Space Sci Rev (2018) 214:19
DOI 10.1007/s11214-017-0439-4

OSIRIS-REx Contamination Control Strategy and Implementation

J.P. Dworkin[1] · L.A. Adelman[1,2] · T. Ajluni[1,2] · A.V. Andronikov[3] · J.C. Aponte[1,4] · A.E. Bartels[1] · E. Beshore[5] · E.B. Bierhaus[6] · J.R. Brucato[7] · B.H. Bryan[6] · A.S. Burton[8] · M.P. Callahan[9] · S.L. Castro-Wallace[8] · B.C. Clark[10] · S.J. Clemett[8,11] · H.C. Connolly Jr.[12] · W.E. Cutlip[1] · S.M. Daly[13] · V.E. Elliott[1] · J.E. Elsila[1] · H.L. Enos[5] · D.F. Everett[1] · I.A. Franchi[14] · D.P. Glavin[1] · H.V. Graham[1,15] · J.E. Hendershot[1,16] · J.W. Harris[6] · S.L. Hill[11,13] · A.R. Hildebrand[17] · G.O. Jayne[1,2] · R.W. Jenkens Jr.[1] · K.S. Johnson[6] · J.S. Kirsch[11,13] · D.S. Lauretta[5] · A.S. Lewis[1] · J.J. Loiacono[1] · C.C. Lorentson[1] · J.R. Marshall[18] · M.G. Martin[1,4] · L.L. Matthias[13,19] · H.L. McLain[1,4] · S.R. Messenger[8] · R.G. Mink[1] · J.L. Moore[6] · K. Nakamura-Messenger[8] · J.A. Nuth III[1] · C.V. Owens[13] · C.L. Parish[6] · B.D. Perkins[13] · M.S. Pryzby[1,20] · C.A. Reigle[6] · K. Righter[8] · B. Rizk[5] · J.F. Russell[6] · S.A. Sandford[21] · J.P. Schepis[1] · J. Songer[6] · M.F. Sovinski[1] · S.E. Stahl[8,22] · K. Thomas-Keprta[8,11] · J.M. Vellinga[6] · M.S. Walker[1]

Received: 6 April 2017 / Accepted: 27 October 2017

Abstract OSIRIS-REx will return pristine samples of carbonaceous asteroid Bennu. This article describes how pristine was defined based on expectations of Bennu and on a realistic understanding of what is achievable with a constrained schedule and budget, and

OSIRIS-REx
Edited by Dante Lauretta and Christopher T. Russell

The authors E. Beshore, J.W. Harris, M.G. Martin, J.M. Vellinga are retired.

Electronic supplementary material The online version of this article (doi:10.1007/s11214-017-0439-4) contains supplementary material, which is available to authorized users.

✉ J.P. Dworkin
jason.p.dworkin@nasa.gov

1 NASA Goddard Space Flight Center, Greenbelt, MD, USA

2 Arctic Slope Research Corporation, Beltsville, MD USA

3 Czech Geological Survey, Prague, Czech Republic

4 Catholic University of America, Washington, DC, USA

5 Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA

6 Lockheed Martin Space Systems, Littleton, CO, USA

7 INAF Astrophysical Observatory of Arcetri, Florence, Italy

8 NASA Johnson Space Center, Houston, TX, USA

Published online: 13 December 2017

how that definition flowed to requirements and implementation. To return a pristine sample, the OSIRIS-REx spacecraft sampling hardware was maintained at level 100 A/2 and <180 ng/cm^2 of amino acids and hydrazine on the sampler head through precision cleaning, control of materials, and vigilance. Contamination is further characterized via witness material exposed to the spacecraft assembly and testing environment as well as in space. This characterization provided knowledge of the expected background and will be used in conjunction with archived spacecraft components for comparison with the samples when they are delivered to Earth for analysis. Most of all, the cleanliness of the OSIRIS-REx spacecraft was achieved through communication among scientists, engineers, managers, and technicians.

Keywords OSIRIS-REx · Bennu · Asteroid · Sample Return · Contamination

Acronyms

AAM3	Asteroid Approach Maneuver 3
ACS	attitude control system
ARC	NASA Ames Research Center
ATLO	Assembly, Test, and Launch Operations
ATP	adenosine triphosphate
CCWG	Contamination Control Working Group
CDR	Critical Design Review
CEWG	Contamination Engineering Working Group
CFD	computational fluid dynamics
DAC	DSMC Analysis Code
DART™	Direct Analysis in Real Time
DNA	Deoxyribonucleic acid
DSMC	Direct Simulation Monte Carlo
DTGS	deuterated glycine trimer
EA	combustion elemental analyzer
EACA	ε-amino-n-caproic acid

[9] Boise State University, Boise, ID, USA

[10] Space Science Institute, Boulder, CO, USA

[11] Jacobs Technology, Tullahoma, TN, USA

[12] Rowan University, Glassboro, NJ, USA

[13] NASA Kennedy Space Center, Titusville, FL, USA

[14] The Open University, Milton Keynes, UK

[15] University of Maryland, College Park, MD, USA

[16] Ball Aerospace, Boulder, CO, USA

[17] University of Calgary, Calgary, AB, Canada

[18] SETI Institute, Mountain View, CA, USA

[19] Analex, Titusville, FL, USA

[20] ATA Aerospace, Albuquerque, NM, USA

[21] NASA Ames Research Center, Moffett Field, CA, USA

[22] JES Tech., Houston, TX, USA

EDL	Earth descent and landing
EDU	engineering design unit
EDX	energy dispersive X-ray spectroscopy
EMP	electron microprobe
FTIR	Fourier transform infrared spectroscopy
GC	gas chromatography
GC-IRMS	GC combustion isotope ratio MS
GSFC	NASA Goddard Space Flight Center
ICP-MS	inductively coupled plasma MS
IEST	Institute of Environmental Sciences and Technology
IRMS	isotope ratio mass spectrometer
ISO	International Organization for Standardization
JSC	NASA Johnson Space Center
KSC	NASA Kennedy Space Center
LA-ICPMS	laser ablation inductively coupled plasma MS
LC	liquid chromatography
LM	Lockheed Martin Space Systems
LPF	large payload fairing
MAVEN	Mars Atmosphere and Volatile EvolutioN Mission
MRD	mission requirement document
MS	mass spectrometry
NASA	National Aeronautics and Space Administration
NRC	National Research Council
NVR	nonvolatile residue
OCAMS	OSIRIS-REx Camera Suite
OCSSG	Mars Organic Contamination Science Steering Group
OLA	OSIRIS-REx Laser Altimeter
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer
OTES	OSIRIS-REx Thermal Emission Spectrometer
OTU	operational taxonomic unit
OVIRS	OSIRIS-REx Visible and Infrared Spectrometer
PDR	preliminary design review
PFTE	polytetrafluoroethylene
PHSF	KSC Payload Hazardous Servicing Facility
PI	principal investigator
ppb	parts per billion
ppm	parts per million
REXIS	Regolith X-ray Imaging Spectrometer
SEM	scanning electron microscopy
SRC	sample return capsule
TAG	touch-and-go
TAGSAM	touch-and-go sample acquisition mechanism
TEM	transmission electron microscopy
ToF-SIMS	time-of-flight secondary ion MS
UHP	ultrahigh purity
ULA	United Launch Alliance
UV	ultraviolet
VC-HS	visibly clean-highly sensitive

VIF	Atlas V vehicle integration facility
XANES	X-ray absorption near edge structure
μ-L^{2}MS	microprobe two-step laser desorption/laser ionization MS

1 Introduction

The OSIRIS-REx mission (Origins, Spectral Interpretation, Resource Identification, and Security Regolith Explorer) is the third mission selected under NASA's New Frontiers Program. The mission was approved for initial competitive development (Phase A) on December 29, 2009. The contamination control strategy for OSIRIS-REx evolved from the Organic Contamination Science Steering Group (OCSSG) approach developed for Flagship missions to Mars (Mahaffy et al. 2004) to one tailored and implementable in a cost-capped NASA program to a primitive asteroid. This manuscript describes the lessons and results in the seven years of implementation and development through launch on September 8, 2016.

The primary objective of the mission is to return and analyze at least 60 g of "pristine" (see below) carbonaceous asteroid regolith (Lauretta et al. 2017). The OSIRIS-REx team selected the B-type near-Earth asteroid (101955) Bennu due to its accessibility and spectral similarity to CI and CM carbonaceous chondrites (Clark et al. 2011). Carbonaceous chondrite meteorites are hypothesized to be fragments of carbonaceous asteroids. These are among the oldest and most primitive solids in the solar system, contain up to 3% carbon, and can include parts per million (ppm) or lower abundances of soluble organic compounds. Meteorite studies suggest that these types of asteroids may have contributed a wide range of organic compounds such as amino acids to the Earth, possibly supporting the emergence of life (e.g., Burton et al. 2012). The spacecraft will rendezvous with Bennu in 2018, then spend over a year characterizing the asteroid before executing a touch-and-go (TAG) maneuver to collect a sample of regolith, which will be returned to Earth for worldwide study on September 24, 2023. The analysis of pristine asteroid regolith samples from a well-characterized geological context will provide key constraints in the history of asteroid Bennu. This encompasses the epoch before it was accreted, through when it may have been geologically active and part of a larger body, to its dynamical orbital evolution from the main belt to Earth-crossing. The team will apply what they learn from the history of Bennu through sample analysis to the potential history of other asteroids.

The OSIRIS-REx spacecraft will collect surface regolith via a touch-and-go sample acquisition mechanism (TAGSAM) that fluidizes loose particles with high-pressure, high-purity N_2/He gas (Bierhaus et al. 2017). The N_2/He gas carries the samples into a cylindrical sample container, enclosed by biaxially oriented polyethylene terephthalate (e.g., Mylar®) flaps; 5% He is added for leak checking prior to launch. The gas escapes through a metal mesh that serves as the outer wall of the cylinder, and entrained particles, up to 2.5 cm for roughly equidimensional particles, or >2.5 cm in the longest dimension for oblong particles, are trapped. Contact pads of stainless steel loops also collect small particles for investigation of the properties of the space-exposed asteroid surface.

The value of these samples could be reduced by the addition of terrestrial contamination, which can directly obscure results and undermine the confidence of measurements and conclusions. For these reasons, the control of the access of contamination to the sample is key.

1.1 Defining Pristine

The driving Mission Level 1 requirement is to "return and analyze a sample of *pristine* carbonaceous asteroid regolith in an amount sufficient to study the nature, history, and distribution of its constituent minerals and organic material." The team designed this Mission Level

1 requirement to capture the importance of contamination by elevating it to the highest level of mission requirements, with enough flexibility to allow Mission Level 2 and 3 requirements to focus on the implementation. In the strictest sense, the "pristine" state is violated by any alteration of the physical, chemical, textural, or other state that compromises sample integrity. Alteration includes changing inherent states, losing sample components, or adding extraneous components. These could include changes in bulk chemistry/mineralogy, trace components, stable isotopic ratios, volatiles (ices and organics), crystallinity and phase state, remnant magnetism, grain-size distribution, grain/clast integrity, texture/structure/layering, and chemical/electronic activation state. This overly broad definition of contamination is beyond the scope of the science requirements of OSIRIS-REx.

Some level of contamination and alteration of the sample is probable. Decisions and actions which impact sample cleanliness can occur at any time in the lifecycle of spacecraft fabrication, operations, and sample curation. Mitigation, therefore, needs to be carefully planned from mission conception. Thus, it is important to strategize about what levels of contamination and alteration of the sample to accept to ensure the success of the mission. Overly aggressive requirements, which do not directly serve the investigations, can drive mission architecture. These driving cases can result in non-value-added cost growth which, if unchecked, can lead to reduction in the scope (descope) of the contamination requirements or even project cancelation. Instead, the aim of the team was to develop a set of realistic contamination requirements as well as a number of planned descope options to allow a graceful relaxation in case of technical or cost avoidance needs. Maintaining schedule for a planetary mission is paramount; a schedule slip that consumes the launch period creates a delay until the Earth and target orbits next align. Such a delay comes at significant economic and political cost. OSIRIS-REx was required to launch within a 39-day planetary launch period or delay a full year. A one-year delay would cause the mission to consume all available cost reserves and was not a programmatically viable option.

A recommendation from NASA's Stardust mission (Sandford et al. 2010) was that a mission needs to define what is meant by "clean" (a.k.a. "pristine" for OSIRIS-REx) from the very beginning (Table 1). *OSIRIS-REx defines pristine to mean that no foreign material is introduced to the sample in an amount that hampers the ability to analyze the chemistry and mineralogy of the sample*. Specific contaminant abundances are set to a level necessary to achieve the NRC (National Research Council) recommended "±30 percent precision and accuracy" (National Research Council 2007) on measurements. The team will carry out a wide range of sensitive and high-spatial-resolution chemical and mineralogical studies of the sample. Accordingly, contamination control must simultaneously preserve, to the extent necessary, the original organic and inorganic compositions of the sample from collection through curation. Achieving this in the New Frontiers-dictated cost-controlled environment is a significant challenge. Fundamental to the OSIRIS-REx mission's approach to contamination control is the belief that judicious knowledge of the nature of low levels of contaminants can effectively mitigate their impact to science analysis.

2 Organization

While OSIRIS-REx launched in 2016, initial planning for contamination control and assessment began in 2009 and matured via weekly input from scientists, engineers, and managers from across the Project. During mission Phase A and B the Contamination Control Working Group (CCWG) was chaired by the OSIRIS-REx Project Scientist and met weekly to

Table 1 Summary of contamination recommendations from Stardust and their application to OSIRIS-REx, tabulated from Sandford et al. (2010)

Stardust team recommendation	OSIRIS-REx implementation
1. Efforts need to be made both for contamination control and contamination knowledge	1. These activities were integrated into the OSIRIS-REx budget and schedule
2. Contamination control and assessment requires cooperative efforts be made that involve the spacecraft manufacturers, the spacecraft operators, the mission's Science Team, and the NASA Curatorial Office	2. Each of these groups has an individual responsible for organizing contamination control and assessment activities, and these individuals work closely together across organizational boundaries
3. Agree on what is meant by the word "clean" and how this definition will translate into operational activities	3. OSIRIS-REx has defined "pristine" as described in this document
4. Document what materials are used; samples of these materials should be collected and archived	4. A major effort on understanding and archiving spacecraft materials was performed
5. Witness plates need to be removed and examined quickly so that problems associated with unexpected or problematic contaminants can be dealt with rapidly	5. The OSIRIS-REx team analyzed contamination control and contamination knowledge samples monthly during ATLO. Amino acid witnesses were analyzed at GSFC with a 1-week turnaround
6. Witness coupons need to be designed so that they can easily be divided and distributed to multiple analysts	6. A plan has been developed for division of witness plates after Earth return since we realized that an easily divisible witness is also easily fragmented during shock events. The use of the frosted surface will aid in identification of exposed surfaces after fragmentation of the witness
7. Sample return spacecraft should carry a significant number of relevant witness coupons	7. Ten witness coupons are flown in the SRC and fourteen on TAGSAM
8. It is generally desirable to use more than one type of witness coupon	8. Two types of witness plates are flown
9. Plans must be made in advance so the NASA Curatorial Office is prepared to store and distribute not only the returned samples, but also the associated contamination control and assessment materials (witness coupons, samples of spacecraft materials, etc.)	9. The OSIRIS-REx team secured written commitments from the NASA organizations responsible for the spacecraft materials archive, samples, and "space-exposed hardware"
10. Devote additional development effort to the production of the cleanest possible aerogel	10. Aerogel is not used by OSIRIS-REx

define and refine the contamination requirements presented at the mission's Preliminary Design Review (PDR). CCWG shared membership with the Curation, Sample Return Capsule (SRC), and Sample Analysis Working Groups. The Sample Analysis Working Group was tasked with the implementation of the contamination knowledge requirements. Once the control and knowledge requirements were set, the CCWG was dissolved and the Contamination Engineering Working Group (CEWG) was formed. CEWG was chaired by the Lead Project Contamination Engineer (NASA Goddard Space Flight Center; GSFC) with routine participation by contamination engineers from Lockheed Martin Space Systems (LM), NASA Kennedy Space Center (KSC), United Launch Alliance (ULA), and the Project Scientist representing the scientists. Other engineers, curators, and managers were invited depending on the topic, but these meetings served to focus the implementation decisions and socialize the key participants who would be working together for years, and very intensely during launch operations.

Since returning a pristine sample is a Mission Level 1 requirement, contamination control plans were regularly analyzed during mission lifecycle reviews by a panel of external experts. To explore the plans and design in greater depth the team held an all-day contamination control and knowledge peer review in November 2013, shortly after the NASA MAVEN (Mars Atmosphere and Volatile EvolutioN Mission) launch. The timing of this review also captured the recent experience of MAVEN and was approximately midway between the mission PDR and mission Critical Design Review (CDR). It provided the ability to study the details of the contamination control and knowledge planning before flight hardware construction began. The review covered all aspects of contamination control and knowledge, from the requirements through the flight hardware implementation to the operations at the launch site and recovery site including curation of the science sample and the knowledge samples. The team brought in experts and walked through the plans, ensuring that nothing major had been missed.

The authority to implement these requirements derives from sample cleanliness being a Mission Level 1 requirement and the fact that the OSIRIS-REx Project Scientist was tasked with spearheading the contamination effort. This meant that contamination science was reported directly to the Principal Investigator via two members of the Science Executive Council (Fig. 1). Simplicity and cost control derive from the presence of a graceful descope plan for cost growth avoidance. It is crucial for the success of this process that the same people who wrote the mission concept and requirements are the ones who implement the cleaning and analysis.

3 Contamination Control

Based on our mission definition of pristine, the team derived Mission Level 2 requirements for contamination control that were (1) traceable to an independent document or analysis, (2) achievable within the project budget and schedule, and (3) rapidly verifiable without impacting the overall mission schedule, particularly during Assembly, Test, and Launch Operations (ATLO). ATLO is the phase of a mission which typically involves the most number of people and organizations, is the most expensive, and is the most time-critical. This time criticality is even more pronounced for a mission with a limited launch period, such as OSIRIS-REx.

Since verification is performed on a surface, the allowable contamination level in the sample was converted to a surface area requirement. Sample scientists generally refer to contamination in samples as mass ratios (e.g., parts per billion, ppb, or ng contaminant per g of sample). Therefore, the derived surface contamination requirement is based on (1) the expected sample mass to be collected, (2) the area of the spacecraft surfaces that may contaminate the sample, and (3) an assumption of how efficiently surface contaminants are transferred to the sample. OSIRIS-REx will return a minimum of 60 g of asteroid material, so a reasonably conservative value for the contamination requirement is based on this sample mass being contaminated by contact with TAGSAM interior surfaces (1916 cm^2). The most likely contamination risks arise from contact with the TAGSAM head itself, the gas employed during the collection, storage conditions in curation, and sample handling and processing. By comparison, the risk of contaminants reaching the sample by outgassing or surface creep from other spacecraft components is low, but nonzero. Therefore, for spacecraft construction the team focused on controlling and monitoring contamination on those

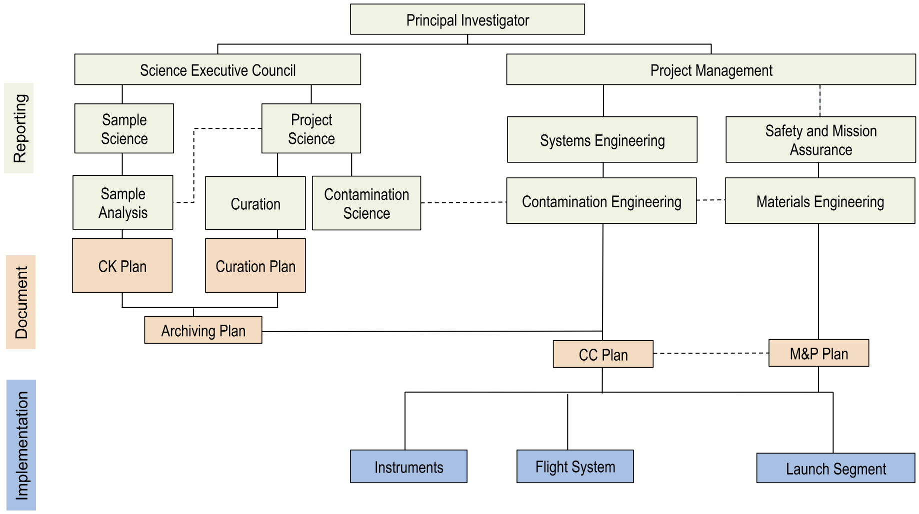


Fig. 1 *The top* (reporting in *green*) shows the organizational chart for contamination control and knowledge. *Direct lines* of authority for contamination knowledge are through science and contamination control and materials and processes (M&P) are through engineering. Cross-communication (*dashed lines*) ensures information transfer across disciplines. *The middle* (document in *orange*) shows the written products generated by the element above. The Sample Analysis Working Group developed the contamination knowledge plan and the Curation Working Group developed the curation plan. These plans were synthesized into the archiving plan. The archiving plan was included as an appendix of the contamination engineering generated contamination control plan (Fig. 2 and Supplemental Material S1) with input from contamination science (united in the CCWG). The materials engineering generated M&P plan was made with knowledge of the contamination control plan but without a direct reference. *The bottom* (implementation in *blue*) shows the different aspects of the OSIRIS-REx construction and test that used these documents. Note that the implementation exclusively relied on engineering documents

surfaces closest to the sample storage capsule, and assumed 100% transfer of contamination. While this is a worst-case scenario, it provides sufficient margin for ensuring the pristine nature of the collected sample. This approach also provides a way to prioritize controlled surfaces; starting with the most distant, covered, small, and unlikely sources of contamination, the risk, and thus the attention, grows as proximity or line-of-sight to the sample increases.

Careful consideration was given to what contaminants would be monitored and controlled for during ATLO. An extremely broad range of scientific investigations will be carried out on the returned sample, and dozens of minerals and thousands of molecular species are of interest. It is clearly impractical to control for the full range of target materials. Table 2 lists several potential organic limits based on various guidelines that were considered and discussed in more detail below.

Initially, the team looked to the Mars Organic Contaminants Science Steering Group (OCSSG) (Mahaffy et al. 2004) for organic contamination requirements (Table 2) and functional contamination control performance (Table 3). The OCSSG molecular requirements would not have been quickly verifiable on TAGSAM surfaces during construction and ATLO because the number of species and required sensitivity of most of the tests are outside of what is possible with routine analyses and rapid turnaround times. Delays in verification would lead to delays in ATLO procedures, with concomitant cost and schedule overruns, and threaten missing the launch period. The cleanroom performance specified by the OCSSG was divided into three categories (Table 3): level 1 (general surfaces of the mar-

Table 2 Each row shows an example of organic contamination control rationale which was considered for OSIRIS-REx. The first column indicates how the example is described in the text. The second column lists any organic compounds specified by the rationale. The third column indicates the allowable abundance of that species in the collected sample. The fourth column gives that abundance on the surface of the TAGSAM sampling hardware. The fifth column evaluates the viability of the rationale against external traceability, achievability within the limits of the facilities available for OSIRIS-REx, and verifiability within the schedule of ATLO

Name	Species	ng/g sample	ng/cm^2 TAGSAM	Viability
OCSSG molecular guidelines[a]	Aromatic	8	0.25	Traceable **Yes**
	Carbonyls and hydroxyls	10	0.31	Achievable No
	Amino acids	1	0.031	Verifiable No
	Amines or amides	2	0.063	
	Aliphatic hydrocarbons	8	0.25	
	DNA	1	0.031	
	Total reduced carbon	40	1.3	
200 A/100 (OCSSG level 2 cleaning guidelines [Table 3])	N/A	N/A	10	Traceable ∼ Achievable No Verifiable **Yes**
NRC-derived (30%)[b]	All detectable species	≤30/ compound	≤0.94/ compound	Traceable **Yes** Achievable ND Verifiable No
30% Precision of worst-case meteorite (Yamato 980115)	Total carbon[c]	57,000	1800	Traceable ∼
	Amino acids[d]	44	1.4	Achievable No Verifiable No
30% Precision of reasonable meteorite (Murchison)	Total carbon[e]	30,000	1000	Traceable ∼
	Amino acids[f]	6300	200	Achievable **Yes** Verifiable **Yes**
Stardust achieved[g]	Amino acids	N/A	180	Traceable **Yes** Achievable **Yes** Verifiable **Yes**

N/A: Not applicable; ND: Not determined; ∼ external traceability is arguable

[a] Mahaffy et al. (2004)

[b] National Research Council (2007)

[c] Chan et al. (2016)

[d] Burton et al. (2014)

[e] Average values in Kerridge (1985)

[f] Glavin et al. (2010)

[g] Elsila et al. (2009)

tian spacecraft carrying organics detectors), level 2 (general martian sample handling and processing facility surfaces), and level 3 (specific sample handling elements coming in direct contact with martian samples). The specifications of level 1 are readily achievable by

Table 3 OCSSG cleaning guidelines summary (Mahaffy et al. 2004). Bold text are outside the capabilities of identified industrial ATLO facilities including those available for OSIRIS-REx

OCSSG cleanliness level	1	2	3
Nonvolatile residue (NVR) level[a]	A/2 (500 ng/cm^2)	**A/100 (10 ng/cm^2)**	**AA3 (1 ng/cm^2)**
Particulate cleanliness level[a]	400	200	**25**
Outgassing flux	100 ng/cm^2/hr	10 ng/cm^2/hr	**1 ng/cm^2/hr**

[a]IEST (2002)

the OSIRIS-REx ATLO facilities at LM and most aerospace cleanrooms. Level 2 can be achieved, although using direct verification on hardware rather than indirect witness plates is impossible due to contamination imparted by the measurement. Finally, the team was unaware of any industrial facility that can meet and verify level 3 cleanliness, including those used to construct martian probes. The shortfalls of level 3 requirements mean that a replacement, scientifically valid requirement needed to be found. Given that carbonaceous chondrites are orders of magnitude richer in organic compounds than martian meteorites, Bennu is also expected to be similarly richer in organic compounds than Mars. Mars-based requirements are more stringent than needed for OSIRIS-REx.

As described in the previous section, the OSIRIS-REx definition of pristine included "Quantitation of the amount of organic carbon present to ±30 percent precision and accuracy over a range of 0.1 ppm to 1 percent" (National Research Council 2007). This rationale was converted into a requirement (see NRC-derived entry in Table 2). However, there were two serious concerns with this approach. First, the detection methods (e.g., Fourier transform infrared spectroscopy, FTIR) for prescreening followed by liquid chromatography-mass spectrometry (LCMS), gas chromatography-mass spectrometry (GCMS), and Direct Analysis in Real Time-mass spectrometry (DART™-MS) (Loftin 2009) each are inherently restricted to a specific range of compounds. But since these methods are similar to the types of measurements commonly carried out in meteorite studies, this is acceptable. Second, analysis costs and potential schedule delays for such open-ended compound searches present an unacceptable risk to OSIRIS-REx.

The team investigated (for example, see "worst-case" (soluble organic-depleted CI meteorite, e.g. Yamato 980115; Burton et al. 2014) and "reasonable" (soluble organic-containing CM meteorite, e.g. Murchison; Glavin et al. 2006) meteorite entries in Table 2) a series of other benchmarks for organic contamination limits, including CI and CM meteorites as Bennu analogs (Clark et al. 2011). However, the range of plausible meteorite organic abundances in Bennu analogs varies by orders of magnitude, and the uncertainty that a new meteorite discovery could change the requirements was a threat to the stability of the requirements and thus to cost. The complexity of a replacement requirement depends on the definition of "pristine." One definition would be to examine a meteorite that has been explicitly identified as "pristine" in the literature (e.g., the Antarctic CR2 carbonaceous chondrite Graves Nunatak (GRA) 95229; Pizzarello et al. 2008). However, any claim of a "pristine" meteorite is subjective and neither sufficiently documented nor universally accepted. Furthermore, demonstrating the contamination in a complex, difficult to characterize system is challenging and open-ended. Finally, as future studies of any sample used as a contamination archetype, particularly one as complex and heterogeneous as a meteorite are performed, the requirements derived from the sample could change. Such requirement changes during the development of a mission levies an unacceptable risk to cost and schedule. However, the bulk organic carbon abundance across carbonaceous chondrites is far less variable than particular soluble compounds; with a total carbon abundance of 1–3% in CI and CM meteorites. The team determined that 30 ppm contamination of 2% carbon bulk carbon measurement affords better than 30% precision to the planned analyses. Yet, the soluble organics, especially those relevant to astrobiology, are more sensitive. Instead, amino acids were used as a target species.

The rationale was threefold. First, amino acids are among the most pervasive compounds in the biosphere (e.g., Friedel and Scheller 2002). Second, modern detection methods are extremely sensitive (femtomole; Glavin et al. 2006). Third, amino acid data already exists on Stardust aluminum foil samples (Elsila et al. 2009). Stardust in many ways is an intellectual predecessor to OSIRIS-REx and was also constructed, integrated, and tested at the LM Waterton Plant. While a different alloy of aluminum (1100 in the Stardust collector versus 6061 in TAGSAM) (Tsou et al. 2003) was used, Stardust aluminum foils witnessed similar ATLO procedures, the deep space environment, return to Earth in a SRC, and curation at NASA Johnson Space Center (JSC) as the OSIRIS-REx TAGSAM head will experience. Elsila et al. (2009) studied several Stardust foils and determined that the most contaminated sample was foil C2092S,0. The low amino acid abundances of Stardust material and the confirmation of the cometary nature of the amino acid glycine by ^{13}C isotope analyses provide confidence that useful measurements can be made in the presence of the nylon-derived contamination observed on Stardust foil C2092S,0. Since amino acids have never been explicitly monitored and controlled as part of contamination control for a NASA mission, the risk of imposing a novel requirement was best understood by setting the contamination of this Stardust foil sample as the upper allowed limit of OSIRIS-REx contamination. Table 5 shows the data on this foil and a total amino acid contamination level of 186 ng/cm^2, which was rounded down to 180 ng/cm^2. Of particular note in the Stardust samples is the high relative abundance of ε-amino-n-caproic acid (EACA), the hydrolysis product of nylon 6, which was used in recovery, curation, and distribution of Stardust materials (Sandford et al. 2010). Amino acid-based polymers, such as nylon and latex, were prohibited on OSIRIS-REx. That action alone would have eliminated 185 ng/cm^2 from Stardust foil C2092S,0, leaving $<$1–2 ng/cm^2 of amino acid contamination.

Like with total carbon, the use of meteorite analogs for inorganic contamination limits is more straightforward because bulk elemental abundance varies less than organics across carbonaceous chondrites. Sufficient limits based on 10% of chondritic abundances were designated (Table 4). For further simplicity, a restricted set of indicator elements was selected as proxies for contamination monitoring that represented distinct and critical areas of scientific study. These elements are all measurable by scanning electron microscopy energy dispersive X-ray spectroscopy (SEM/EDX). To make these requirements useful across the team, they were converted to the language of contamination engineering, based on films and particles described in IEST-STD-CC1246D (IEST 2002) and assuming a collection of 60 g of sample (the minimum expected) inside the 1916 cm^2 surface area TAGSAM head.

IEST-STD-CC1246D defines particulate contamination per 0.1 m^2 (N) in terms of levels (L) for particles size x according to the equation $\log \mathrm{N} = -0.926(\log^2 x - \log^2 L)$. The results of this equation are then binned by particle size. For example, level 100 has a maximum of 1780 5 µm, 264 15 µm, 78.4 25 µm, 10.7 50 µm, and 1 100 µm particles per 0.1 m^2. Films or nonvolatile residue (NVR) are simply defined relative to “A” which is 1000 ng/cm^2 of contamination, so A/2 is 500 ng/cm^2.

Under the anticipated conditions of ATLO, inorganics are expected to be mostly particulates, but organics should still dominate the particulate population. Thus, the inorganic

Table 4 Indicator elements and their control limits. Individual elements serving as representatives or indicators of suites of elements important for various scientific investigations. Each element has a carbonaceous chondrite derived contamination limit in the sample, which is then converted into a surface requirement for the sampling system in the third column. The fourth column shows the abundance of each element if it were to contaminate a surface at 100 A/2 (assuming pure spherical particles). Thus, meeting the 100 A/2 requirement meets the C and Ni limits, but contamination knowledge is needed to ensure that unexpectedly high levels of K, Sn, Nd, and Pb are not major contributors to the contamination

Element	Indicator	Contamination limit (ng/cm^2)	Level 100 (particles) + A/2 (NVR) (ng/cm^2)
C	Organics	1000	34 + 500
K	Terrestrially abundant lithophile	170	14 + 500
Ni	Extraterrestrially abundant siderophile	34,000	143 + 500
Sn	Industrial contaminant	0.53	117 + 500
Nd	Lanthanide, lithophile	1.5	113 + 500
Pb	Chalcophile, geochronology, industrial contaminant	180	182 + 500

Table 5 Amino acid abundance on Stardust foil C2092S,0 (Elsila et al. 2009)

Amino acid	Primary source	$pmol/cm^2$	ng/cm^2
Glycine	Cometary	68	5.1
β-Alanine	Unknown	7	0.6
D-Alanine	Not detected	<4	<0.4
L-Alanine	Contamination	12	1.1
ϵ-Amino-n-caproic acid (EACA)	Contamination	1413	185.2
Total		1500	192.0
Total contamination		1425	186.3

elements in Table 4 are expected to be a small component of the total. With these assumptions, a theoretical worst case with pure elemental particles is generally met by an achievable level 100 particulate requirement and a NVR level of A/2 for the sensitive areas of the OSIRIS-REx flight system. Since there are still pathological conditions that would violate the intent behind the requirement while still meeting level 100 A/2 standard (e.g., 100 ng/cm^2 of tin particles is below level 100 but exceeds the total science contamination limit for tin), the team requested the ability to check for the unexpected.

The team adopted an organic contamination requirement based on the 100 A/2 limit for carbon and the other elements in Table 4, with the addition of amino acids as a test for organic contamination. The goal was to minimize amino acid contamination as much as practical, since the control of amino acids was novel. This approach included measuring the amino acid, particle, and NVR contamination on proxy witness plates throughout ATLO. This effort is needed because the act of measuring flight hardware via established methods (washes, wipes, tape lifts) is likely to contaminate the hardware. Furthermore, since cleaning is impossible after launch, and verification of contamination after launch would be impossible until the sample acquisition hardware was returned to Earth, the team set all contamination control limits to conservative levels at time of launch.

Table 6 Contamination sampling terminology used across the project

Term	Description
Hardware (or process) coupons	Pieces manufactured from the same raw materials, using the same equipment and processes specifically for archive at JSC or offal (excess material after machining) earmarked for archive at JSC
Contamination knowledge plates	Silicon and aluminum foils prepared by JSC for monthly collection and replacement for the purpose of archiving the environmental effects on the spacecraft for both particulate and NVR. 25% was analyzed, while the remainder is archived at JSC for future use
Contamination monitoring plates—particulate	Silicon wafers collected and analyzed by LM monthly during ATLO for determining background facility particulate fallout rates
Contamination monitoring plates—NVR	Aluminum foil collected and analyzed by LM monthly during ATLO for determining background facility NVR
Contamination monitoring plates—amino acids	Aluminum foil collected and analyzed by GSFC monthly during ATLO for determining background facility amino acid load
Hardware verification samples—particulate	Millipore slide for limited exposure used for verification of cleanliness levels for SRC canister interior, TAGSAM head, Launch Container by LM
Hardware verification samples—NVR	Aluminum plate or aluminum foil for limited exposure used for verification of cleanliness levels for SRC canister interior, TAGSAM head, Launch Container by LM
Hardware verification samples—amino acids	Aluminum foil for limited exposure used for verification of cleanliness levels for SRC canister interior, TAGSAM head, Launch Container by GSFC
Flight witness plates	Designed to collect material during flight; returned to Earth for analysis and archive in 2023

Table 7 OSIRIS-REx Level 2 contamination requirements (mission requirement document, MRD)

MRD	Requirement
107	OSIRIS-REx shall limit the contamination on the TAGSAM head, TAGSAM launch container interior, SRC canister interior to levels at or below those specified by IEST-STD-CC1246D level 100 A/2 until launch
108	OSIRIS-REx shall limit total hydrazine contamination on the TAGSAM Head surface to <180 ng/cm^2
109	OSIRIS-REx shall return and maintain the bulk sample exposed to total amino acid contamination <180 ng/cm^2 on the TAGSAM head surface
110	OSIRIS-REx shall document the contamination acquired by the TAGSAM head during flight
111	OSIRIS-REx shall generate and follow the project contamination control plan
406	OSIRIS-REx shall provide a ≥ 1 g sample of all materials of which the TAGSAM head, TAGSAM launch container interior, SRC canister interior, or witness material are composed

OSIRIS-REx uses high-purity hydrazine monopropellant thrusters. Hydrazine is a strong base and powerful reducing agent, largely due to the adjacent nitrogen lone pair electrons making it an alpha effect nucleophile. The team thought it prudent to recognize the potential reactivity of hydrazine on the sample and limit the exposure of unreacted hydrazine on the sample.

