaminants; deposition of particulate and molecular contaminants; temperature; relative humidity and room pressure.

A method for monitoring airborne-particle concentrations in cleanrooms is given in ISO 14644-2. Additional measurement methods can be found in ISO 14644-3.

7.6 Packaging, storage and transport

7.6.1 Packaging

Packaging shall be used to protect hardware during storage and transport. Packaging materials shall not increase the contamination of the hardware or contain volatile or transferable contaminants.

7.6.2 Storage

Storage areas shall provide adequate protection to the package and the product for the intended storage period.

7.6.3 Transport

Containers shall be used during transport. The materials from which the containers are made shall be selected considering volatile and transferable contaminants, the method of transport and the transport environments.

7.7 Cleaning of flight hardware

7.7.1 General

The supplier shall meet the cleanliness requirements for the hardware and the contamination budget as stated in the CCCP. For fluids, cleanliness levels shall be determined in accordance with ISO 14952-2 and ISO 14952-3. Cleaning of flight hardware is critical for the stages of assembly, integration, testing, transportation and launch operations. The supplier shall select the cleaning procedures, methods, equipment, frequency and agents that are most suitable for each stage of processing, according to the species of contaminant and compatibility with the hardware.

NOTE IEST-STD-CC1246 (see Reference [21]) can be applicable for defining hardware cleanliness.

7.7.2 Cleaning procedures

The scope of the cleaning processes shall be outlined in the CCCP, quoting independent existing documents if necessary. The required skills, cares, specification of cloths, cleaning agents, aids and equipment, directives and stages, etc., including their cleanliness levels, shall be described and qualified.

Processes giving a “generally clean” level of cleanliness (see 3.1.25) may be used before further cleaning using a precision-cleaning process, or without further cleaning if quantitative cleanliness levels are not required. The cleanliness level “generally clean” shall not be designated for hardware that is sensitive to contamination.

“Visibly clean” inspections shall be performed in accordance with approved procedures and can provide a quantitative evaluation of cleanliness levels.

7.7.3 Bakeout

Bakeout of flight hardware can be an effective measure to reduce outgassing rates and potential contaminants. Bakeout may be conducted in a vacuum or in a flowing, controlled gas environment, such as clean, dry, gaseous nitrogen. Bakeout procedures are not all equivalent with respect to results. Engineering analysis and judgement shall be used to select the bakeout procedure that is cost-effective and that meets system performance requirements.

Bakeout may be conducted at any level of hardware assembly, from component to system, depending upon analyses and system performance requirements. Special care should be taken to prevent cross-contamination when the articles under bakeout have sensitive hardware.

Bakeout procedures shall be included or referenced in the CCCP, specifying conditions such as the level of vacuum or gas and gas flow rate, the temperature, the duration and monitoring methods.

7.7.4 Contaminant source containment

It may be possible to reduce contamination by using coatings, anticreep barriers and shields.

7.7.5 Purging

Clean gases can be used to purge flight hardware, in order to prevent contaminants from entering critical components. Clean nitrogen, helium, argon and air have been used. Safety shall be taken into account; ISO 15859-3, ISO 15859-4 and ISO 15859-9 may be used as applicable. Additional filtration at the point of use may be required to meet cleanliness requirements. Purge-gas requirements, purge times and allowable non-purge times shall be included in the CCCP as applicable.

Annex A
(informative)

Material properties — Electronic databases

This annex includes a number of online resources that provide relevant information on the properties of materials used for space systems:

— NASA Goddard Space Flight Center (GSFC) outgassing data: https://outgassing.nasa.gov/

— NASA Materials and Processes Technical Information System (MAPTIS): https://maptis.nasa.gov/

— ESA outgassing data: https://modesa.esa.int/

http://esmat.esa.int/Services/Preferred_Lists/preferred_lists.html

— JAXA Materials Database: https://matdb.jaxa.jp/main_e.html

Annex B
(informative)

Contamination analysis

B.1 General

The quantitative modelling of the contamination environment is complex. Several types of contaminants exist, with diverse outgassing characteristics. Effused outgas interacts with surface, atmosphere components, and other environmental parameters such as solar radiation and atomic oxygen. See also Reference [18].

B.2 Mechanism of contamination

B.2.1 Molecular contamination

The molecular contamination process includes the following three steps.

1) Effusion

   Outgas from the source materials and deposited molecules on surfaces are effused into vacuum environment. Materials/surfaces of higher temperature effuse more molecules.

