CONTAMINATION CONTROL POLICY
LAST PUBLICATIONS IN STANDARDIZATION

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ABSTRACT

Lessons learned have shown that the risk of damage and performance loss of sensitive surfaces on spacecrafts due to chemical and/or particulate contamination had to be considered as a real concern. Nowadays, more and more stringent constraints of quality and reliability require to control contamination at different steps during the development of a satellite. To satisfy these specifications in this particular case, a set of normative references has been established in order to harmonize the rules between the various industrial partners at national and international levels. These documents are updated periodically to take into account new needs in contamination control policy.

In this paper, we will introduce the joint effort between the different organizations in terms of space standardization. Then, we will focus on the ECSS-Q-70 branch, related to space product assurance and especially on the last issues of the cleanliness standards for space critical components. Besides, as new parts in the ISO 14644 series dedicated to cleanrooms and other controlled environments have been published or revised recently, some of them will be presented. Finally, in order to illustrate how these cleanliness standards have to be applied, we will describe the global approach of a 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 cooperations are emerging, concurrently to more demanding economic constraints.

From a general point of view, recognised 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
- share technological know-how and innovations.

2. SPACE STANDARDIZATION : A BRIEF OVERVIEW

2.1. general approach

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, many coordinated standardization activities are 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 where France is represented by the BNAE (Bureau de Normalisation de l'Aéronautique et de l'Espace), duly commissioned by AFNOR (Association Française de Normalisation).
- 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.

2.2. particular case : CNES approach

The French Space Agency plays a driving role in space standardization [2] and takes an active part not only in ECSS program but also in other organizations such as ISO, CEN, CCSDS, AFNOR, BNAE…

Two entities have been created at CNES to manage standardization activities : the "Comité de Normalisation" (CDN) in charge of defining policy and strategy and the "Bureau de Normalisation" (BN) in charge of establishing an evolutive CNES standard guide in accordance with CDN, called RNC (Référentiel Normatif du CNES).

RNC, built in 1998 on the same basis of the ECSS system, is a complete set of standards coming from various sources and divided into 4 branches for management, product assurance, engineering including one dedicated to launchers specificities and another one for regulations about safety, space debris, manned mission… Today, more than 200 documents of different levels are available. Within the framework of CNES, the RNC remains the reference to be applied for the selection of contractual specifications governing the relations between the various parties and defining the responsibilities and expected results. However, a simplified standard guide has been tailored for limited-scope projects developed by SMEs and/or laboratories and in-house project supervision.

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 :

- 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…[2]
- 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 (Fig. 1) 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.

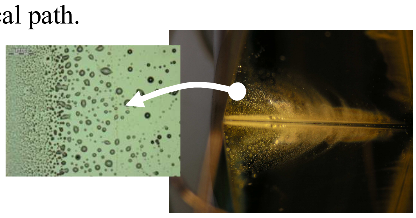

Fig. 1. droplets of organic contamination on optics

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 (Fig. 2) 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.

Fig. 2. darkening of a white paint on LDEF

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, to be scheduled in spacecraft design,
- a preliminary bakeout of materials,
- an extreme vigilance when cleaning,
- a strict cleanroom environment for equipment assembly and integration,
- 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 in Table 1 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 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.

Table 1. main normative references used for space contamination control

standard	title	date
ECSS-Q branch : space product assurance		
ST-70	materials, mechanical parts and processes	2009
ST-70-01	cleanliness and contamination control	2008
ST-70-02	thermal vacuum outgassing test for the screening of space materials	2008
ST-70-05	detection of organic contamination of surfaces by infrared spectroscopy	2009
ST-70-29	the determination of offgassing products from materials and assembled articles to be used in a manned space vehicle crew compartment	2008
70-50	particulate contamination control in cleanrooms by particle fallout measurements	in prep.
70-71	data for selection of space materials and processes	2004
ISO 14644 series : cleanrooms and associated controlled environments		
part 1	classification of air cleanliness	1999
part 8	classification of airborne molecular contamination	2006
part 9	classification of surface particle cleanliness	2009
IEST-STD		
CC1246D	product cleanliness levels and contamination control program	revision

The general scope of the main normative references cited in Table 1 is defined below.

ECSS-Q-ST-70 : This level 2 document 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 [3].

contamination control programme

ECSS-Q-ST-70-01 : This standard 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.

selection of materials and processes

ECSS-Q-ST-70-02 : This reference document described 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 : In order to evaluate the suitability of assembled articles and materials for use in a space vehicle crew compartment and consider toxic hazards, this standard defines a test procedure to quantify the offgassed products from non-metallic materials under a set of closely controlled conditions.

ECSS-Q-ST-70-71 : 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 if available regarding specific applications and space constraints.

contamination measurements

ECSS-Q-ST-70-05 : This document 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 : This standard under preparation 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-CC1246D : This standard provides a basis and a uniform method for specifying product cleanliness levels and contamination control programme requirements. The emphasis is on contaminants that can impact product performance [4].