Different subdisciplines use different terminology, so definitions had to be standardized for the different types of contamination witnesses (Table 6). Level 2 requirements as de-

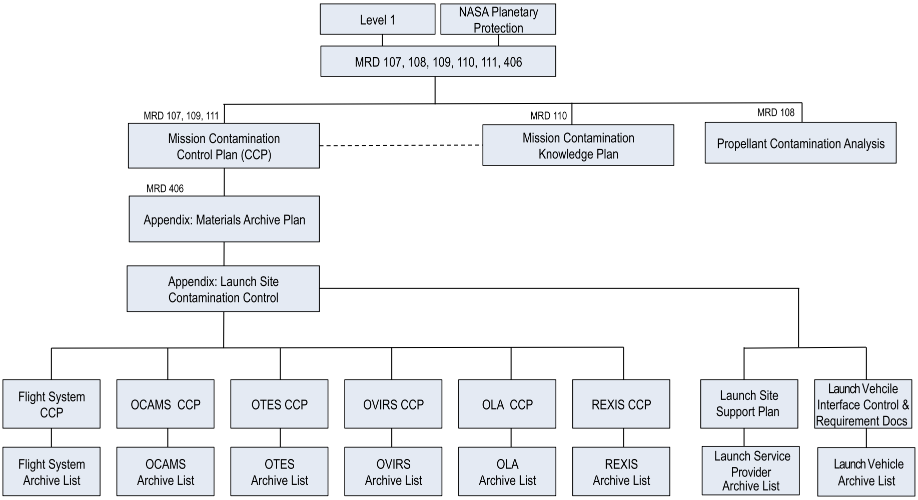


Fig. 2 The flow of requirement documentation from the NASA planetary protection and OSIRIS-REx *Level 1* requirements to *Level 2* documents (mission requirement documents (MRD) numbers in Table 7 are shown). These *Level 2* documents are used by numerous *Level 3* documents for the flight system, each instrument (OCAMS, OTES, OVIRS, OLA, and REXIS), launch service provider, and launch vehicle

scribed in Table 7 for both contamination control and contamination knowledge were established. These requirements are more stringent than those already imposed by NASA for OSIRIS-REx to meet the requirements of Planetary Protection, Category II outbound and Category V unrestricted Earth return (NASA 2011). The flow of requirements and documentation is shown in Fig. 2.

Contamination control requirements are defined to provide a simpler and more generic test. But in anticipation of "unknown unknowns" the Sample Analysis Working Group was responsible for observing and cataloging the unexpected via contamination knowledge investigations (see Sect. 5). Contamination knowledge analyses are open-ended, but only on limited samples and with no impact to schedule. This effort provided the information needed to maximize the scientific benefit of the returned sample, without potentially halting ATLO for months.

3.1 Amino Acid Transfer Efficiency

Once the team identified amino acids as a critical analyte, they performed a simple test to evaluate the transfer efficiency of dry amino acids. This test allowed for the determination of the probability of adhering amino acids (and presumably other charged species) entering the sample. To simulate regolith, the team used silica fume due to its high surface areas and copper-clad steel balls to grind the silica fume into the TAGSAM aluminum surfaces; 75% of the simulated regolith by mass was steel balls.

Two 60-g-total identical mixtures of silica fume and copper-clad steel balls were cleaned by heating at 700 °C in air for 24 hours in a muffle furnace. A TAGSAM engineering design unit (EDU) with a film of known contamination (1.0 mg of D-isovaline dissolved in 1:1 water:methanol) applied to the interior surfaces of TAGSAM was filled with regolith simulant and openings sealed with Kapton tape. The doped TAGSAM, one sample of regolith simulant, and a custom-made vibration fixture plate were taken to a Ling B335 Shaker/SAI120

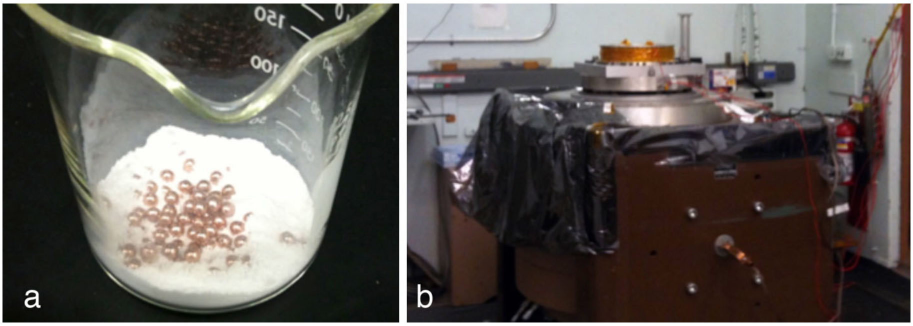


Fig. 3 Setup for the transfer efficiency test with (**a**) 60 g of fume and balls prior to cleaning. (**b**) TAGSAM EDU wrapped in Kapton on the shaker table

Amplifier in Building 7 at GSFC (Fig. 3) and shaken for 1 minute at 20 Hz with a 2-cm vertical displacement and maximum 5 g acceleration.

After vibration was complete, the mount and unit was removed and disassembled. The sample and blank were separated into balls and fume for analysis. The samples were extracted in 100 °C water for 24 hours, split with half hydrolyzed in 150 °C HCl vapor for 3 hours, both halves were separately desalted, derivatized with *o*-phthaldialdehyde/N-acetyl-L-cysteine (OPA/NAC), and analyzed via a Waters® ACQUITY™ ultraprecision liquid chromatograph and fluorescence detector couplet to a Waters® LCT Premier™ time-of-flight mass spectrometer LCMS according to Glavin et al. (2006, 2010). The results indicate that (1) the worst-case transfer efficiency of an aliphatic amino acid from TAGSAM to this simulant is 0.03 ng/g from 1 mg coating the interior of TAGSAM (an efficiency of 0.5 ppm); and (2) amino acids from an essentially uncleaned TAGSAM surface appear at only 0.22 ng/g of regolith. This abundance of total amino acid contamination is actually *below* even the 1 ng/g level of amino acids specified by OCSSG.

These results differ from previously reported lysine transfer tests performed in relation to Mars sample handling requirements (0.1% from aluminum to sand without agitation) (Mahaffy et al. 2004). We suggest the difference may be that the sand could have contained far more moisture which would greatly aid in transfer. It is reasonable that dry transfer, such as expected on airless Bennu regolith is more relevant to OSIRIS-REx.

3.2 Amino Acid Cleaning

Since amino acid requirements for ATLO are novel, the team performed a number of tests to determine the effectiveness of precision cleaning techniques on the removal of amino acids, as well as the potential for amino acid contamination derived from the solvents and gloves used at LM and GSFC.

Common steel screws were used as the substrate to test LM precision cleaning protocols relative to a procedural blank (a glass vial cleaned by heating to 500 °C in air for >8 hours with no screw). The glass vials were borosilicate conical screw cap test tubes with a piece of aluminum foil used to prevent the polytetrafluoroethylene (PFTE, e.g., Teflon®) lined cap from touching the vial. The vials were shipped to LM for use, where samples were placed in the glass vials to be returned to GSFC for analysis. The identical procedure was performed for all amino acid contamination monitoring plates from LM. The plates collected at KSC were wrapped in 500 °C cleaned foil and sent to GSFC for subdivision and analysis.

Table 8 Amino acid testing results, blank corrected. For these experiments the samples were split, with half analyzed without hydrolysis (free amino acids) and the other half acid-hydrolyzed, according to Glavin et al. (2006), to show both free amino acids and those bound (presumably as peptides in this case). Bags were extracted in water and reported as concentration in solution

Sample	Free amino acids (ng/cm^2)	Total amino acids (ng/cm^2)
Uncleaned screw	14.91	89.64
Dirtied screw	54.58	252.01
Dirtied and cleaned	0.50	1.97
Nylon packaged	13.69	101.13
Nylon packaged and cleaned	0.50	1.50
Kimberly Clark 55082 medium purple nitrile glove used at GSFC	n.d.	67.3 ng/g
Kimtech G3 medium tan nitrile gloves used at LM	n.d.	646.2 ng/g
TechNitrile medium blue nitrile gloves	n.d.	150.3 ng/g
Dry Kimtech glove rubbed on foil	n.d.	0.97
Fisher Optima 2-propanol wet Kimtech glove rubbed on foil	n.d.	0.13
Nylon (KNF LB106)	n.d.	38,000 ng/g
PFTE (KNF LB605)	n.d.	17 ng/g
Polypropylene (KNF LB3022)	n.d.	7.8 ng/g
Tyvek® (Beacon Converters A7373)	n.d.	6.3 ng/g
Lamellar polypropylene (KNF Kenlam 7150)	n.d.	1.4 ng/g
Lamellar polyethylene (Beacon Converters FR2176)	n.d.	0.060 ng/g
Aluminum (Reynolds extra heavy duty foil hot bag)	n.d.	0.015 ng/g
2-Propanol (Fisher ACS)	n.d.	<0.05 ng/g
2-Propanol (Fisher Optima)	n.d.	<0.05 ng/g

n.d. = not determined

The samples were as follows: a screw removed from the parts box without any cleaning "uncleaned" placed in a sample vial in the LM cleanroom, a screw which was taken to the cleanroom and dirtied by being exposed to human breath sufficient to provide some condensation, an identical dirtied screw which was cleaned by sonicating in Brulin 815 GD™ detergent, rinsed with water, and then precision cleaned using a pinpoint spray of polished water (135 ± 5 °F and 45 ± 5 psi), a screw which had been heat sealed in a nylon bag, and an identical packaged screw which was subsequently cleaned as above. Three types of gloves and six types of bags were analyzed after exposure to 5 mL room temperature water for 24 hours; and two types of 2-propanol were analyzed (Table 8).

Each sample was analyzed via LCMS with the AccQ•Tag™ protocol (Boogers et al. 2008) on a Waters® ACQUITY™ and LCT Premier™ time-of-flight mass spectrometer equipped with an electrospray ionization source (positive ion mode), mass resolution setting of 5000 m/Δm. We elected to use this protocol over the OPA/NAC method and chromatography Glavin et al. (2006, 2010) since the derivatization product is stable enough to allow for unattended sequential analysis, AccQ•Tag™ does not require desalting because it is not susceptible to multivalent cation interference, and chiral separation was not required—

combined, this resulted in more rapid analyses to meet the 1-week requirement for ATLO amino acid analyses. Sample was introduced via a Waters® ACQUITY UPLC® with fluorescence detector. For LC analysis a 250-μL syringe, 50-μL loop, and-30 μL needle were used. The total injection volume was 1 μL. A set of nine calibrators of proteinogenic amino acids (0.25 to 250 μM) was prepared in water and analyzed. A linear least-square model was fit to each analyte. Both mass and fluorescence traces were quantitated. The blank sample was used to subtract procedural and laboratory background; trace levels of glycine were observed in the blank. Sample transfers were performed in an International Organization for Standardization (ISO) 5 laminar flow bench. The identical analytical procedure was used on authentic contamination monitoring plates. Each amino acid was individually quantified. This analytical method was used on all amino acid contamination control analyses, with the more involved Glavin et al. (2006, 2010) method reserved for contamination knowledge analyses (below).

The cleaning method tested was determined to be effective in removing amino acid contamination. The cleaning appears more efficient at removing bound amino acids than free. This is reasonable because they are most likely present in particulates (e.g., skin flakes).

The team also estimated the amount of amino acid loss during spacecraft thermal-vacuum testing. Thermal-vacuum testing was performed after assembly when component cleaning is no longer possible, but could serve to further decrease the contamination acquired during earlier assembly and test operations. The team simulated LM thermal-vacuum conditions at GSFC with a laboratory manifold. The experiment was simple, yet sufficient for the purpose and time available.

Each sample for this experiment was created by adding an amino acid solution (392 μL of 1.5 μM each of 16 biological amino acids) to a 12-mm outer diameter (10-mm inner diameter, fill height of 5 mm) amber vial, which was then dried at $<30\ ^\circ\mathrm{C}$ under reduced pressure (~ 1 torr). If this solution dried evenly over the interior of the vial and the vial was a perfect cylinder, then the amino acid film would have been nearly identical to the total amino acid abundance in the "dirtied" screw in Table 8. However, in that experiment only 27% of the amino acids were free, as opposed to bound in peptides or cells.

Each vial was then placed individually in a quartz finger and held at 100 °C under vacuum ($\sim 1 \times 10^{-5}$ torr) in a tube furnace. Six vials were used in total, each heated for a different time period (unheated, 1 hour, 7 hours, 24 hours, 48 hours, and 120 hours). After heating, each sample was analyzed via the AccQ•Tag™ method.

Analysis of the free amino acids showed a decrease in concentration over time. The analysis showed a reduction of approximately 50% of each free amino acid after 24 hours of vacuum heating. Due to the plausible concentrations used and the small volume permitted in the experimental setup, the signal-to-noise ratio for a given peak was insufficient to allow the accurate quantitation of rates. Regardless, half-lives are in the range of hours, not minutes nor days. A trade between the effectiveness of the precision cleaning and the cost and schedule for thermal-vacuum cleaning resulted in the flight TAGSAM head being heated to $95 \pm 5^\circ$ C for 24 hours at $\leq 1 \times 10^{-5}$ torr.

3.3 Spacecraft Requirements and Implementation

The OSIRIS-REx spacecraft was processed in an ISO 7 cleanroom at LM, with some tests performed in an ISO 8 cleanroom. These environments were monitored with contamination monitoring and contamination knowledge plates both prior to and during occupation by OSIRIS-REx hardware and personnel. Some of these were shared cleanrooms, so the LM contamination engineers required knowledge and the ability to control the activities and materials used by the other programs.

Fig. 4 Personnel properly gowned in the LM ISO 7 cleanroom and TAGSAM head protected by a PFTE bag

Hardware verification samples were also collected at key times. To minimize contamination, sensitive surfaces were bagged in PFTE whenever possible (Fig. 4), and a qualification TAGSAM head was used instead of the flight head for most of the ATLO. The identical, but clean, flight TAGSAM head was integrated just prior to a final SRC fit-check and final stowage in the launch container. The launch container was maintained under a near continuous positive pressure purge. This procedure provided for the minimal environmental exposure of the sampling hardware. Furthermore, when sampling hardware was exposed, only the minimum number of personnel required to perform the work were allowed in the room. All personnel in the facility were gowned in nylon-free cleanroom suits with the nose and mouth covered. Gloves were taped to the gown and wiped with Fisher Optima 2-propanol. Double gloves were used when working with critical hardware. Makeup, perfume, and cologne were prohibited; tobacco users were required to rinse their mouth with water 30 minutes before entering the cleanroom. Sensitive surfaces were cleaned to 50 A/2 to meet the 100 A/2 at launch requirement. Exterior surface of the spacecraft was maintained at 500 A/2 and internal surfaces at visibly clean-highly sensitive (VC-HS) levels. VC-HS level is defined by NASA-SN-C-0005 as "The absence of all particulate and nonparticulate matter visible to the normal unaided (except corrected vision) eye . . . [when viewed with] $\geq$100 foot candles [of light at a distance of] 6 to 18 inches. . . [from] exposed and accessible surfaces . . . Particulate is identified as matter of miniature size with observable length, width, and thickness. Nonparticulate is film matter without definite dimension." (NASA 1998). Details of the spacecraft contamination control implementation are in the Mission Contamination Control Plan (see Supplemental Material S1).

The launch vehicle fairing was cleaned to VC-HS levels under ultraviolet (UV) illumination. This effort was necessary to further minimize particulate contamination on the TAGSAM and system, since all the instruments were uncovered and pointed up at launch. The fairing interior environment was additionally sampled with a 930 cm^2 (1 $\times$ 1 ft) aluminum foil contamination-monitoring plate. This plate was assembled from a KSC-supplied clean ASTM E1235-12 NVR plate as the substrate since these NVR plates are routinely used to monitor Atlas V fairings. This substrate, which was wrapped with the same 500 °C heat-cleaned aluminum foil used for other amino acid contamination monitoring plates, served as a clean backing for the amino acid collection surface; a second smaller clean aluminum foil was attached to the lower foil with Kapton tape (Fig. 5). This ensured that the amino acid monitoring surface did not contact the NVR plate (since both sides of the amino acid monitoring foil are extracted for analysis), that the geometry did not require any changes to

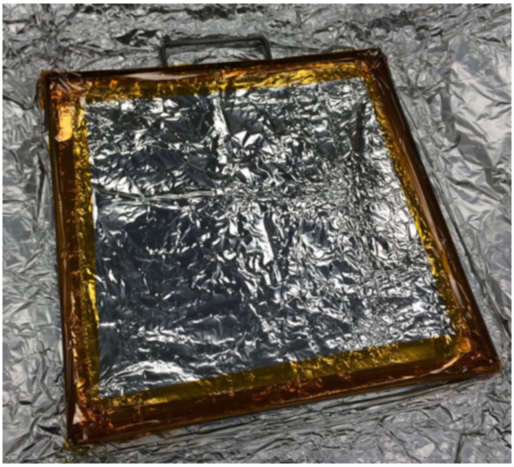


Fig. 5 Amino acid contamination monitoring plate adapted from a standard 1 × 1 ft. ASTM E1235-12 NVR plate for the 4-m Atlas V fairing

the existing fairing mounting hardware, and that there were no risks of foreign object debris generated by the plate. The amino acid monitoring plate was held vertically on a bracket inside the fairing between encapsulation on August 24, 2016, and final fairing closeout on September 6, 2016. After any parts of the foil touching tape were torn off and discarded during preparation in an ISO 5 laminar flow bench, approximately 10% of the foil was measured for amino acid abundances, 15% for other contamination knowledge analyses, and the remainder archived at JSC.

3.4 Contamination Control Results

Unexpected events are possible during spacecraft processing. For contamination control, the two events with the most significant impacts were: first, an unexpected SRC outgassing event that took place during spacecraft thermal-vacuum testing, and second, that more mechanical testing than anticipated was required. The SRC outgassing event was caused by higher than modeled temperatures on the SRC due to reflections. It was fully mitigated with an additional higher temperature vacuum bakeout of the backshell and spot cleaning of the spacecraft. The additional mechanical testing meant that the SRC and TAGSAM head were actuated more than anticipated. This allowed for more particulates (primarily SRC heatshield material) to collect on hardware verification samples. These impacts lead the team to believe that there might be a violation of the level 100 particulate requirement. However, due to adherence to protocols and cleaning for amino acid mitigation, the NVR values were substantially below their requirements, which proved to balance the contamination budget.

The intent of the 100 A/2 requirement is to meet the elemental abundances in Table 4. The contamination knowledge plates were routinely analyzed for particulate elemental distribution at JSC via SEM/EDX spectroscopy. A JEOL 7600 field emission SEM at 15 kV in backscatter mode and EDX using a Noran microanalysis detection system with acquisition times ranging from 20 to 100 s per ≥0.05 µm particle was used. Using contamination knowledge plates, the team confirmed that the particles on the contamination control plates were below the levels of concern for the critical inorganic elements and that the majority of the material (as expected) is carbon based. Assuming the worst-case assumption that the particles are graphite, the total carbon contamination was determined to be below 534 ng/cm^2 of carbon (Table 9).

Table 9 Summary of all contamination control results for OSIRIS-REx sampling hardware shown in the IEST-STD-CC1246D (IEST 2002) particle levels and NVR abundances measured for the indicated components. Then for a worst-case analysis, the contamination levels were converted (→) into elemental carbon abundance to allow for a comparison to the rationale in Table 4. Particulate level was converted into C by assuming spherical graphite particles of the maximum size for each bin and NVR was assumed to be pure C. Contamination knowledge SEM/EDX analyses had demonstrated that the other elements in Table 4 were well below their threshold. The total measured amino acids for these components are also shown. Amino acids were dominated by glycine

Hardware	Particle				NVR				Total C ng/cm^2	Amino acids ng/cm^2
	level		ng/cm^2 C		level		ng/cm^2 C			
Requirement	100	→	34	+	A/2	→	500	=	534	180
SRC	176	→	323	+	A/5.6	→	180	=	503	13.1
Launch container	100	→	34	+	A/10	→	100	=	134	2.32
TAGSAM head	116	→	61	+	A/16	→	220	=	281	0.96

Though amino acids had never been regulated for contamination control, the performance was far below requirements without the use of nonstandard or "heroic" cleaning procedures (Table 9). Analyses were performed at GSFC using the identical analytical procedure as with the amino acid cleaning test. All analyses were conducted and written reports delivered to the contamination engineering within one week of receipt. The dominant amino acid detected was glycine, as expected. In addition to exceptional performance on the sensitive hardware, all ATLO facilities performed very well. Figure 6 shows the sum of amino acids collected on contamination monitoring plates in the LM cleanrooms, KSC cleanroom, and Atlas V fairing. Depending on the activity, new plates were exposed days before the old plates were collected, so Fig. 6 overestimates the exposure time by 6%. The team confirmed that the amino acid contamination was linearly correlated with exposure time by comparing a contamination monitoring plate deployed for three months concurrently with three one-month plates.

3.5 Hydrazine

Hydrazine is known to react with organics via a Wolff-Kishner reduction, and reactions based on semicarbazide formation (e.g., Kolb et al. 1994) are also possible. The team conducted simple tests of the reactivity of various organic compounds exposed at room temperature for five minutes with anhydrous hydrazine at vapor pressures ranging from 9×10^{-4} to 15 torr. The exposed species included 2 mmol each of methanol, ethanol, isopropanol, and acetone; 80 µmol 1-butanol; 1 and 50 µmol pyruvic acid; and a solid film made of a mixture of 0.2 µmol of each of the following amino acids: aspartic acid, glutamic acid, serine, glycine, D,L-alanine, β-alanine, D,L-α-, D,L-β-, γ-aminobutyric acid, α-isobutyric acid, D,L-isovaline, D,L-valine, D,L-isoleucine, and D,L-leucine. Amino acids were dissolved in room temperature polished water and analyzed by LCMS according to Glavin et al. (2006). Other species were measured by headspace injection in a Thermo Scientific™ Trace DSQ™ GCMS (with cryo-oven) with a Restek Rtx®-35 amine column (30 m, 0.25 mm internal diameter, 0.5 µm d_f) at 1 mL/min He constant flow from 30 °C for 3 minutes ramping at 10° C/minute to 250 °C for 5 minutes and a split injector set to 200 °C at 10 mL/min.

Following exposure to hydrazine, the acetone was lost, presumably reduced to propane (which was not observed under the GC conditions), and the pyruvic acid was reduced to propionic acid in all experiments within the 5 minutes required to collect and analyze the

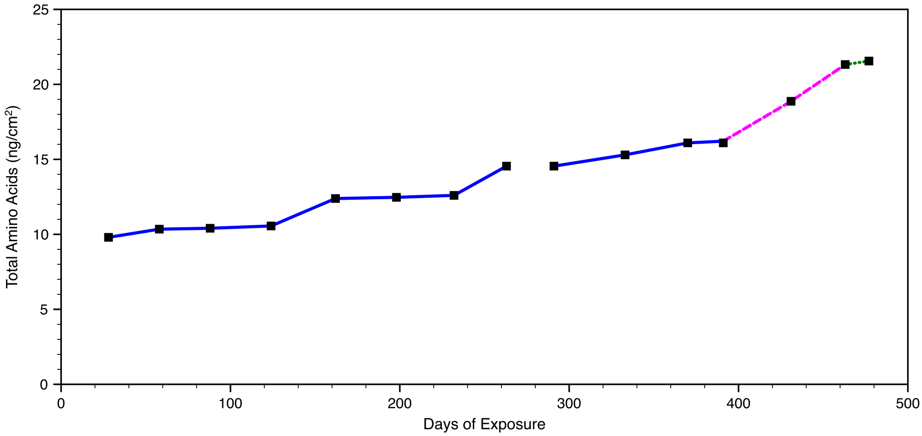


Fig. 6 Total amino acid abundance on environmental monitoring plates in LM and KSC cleanrooms and Atlas V Large Payload Fairing (LPF). The *blue line* is exposure at the LM cleanrooms (ISO 7 and 8) (the gap is during the thermal-vacuum testing, when no monitoring plates could be deployed). The *pink dashed line* indicates exposure in the KSC Payload Hazardous Servicing Facility (PHSF) cleanroom (ISO 8). The *green dotted line* indicates exposure inside the Atlas V fairing. Periods in ISO 8 cleanrooms show steeper slopes than periods in the ISO 7 cleanroom

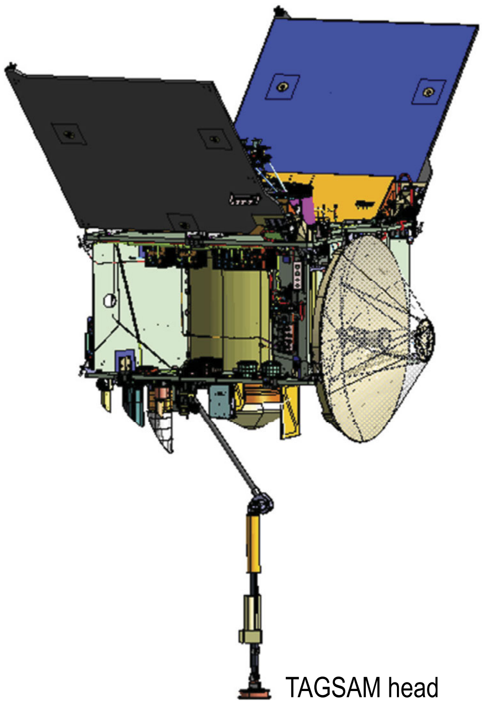


Fig. 7 Sampling configuration. This is the spacecraft configuration that introduces hydrazine contamination on the TAGSAM head (indicated)

sample. Since most Wolff-Kishner reductions are performed in the presence of a strong base under reflux conditions for hours, the reactions observed were faster than anticipated under ambient temperatures and low pressure. As expected the alcohols were unaffected. Though structures can be drawn to cyclize or dimerize the amino acids, no loss of amino acids or appearance of new peaks was observed even when amino acids were dissolved in liquid anhydrous hydrazine at room temperature. On the basis of these tests, the team decided that it is sufficient to design the spacecraft to cant the thrusters away from the sampling site and determined that the collection process with this thruster design will deposit <180 ng/cm^2 hydrazine on the TAGSAM surface. This hydrazine will rapidly evaporate from bare metal at sampling temperatures but traces might be adsorbed by minerals or react with free carbonyls.

While the science team for NASA's Phoenix mission to Mars was interested in understanding thruster plume products (Plemmons et al. 2008), OSIRIS-REx is the first mission to impose a maximum hydrazine flux as a scientific requirement, and as such there was no existing precedent (model-based, testing-based, or otherwise) to aid in defining the appropriate limit. In the absence of historical knowledge, the team used analogy to the amino acid limit of 180 ng/cm^2 on the TAGSAM head. To minimize contamination from all sources, the TAGSAM head remains in the launch container until just prior to Asteroid Approach Maneuver 3 (AAM3), at which point the launch-container cover is ejected and the head is removed from the container to its "parked" position just outside the launch cover. In this configuration, there is expected to be no measurable amount of hydrazine deposited on the head. The two other primary configurations of the head are sampling configuration (Fig. 7), and sample-mass measurement (Fig. 8). All spacecraft motion and articulation in the sample-mass measurement configuration is done via reaction wheels, and so thruster plume impingement (and therefore hydrazine deposition) is not a factor.

Hence, the only times when the spacecraft thrusters could deposit hydrazine onto the TAGSAM head are when the head is in the sampling configuration (Fig. 7). This occurs during initial deployment and checkout, baseline sample-mass measurements, the TAG rehearsals, and the TAG event(s). The thruster firings that occur during these times are the checkpoint burn, the matchpoint burn, and the backaway burn. These cases were modeled to determine the amount of hydrazine deposited on the TAGSAM head. The quantity of hydrazine that may reach and react with the regolith is a function of the plume dynamics, the fraction of unreacted hydrazine in the plume, and the vapor pressure of hydrazine in vacuum on the warm TAGSAM surface. Different TAGSAM components are predicted to be 25 °C to 55 °C during TAG with a maximum temperature requirement of 75 °C, all well above the condensation temperature of hydrazine under vacuum, from −93 °C to −133 °C with a maximum around −108 °C (Weijun et al. 2008).

Limited data exist on the amount of unreacted hydrazine in a thruster plume. Most contamination-focused plume impingement analyses assume steady-state consumption of 100%, leaving no unreacted hydrazine in the plume. Testing done in support of the Phoenix Mars mission (Plemmons et al. 2008) suggests the amount of unreacted hydrazine is $<0.05\%$, and likely $<0.01\%$. However, the Phoenix thruster type tested was different than OSIRIS-REx attitude control system (ACS) thrusters, and the measurement was conducted over a steady-state burn and did not include (or at least did not isolate) initial less efficient transient period at burn start-up nor operate in the pulsed mode employed by OSIRIS-REx. Testing an OSIRIS-REx ACS thruster under the relevant conditions proved to be cost prohibitive. Instead, the team took a worst-case value of 0.05% unreacted hydrazine from the upper limit for the Phoenix tests.

The primary tools used to determine the flux of hydrazine on the TAGSAM head are the ANSYS Fluent computational fluid dynamics (CFD) solver and DAC (Direct Simulation Monte Carlo (DSMC) Analysis Code). The CFD tool (Fig. 9) is used for the volume in which the gas density is sufficiently high that continuum solutions are accurate descriptions of the thruster plume dynamics. These solutions formulate boundary surfaces, which are

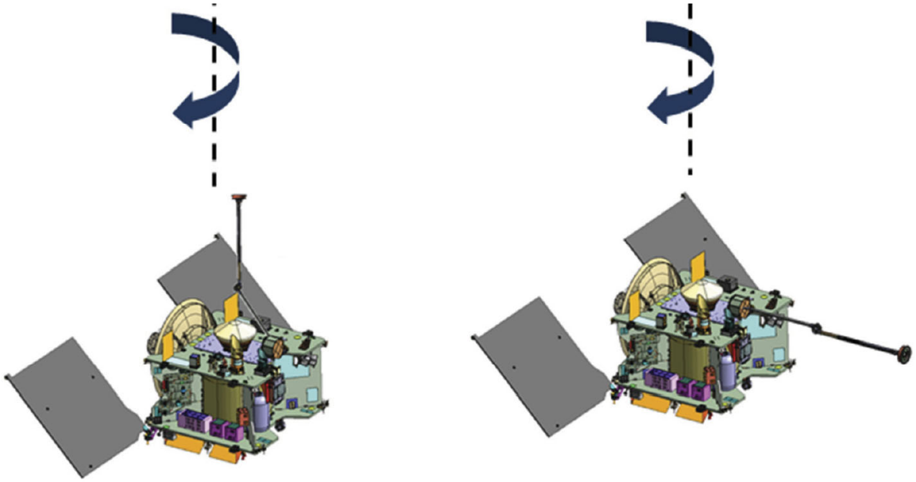


Fig. 8 Sample mass measurement configuration. The change in moment of inertia with the TAGSAM arm extended in two positions before and after sampling are measured while the spacecraft rotates about the indicated axis to determine the collected sample mass. No thrusters are used in this configuration, and thus these events are not contributors to hydrazine contamination

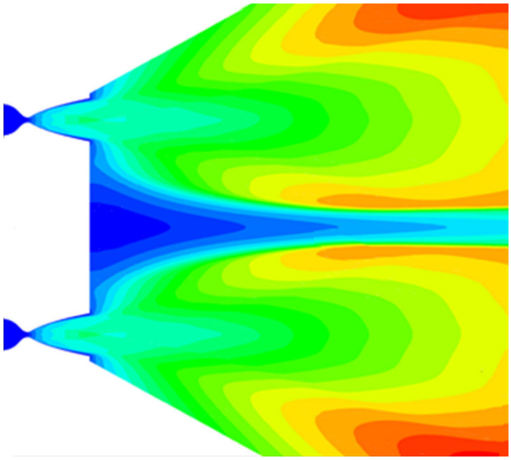


Fig. 9 An example output of the CFD code shows that the proximity of two thrusters (*from the left*) creates a nonuniform plume flowfield and may contribute to enhanced flux on the TAGSAM head that is not captured by scaling results from a single thruster. Plume color relates to plume speed, from low (*blue*) to high (*red*). The interaction between the two plumes can be seen in the slow region in the center

the initial conditions for the DSMC code, which then simulates the dynamics of individual particles.

Analysis of DSMC results revealed two subcases for the TAG geometry: one in which the TAGSAM head is in free space and the other when it is near the surface of Bennu (Fig. 10). The near-surface case is distinct because plume interactions with the surface result in density contours that are different from those when the spacecraft is far from the asteroid (i.e., in "free space"). In particular, the presence of the surface creates a recirculation that increases the amount of thruster plume flux on the head, including the unreacted hydrazine.

The first is the portion of the burn that occurs when the head is on or near the surface. "Near the surface" is conservatively defined as $\leq$7 m range between the thrusters and the surface. Since the thrusters are nominally 3 m from the surface at the time of TAG, a 7 m

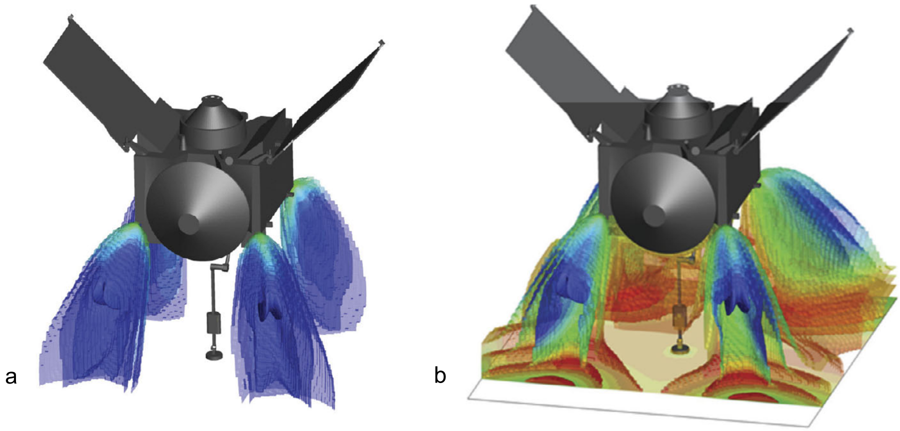


Fig. 10 (**a**) Illustrates plume behavior in free space, while (**b**) illustrates plume behavior when at the asteroid surface. The interaction with the asteroid surface causes an enhancement of thruster plume deposition on the TAGSAM head relative to the free space geometry. Plume color relates to plume density, from low (*blue*) to high (*red*)

range threshold for this condition means that there is a measurable enhancement of plumes on the head for an additional 4 m as the spacecraft backs away from the asteroid. The second is the portion of the burn that occurs beyond 7 m, at which point the plume geometry is equivalent to firing thrusters in free space.

Using the calculated hydrazine flux on the head and the planned mission thruster profile during TAG, the team derived the total hydrazine fluence on the TAGSAM head. The analysis also utilized the following reasonable assumptions: condensation temperature of hydrazine in vacuum is −108 °C; the TAGSAM head will be warmer than −108 °C for the TAG maneuvers; for any deposited hydrazine on clean head (prior to first TAG), all hydrazine will leave the TAGSAM surface because of TAGSAM surface temperatures (Chirivella 1975; Carré and Hall 1983); and after first TAG, the team assumed 100% sticking coefficient. The last assumption implies all hydrazine deposited on the head stays on the head and is available to contaminate the sample. This assumption derived from the possibility that the TAGSAM head may be coated in a thin layer of potentially reactive dust after the first TAG. The results of these assumptions applied to the DSMC code (Table 10) demonstrate that under nominal conditions (one TAG), if the worst-case assumptions hold (0.05% unreacted hydrazine and 100% sticking coefficient) OSIRIS-REx will collect 120 ng/cm^2 hydrazine. However, if subsequent TAGs are required, but the TAGSAM head becomes covered with dust from Bennu, this hydrazine requirement will need to be waived in favor of collecting a sample under these off-nominal conditions. If a second TAG is required on a dirty head, <400 ng/cm^2 hydrazine could be accreted, and <650 ng/cm^2 hydrazine for a third TAG. These are conservative values based on the above assumptions; actual values are likely to be lower.

4 Materials Restrictions

To help meet the contamination control requirements there were a number of materials that were prohibited or restricted for areas adjacent to the sampling head in addition to the high-outgassing materials typically prohibited on spacecraft (https://outgassing.nasa.gov/). Areas

Table 10 Summary of calculated hydrazine impingement on the TAGSAM head

Mission phase	Fluence (ng/cm^2) during first TAG	Fluence (ng/cm^2) during subsequent TAG(s)[b]
Approach	0.48[a]	n/a
Rehearsal #1	0.29[a]	29.35
Rehearsal #2	0.76[a]	76.04
TAG	118.30	171.92
Subtotal	<120	<277

n/a Not applicable. Approach does not recur after the first TAG

[a]This hydrazine is expected to evaporate prior to collection

[b]Assuming the head was covered in dust from the previous attempt

with no plausible path to the sample were not subjected to these added restrictions. For example, the OSIRIS-REx Thermal Emission Spectrometer (OTES) (Christensen et al. 2017) detector is a deuterated glycine trimer (DTGS)—a potentially very concerning contaminant in both amino acid and isotopic measurements. But the DTGS is essential for OTES operation and has no reasonable path to the sample from deep within the instrument. Conversely, there was a risk that the Regolith X-ray Imaging Spectrometer (REXIS) cover release mechanism Frangibolt® could be powered on long enough not only to break the titanium bolt (∼1 minute of heating and ∼150 °C) to release the cover but also to unnecessarily continue heating the unit (∼2 minutes of heating and over 350 °C). Experiments in an instrumented vacuum chamber showed that the extra heating decomposes the outer polymer coating to an oily mixture of silicones, hydrocarbons, and esters. The mitigation was the addition of additional software controls and the addition of a separation switch into the mechanical design.