2) Transportation

   Effused molecules linearly move with the originated direction. View factor of the contamination source surface and contaminated surface define the ratio of molecules arriving onto the contaminated surface per total effused. Surface with larger view factor receives more molecules.

3) Deposition

   Molecules which arrive onto contaminated surface stay for a while. Molecules on higher temperature surface stay for a shorter time. Under strong UV or AO irradiation, rapid crosslinking or oxidization can occur within a short period.

B.2.1.1 Production of molecular contaminant

B.2.1.1.1 Contamination source

B.2.1.1.1.1 Outgassing from non-metal materials

Effused outgas includes originally existing gaseous species and decomposition products.

Outgassing of organic materials can be approached as a surface evaporation combined with diffusion for bulk contaminant species. These species can be either initially present components, or decomposition products.

Initially present outgassing species can be: water, solvents, additives, uncured monomeric material, lubricants, ground contamination species, due to e.g. processes, test, storage, handling, prelaunch and launch.

B.2.1.1.1.2 Secondary effusion surface

Contaminant molecule are re-emitted after short stay, or reflected on surfaces. These surfaces are considered as secondary effusion surface, or reflective surface. Higher temperature surfaces such as solar alley paddle can be secondary effusion surface.

B.2.1.2 Transportation of molecular contamination

B.2.1.1.1 determined the amount of contaminant produced by the spacecraft. Here, the amount of contaminant that reaches and adheres to the sensitive surface is estimated.

The main transportation path of the contaminant is the line of sight from a contamination source to the target. However, the contaminant can arrive to the target out of a line of sight. On extremely sensitive surfaces, the transportation passes out of the line of sight are also important.

B.2.1.2.1 Direct flux (line of sight transportation)

When the mean free path of the main contaminant molecules is larger than the spacecraft dimension, the effused contaminant molecules move linearly in the direction of the initial velocity vector.

The rate at which the contaminant reaches a given point is determined by the outgassing rates from all possible contamination sources and the positional relationships of the contaminated surface to each source.

B.2.1.2.2 Reflection of surfaces (out of sight transportation)

Contamination occurs even if the sensitive surface is not directly on the line of sight with the contamination source. The contamination source effuses outgas to the intermediate surface, which in turn releases the substance to the contaminated surface.

A molecule reflects on a surface when the accommodation coefficient during a collision is zero, i.e. when there is no energy transfer between the molecule and the surface during that collision. A reflection of a molecule is always specular, although this is dependent on surface roughness, root mean square.

B.2.1.2.3 Re-evaporation from surfaces (out of sight transportation)

A molecule having a non-zero residence time can re-evaporate from a surface. Re-evaporation is diffuse, i.e. the molecule leaves the surface following a Lambertian distribution law.

B.2.1.2.4 Return flux (molecular scattering with natural air molecule (out of sight transportation)

Effused contaminants from spacecraft can also be scattered back from collisions with surrounding atmospheric molecules. This interaction results in an ambient scattering of the contamination species, and can sometimes lead to an increase in the local pressure. The return flux depends on the atmospheric density. The contribution is large at low orbits such as the ISS, but decreases as the altitude increases, and is almost negligible in geosynchronous orbits.

B.2.1.2.5 Self scattering (molecular scattering with contaminant molecule) (out of sight transportation)

Contaminant molecule self-scatter due to the collision of two molecules.

B.2.1.3 Transportation model

B.2.1.3.1 Transportation between surfaces

B.2.1.3.1.1 General

This document only deals with the methods and models for transport of neutral molecules. There is no available model of ion transport devoted to contamination.

Three levels of complexity and accuracy in modelling the transport of neutral molecular contaminants can be distinguished.

B.2.1.3.1.2 Field of view model

The arrival rate of molecules in vacuum is the product of the ratio of mass effused from the contamination source and the geometric view factor, which is a simple ratio of molecules effused from the source and impacting the contaminated surface. The outgassing view factor is very similar to the thermal view factor or angle coefficient used in the calculation of radiant heat balance. Therefore, this view factor can be calculated geometrically or by ray tracing based on the Monte Carlo method.

This model simulates collisionless transport. In such a case, the fraction of contaminants coming from surface j to surface i is given by the view factor V_{ij} of surface i seen from surface j (including the cosine factor coming from the Lambertian emission law). These view factors are similar to the ones of radiative thermal analysis. They can be computed geometrically or by Monte-Carlo ray tracing. The incident mass on a surface i is then given by

$$S_j V_{ij} \frac{dm_j}{dt} \tag{B.1}$$

where j runs over all surfaces and dm_j/dt denotes the outgassing mass rate of surface j.

