SPACECRAFT CONTAMINATION CONTROL POLICY THE EUROPEAN APPROACH

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Abstract
Lessons learned have shown that the risk of damage and performance loss of sensitive surfaces on spacecrafts due to molecular and/or particulate contamination had to be considered as a real concern. Nowadays, more and more stringent constraints of quality and reliability require contamination control at different steps during the development of a satellite. In Europe, to satisfy these specifications a set of normative references has been established in the frame of the European Cooperation on Space Standardization (ECSS) in order to harmonize the rules between the various industrial partners and space agencies at national and international levels. These documents are updated periodically to take into account new needs in the spacecraft contamination control policy. In this paper, we will introduce the joint effort between the different organizations, not only at European level, in terms of space standardization. Then, we will focus on the European Cooperation on Space Standardization ECSS-Q-70 branch, related to space product assurance and especially on the last issues of the cleanliness standards for space critical components. Finally, in order to illustrate how these cleanliness standards have to be applied, we will describe the global approach of a spacecraft contamination control programme and remind of some useful guidelines for each development phase of a spacecraft from design to launch.

1. Introduction

The importance of standardization for space activities is growing as more and more sophisticated equipments, increased mission duration, increased reliability are needed and new international cooperation is emerging, concurrently to more demanding economic constraints.
From a general point of view, recognized standards are a powerful tool to make the development, manufacturing and supply of products and services more efficient, safer and cheaper, facilitate fair trading between organizations, promote forceful competition among suppliers, maintain best practices regarding management and technical aspects, and share technological know-how and innovations.

2. Space standardization: a brief overview

The design and manufacturing of challenging complex systems require a high level of cooperation and true methodological uniformity between agencies and industry involved in a space project as achievement of consensus is the major goal. The end product must satisfy the customer needs in terms of technical quality, performance, schedule and cost-effectiveness.
In order to define the best exchange rules, common to the different participants, a lot of coordinated standardization activities have been conducted in the aerospace field from national to international level.
At international level, space standards are established in the framework of ISO, the International Organization of Standardization, mainly within the technical committee ISO/TC20.
At European level [1], the European Cooperation for Space Standardization (ECSS) began in 1993 with the mission to develop a coherent, single system of user-friendly standards for the European space community: ESA, its member states and their space industry represented via Eurospace. In practice, the ECSS standards are complementary and interconnected; they apply to any party involved in the definition, development, manufacturing, verification or operation of any assembly, equipment, subsystem, system or service used for the European elements of any space mission. The main objectives are to increase the efficiency of the European space industry and strengthen its competitiveness, to promote collaboration and enhance communication in case of cooperation programs, to avoid duplication of standards by a process of harmonization with international and European standards.

3. Focus on cleanliness and contamination control policy

3.1 Space contamination issues

Contamination is defined as any unwanted matter on the surface or in the environment of interest, that can affect or degrade the relevant performance or life time of a spacecraft hardware. Three categories can be differentiated as follow [2]:

- molecular contamination: undesired foreign film matter without definite dimension, often formed into droplets. Such films often arise from outgassing of polymer materials during heat and vacuum applications but they can also result from chemical residues, fingerprints…
- particulate contamination: undesired foreign matter of miniature size with observable length, width, and thickness which occur most of time during on ground activities.
- microbiological contamination: entity of microscopic size, encompassing bacteria, fungi, protozoa and viruses (in this paper, we will not consider this third particular category).

The impact of contamination depends on the nature of the surface and on the type of contaminants, either molecular or particulate. Damages could be detrimental to a large variety of subsystems sensitive to contamination such as optics, thermal control coatings, solar arrays… and may even compromise mission objectives. Indeed, materials properties may be more or less altered at mean or long term. In case of molecular deposits, films tend to form rather on the coldest surfaces of a spacecraft. But it is noticeable that even warm surfaces can be affected as well because of a photochemical deposition process initiated by the interaction between the solar UV and contamination.

For illustration, some specific effects of contaminants are more precisely described below.

Deposits on optical equipment - The transmission and reflection of optical devices like lenses or mirrors can be seriously deteriorated due to absorption of organic contamination in different spectral ranges. In that case, it is typically a concern for low-temperature infrared detectors. In addition to this resulting decrease in signal strength, an increase in noise can be related to surface obscuration and scattering due to the level and size distribution of particles depending on their location on the optical path.