Principal compounds that decompose to amino acids or contain biological impurities were prohibited (Table 11). Nylon and other polyamides and latex are amino acid polymers and were prohibited. Nomex® and Kevlar® also degrade to amino acids, though with structures unexpected in Bennu samples. Regardless, the use of Nomex® was limited to technician's suits during hazardous operations. Natural rubber was prohibited to avoid the protein contamination. To reduce the risk of mercury vapor exposure, all fluorescent lights were required to be encapsulated in a secondary shield to prevent release of mercury in case of breakage.

Table 11 also gives an illustrative list of compounds that, although long, is not comprehensive. A list of all prohibited chemicals is impossible to compile because it is dependent on the location and application, and often requires too much knowledge of organic chemistry by nonspecialists to decipher. Instead materials engineers and scientists reviewed materials lists for compounds of concern using their knowledge of chemistry to approve or recommend alternatives (see below).

It turned out that the most difficult material restriction was nylon. Nylons are very common in cleanrooms, spacecraft, and launch vehicles. The prevalence of nylon (bags, ties, tethers, wipes, casters, thermocouples, etc.) was not anticipated. Moreover, communicating the banning of nylon with all mission partners proved more difficult than expected. The difficulty is partly due to the prevalence of nylon, the lack of nylon labeling on many products, and occasional confusion over polyamides and polyimides (the latter of which are not a contamination concern). Nylon is spread via contact transfer, and this becomes efficient when

Table 11 A representative list of compounds of contamination concern. Species in **bold** were specifically targeted by OSIRIS-REx, and items in *italics* are routinely controlled by most missions, including OSIRIS-REx. Other species are of interest but not explicitly controlled

Biology	People	Outside	Building materials	Polymers	Inorganic	Processes	Industrial organics	Compounds
Birds microbes *rodents* *spiders, etc.*	*Food* glossy magazines and catalogs *moisturizer* *perfume* *sun screen* *sweat and other excretions* *tobacco residue* vitamins	*Asphalt* *fumes car exhaust* *herbicide* *insecticide* *paint fumes* *pollen* *smoke*	*Carpet* plywood varnish	Bakelite Delrin **latex** **nylons** ***silicones*** silk	Borax diamond **fluorescent lamps (Hg)** lanthanides silanes silicates	Heat-sealing plastics *soldering* *welding*	*Creosote* *detergents and soaps* *glues* *grease* leather *oils* **natural rubber** *wax*	Acetaldehyde, acetic anhydride, acetone, acetonitrile, acrylic acid, acrylonitrile, **amino acids**, aniline, barbituric acids, benzene, benzoic acid, benzyl alcohol, bromobenzene, butadiene, butyl acetate, butylamines, butyric acids, carbon disulfide, carbon tetrachloride, chloroform, cresols, cyanide, cyanoacetylene, cyanogens, dichloroethane, dichloromethane, diethyl ether, dimethyformamide, dimethylsulfoxide, dioxane, ethanolamine, ethylene glycol, ethyl acetate, ethylamine, ethylenediamine, formaldehyde, formamide, furfural, glutaronitrile, glyceric acid, glycerol, glycolic acid, glyoxal, hydantoins, hydroxy acids, imidazole, indole, malic acid, malonic acid, malononitrile, methylamine, methyl bromide, naphthalene and other polycyclic aromatic hydrocarbons, nitropropane, nitrobenzene, orotic acids, oxalic acid, paraformaldehyde, phenol, phthalic acid, piperazine, propylamines, purines, pyrimidines, pyruvic acid, pyruvonitrile, quinolines, strong acids, strong bases, styrene, succinic acid, succinic anhydride, tetrahydrofuran, toluene, urea, valeric acids, xylenes

wet, so it was better to vacuum nylon that could not be removed than to wipe it with solvents. Afterward it could be covered, for example, with Kapton tape. This protocol was even applied to journalists on the August 20, 2016, Media Day (Clark 2016a). The overall effort to mitigate nylon contamination was demonstrated to be very effective, as nylon monomers were near or below detection limits in amino acid analyses of witness plates.

To the extent possible, the team attempted to minimize the diversity of organic polymers (e.g., silicones, lubricants, adhesives) in sensitive areas of the spacecraft. Such polymers are necessary for spacecraft construction, but minimizing chemical *diversity* of the contaminating species reduces the complexity of the contamination and therefore simplifies identification and interpretation of contaminants. This required excellent communication within the team, particularly among the scientists, contamination engineers, and materials engineers. The minimization of diversity was also aided by the archiving requirement: to supply a sample of each material to be archived at JSC, should a scientist need to analyze a suspected contaminant in parallel with samples from Bennu. Other restrictions were simpler to implement: the use of fluorescent lamps is rapidly declining, and those present were already encapsulated; and natural rubber is uncommon. Including them is important, however; it prevents missed restrictions by not second-guessing the facilities and provides an easy accomplishment for those laboring to meet the more difficult requirements.

In spite of these restrictions, some materials came as a surprise and created the need for late changes to materials and procedures. The late discovery of "surprise materials" was due to insufficient communication across engineering disciplines and scientists having limited understanding of the materials used in spacecraft construction. For example, one process required diamond abrasive, while another used a coating that included amorphous silica. Since both nanodiamonds and amorphous silica are of scientific interest in primitive asteroids, the diamond-abraded surface was cleaned and verified diamond-free at JSC via FTIR, and the silica-containing material was removed. The diversity of materials and processes in spacecraft construction and testing is enormous. It is vitally important to specify all materials of concern with spacecraft partners even if the scientists on the team have no expectation that they are used in engineering applications. Engaging the full set of engineers and technicians on the rationale behind the contamination requirements and empowering them to speak up when they see that a process poses an avoidable risk can reduce the use of high-heritage but undesirable procedures.

Another example occurred when there was a change in the materials in the SRC avionics deck. This decision created a situation where the fasteners were of like metals and would gall. The galling problem was not discovered until it was too late to implement a mechanical solution. Instead a film of Braycote 601EF lubricant was used. Though Braycote 601EF is used elsewhere on the spacecraft, this is a location where it could creep to the sample. Since the surfaces are in the cold and dark interior of the SRC, it is expected not to photo-degrade as seen by Rosetta, for example (Schläppi et al. 2010). In addition, the mission caries a residual risk of Braycote contamination, to remind the team of this event when the sample is analyzed starting in 2023. The flight witness plates, discussed below, will be studied to determine the impact of this lubricant. Nevertheless, this contamination risk could have been avoided with more cross-communication between engineering disciplines.

4.1 Materials Testing

Conversely, excellent communication between the subdiscipline engineers led to the chemical investigation of products whose chemical makeups were unclear and/or proprietary.

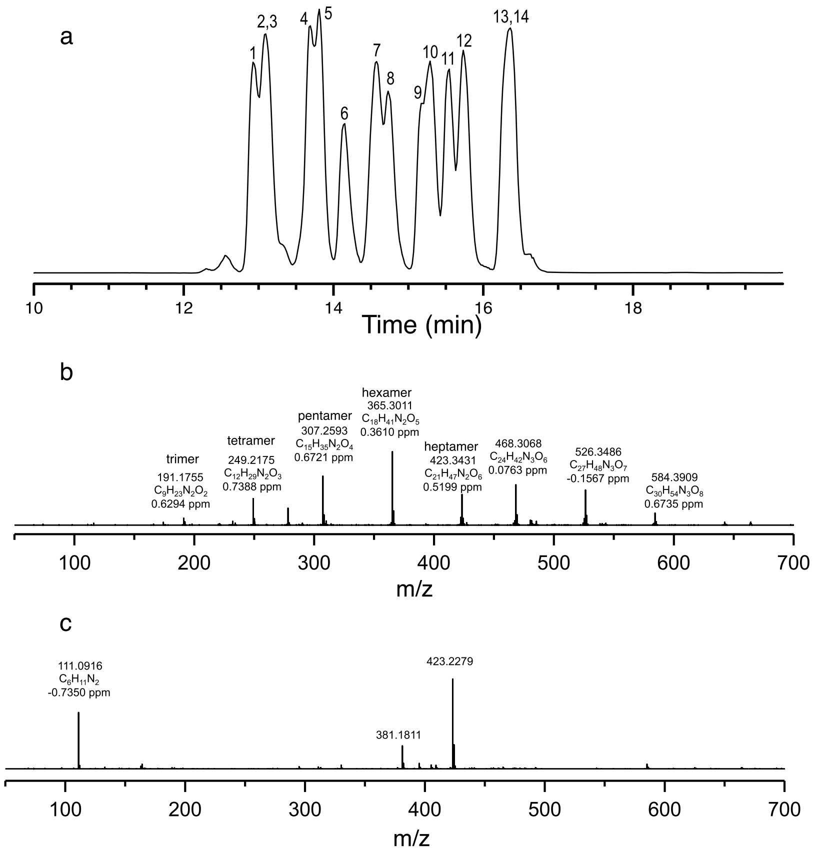


Fig. 11 (**a**) The isomers of OPA/NAC derivatized tripolyoxypropylenediamine in Bondline™ 6460 as seen in the single ion chromatogram centered at 452.2214 m/z. by LCMS. Individual isomers were not identified, but likely isomers are numbered, chromatographic conditions were not optimized. (**b**) Polyproplyenediamine trimer through heptamer plus additional larger species as seen by DART™-MS. (**c**) The comparatively simpler mix of compounds observed in EPO-TEK® 353ND as seen by DART™-MS

In one case, Sonotech® Soundsafe® ultrasonic couplant was to be used during the testing of Frangibolts®. GCMS and LCMS analyses at GSFC showed myriad organic compounds with varying degrees of concern, principally hydantoin and various amines. Upon review of the required properties, pure glycerol was substituted with excellent results.

In another case, selection of a scientifically acceptable adhesive was required for the exterior of OSIRIS-REx Visible and Infrared Spectrometer (OVIRS). Engineers suggested Bondline™ 6460, but manufacturer's literature indicated that it contained polyoxypropylenediamine. Analysis at GSFC (Fig. 11) was conducted via LTQ Orbitrap XL hybrid mass spectrometer equipped with DART™ source (He gas, 350 °C, positive ion mode), with a mass resolution of 60,000 and lock mass enabled (on a polysiloxane compound found in air background). Results indicated the presence of at least the trimer through heptamers of polyoxypropylenediamines along with other compounds. Subsequent LCMS analysis of unhydrolyzed OPA/NAC derivatized methanol solution of Bondline™ 6460 also determined that the polyoxypropylenediamines are of mixed chirality (e.g., all 14 diastereomers of tripolyoxypropylenediamine were likely observed in Fig. 11a). This could complicate, or at least cast doubt on, enantiomeric analyses in the returned sample. Fortunately, EPO-TEK® 353ND is an able replacement and appears to primarily use 2-ethyl-4-methylimidazole as the curing agent instead. Though imidazoles are of interest, they are achiral. A sample of the EPO-TEK® 353ND as used was archived at JSC in the event that it presents a concern in the returned sample. This along with other materials and contamination control reports, was shared with the contamination knowledge scientists and placed on the internal science team website for review.

5 Contamination Knowledge

The contamination control efforts described are based on reasonable assumptions of the composition of contaminants and provide no information on the contamination after launch. While the adopted 100A/2 contamination control limit has the advantage of being verifiable without the need for complex measurements that could pose schedule risk during ATLO, little is learned about the nature of the contaminants. A separate and parallel contamination knowledge effort was necessary to ensure that sample measurements are well understood and accurately corrected for background and are not compromised by unexpected composition of the contamination. Thus, in addition to samples collected during ATLO for particles, films, and amino acids, contamination knowledge witness plates were regularly deployed throughout the course of ATLO in the vicinity of TAGSAM and spacecraft assembly operations (Fig. 12).

Similarly, an array of sapphire and Al witness plates are flown on the spacecraft and exposed before, during, and after sampling. These plates are then returned along with the samples to understand the contamination acquired during flight.

Contamination knowledge was also employed to investigate anomalies. For example, the REXIS detector assembly mount with detector flexible printed circuits was inadvertently contaminated by a defective heating element during component-level thermal-vacuum testing. The contamination knowledge scientists were enlisted to analyze several samples and controls within in a few days of the event. SEM/EDX was used to determine that the contamination was composed of numerous elements (e.g., Na, Mg, S, K, Ca, Cr, Fe, Ni, Cu, Zn, Cd, Sn, Ba, Pb, Bi) including several from Table 4. The Principal Investigator (PI) used this information to decide that this contamination posed an unacceptable risk to sample science. Since this was irreparable damage, the backup detector had to be used on REXIS instead (Masterson et al. 2017).

To help determine the sources of collected contaminants, selected sample return capsule materials, purge filters, and gloves used in the ATLO facilities have been archived and will be distributed for analysis in parallel with samples of Bennu, as requested. Finally, samples of the spacecraft monopropellant (high-purity anhydrous aniline-free hydrazine), gas used for sample collection, and cleanroom air samples were collected and analyzed for trace volatile organics before and after launch.

5.1 Contamination Knowledge Plates

During spacecraft assembly, the curators and other science team members worked with the mission engineers and ATLO personnel to archive materials from the spacecraft, and to monitor cleanliness levels in the LM and KSC cleanrooms through deployment of Si wafer and Al foil witness plates (Fig. 12). To minimize particle loss during shipping, a pair of plates

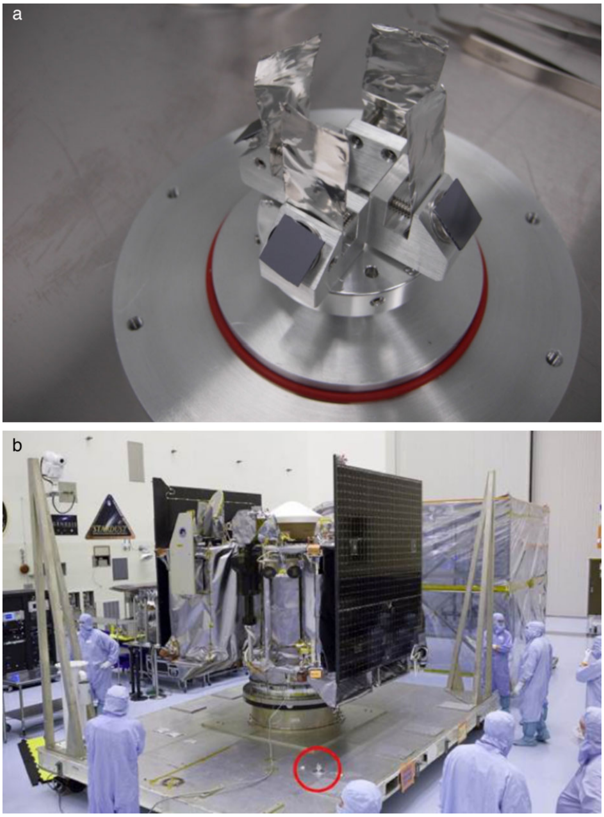


Fig. 12 (**a**) Contamination knowledge plates consisted of precision cleaned silicon wafers mounted on SEM sample holders to collect particles and high-purity aluminum foils for organic NVR analysis. These were deployed in parallel with the contamination monitoring plates. Following one month of exposure, the entire unit was sealed in an aluminum housing bolted to the baseplate after exposure. (**b**) Location of contamination knowledge witness plate (in *red circle*) on shipping container base soon after arrival in the PHSF

was hand-carried to JSC. The collection of archived items and witness plates are stored in a dedicated stainless steel nitrogen-purged cabinet in Class ISO 7 cleanroom at JSC.

Each contamination knowledge plate exposed four Si and four Al surfaces; three of each (75%) were archived to be inspected later in parallel with the returned asteroid samples; the remainder was analyzed to provide relatively prompt information on the contamination environment of the spacecraft assembly facility. Thousands of particles were examined by SEM for size, texture, and bulk elemental abundances. This work served the long-term need of assessing the contamination background that will be important for interpreting returned sample measurements. But these studies were also carried out within 1–2 weeks of delivery to JSC so that unexpected contaminants that could pose unacceptable science risks could be identified in time to mitigate the issue. This approach also protected the ATLO schedule from delays associated with the scientific investigations of contamination. This reporting structure, however, also allowed the Principal Investigator the ability to promptly review contamination knowledge data to determine if an interruption in ATLO was warranted (Fig. 13). In addition, all reports were shared with the contamination engineers and placed on the internal science team website for any member of the team to review.

The design of the contamination knowledge program allowed the analytical arsenal of the OSIRIS-REx scientists to be engaged to study samples as necessary. Given the complexity, time required, and cost of some analyses, they were not to be used unless a previous test indicated a need (Fig. 14). Due to the general high cleanliness of the samples, the most

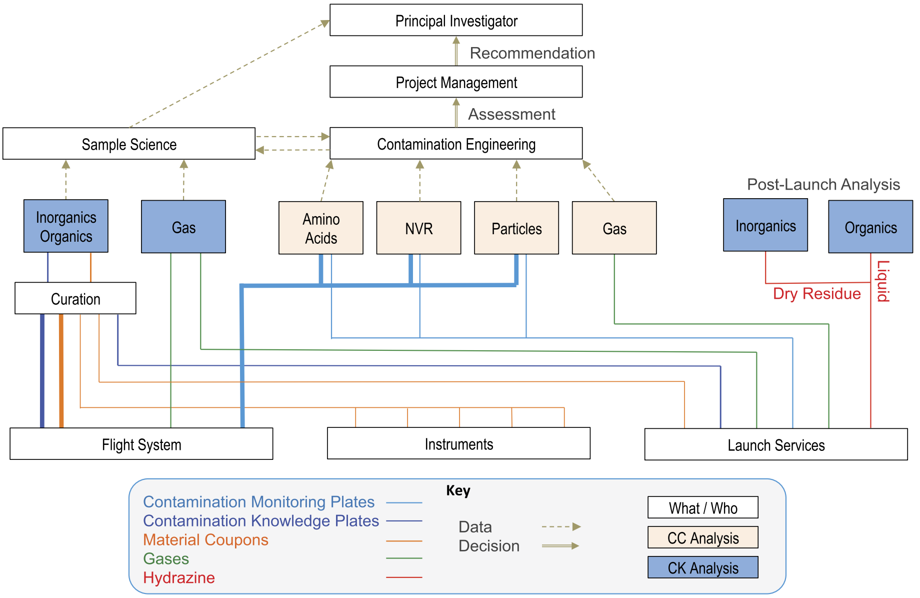


Fig. 13 The pathway from hardware to analysis to a decision. The three types of generators of contamination control, contamination knowledge, and archiving samples are shown *at the bottom*. Materials follow the *solid lines* for their destination for analysis, line thickness schematically indicates the number of samples. Contamination control samples are sent directly to the analysts, except for hydrazine (monopropellant); all other samples are sent to curation for subdivision for archiving and distribution. Once the samples are analyzed the data (*dotted lines*) are sent to either sample science or contamination engineering for review. Science and engineering share results. Contamination engineering assesses the results and delivers the information to project management, who makes a recommendation to the principal investigator if a decision is required on if or how to mitigate off-nominal results. Sample science passes the contamination knowledge reports directly to the principal investigator for consideration. The hydrazine analysis was performed after launch for knowledge only

arduous techniques were not employed. However, all collected particles and 75% of the Al foils remain available for much more detailed analyses if necessary.

5.2 Contamination Knowledge Plate Results

Each contamination knowledge plate was designed for easy subdivision for analysis by SEM/EDX on silicon wafers and organic analysis on aluminum foils. A detailed description of the results is outside the scope of this manuscript. However, some representative findings are below.

Contamination knowledge plate #4 was exposed in the OSIRIS-REx cleanroom June 12, 2015, to July 14, 2015, at LM. During this time OTES and the OVIRS were installed, and a number of power subsystems were tested on the spacecraft. SEM examination of one Si wafer from contamination knowledge plate #4 identified ∼40 particles and particle groups (excluding Si particles from the mount) 1.5–32 μm in size when measured along the longest dimension (Fig. 15). Most particles are carbonaceous material and metal/metal oxides that could be attributed to aluminum and stainless steel. One Pb-bearing brass 7×16 μm particle was identified. One siliceous mineral particle contained K. Three fiber-like particles were observed: one was C-rich, and two were Al-rich. Other than the Pb particle, these particle

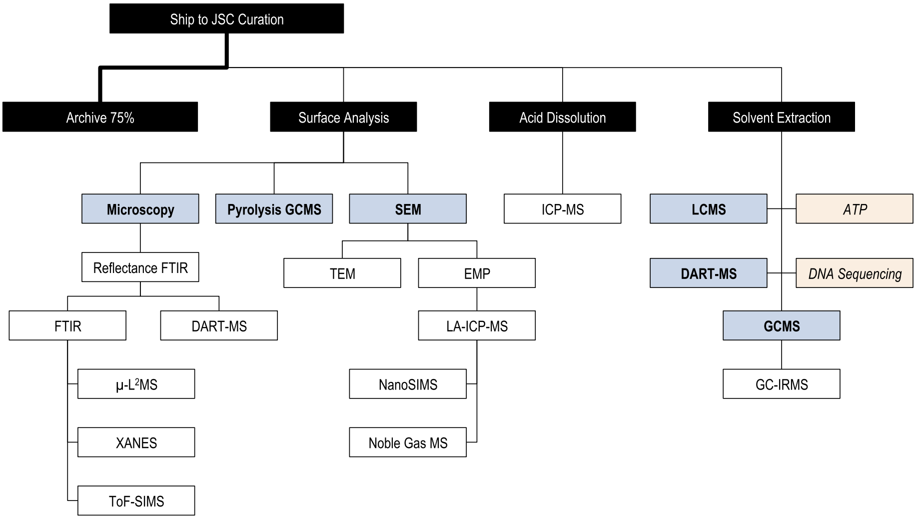


Fig. 14 The analytical flow of contamination knowledge plates allowed analyses by a comprehensive array of instruments and techniques available. After receipt at JSC, 75% of the samples are archived (*thick line*) to be available for parallel analysis with Bennu samples. The *blue boxes* with *bold text* show methods performed on each sample. The *orange boxes* with *italic text* show methods performed on a small subset of samples. The *white boxes* show methods that were available, but not employed. Microprobe two-step laser desorption/laser ionization mass spectrometry (MS) (µ-L^2MS), X-ray absorption near edge structure (XANES), time-of-flight secondary ion MS (ToF-SIMS), transmission electron microscopy (TEM), electron microprobe (EMP), laser ablation inductively coupled plasma MS (LA-ICPMS), inductively coupled plasma MS (ICP-MS), ATP luminosity analysis (ATP), GC combustion isotope ratio MS (GC-IRMS)

counts and compositions were acceptable, and there were generally no unexpected elements to invalidate the assumptions used to derive the level 100 particulate requirement, and the contamination level of the indicator elements (Table 4) were not violated. However, the Pb-bearing particle was of concern since Pb is a key element of scientific interest. Analysis of the Pb-bearing particle indicated a texture and elemental composition consistent with leaded-brass (Pb being a common additive to brass to improve machinability). After a review of drawings and discussions with the LM contamination engineers it was discovered that a brass set-screw was used adjacent to the contamination knowledge plate. This screw was removed. Since it was relatively far from the spacecraft, the team has confidence that no Pb-bearing brass particles found their way to the spacecraft, let alone into the sample-collection hardware.

In parallel, one aluminum foil from contamination knowledge plate #4 was analyzed for organic compounds. The contamination monitoring amino acid analysis showed this to be the dirtiest single exposure during ATLO (Fig. 6). It was an early and busy period in the cleanroom (which was also shared with the NASA InSight spacecraft at the time), and the highest 1-month quantity of total amino acids were detected (9.8 ng/cm^2). It is unclear if the source of this higher level of contamination was the level of activity, the time it took personnel to learn the new procedures, or another source. Contamination knowledge amino acid analysis agreed qualitatively with contamination control analysis and confirmed that the glutamic acid detected was exclusively the L-enantiomer dominant in biology, using the derivatization and workup of Glavin et al. (2006, 2010) as previously described. (Note, however, the LCMS analysis was performed on a different Waters® ACQUITY™

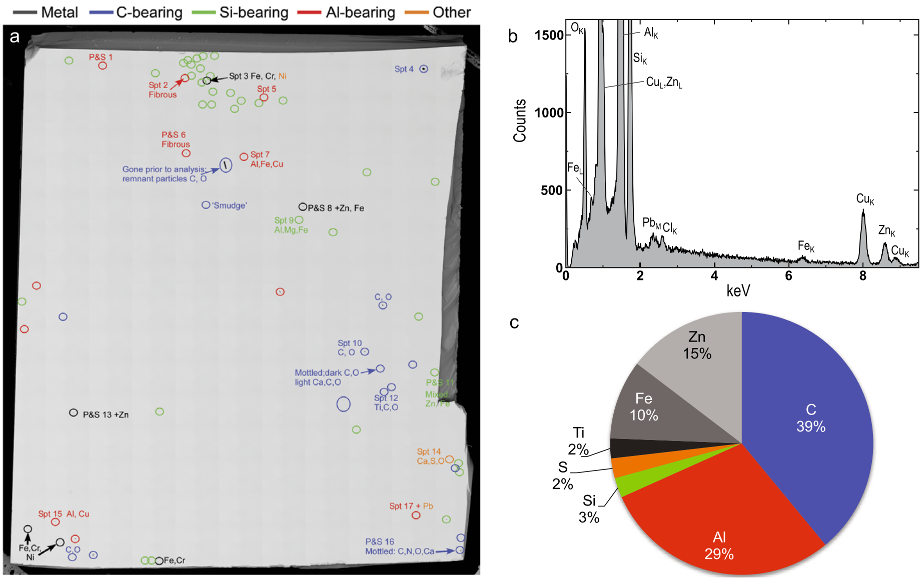


Fig. 15 (**a**) Contamination knowledge plate #4 microscope image with locations and categories of particles analyzed by EDX indicated. (**b**) EDX spectrum of the Pb-bearing particle. (**c**) Elemental distribution by number of particles (Pb is a component of $<1\%$ of the total particles)

coupled to a Waters® Xevo™ quadrupole-time of flight mass spectrometer, as the Waters® LCT Premier™ time of flight mass spectrometer was occupied with AccQ•Tag™ analyses.) A sample of foil which was not water extracted was also analyzed by pyrolysis GCMS (CDS Analytical Pyroprobe 5200 fed into a Thermo Scientific™ Trace gas chromatograph coupled with a Thermo Scientific™ DSQII™ quadrupole mass spectrometer) using a Restek RT-Q-Bond®, 30-meter, 0.25-mm internal diameter, 8-µm d_f column to allow for the analysis of small volatile compounds. GC flow rate was 1.5 mL/min in the constant flow mode. The temperature program was 50–250 °C at 10 °C/min with a 20-min final hold time. The quadrupole mass analyzer was scanned from 20 to 500 m/z. A procedural blank foil was analyzed before each sample. A number of small organics were observed (methanol, acetaldehyde, 1-butene, propenal, acetone, cyclopentane, 1-hexene, benzene, and 1-heptene). All of these species were also seen in the blank, but at lower abundances, and no compounds not also detected in the blank were observed. It is therefore concluded that these highly volatile compounds were more representative of the laboratory environment where the analyses were made than ATLO exposure. DART™-MS analysis of the extract was indistinguishable from a procedural blank consistent with a very clean sample.

5.3 Microbial DNA Analysis Results

Evaluations of cleanrooms have revealed that, while they are generally low in microbial number, there is substantial diversity, often with unique extremophiles represented (Mahnert et al. 2015). The team performed a single spot check of one cleanroom; a more thorough study is planned for the future from archived contamination knowledge plates. To identify potentially contaminating microorganisms the team assessed via 16S and ITS metagenomic sequencing a sample of the Al foil from contamination knowledge plate #8 exposed in an

Table 12 Microbes identified by DNA sequencing a sample of contamination knowledge plate #8, which was exposed during OSIRIS-REx vibration testing at LM

Fungi	Bacteria	Archaea
Clavispora/Candida intermedia	*Brevibacterium paucivorans*	*Natronococcus amylolyticus*
Fusarium cerealis	*Eubacterium* species	
Hortaea werneckii	*Lactobacillus fermentum*	
Malassezia restricta	*Pseudomonas alcaligenes*	
Penicillium citrinum	*Reyranella soli*	
Penicillium crustosum	*Sphingobium* species	
Phoma species		

ISO 8 cleanroom during vibration testing. While in the ISO 8 cleanroom, the instruments and sensitive hardware were bagged, and the spacecraft was spot-cleaned after testing, so the spacecraft should have a lower level of contamination than experienced by the contamination knowledge plate exposed to the room.

To gauge microbial diversity, DNA was extracted from a polyester swab (Puritan) used to collect a surface sample from the knowledge plate and molecular biology grade water in which the plate had been submerged with continuous vortexing for 5 minutes following swab collection. DNA extraction was carried out via a combination of custom and kit methodologies. Custom extraction involved processing the swab tip with a Mini-Beadbeater (BioSpec Products) and subsequent DNA collection and cleanup with the QIAamp BiOstic Bacteremia DNA Kit (Qiagen). DNA was extracted from water with the DNeasy PowerWater Kit (Qiagen). An identical swab tip and aliquot of molecular grade water were also processed in parallel with accompanying reagent and standard negative controls. DNA concentration was determined with a Qubit fluorimeter (ThermoFisher Scientific™). The extracts were amplified with 16S primers for bacteria and archaea (515F-806R and 27Fmod-519Rmod) and ITS primers for fungi (ITS1F-ITS2R) with barcodes attached to the forward primer. Prior to library preparation, the amplified products were pooled and purified using Agencourt® AMPure® XP beads (Beckman Coulter®). Illumina® library preparation and sequencing with the MiSeq platform followed the manufacturer's recommended protocols (Illumina®). Operational taxonomic units (OTUs) were generated from the resulting paired-end sequence data after it was joined, and barcodes, ambiguous base calls, and sequences <150 bp were removed. The OTUs were further defined by clustering at 3% divergence threshold. UCIHIME was used to remove chimeras (Edgar et al. 2011). Taxonomic classifications were generated using BLASTn against curated databases resulting from GreenGenes (http://greengenes.lbl.gov/cgi-bin/nph-index.cgi), RDPII (http://rdp.cme.msu.edu/), and NCBI (https://www.ncbi.nlm.nih.gov/). Sequences identified in the control samples were subtracted from the knowledge plate samples, ensuring that the microorganisms identified were unique to the knowledge plate. A summary of the results is shown in Table 12.

While a complete microbial census of the cleanroom was not carried out, 16S rRNA gene signatures from knowledge plate #8 revealed a pattern of microbial diversity consistent with full-scale assessments (La Duc et al. 2012). The majority of OTUs belong to microorganisms that are human-associated or common in the environment. However, sampling the small surface area of the knowledge plate did reveal the presence of organisms with increased capabilities of survival under extreme conditions (e.g., *H. werneckii* and *N. amylolyticus*). As the stringent cleanliness standards governing cleanrooms often selects for these types of microbes (Mahnert et al. 2015), it is these characteristics of persistence that are of utmost

Table 13 Gas samples collected and analyzed

Location	Sample type
Air	LM ISO 7 cleanroom
Air	LM ISO 7 supplemental cooling cart
Air	LM ISO 8 cleanroom
Air	PHSF high bay
Air	Faring air supply used during faring transport
Air	VIF faring air supply
Air	VIF Centaur common equipment module air supply
Nitrogen/helium	Source gas for TAGSAM bottles
Nitrogen/helium	Source gas for TAGSAM bottles through bottle loading manifold
Nitrogen/helium	Pressurized TAGSAM qualification bottle after 24 hours at 40–45 °C
Nitrogen/helium	TAGSAM gas during NSI actuation
Nitrogen purge	LM purge for spacecraft
Nitrogen purge	PHSF facility purge for spacecraft
Nitrogen purge	Spacecraft in fairing transport purge
Nitrogen purge	VIF T-0 purge system
Nitrogen purge	Launch pad T-0 purge system

Fig. 16 Gas sampling was performed using 500-mL evacuated containers. This collection is of the purge system for the truck transport of the fairing-encapsulated spacecraft from the PHSF to the launch complex

concern to planetary protection officials (e.g., Smith et al. 2017), but of less importance for contamination control. As such, a comprehensive microbial evaluation of the remaining knowledge plates is planned, as it may be useful for future missions with stricter planetary protection requirements than OSIRIS-REx.

5.4 Gas Analysis Results

Contamination knowledge analysis of TAGSAM gas, purge, and air samples (Table 13) was done by the JSC Toxicology and Environmental Chemistry group with the same type of canisters (Fig. 16) and the same target analytes as was done for Stardust (Sandford et al. 2010). GCMS measurements of one hundred target volatile organics typically showed only low levels of acetaldehyde (∼0.03 ppm), acetone (0.04 ppm), and more 2-propanol (∼0.1 ppm) in air—2-propanol was used as part of the cleaning process of the test hardware, and as a wipe for gloves used in the cleanrooms. For most of the collected gas samples, all other target molecules were below ∼1 ppm detection limits.

The gas to be loaded into the TAGSAM bottles, which was collected for analysis directly from the manufacturer, showed no compounds above detection limits (∼0.01 ppm). Analysis of the gas when collected through the flight-loading manifold found 0.02 ppm of acetone and 0.6 ppm of 2-propanol. After an engineering model TAGSAM bottle was loaded with collection gas, then heated at 40–45 °C for 24 hours, the gas showed 0.01 ppm of acetone and 1.1 ppm of 2-propanol. These trace contaminants likely arose from the cleaning of the bottle and manifold.

A potential contamination risk was identified in the way the high-pressure 95:5 N_2:He gas is injected into the asteroid surface during the TAG event. The pressurized TAGSAM collection gas is released by firing a NASA standard initiator (NSI) pyrovalve. The gas is directed into the asteroid surface through a short 316L stainless steel convoluted tube that connects the gas bottle to the TAGSAM head. The firing of a pyrovalve produces particulate debris and combustion byproducts that may be entrained in the gas flow. However, there are very few published reports on the nature of pyrovalve “blowby,” and it is very likely that the nature and abundance of blowby materials is highly dependent upon the particular pyrovalve used, associated plumbing, and the composition of pyrotechnic initiator/booster charge and its decomposition products (Bement 1997). One combustion modeling study identified over 40 chemical compounds produced during the pyrotechnic detonation (Woods et al. 2008). In addition, the high-pressure gas mobilizes particles from the pyrotechnic initiator, valve material and plumbing interior surfaces (Groethe et al. 2008). We selected a pyrovalve, however, which mitigates the blowby of combustion products by formation of a metal-metal seal during the pyrotechnic event. This impulsive sealing event causes fractures which were found to release some particulates into the gas stream.

To assess the potential contamination of the pyro device, the team carried out a test firing of a NSI connected to a high-purity TAGSAM gas bottle to collect and characterize particles and volatiles entrained in the gas for contamination knowledge. The NSI and gas bottle were flight spares, and the associated plumbing system was composed of stainless steel but was not a flight-like configuration for this test. The gas was directed through a PFTE filter and collected in a 6-L canister that had been provided by the JSC Toxicology and Environmental Chemistry group. The canister preparation was similar to those used for the other gas analyses, but was larger to partially accommodate the high-pressure gas from the TAGSAM bottle (the total gas loaded was less than half the actual TAGSAM bottle pressure). The collected gas was analyzed for the same suite of 100 species targeted for all other OSIRIS-REx gas analyses. As with the contamination knowledge plates, the PFTE filter was inspected by optical microscopy and SEM/EDX to determine the compositions of the impacting particles.

The collected gas showed no combustion byproducts but higher levels of the same compounds attributed to pre-cleaning of the gas manifold: 0.06 ppm acetone, 3.3 ppm 2-propanol, and a trace (∼0.01 ppm) acetaldehyde. Again, these are the same species found from cleaning procedures and unlikely from blowby.

Visual inspection of the PFTE filter showed much more particulate debris than expected. The filter was penetrated by a number of large (hundreds of μm) impactors, including two recovered metal grains larger than 1 mm. Numerous 1- to 10-μm-sized particles were also

Fig. 17 Collection of flight hydrazine monopropellant for chemical and isotopic analysis

found embedded in the filter surface, but they comprise a small fraction of the particulate mass. Examination by SEM/EDX showed that the largest metal fragment and a subsampling of the small particles on the PFTE filter are composed of stainless steel (∼99% by number).

Far more particulate was generated in the NSI firing than anticipated. However, the particles are of uniform composition, an identical NSI are available for study from the materials archive, and the absence of pyro gas contamination should simplify the task of background correction during returned sample analysis. The TAGSAM blowby test showed the importance of not making assumptions about the nature of contaminants and the valuable role that sample analysis can play in guiding mission operations and design.

5.5 Monopropellant Analysis Results

To better understand the potential impact of any impurities in hydrazine on the sample, the team collected flight samples of aniline-free ultrahigh-purity flight hydrazine monopropellant during spacecraft fuel loading (Fig. 17). Since one complete thruster was archived, it will be possible to recreate the monopropellant as flown and perform any needed experiments with the spare thruster and effectively identical fuel if future scientific results require better knowledge of potential contamination caused by the monopropellant.

Two 125-mL samples were collected in cleaned glass bottles with PFTE caps cleaned to IEST (Institute of Environmental Sciences and Technology) level 25 A. Level 25 A is the cleanliness level used for standard NASA Kennedy Space Center (KSC) propellant analyses. One set of samples collected was dried in PFTE beakers; these are archived at JSC for future inorganic analysis. The second sample of liquid hydrazine was sent for organic and stable isotopic analysis at GSFC. In addition, an identically cleaned bottle was sent and filled with Millipore water to serve as an organic blank.