B.2.1.3.1.3 Simplified Monte-Carlo

Collisions of contaminants are simulated in a simplified way, the density and speed of possible partners for molecular collisions are given a priori:

— for ambient scatter, the ambient density and speed are easily known, but wakes (or “shades”) are usually not treated;

— for self-scatter, the contaminant density is very simplified and usually taken proportional to $1/r^2$ and with spherical symmetry, where r is the radial distance from the contaminant source.

This simplifying assumption has a consequence: the fraction of contaminants coming onto surface i from surface j is still a constant (depending on assumed densities) that can be called an effective view factor.

The effective view factor is:

The view factor (field coefficient model) in the collision-free process

− (Minus) the scattered molecules

+ (Plus) the molecules effused to other direction but returned to the surface j by collision

The deposition rate is calculated in the same manner as in the view factor model.

This method is usually limited to one collision per molecule because the uncertainties due to the densities given a priori increase with collision number. This effective view factors can conveniently be computed by Monte-Carlo ray-tracing method.

Both methods can include other contaminant sources such as vents and plumes. The view factors are then replaced by interception factors.

B.2.1.3.1.4 True Monte-Carlo (direct simulation Monte-Carlo, DSMC)

This computes multiple collisions in a realistic way. The collision probabilities are computed auto-coherently from the densities given by the simulation. This method is more time consuming and requires more work for programming (in particular, contrarily to previous two methods, it requires a meshing of volume and not only of spacecraft surfaces).

Either method can be better suited, depending on the spacecraft configuration.

A potential contamination of a sensitive protected surface through multiple collisions requires a precise DSMC simulation. In simpler cases, when contamination essentially happens in line-of-sight, it is more appropriate to use the less time-consuming and more widespread methods mentioned in B.2.1.3.1.2 or B.2.1.3.1.3.

B.2.1.3.2 Surface migration

Reflections on surfaces and re-evaporation are easy to implement and are usually included in models, the latter (re-evaporation) often as part of the outgassing process. Migrations on surfaces on the contrary are complex processes and there is no commercial model available.

B.2.1.4 Molecular deposition

When molecules are incident on the solid surface, one of the following occurs.

1) Molecule bounces off the surface of the solid.

2) The molecule stays on the solid surface for a certain time and then leaves.

When a molecule bounces off a solid surface, the molecule does not exchange energy with the solid surface. It bounces at the same angle as the incident angle.

When a molecule stays on a solid surface for a certain time and then leaves, the molecule exchanges energy with the solid surface. When the molecules leave the solid surface, their departure angles are independent from the incident angle.

When the molecule is incident on the solid surface as shown in Figure B.1, the degree of energy exchange between the solid surface and the molecule is represented by a thermal accommodation coefficient. The thermal accommodation coefficient α is defined by Formula (B.2):

$$\alpha = \frac{T_0 - T_2}{T_0 - T_1} \tag{B.2}$$

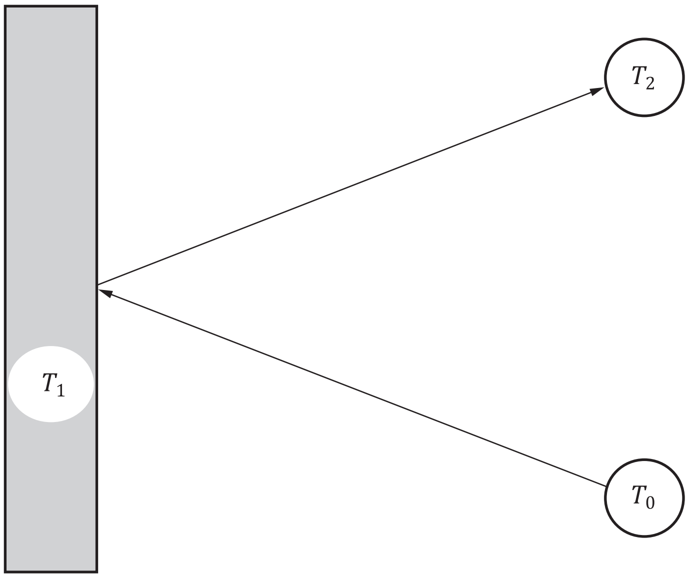


Figure B.1 — Relations of T_0, T_1 and T_2

$\alpha = 0$: the molecule bounces off the solid surface.