ISO 14644 part 8 : This ISO document 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 : This part 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. recommended practices for contamination control

As previously seen, effective cleanliness and contamination control (C&CC) is essential for the success of most aerospace programs. ECSS-Q-ST-70-01 defines the principles and the requirements in order to achieve such a goal. An effective control process is usually applied all along the project life cycle, from its definition in the early phases, until its implementation, in phases B, C, D, E and F. An example overview of a cleanliness and contamination process flow chart is provided in ECSS-Q-ST-70-01 and here reported in Fig. 3.

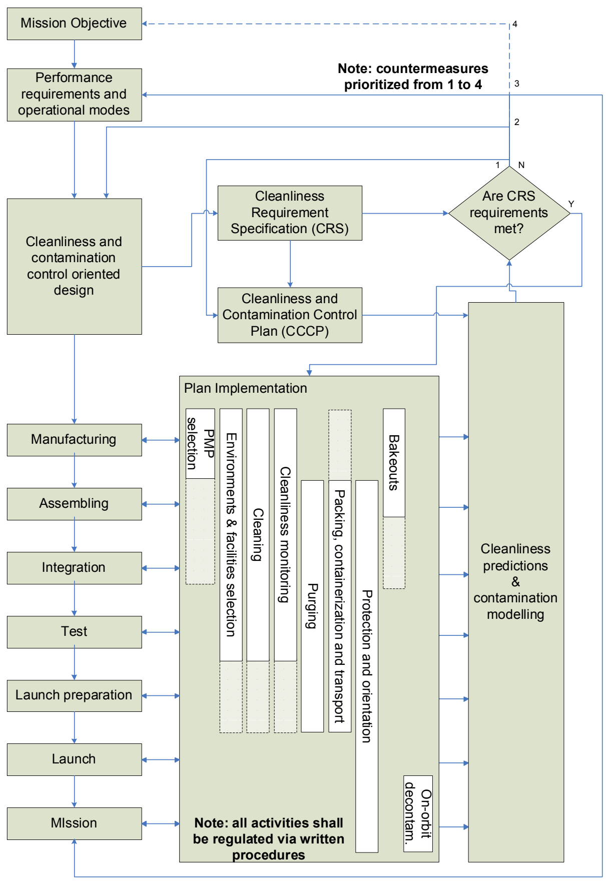

Fig. 3. C&CC process overview

As illustrated in Fig. 3, cleanliness and contamination control for a space program is an iterative process that flows from the mission objective directly into design, MAIT phases and operations.

Once the performance requirements and operational modes have been derived from the mission objectives, a C&CC oriented design is established. As an output of this process, the first document that is produced is the Cleanliness Requirements Specification (CRS) whose principal purpose is to establish cleanliness and contamination levels to be achieved at different MAIT, launch and mission stages. The specified acceptable contamination levels are derived from the acceptable performance losses, simulated through dedicated modelling in 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 often describes the effects of contaminants on their performance. The CRS has to be defined as early as possible in the programme, in order to properly address it during the design phase, the first issue is usually requested for the project's System Requirement Review (SRR).

In reply to the CRS, a Cleanliness and Contamination Control Plan (C&CCP) is established. The main purpose of the C&CCP is to define 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 program, from design to end of life. The C&CCP is prepared for all levels of configuration items defined in the project, e.g. system, subsystem, equipment. As it is also of fundamental importance for the space system's performance, the C&CCP has to be established as early as possible in the programme, in order to properly address the design and the following phases. 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 are established to estimate the expected on ground and in-orbit molecular and particulate contamination levels. During the plan implementation, through all project's phases, the contamination predictions are consolidated with the results of molecular and particulate monitoring. From the first issue of the C&CCP and all along the different project's phases, the contamination predictions are compared with the maximum levels required by the CRS. If the contamination predictions or, when available, actual measurements result in a higher than the specified level, then corrective actions and precautions to reduce contamination are investigated and implemented. Such countermeasures are usually prioritized starting from the modification of C&CC activities, through the modification of the plan, moving to variations of design, operational modes and performance requirements and, as a very last resort, affecting the mission objective.

recommended practices - general

As already anticipated, the C&CC programme should be established as early as possible. This will surely help to maintain a better control of the project's schedule and costs ; as in other disciplines, also in C&CC often 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.

Another recommendation is about the need to involve all interested parties in the definition of the right programme. Without such an approach, people that have to implement it might just ignore its existence or, as another example, some C&CC planned actions could interfere with other tasks or just not to be compatible with the project schedule.

Finally, it might be trivial but it is important to stress that once the appropriate C&CC programme is established, then it is of paramount importance that it is also implemented. Very often a tremendous effort is put in the development of the right C&CC programme but much less is put in its implementation. Continuity in this sense is very important.

recommended practices - design

Many recommendations are given in Annex E of ECSS-Q-ST-70-01 on cleanliness-oriented design.