The stable nitrogen and hydrogen isotopic compositions of hydrazine propellant were measured to be $\delta^{15}N_{\mathrm{AIR}} = +4.7 \pm 1.5‰$ and $\delta \mathrm{D}_{\mathrm{VSMOW}} = +154 \pm 23‰$. The δ^{15}N analysis was carried out using a Costech ECS 4010 combustion elemental analyzer (EA) connected through a Thermo Finnigan™ Conflo III interface to a Thermo Finnigan™ MAT 253 isotope ratio mass spectrometer (IRMS). Seven tin cups were individually loaded with ∼0.2 µL of hydrazine and were then sealed and introduced to the EA-IRMS for analysis through the zero-blank autosampler of the EA. Three cups containing solid L-alanine of known isotopic composition ($\delta^{15}N_{AIR} = -5.56‰$, Iso-Analytical) were also analyzed in order to calibrate the measured isotopic values. For δD analyses, 0.5 µL of a 1:50 hydrazine:1,4-dioxane solution were injected into a Thermo Scientific™ Trace™ GC whose output is split, with approximately 10% directed into a Thermo Scientific™ DSQII™ electron-impact quadrupole MS that provides mass and structural information for each eluting peak. The remaining ~90% passes through a Thermo Finnigan™ GC-TC interface, where amino acids are quantitatively pyrolyzed to hydrogen gas, and into the Thermo Finnigan™ MAT 253 IRMS for δD analyses. High-purity H_2 ($\delta D_{VSMOW} = +75.2‰$, Oztech) was introduced through the dual inlet of the IRMS and used as a reference gas, while a solution of biphenyl of known isotopic composition ($\delta D_{VSMOW} = -41.2‰$; Indiana University) was injected through the GC-IRMS and used for isotopic calibration. The GC was outfitted with a Restek 30-m Rxi®-5mx column, and a flow rate of 0.5 mL/min was used. The following oven program was used for hydrazine analysis: splitless injector held at 220 °C, initial oven temperature of 45 °C held for 6 minutes, ramped at 5 °C/min to 65 °C, ramped at 30 °C/min to 300 °C, held for 3 minutes.

GCMS analysis showed only hydrazine with all trace species consistent with column bleed or column stationary phase. Amino acid analyses of lyophilized hydrazine showed 0.01 ng/g β-alanine and 0.45 ng/g γ-amino-n-butyric acid. These are very close to blank levels and may derive from contamination sublimating into the hydrazine during workup. Diluted hydrazine was infused into a Thermo Scientific™ LTQ Orbitrap XL™ hybrid mass spectrometer using positive ion mode electrospray, but no masses, other than hydrazine, were observed which were not also present in a base extraction of the infusion capillary tube.

6 Materials Archive

Hardware and process coupons of materials that have plausible access to the sample or were of contamination concern due to the materials involved were archived at JSC in six dedicated nitrogen-purged cabinet desiccator boxes housed in an ISO 7 cleanroom. Prior to the start of this archive, the team monitored the background cleanliness levels in the archiving cabinet. They deployed witness plates in an empty desiccator purged with curation grade nitrogen over a one-year period. A total of eight witness plates (10 cm^2 aluminum foils) were initially deployed and collected at the following exposure times: 1, 2, 5, 14, 28, 60, 120, and 365 days. The samples (along with a blank) were sent after collection to GSFC for analysis. Analyses as previously described were conducted on the foils: LCMS (Glavin et al. 2008); derivatization GCMS (Mawhinney et al. 1986); pyrolysis GCMS; DART™-MS; as well as ATP luminosity analysis for cell counts (PallChek™ Rapid Microbiological System). The LCMS data showed that with the exception of the Day 1 sample (which was contaminated during handling and workup) all other samples had 0.05–0.8 ng/cm^2. The lowest and highest abundances were in the 365 day and 120 day exposures, respectively. So total abundance is not an accumulation of material over time. The GCMS analysis showed a steady increase of volatile compound buildup on the witness plates over the course of the experiment, but all were at very small amounts, usually equal to or less than the amount of volatiles found in the analytical laboratory background. The DART™-MS analyses of the acid-hydrolyzed extracts were all similar in appearance over the time course study. Finally, the luminosity analysis of a 5 cm^2 foil found that the samples were below the limit of detection for the

Component	Aluminum	Epoxy	Foil	Honeycomb	Lubricant	Miscellaneous	NVR	Paint	Polymer	Sapphire	Steel	Titanium	Total
KSC	2	4	1		1	6	7		4				25
OCAMS		3			2	2		2	1				10
OLA		15	1										16
OTES					1								1
OVIRS		2			1			1					4
REXIS		1			1	2			1			1	6
Spacecraft		4		3		8			1				16
SRC	30	51	1	1	3	18	6		3	3	45	1	162
Support	1		7		1	19	2		11				41
TAGSAM	31	11			1	9	4			9	57	4	126
Total	64	91	10	4	11	64	19	3	21	12	102	6	407

Fig. 18 The number of different items in the archive shown by origin or location on the spacecraft and by material type. Abundances are shown by number and color with *darker blue* indicating more samples. See Supplemental Material S2 for a complete list

luminometer (1 fmol ATP or ~1000 "typical" bacterial cells). While luminometer analyses are not intended to be definitive assessments of bioburden, it is interesting that the luminometer results suggest <200 cells/cm^2 in all samples. If all the amino acids were derived from cells, then ~5000 cells/cm^2 would have been expected (Neidhardt et al. 1990); thus the source is unlikely to be dominated by viable cells.

The results of this year-long monitoring showed that the curation cabinet was very clean and that buildup of volatile organic compounds was at levels at or below background or blank in the analytical labs, and thus ready to receive samples.

Archiving began in February 2014, with the reception of the first item in the collection—lubricant used on the OTES rotary actuator. As SRC and TAGSAM were built from March 2014 until their availability for ATLO and integration in summer of 2015, items were obtained and sent to JSC for archiving. Additionally, as various instruments were assembled and readied for integration, the instrument providers identified and packaged coupons to send to JSC for the archive. Finally, as instruments and subassemblies of the spacecraft were tested and integrated, coupons and items were continuously sent to JSC through integration at KSC, finishing ~90 days after launch with the final archived items being related to launch operations. In total, 407 items were received for the materials archive.

As previously described, through the ATLO process (from March 2015 until late August 2016) Si wafer and Al foil witness plates were deployed in the various cleanrooms in LM and KSC. These plates each contained four Si wafers and four Al foils, with one of each type per plate analyzed and the remainder being archived; 128 individual witness plates (64 Si wafers and 64 Al foils) were collected in total.

Key summary information for each archived item is presented in an online catalog that will be accessible via https://curator.jsc.nasa.gov/ prior to sample return. Each catalog entry for coupons and hardware lists the material, its location on the spacecraft (e.g., SRC, TAGSAM, spacecraft, instrument, or launch operations), a description of that item (including weight or dimensions), the company that made the item and its webpage or other contact information, the archiving location, archiver, archive date, part number, and photo or drawing of the location on the spacecraft. The materials can be grouped into several general categories including metals (stainless steel, aluminum, titanium alloys, BeCu alloy, and the brass set screw discussed previously), epoxies, paints, polymers, lubricants, sapphire, and a lengthy list of miscellaneous and support materials such as gloves, tape, and bags. A sample from the cold plate during thermal-vacuum testing was also archived; this provides a worst-case spacecraft-wide average of NVR. Materials involved in potential contamination events (e.g., the brass screw revealed by contamination knowledge plate 4), were also archived. A brief summary of materials presented by spacecraft component or location of origin and material type is presented in Fig. 18. The list of materials in the catalog is in the Online Supplemental Material 2.

7 Flight System

Once a spacecraft leaves Earth, additional cleaning and testing is impossible. However, the team needs a method to gain contamination knowledge of the state of the sampling system and provide contamination knowledge for the sample's return to Earth in 2023. Thus, contamination control and knowledge also extended to aspects of the design of the OSIRIS-REx flight system. Naturally, these design specifications could not be allowed to increase the risk to the spacecraft nor cause harm to the sample. Due to cost and complexity concerns, it was decided not to include active contamination monitoring (e.g., a spacecraft mass spectrometer, pressure gauge, or quartz crystal microbalance).

7.1 Flight Witness Plates

The most cost-effective method of contamination monitoring is a laboratory analysis of returned blanks or control samples in the form of witness plates. The first decision is the composition of the witnesses, which is a compromise between science and engineering. Based on the recommendation of Sandford et al. (2010), the team required two different materials. One should be similar to the sampling system to serve as a good proxy to the surfaces that could collect contamination, and the other should be chemically similar, but distinct from the sample. Electrical conductivity of one set of plates is desirable to facilitate electron-beam analyses.

The team considered aluminum, gold, titanium nitride, and silicon for the conductive material. The sampler is primarily 6061 aluminum alloy, so high-purity aluminum was used instead of an alloy to simplify mass spectral analyses. Aluminum is monoisotopic, which results in less interference in some analyses. Yet pure aluminum rapidly forms a dielectric oxide surface coating which is very hard to clean of particulates; this made the precision cleaning of these components more laborious. However, since our sampling system is likely to gouge the sampler and make aluminum debris, aluminum flakes are expected, well understood, and easily compensated for in analyses.

For the other witness, the team discussed zeolites, Tenax or related resins, and other adsorbents. Anything particulate was rejected for foreign object debris concerns and the risk of it contaminating the sample. Based on meteorite studies, the sample is expected to contain ferromagnesian silicates, so the scientists opted to use quartz, as it is unlikely to be in the sample. However, there was an engineering concern that a quartz plate could shatter and damage mechanisms. Instead, the team chose to use sapphire (Al_2O_3), as flown successfully on NASA's Stardust mission. This is an example where spacecraft safety tipped the balance between engineering and science recommendations.

Each plate is a monolith, and the thickness of each plate is unique (similar to what was done on NASA's Genesis mission (Burnett 2013)), meaning that plate identity can be verified by measurement if there is a mix-up or breakage. Sandford et al. (2010) also advised that the witnesses should be prepared in a way that they can be easily subsampled. However, pre-scoring the witnesses was an engineering concern due to possible breakage in space. Instead, the exposed surface of the sapphire was diamond abraded (and cleaned and verified as diamond-free by FTIR). This provides a unique signature of the exposed surface, allowing the witness to be shattered for distribution and allowing the curators to select exterior pieces, which record exposure. This rough surface also provides a modest increase in surface area, but prevents reflectance spectroscopy. It was later determined that the witness plates on the TAGSAM head create a glint into SamCam of the OSIRIS-REx Camera Suite (OCAMS), so both the sapphire and aluminum witness plates had to be abraded to mitigate this problem.

Based on the sensitivity requirements of the techniques expected to be used for sample analysis, and reserving 75% to archive, the team needs a minimum of 10 cm^2 surface area on each of the two types of witnesses.

The simplest case would be to fly a single pair of passive witness plates. However, witness plates cannot establish the direction of molecular flow. This means that it would be impossible to determine if a compound found on a witness plate that was exposed to both the sample and the spacecraft is extraterrestrial, contamination, or both. For a witness plate to be scientifically useful, it must have the same history as the sample collector, with the exception of the presence of sample. This means that the witnesses must be physically close to the sample, but cannot be contaminated by the sample. For OSIRIS-REx, the sample is exposed to two different environments: the TAGSAM head prior to collection, which is exposed to the inside of the launch container; and the spacecraft and the TAGSAM head during and after collection, which is exposed to the spacecraft and the inside of the SRC canister.

If asteroid material outgases onto a witness plate or sheds dust onto it, it may be impossible to determine if the analyte on the witness plate is sample or contamination. This renders the witness plate useless. Thus, it is necessary to protect the witness plate from the sample with a physical barrier to preserve the reconstruction of the contamination history of the sample by comparing witness plates. Ideally, this can be accomplished with a witness plate on TAGSAM that is exposed until the TAG event (α), a witness plate on TAGSAM that is exposed at the moment of the TAG event (β), and a witness plate in the SRC that is not exposed until the SRC is opened in proximity to the sample (γ). Thus, contaminant would then be materials found in $\alpha - \beta + \gamma$.

However, for the purpose of simplicity and cost effectiveness, it is important that any required movements of witness plate covers are leveraged off of other spacecraft actions. The lack of dedicated witness plate motors means that the exposure of witnesses is dependent upon other spacecraft actions; this left a gap in the exposures, so an additional witness plate is continuously exposed to span the gap in time. The arrangement and exposure sequence of the flight witness plates is shown in Fig. 19. The witness plates close via spring actuation and are not hermetically sealed, but the material captured on the witness is preserved via a tortuous path seal. The timeline on the bottom panel is schematic and not to scale, but the gap in exposure of b to c is driven by the ejection of the launch cover prior to TAG, and the gap in exposure between 2 and 3 is driven by the verification of TAGSAM stowage in the SRC. More detailed timing is described in Williams et al. (2017) and Bierhaus et al. (2017).

It is likely that sample dust will be shaken loose from the TAGSAM head inside the SRC canister. Thus, it is possible that particles could be ground into a witness plate. A screen is placed over half of the witness plates that will have potential exposure to regolith (witnesses c, 2, 3 shown in Fig. 19) to minimize the amount of regolith allowed to touch the witness surface, while still permitting volatiles to encounter the witness. A 400-mesh (37-μm) screen is permeable enough to allow contamination gases to pass, but should prevent significant quantities of regolith from being ground into the witness plates during Earth descent and landing (EDL) when there is maximum mechanical stress on the sample in the SRC.

7.2 Sample Return Canister Air Filter

The SRC is not hermetically sealed, but allows gas to exit during launch and enter during EDL. All this gas flow is directed through the SRC Sample Canister Air Filter, which prevents gas and particulate contaminants from entering the sample canister.

In addition, the filter could also capture asteroid-derived volatiles evolving from the sample after SRC closure. Any outgassing that occurs from the collected samples in TAGSAM

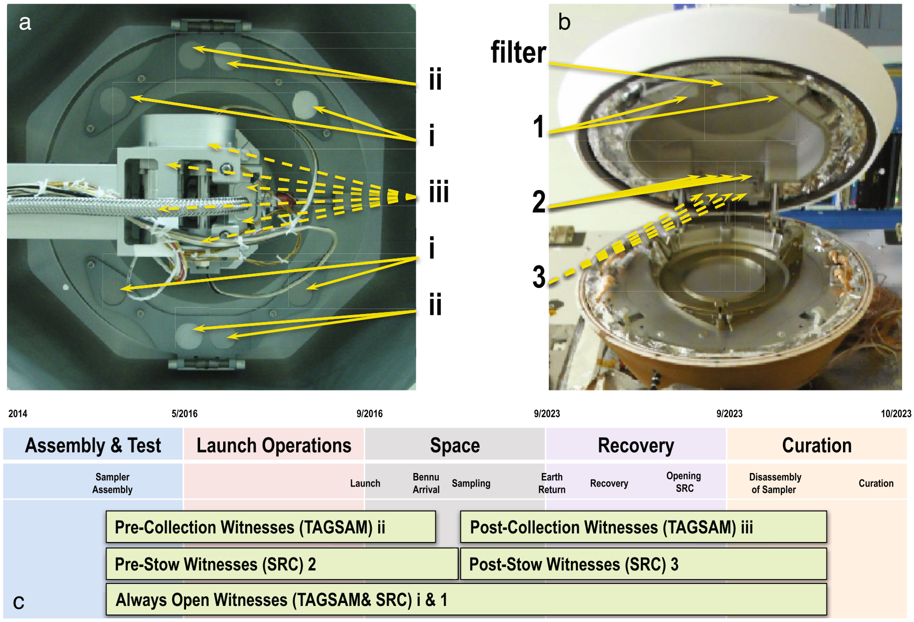


Fig. 19 (**a**) Location of TAGSAM and (**b**) SRC flight witness plates and (**c**) the timing of their exposure. TAGSAM witness *i* is exposed continuously. TAGSAM witness *ii* is covered by spring-mounted seals when the head is removed from the launch container. The six TAGSAM witness *iii* are not visible in the image and are only exposed after TAGSAM arm separation when the TAGSAM head is seated in the SRC. SRC witness *1* is exposed continuously (but under the SRC rim and not visible in the figure). SRC witness *2* is exposed in the image but covered when the SRC is opened to accept the sample. SRC witness *3* is covered until it is exposed at the same time SRC witness *2* is covered. The SRC air filter is also indicated. Dashed arrows indicate that the witness is covered in the image

after it is stowed in the sample canister could result in the deposition of escaping volatiles on the inside of the sample canister or on the avionics deck or in the filter. Any areas in the enclosed sample canister/TAGSAM/avionics-deck volume that are on average cooler could serve as cold traps that concentrate these volatiles. After reentry and recovery of the capsule and extraction of the sample canister at the Utah Test and Training Range, a N_2 gas purge of the canister will be started through the canister septum. The resulting flow of air will exit through the canister air filter, and this will encourage any volatiles located in the canister into the filter. Thus, if the TAGSAM contains volatiles that can outgas from the collected samples and cold trap within the canister, it is in the air filter where there is the best chance of detecting them.

The Sample Canister Filter used on the OSIRIS-REx Sample Canister is a nearly identical copy of the filter used on the Stardust spacecraft and consists of a structure containing alternating layers of filtrete material and active absorbing materials. The location of the filter is indicated in Fig. 19, and Fig. 20 shows a schematic of the filter's cross section. Since the OSIRIS-REx filter is nearly identical to the filter used by Stardust, performance testing the OSIRIS-REx filter was modeled on the procedures used for testing the Stardust filter (Tsou et al. 2003) to test the efficiency of the filter at capturing various organic gases, water vapor, and particulates. Three filters identical to the flight unit were tested for their organic, moisture, and particulate performance.

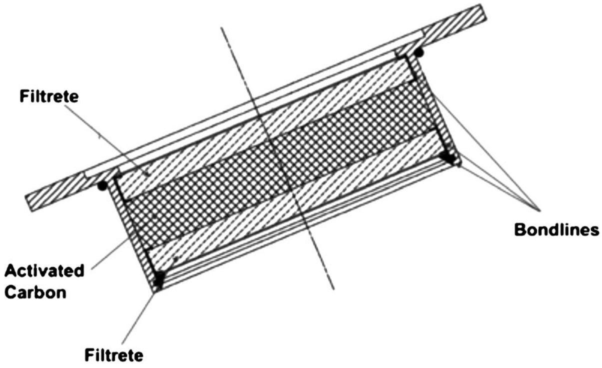


Fig. 20 The SRC filter consists of layers of filtrete material and activated carbon. The body is 6.35 cm outer diameter and 2.2 cm thick, the same design as used on Stardust (Tsou et al. 2003)

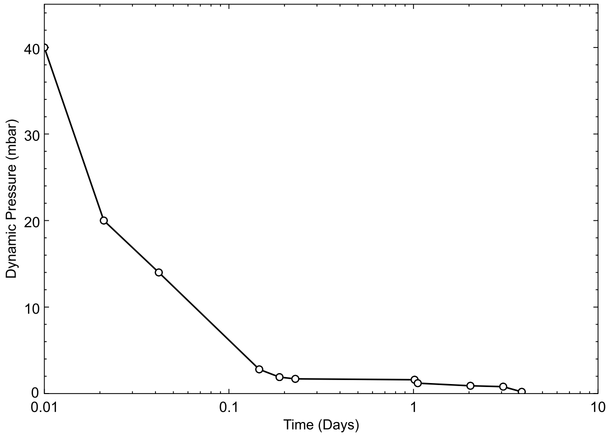


Fig. 21 The dynamic pressure of the SRC filter decreased at a rate that diminished with time

7.3 SRC Filter Efficiency for Organics

The filter's ability to capture a variety of contaminant gases was tested. Tests were made using a specially designed apparatus that allowed controlled gas flow through the filter and that allowed the filter to be degassed in a vacuum prior to the test, as would be the case for the flight filter, at NASA Ames Research Center (ARC). A 2-liter gas bulb containing 1230 mbar N_2, 7 mbar ethanol, 7 mbar acetone, 7 mbar hexane, 7 mbar benzene, and 2 mbar CO was prepared and mounted on the inlet side of the filter (SRC exterior). A second evacuated 2-liter receiving bulb was placed on the opposite side of the filter so that it could capture any gases passing through the filter. The filter was then pumped on for an extended period of time. As expected, the filter initially pumped down at a nearly exponential rate, but slowed as the filter degassed. It took several days for the filter to approach the ambient pressure of $\sim 1 \times 10^{-5}$ mbar of the vacuum system (Fig. 21).

Once the filter had been largely degassed, the test gases were flowed through the filter using a flow rate and duration like that expected for the reentry of the SRC (vacuum to 1 atm in 10 minutes). The original test gas bulb and receiver bulb were then removed from the apparatus so the composition of the gases in each could be measured and compared. Each bulb was used to deposit sample gas onto a CsI window cooled to 10 K in the vacuum chamber of a FTIR equipped cryo-vacuum system. The infrared spectrum of the resulting mixed-molecular ice was then obtained, and the positions and strengths of any absorption

Fig. 22 Comparison of the infrared spectra of unfiltered and filtered gases. The SRC filter trapped the vast majority of the introduced contaminant gases: ethanol (E), benzene (B), acetone (A), and hexane (H)

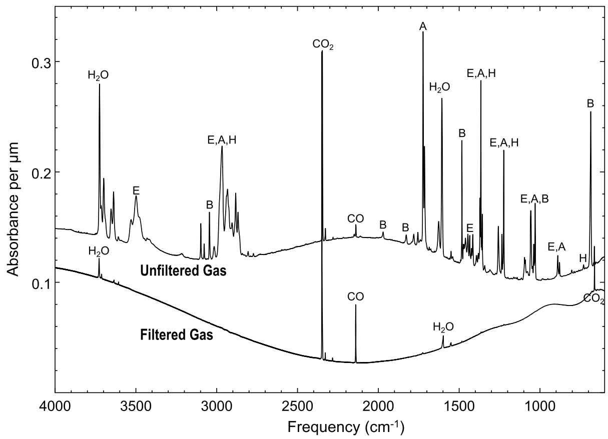


Table 14 Gas trapping efficiencies of the SRC filter

Compound	Integration range (cm^{-1})	Filter efficiency (%)
Ethanol	3534–3345	99.37
Benzene (4 bands)	3110–2998	>94
Hexane+ethanol+acetone	2999–2845	>98.5
CO	2157–2129	84
Benzene	1988–1960	>90
Benzene	1843–1813	>99.2
Acetone	1731–1698	99.05
Benzene	1488–1477	98
Mostly ethanol	1477–1407	99.4
Hexane+ethanol+acetone	1397–1348	99.27
Hexane+ethanol+acetone	1266–1216	99.4
Ethanol+acetone+benzene	1106–1024	98.7
Acetone+ethanol	898–873	>98
Hexane	739–722	>95
Benzene	701–676	>97.1

Note—both spectra show bands near 2350 and 663 cm^{-1} due to CO_2 and in the 3730–3570 cm^{-1} 1640–1590 cm^{-1} regions due to H_2O. These gases were not part of the original gas mixture and are likely contaminants associated with gases already trapped in the filter due to prior exposure to atmosphere, and the cryo-vacuum system used to condense the gases for FTIR measurement

bands detected were measured (Allamandola 1984; Hudgins et al. 1994). The measured band strengths of individual molecular species in the samples were then used to compare the filtered and unfiltered gases to determine how efficiently the filter stopped individual molecular components of the original gas mixture.

Figure 22 and Table 14 show the results of this test. In most respects the results of this filtering test are very similar to those seen for the Stardust test filters (Tsou et al. 2003). In virtually all cases where absorption bands could be detected in both the unfiltered and filtered samples, the filter stopped ∼99+% of the ethanol, hexane, acetone, and benzene. CO is filtered with lower efficiency, but was included in the test as a calibration tracer and is not considered to be an issue as a sample contaminant. Nonetheless, it is interesting to note that the OSIRIS-REx filter stopped the CO with better efficiency than the Stardust filters (passing 16% versus >70%).

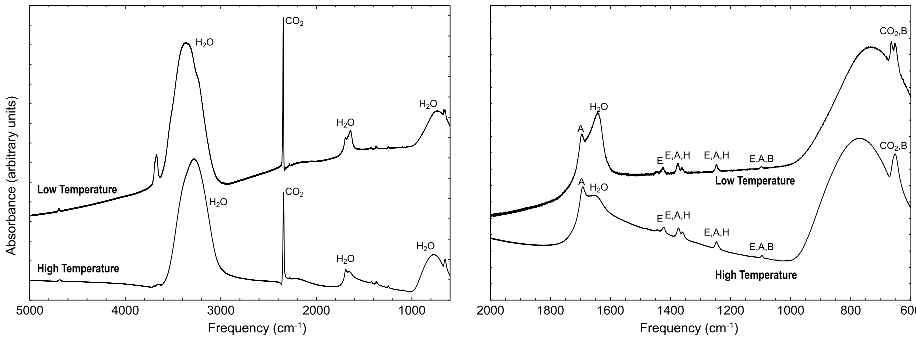


Fig. 23 The FTIR spectra of the condensed gases liberated from the SRC filter by the heat soak tests

Since the flight filter is expected to be heated by conduction from the SRC heatshield (heat soak) following the completion of reentry, the filter's ability to trap and hold contaminant gases when heated was tested. After the filter was used for the gas trapping test, it was briefly pumped to $<10^{-3}$ mbar followed by testing at the above conditions, first at 50 °C then at 70 °C at similar timescales to the heat soak of the returned SRC (peak temperatures at 20 and 30 minutes, respectively). These temperatures are the expected and maximum temperature of the SRC interior. Figure 23 shows the infrared spectra of the condensed gases that escaped the tested filter during the two heat soak tests.

The dominant absorption features are due to H_2O and CO_2, molecules that were not components of the original test gas. These species indicate that the heat soak liberated H_2O and CO_2 that were present in the filter prior to the original trapping test. Since the SRC (and filter) were subjected to spacecraft thermal-vacuum testing, higher temperatures may be needed to liberate these atmospheric gases in the flight filter compared to this test.

7.4 SRC Filter Efficiency for Water Vapor

As in Tsou et al. (2003), another flight-design air filter was tested for humidity-trapping efficiency at JSC. The filter received a bakeout and dry air purge before each test to ensure the test started with a dry filter. Room-temperature air samples with both 90% and 40% humidity were tested at a 1.5-L/min flow rate. The flow rate was calibrated against Dry-Cal DC Lite primary flow meter and ranged from 1.48 to 1.52 over five readings within a 30-second period. Humid air was supplied and hydrated via a bubbler (Fig. 24), which was then sent through a Vaisala model HMT333 humidity sensor to measure inlet humidity, then sent through the filter in the test housing, and then through a flow controller and into an outlet humidity sensor.

The 90% test showed an initial output humidity which stayed very low, indicating the filter has high efficiency over the first ∼20 minutes of testing. For the first 20 L (the approximate volume of the Sample Canister) of humid air that passed through the filter, the outlet humidity stayed below 10% (Fig. 25, Table 15). The total duration of the test was 225 minutes, during which humidity on the outlet side of the filter reached a maximum of 73%. The 40% humidity test was carried out using exactly the same procedures. Nearly 22 L of air passed through the filter before the efficiency dropped below 90%. It took ∼40 minutes for the relative humidity of the output air to increase above 10%, so the filter's ability to keep outlet relative humidity $<10\%$ was once again achieved well after the ∼20-liter capacity of the SRC was attained. These results are comparable to or better than those for the Stardust filters (Tsou et al. 2003).

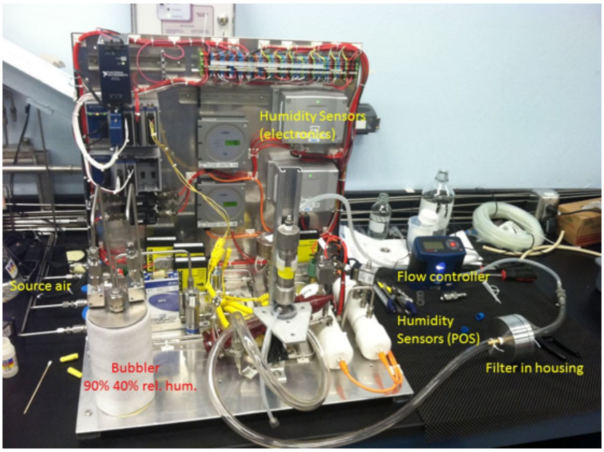


Fig. 24 Test stand used for the SRC filter humidity tests at the JSC Gas Laboratory for Analytical Chemistry

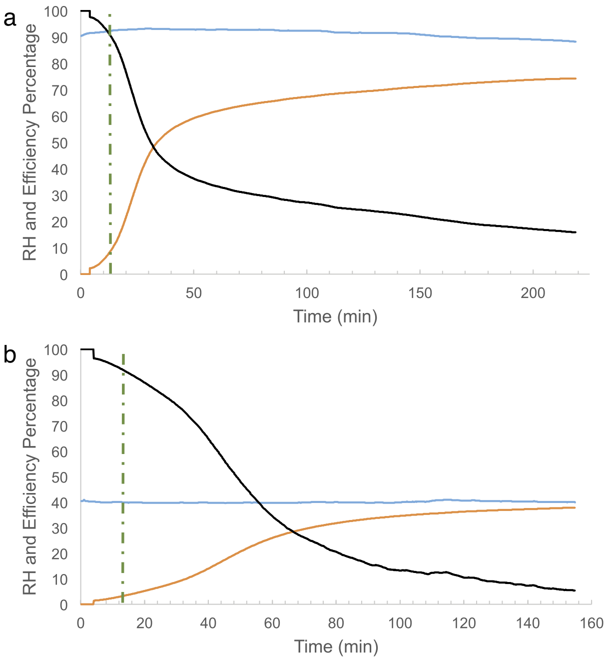


Fig. 25 SRC filter performance for the 90% (*top*) and 40% (*bottom*) humidity tests. The *blue lines* are the inlet humidity, *orange* is the outlet humidity, and *black* is the filter efficiency. *Vertical dashed green line* at 13.3 min corresponds to 20 liters of air passing through the filter

7.5 SRC Filter Efficiency for Particulates

A separate OSIRIS-REx filter was tested for its ability to trap particulates. This test used a P-Trak Model 8525 (TSI Inc.) ultrafine particle counter with a probe that provided a 0.6-L/min flow rate to measure particles in the size range of 0.02 to 1 µm. Initially, measurements of unfiltered air were made at JSC in three different environments: (a) the interior of Building 229, where particle counts were ∼3000 counts/cm^3; (b) the exterior of building 229, where particle counts were ∼25,500 counts/cm^3; and (c) with a candle smoke source with particle counts of 100,000 to 300,000 counts/cm^3. After each of these measurements, a new set of measurements was made of air run through the OSIRIS-REx test filter. Filtered

Table 15 Humidity performance versus volume of gas through the SRC filter

	90% Humidity mass (g)	40% Humidity mass (g)
Initial	1196.10	1196.12
Final	1198.01	1196.72
Change	1.91	0.60

Efficiency	90% Humidity total volume (L)	40% Humidity total volume (L)
100%	6.025	6.025
95–99.99%	13.273	11.678
90–94.99%	19.598	22.658
85–89.99%	23.543	31.130
80–84.99%	26.269	38.352
75–79.99%	28.440	43.881
70–74.99%	30.361	47.942
65–69.99%	32.149	51.255
60–64.99%	33.913	54.051
55–59.99%	35.793	56.552
50–54.99%	37.955	58.954
45–49.99%	40.721	61.326

Table 16 Particulate trapping efficiency results of the SRC filter

Unfiltered (counts/cm^3)	Filtered (counts/cm^3)	Efficiency (%)
3000	11	99.63
25,500	33	99.87
200,000	8	99.996

readings for a, b, and c were 4 to 23 counts/cm^3 (over a 25-minute period of time), 20 to 46 counts/cm^3 over a 5-minute period of time, and 4 to 12 counts/cm^3 over a 10-minute period of time. The results are shown in Table 16.

The trapping efficiency of Stardust filters was measured for particles in 0.3- to 0.5-μm range to be 99.9% or better, and the efficiency was greater than this for larger particles. Our results extend to smaller particle sizes and are comparable to or better than those for the Stardust filters. In particular, the Stardust results on cigarette smoke, which is dominated by small particles (<1 μm), show 99.9% efficiency compared to the OSIRIS-REx results on comparably sized candle smoke ($\ll 1$ μm) that show 99.996% efficiency. Again, these results compare favorably with results from Stardust test filters (Tsou et al. 2003).

7.6 Analysis of the Returned Air Filter

The team will further improve our knowledge of the degree of sample contamination by analyzing the SRC air filter after the SRC is recovered. It will be important to analyze each of the layers of the filter independently, since gradients in detected molecules and particulates within the vertical structure of the filter will provide information concerning whether any filter-trapped materials were leaving the canister (escaping asteroidal materials) or entering the canister (external contaminants).

Furthermore, as with Stardust (Sandford et al. 2010), the team will collect gas, soil, and related samples from the SRC recovery site and purge the SRC with N_2 upon recovery. Samples found in the SRC can then be compared with these materials to ascertain whether or not they are contaminants associated with recovery of the SRC.

8 Launch Vehicle

Perhaps the most hectic and critical periods in ATLO are the final preparations for launch and the launch itself. This period also has the most number of organizations working together; the PI and project office, LM, KSC's Launch Service Program personnel assigned to the OSIRIS-REx mission, the launch service provider (ULA) personnel, and Eastern Range personnel. Each has its own bureaucracy and culture. To better unite the team, the Principal Investigator and the Project Scientist had casual conversations and gave presentations to the technicians so they would better understand the importance of the OSIRIS-REx mission and the rationale behind the atypical contamination requirements that impacted their activities. This gave them ownership in the mission and encouraged them to rethink their process from a contamination perspective—proactively addressing any concerns that came up. It was also helpful to explain the rationale behind the contamination requirements to the stakeholders and vendors to improve compliance and encourage suggestions for solving issues.

Launch site activities start in the PHSF. One of the factors that led to the selection of the PHSF was that the air handling system for the building only serves one spacecraft. In a facility with a shared air system, an anomaly in one cleanroom can impact another. If the spacecraft generating the contamination is for a classified project, it could be difficult or impossible to obtain information about the event.

The OSIRIS-REx contamination requirements imposed changes to the spacecraft processing. Activities like mating of the spacecraft to the payload adapter and payload fairing encapsulation prior to transportation to the ULA Atlas V Vehicle Integration Facility (VIF) had never been done before. Furthermore, although the PHSF cleanroom is ISO 8, the facility needed to be able to maintain an ISO Class 7 for a short period of time for the final closeout of the SRC. The PHSF cleanroom was tested for NVR and particulate contamination prior to spacecraft arrival, and a detailed crane inspection and facility walk-down were performed to ensure the facility was ready. Advanced preparation included collecting one month of NVR and particle fallout data. The facility's maintenance schedule included daily cleanings of the facility and garmenting to be consistent with a Class 7 cleanroom. Since transportation of the encapsulated spacecraft to the VIF required a ULA diesel truck, the exhaust was pumped away from the airlock via a positive flow snorkel. Hydrocarbons were monitored during a rehearsal and found to be sub-ppm. Schedule (and thus cost) was controlled during hazardous operations in the PHSF with a slight modification for access to the airlock for launch vehicle operations. This allowed for processing flight hardware in the airlock to prepare for spacecraft mate operations.

The use of a modified witness plate bracket (Fig. 5) inside the fairing to capture additional amino acid data was new, and needed to be demonstrated to do no harm in the high airflow environment of the fairing. Since the VIF is not an environmentally controlled facility, clean enclosures were required for the four "boat tail" doors for access to the Centaur Equipment Module and spacecraft (Fig. 26). Each enclosure was cleaned and certified to meet ISO

Fig. 26 OSIRIS-REx fairing "boat tail" doors and one clean tent are nearly ready to be removed for final closeout

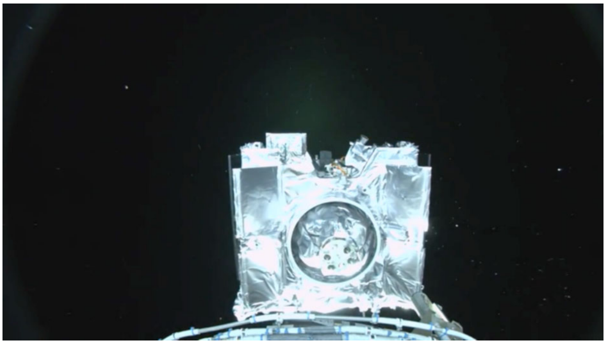


Fig. 27 The OSIRIS-REx spacecraft separating from the Atlas V Centaur stage

Class 8 with ISO Class 6.7 air source, and only one tent door was permitted open at a time to maintain positive flow out of the fairing at all times.

An additional two payload access doors above the spacecraft were included in the fairing. The purpose of the doors was to allow visual inspection in the event of a major anomaly. Opening the doors would degrade the cleanliness of the spacecraft, but could prevent the potential loss of the mission's launch period. Fortunately, the doors were never opened for an anomaly. When these upper doors were opened to apply sealant (which was subsequently archived) for closeout, all personnel and equipment remained >0.6 m from the opening, and the fairing airflow was set to maximum.

The Atlas V and VIF use nylon or suspected nylon components extensively. Eliminating these components was viewed as a significant risk to the launch vehicle performance. This risk was mitigated by covering the nylon parts and requiring glove changes whenever nylon was contacted. Since the amino acid contamination monitoring plate showed no evidence of nylon hydrolysis products, these measures appear to have been successful.