$\alpha = 1$: the molecule stays on the solid surface and leaves the surface after reaching the same temperature as the solid surface.

The thermal accommodation coefficient of the molecule incident on the solid surface depends on many parameters: the energy and mass of incident molecule, incident angle, mass and energy of solid molecule, and surface roughness.

With the combination of relatively low temperature molecules and dirty rough surfaces, thermal accommodation coefficient is often considered as 1. That is, at spacecraft contamination analysis, molecules incident on the solid surface always stay on the surface for a certain period of time.

Therefore, the concentration of contaminating molecules in the vicinity of the surface is always higher than in the gas phase free space. This phenomenon is called adsorption.

There are two types of adsorption, physical adsorption and chemical adsorption. Physical adsorption is weak adsorption due to intermolecular force (van der Waals force). Chemical adsorption is strong adsorption due to covalent bond between solid molecules forming the surface and contaminating molecules.

In the field of surface science, the two are clearly distinguished. However, in this document, adsorption means physical adsorption unless otherwise defined.

B.2.1.4.1 Deposition model

Molecules incident on the solid surface are always adsorbed on the surface. On the other hand, molecules already deposited on the solid surface leave the surface after a certain time. The change in the contaminant molecules mass on the solid surface is the difference between the amount adsorbed on the solid surface and the amount leaving the solid surface. It is expressed by Formula (B.3).

$$\dot{m}_{\mathrm{dep}} = \dot{m}_{\mathrm{i}} - \dot{m}_{\mathrm{l}} \quad \text{(B.3)}$$

where

$\dot{m}_{\mathrm{dep}}$ is the deposition rate on the surface (g/cm²/s);

$\dot{m}_i$ is the incident rate on the surface (g/cm^2/s);

$\dot{m}_l$ is the desorption rate from the surface (g/cm^2/s).

The ratio of molecules deposited on the surface out of the molecules incident on the surface is defined as the sticking coefficient (S). The sticking coefficient is expressed by Formula (B.4).

$$S = \frac{\dot{m}_{dep}}{\dot{m}_i} = C_p - \frac{\dot{m}_l}{\dot{m}_i} \tag{B.4}$$

where C_p is the capture coefficient (probability of incident molecules remaining on the surface).

The capture coefficient C_p is the equivalent with the thermal adaptation coefficient in its physical meaning. The thermal adaptation coefficient increases as the mass of the incident molecule increases relative to the mass of the molecules constituting the surface, and asymptotically approaches 1. In the field of contamination management, it is treated as $C_p = 1$.

$$S = 1 - \frac{\dot{m}_l}{\dot{m}_i} \tag{B.5}$$

NOTE In the surface science field, C_p is called the condensation coefficient as the probability of causing physical adsorption. In the surface science field, the sticking coefficient S is defined as the probability of chemisorption.

In the field of contamination management, these terms are used in a different meaning from surface science. This document follows the definition of the field of contamination management.

B.2.2 Plume contamination

Plume species can result from combustion, unburned propellant vapours, incomplete combustion products, sputtered material and other degradation products from a propulsion or attitude control system and its surroundings swept along with the jet.

Plumes can also be produced by dumps of gaseous and liquid waste materials of the environment control and life support systems in manned spacecraft or by leaks in systems or internal payloads. Overboard disposal of materials causes increased molecular column densities and can cause molecular deposition. Plumes can consist of gaseous (molecular) species, liquid droplets and solid particles. Particles can also be formed due to icing or presence of inorganic material during water dumps.

Return flux or back flow is possible due to ambient scattering, self scattering or diffusion processes.

B.2.2.1 Plume model

Evaluation of plumes of thrusters or vents is often described by specific application related models. Parametric descriptions of plumes constitute an interesting alternative to spacecraft designers.

The mass flux Φ of a plume can be expressed in the most generic form by Formula (B.6):

$$\Phi(r,\Theta) = f\left(r,\Theta,\frac{dm}{dt}\right) \tag{B.6}$$

where

$\Phi(r, \Theta)$ is the flux at a given position from the vent;

r is the radial distance from the vent;

Θ is the angle from the centre line of the vent;

dm/dt is the mass flow from the vent.

where, moreover, the function f depends on the plume type. However, Formula (B.6) can in general be reduced in a good approximation to the product

$$\Phi(r,\Theta)=A\left(\frac{\mathrm{d}m}{\mathrm{d}t}\right)f_1(\Theta)r^{-2} \tag{B.7}$$

where A is the normalization coefficient.