Deposits on thermal coatings - The thermo-optical characteristics of these coatings (especially the solar absorptance/emittance ratio) can be modified, the most sensitive surfaces having a low α_s and ε. Indeed, the solar absorptance coefficient will rise, causing an efficiency loss and a warming up of the satellite. Moreover, degradation may be accelerated in the presence of irradiation such as UV sometimes in synergy with low-energy protons or electrons, since they tend to polymerize and definitively fix the non volatile contaminants. This is particularly harmful for sunlit surfaces such as thermal radiators or solar arrays.

Effects on electronic components - A localised material outgassing in closed spaces which are not enough vented to the outside (meaning to the space vacuum) causes a relatively high pressure and can generate electrical discharges or arcs and then high-voltage equipment failure. Besides a contaminant layer can either insulate or corrode electrical contacts, especially in the presence of halogenated flux residues.

Miscellaneous effects - Other effects should be noted as well, for instance: lower mechanical precision due to particulate contamination, star sensor disturbance due to stray light diffused by a local atmosphere of gaseous contaminants around the satellite, etc.

Therefore, to ensure a successful mission, a particular effort is required to mitigate contamination levels and then performance loss of spacecraft hardware during mission.

3.2 Risk prevention and mitigation

Contamination control is the only way to prevent risks for on ground and in orbit activities, which basically implies strict criteria for materials selection, the identification of sensitive functional surfaces and their thermal environment, the identification of critical items as contamination sources, the use of protective equipment and suitable locations of vents, a preliminary bakeout of materials, an extreme vigilance when cleaning, a strict cleanroom environment for equipment assembly and integration, and an appropriate tool for outgassing kinetics modelling. Based on lessons learned, an effective contamination control plan should be built up taking into account all specific constraints of a space project. For achieving this objective, relevant standards are highly recommended and provide very helpful guidelines.

3.3 Normative references

An overview of the most used and periodically updated documents is presented hereafter. Most of them come from the Q-branch of ECSS called "space product assurance", which addresses materials, components, mechanical parts and processes. In this branch, the normative references related to materials selection for space use and contamination control are collected together. Moreover, regarding contamination control in cleanroom, it had been common practice throughout industry to classify cleanrooms according to US Federal Standards 209 E. However, this standard has been withdrawn in 2001 and replaced by the ISO 14644-1, Cleanrooms and associated controlled environments - classification of air cleanliness (under revision), for air cleanliness classification with a more straightforward denomination scheme and ISO 14644-2 for proving continued compliance of a cleanroom with the part 1. Complementary standards have been published in the same ISO series, the other parts addressing the measurement of other key physical parameters, the operational aspects and new classification systems for particulate and chemical cleanliness on surfaces.

The general scope of the main normative references is defined below with the last issue date.

ECSS-Q-ST-70, Materials, mechanical parts and processes (2009), is a level 2 document that dictates the rules for materials, mechanical parts and processes approval to satisfy mission performance requirements by defining the documentation requirements and relevant procedures, applicable at all levels in the production of a space system.

<u>Contamination control program</u>

ECSS-Q-ST-70-01, Cleanliness and contamination control (2008), defines the cleanliness requirements and gives many recommendations regarding the way to achieve and maintain them during the different phases of the development of a space product on ground, at launch and in flight.

ISO 15388, Space systems — contamination and cleanliness control (under revision), establishes general requirements for contamination and cleanliness control to be applied, at all tiers of supply, to the development of space systems including ground processing facilities, ground support equipment, launch vehicles, spacecraft, payloads, habitable systems and ground processing and on-orbit operations. It also provides guidelines for the establishment of a contamination and cleanliness control program.

ECSS-Q-ST-70-02, Thermal vacuum outgassing test for the screening of space materials (2008), describes a thermal vacuum method for the screening of materials to be used in unmanned spacecraft or in vacuum facilities. Critical test parameters and outgassing and condensation acceptance criteria may be tailored depending on the mission specific constraints.

ECSS-Q-ST-70-29, The determination of offgassing products from materials and assembled articles to be used in a manned space vehicle crew compartment (2008), defines a test procedure to quantify the offgassed products from non-metallic materials under a set of closely controlled conditions in order to evaluate the suitability of assembled articles and materials for use in a space vehicle crew compartment and consider toxic hazards.

ECSS-Q-ST-70-71, Data for selection of space materials and processes (2004), is based on a list of space-proven and widely used materials and processes. The purpose of this standard is to orientate spacecraft and payload designers in their choices. Guidance is provided for a restricted number of materials among the 19 classes (metallic and non metallic) but on which enough tests have been performed. Data sheets are given in annexes with information regarding specific applications and space constraints.