The last view of the spacecraft separating from the payload adaptor on the Atlas V Centaur shows numerous particles reflecting in the sunlight (Fig. 27). These are likely ice and fragments from the separation of the payload launch adaptor, more sources of unavoidable particulates. The launch container and SRC filter and seals should have protected the TAGSAM and SRC interior from these. If this is ultimately found not to be the case, the contamination was captured and recorded on the flight witness plates.

9 Conclusion

NASA's Viking landers were assembled at LM (then Martin Marietta); and every organic component, no matter its location, was analyzed by FTIR and MS and cataloged; and each entire lander was heat-sterilized. This level of contamination control (and planetary protection) is beyond the scope of a New Frontiers-class mission. Instead, OSIRIS-REx benefited from previous missions' innovations, including the development of aniline-free hydrazine for Viking and the use of proxy materials as indicators of contamination. OSIRIS-REx offers lessons for future missions: the demonstration that amino acids can be controlled to such low levels in an industrial cleanroom, the use of the science team for contamination knowledge analyses, and the close interaction between engineers and scientists for contamination control.

The process of developing and implementing contamination requirements cannot start too early in the mission planning process, and must be maintained throughout implementation across the whole project. This required authority behind the requirement, in this case by making contamination a Mission Level 1 priority and having it be shepherded by project leadership.

Team communication was harder than expected—and it was already expected to be difficult from the start. Learning from our experience, future missions should allocate even more time and cost margin, with ready descopes for cost containment agreed upon. A unification of language is helpful, particularly to have the science team develop requirements in the language of the engineers and technicians responsible for implementing it. Likewise, it is important for the scientists to understand what is and is not possible and verifiable in a nonlaboratory environment. Just because a measurement can be made under ideal laboratory conditions does not mean it can be made under the schedule pressure and environment of ATLO. Close communication among the science, engineering, and management stakeholders is the best path to understand what changes are possible and reasonable. Communication lapses were evident late in the overall process, showing up as missed requirements. Most notably, rework was required since the science team writing the requirements did not include a prohibition on amorphous silicates, because the team did not know that such materials had an application in aerospace. It is also important that the people who write the requirements are involved in the implementation of the requirements. This allows for an understanding of the intent of the requirement in marginal conditions, prevents the creation of requirements that are impossible to implement, and prevents implementation that undermines the science behind the requirements.

There is a constant struggle between maintaining spacecraft and ATLO processing heritage and contamination requirements—especially novel ones. To compromise, the contamination engineers tried to be flexible, but that was sometimes interpreted at the working level as indecision or as an indication that all the requirements were not well thought out and arbitrary. The solution seems obvious—increase communication and inclusiveness across all those involved in making the mission a success, from scientists to managers to engineers to technicians, early and often. Yet communication via presentations and working groups cannot replace the timely production and approval of configuration managed documentation.

The use of contamination knowledge and the materials archive enabled considerable flexibility. High-heritage materials of contamination concern could be used, with contamination knowledge responsible for unraveling their impact. At the same time, ongoing analyses of the ATLO contamination monitoring and contamination knowledge plates both created confidence in the methods and allowed prompt reaction to anomalies and detection of trends.

Fig. 28 The launch pad (**a**) at Space Launch Complex 41 with the VIF (**b**) with OSIRIS-REx inside is seen through the smoke from the AMOS-6/SpaceX Falcon 9 static fire test explosion and fire at the adjacent Space Launch Complex 40 (**c**) on September 1, 2016. Although the VIF was only about 2 km downwind from the fire and the shared water pump between the launch sites was damaged, OSIRIS-REx was protected from contamination due to a combination of planning and swift work. Photo credit: *Top*: Dworkin, *Bottom*: (Clark 2016b)

Finally, the unexpected can happen (Fig. 28), and having a committed, connected team with enough freedom and flexibility to act in the face of obstacles is crucial.

Acknowledgements This material is based upon work supported by the National Aeronautics and Space Administration under Contracts NNH09ZDA007O, NNG12FD66C, and NNM10AA11C issued through the New Frontiers Program. We wish to thank the hundreds of people and their families who labored and sacrificed to make OSIRIS-REx a reality.

References

L.J. Allamandola, Absorption and emission characteristics of interstellar dust, in Galactic and Extragalactic Infrared Spectroscopy, in *Proceedings of the XVIth ESLAB Symposium*, Toledo, Spain, December 6–8, 1982, ed. by M.F. Kessler J.P. Phillips (Springer, Dordrecht, 1984), pp. 5–35

L.J. Bement, Functional performance of pyrovalves. J. Spacecr. Rockets **34**, 391–396 (1997)

E.B. Bierhaus, B.C. Clark, J.W. Harris, K.S. Payne, R.D. Dubisher, D.W. Wurts, R.A. Hund, R.M. Kuhns, T.M. Linn, J.L. Wood, A.J. May, J.P. Dworkin, E. Beshore, D.S. Lauretta, The OSIRIS-REx touch-and-go sample acquisition mechanism (TAGSAM) and flight system. Space Sci. Rev. (2017, this issue)

I. Boogers, W. Plugge, Y.Q. Stokkermans, A.L.L. Duchateau, Ultra-performance liquid chromatographic analysis of amino acids in protein hydrolysates using an automated pre-column derivatisation method. J. Chromatogr. A **1189**, 406–409 (2008)

D.S. Burnett, The genesis solar wind sample return mission: past, present, and future. Meteorit. Planet. Sci. **48**, 2351–2370 (2013)

A.S. Burton, S. Grunsfeld, J.E. Elsila, D.P. Glavin, J.P. Dworkin, The effects of parent-body hydrothermal heating on amino acid abundances in CI-like chondrites. Polar Sci. **8**, 255–263 (2014)
A.S. Burton, J.C. Stern, J.E. Elsila, D.P. Glavin, J.P. Dworkin, Understanding prebiotic chemistry through the analysis of extraterrestrial amino acids and nucleobases in meteorites. Chem. Soc. Rev. **41**, 5459–5472 (2012)
D.J. Carré, D.F. Hall, Contamination measurements during operation of hydrazine thrusters on the P78-2 (SCATHA) satellite. J. Spacecr. Rockets **20**, 444–449 (1983)
Q.H.S. Chan, Y. Chikaraishi, Y. Takano, N.O. Ogawa, N. Ohkouchi, Amino acid compositions in heated carbonaceous chondrites and their compound-specific nitrogen isotopic ratios. Earth, Planets Space **68**, 7 (2016)
J.E. Chirivella, Hydrazine Engine Plume Contamination Mapping. Final report AFRPL TR-75-16 (1975)
P.R. Christensen, V.E. Hamilton, G.L. Mehall, D. Pelham, W. O'Donnell, S. Anwar, H. Bowles, S. Chase, J. Fahlgren, Z. Farkas, T. Fisher, O. James, I. Kubik, I. Lazbin, M. Miner, M. Rassas, L. Schulze, K. Shamordola, T. Tourville, G. West, R. Woodward, D. Lauretta, The OSIRIS-REx thermal emission spectrometer (OTES) instrument. Space Sci. Rev. (2017, this issue)
B.E. Clark, R.P. Binzel, E.S. Howell, E.A. Cloutis, M. Ockert-Bell, P. Christensen, M.A. Barucci, F. DeMeo, D.S. Lauretta, H. Connolly, A. Soderberg, C. Hergenrother, L. Lim, J. Emery, M. Mueller, Asteroid (101955) 1999 RQ36: spectroscopy from 0.4 to 2.4 μm and meteorite analogs. Icarus **216**, 462–475 (2011)
S. Clark, One of NASA's cleanest spacecraft ever is ready to fly. Spaceflight Now. Spaceflight Now Inc. (2016a)
S. Clark, Quick work saved the OSIRIS-REx asteroid mission from nearby explosion. Spaceflight Now. Spaceflight Now Inc. (2016b)
R.C. Edgar, B.J. Haas, J.C. Clemente, C. Quince, R. Knight, UCHIME improves sensitivity and speed of chimera detection. Bioinformatics **27**, 2194–2200 (2011)
J.E. Elsila, D.P. Glavin, J.P. Dworkin, Cometary glycine detected in samples returned by Stardust. Meteorit. Planet. Sci. **44**, 1323–1330 (2009)
J.K. Friedel, E. Scheller, Composition of hydrolysable amino acids in soil organic matter and soil microbial biomass. Soil Biol. Biochem. **34**, 315–325 (2002)
D.P. Glavin, M.P. Callahan, J.P. Dworkin, J.E. Elsila, The effects of parent body processes on amino acids in carbonaceous chondrites. Meteorit. Planet. Sci. **45**, 1948–1972 (2010)
D.P. Glavin, J.P. Dworkin, A. Aubrey, O. Botta, J.H. Doty III., Z. Martins, J.L. Bada, Amino acid analyses of Antarctic CM2 meteorites using liquid chromatography-time of flight-mass spectrometry. Meteorit. Planet. Sci. **41**, 889–902 (2006)
D.P. Glavin, J.P. Dworkin, S.A. Sandford, Detection of cometary amines in samples returned by Stardust. Meteorit. Planet. Sci. **43**, 399–413 (2008)
M. Groethe, S. McDougle, R. Saulsberry, Measurement of debris in the flow from pyrotechnic reaction using an instrumented Hopkinson pressure bar, in *44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, American Institute of Aeronautics and Astronautics, 2008)
D.M. Hudgins, S.A. Sandford, L.J. Allamandola, Infrared spectroscopy of polycyclic aromatic hydrocarbon cations. 1. Matrix-isolated naphthalene and perdeuterated naphthalene. J. Phys. Chem. **98**, 4243–4253 (1994)
IEST, IEST-STD-CC1246D: Product Cleanliness Levels and Contamination Control Program (Institute for Environmental Science and Technology, Rolling Meadows, IL, 2002)
J.F. Kerridge, Carbon, hydrogen and nitrogen in carbonaceous chondrites: abundances and isotopic compositions in bulk samples. Geochim. Cosmochim. Acta **49**, 1707–1714 (1985)
V. Kolb, J. Dworkin, S. Miller, Alternative bases in the RNA World: the prebiotic synthesis of urazole and its ribosides. J. Mol. Evol. **38**, 549–557 (1994)
D.S. Lauretta, S.S. Balram-Knutson, E. Beshore, W.V. Boynton, C. Drouet d'Aubigny, D.N. DellaGiustina, H.L. Enos, D.R. Gholish, C.W. Hergenrother, E.S. Howell, C.A. Johnson, E.T. Morton, M.C. Nolan, B. Rizk, H.L. Roper, A.E. Bartels, B.J. Bos, J.P. Dworkin, D.E. Highsmith, M.C. Moreau, D.A. Lorenz, L.F. Lim, R. Mink, J.A. Nuth, D.C. Reuter, A.A. Simon, E.B. Bierhaus, B.H. Bryan, R. Ballouz, O.S. Barnouin, R.P. Binzel, W.F. Bottke, V.E. Hamilton, K.J. Walsh, S.R. Chesley, P.R. Christensen, B.E. Clark, H.C. Connolly, M.K. Crombie, M.G. Daly, J.P. Emery, T.J. McCoy, J.W. McMahon, D.J. Scheeres, S. Messenger, K. Nakamura-Messenger, K. Righter, S.A. Sandford, OSIRIS-REx: sample return from asteroid (101955) Bennu. Space Sci. Rev. **212**(1–2), 925–984 (2017)
M.T. La Duc, P. Vaishampayan, H.R. Nilsson, T. Torok, K. Venkateswaran, Pyrosequencing-derived bacterial, archaeal, and fungal diversity of spacecraft hardware destined for Mars. Appl. Environ. Microbiol. **78**, 5912–5922 (2012)

K.B. Loftin, Development of Novel DART™ TOFMS Analytical Techniques for the Identification of Organic Contamination on Spaceflight-Related Substrates and Aqueous Media. Doctoral Dissertation, University of Central Florida, Orlando, 2009

P.R. Mahaffy, D.W. Beaty, M.S. Anderson, G. Aveni, J.L. Bada, S.J. Clemett, D.J. Des Marais, S. Douglas, J.P. Dworkin, R.G. Kern, D.A. Papanastassiou, F.D. Palluconi, J.J. Simmonds, A. Steele, J.H. Waite, A.P. Zent, E. Stansbery, Report of the organic contamination science steering group, in *37th Annual Lunar and Planetary Science Conference*, ed. by S. Mackwell (2004)

A. Mahnert, P. Vaishampayan, A.J. Probst, A. Auerbach, C. Moissl-Eichinger, K. Venkateswaran, G. Berg, Cleanroom maintenance significantly reduces abundance but not diversity of indoor microbiomes. PLoS ONE **10**, e0134848 (2015)

R.A. Masterson, M. Chodas, L. Bayley, B. Allen, J. Hong, P. Biswas, C. McMenamin, K. Stout, E. Bokhour, H. Bralower, D. Carte, S. Chen, M. Jones, S. Kissel, H. Schmidt, M. Smith, G. Sondecker, L.F. Lim, J. Grindlay, R.P. Binzel, Regolith X-ay Imaging Spectrometer (REXIS) aboard the OSIRIS-REx Asteroid Sample Return mission. Space Sci. Rev. (2017, this issue)

T.P. Mawhinney, R.S. Robinett, A. Atalay, M.A. Madson, Analysis of amino acids as their tert.-butyldimethylsilyl derivatives by gas-liquid chromatography and mass spectrometry. J. Chromatogr. **358**, 231–242 (1986)

NASA, NPR 8020.12D: planetary protection provisions for robotic extraterrestrial missions. Directorate, Science Mission, NASA Procedural Requirements, NPR 8020.12D 2011. http://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=8020&s=12D

NASA, SN-C-0005 revision D: space shuttle contamination control requirements, Lyndon B. Johnson Space Center (1998). https://prod.nais.nasa.gov/eps/eps_data/123414-DRAFT-001-005.pdf

National Research Council (U.S.), Task group on organic environments in the solar system. Exploring Organic Environments in the Solar System, National Academies Press, Washington, DC (2007)

F.C. Neidhardt, J.L. Ingraham, M. Schaechter, *Physiology of the Bacterial Cell: A Molecular Approach* (Sinauer Associates, Sunderland, 1990)

S. Pizzarello, Y. Huang, M.R. Alexandre, Molecular asymmetry in extraterrestrial chemistry: insights from a pristine meteorite. Proc. Natl. Acad. Sci. USA **105**, 3700–3704 (2008)

D.H. Plemmons, M. Mehta, B.C. Clark, S.P. Kounaves, L.L. Peach, N.O. Renno, L. Tamppari, S.M.M. Young, Effects of the Phoenix Lander descent thruster plume on the Martian surface. J. Geophys. Res., Planets **113**, E00A11 (2008). doi:10.1029/2007JE003059

S.A. Sandford, S. Bajt, S.J. Clemett, G.D. Cody, G. Cooper, B.T. Degregorio, V. de Vera, J.P. Dworkin, J.E. Elsila, G.J. Flynn, D.P. Glavin, A. Lanzirotti, T. Limero, M.P. Martin, C.J. Snead, M.K. Spencer, T. Stephan, A. Westphal, S. Wirick, R.N. Zare, M.E. Zolensky, Assessment and control of organic and other contaminants associated with the Stardust sample return from comet 81P/Wild 2. Meteorit. Planet. Sci. **45**, 406–433 (2010)

B. Schläppi, K. Altwegg, H. Balsiger, M. Hässig, A. Jäckel, P. Wurz, B. Fiethe, M. Rubin, S.A. Fuselier, J.J. Berthelier, J. De Keyser, H. Rème, U. Mall, Influence of spacecraft outgassing on the exploration of tenuous atmospheres with in situ mass spectrometry. J. Geophys. Res. Space Phys. **115**, A12313 (2010). doi:10.1029/2010JA015734

S.A. Smith, J.N. Benardini III, D. Anderl, M. Ford, E. Wear, M. Schrader, W. Schubert, L. DeVeaux, A. Paszczynski, S.E. Childers, Identification and characterization of early mission phase microorganisms residing on the Mars science laboratory and assessment of their potential to survive Mars-like conditions. Astrobiology **17**(3), 253–265 (2017). doi:10.1089/ast.2015.1417

P. Tsou, D.E. Brownlee, S.A. Sandford, F. Hörz, M.E. Zolensky, Wild 2 and interstellar sample collection and Earth return. J. Geophys. Res., Planets **108**(E10), 8113 (2003). doi:10.1029/2003JE002109

Z. Weijun, J. David, O. Yoshihiro, I.K. Ralf, Formation of nitrogen and hydrogen-bearing molecules in solid ammonia and implications for solar system and interstellar ices. Astrophys. J. **674**, 1242–1250 (2008)

B. Williams, P. Antreasian, E. Carranza, C. Jackman, J. Leonard, D. Nelson, B. Page, D. Stanbridge, D. Wibben, K. Williams, M. Moreau, K. Berry, K. Getzandanner, A. Liounis, A. Mashiku, D. Highsmith, B. Sutter, D.S. Lauretta, OSIRIS-REx flight dynamics and navigation design. Space Sci. Rev. (2017, this issue)

S. Woods, R. Saulsberry, C. Keddy, H. Julien, Estimation of temperature and other properties in pyrotechnic reactions using pressure measurements and application of thermodynamic equilibrium code, in *44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, American Institute of Aeronautics and Astronautics (2008)

Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer (OSIRIS-REx)

Mission Contamination Control Plan

OSIRIS-REx-PLAN-0011

Revision -

December 2013

Prepared by: Charles Lorentson
NASA - Goddard Space Flight Center

Goddard Space Flight Center
Greenbelt, Maryland

National Aeronautics and Space Administration

CONFIGURATION MANAGEMENT (CM) FOREWORD

This document is a ORIGINS-SPECTRAL INTERPRETATION-RESOURCE IDENTIFICATION-SECURITY-REGOLITH Explorer mission (OSIRIS-REx) Project CM-controlled document. Changes to this document require prior approval of the applicable configuration control board (CCB) chairperson or designee. Proposed changes shall be submitted to the OSIRIS-REx Configuration Management Office, along with supportive material justifying the proposed change. Changes to this document will be made by complete revision. This document will expire once a Launch Vehicle Interface Control Document (LV-ICD) has been signed.

In this document, a requirement is identified by “shall,” a good practice by “should,” permission by “may” or “can,” expectation by “will,” and descriptive material by “is.”

Questions or comments concerning this document should be addressed to:

OSIRIS-REx Configuration Management Office
Mail Stop 433
Goddard Space Flight Center
Greenbelt, Maryland 20771

OSIRIS-REx
Mission Contamination Control Plan

Signature Page

Prepared by:

12/16/13

Chris Lorentson — Date
OSIRIS-REx Project Contamination Control Manager
NASA/GSFC, Code 433

Reviewed by:

David F. Everett 12/16/13

David Everett — Date
OSIRIS-REx Project Systems Engineer
NASA/GSFC, Code 599

Arlin Bartels 2013/12/16

Arlin Bartels — Date
OSIRIS-REx Flight Mgr.
NASA/GSFC, Code 433

Mary Walker 12/18/13

Mary Walker — Date
OSIRIS-REx Instrument Systems Mgr.
NASA/GSFC, Code 433

Ronald Perison 12/12/13

Ron Perison — Date
OSIRIS-REx Chief S&MA Officer
NASA/GSFC, Code 323

Approved by:

12/17/13

Mike Donnelly — Date
OSIRIS-REx Project Manager
NASA/GSFC, Code 433

OSIRIS-REx Mission Contamination Control Plan
Document Change Record

REV/ VER LEVEL	DESCRIPTION OF CHANGE	APPROVED BY	DATE APPROVED
Revision -	Initial Release	CCR 0171	December 2013

OSIRIS-REx Mission Contamination Control Plan
Table of Contents

OSIRIS-REx Mission Contamination Control Plan

1.0 Introduction

The Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx) will characterize the surface features and spectra of near-Earth asteroid Bennu and return a pristine sample of the surface of the asteroid to Earth. Asteroids are the direct remnants of the original building blocks of the terrestrial planets. Knowledge of their nature is fundamental to understanding planet formation and the origin of life. The return to Earth of pristine samples with known geologic context will enable precise analyses that cannot be duplicated by spacecraft-based instruments, revolutionizing our understanding of the early Solar System.

The OSIRIS-REx project is led by the Principle Investigator (PI) at the University of Arizona, and managed by the NASA Goddard Space Flight Center (GSFC). The prime contractor for the OSIRIS-REx spacecraft is Lockheed Martin Space Systems Company (LMSSC) in Denver, CO, which is responsible for spacecraft design, integration of science instruments, the Touch-And-Go Sample Acquisition Mechanism (TAGSAM), the Sample Return Capsule (SRC), launch operations support, SRC recovery, and support of mission operations.

The OSIRIS-REx instruments payload consists of the OSIRIS-REx Camera Suite (OCAMS), the OSIRIS-REx Laser Altimeter (OLA), the OSIRIS-REx Visible and IR Spectrometer (OVIRS), the OSIRIS-REx Thermal Emission Spectrometer (OTES), and a student experiment: the Regolith X-ray Imaging Spectrometer (REXIS). These instruments are provided by the University of Arizona, Canadian Space Agency, GSFC, Arizona State University, and Massachusetts Institute of Technology/Harvard University, respectively. OSIRIS-REx is also composed of the previously mentioned TAGSAM which will collect the sample, and the SRC which will carry the TAGSAM sampler head back to a safe landing on Earth after separation from the OSIRIS-REx spacecraft.

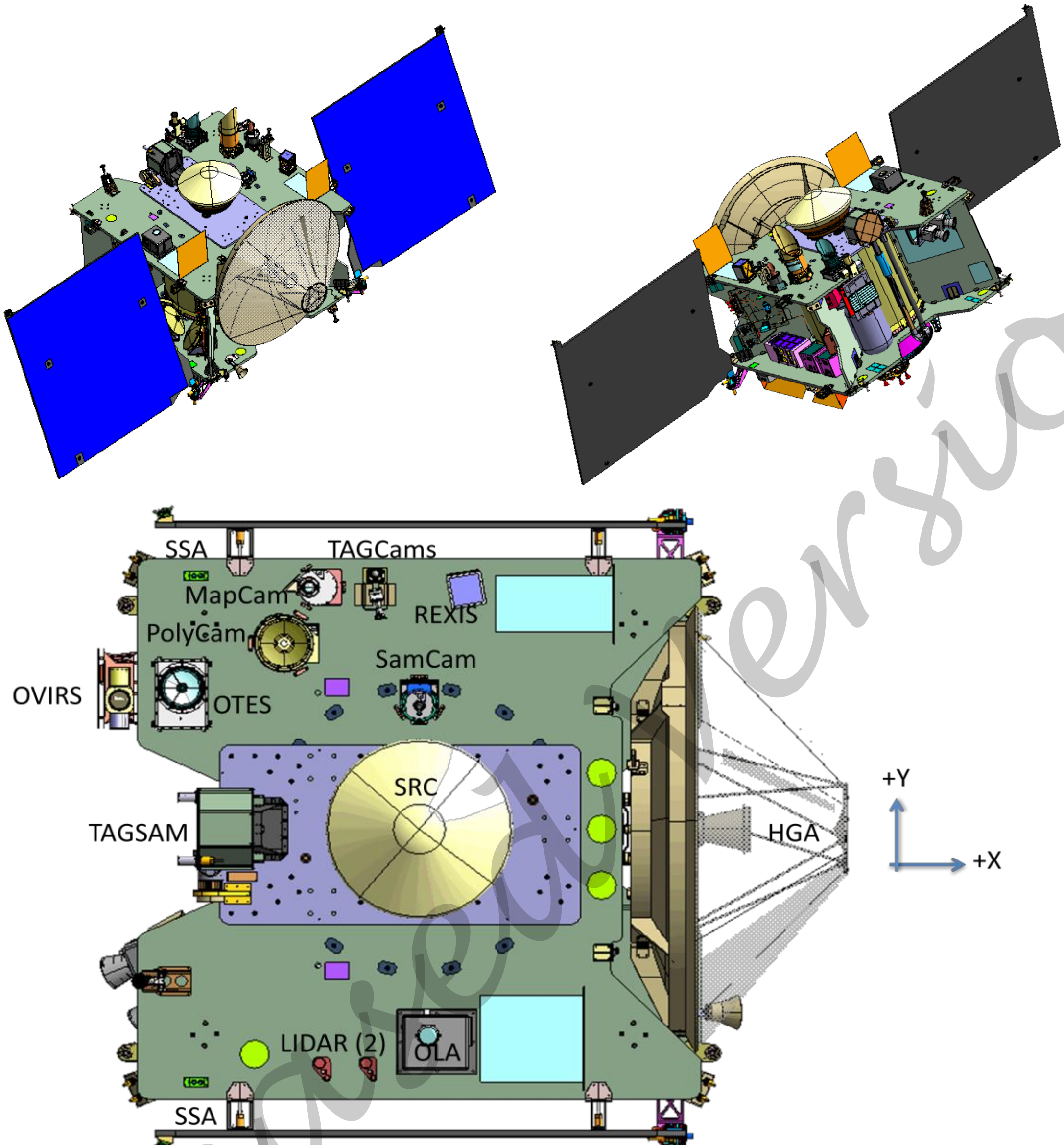


Figure 1-1 OSIRIS-REx S/C and Instrument Suite

OSIRIS-REx will be launched on a NASA Launch Services-II provided Atlas 411 Launch Vehicle (LV) during what is anticipated to be a 39-day planetary launch window opening on or about September 3, 2016. OSIRIS-REx will launch to a C3 of at least 29.3 km^2/s^2, perform an Earth flyby about 1 year after launch, capture in the vicinity of asteroid Bennu in October 2018, sample the asteroid in mid 2019, and depart the asteroid in March of 2021. The samples will be returned to Earth via releasing the SRC for landing at Utah Test and Training Range (UTTR) on or about September 24, 2023.

While planetary protection requirements are Category II outbound and Category V, Unrestricted Earth Return, the organic contamination control requirements will drive Mars-like cleanliness protocols.

The addition of Earth based materials into the sample returned from the asteroid would complicate analysis of the environment and composition of the asteroid. This could hinder the scientific study of the returned sample. For this reason a primary goal of the mission is to return a “pristine” sample of the asteroid for study. Knowledge of what materials we may have added to the sample through flight and ground activities is absolutely critical. For this reason, contamination control is even more essential for this mission than for most. Limiting what terrestrial materials may be integrated with the sample as well as understanding what those materials are is a crucial element to providing a successful completion of this mission.

In order to obtain the most accurate data, the instrument and spacecraft must also operate at peak performance. Adverse particulate and molecular contamination can degrade the analysis of the mission asteroid sample as well as instrument and spacecraft performance. Through a carefully planned contamination control program, the sample acquisition and return hardware, instruments, and spacecraft can be protected from harmful contamination effects.

1.1 Scope of Document

This document defines the OSIRIS-REx contamination requirements necessary for mission success. Methods of contamination control with respect to materials and processes during design, fabrication, assembly, integration, test, and launch for the flight system and its instruments are addressed in this document. Sources of contamination for OSIRIS-REx will be identified and contamination allowances and budgets will be defined. In addition, contamination controls for OSIRIS-REx development and cleaning requirements for OSIRIS-REx hardware will be established. Furthermore, the plan will outline cleanliness monitoring and verification techniques.

This plan also covers transportation of the flight system to the launch site, contamination requirements on the launch vehicle, and contamination requirements during launch site operations. These will be covered in the appendix of this OSIRIS-REx Contamination Control Plan as well as the OSIRIS-REx Launch Services Support Plan (LSSP). Contamination control for OSIRIS-REx at the Payload Processing Facility and at the Launch Pad facilities will also be covered in the appendix.

The use of witness plates and other forms of Contamination Knowledge will be used to limit the impact of contamination transfer to the sample acquisition hardware. This plan will also address methods to develop contamination knowledge and materials archiving to lessen the impacts of stringent contamination control procedures where practical.

1.2 Responsibilities

GSFC is responsible for the cleanliness and overall contamination control program for the OSIRIS-REx mission.

GSFC subcontractor contamination control should be consistent with the approach contained in this document and ensure that necessary contamination control requirements are met.

Lockheed Martin is the OSIRIS-REx spacecraft vendor and shall be responsible for generating a spacecraft contamination control plan consistent with this mission contamination control plan for all spacecraft hardware and flight system integration activities. This spacecraft contamination control plan shall also be consistent with all instrument Interface Requirements Control Documents (IRCD). GSFC will review and approve the spacecraft Contamination Control Plan.

The instruments shall generate an instrument-specific contamination control plan per the OSIRIS-REx Mission Assurance Requirements (MAR) Document. In addition, the instruments shall meet the instrument and spacecraft compatibility requirements referred to in the MAR, the instrument Interface Requirements Control Documents (IRCD), and defined in this contamination control plan, in order to avoid spacecraft to instrument contamination and instrument cross contamination. GSFC will review and approve the instrument Contamination Control Plans. Instrument cleanliness shall be verified upon delivery to OSIRIS-REx flight system.

Instrument cleaning from delivery to launch shall be the responsibility of the Instrument Provider unless a detailed procedure is provided to GSFC and/or LM and negotiated in the hardware element to flight system Interface Control Document (ICD).

Any questions about this document should be directed to the GSFC OSIRIS-REx Contamination Control Manager, Code 546 or the OSIRIS-REx Project Office.

1.2.1 Implementation of Requirements

The following table describes how contamination control and the requirements of this plan are implemented. Referenced manager/engineer is the responsible party at the relevant level of hardware development (Instrument/Spacecraft/Flight system):

Table 1.2.1-1: Implementation

Activity	Responsibility	Verification
Flow down of requirements to subcontractors	Subsystem Engineer	Contamination Engineering
Implement compatibility requirements (i.e. surface cleanliness, outgassing certification, and venting)	Instruments, subsystem engineers, Flight system Manager, ATLO Manager	Contamination Engineering, Quality Assurance
Inspections/Cleaning	ATLO Manager, Contamination Engineering	Contamination Engineering, Quality Assurance
Implementation of facility requirements and appropriate control of work area	ATLO manager	Contamination Engineering
Incorporate requirements into work order authorizations (WOA)	ATLO manager, Subsystem Engineer	Contamination Engineering, Quality Assurance
Incorporate requirements into plans and procedures	Instruments, subsystem engineers, Flight system Manager, ATLO Manager, Contamination Engineering	Contamination Engineering, ATLO Manager
Material lists	Instruments, Subsystem Engineer	Materials Engineer
Facility certification and maintenance	Facilities Contractor	Contamination Engineering, Quality Assurance
Hardware cleaning (GSE and Flight)	Facilities Contractor, Contamination Engineering	Contamination Engineering, Quality Assurance
Facility monitoring	Facilities Contractor	Contamination Engineering, Quality Assurance
Facility Maintenance Restrictions	Environmental Test Engineering and Integration, Contamination Engineering, Facilities Management	Contamination Engineering, Quality Assurance
Purge cart and implementation of instrument purge	ATLO manager	Contamination Engineering
Purge manifold and purge lines on flight system	Mechanical Engineering	Contamination Engineering, ATLO manager
Purging procedure	Contamination Engineering	ATLO manager
Bagging Concept	Mechanical Engineering and Contamination Engineering	ATLO manager
Molecular adsorber mounting and frame hardware	Mechanical Engineering	ATLO manager
Molecular adsorbers	Contamination Engineering	ATLO manager

Activity	Responsibility	Verification
Molecular adsorber and vent close-outs	Mechanical Engineering, Blanket Shop	Contamination Engineering
Verification of Surface Cleanliness Requirements during ATLO	Facilities Contractor , Contamination Engineering	Contamination Engineering, Quality Assurance
Implementation of bake-outs	Subsystem Engineers, Test engineer	Contamination Engineering
Contamination Knowledge Witnesses	Contamination Engineering	Science Team Representative
Materials Archiving	Instrument Manager, Subsystem Engineers	Curation Team

1.3 Applicable and Reference Documentation

The following documents become part of this document to the extent referenced in this document. When a specific version is specified for a referenced document, only that version applies. For undated references, the latest edition of the referenced document applies.

1.3.1 Precedence of OSIRIS-REx Documents

The following applicable documents are in order of precedence. Reference numbers for these documents are listed in Section 1.3.2

OSIRIS-REx Mission Requirements Document
OSIRIS-REx Mission Assurance Requirements
OSIRIS-REx Mission Contamination Control Plan
OCAMS/OVIRS/OLA/OTES/REXIS/Spacecraft Contamination Control Plans
Flight system to Instrument ICD's

1.3.2 OSIRIS-REx Applicable and Reference Documents

OSIRIS-REx-SYS-RQMT-0001	OSIRIS-REx Mission Requirement Document (MRD)
OSIRIS-REx-SYS-RQMT-0003	OSIRIS-REx Mission Assurance Requirements (MAR)
OSIRIS-REx-PLAN-0021	OSIRIS-REx Materials and Process Selection, Implementation, and Control Plan (MPCP)
OSIRIS-REx-ICD-0001	Spacecraft to OCAMS Interface Req. Control Document
OSIRIS-REx-ICD-0002	Spacecraft to OVIRS Interface Req. Control Document
OSIRIS-REx-ICD-0003	Spacecraft to OTES Interface Req. Control Document
OSIRIS-REx-ICD-0004	Spacecraft to OLA Interface Req. Control Document

OSIRIS-REx-ICD-0005	Spacecraft to REXIS Interface Req. Control Document
OSIRIS-REx-SYS-SPEC-000X	OSIRIS-REx Purge System Specification
OSIRIS-REx-SYS-ANYS-000X	Initial Flight system Level Direct Flux Analyses
OSIRIS-REx-SYS-ANYS-000X	Initial Thruster Impingement Analyses
OSIRIS-REx-I&T-PLAN-000X	OSIRIS-REx Spacecraft and Flight system Integration and Test Plan
OREX-DOC-05.01-00005	OCAMS Instrument Contamination Control Plan
OVIRS-PLAN-0018	OVIRS Contamination Control Plan
OTES-CD-0005	OTES Contamination Control Plan
MDA-OLA-PLN-12364 A	OLA Contamination Control Plan
OSIRIS-REx-SYS-PLAN-000X	REXIS Contamination Control Plan
NFP3-PN-11-MA13-1	Spacecraft Contamination Control Plan

1.3.3 Federal Specifications

TT-I-735	Isopropyl Alcohol
FED-STD-209E	Airborne Particulate Cleanliness Classes in Cleanrooms and Clean Zones

1.3.4 Military Specifications

MIL-D-16791	Detergents General Purpose (Liquid, Non-ionic)
MIL-PRF-27401D	Propellant Pressurizing Agent, Nitrogen
MIL-STD-1246C	Product Cleanliness Levels and Contamination Control Program

1.3.5 NASA Specifications

Web site for replacement of NASA Reference Publication 1124	Outgassing Data for Selecting Spacecraft Materials [http://outgassing.nasa.gov]

JSC-SN-C-0005C	Contamination Control Requirements for the Space Shuttle Program
GSFC-TLS-PR-7324-01	Contamination Control Procedures for the Tape Lift Sampling of Surfaces
KTI-5212	KSC Material Selection List for Plastic Films, Foams, and Adhesive Tapes

1.3.6 ISO Documents

ISO-14644-1	Cleanrooms and associated controlled environments - Part 1: Classification of air cleanliness [Replacement for FED-STD-209E - Clean Room and Work Station Requirements, Controlled Environment]
ISO-14644-2	Cleanrooms and associated controlled environments - Part 2: Specifications for testing and monitoring to prove continued compliance with ISO 14644-1 [Replacement for FED-STD-209E - Clean Room and Work Station Requirements, Controlled Environment]
ISO-14644-4	Cleanrooms and associated controlled environments - Part 4: Design, construction and start-up
ISO-15859-3	Nitrogen [Alternative to MIL-P-27401 Propellant Pressurizing Agent, Nitrogen]

1.3.7 Other Specifications

AIAA 91-1977	Cleanliness considerations in the Design, Manufacturing, and Testing of Satellite Surface Tension Propellant Tanks
ASTM E-595	Methods of Test, Total Mass and Controlled Volatile Condensable Materials from Outgassing in a Vacuum Environment
ASTM F-50	Practice for Continuous Sizing and Counting of Airborne Particles in Dust-Controlled Areas and Cleanrooms Using Instruments Capable of Detecting Single Sub-Micrometer and Larger Particles
IEST-RP-CC-006	Testing Cleanrooms
IEST-RP-CC-018	Cleanroom Housekeeping -Operating and Monitoring Procedures
IEST-STD-CC1246D	Product Cleanliness Levels and Contamination Control Program [Replacement for MIL-STD-1246C]

2.0 Contamination Control Requirements

The OSIRIS-REx driving contamination requirements are based on the acquired sample contamination control requirements specified in the MRD. While this is the primary driver for the mission requirements, the instrument contamination requirements, spacecraft contamination requirements, and on-orbit contamination transfer also impact the overall contamination environment. The sample contamination requirements are derived based on the maximum amount of contamination in the acquired sample which will still allow the measurement and evaluation of scientific elements necessary to achieve mission success criteria. Contamination transfer to the sample or associated sample acquisition or return hardware will drive the contamination control requirements when the hardware performance does not establish a more sensitive contamination requirement.