For a thruster, the function f_1 is peaked around $\Phi = 0$ and can be expressed as a sum of decreasing exponentials or as a (high) power law of cos(Θ) or both. It is in some extent specific of each thruster.

Plumes from vents are more standard and the f_1 function can consequently be fixed: the mass flux is approximated by the following engineering model:

$$\Phi(r,\Theta)=\left[\frac{(n+1)}{(2\pi)}\right]\left(\frac{\mathrm{d}m}{\mathrm{d}t}\right)cos^n(\Theta)r^{-2} \tag{B.8}$$

where $1 < n < 2$ is used for space station design. The divergence is larger than the one of thrusters.

B.3 Contamination prediction

B.3.1 General

Numerical analysis enables prediction of contaminant deposition on sensitive surfaces such as optical components at EOL. When there is no surface that requires strict contamination control (e.g. an optical lens), integrating the worst-case outgas determines the compatibility to the requirement. CVCM (collected volatile condensable material) and TML (total mass loss) obtained by the outgassing test (see ASTM E595) are used for the worst-case estimation.

When strict contamination control is required, contamination condition at spacecraft EOL is estimated using more complex outgassing, transfer and condensation models. Analytical prediction utilizes input data such as outgassing or mass flow rate, surface adaptation coefficient and adsorption coefficient. These data are obtained by test e.g. using ASTM E1559.

B.3.2 Contamination analysis

B.3.2.1 General

Contamination analysis estimates the amount of contaminant deposition on the contamination sensitive surfaces at the end of the on-orbit life. Analysis simulates the behaviour of effusion, transportation, and deposition of contaminant molecules using functional models. Multiple analysis tools are operated in each country.

Contamination analysis is performed according to the following processes.

a) List the outgassing source materials with their mass, ESA, location and operational temperature range.

b) Obtain outgassing rate of source materials by test or data sources. Outgassing compound that do not deposit on the coldest surface of the spacecraft can be omitted.

c) Model the outgassing rate as a mathematical function.

d) Estimate the total effused outgas during the spacecraft operation period from each material using the function.

e) Make a geometrical CAD model of the spacecraft.

f) Allocate outgassing source materials and their mass or ESA on each node.

g) Calculate the total effused outgas from a node integrating used materials.

h) Define reflection rate and deposition rate of each node (when needed).

i) Allocate molecule of ambient air surrounding the spacecraft (when scattering is considered).

j) Simulate the contaminant transportation among nodes using the analysis tool.

B.3.2.2 Total outgassed mass estimation

Materials used for spacecraft are usually complex. Effused gas is also mix of multiple species. Gas effusion mechanism include both surface deposition/re-effusion, internal distribution. Therefore, one relation cannot represent all different materials performance.

Formulae (B.9) to (B.12) have been proposed and used to describe time dependent characteristics of outgassing. For substances that release gas at a constant rate regardless of the mass of the source, the effusion process can be described as a zero-order reaction. It is applicable to processes such as evaporation from the bulk or sublimation.

However, in practical materials, both the contaminant source material and effused outgas are complex. Surface adsorption/desorption and internal diffusion occur simultaneously as the release mechanism.

Comparison of various functions and ASTM E1559 outgassing rate test data reveals that the appropriate model differs depending on the material. Among them, the power model fits the widest range of materials.

— Zero-order reaction model:

$$M = a * t + b \quad \text{(B.9)}$$

where

M	is the outgassed mass;
t	is the time;
a, b	are the material specific constants.

Release at a constant rate until the source is depleted.

Simulates the sublimation of pure material e.g. naphthalene.

— Power model:

$$M = a * t^{b} + c \quad \text{(B.10)}$$

where c is the material specific constant.

A model that is empirically matched to complex systems.

— Natural logarithmic model:

$$M = a * \ln(t) + b \quad \text{(B.11)}$$

A model that simulates surface desorption. Generally suitable for metals.

— First order reaction model:

$$M = a * \exp(b * t) + \mathrm{c} \quad \text{(B.12)}$$

The outgas rate approaches a certain amount.