<u>Contamination measurements</u>

ECSS-Q-ST-70-05, Detection of organic contamination of surfaces by infrared spectroscopy (2009), discusses methods for direct or indirect measurements of organic contaminants on surfaces using infrared spectroscopy, a simple and rapid analytical technique. It is widely used for qualitative and quantitative interpretation of deposits spectral data.

ECSS-Q-70-50, Particulate contamination control in cleanrooms by particle fallout measurements (under public review), is the companion piece to the ECSS-Q-ST-70-05 for particulate contaminants. It should provide requirements and guidelines for visual inspection and measurement of particles levels on spacecraft or cleanrooms surfaces.

IEST-STD-CC1246, Product cleanliness levels and contamination control program (under revision), provides a basis and a uniform method for specifying product cleanliness levels and contamination control program requirements. The emphasis is on contaminants that can impact product performance.

ISO 14644 part 8, Cleanrooms and associated controlled environments - classification of airborne molecular contamination (under revision), assigns classification levels to specify the limits of airborne molecular contamination (AMC) concentrations within cleanrooms and associated controlled environments. The document provides a protocol to include test methods, analysis, and time weighted factors within the specification for classification.

ISO 14644 part 9, Cleanrooms and associated controlled environments - classification of surface particle cleanliness (2009), provides a classification system for the determination and designation of cleanliness levels based on surface particle concentrations in cleanrooms and associated controlled environments. Recommendations on testing and measuring methods as well as information about surface characteristics are given in informative annexes. Nota: another part to be published next year will assign classification of chemical contamination on surfaces.

3.4 Spacecraft cleanliness and contamination control per ECSS-Q-ST-70-01

As previously seen, effective cleanliness and contamination control (C&CC) is essential for the success of most aerospace programs. The ECSS-Q-ST-70-01 standard (hereinafter referred to as “the standard”) defines the principles and the requirements in order to establish an effective control process that is usually applied all along the project life cycle, from its definition to End of Life (EoL). An example overview of a cleanliness and contamination process flow chart is provided in the standard and here reported in Figure 1.

The proposed flow chart is actually a synthesis of the approach defined in the standard, i.e. an iterative process that flows from the mission objective directly into design, Manufacturing, Assembly, Integration and Testing (MAIT) phases as well as in-flight operations with continuous feedback to the defined policy.

Once performance requirements and operational modes are derived from the mission’s objectives, a C&CC oriented design is then established. The first output of this process is the Cleanliness Requirements Specification (CRS) whose principal purpose is to establish, for the key project stages, the maximum allowable cleanliness levels. The specified acceptable contamination levels shall be directly derived from the acceptable performance losses, usually predicted or simulated through performance’s loss analyses and/or assessments. The CRS provides as a matter of fact the acceptable contamination levels for all on ground and in-flight phases to guarantee that the spacecraft performances are met. For such a purpose the CRS has also to define and identify the spacecraft items and the environmental areas that are sensitive to contamination and shall describes the effects of contaminants on their performance. The CRS shall be defined as early as possible in the programme and the first issue is usually requested for the project’s System Requirement Review (SRR).

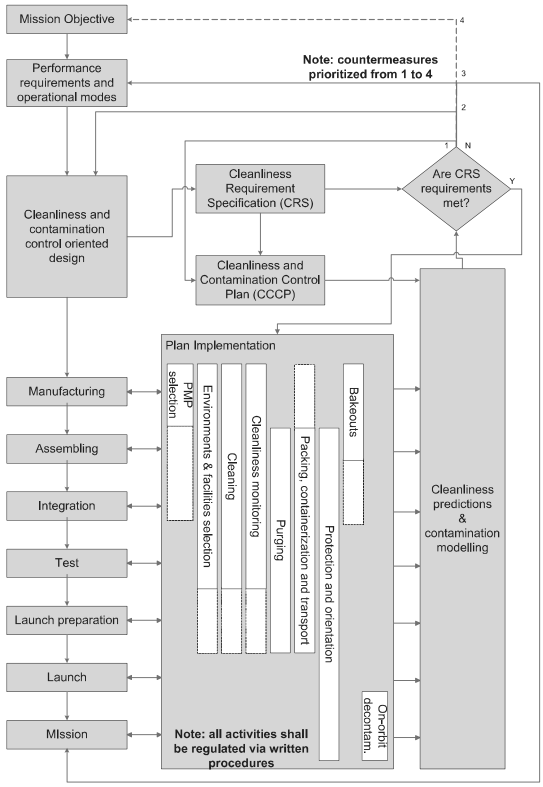

Figure 1 - C&CC process overview

In reply to the CRS, a Cleanliness and Contamination Control Plan (C&CCP) shall be established. The main purpose of the C&CCP is to establish the data content requirements in order to set out the ways in which the required cleanliness levels are achieved and maintained during the life of the programme, from design to EoL. The C&CCP is usually prepared for all levels of configuration items defined in the project, e.g. system, subsystem, equipment. Also the C&CCP shall be established as early as possible in the programme and the first issue is usually requested for the project’s Preliminary Design Review (PDR).