The instrument contamination requirements consist of internal and external requirements that help minimize performance degradation and take into account requirements for instrument optics, instrument detectors, instrument filters, and thermal control surfaces. Spacecraft contamination requirements other than the sample hardware are based on star tracker contamination requirements, allowable thermal control surface degradation, coarse sun sensor performance requirements, and to a lesser extent, solar array performance requirements. In addition, the on-orbit contamination transfer and environmental concerns are also considered in deriving the OSIRIS-REx contamination control approach. Those concerns include: outgassing of materials, venting and vent paths, electrostatic return of molecular contaminants, propulsion effluent from thruster firings, polymerization effects, solar activity, and environments of asteroid orbits.

Design, fabrication, assembly, integration, testing, packaging, transportation and launch site activities will be performed in a manner that minimizes the probability of contaminating contamination sensitive surfaces and samples.

2.1 Overall Contamination Control Requirements

Cleanliness for the OSIRIS-REx instruments and the spacecraft will follow the standards outlined in ISO-14644 [formerly FED-STD-209E], IEST-STD-CC1246D [formerly MIL-STD-1246C], and JSC-SN-C-0005. During all project phases, an active contamination monitoring and verification program will be in effect for flight hardware, using black light and white light inspections, tape lift particulate measurements, image analysis particulate counting, non-volatile residue swab samples, molecular washes, in-situ molecular monitors, and/or witness samples. All instruments, subsystems, and/or components shall meet outgassing certification requirements prior to integration with the flight system. Techniques such as Black and White light inspections, image analysis, tape lift samples, and/or wash samples will be performed on a schedule, as defined in Section 8.2, such that the Flight system will be sustained at the specified levels in section 2.4. Cleanliness levels may be measured using an equivalent Percent Area Coverage [PAC] level as described in Table B-6 if desired.

2.2 OSIRIS-REx Instrument Contamination Requirements

The OSIRIS-REx Instruments mission cleanliness levels are specified in Table 2.2-1. These levels are required to ensure instrument to instrument, and instrument to sample hardware compatibility. This compatibility requirement can be verified via tape lift samples, image analysis, visual inspections, and/or wash samples on representative instrument surfaces. Black and white light inspections if performed should be performed to the criteria of JSC-SN-C-0005 or an equivalent procedure. Some instruments will have stricter requirements on their respective contamination sensitive surfaces than other hardware. Where these requirements are in conflict, the more stringent requirement must prevail where contamination transfer may occur in order to provide the necessary operating environment for all hardware elements.

Table 2.2-1 lists the instrument sensitivity levels as specified by the instrument vendors. These instrument sensitivity levels are taken from the individual instrument contamination control plans and will be included here as a relative estimate of the instrument contamination control requirements necessary for adequate performance of each instrument. Actual mission budgeted cleanliness levels may be more stringent than these requirements in order to restrict harmful contamination transfer to more sensitive surfaces or hardware elements. This budget, including contamination levels at hardware delivery, will be presented later in this plan. Actual instrument sensitivity levels should be verified in the configuration management version of the instrument's Contamination Control Plan if there are any discrepancies.

Table 2.2-1: OSIRIS-REx Instrument Sensitivity Levels.

Note: The instrument sensitivity levels here have been taken from the individual instrument contamination control plans and are to be included here as a relative estimate of the instrument contamination control requirements. Current required cleanliness levels should be verified in the configuration management version of the instrument's Contamination Control Plan.

INSTRUMENT	**COMPONENT**	**BEGINNING-OF-LIFE**		**END-OF-LIFE**	
		Particulate	**Molecular**	**Particulate**	**Molecular**
OCAMS	Internal Surfaces	Level 400	Level D	Level 400	Level D
	External Surfaces	Level 800	Level D	Level 800	Level D
OVIRS	Internal Surfaces	Level 400	Level A/2	Level 400	A
	External Surfaces	Level 400	Level A/2	Level 400	A
OTES	All Surfaces	Level 800	Level B	Level 800	Level D
OLA	External Surfaces	VC-HS	VC-HS	VC-HS	VC-HS
REXIS	All Surfaces	Level 400	Level D	Level 400	Level D
Sample Hardware (for comparison)	All surfaces contacting sample	Level 50 (at final cleaning)	Level A/3 (at final cleaning)	Level 100 (measured at launch)	Level A/2 (measured at launch)

2.2.1 Instrument Outgassing Certification Requirements

The instruments shall meet an outgassing certification requirement during thermal vacuum testing or at the end of the instrument bakeout, prior to delivery to the flight system, as defined in Table 2.2.1-1. The bake-out/outgassing certification performance shall be measured using a temperature-controlled Quartz Crystal Microbalance (TQCM) at chamber pressures below **1×10^{-5}** torr. This device provides information to enable a determination of the duration and effectiveness of the thermal vacuum bakeout as well as measures compliance to the outgassing certification requirements. During certification, the flight hardware shall be maintained at **10** ^{o}C above the maximum allowable flight temperature (AFT) and the TQCM shall be controlled at –**20** ^{o}C or lower throughout the test to measure the total outgassing of volatile outgassed condensables. The TQCM must be mounted within the chamber such that the TQCM has a representative view of the flight hardware or is monitoring the hardware vent. The outgassing certification is required to demonstrate compliance with outgassing levels specified in this document. The purpose of this certification is not only to measure the impact of the instrument on other flight system contamination sensitive hardware, but also to insure that each component will not self contaminate its own sensitive hardware. Any outgassing above the levels specified in this plan may degrade the science and effective performance of one or more components of this flight system. While a bakeout is not strictly required prior to certification, the higher temperatures used in a bakeout phase typically remove contaminants in a more speedy and more efficient manner than an extended certification vacuum period.

The outgassing certification test will be deemed successful when the outgassing rates in Table 2.2.1-1 are achieved for at least **5** consecutive hours during the certification phase. It is also required that a cold finger or scavenger plate shall be used to provide a qualitative assessment of the instrument outgassing effluent at the end of the certification test. The results of the thermal vacuum bakeout / outgassing certification test shall be verified and provided to the OSIRIS-REx Project for approval. The data set shall be recorded at least once every **30** minutes during testing and shall contain, as a minimum, TQCM data, temperature of hardware, chamber/shroud temperature, TQCM temperature, and chamber pressure. In addition, the chamber configuration and cold finger data (qualitative contamination measurement) shall be delivered with the results. All instruments unable to satisfy the outgassing certification requirement must obtain a waiver.

Table 2.2.1-1: Outgassing Requirements for Instruments.

***Note**: The final molecular transport analysis will be completed after CDR. Current values may change following the final revision of this analysis.

Instrument	**Component**	**TQCM temperature**	**Outgassing Certification Rate**
OCAMS	Instrument level	-20C	$\leq 1 \times 10^{-12}$ g/cm^2-s
OVIRS	Instrument level	-20C	$\leq 1 \times 10^{-12}$ g/cm^2-s
OTES	Instrument level	-20C	$\leq 1 \times 10^{-12}$ g/cm^2-s
OLA	Instrument level	-20C	$\leq 1 \times 10^{-12}$ g/cm^2-s
REXIS	Instrument level	-20C	$\leq 1 \times 10^{-12}$ g/cm^2-s
Sample Hardware	Hardware contacting sample	-20C	$\leq 1 \times 10^{-12}$ g/cm^2-s

If the instrument is unable to adequately analyze the chamber configuration to meet these requirements, the OSIRIS-REx project may be able to analytically convert the outgassing certification requirement to an equivalent TQCM rate given the instrument unique test configuration. If this analysis is desired, the instrument will submit the unique test configuration and chamber data to GSFC at least **30** days prior to the outgassing certification test in order to allow adequate time for GSFC to calculate the equivalent TQCM rate. Required data includes: test configuration, chamber dimensions, pumping efficiency, shroud and hardware temperature, location of scavenger plates, cold plates, and cold finger, and location of the TQCM relative to the hardware.

2.2.2 General Instrument Integration and Test Requirements

The instruments shall be integrated to the Flight system in an operational ISO Class **7** (formerly Fed-STD-209 Class **10,000)** cleanroom. If the room is not meeting ISO Class 7 conditions, work shall be delayed until Class 7 conditions can be restored, or the instrument and/or sample return hardware can be suitably protected from enhanced contamination exposure.

Doors, Apertures, Covers

Instrument protective covers will remain on unless integration and test activities prohibit this. Instrument use of protective covers is defined in the Contamination Control Requirements Section of the respective instrument's OSIRIS-REx Flight system to Instrument ICD. Instrument doors, if any, should be opened within a cleanroom determined and approved by the instrument contamination engineer, with the possible exception of thermal vacuum testing.

Bagging

The instruments will be bagged whenever possible. Instrument doors may be opened within a cleanroom determined and approved by the instrument contamination engineer.

Purge

A nitrogen purge shall be available to the instruments during integration, test (except during thermal vacuum testing), and storage. Nitrogen or clean, dry air will be provided during transportation to the launch site. Purge requirements are discussed in Section 8.4. Purge interface requirements can be found in the Contamination Control Requirements Section of the respective instrument's OSIRIS-REx Flight system to Instrument ICD. Purge System descriptions and requirements will also be found in the OSIRIS-REx Purge System Specification. A quick summary is presented below.

Table 2.2.2-1: Purge Requirements for Instruments/Sample Hardware

Component	Purge Required	Purge Rate	Purge Notes
OCAMS	Yes	5 SCFH	N/A
OVIRS	Yes	5 SCFH aperture closed 20 SCFH aperture open	Primarily for Moisture Reduction 1 hour max interruption per incident
OTES	Yes	5 SCFH	1 hour max interruption per incidence
OLA	No	N/A	He purge may be necessary for calibration purposes only during testing
REXIS	No	N/A	N/A
Sample Hardware	Yes	5 SCFH	Purge is to maintain knowledge of contamination exposure

2.3 OSIRIS-REx Spacecraft Subsystem Requirements

Some spacecraft subsystem surfaces are considered to be contamination sensitive. In fact, the sample acquisition and return hardware developed as part of the spacecraft contract are the most contamination sensitive elements on the flight system. These surfaces and their respective contamination sensitivity levels are listed in Table 2.3-1. To prevent cross contamination, the subsystem components listed in the table will be cleaned to the flight system contamination levels or the contamination levels listed in Table 2.3-1, whichever, is cleaner.

In general, the flight system will be maintained at a level **500A/2** per IEST-STD-CC1246D during assembly. During spacecraft integration, all mating surfaces will be cleaned to and verified to level **500A/2** per IEST-STD-CC1246D equivalent using a VC-HS inspection by a person trained in contamination control inspection techniques before becoming inaccessible. All box exterior surfaces, interior to the spacecraft bus, will also be cleaned and verified to IEST-STD-CC1246D level **500A/2** equivalent using the same VC-HS inpsection prior to Flight system integration. Upon completion of integration, all exterior surfaces on the flight system and subsystems not requiring a more stringent cleaning will be cleaned and verified to an IEST-STD-CC1246D level **500A/2.** Tape lifts, image analysis, and wash samples can be taken at regular intervals. Black and white light inspections can also be made frequently during integration to maintain these levels. A detailed cleaning and monitoring schedule can be found in Table 11.2-1.

Table 2.3-1: OSIRIS-REx Subsystem Sensitivity Levels

Sub-System	At Launch			End-of-Life (or sample safely stowed for sample return hardware)	
	Particulates	Molecular	Amino Acid	Particulates	Molecular
Sample acquisition Hardware	Level 100	Level A/3	180 ng/cm^2	Level 100*	Level A/2
SRC Canister (internal)	Level 100	Level A/3	180 ng/cm^2	Level 100*	Level A/2
Instrument Deck	Level 300	Level A/2	N/A	Level 400*	Level A
TAGSAM Hardware not directly contacting sample (rest of SARA)	Level 300	Level A/2	N/A	Level 400*	Level A
Propulsion (Internal)	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Propulsion (External)	VC-HS	VC-HS	N/A	Level 550	Level A
Spacecraft Radiators	Level 500	Level A/2	N/A	Level 550	Level A
Solar Arrays	Level 500	Level A/2	N/A	Level 550	Level A
Star Trackers	Level 500	Level A/2	N/A	Level 550	Level A
Sun Sensors (Coarse)	Level 500	Level A/2	N/A	Level 550	Level A

* NOTE: Neglecting regolith particles from sample collection of the asteroid and those particle generating activities previously anticipated and identified to the science team

2.3.1 Spacecraft Subsystem Outgassing Certification Rates

All flight hardware shall meet outgassing certification rates prior to integration to the flight system per Table 2.3-2. Outgassing rates shall be measured with a TQCM, set at the temperature requirements of -20C, at chamber pressures below **$1x10^{-5}$** torr. All bakeouts will be conducted at the maximum hardware temperature with appropriate safety margin. Outgassing certification shall be done at 10°C above the maximum operational on-orbit temperature. The TQCM shall be mounted within the chamber such that the TQCM has a representative view of the flight hardware or is monitoring the hardware vent. The hardware outgassing certification shall be deemed successful when the outgassing requirements are achieved for at least **5** consecutive hours. For all bake-outs, an 8 hour cold finger (or scavenger plate) sample shall be taken at the end of the certification test prior to vent-back for a qualitative assessment of hardware outgassing effluent at the end of the certification test.

Table 2.3-2: Outgassing Requirements for Spacecraft Components.

*****Note**: The final molecular transport analysis will be completed after CDR. Current values may change following this analysis.

Subsystem	Outgassing rate (g/cm2/sec)	TQCM Temperature (deg C)
High Gain Antenna reflector (Backside is considered MLI)	5×10^{-12} g/cm^2-s	-20
Sample Return Capsule (top surface)	5×10^{-12} g/cm^2-s	-20
Radiators	5×10^{-11} g/cm^2-s	-20
Solar Array Holding Fixtures	5×10^{-12} g/cm^2-s	-20
Solar Array Backside	2.5×10^{-12} g/cm^2-s	-20
Solar Array Cellside	3×10^{-11} g/cm^2-s	-20
TAG Boom ends	5×10^{-12} g/cm^2-s	-20
MLI (Bus and instrument deck)	2.5×10^{-12} g/cm^2-s	-20
Electronic boxes	2.5×10^{-11} g/cm^2-s	-20
Apertures and closeout nodes	1×10^{-12} g/cm^2-s	-20

Support equipment used in the vacuum chamber must meet the minimum flight hardware material requirements (CVCM 1%, TML 0.1%). It is also required that a pre-test chamber bake-out, with ground support equipment and cables, and an outgassing background measurement, with a TQCM, be performed prior to loading the flight hardware in the chamber. This assures that the chamber and ground support equipment will not contaminate the flight system flight hardware and will provide a TQCM background measurement to be subtracted from the TQCM measurements recorded during the actual test. Without the background measurements, the outgassing background in the chamber is assumed to be negligible during the certification test. The pre-test chamber bake-out requirement may be waived by the OSIRIS-REx contamination engineer if chamber cleanliness can be verified by other means.

The results of the thermal vacuum bakeout / outgassing certification test shall be verified and provided to the OSIRIS-REx Project for review. The data set shall be recorded at least once every **30** minutes during testing and shall contain, as a minimum, TQCM data, temperature of hardware, chamber/shroud temperature, TQCM temperature, and chamber pressure. In addition, cold finger and scavenger plate data shall be delivered with the results. All subsystems unable to satisfy the outgassing certification requirement must obtain a waiver. Contact the Contamination Engineer for more test details.

As stated above, OSIRIS-REx Contamination Engineering can analytically convert the outgassing certification requirement to an equivalent TQCM rate given the instrument unique test configuration if the spacecraft vendor is unable to perform this analysis. If this analysis is desired, the subsystem will submit the unique test configuration and chamber data to OSIRIS-REx Contamination Engineering at least **30** days prior to the outgassing certification test in order to allow adequate time for OSIRIS-REx Contamination Engineering to calculate the equivalent TQCM rate. Required Data includes: test configuration, chamber dimensions, pumping efficiency, shroud and hardware temperature, location of scavenger plates, cold plates, and cold finger, and location of the TQCM relative to the hardware

2.4 OSIRIS-REx Flight system Requirements

All flight system surfaces not having a more stringent requirement shall meet an exterior contamination cleanliness level of **500A/2** per IEST-STD-1246C during final assembly and integration. [redacted] (For this mission a trained contamination specialist shall be someone familiar with IEST contamination control procedures who has cleaned and verified highly contamination sensitive hardware in the past. Not simply someone who has cleaned flight or lab hardware at some previous time.) All internal spacecraft surfaces will be cleaned to a level **VC-HS**. Upon completion of integration, all exterior surfaces will be cleaned and verified to level **500A/2** and maintained at that level through testing until launch. Table 11.2-1 contains a detailed cleaning and monitoring schedule.

2.4.1 Flight system Bagging

Because of contamination sensitivities, when the Flight system is outside of an ISO Class **7**/8 (Fed-STD-209 Class **10,000/100,000)** cleanroom, it must be bagged. The only exception is when I&T activities would prohibit bagging. This reason for this exception will included on the work order authorization and shall require OSIRIS-REx Project approval. Additionally, when the flight system is not being worked on in the cleanroom, for an extended period of time, it must be protected with a bag, cover, or drape, if possible, to protect from particulate fallout and minimize required cleanings. During any type of transportation outside the facilities, as in the case of launch site transportation, or during storage, the flight system should be bagged in approved bagging film and stored in a shipping container.

OSIRIS-REx shall be bagged using a contamination and ESD acceptable film. The bags will be designed especially to accommodate the configuration of OSIRIS-REx with special attention to required lifting points. The film may be purchased in a verified clean condition or may be precision cleaned to better than the flight system levels it will contact prior to final assembly in the cleanroom environment (Class 100A/3 is a typical bagging material delivery cleanliness verification level when verified by the vendor). The assembly of the bag will be implemented in the cleanroom. A designated number of bags (minimum of 2 for an additional "double bag" is required, but for "risky" bagging schemes, additional bags may be warranted in case of additional tears during installation) will be made to assure that rupture of a bag being used will not interrupt OSIRIS-REx bagging for a prolonged period.

The bagging concept will be formulated by LM Mechanical Engineering (if support structures are needed) and Contamination Engineering prior to the OSIRIS-REx Flight system Critical Design Review. Final determination of the bagging material and purchased cleanliness condition will be made by LM and approved by the mission CCE.

Individual instrument bags shall be provided by the instrument provider, unless a detailed design analysis is provided to and negotiated with the OSIRIS-REx project prior to integration. These bags will protect the instrument prior to and after integration to the flight system.

The following bagging materials are options to be approved for use on OSIRIS-REx: **Llumalloy** (If still available), Dun-shield 200 by DunMore Corp, or other like material approved by the OSIRIS-REx CCE. Other materials meeting the selection criteria may be approved for use. Selection criteria include ESD, hypergolic compatibility, cleanliness, flammability, and non-shedding. Test methods for evaluating flammability, ESD, and hypergolic compatibility are referenced in KSC document, Material Selection List for Plastic Films, Foams, and Adhesive Tapes. Additional ESD requirements can be found in the OSIRIS-REx Electrical System Specification.

2.4.2 OSIRIS-REx Cleanliness Levels from Assembly to End-of-Life

The following contamination budget table defines internal and external surface cleanliness levels for instruments, spacecraft subsystems and the integrated flight system from instrument delivery to end-of-life. While these levels are the expected contamination levels for the specified hardware, not all budget points will require specific tape lift/NVR rinse verification. These verifications will be required at hardware subsystem deliveries, at the end of integration, and prior to launch. Other budget points may be verified by inspection unless a contamination event has been observed. Additional verifications may be required if deemed necessary by the Project CCE or Flight system CCE with project concurrence. Cleanliness levels presented after launch are detemined by analysis and are verified by analysis only. These analytical values are dependent on well verified hardware cleanliness at launch.

Table 2.4.2-1: OSIRIS-REx Surface Cleanliness Level Budget from Instrument/Subsystem Delivery through Sample Acquisition

Event	External Surfaces	Internal Surfaces
Instruments delivered to Flight system	Level 300A/2	As specified by the specific Instrument CCP unless surface has direct contribution to external surfaces, then Level 300A/2
SRC delivery to SARA	Level 300A/2, 180 ng/cm^2 of amino acids	Level 50A/3, 180 ng/cm^2 of amino acids
Sample Acquisition Hardware delivery to SARA	Level 50A/3, 180 ng/cm^2 of amino acids	Level 50A/3, 180 ng/cm^2 of amino acids
SARA delivery to Flight system	Level 300A/2, 180 ng/cm^2 of amino acids	Level 50A/3, 180 ng/cm^2 of amino acids
Spacecraft Subsystems delivery to Integration	Level 300A/2	Level 300A/2 (instrument deck)
Flight system at start of Integration	Level 300A/2	Level 300A/2 (interior to bus)
Flight system at end of Integration and Test (Instrument deck)	Level 300A/2	Level 300A/2
Flight system at end of Integration and Test (Non Instrument Deck)	Level 500A/2	Level 500A/2
Flight system during Launch Site Preps	Level 500A/2	Level 300A/2 (Instrument Deck)
Flight system at Encapsulation	Level 500A/2	Level 300A/2 (Instrument Deck)
Flight system at Launch	Level 525A/2	Level 325A/2 (Instrument Deck)
Instruments at Launch	Level 325A/2	Level 325A/2
Sample Acquisition and Return Hardware at Launch	Level 50A/3	Level 50A/3
Flight system at Orbit Insertion	Level 575A	Level 400A (Instrument Deck)
Flight system at Sample Acquisition	Level 575A	Level 400A (Instrument Deck)
Instruments at Sample Acquisition	Level 400A	Level 400A
Sample Hardware at Sample Acquisition	Level 100A/2	Level 100A/2

2.4.3 OSIRIS-REx Flight system Thermal Vacuum Testing/ Outgassing Certification

The OSIRIS-REx Flight system will be subjected to flight system level thermal vacuum testing. The OSIRIS-REx Flight system level thermal vacuum test will be performed in a LM approved thermal vacuum chamber. The chamber shall be maintained as an ISO Class **8** or better clean environment. Full cleanroom garments will be worn while working within the chamber.

The thermal vacuum test will be monitored with a series of temperature controlled quartz crystal microbalances (TQCMs) and the following instrumentation: passive fallout coupon samples, cold finger, scavenger plates and optical coupon plates. The outgassing certification portion of the OSIRIS-REx flight system thermal vacuum test will be used to verify the on-orbit contamination analyses. All temperature transitions will be controlled to minimize contamination. In addition, cold plates will be used, as required, to minimize contamination from known high outgassing sources. An analysis will be performed prior to the thermal vacuum test to verify no subsystem or instrument will be susceptible to contamination and so that precautions can be taken to minimize contamination to problem areas.

Support equipment used in the vacuum chamber must meet flight hardware material requirements. A pre-test chamber bake-out, with ground support equipment and cables, and an outgassing background measurement, with a TQCM, shall be performed prior to loading the flight hardware in the chamber. This assures that the chamber and ground support equipment will not contaminate the flight hardware. The pre-test outgassing levels shall be measured and verified to meet the chamber certification levels defined in OSIRIS-REx Flight system Thermal Vacuum Plan.

Outgassing certification rates shall be verified during a hot cycle of thermal vacuum testing. The last hot cycle of the thermal vacuum testing is preferred. During certification, the flight hardware shall be maintained at its maximum on-orbit operation temperature. The hardware outgassing rate shall be measured with a series of TQCMs for at least **5** consecutive hours. The TQCMs must be mounted within the chamber such that each TQCM has a representative view of the flight hardware or is monitoring a hardware vent. The TQCM temperatures shall be defined in the OSIRIS-REx Flight system Thermal Vacuum Plan. If the flight hardware does not meet the outgassing certification requirements, the flight system shall be subjected to a contingency bakeout.

3.0 Contamination Sources and Analyses

Possible sources of contamination must be identified in order to protect OSIRIS-REx from contamination and to effectively clean contaminated components. Table 3.0-1 is a listing of typical possible contamination sources at various development stages.

Quantitative estimates of contamination sources and deposits will be made for critical surfaces through the analyses as listed below. A physical description of the contamination environment (molecular/particulate) of the surrounding critical surfaces will be provided by OSIRIS-REx Contamination Engineering. The analyses will consider the locations, geometry, and operation of sensitive surfaces relative to potential contamination sources.

Table 3.0-1: Contamination Sources for OSIRIS-REx

Mission Phase	Molecular	Particulate
Fabrication	Machining oils, fingerprints, air fallout	metal chips, filings, air fallout, personnel
Assembly and Integration	air fallout, outgassing, personnel, cleaning, solvents, soldering, lubricants, bagging material	air fallout, personnel, soldering, drilling, bagging material
Test	air fallout, outgassing, personnel, test facilities, purges	air fallout, personnel, test facilities, purges, redistribution
Storage	bagging material, purges, containers	bagging material, purges, containers
Transport	bagging material, purges, containers	bagging material, purges, containers, vibration
Launch Site	bagging material, air fallout, outgassing, personnel, purges	bagging material, air fallout, personnel, checkout activities, other payload activities, purges
Launch	Outgassing, venting, launch vehicle	vibration and/or redistribution, launch vehicle
OSIRIS-REx On-Orbit	Outgassing, atomic oxygen, propulsion effluent, glow, electrostatic return, polymerization effects	OSIRIS-REx cloud, micrometeoroid and debris impingement, material erosion

3.1 Thruster Impingement

The spacecraft should be designed to minimize thruster impingement on contamination sensitive surfaces. These surfaces include the sample acquisition site. Thruster firing impacting the acquisition site may degrade the species in the returned sample. Impingement of the thrusters with the actual acquisition sight should be minimized as much as possible. The spacecraft propulsion system will be using ultra-pure hydrazine as a propellant. A preliminary analysis was performed indicating the effects of plume analysis on sample site during the mission phase A period. A follow-up analysis will need to be performed to determine the thruster effluent deposition levels on the sample hardware and instrument exterior surfaces through sample acquisition and mission end of life. The deposition levels shall be no more than **180** ng/cm^{2}on TAGSAM surfaces. The effects from orbit insertion burns, attitude correction burns, TAG events, and any required special maneuvers are to be included in the analyses.

3.2 Atomic Oxygen Effects

The duration of OSIRIS-REx at altitudes that would generate appreciable atomic oxygen erosion of exposed materials is **negligible**. No atomic oxygen erosion requirements are specified for this mission.

3.3 In-Flight Analyses

Contamination mass transport analyses of in-flight contamination will be performed by the GSFC Contamination Engineering for the OSIRIS-REx mission. The molecular impingement rate on sensitive surfaces as well as the total amount of contaminants depositing on those surfaces will be calculated over the life of the mission. The contaminant flux to each instrument aperture, as well as other contamination sensitive surfaces, will be provided to each instrument provider. The mass transport analyses will take into account in-flight outgassing, electrostatic return mechanisms, instrument and spacecraft venting, and propulsion plume impingement. The analyses are to be documented and available for review.

The subsystem and spacecraft outgassing requirements (Tables 2.2.1-1 and 2.3-2) will be derived from the in-flight analyses, based on sample hardware and instruments contamination requirements. In addition, the analyses to be used will verify the effects of the propulsion system and choose the optimal flight system vent locations.

An additional analyzed effect will be to determine those non line-of-sight materials which may impact the sample acquisition hardware and will need to be archived for potential future study.

Mass transport analyses should also be performed for each instrument to determine their acceptable contamination accumulation as well as to determine the potential benefits of any in-flight decontamination procedures.

3.4 Particle Redistribution Analysis

A particle redistribution analysis will be performed by the GSFC Contamination Engineering for the OSIRIS-REx Flight system, if necessary. The analysis will predict particle redistribution on the Flight system due to launch forces, launch vibration, and launch vehicle cleanliness. The change in exterior particulate cleanliness levels on sensitive surfaces during launch will be calculated. This analysis is performed by the launch vendor for each mission. If this analysis is deemed to be adequate, no further analysis will be performed. However, if this analysis is not of sufficient detail, a more refined analysis will be performed as instructed above.

3.5 Venting Analyses

OSIRIS-REx will be using directional venting to aid in contamination control procedures. Since this process does not allow free flow of entrapped air volume, Mechanical Engineering will need to perform an OSIRIS-REx de-pressurization analysis to size the spacecraft vent paths with respect to bus volume. The vents will be sized to keep the maximum delta-pressure on the spacecraft below the allowable pressure differential. Spacecraft vent placement on the spacecraft bus will be determined by the results of this analysis and the output from the molecular mass transport analysis mentioned above. The size and efficiency, if any, of the molecular getters, located in the spacecraft bus, will be calculated as well. Section 4.1.1 provides the details for the spacecraft vent.

In addition, venting analyses will be used to verify instrument and subsystem vent locations to prevent spacecraft to instrument, instrument to sample hardware, spacecraft to sample hardware, and instrument to instrument cross contamination.

A separate venting analysis must also be performed on the Sample Return Canister (SRC) as it must survive not only a depressurization on ascent, but also a re-pressurization event on sample return. This analysis should consider contamination concerns when placing volume vent locations and blanket placement to limit contamination cross transfer.

3.6 Miscellaneous Analyses

A number of other analyses will be performed by either GSFC or LM Contamination Engineering for the OSIRIS-REx program to include:

The OSIRIS-REx thruster impingement analyses will be performed to verify thruster placement with respect to effluent impingement, pressure, and heating effects. Trade study results can be requested from the OSIRIS-REx Contamination Engineer.

Contaminant polymerization studies will be performed by GSFC, if needed, based on the need of the instruments.

4.0 Design, Materials and Processing Requirements

4.1 Venting

The Flight system exterior components, spacecraft vents, and Instruments must be designed such that all outgassing and propulsion plume products are vented away from instruments, sample acquisition hardware, and sensitive parts of the Flight system. Sensitive components include apertures, thermal control surfaces, star trackers, sun sensors, sample hardware, and solar arrays. Correct venting design may require the use of directional venting, baffles, filters and/or labyrinth seals.

Venting analyses will be performed by LM Contamination Engineering and/or Mechanical Engineering to verify instrument and subsystem vent locations in order to prevent cross contamination from improper venting. Details of the instrument vent locations should be defined in the Instrument Mechanical Interface Control Drawings (Mechanical Implementation Details) of each Flight system to Instrument ICD. As much of this spacecraft has an open design, blanket locations will often dictate the location of these vents and should be verified in all ICD documentation.

4.2 Materials

In order to control contamination and protect sensitive surfaces, the use of minimal contaminating materials and the use of covers and protective shields must be considered. Manufacturing materials should be low outgassing, non-shedding and non-flaking. The materials should be chosen from the following web site: http://outgassing.nasa.gov which is a replacement for NASA Reference Publication 1124. Manufacturing materials not listed in the reference publication shall be tested by Code 541, Materials Branch, in accordance to ASTM E595; "Methods of Test, Total Mass and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment".

Materials shall meet the CVCM level of 0.1% and TML of 1.0% by weight, in order to be used in fabrication and assembly. If a material does not meet these standards, it must be discussed with the Contamination Engineer (GSFC 546) and Materials Engineer (Code 541) for a possible waiver.

Additional materials requirements not related to contamination control must also be met. These requirements are specified in the OSIRIS-REx Materials and Processes Selection, Implementation, and Control Plan (MPCP).

4.2.1 Material Restrictions

Materials for flight system design may be limited for a number of reasons. Two primary reasons are general contamination produced and mission specific contamination concerns. For OSIRIS-REx, both concerns are present and may limit the acceptable materials which may be used. This CCP is the primary source for contamination related materials restrictions. Materials restrictions for non-contamination related reasons will be addressed by the OSIRIS-REx Materials Identification and Usage Lists (MIUL) maintained by materials engineering.

4.2.1.1 General Contamination Materials Restrictions

The following materials are known to cause outgassing or surface contact contamination problems and shall be prohibited or the quantity used shall be tightly controlled and demonstrated to not pose a threat to contamination sensitive surfaces.

- Silicones shall be prohibited/limited in areas where mass transport modeling demonstrates that they may be transported to contamination critical surfaces unless specifically approved by the OSIRIS-REx Contamination Engineer and the OSIRIS-REx Materials Engineer. Silicones are difficult to remove using either chemical or vacuum baking cleaning techniques. Silicones may creep due to low surface tensions. Silicones also polymerize into a dark highly absorbing contaminant deposit.
- Silicones used in other areas shall be limited and minimized in quantity. Those used will have the lowest TML and CVCM outgassing properties available for the application.
- Foams
- Non-flight adhesives (in masking tapes, temporary bonding activities, and other fabrication and test activities) for ground operations shall be generally prohibited. Where use is unavoidable, the quantity used will be minimized and all residues shall be removed from flight hardware surfaces as well as any surfaces where there is a possibility of transfer to a flight surface.

In addition, some materials are known particle generators and usage of such materials shall be controlled and monitored, particularly near contamination sensitive surfaces.

- Paints which can become particle generators when improperly applied (e.g., over spray or excessive thickness) or cured (insufficient humidity or temperature or insufficient or excessive curing of a base layer prior to application of second layer). Silicates may present particle

generating hazards.
- Some surfaces become particle generators when over-handled -- e.g., painted surfaces and surfaces with flexible substrates with metallic or paint coatings.
- Paints containing large pigment particles.
- Some dry lubricants
- Surfaces prone to corrosion or oxides.
- Fabrics with brittle constituents (e.g., composites, graphite or glass).
- Perforated materials when insufficient post-cleaning is performed or material is highly susceptible to tear propagation (e.g., MLI).
- Metal oxides (bare (untreated) aluminum and magnesium, iron, non-corrosion resistant steel, etc.).
- Materials containing fabric or fabric scrim (these materials must have all edges sealed with tape if used in optic cavities or near optic cavities.
- Braided metallic or synthetic wires, ropes, slings, etc. (these must be sheathed entirely).
- Woven materials especially cut or unfinished ends (metal braid, EMI shielding, lacing cord, expando sleeving).
- Materials with thin films that might erode or crack and flake (ITO Teflon MLI, metallized packaging materials).

4.2.1.2 Mission Specific Materials Restrictions

Due to the sensitivity of this mission to the contamination environment, several materials have been deemed unacceptable for use on this particular mission. Aside from the materials issues mentioned above, materials which would produce amino acid like materials have also been restricted. Because amino acids are one of the primary focal points of the science data, materials producing these species would degrade the mission science. These materials include Latex, Nylon, and poly**a**mide materials. Poly**i**mides (like Kapton) are acceptable for use however.

4.3 Mechanisms and Deployments

Mechanisms and hardware deployments shall not generate particulate debris or molecular contaminants that will cause adjacent external surfaces or other external contamination sensitive surfaces to exceed their allotted cleanliness levels. Design of internal mechanisms shall restrict or prohibit the venting of lubricant via a labyrinth seal, if possible. In addition, effluent from vents in mechanisms will not impinge upon external contamination sensitive surfaces. Particulate debris generation and molecular contamination generation of mechanisms and hardware deployments will be verified via test data or analyses.

4.4 Processing Requirements

Contamination control measures should be used during all manufacturing phases and storage/transportation. Surfaces should be kept clean, and if any debris is generated during the manufacturing process it should be immediately vacuumed with an ESD compatible vacuum or wiped off with solvent dampened extracted wipes. Some surfaces cannot be wiped with a solvent. ITO is such a surface. Germanium surfaces may be wiped, but require gentle handling. Kapton can be wiped with a solvent dampened extracted wipe without excessive concern for the surface. Black Kapton can be wiped with an extracted wipe dampened with a solvent, but excessive solvent use is not advisable. Detailed information and cleaning procedures for OSIRIS-REx surfaces will be found in the OSIRIS-REx Cleaning and Verification Procedure.

All ground support equipment should be cleaned and inspected to **VC** (visibly clean) per JSC-SN-C-0005 before it enters the cleanroom. Cables should be bagged and all suspect equipment should be precision cleaned. Equipment with cooling fans must remain downstream from sensitive hardware or remain outside of the cleanroom. Support equipment used in the vacuum chamber must meet flight hardware material requirements and will be subjected to a bakeout prior to hardware bakeout and thermal vacuum testing. Whenever hardware is not being worked on for an extended period of time, it should be covered or bagged. Covering materials and drapes must be contamination and electrostatic discharge (ESD) approved. Protective bagging and covering materials at the launch site must also be hypergolic compatible and pass flammability acceptance levels as per KSC requirements. Additional bagging requirements can be found in Section 2.4.1.

All work order authorizations involving hardware-related work on the flight system (including mechanical operations, blanket installation, electrical mating and/or rework, subsystem installation, etc.) must include steps to verify all tools and materials are clean prior to work and are accounted for when work is complete. In addition, a visual inspection for molecular and particulate contamination must be performed and the area cleaned in accordance to the appropriate hardware or facility Cleaning and Verification Procedure.

To prevent electrostatic discharge (ESD) damage to any of the electronic components, precautions beyond contamination control measures will be required. This may mean using antistatic packaging films that also meet the contamination requirements of Section 2.4.1, ESD approved garments, and grounded wrist straps. Additionally, the temperature and humidity of the work environment will have to be controlled. Concerns pertaining to ESD should be brought to the attention of Quality Assurance.

5.0 Contamination Knowledge Requirements

Unlike many other contamination sensitive missions, the particular type and species of contaminant are of significant importance to the OSIRIS-REx mission. For this reason, knowledge of what contaminants and contaminant sources are present is a critical element of the contamination control plan for this mission. These Contamination Knowledge (CK) requirements involve three primary areas. Flight witness plates which will measure the contamination environment in-flight. Ground contamination monitoring plates which will measure the contamination environment while processing during ground operations. And material archiving which will preserve material species for later study should a need arise to study the source of particular contaminating elements which effect the returned sample. Use of the CK element has enabled the contamination requirements presented in this plan to be, while highly stringent, at least achievable.