Outgassing rate test duration is usually much shorter than the spacecraft on-orbit life (e.g. 144 h). Life-long outgassed mass is estimated using extrapolation of the modelled function. Test data of complex material often show change of relations. Lighter molecule condensed on the surface are released first. Heavier molecules are effused later by internal distribution. The heavier molecules have higher deposition rate than lighter molecules.

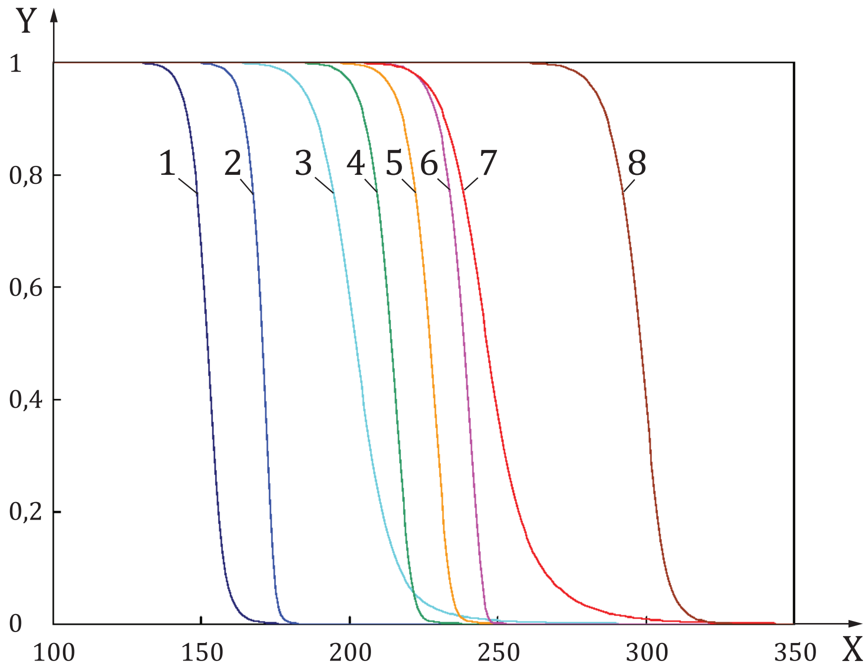
In the analysis, a function is fitted to the outgas rate measurement value of about 72 h to 144 h. The total outgas amount is calculated by extrapolating and integrating for the on-orbit operation period.

B.3.2.3 Transportation simulation

Transportation of contaminant molecule is calculated using an analytical tool. Many tools have been modified based on thermal analysis tools by replacing the energy radiation with the movement of contaminant molecules. Direct flux is the dominant transportation path of contaminating molecules. The ratio of multiple reflections increases when there is a high temperature surface in the vicinity or in a semi-closed space (such as a box or a cylinder with few openings). In such a case, it is necessary to increase the reflection order.

B.3.2.4 Deposition rate

The sticking coefficient is the proportion of contaminant molecules that stay on the contaminated surface of the molecules that arrived the contaminated surface. The deposition rate is the difference between the incidence rate of molecules on the contaminated surface and the desorption rate from the contaminated surface. The desorption rate from the contaminated surface depends on the temperature of the surface. Therefore, the sticking coefficient is a function of the temperature of the contaminated surface (Figure B.2).



Key

X temperature [K]

Y sticking coefficient

1 water

2 2-ethyl-1-1hexanol

3 2, 2-dimethoxy-1,2-diphenyl-ethanone

4 phthalates (plasticizers)

5 unidentified specimen (1)

6 unidentified specimen (2)

7 unidentified specimen (3)

8 irganox 1 076

Figure B.2 — Sticking coefficient

Materials used for spacecraft contain multiple molecular species. Since the sticking coefficient varies depending on the molecular species, the sticking coefficient of the material used in the spacecraft is the sum of the individual sticking coefficients. Several models describe the sticking coefficient as a function of temperature. However, description of the sticking coefficient by a single function has not been established. A function which fits to the experimental outgas rates differs depending on the material. Therefore, no single function can represent an integrated sticking coefficient of individual molecular species released from a single source material.

In the contamination analysis, it is necessary to set the sticking coefficient for each node from the predicted on-orbit temperature.

— Adhesion model A:

$$S_T = a\,(T - T_0) + 1 \tag{B.13}$$

— Adhesion model B:

$$S_T = \exp\left[a\,(1 / T - 1 / T_0)\right] \tag{B.14}$$

— Adhesion model C:

$$S_T = 1 / [1 + \exp (T - T_c) / \Delta T_c] \tag{B.15}$$

where

S_T	is the adhesion coefficient at contaminated surface temperature T;
a	is a constant specific to the material (>0);
T_0	is the contaminated surface temperature when the adhesion coefficient is 1 (material specific);
T_c	is the contaminated surface temperature when the adhesion coefficient is 0,5 (material specific).