As part of the C&CCP, particulate and molecular contamination predictions shall be established to estimate the expected on ground and in-flight molecular and particulate contamination levels, and predictions shall be consolidated with the results of molecular and particulate monitoring throughout the project. The (consolidated) predictions are then continually compared with the maximum levels required by the CRS. If the predictions result in higher than specified levels, then corrective actions and precautions to reduce contamination are investigated and implemented. Such countermeasures are usually prioritized starting from the modification of C&CCP, moving to variations of design, operational modes and performance requirements and as a very last resort affecting the mission objective.

The reason to start the C&CC programme as early as possible is to maintain a better control of the project’s schedule and costs; as in other disciplines, also in C&CC anticipated actions impose no or little added effort to the project and can simplify problems during the later stages, when solutions are less effective, more costly and time consuming.

Design - General requirements as well as good practices and recommendations are provided in the standard for a cleanliness-oriented design. Some of the proposed rules can be effective both on-ground, during the integration and testing phases, as well as in-flight. The primary aim is to minimise the view factors of the sensitive items with respect to contaminant sources, e.g. with the implementation of directional ventings, baffles and shields, and to minimise the sensitive items' exposure times to a potential contaminating environment, e.g. with the use of deployable covers only operated in space. Other proposed rules are pertinent to the on-ground phases only, such as the use of temporary covers or hoods to reduce contamination and the implementation of purging interfaces. Particularly dedicated to the in-flight contamination control is the use of heaters to regularly decontaminate or minimise/prevent contamination build-ups. When this is implemented, the design shall carefully study the physical configuration together with the intended decontamination operations, to avoid the mere transfer of contamination from one sensitive surface to another sensitive surface.

Selection of materials and processes - As part of a C&CC oriented design, the selection of materials and processes is a fundamental step that shall aim to the minimisation of the contamination potential. From a molecular contamination perspective, low outgassing materials should be chosen and materials with relatively high vapour pressure should be avoided. ECSS-Q-70-71, Data for selection of space materials and processes, together with ECSS-Q-ST-70-01 are a good base for a preliminary selection, but very often the selection process has to be complemented with further materials' characterization since the evaluation of the in-flight levels requires an in-depth knowledge of the kinetics of the phenomenon; in-flight predictions based on screening data would as a matter of fact results in totally unrealistic figures. However, it is recognized that a kinetic characterization of all outgassing materials of a spacecraft could result in an extremely costly process, it is therefore important to be able to determine those that contribute the most and concentrate the efforts on them.

If the contamination potential of selected materials is too high and materials alternatives are not available, bakeouts shall be performed. Bakeouts are however not limited to materials but apply also to higher product levels, such as the equipment, subsystem, etc. As a general rule, it is more efficient to perform a bakeout at the lowest possible product level to allow reaching higher bakeout temperatures. In addition, any bakeout has to be demonstrated effective, either by outgassing testing the material/item before and after the bakeout or directly monitoring the process with a Quartz Crystal Microbalance (QCM).

From a particulate contamination perspective, the use of flaking, crumbing and chipping materials has to be avoided.

Manufacturing, Assembly, Integration and Testing - For the manufacturing phase, the standard mainly focuses on the conformity of manufacturing facilities, the cleaning and the cleanability of manufactured parts. The conformity of manufacturing facilities to the required standards has to be verified prior starting the manufacturing; the auditing exercise is often used for this purpose. All elements manufactured in non-controlled areas or under non-clean conditions have to be the object of a cleaning process until the cleanliness requirements are met, before they are packaged for delivery. In the case of elements that cannot be cleaned after manufacturing, the manufacturing areas cannot be totally uncontrolled and they have to be chosen in such a way that the cleanliness level requirements, for the manufactured elements, are guaranteed. As a general rule, the lower is the product levels the easier and more effective is the cleaning.