The CK elements listed above allow the science team for this mission to essentially calculate a contamination "background". This background would show what species and how much of each contaminant was likely present within the sample. This background can then be subtracted from the sample during analysis much like a dark field measurement is usually subtracted from other types of detectors. Knowledge of this background allows a practical level of contamination, to be present and still achieve mission requirements, reducing the cost of contamination implementation of highly stringent cleanliness levels.

5.1 Contamination Knowledge Flight Witness Plates

During the flight portion of the OSIRIS-REx mission, CK data will be accumulated through the use of flight witness plates. To provide representative data, **Flight witness plates** are located by the sample acquisition hardware (TAGSAM head and SRC canister). These plates accumulate species which may be **transferred TO or FROM the sample** and which may hinder future measurements by the science team. The witness plates are composed of two materials (Aluminum, and Sapphire) in order to best collect a representative sample of the CK background. Since each of these materials can be analyzed by different methods, this gives more flexibility to the background calculation.

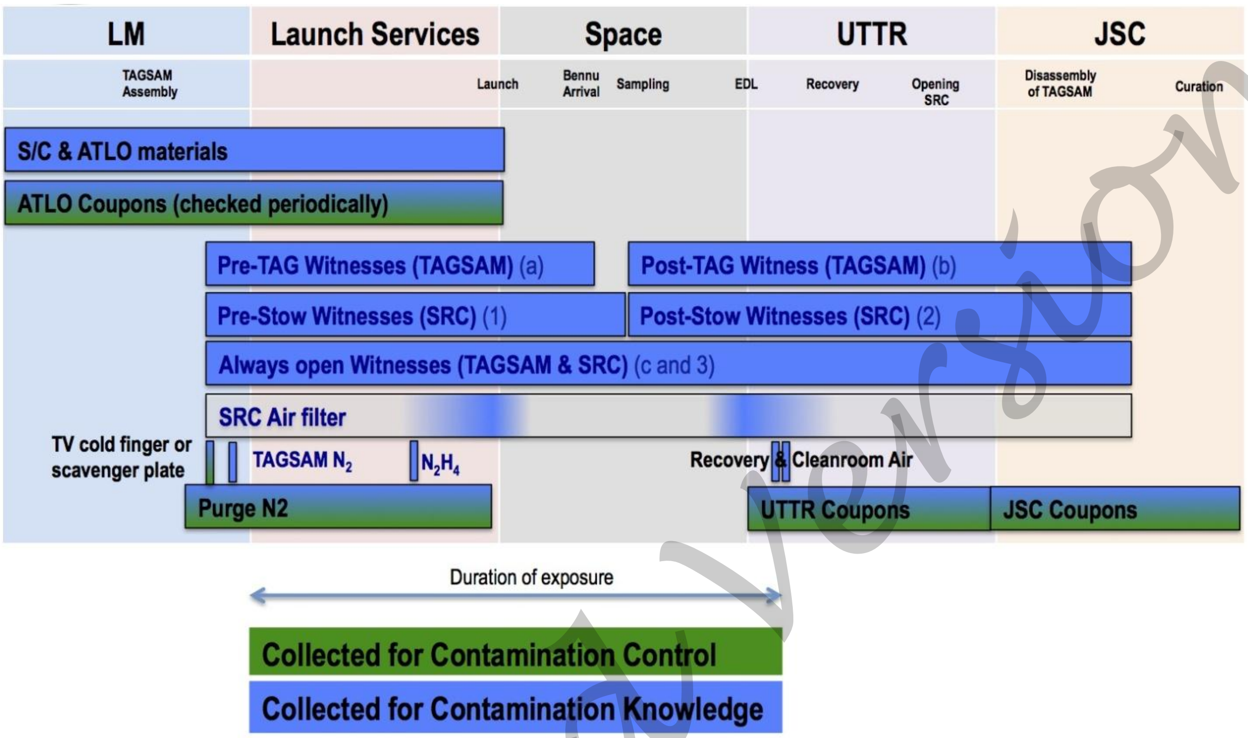
Obtaining CK with a single flight witness plate would be the easiest method, but is not adequate to obtain the most useful background knowledge. Contaminant species accumulated on the witness plate could have been from the spacecraft, from the sample itself, or from a source to which the witness was exposed, but the sample was not. More witness definition is required to separate the effects of these different accumulations. Multiple plates allow the science team to subtract accumulation from different phases in order to better identify contamination sources. Flight witness plates will be required for three time periods of the mission. Each period has a distinct focus and increases the CK of that time period. The comparison of these plates in conjunction with the other plates provides the most complete picture of what the sample has experienced, however any CK developed from any number of these plates has value. If a particular plate is compromised, the others still provide valuable CK as well as some redundancy.

Each of the three time periods is represented on both the TAGSAM and the SRC hardware. These time periods are:

1) Before the mission sample has been acquired.
2) After the mission sample has been acquired.
3) The period between these two is required due to the timing of the Design Reference Mission (DRM).

Table 5.1-1 shows the timeline of exposure for each of these plates. The witness plates located on the TAGSAM head are labeled a, b, and c. The witness plates located on the SRC are labeled 1, 2, and 3. The witness materials and witness exposure period are paired between the two groups. The SRC Air Filter may provide some additional CK to assist with the study of these plates.

Table 5.1-1: Flight Witness Plate Exposure Timeline.



The first time period (1,a) is of general outgassing and molecular transfer from elements of flight hardware **TO** TAGSAM sample sensitive hardware (TAGSAM head, Launch container, and SRC canister (TLS) hardware). These plates show contaminants sources prior to acquisition which may be transferred to the sample. These plates are exposed from encapsulation through sample acquisition. These plates are intended to demonstrate any material which could have accumulated on the TLS hardware, but did not leave via changing environmental conditions and may transfer to the sample by direct contact.

The second period (2,b) is after sample acquisition through recovery. These plates measure contamination which may be transferred **TO** the sample via outgassing **after** the sample has been acquired. These species may also react with the sample directly due to environmental conditions. These plates will also demonstrate any species that may have outgassed **FROM** the sample after acquisition. The combination of these plates with the first period plates can separate out the species lost from the sample from those accumulated from general contamination transfer.

A third set of plates (3,c) is exposed for the entire duration as a “total” accumulated contaminant mass measurement. These plates fill in the gaps in witness exposures 1a and 2b. Gaps arise since the opening and closing of witness plates is driven by other s/c operations (e.g. removing the TAGSAM from the launch container). These plates also provide information on any interactions between the contaminants in group 1 with those from group 2.

5.2 Contamination Knowledge Ground Contamination Monitoring Plates

A series of **ground contamination monitoring plates** will be exposed throughout ATLO to capture the contaminant species to which the hardware was exposed from both known and unknown sources during ground processing. To avoid confusion with the plates used in section 5.1, the plates used for this ground based contamination monitoring and archiving will be referred to as contamination monitoring plates rather than witness plates as is common. These plates will be collected on a regular basis and archived at the mission archive site for potential future analysis. These plates are in addition to the normal facility monitoring plates used to insure proper performance of the clean area. These archived plates will typically be exposed and exchanged on the same schedule and same location as the facility contamination monitoring plates

The contamination monitoring plates will typically be exposed on a monthly basis, but may be exposed for lesser time periods to distinguish critical events. The archived plates will not be cleaned and reused as many contamination monitoring plates are used, but will be stored in as used condition until archived. Both types of plates should be positioned in the cleanroom to accumulate representative samples of what the flight hardware will experience. They should be placed in locations where they will not be touched, handled, or need significant movement during ATLO operations.

These plates will also be used during the recovery phase at UTTR and at the JSC archiving site. Table 5.1-1 lists periods of exposure times for these monitoring plates as well. The green contamination control monitoring plates at UTTR and JSC will be the standard plates used to monitor these facilities for proper cleanroom operation since they will be housing the returned sample and must be adequately controlled.

5.3 Materials Archiving for Contamination Knowledge

Materials which are in direct line of sight to the sample TLS sensitive hardware will need to be archived for later analysis. These materials contain contaminating species which may transfer to the sample and obscure the science data collected via contact transfer or molecular outgassing. This will include all TAGSAM, TAGSAM arm, SRC, and launch container hardware. While much of the science deck of the spacecraft will have a direct line of site to sample hardware during integration operations, transfer from non SARA hardware should be limited to outgassing/offgassing and should be archived by use of the flight witness and ground contamination monitoring plates. Spacecraft hardware archiving lists and specific requirements will be detailed in the OSIRIS-REx spacecraft CCP. A sample of these materials of at least 1 gram shall be saved from the specific material type and lot at the JSC Curation facility. A separate archived sample is required for each unique set of hardware manufacturing conditions. If the hardware was processed at a different time, on a different machine, or using different materials, a new archive sample shall be acquired. Sample archiving acquisition, storage and transport details are given in the OSIRIS-REx Materials Archiving Plan presented as appendix D of this CCP.

Materials which are not direct line of sight but may be transferred to the sample hardware by other means may also need to be archived. This would include any materials which would display significant shedding of particulate material (ie. velcro, foam, or paints with flaking concerns). Lubricants will also need to be archived due to the specific nature of these materials. Lubricant are easily transferred by contact transfer and creep mechanisms. Transfer techniques which are not as present in most other materials. As each of these transfer mechanisms could cause transfer of contaminants to the sample which are not collected on the flight or ground plates, these materials will need to be archived.

For materials that are not line of sight, but may outgas, the archiving of potentially transferred materials is covered by the use of ground and flight contamination monitoring plates and witness samples. For most instrument, and non science deck spacecraft hardware no archiving of these materials is required other than the specific exemptions listed above.

5.4 Contamination Knowledge Requirements for Gases

Gaseous materials used on both the flight system as well as during ATLO activities which encounter the sampler return hardware will also need to be archived. This would include a sample of the purge gas used during ATLO, the nitrogen used in sample acquisition, and the purge gas used during retrieval and archiving at the curation facility. A sample of these materials of at least 1 gram shall be saved from the specific material type and lot at the JSC Curation facility. Sample archiving acquisition, storage and transport details are given in the OSIRIS-REx Materials Archiving Plan portion of this document (Appendix D).

5.5 Materials Archiving of the Hydrazine Thrusters

Due to the reactive nature of the hydrazine material, keeping a sample of this gas for archiving will not adequately represent the material as used during either flight or fabrication. The material is likely to react with the environment and may pose a risk to the curation facility personnel. For this reason a detailed analysis of the gas will be archived, and a fired thruster will be archived as well. These will be the representative sample of the thruster environment experienced by the sample. Sample archiving acquisition, storage and transport details are given in the OSIRIS-REx Materials Archiving Plan portion of this document (Appendix D).

5.6 Archiving of Contamination Monitoring Solvent rinse/washes

Because the solvent rinses used in cleaning the flight hardware are a good representative sample of the materials on the surface, a sample of these rinses will also need to be archived for potential future study. While not every rinse needs to be archived, the primary and final cleaning of sample hardware acquisition components should be archived. In addition, a sample of the scavenger plate rinse from thermal vacuum testing of the sample hardware, or flight system hardware should also be archived. A sample of these materials of at least 1 gram shall be saved from the specific material type and lot at the JSC Curation facility. Sample archiving acquisition, storage and transport details are given in the OSIRIS-REx Materials Archiving Plan portion of this document (Appendix D).

5.7 Coordination with Science Team CK Plan

As scientific study is always a changing process, the details laid out for contamination knowledge in this plan may need to be changed based on future analysis. As this plan is intended more as a definition of how to implement the processes needed to collect contamination knowledge information rather than the study of the CK itself, all requirements must be coordinated with the OSIRIS-REx Contamination Knowledge Plan provided by the mission Science team. If these plans are in conflict, the Contamination Knowledge Plan shall take precedence for CK collection activities.

6.0 Cleanroom Facilities and Operational Requirements

Integration of OSIRIS-REx shall occur in both an ISO Class 7(Fed-Std-209 Class 10,000) as well as an ISO Class8(Fed-Std-209 Class 100,000) or cleaner facility. When the TLS sample acquisition hardware or sensitive instrument hardware must be exposed, the facility must be a Class 7 facility. During periods when the sensitive hardware is being protected or the TLS hardware is not present, a Class 8 facility may be used. The facility shall provide a HEPA filtered bank at the ISO certified flow rate for the specified cleanroom class. Air flow shall be vertical, from top to bottom whenever possible. The most sensitive hardware will be placed closest to the HEPA filters in the cleanroom and less sensitive hardware will be kept downstream from the more sensitive hardware. Typical cleanroom temperature should be maintained at 72 +5/-10°F and the relative humidity should be maintained at 30 to 50%.

Spacecraft hardware and ground support equipment shall be cleaned to the required levels by Contamination Control Technicians in a precision cleaning room. All hardware cleaned in the precision cleaning room shall be double bagged for transportation to the cleanroom facility if not within the cleanroom facility. For convenience, a precision cleaning station may be set up outside the cleanroom facility where appropriate.

The following subsections detail the typical operations of this type of cleanroom for this class of mission. Following the specific techniques in these sections will insure the proper operation of the cleanrooms used to house mission hardware at acceptable levels. While the specific techniques in these sections are more guidelines than specific requirements, the areas covered must be addressed in all cleanrooms used on this mission. Providing a method to address the proper operations specified in these sections is a requirement and if the following techniques are not used, an approved alternate method must be presented and approved by the mission CCE.

6.1 Cleanroom Garments

Personnel entering the cleanroom are required to use a shoe cleaner, walk on a series of tacky mats, and use the air shower if available. Cleanroom type garments will be worn in the cleanroom at all times. The best garments are usually made of polyester and are efficient particulate filters to human generated contamination. In addition, garments must meet ESD standards. Full cleanroom garments, including bunny suits, face masks, hoods, boots, and gloves shall be worn on the OSIRIS-REx program when in an ISO Class 7 (Class 10K) cleanroom or when the TLS hardware is exposed. This garmenting is highly recommended in all other cleanroom environments as well. Details on gowning and personnel operation procedures will be found in the specific facility Personnel Operations Procedure.

6.2 Non Volatile Residue Levels in the Facility

Monitoring of the molecular cleanliness level (typically NVR level) of the cleanroom is necessary to insure the cleanroom does not adversely contaminate the OSIRIS-REx hardware. Molecular contamination monitoring plates (or foils) are typically used to monitor the molecular contamination level in the facility. At least **2** plates will be exposed at any given time. The plates will be analyzed **once** per month, staggered so one plate is measured every **60** days. The acceptable level of NVR on the plate after 2 months is **Level A** per IEST-STD-CC1246D, **1 mg/0.1m^{2}.**

Amino acid specific residue testing shall also be performed once the SARA hardware is present in the facility. Prior to SARA being in the facility, no amino acid testing is required as all hardware shall be cleaned prior to integration with the flight system. This residue is measured on foils specially prepared for this use. The foils will be provided by the GSFC science team, or may be prepared by the vendor if the appropriate preparation techniques can be implemented on site with the approval of the GSFC science team. These monitoring foils shall be placed within the facility for exposure of a minimum of 60 days and shall not exceed 180 ng/cm^2 when analyzed. These foils will need to be analyzed by GSFC science team either at the LM facility or via shipment of the foil samples to GSFC. The vendor is NOT required to perform this analysis.

6.3 Particle Counts in the Facility

The facility environments will be continuously monitored with a particle counter near the personnel work area. If the particle counts exceed the room specification (Class 7 or 8), personnel will leave the facility and/or contamination-generating operations will stop, as directed by the Integration and Test Manager, the Integration and Test Manager's representative, or Quality Assurance. If facility in house monitoring is not available, a suitable portable particle counter placed near the hardware is also adequate. If continuous monitoring cannot be made available, a well defined regular schedule of monitoring shall be provided for approval. Non continuous monitoring shall require more frequent inspections of the hardware be performed to insure no contamination events have occurred. The less frequent the monitoring, the more frequent the inspections must be performed. Initial calibration of the cleanroom alone is not adequate to monitor the proper operation of the cleanroom. This would allow the cleanroom to operate out of spec without any indication of a contamination event until it has already caused a significant disruption and possible damage to the hardware.

6.4 Cleanroom Maintenance

A properly maintained facility will be cleaned a minimum of twice per week or more often as necessary. The cleanroom will be vacuumed, than mopped with deionized water and low-residue, non-ionic detergent. Scaffolding and other work fixtures will be cleaned at that time. **LM** will perform the facility cleaning operations during flight system integration using the procedures outlined in the facility Personnel Operations Procedure at all LM facilities. Launch site facility cleaning schedules and responsibilities will be detailed in the launch site contamination control plans listed in appendix C of this document.

6.5 Support Materials

Tools, GSE, and any other items containing materials that shed, slough, or flake particles or outgas molecular contaminants at room temperature are prohibited from the clean room. The cleanliness requirements for tools and GSE are given in Section 8.1.

In addition, only non-retractable ball point pens should be used for writing in the cleanroom. Documents needed in the cleanroom will be on lint-free cleanroom paper, cleaned, and bagged for transport. If this practice is not possible, the documents shall be bagged and sealed in clean bagging material and remained bagged while in the cleanroom. All documents shall be kept downstream of flight hardware.

Additional material and personnel regulations will be found in the facility Personnel Operations Procedure. Where there is any conflict with these requirements, the more stringent requirement will prevail.

6.6 Facility/Maintenance Restrictions During ATLO

The following table describes the facility and maintenance restrictions while OSIRIS-REx is in the ATLO complex. While these restrictions are not specifically imposed on the instrument vendors, the restrictions posted in this table can help prevent contamination events and should be followed whenever possible.

Table 6.6-1 Facility/Maintenance Restrictions

Activity	Restrictions	Restriction Time Period
Combustion Engine Operation Standard Operations (Mowing Grass, normal deliveries)	No restrictions	From OSIRIS-REx assembly to shipping date
Combustion Engine Operation (Buses, idling trucks, etc)	Not permitted outside near air intakes	From OSIRIS-REx assembly to shipping date
Combustion Engine Operation Non-standard Operations (cranes, forklifts, trucks, construction, generators, etc)	Need Approval. May be allowable depending on location of flight hardware	From OSIRIS-REx assembly to shipping date

Activity	Restrictions	Restriction Time Period
Herbicides / Pesticides	Not permitted outside/inside ATLO Complex.	From 1 months prior to OSIRIS-REx assembly to shipping date
Painting (exterior)	Ask for approval prior to painting outside ATLO Complex	From 2 weeks prior to OSIRIS-REx assembly to shipping date
Painting (interior)	Ask for approval, some complex locations acceptable.	From 2 weeks prior to OSIRIS-REx assembly to shipping date
Roofing / Roofing Repairs	None within ½ mile of ATLO Complex	From 2 weeks prior to OSIRIS-REx assembly to shipping date
Paving	None within ½ mile of ATLO Complex	From 2 weeks prior to OSIRIS-REx assembly to shipping date
Facility floor cleaning/stripping/waxing	Ask for approval. Not permitted within building housing OSIRIS-REx flight hardware.	From OSIRIS-REx assembly to shipping date
Facility Floor Maintenance (Pouring/replacing/repairing floors)	Ask for approval within complex	From 2 weeks prior to OSIRIS-REx assembly to shipping date
Solvent usage in ATLO high bay	Non typical solvent use (i.e. IPA, Acetone, Freon) requires approval	From OSIRIS-REx assembly to shipping date
Sealants, caulks (Windows, bathrooms, ceiling tiles, HEPA filters, etc)	Ask for approval within ATLO Complex	From 2 weeks prior to OSIRIS-REx assembly to shipping date
Adhesive bonding, gluing (installation of carpets, base board molding, flooring, etc)	Restricted in ATLO complex; Ask for permission based on specific location within building	From 2 weeks prior to OSIRIS-REx assembly to shipping date
Sandblasting, sanding, grinding, jack hammering	Not permitted near air intakes in ATLO Complex	From 2 weeks prior to OSIRIS-REx assembly to shipping date
Repair, replacement, or lubricant of cleanroom equipment (Air handling equipment, cranes, doors, etc)	Ask for approval. Not permitted within building housing OSIRIS-REx flight hardware.	From 2 weeks prior to OSIRIS-REx assembly to shipping date

Activity	Restrictions	Restriction Time Period
Use of equipment with air bearing	Notify project to allow protection of critically sensitive operations if in same facility	From OSIRIS-REx assembly to shipping date
Fluorescent lamps	Lamp tubes must be encapsulated and cannot be handled within the cleanroom environment	From 2 weeks prior to OSIRIS-REx assembly to shipping date

7.0 Contamination Control during Fabrication and Assembly

7.1 OSIRIS-REx Instruments during Fabrication and Assembly

The Instrument Providers are responsible for the Contamination Control of their instruments during instrument fabrication and assembly at the instrument facilities. The Instrument Providers are also responsible for instrument transportation to LM per the instrument contamination control plan and other applicable instrument documentation. Instruments shall be delivered to the flight system meeting the cleanliness compatibility requirements specified in Section 2.2.

The Instrument Providers shall supply an instrument Contamination Control Plan to detail the contamination requirements and contamination control procedures necessary to insure proper performance of the instrument hardware. This document shall be the guiding document during instrument fabrication and assembly operations.

7.2 OSIRIS-REx Spacecraft during Fabrication and Assembly

OSIRIS-REx spacecraft will be provided by LM-Denver. The Spacecraft Provider shall provide a spacecraft contamination control plan (CCP) which will be the guiding document during spacecraft fabrication and assembly operations. The spacecraft and all subsystems shall be delivered to the flight system meeting the cleanliness compatibility requirements specified in Section 2.3-1 and Section 2.4.2-1.

To facilitate the ability to maintain these levels, the spacecraft shall generally be maintained at level **500A/2** per IEST-STD-CC1246D throughout the fabrication process where more stringent cleanliness requirements are not specified for sensitive hardware elements (ie SARA, SRC, and sample TLS hardware). This cleanliness level may be verified at most times by meeting VC-HS inspection by a contamination trained individual. The cleanliness level must be verified prior to delivery for integration and following the completion of integration operations. As surfaces become inaccessible they must pass an inspection to VC-HS and be cleaned if necessary to level **500A/2** per IEST-STD-CC1246D or better prior to final closeout. VC-HS inspection by a contamination trained individual shall be deemed equivalent to, or better than level 500 A/2 for these periods.

The following guidelines apply during spacecraft and subsystem fabrication and assembly.

Internal electronic box level and board level fabrication and assembly shall be governed by the proven cleanliness practices of the box vendor.

During manufacturing operations such as machining, welding and soldering contaminants should be cleaned off of the hardware by wiping and/or vacuuming. Lubricants and cutting oils (i.e. oils and greases) should be cleaned off as soon as possible after the manufacturing operation using appropriate solvents. Prior to priming or painting, the surface should be cleaned free of particulate or molecular deposits and be inspected to VC-HS as an equivalent for level **500A/2** per IEST-STD-CC1246D. If an area becomes inaccessible during fabrication, it must be cleaned and inspected to this same level before becoming inaccessible. Upon completion of a fabrication operation, the components will be subjected to a gross cleaning procedure involving solvent washes and particulate removal. The clean fabricated components will then be bagged.

Assembly of fabricated components will take place in an ISO Class8(FED-STD-209 Class 100,000) facility. During assembly, parts will be inspected and cleaned to **VC-HS,** unless required to be cleaner, prior to becoming inaccessible. The following guidelines should be adhered to in the assembly process.

Parts, surfaces, holes and so forth must be cleaned with isopropyl alcohol (IPA) moistened wipes or swabs. Only approved wipes, that are low in particulate generation and low non-volatile residue, shall be used. Wiping should be in one direction only and each pass should be with a new clean area on the existing wipe or using a new wipe. In some instances, wipes will be ineffective and extracted swabs moistened with alcohol may be used. Cleaning will continue until all surfaces are visibly clean, highly sensitive upon inspection. Any cleaning of painted surfaces will be done according to the procedure recommended by the manufacturer or be performed by the responsible hardware vendor. Prior to any final assembly, all surfaces must be vacuumed and wiped with the appropriate solvent, giving special attention to holes, crevices and riveted regions. Assemblies will be inspected for oil or grease deposits, and if any are found, the areas will be wiped with IPA moistened wipes or other appropriate solvent, using a clean wipe area for each pass and wiping in one direction.

7.3 OSIRIS-REx Flight system during Fabrication and Assembly

The Flight system integration will occur in the LM ATLO complex in both an ISO Class7(FED-STD-209 Class 10,000) facility as well as an ISO Class8(FED-STD-209 Class 100,000) facility operated as an ISO class 7 facility at various times. Parts from a less controlled fabrication and assembly area will be cleaned to VC-HS or the required levels defined in Tables 2.3-1 and 2.4.2-1, prior to entry into the cleanroom.

Accessible areas of the [redacted] Parts that have been machined, welded, or riveted will be inspected to a general **VC-HS** level with white and black lights, or to the required more stringent IEST-STD-CC1246D level prior to entering the cleanroom.

Solar panels, coarse sensors and radiators will be cleaned according to the OSIRIS-REx Spacecraft CCP approved procedure. Instrument providers are responsible for instrument cleaning during flight system operations, unless permission and a detailed cleaning procedure are provided to OSIRIS-REx, or LM contamination control engineering.

8.0 Contamination Control during Integration and Test

OSIRIS-REx will be integrated at LM in the ATLO Complex. Integration will occur in both ISO Class 7 (FED-STD Class 10,000) and Class 8(FED-STD Class 100,000) facilities. Room temperatures will be in the 72 +5/-10°F range and typical humidity requirements are 30 to 50%. Personnel working in the cleanroom will wear full cleanroom outfits, booties, hoods, masks and approved gloves. When working with solvents, polyethylene or low NVR Nitrile gloves should be worn. Latex gloves shall not be used on the OSIRIS-REx mission. Detailed gowning procedures and personnel operating procedures will be posted if different than standard operating procedures for the facility. The approved bagging materials for the OSIRIS-REx mission are listed in Section 2.4.1.

8.1 Ground Support Equipment

Tools and Ground support equipment (GSE) required for testing will be cleaned to **VC** per JSC-SN-C-0005C with IPA and prior to entry into the cleanroom. If the precision clean area is not attached to the cleanroom, the tools shall be bagged for transport to the cleanroom. Large pieces of GSE may be cleaned and inspected outside the facility roll up door and immediately taken into the cleanroom after cleaning and inspection, without being bagged. In addition, tools and GSE that comes into contact with flight hardware must be inspected to **VCHS** level under black light and white light per JSC-SN-C-0005 prior to entering the cleanroom. If at any time, the tools or GSE become visibly contaminated, the hardware will be re-cleaned and inspected. Any GSE that will come into direct contact with the sample acquisition TLS hardware must be be more thoroughly cleaned to insure these highly sensitive parts are not contaminated. These tools shall be cleaned as detailed above, but this inspection must performed by a contamination trained individual whose cleaning technique has been verified to meet IEST-STD-CC1246D Level 300 prior to allowing these tools contact with this hardware.

Tools and GSE containing materials that shed, slough, or flake particles or transfer or outgas molecular contaminants at room temperature are prohibited from the clean room. Critical ground support equipment containing fans must be positioned downwind from the instrument module, spacecraft, and/or flight system with respect to the HEPA filters. Printers are not allowed in the cleanroom. Additional material restrictions can be found in Section 4.2.1.

8.2 Contamination Control Flow

The Contamination Control Flow throughout integration and test can be found in Figure 8.2-1 TBD. Figure 8.2-1 will be a simplified OSIRIS-REx integration and test flow and is intended to show cleanliness inspections and cleanings with respect to activities, not detailed integration and test activities. Detailed integration and test flow can be found in the OSIRIS-REx Assembly, Test, and Launch Operations (ATLO) Plan.

Figure 8.2-1 Contamination Control Flow throughout the I&T process
TBD

8.3 OSIRIS-REx Instruments during Integration and Test

Prior to delivery to the flight system, all OSIRIS-REx Instruments must pass the outgassing certification requirement as defined in Section 2.2.1. If the instrument outgassing requirements are not met, the instrument must obtain a waiver from the OSIRIS-REx Project/Contamination Engineer or be baked-out to the required levels. Upon delivery to the flight system the instrument exterior cleanliness level will be inspected to the levels in Section 2.2. Instruments not meeting the cleanliness requirements must be cleaned by their instrument support team and then re-inspected.

Instrument bench acceptance testing will be performed in an ISO Class **7**(Fed-Std-209 Class **10,000**) clean tent or cleanroom environment for the contamination sensitive instruments. The instrument will be purged per the requirements in the respective Spacecraft to Instrument IRCD. Following these inspections and testing, the instrument will be bagged and delivered to the appropriate cleanroom facility for integration.

If needed, the instruments will be continuously purged with dry, filtered nitrogen throughout integration and test, as required and defined in the instrument to spacecraft ICD. If the purge must be interrupted, the duration of the interruption shall not exceed instrument requirements. Instrument personnel will inspect instruments to the cleanliness levels in Section 2.2, per the schedule in Section 11.2. If an instrument does not meet the required cleanliness level, the instrument shall be cleaned until it meets the requirement. The instruments will be bagged and purged(if required) during all periods of inactivity, or if the hardware is outside of the cleanroom. If an instrument or hardware is removed from the cleanroom for testing in an unbagged condition, or some other reason such as calibration, it must be re-verified to the external cleanliness requirements in Section 2.2 or 2.3, before it can reenter the cleanroom. **The instrument support team** is responsible for cleaning and maintaining their respective instruments during flight system integration and testing. Flight system personnel will only clean external instrument surfaces with specified direction and permission as well as a detailed written procedure from the instrument provider.

8.4 Purging Requirements

A nitrogen purge will be available for OSIRIS-REx instruments as required, during integration and test until launch. The nitrogen purge will be filtered to **0.5** microns or smaller and shall conform to MIL-PRF-27401D, Grade **C** and ISO 15859-3 or an approved equivalent standard. It may be necessary to switch the purge gas from nitrogen to clean, dry air for instrument purging during transportation to the launch site for safety reasons. At the launch site the use of a t-0 purge line will be necessary.

The purge interfaces and purge rates will be defined in the Flight system to Instrument Interface Control Documents. The purge system, purge panel, and associated safety requirements will be defined in the OSIRIS-REx Purge System Specification or equivalent LM purge specification document.

8.5 Integration of Subsystems and the Flight system

All subsystems and/or components must meet an outgassing certification requirement prior to integration per Section 2.3.1. At the time of integration, components or subassemblies will be inspected to their required cleanliness levels. All spacecraft hardware and ground support equipment shall be cleaned, by the appropriate support personnel, prior to the hardware entering the designated integration facility.

Oils, greases and other similar agents that may be contamination hazards will not be used during integration without the permission of the Contamination Engineer. Joints or crevices will be covered during integration to minimize the build up of contaminating debris. Rivets, bolts, nuts and so forth must be cleaned to remove any type of contamination such as lubricants and machining oils prior to integration and test.

Frequent white light and black light inspections will be made during integration to ensure that the flight system is maintained at the levels specified in Sections 2.3 and 2.4. All fluorescent and "black" lamps used to perform inspections must be adequately encapsulated for use around the OSIRIS-REx hardware.

The completed flight system will be cleaned to the levels as specified in Sections 2.2, 2.3, and 2.4. Direct sampling of the flight system surfaces can involve taking tape lifts, solvent wash samples, swab samples, image analysis, and black/white light inspections. Particular attention should be given to areas, which will become inaccessible during integration. All areas as they become inaccessible will be cleaned to the required cleanliness levels defined in Section 2.3. The cleaning procedures may entail vacuuming, CO_2 snow cleaning, and/or solvent wiping.

The flight system (except attach points) should be bagged per Section 2.4.1 with approved bagging film during crane operations.

8.6 Test Facilities

Following integration, OSIRIS-REx will be subjected to environmental testing. Figure 8.2-1 will be a simplified flowchart of the environmental testing sequence. In the testing facilities, the instruments will be bagged individually when possible and continuously purged with nitrogen where required. If an instrument has an aperture cover, these covers should be installed whenever possible. In addition, the flight system will also be bagged, when possible. Testing facilities will be held at 72 +5/-10°F temperature and 30 to 50% humidity conditions. If a particular test requires the removal of bagging, the facility will be cleaned and the personnel who come in contact with the flight system and instruments must be wearing cleanroom bunny suits, booties, hoods, masks and gloves. If solvents are used, polyethylene or low NVR nitrile gloves (often blue) must be worn. Latex gloves (often yellow), or rubber (black), etc shall not be used with OSIRIS-REx.

8.6.1 EMC/EMI Facility

At LM, the EMC/EMI facility is an ISO Class 8 (Class 100,00) Clean Zone (TOCZ) operated with Class 7 (Class 10,000) protocols. Personnel requiring access to the facility may need additional cleanroom training. The facility has humidity and temperature control. The instruments and spacecraft shall remain bagged as much as possible, unless integration and test activities in the EMC/EMI room prohibit bagging. The instruments will be purged continuously where required.

8.6.2 Vibration Cell

The vibration cells are not cleanroom facilities; however, they will be operated as a Class 8 clean area through facility cleanings, materials restrictions, and implementation of personnel cleanroom protocol. Full cleanroom garments will be worn. Personnel in the facility will be limited. The cell will be cleaned prior to flight system arrival and maintained clean while the flight system is in the facility. The doors to the cell will remain closed to maintain the room cleanliness, unless operations require temporary door opening. The instruments will remain bagged and purged at all times while in the vibration cell. The flight system will be bagged as much as possible, unless prohibited by test activities.

8.6.3 Acoustic Facility

The Acoustics Facility is classified as a Class 8 clean area through facility cleanings, materials restrictions, and implementation of personnel cleanroom protocol. All personnel working in the acoustics facility will wear full cleanroom garments. The room shall be cleaned prior to flight system arrival and maintained clean while the flight system is in the facility. The instruments will remain bagged and purged at all times. The flight system will be bagged as much as possible, unless prohibited by test activities.

8.6.4 Thermal Vacuum Chamber

The **SSL 65'** thermal vacuum chamber will be operated as a Class **7** cleanroom due to the requirement for exposure of sensitive hardware elements during this test. Additional cleanroom training may be required by personnel working in the chamber, to become familiar with unique chamber protocol and restrictions. All personnel will enter the chamber through a gowning area. Full cleanroom garments will be worn. Personnel will be kept to a minimum inside the chamber. A ground support equipment, tool, and hardware cleaning station will be set up outside the gowning area. Care must be taken to account for all materials, tools, and equipment brought in and out of the chamber. The chamber will be cleaned and inspected prior to loading OSIRIS-REx into the chamber. A crane may be used to load OSIRIS-REx into the chamber. The flight system must be draped with clean bagging film anytime the chamber lid is opened during thermal vacuum preparations. The chamber will be inspected and re-cleaned, if necessary, after all work is completed prior to closing the doors. The red tag covers on contamination sensitive components shall be removed at the last possible moment. The instruments will remain bagged and purged until the last possible moment prior to closing the chamber doors.

Contamination monitoring during the flight system thermal vacuum test is addressed in Section 2.4.3. As specified in that section, the chamber must have a pre-test certification of the outgassing rate, including GSE, prior to loading the OSIRIS-REx flight system into the chamber. All test instrumentation shall be installed on the flight system in an ISO Class 7 facility or comparable clean area prior to moving the spacecraft to the thermal vacuum chamber. After installation of instrumentation is complete, the flight system will be double bagged and transported to the chamber.

9.0 Contamination Control during Transportation and Storage

After delivery, all instruments will be bagged and purged during storage or transportation. Subsystems and subassemblies, which do not have any special requirements for handling and storage prior to integration, will be cleaned to their respective cleanliness requirement and bagged unless integration or test activities prohibit it. All systems will be stored in an air-conditioned area with controlled access. The flight system will be bagged with approved bagging material per Section 2.4.1 when outside of the cleanroom, unless integration and test activities prohibit it.

For transportation outside the LM ATLO complex, the flight system shipping container will be used for protection. The flight system shipping container will be pre-cleaned, prior to use, to Level **VCHS per** JSC-SN-C-0005C**.** Nitrogen or dry, filtered ultra high purity air will be used to purge the shipping container per the OSIRIS-REx Purge System Specification and the instrument interface control documents. Temperature and humidity will be controlled and monitored in the shipping container to meet OSIRIS-REx flight system requirements. In addition, particulate contamination monitoring plates and NVR monitors will be mounted inside the shipping container to monitor the contamination environment during transportation.

10.0 Contamination Control at the Launch Site

The details of the contamination control procedures to be used during launch site processing will be added as Appendix C of this plan. The OSIRIS-REx launch site contamination control requirements for the flight system, the facilities, and the launch vehicle will be delineated in this Appendix. The OSIRIS-REx Contamination Engineer, launch vehicle team, and the launch vehicle and facilities staff will coordinate the launch site activities to be presented in the Appendix. Further details will also be provided in the Launch Services Support Plan (LSSP) which focuses more on what materials are supplied by each mission group.

The launch site plan will minimize contamination generation whenever possible. Instrument soft/hard covers will remain in place during Launch Site operations whenever possible. The current baseline is to remove these covers immediately prior to fairing encapsulation.

T-0 purges will remain in place whenever possible in order to meet the purge requirements of the instruments and mission hardware.

11.0 Implementation of Contamination Control Requirements

The Integration and Test Manager, Quality Assurance, and Contamination Engineer will be responsible for ensuring that contamination control measures are implemented throughout the design, fabrication, assembly, integration, testing, storage and transportation of the OSIRIS-REx mission.