Annex C
(informative)

Factors of combined uncertainty

There are several factors that affect contamination. Each factor contains uncertainty and/or assumption. Some elements still have higher uncertainty than others. They produce large combined uncertainty in the analysis result. Reducing uncertainty in the factors that strongly contribute the contamination estimation will improve the combined uncertainty of the analysis result.

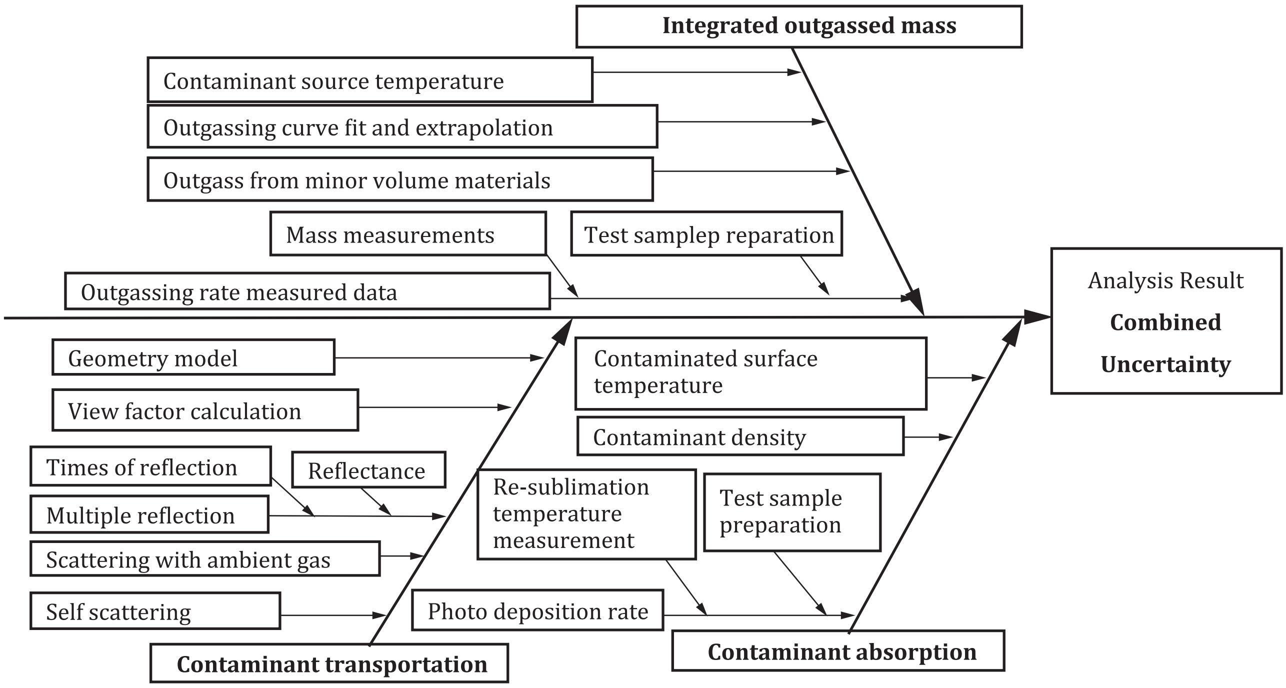


Figure C.1 — Factors of combined uncertainty

Bibliography

International Standards

[1] ISO 9000:2015, *Quality management systems — Fundamentals and vocabulary*

[2] ISO 10795:2019, *Space systems — Programme management and quality — Vocabulary*

[3] ISO 11221:2011, *Space systems — Space solar panels — Spacecraft charging induced electrostatic discharge test methods*

[4] ISO 14625:2007, *Space systems — Ground support equipment for use at launch, landing or retrieval sites — General requirements*

[5] ISO 14644-2, *Cleanrooms and associated controlled environments — Part 2: Monitoring to provide evidence of cleanroom performance related to air cleanliness by particle concentration*

[6] ISO 14644-3, *Cleanrooms and associated controlled environments — Part 3: Test methods*

[7] ISO 14644-4, *Cleanrooms and associated controlled environments — Part 4: Design, construction and start-up*