For the assembly and integration phases, the standard mainly focuses on the selection and verification of the conformity of the facilities, the protection and attitude of sensitive surfaces. For the selection of assembly and integration facilities the allocated contamination budget and the duration of the integration are considered principal tools. Known the integration schedule, in fact, a preliminary prediction budget has to be established. Results shall be compared with the required levels (at the end of activities) and, in cases of exceeding, iteration shall be performed on the environment selection. For the conformity verification facilities, the same considerations made for the manufacturing apply.

Also for the testing, the standard mainly focuses on the selection and verification of the conformity of the facilities. In this context cleanliness inspections of the facilities are often required as well as a proper test design to minimise the contamination potential. Examples are the implementation of cold traps in vacuum chambers, controlled de-pressurisation – re-pressurisation cycles and minimisation/containment of contamination sources from support equipments.

A key point for the whole MAIT phase is the need of trained personnel with respect to the cleanliness control policy. As for other disciplines, it is not requested to have all personnel trained at the same level. What is important is the personnel is trained and informed about the criticality of the performed activities in

term of cleanliness and contamination potential.
Pre-launch - For the pre-launch phase, the same as defined for the MAIT generally applies. However, this phase is usually more constrained than MAIT. Many are the reasons: some related to the freedom of operations that cannot always be performed till the very last minute (e.g. for the exposure of monitoring witnesses), some others are related to environments that can be 'chosen' to a very limited extend, such as the one provided inside the fairing.
Nevertheless, in a proper C&CC programme the launch authority shall be consulted and the needs shall be discussed and agreed between the different parties. There are cases for examples where umbilical purging lines have been requested to and provided by the launch authority to ensure purging till the launch.
Tests to characterize the contamination potential of fairing materials are sometimes required. Results are then used in prediction modelling to evaluate the contamination build-ups inside the fairing when the Spacecraft is already encapsulated.
Cleanliness monitoring - In all MAIT and pre-launch phases a key role is played by cleanliness monitoring. Different techniques are addressed in the standard: some are qualitative, such as the visual inspections, whilst others allow a proper level's quantification and are the ones that shall be used to consolidate the contamination predictions. When quantitative measurements are not directly performed on the flight HW surfaces, with extraction techniques such as wipe tests and tape lifts, the uses of witnesses is very common. Concerning molecular contamination witnesses, ZnSe and CaF_2 crystals are often used and when they are exposed they permit a direct measurement of molecular contamination through FTIR techniques, as addressed in ECSS-Q-ST-70-05. The use of stainless steel witnesses has the advantage to offer a wider exposed surface, resulting in higher measurement's sensitivity, but also the drawback related to the transfer operation of contaminants onto the crystal that is consequently measured. Particulate contamination monitoring through witnesses is normally performed by using particle fallout (PFO) plates measured with a PFO-meter. This method provides a very quick measurement of the total obscuration but it is not giving any information on the particle distribution. When such information is needed the exposure of silicon wafers, or a tape lift if there is no risk of damage for the sampling surface, and subsequent microscopic particle counting are performed. In both cases of direct measurements on flight HW and indirect measurements on witnesses, the choice of surfaces where contamination extractions are performed and the locations of witnesses have to be carefully analysed, to be representative of the surfaces that are monitored. As an example, witnesses should always be close to and have a similar orientation of the sensitive surfaces they represent. When witnesses are used, it is also important to insure continuity of the monitoring: the witnesses should always follow the HW they are representing, and their number should be chosen in a way that witnesses' measurements can be performed without leaving the HW unmonitored. Redundancy of monitoring witnesses is required to prevent issues in case of accidental contamination of the witnesses themselves.
Packaging, storage and transport - A proper packaging, storage and transport policy is another key aspect of an effective C&CC programme. If packaging, storage and transport are not performed in a controlled way, the effort put in all other activities can be frustrated and achieved levels seriously compromised. In this respect, the standard mainly focuses on the selection of adequate packaging materials, the storage in controlled environments, the use of protections and the adequacy of transport containers (allowing an easy cleanability, the possibility to control the inner environment and provisions for monitoring devices, such as molecular and particulate witnesses).

4. Conclusion
Contamination control is an important driver in the success of most space missions, most of spacecraft indeed having equipment sensitive to molecular and/or particulate contamination. Even at low levels, the presence of contaminants can be detrimental to mission performance requirements all the more so as ageing of deposits can be accelerated by the synergistic effects with the space environment. So it is necessary to define acceptable contamination requirements, formulate a contamination control plan and carry it through to meet these levels. In this respect, standardization working groups are busy to establish the best practices and review in depth the existing standards. The ECSS-Q-ST-70-01 standard defines the principles and the requirements in order to establish an effective cleanliness and contamination control process.

References
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