Some rules can be effective both on-ground, during the integration and testing phases, as well as in-flight. They generally aim to minimise the view factors of the sensitive items with respect to contaminant sources, such as the implementation of directional ventings, baffles and shields, and/or to minimise the sensitive items' exposure times to a potential contaminating environment, such as the use of deployable covers only operated in space.

Other 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.

recommended practices - selection of materials and processes

The selection of materials and processes is a fundamental step in the C&CC programme and should aim to the minimisation of the contamination potential. In this respect low outgassing materials should be chosen and materials with relatively high vapour pressure should be avoided. The use of flaking, crumbing and chipping materials has also to be avoided.

In this context, the information contained in the two standards ECSS-Q-70-71 and ECSS-Q-ST-70-01 is a good base for a preliminary selection only, and very often has to be complemented with further materials' characterization. Considering for example material outgassing, the preliminary materials selection is usually based on the screening data contained in ECSS-Q-70-71 and the criteria contained in ECSS-Q-70-01 but the evaluation of the in-flight levels requires an in-depth characterization of the kinetics of the phenomenon. In-flight predictions based on screening data would, as a matter of fact, results in totally unrealistic figures. Since it is however recognized that such a characterization of all outgassing materials of a S/C could result in an extremely costly process, it is then very 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 are normally 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 temperature. Another good practice, more and more becoming a requirement, aims to demonstrate bakeouts' effectiveness by monitoring the process.

recommended practices - Manufacturing, Assembly, Integration and Testing

An effective C&CC is also necessary during the Manufacturing, Assembly, Integration and Testing (MAIT). Since MAIT normally constitutes an extended period where the flight HW is manipulated and become in contact with other potentially contaminating HW and environments, a proper C&CC can really make a big difference on the final achieved cleanliness levels.

One of the key points for a successful C&CC, as stressed in all ECSS-Q-ST-70-01 paragraphs concerning MAIT, 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 that the personnel is trained and informed about the criticality of the performed activities in terms of cleanliness and contamination potential.

For the manufacturing phases, ECSS-Q-ST-70-01 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 ; a proper cleanliness control in the manufacturing phase is therefore considered a very good starting point for the following ones.

For the assembly and integration phases, ECSS-Q-ST-70-01 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 the principal tools. Known the integration schedule, in fact, a preliminary prediction budget can be established. Results are compared with the required levels and, in cases of exceeding, iteration are performed on the environment selection. For the conformity verification of facilities, the same considerations made for the manufacturing apply.

Besides the good practices already anticipated for the design phases, such as the use of temporary covers and purging, another one is to orient the sensitive surfaces during the integration and testing activities in a way that contaminants depositions are minimised, e.g. keeping the sensitive surfaces vertically or downward can be effective in terms of particulate deposition.

Also for the testing, ECSS-Q-ST-70-01 mainly focuses on the selection and verification of the conformity of the facilities. In this context cleanliness inspections of the facilities are very 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.

recommended practices - pre-launch

For the pre-launch activities, the same good practices and recommendation given for MAIT activities generally apply. It is however to be borne in mind that this phase is usually more constrained than MAIT. Many are the reasons, some related to the freedom of operations that cannot always be performed to the last moment before launch, such as the exposure of monitoring witnesses, some others to environments that can be modified to a very limited extend, such as the one provided in the fairing.

Nevertheless, in a proper C&CC programme the launch authority is consulted and the needs are discussed between the different parties and suitable solutions found. 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 often performed and recommended. Results can be used in prediction modelling to evaluate the contamination build-ups inside the fairing when the S/C is already encapsulated.

recommended practices - cleanliness monitoring

In all MAIT and pre-launch phases, a very important role is played by cleanliness monitoring. Different techniques are addressed by the ECSS-Q-ST-70-01 standard ; some are qualitative, such as the visual inspections, whilst others allow a proper level's quantification and are the ones that have to 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 use of witnesses is very common. Concerning molecular contamination witnesses, ZnSe (Fig.4) and CaF_2 crystals are often used and they permit a direct measurement of molecular contamination through FTIR techniques.

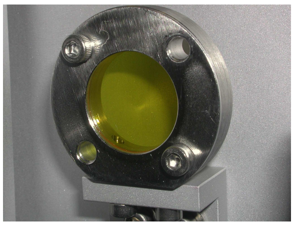

Fig. 4. ZnSe molecular witness

The use of stainless steel witnesses has the advantage to offer a wider exposed surface, resulting in higher measurement's sensitivity, but also the drawbacks linked to the transfer of contaminants onto the crystals that are 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 and subsequent microscopic particle counting is recommended.

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 monitored HW, and their number should be chosen to insure that witnesses' measurements are performed without leaving the HW unmonitored. Redundancy of monitoring witnesses is also recommended to prevent issues in case of accidental contamination of the witnesses themselves.

recommended practices - 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 the achieved levels seriously compromised. In this respect, the ECSS-Q-ST-70-01 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 spacecrafts indeed having equipments 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. Regarding cleanliness and contamination control, most of guidelines are provided in the ECSS-Q-ST-70-01, which is a very complete normative document with a lot of useful references to other standards.

5. REFERENCES

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