[8] ISO 14644-5:2004, *Cleanrooms and associated controlled environments — Part 5: Operations*

[9] ISO 14644-7, *Cleanrooms and associated controlled environments — Part 7: Separative devices (clean air hoods, gloveboxes, isolators and mini-environments)*

[10] ISO 14644-8, *Cleanrooms and associated controlled environments — Part 8: Assessment of air cleanliness by chemical concentration (ACC)*

[11] ISO 14952-1:2003, *Space systems — Surface cleanliness of fluid systems — Part 1: Vocabulary*

[12] ISO 15859-3, *Space systems — Fluid characteristics, sampling and test methods — Part 3: Nitrogen*

[13] ISO 15859-4, *Space systems — Fluid characteristics, sampling and test methods — Part 4: Helium*

[14] ISO 15859-9, *Space systems — Fluid characteristics, sampling and test methods — Part 9: Argon*

ECSS documents

[15] ECSS-Q-ST- 70-01C, *Space product assurance — Cleanliness and contamination control*

[16] ECSS-U-ST-20C – Space sustainability – Planetary protection (1 August 2019)

[17] ECSS-Q-ST-70-58C – Bioburden control of cleanrooms

[18] ECSS-E-10-04A Space engineering - Space environment

NASA documents

[19] NPD 8020.7E, *Biological Contamination Control for Outbound and Inbound Planetary Spacecraft*

[20] NPG 8020.12B, *Planetary Protection Provisions For Robotic Extraterrestrial Missions*

IEST documents

[21] IEST-STD-CC1246, *Product Cleanliness Levels and Contamination Control Program*

[22] IEST-RP-CC003, *Garment System Considerations for Cleanrooms and Other Controlled Environments*

[23] IEST-RP-CC003.2*(Supplement), Garment Sterilization Considerations for Microbiologically Controlled Environments*

[24] IEST-RP-CC006, *Testing Cleanrooms*

[25] IEST-RP-CC012, *Considerations in Cleanroom Design*

[26] IEST-RP-CC016, *The Rate of Deposition of Nonvolatile Residue in Cleanrooms*

[27] IEST-RP-CC022, *Electrostatic Charge in Cleanrooms and Other Controlled Environments*

[28] IEST-RP-CC023, *Microorganisms in Cleanrooms*

[29] IEST-RP-CC026, *Cleanroom Operations*

ASTM documents

[30] ASTM E1216, *Standard Practice for Sampling for Particulate Contamination by Tape Lift*

[31] ASTM E1235, *Standard Test Method for Gravimetric Determination of Nonvolatile Residue (NVR) in Environmentally Controlled Areas for Spacecraft*

[32] ASTM E1548, *Standard Practice for Preparation of Aerospace Contamination Control Plans*

[33] ASTM E1549, *Standard Specification for ESD Controlled Garments Required in Cleanrooms and Controlled Environments for Spacecraft for Non Hazardous and Hazardous Operations*

[34] ASTM E1559, *Standard Test Method for Contamination Outgassing Characteristics of Spacecraft Materials*

[35] ASTM E1560, *Standard Test Method for Gravimetric Determination of Nonvolatile Residue from Cleanroom Wipers*

[36] ASTM E1731, *Standard Test Method for Gravimetric Determination of Nonvolatile Residue from Cleanroom Gloves*

[37] ASTM E1997, *Standard Practice for the Selection of Spacecraft Materials*

[38] ASTM E2042, *Standard Practice for Cleaning and Maintaining Controlled Areas and Clean Rooms*

[39] ASTM E2088, *Standard Practice for Selecting, Preparing, Exposing, and Analyzing Witness Surfaces for Measuring Particle Deposition in Cleanrooms and Associated Controlled Environments*

[40] ASTM E2090, *Standard Test Method for Size Differentiated Counting of Particles and Fibers Released from Cleanroom Wipers Using Optical and Scanning Electron Microscopy*

[41] ASTM F50, *Standard Practice for Continuous Sizing and Counting of Airborne Particles in Dust Controlled Areas and Clean Rooms Using Instruments Capable of Detecting Single Sub Micrometre and Larger Particles*

[42] ASTM F51, *Standard Test Method for Sizing and Counting Particulate Contaminant In and On Clean Room Garments*

Other documents

[43] COSPAR's Planetary Protection Policy

[44] United Nations Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, Article **IX**, 10 October 1967

ICS 49.140

Price based on 32 pages