11.1 Cleanliness Inspection and Monitoring Methods

Cleanliness inspection and monitoring methods, which will be used for the OSIRIS-REx mission, are contamination monitoring plates; optical witness samples (OWS), black and white light inspections, washes, swab sampling, tape lifts, and a real time Non-Volatile Residue monitor. Descriptions of these techniques are as follows:

Contamination Monitoring Plates (or foils):

Contamination Monitoring Plates are used to determine particulate levels, particle fallout rates, amino acid residue levels, and Non-Volatile Residue (NVR) levels. Contamination Monitoring plates collect particulates passively during cleanliness monitoring procedures. Contamination Monitoring plates should be placed as close as possible to contamination sensitive areas, to obtain the most accurate particulate readings. The spacecraft particle monitoring plates at GSFC are generally silicon wafers because of the image analyzer's ability to process the wafers and determine pretest cleanliness. Occasionally, Teflon grids are used. Facility fallout plates are usually 1 ft^2 stainless steel plates that are washed and analyzed for molecular or particulate contamination. Amino acid plates are typically pyrolyzed ($500^oC > 12$ hrs in air) aluminum foil. The foils are usually a 4 cm^2 area cut out of a larger foil area in order to avoid adhesives on the edge surfaces. These foils are typically placed into tared glass tubes and mailed to GSFC for analysis.

Optical Witness Samples:

Optical Witness Samples (OWS) consist of quartz glass with a thin film of aluminum and a magnesium fluoride coating to represent an optical surface. Molecular contamination is allowed to deposit on the samples during cleanliness monitoring. After monitoring, the reflectance degradation of the optical witness samples is measured.

Light Inspections:

Visual Inspection is done periodically using black (UV) light or white light. Visibly clean, using white light is the absence of all particulates and non-particulates visible to the normal unaided eye (except corrected vision). The three levels of visibly clean and observational distances are listed in Table B-1. UV inspection light sources are no less than 100 watts and located no more than 50cm from the inspected item. During UV inspection, light from other sources should not be more than 5 ft-candles. If visual contamination is evident, the hardware must be cleaned and then re-inspected under the same light conditions. If during UV inspection there is any evidence of fluorescence the item/surface must be re-cleaned. If re-cleaning does not reduce the fluorescence, it must be determined whether the fluorescing material is a contaminant or the substrate surface.

Washes:

A surface, which is to be inspected, is washed with alcohol or an appropriate solvent and the solvent and residue is collected. This rinse is then subjected to quantitative and qualitative analyses and the type of contaminant residue is chemically identified.

Tape Lifts:

Tape lift samples are taken of the inspection surface to determine the surface particulate cleanliness level according to IEST-STD-CC1246D. The tape lift samples are prepared, taken and read by an approved tape lift procedure. Tape lifts can not be taken on painted surfaces, ITO coated surfaces, or on other delicate coatings.

Real Time Non-Volatile Residue Monitor:

A real time non-volatile residue monitor can be utilized on the OSIRIS-REx Program. The monitor can measure NVR build up over time. The NVR is measured electronically with a surface acoustic wave sensor. This monitor can be placed in the vicinity of the flight system.

11.2 Verification and Cleaning Schedules

Cleanliness verification and monitoring will occur as listed below at a minimum and more frequently if the OSIRIS-REx Contamination Control Manager deems that extra cleanliness monitoring is necessary. The hardware surfaces will be inspected for compliance to the cleanliness requirements in Table 11.2-1. If the contamination levels on the hardware exceed the cleanliness requirements, a cleaning will be scheduled. Each cleaning will be conducted under a work order authorization developed for the specified cleaning or as a step in a more extensive procedure. The cleanings shall be performed by Contamination Control Technicians or by the OSIRIS-REx Contamination Engineering Group. The detailed cleaning procedures can be found in the hardware approved cleaning and verification procedure. The instrument providers will be notified for cleanliness inspections and hardware cleanings affecting or in the vicinity of their instrument. Results from the inspection methods and cleanliness verification on the flight system will be provided to the instrument providers. Instrument unique cleanliness verification and contamination monitoring plate change-out will occur per the requirements in the respective Flight System to Instrument ICD. The instrument providers are responsible for cleaning the instruments unless permission is given and a detailed cleaning procedure is provided.

Table 11.2-1: Verification and Cleaning Schedule

Reason for Inspection or Cleaning	**Item to be inspected or cleaned**	**Cleanliness Requirement**	**Method**
Instrument Delivery	Instrument	300 A/2	Tape Lift/NVR Rinse
Sub-System Delivery	Sub-Systems	300 A/2	Tape Lift/NVR Rinse
Integration	Instrument, Sub-Systems, Flight system	VC-HS	Inspection
Post Integration	Flight system	VC-HS	Inspection
Vibration Testing	Flight system	VC-HS	Inspection

Post Vibration Testing	Flight system	VC-HS	Inspection
Acoustics Testing	Flight system	VC-HS	Inspection
Post Acoustics Testing	Flight system	VC-HS	Inspection
Pre-Thermal Vac	Flight system	VC-HS	Inspection
Thermal Vac	Flight system	VC-HS	Inspection
Post Thermal Vac	Flight system	VC-HS	Inspection
Post Mass Properties	Flight system	VC-HS	Inspection
Pre-Ship	Flight system	500 A/2	Tape Lift/NVR Rinse
Shipping	Flight system	VC-HS	Inspection
Transportation	Flight system	VC-HS	Inspection
Launch Site	Flight system	500 A/2	Tape Lift/NVR Rinse

12.0 Employee Training

Contamination Control and Cleanroom Practices training should be conducted for all personnel involved in the fabrication, assembly, integration, testing, transportation, storage, and launch site activities of the OSIRIS-REx instruments, subsystems and flight system. Areas which can be studied in the training sessions are as follows: Definition of contamination and how it affects the OSIRIS-REx mission; the importance of maintaining contamination control from fabrication through launch; reviewing instrument and subsystem sensitivities; knowledge of the instrument and spacecraft contamination control plans and related contamination documents; specific techniques for cleaning, inspection, and packaging; monitoring techniques in the cleanroom and in the shipping containers; and cleanroom dressing procedures and rules for working in a controlled cleanroom area.

APPENDIX A: Acronyms and Definitions

A.1 Acronyms

BOL	Beginning of Life
CCM	Contamination Control Manager
CPT	Comprehensive Performance Test
CVCM	Collected Volatile Condensable Materials
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EOL	End of Life
ESD	Electrostatic Discharge
FED-STD	Federal Standard
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
HEPA	High Efficiency Particulate Air
ICD	Interface Control Document
IPA	Isopropyl Alcohol
I & T	Integration and Test
ITO	Indium Tin Oxide
LM	Lockheed Martin
MAR	Mission Assurance Requirements
MIL-STD	Military Standard
MLI	Multi-Layer Insulation
NASA	National Aeronautic and Space Administration

NVR	Non-Volatile Residue
OSIRIS-REx	Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer
OWS	Optical Witness Sample
PAC	Percent Area Coverage
QA	Quality Assurance
TML	Total Mass Loss
T/B	Thermal Balance
TBD	To Be Determined
TBR	To Be Resolved
TLS	TAGSAM head, Launch Canister, SRC Canister
T/V	Thermal Vacuum
TQCM	Temperature-Controlled Quartz Crystal Microbalance
UHP	Ultra High Purity
UV	Ultraviolet
VC	Visibly Clean
VC-HS	Visibly Clean – Highly Sensitive
WOA	Work Order Authorization

A.2 Definitions

Action Level	The Maximum allowable contamination level set by the user in the context of controlled environments and cleanliness, which, when exceeded, requires immediate intervention, including investigation of cause, and corrective action.
Alert Level	The contamination level set by the user in the context of controlled environments and cleanliness, giving early warning of a potential drift from normal conditions. NOTE: When alert levels are exceeded, this should result in increased attention to the process.
Cleanroom	Room in which the concentration of airborne particles is controlled to specified limits.
Cold Finger	A cold finger is used in vacuum tests to provide qualitative and quantitative information about the molecular environment of the vacuum chamber at the end of the test. It is a stainless steel cylinder of known surface area, typically 1 ft^2, which is flooded with LN_2 during the last 8 hours a test. When flooded, the cylinder resides at ~80 K and collects any molecules that hit the cylinder and are condensable at that temperature. When the chamber is brought back to ambient, the cold finger is rinsed with a solvent, and the residue is analyzed to determine its mass and constituents. The results from cold finger analyses are used to determine if any unexpected molecular contamination is present.
Contamination	Any unwanted material that causes degradation in the desired function of an instrument or flight hardware.
Contamination Control	Organized action to control the level of contamination.
Fiber	A fiber is a particle whose length-to-width ratio exceeds 10:1 with a minimum length of 100 microns.
Gross Cleaning	Cleaning hardware surfaces to visual inspection standards.
Molecular Adsorber	A zeolite-coated ceramic honeycomb used to adsorb outgassed molecular contaminants. It is also known as a molecular sieve.
Nitrogen Purge	Pressurized flow of clean, dry nitrogen through a system in order to displace impurities and reactive species.

Non-Volatile Residue	Soluble material remaining after evaporation of a volatile liquid which usually causes degradation in the desired function of an instrument or flight hardware.
Flight system	The flight system consists of the complete OSIRIS-REx flight assembly, all OSIRIS-REx instruments, and all subsystem hardware and bus components.
Particle	A particle is a small quantity of solid or liquid material which has a definable shape or mass with a length to width ratio less than 10:1.
Particle Size	(1) The apparent maximum linear dimension of a particle in the plane of observation, as observed with an optical microscope; (2) The equivalent diameter of a particle detected by automatic instrumentation. The equivalent diameter is the diameter of a reference sphere having known properties and producing the same response in the sensing instrument as the particle being measured; (3) The diameter of a circle having the same area as the projected area of a particle, in the plane of observation, observed by image analysis; (4) The size defined by the measurement technique and calibration procedure.
Percent Area Coverage	An alternative method of specifying particle concentration levels on a surface. PAC is the fraction of the surface that is covered by particles. Percent area coverage is reported as the sum of the projected areas of the particles divided by the total surface area.
Precision Cleaning	Precision cleaning is cleaning procedure done in a controlled environment to attain a specific level of cleanliness. This procedure follows gross cleaning.
Sensitive Surface	Any surface of flight hardware that must meet a specified cleanliness level to assure the minimum performance levels.
Solvent Flushing	Method of cleaning surfaces with a stream of filtered solvent under pressure, which is directed against a surface to dislodge and rinse away any foreign material.
Solvent Washes	A quantitative method of verifying IEST-STD-CC1246D molecular cleanliness levels by measuring molecular contamination in a solvent, which was washed over a surface and collected.
Spacecraft	The spacecraft refers to all bus components, structure, electronic boxes, communication hardware, propulsion hardware, and attitude control subsystem hardware in an integrated assembly, not including instruments.

Surface Cleanliness Level	An established level of maximum allowable particulate and/or NVR contamination ranging from visibly clean to specific IEST-STD-CC1246D levels (e.g., Level 100A, etc. as shown in Figure B-1 and Tables B-4 and B-5).
Swab Sample	A qualitative method of identifying contaminants by analyzing the residue on a solvent-soaked swab that was wiped over a surface.
Tape Lifts	A quantitative method of verifying IEST-STD-CC1246D particulate cleanliness levels by measuring particulate contamination on a sample of tape that has come in contact with the surface one wishes to examine.
Vapor Degrease	Item to be cleaned is exposed to heated solvent vapors that condense on the part and wash away contaminant.
Visibly Clean	The achievement of a clean surface as seen without optical aids (except corrected vision) as measured by a specified method.

APPENDIX B: Reference Tables and Figures

Table B-1: Visibly Clean Levels and Inspection Criteria
(from JSC-SN-C-0005C)

VC Level	Incident Light Level (1)	Observation Distance	Remarks
Standard	≥ 50 foot-candles	5 to 10 feet	(2) (3) (5)
Sensitive	≥ 50 foot-candles	2 to 4 feet	(2) (3) (5)
Highly Sensitive	≥ 50 foot-candles	6 to 18 inches	(3) (4)

NOTES:

(1) One foot-candle (lumens per square foot) is equivalent to 10.76 lumens per square meter.

(2) Cleaning is required if the surface in question does not meet VC under the specified incident light and observation distance conditions.

(3) Exposed and accessible surfaces only.

(4) Initial cleaning is mandatory; Note (2) applies thereafter.

(5) Areas of suspected contamination may be examined at distances closer than specified for final verification.

Table B-2: Cleanroom Class limits (from ISO 14644-1)

Selected airborne particulate cleanliness classes for cleanrooms and clean zones

ISO Classification Number (N)	Maximum concentration limits (particles/m^3 of air) for particles equal to and larger than the considered sizes shown below (concentration limits are calculated in accordance with equation (1) in 3.2*)					
	0.1µm	0.2 µm	0.3 µm	0.5 µm	1 µm	5 µm
ISO Class 1	10	2				
ISO Class 2	100	24	10	4		
ISO Class 3	1 000	237	102	35	8	
ISO Class 4	10 000	2 370	1 020	352	83	
ISO Class 5	100 000	23 700	10 200	3 520	832	29
ISO Class 6	1 000 000	237 000	102 000	35 200	8 320	293
ISO Class 7				352 000	83 200	2 930
ISO Class 8				3 520 000	832 000	29 300
ISO Class 9				35 200 000	8 320 000	293 000

NOTE: Uncertainties related to the measurement process require that concentration data with no more than three significant figures be used in determining the classification level.

* $C_n = 10^N \times [0.1/D]^{2.08}$

Where:

C_n is the maximum permitted concentration (in particles per cubic meter of air) of airborne particles that are equal to or larger than the considered particle size. C_n is rounded to the nearest whole number, using no more than three significant figures.

N is the ISO classification number, which shall not exceed a value of 9. Intermediate ISO classification numbers may be specified; with 0.1 the smallest permitted increment of N.

D is the considered particle size, in micrometers.

0.1 is a constant, with a dimension of micrometers.

Table B-3: Cleanroom Class limits (from Fed-STD-209)

AIRBORNE PARTICULATE CLEANLINESS CLASSES

Class limits are given for each class name. The limits designate specific concentrations (particles per unit volume) of airborne particles with sizes equal to and larger than the particle sizes shown*

Class Name**		Class limits									
		0.1 µm		0.2 µm		0.3 µm		0.5 µm		5 µm	
		Volume units		Volume units		Volume units		Volume units		Volume units	
SI	English***	(m^3)	(ft^3)	(m^3)	(ft^3)	(m^3)	(ft^3)	(m^3)	(ft^3)	(m^3)	(ft^3)
M 1		350	9.91	75.7	2.14	30.9	0.875	10.0	0.283	–	–
M 1.5	1	1 240	35.0	265	7.50	106	3.00	35.3	1.00	–	–
M 2		3 500	99.1	757	21.4	309	8.75	100	2.83	–	–
M 2.5	10	12 400	350	2 650	75.0	1 060	30.0	353	10.0	–	–
M 3		35 000	991	7 570	214	3 090	87.5	1 000	28.3	–	–
M 3.5	100	–	–	26 500	750	10 600	300	3 530	100	–	–
M 4		–	–	75 700	2140	30 900	875	10 000	283	–	–
M 4.5	1 000	–	–	–	–	–	–	35 300	1 000	247	7.00
M 5		–	–	–	–	–	–	100 000	2 830	618	17.5
M 5.5	10 000	–	–	–	–	–	–	353 000	10 000	2 470	70.0
M 6		–	–	–	–	–	–	1 000 000	28 300	6 180	175
M6.5	100 000	–	–	–	–	–	–	3 530 000	100 000	24 700	700
M 7		–	–	–	–	–	–	10 000 000	283 000	61 800	1 750

*The class limits shown in Table I are defined for classification purposes only and do not necessarily represent the size distribution to be found in any particular situation.

**Concentration limits for intermediate classes can be calculated, approximately, from the following equations:

$$\text{particles}/m^3 = 10^M (0.5/d)^{2.2}$$

where M is the numerical designation of the class based on SI units, and d is the particle size in micrometers, or

$$\text{particles}/ft^3 = N_C (0.5/d)^{2.2}$$

where N_C is the numerical designation of the class based on English (U. S. customary) units, and d is the particle size in micrometers.

***For naming and describing the classes, SI names and units are preferred; however, English (U.S. customary) units may be used.

Figure B-1: Cleanliness Levels (from IEST-STD-CC1246D)

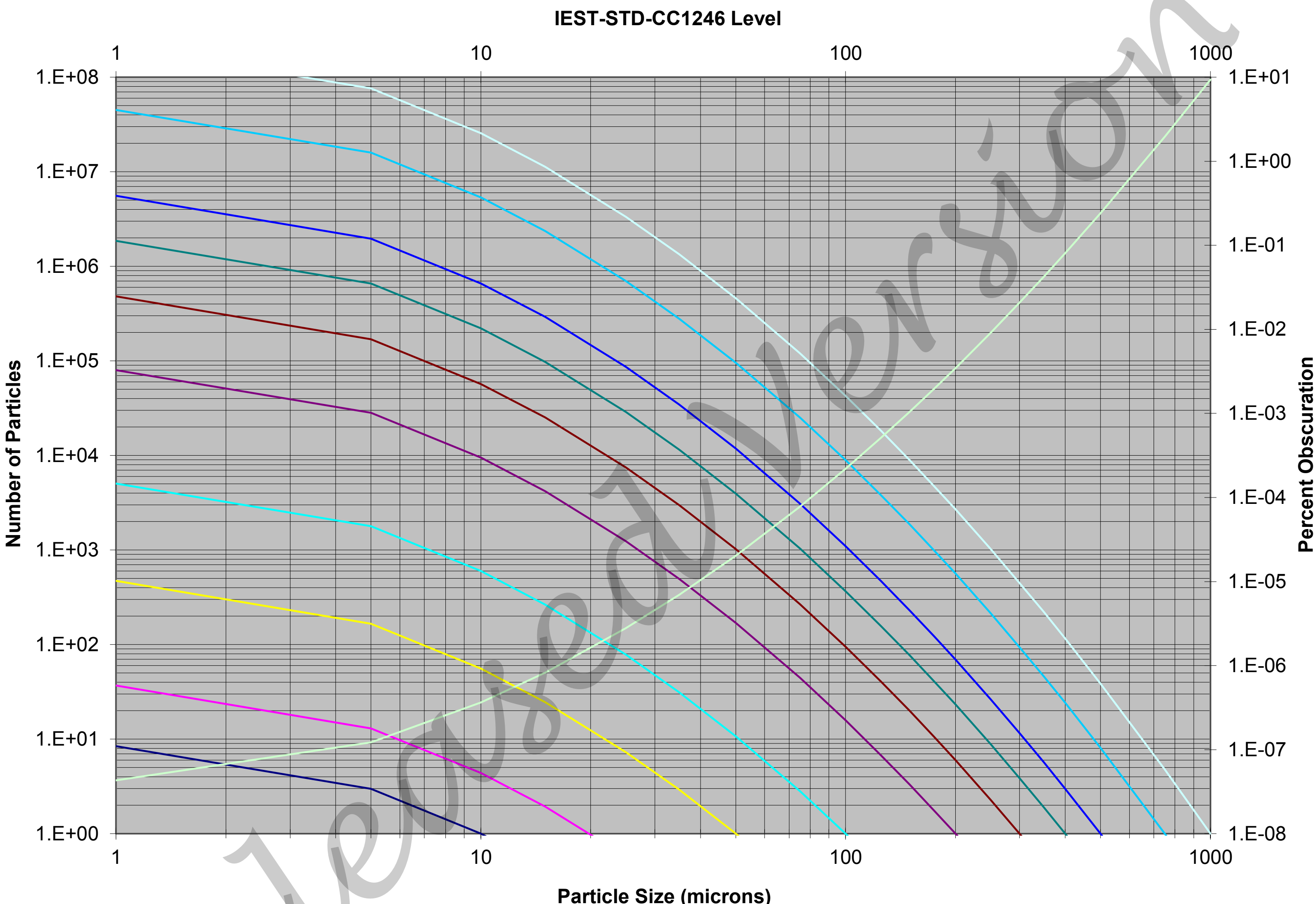


Table B-4: Classification of Levels (from IEST-STD-CC1246D)

Particulate Cleanliness Levels

Level	Particle Size, µm	Count per 1 ft^2	Count per 0.1 m^2	Count per liter
1	1	1.0	1.08	10
5	1	2.8	3.02	28
5	2	2.3	2.48	23
5	5	1.0	1.08	10
10	1	8.4	9.07	84
10	2	7.0	7.56	70
10	5	3.0	3.24	30
10	10	1.0	1.08	10
25	2	53	57	530
25	5	23	24.8	230
25	15	3.4	3.67	34
25	25	1.0	1.08	10
50	5	166	179	1660
50	15	25	27.0	250
50	25	7.3	7.88	73
50	50	1.0	1.08	10
100	5	1785	1930	17850
100	15	265	286	2650
100	25	78	84.2	780
100	50	11	11.9	110
100	100	1.0	1.08	10
200	15	4189	4520	41890
200	25	1240	1340	12400
200	50	170	184	1700
200	100	16	187.3	160
200	200	1.08	10	1.0
300	25	7455	8050	74550
300	50	1021	1100	10210
300	100	95	103	950
300	250	2.3	2.48	23
300	300	1.0	1.08	10
500	50	11817	12800	11817
500	100	1100	1190	11000
500	250	26	28.1	260
500	500	1.0	1.08	10
750	50	95807	105000	958070
750	100	8919	9630	89190
750	250	214	231	2140
750	500	8.1	8.75	81
750	750	1.0	1.08	10
1000	100	42658	46100	426580
1000	250	1022	1100	10220
1000	500	39	42.1	390
1000	750	4.8	5.18	48
1000	1000	1.0	1.08	10

Table B-5: Classification of Cleanliness Levels (from IEST-STD-CC1246D)

Non-volatile Residue Cleanliness Levels

Level	Limit, NVR mg/0.1m^2 1/ (or µg/cm^2)	Limit, NVR Mg/liter
A/100	0.01	0.1
A/50	0.02	0.2
A/20	0.05	0.5
A/10	0.1	1.0
A/5	0.2	2.0
A/2	0.5	5.0
A	1.0	10.0
B	2.0	20.0
C	3.0	30.0
D	4.0	40.0
E	5.0	50.0
F	7.0	70.0
G	10.0	100.0
H	15.0	150.0
J	55.0	250.0

1/ Limits on non-volatile residue (NVR, mg) for surface, liquid, or gas to meet the level of cleanliness.

(One square foot = 0.0929m^2)

Table B-6: Cleanliness Levels versus PAC

Cleanliness Level *	Percent Area Coverage
100	0.00022
200	0.0035
300	0.020
350	0.044
400	0.080
450	0.14
500	0.24
550	0.4
600	0.6
650	0.9
700	1.4
750	2.0

* Per IEST-STD-CC1246D

APPENDIX C: Launch Site Contamination Control Procedures

TBD

APPENDIX D: Materials Archiving Plan

Instructions for archiving items for contamination knowledge during ATLO
JSC will provide pre-cleaned Teflon bags (or other container), Teflon tape, and forms to fill out and include with the items to be archived. Bags range in size from 6"x6" to 12"x12" to 18"x18" to 24"x24". If a bag is an inappropriate container, pre-cleaned glass vials, aluminum or stainless steel containers can be sent. Please contact Righter and/or Nakamura-Messenger to discuss and identify the appropriate container and size.
The form will include the following information, which will ultimately be entered into the JSC database:

Date: Location: Person:

Item and location on spacecraft or SRC:

MEL#:

Material:

Size and/or weight:

Reason for archiving:

Manufacturer: Lot#:

Manufacturer URL or other contact information:

Bag type: Bag size:

Vial type: Vial size:

Photographs attached? Y N

Any special handling required?:

Specific comments to add to the database:

Item should be handled with nitrile gloves, placed in the bag (or container), bag sealed with Teflon tape, labeled clearly, and then sent along with the form to JSC:
Kevin Righter
Mailcode KT
NASA Johnson Space Center
2101 NASA Parkway
Houston, TX 77058
281-483-5125

The originator of the form and item to be archived should also email Kevin Righter (Kevin.righter-1@nasa.gov) and Keiko Nakamura-Messenger (Keiko.nakamura-1@nasa.gov) to notify them that the item(s) has(have) been sent to JSC so they can anticipate their arrival.

Online Supplemental Materials 2

Summary table of materials archived for contamination knowledge analysis. Details on each component and how to request samples will be available at https://curator.jsc.nasa.gov/ prior to OSIRIS-REx sample return.

Generic	Major Comp.	Description	Material Desc.	Sample Size
OR-MA-0001	OTES Instrument	Rotary actuator internal to OTES instrument	Lubricant; Christo-Lube MCG-117	~ 1 g
OR-MA-0002	Spacecraft	Solar array panel structural assy +y	Honeycomb Composite	10 cm^2
OR-MA-0003	Spacecraft	Solar array panel structural assy -y	Honeycomb Composite	10 cm^2
OR-MA-0004	SRC	Latch claw SRC	Aluminum	10 cm^2
OR-MA-0005	SRC	Latch claw SRC	Aluminum	10 cm^2
OR-MA-0006	SRC	Hinge toggle link - SRC	Aluminum	10 cm^2
OR-MA-0007	SRC	Hinge drive toggle link - SRC	Aluminum	10 cm^2
OR-MA-0008	SRC	Toggle link coupon	Aluminum	10 cm^2
OR-MA-0009	SRC	Canister control link - SRC	Aluminum	10 cm^2
OR-MA-0010	SRC	Bolt, SRC canister/avionics deck hinge assy	Stainless Steel	~ 1 inch
OR-MA-0011	SRC	Washer - SRC sample canister hinge assy	Stainless steel; CRES A286	~ 1 cm wide
OR-MA-0012	SRC	Washer coupon SRC sample canister hinge assy	Stainless steel; CRES A286	0.25"
OR-MA-0013	SRC	Braycote 601	Lubricant; Perflourinated Polyether	
OR-MA-0014	SRC	Braycote 601	Lubricant; Polyether; Perflourinated	
OR-MA-0015	SRC	SRC filter shell	Aluminum	~9.5 round x 2.5 cm high
OR-MA-0016	SRC	SRC filter shell	Aluminum	~9.5 round x 2.5 cm high
OR-MA-0017	SRC	SRC filter unit	Aluminum, filter, epoxy	~9.5 round x 2.5 cm high
OR-MA-0018	SRC	SRC filter unit	Aluminum, filter, epoxy	~9.5 round x 2.5 cm high
OR-MA-0019	SRC	SRC filter unit	Aluminum, filter, epoxy	~9.5 round x 2.5 cm high
OR-MA-0020	SRC	SRC filter unit	Aluminum, filter, epoxy	~9.5 round x 2.5 cm high
OR-MA-0021	Support Materials	Swab for possible ArcJet testing at Ames	Swab	2.5 " long
OR-MA-0022	OCAMS	Colorless First Contact	Polymer; cleaning solution	31 mm pellet cup
OR-MA-0023	OCAMS	Dow Corning DC 93-500	Epoxy - elastomer adhesive	31 mm pellet cup
OR-MA-0024	OCAMS	Nusil SCV1-2599	Epoxy - silicone adhesive	31 mm pellet cup (half)
OR-MA-0025	OCAMS	Braycote 602EF	Lubricant - braycote 602EF	3 ml syringe
OR-MA-0026	OCAMS	Nyebar	Lubricant - Nyebar fluorocarbon "epoxy"	60 ml bottle
OR-MA-0027	OCAMS	AEROGLAZE Z307	Paint; black paint	nine 2" x 2" squares
OR-MA-0028	OCAMS	Witness plates	glass witness plates	4" dia. metal can
OR-MA-0029	OCAMS	Epoxy used on witnesses	Epoxy - Scotchweld 2216B/A	in Aluminum pan
OR-MA-0030	OCAMS	Alion white paint	Paint; Z93C55 thermal control coating	nine 2" x 2" squares
OR-MA-0031	SRC	braided shielding coupon; sample canister hinge assembly	Stainless steel; 316L; LM-DB10911B-0025	~ 10 inch

OR-MA-0032	TAGSAM	outer pogo tube coupon; sampler arm pogo subassembly	Aluminum 6061-T6	~ 2 cm long section
OR-MA-0033	TAGSAM	wrist motor fitting assembly coupon; wrist drive assembly	Aluminum 6061-T652	10 cm^2
OR-MA-0034	SRC	EMI gasket; sample canister hinge assembly	beryllium copper	~ 6" long, 0.25" diam.
OR-MA-0035	TAGSAM	driven shaft coupon; wrist drive assembly	Stainless steel; A386-CRES	~ 3.5 cm long
OR-MA-0036	SRC	avionics deck connector bracket coupon	Aluminum	10 cm^2
OR-MA-0037	TAGSAM	driven gear key (-022); wrist drive assembly	Stainless steel; A386-CRES	~ 3.125 cm long
OR-MA-0038	TAGSAM	washer coupon; wrist drive CRES	Stainless steel; CRES-NAS620C4	No.4, 0.032" thick
OR-MA-0039	TAGSAM	set screw coupon; wrist drive assembly	Steel-AN565FC428H8	~ 1 cm long
OR-MA-0040	SRC	tray assembly (-107); capture ring assembly	Aluminum alloy; 7050-T7451	10 cm^2
OR-MA-0041	SRC	tang bracket assembly (-104); tang assembly	Aluminum	10 cm^2
OR-MA-0042	SRC	spring mandrel (-109); deployable witness plate assembly SRC	Aluminum	10 cm^2
OR-MA-0043	SRC	LH spring (-111); deployable witness plate assembly SRC	Stainless steel	~ 1" long
OR-MA-0044	TAGSAM	wrist end fitting assembly (-504); wrist drive assembly	Aluminum 6061-T651	10 cm^2
OR-MA-0045	SRC	retainer clip deployed (-107); sample canister top assembly	Stainless steel	10 cm^2
OR-MA-0046	TAGSAM	washer coupon; wrist drive assembly	Stainless steel; CRES - NAS620C4	0.209" OD, 0.032" thick
OR-MA-0047	TAGSAM	screw coupon; wrist drive assembly	Stainless steel; A286-CRES, NAS1352NO4-8	~1.5 cm long
OR-MA-0048	TAGSAM	washer coupon; wrist drive assembly	Stainless steel; 300 CRES - NAS620CAL	~0.5 cm wide
OR-MA-0049	TAGSAM	nut coupon; wrist drive assembly	Stainless steel; CRES	~ 1 cm top diameter
OR-MA-0050	SRC	locking nut coupon; SRC hinge assembly	Stainless steel; CRES, MS21043-3	0.1900" od
OR-MA-0051	TAGSAM	screw coupon; wrist assembly; CRES-NAS1352N04-4	Stainless steel; CRES-NAS1352N04-4	0.8 cm long
OR-MA-0052	SRC	SRC washer coupon; SRC hinge assembly	Stainless steel; A286 CRES NAS1149E0363R	0.438" OD
OR-MA-0053	TAGSAM	driven shaft spacer coupon (-014); wrist drive assembly	Stainless steel; A386-CRES	~ 2.5 cm long, ~ 1 cm diameter
OR-MA-0054	TAGSAM	wrist end fitting key coupon (-021); wrist drive assembly	Stainless steel; A386-CRES	~ 8 cm long
OR-MA-0055	TAGSAM	detent pin coupon (-006); wrist drive assembly	Stainless steel; A386-CRES	~ 2 cm long
OR-MA-0056	Support Materials	AcrJet test piece S-01	PICA	flakes
OR-MA-0057	Support Materials	ArcJet test piece S-02	PICA	flakes
OR-MA-0058	Support Materials	ArcJet test piece S-03	PICA	flakes
OR-MA-0059	SRC	Washer coupon, SRC top assembly	Stainless steel; 300 CRES - NAS620C8L	~0.5 cm OD
OR-MA-0060	SRC	SRC canister coupon (-502), sample canister hinge assembly	Aluminum alloy; 7075-T7351	~13 cm x 3.5 cm
OR-MA-0061	TAGSAM	Driven Gear coupon (-006), wrist drive assembly	Stainless steel; 17-4 PH CRES	~ 4 cm diameter
OR-MA-0062	TAGSAM	Microswitch bracket coupon (-105), capture ring assembly	Aluminum	10 cm^2
OR-MA-0063	TAGSAM	RH Torsion Spring, capture ring assembly	Stainless steel	~ 2" long
OR-MA-0064	SRC	Pin Coupon (-103), deployable witness plate assembly SRC	Stainless steel	~ 12 cm long
OR-MA-0065	SRC	Witness Plate Bracket Coupon (-106), sample canister top assembly	Aluminum	10 cm^2
OR-MA-0066	SRC	RH Spring coupon (-112), Deployable Witness Plate Assembly SRC	Stainless steel	~ 1" long

OR-MA-0067	TAGSAM	SARA Panel Structure Coupon	Honeycomb Composite	5 cm x 5 cm x 3.5 cm
OR-MA-0068	SRC	Cap Screw, SRC Top Assembly	Stainless steel; CRES, NAS1352N08-8	~1.5 cm long
OR-MA-0069	TAGSAM	Hard Stop Coupon (-104), Capture Ring Assembly	Stainless steel; A286	~12 cm long
OR-MA-0070	SRC	Screw coupon, SRC Top Assembly	Stainless steel; CRES	~ 1 cm long
OR-MA-0071	TAGSAM	Cam Coupon (-102), Capture Ring Assembly	Stainless steel	10 cm^2
OR-MA-0076	SRC	SARA/SRC TVAC residue from foil witness plates - Control Witness	NVR; residue	in 3" aluminum dish
OR-MA-0077	SRC	SARA/SRC TVAC residue from foil witness plates - Front TQCM Witness	NVR; residue	in 3" aluminum dish
OR-MA-0078	SRC	SARA/SRC TVAC residue from foil witness plates - Back of Chamber Witness	NVR; residue	in 3" aluminum dish
OR-MA-0079	SRC	SARA/SRC TVAC residue from foil witness plates - Below SRC Witness	NVR; residue	in 3" aluminum dish
OR-MA-0080	SRC	SARA/SRC TVAC residue from foil witness plates - Side TQCM Witness	NVR; residue	in 3" aluminum dish
OR-MA-0081	SRC	SARA/SRC TVAC residue from foil witness plates - Scavenger Plate Witness	NVR; residue	in 3" aluminum dish
OR-MA-0082	SRC	heater, SRC avionics deck (opposite of canister side)	Acrylic adhesive tape	~8 " plus cable
OR-MA-0083	SRC	Avionics Deck Connector bracket coupon (-101) Sample canister top assembly	Aluminum 7050-T7451	10 cm^2
OR-MA-0084	Spacecraft	3M 471 tape, spacecraft structure	Vinyl; blue vinyl; rubber adhesive	1.5" x 1"
OR-MA-0085	SRC	SRC shim coupon (-108)	Aluminum foil	3 cm x 2 cm
OR-MA-0086	TAGSAM	TAGSAM sapphire witness plate, launch coupon (-111)	Sapphire	1" diameter
OR-MA-0087	TAGSAM	frangibolt catch can coupon (-007) TAGSAM top assembly	Aluminum 6061-T651	10 cm^2
OR-MA-0088	TAGSAM	gear cover coupon (-011), wrist drive assembly	Aluminum 6061-T651	10 cm^2
OR-MA-0089	TAGSAM	nut coupon, capture ring assembly	Stainless steel; A286 CRES, NAS509-4C	~ 1 cm diameter
OR-MA-0090	TAGSAM	cam pin coupon (-103), capture ring assembly	Stainless steel; A286 CRES	~ 10 cm long
OR-MA-0091	SRC	washer coupon, sample canister top assembly	Stainless steel; CRES steel, NAS620C10L	0.354" OD
OR-MA-0092	SRC	roll pin coupon, deployable witness plate assembly	Stainless steel; CRES; MS16562-201	~ 1 cm long
OR-MA-0093	SRC	Stow guide bracket assembly right (-102), sample canister top assembly	Aluminum; 7050-T7451	10 cm^2
OR-MA-0094	TAGSAM	Self-locking nut coupon, capture ring assembly	Stainless steel; CRES, NAS1291C02M	0.2 cm
OR-MA-0095	SRC	SRC wire mesh screen coupon (-107)	Stainless steel	3 cm x 2 cm
OR-MA-0096	SRC	Tang coupon (-105), Tang assembly	Titanium 6AL-4V	10 cm^2
OR-MA-0097	TAGSAM	TAGSAM sapphire coupon (-115)	Sapphire	1 " diameter
OR-MA-0098	SRC	witness plate cap screws coupon, SRC top assembly	Stainless Steel; heat-resistent steel, NAS1352N08-10	~ 2 cm long
OR-MA-0099	SRC	cap screw coupons, capture ring assembly	Stainless Steel; CRES NAS1352N02-10	~2 cm long
OR-MA-0100	SRC	cap screw coupons	Stainless Steel; CRES NAS1352N02-10	~ 2 cm long
OR-MA-0101	SRC	SRC screw, capture ring assembly	Stainless Steel; A286 CRES	~0.4" length
OR-MA-0102	Support Materials	brass fastener from GCKP stand	Brass	~ 1.5"
OR-MA-0103	Support Materials	Si wafer blanks	Silicon wafer	~ 1 cm x 1 cm
OR-MA-0104	Support Materials	Si wafer blanks from cleaning	Silicon wafer	~ 1 cm x 1 cm
OR-MA-0105	Support Materials	Si wafers	Silicon wafer	~ 1 cm x 1 cm
OR-MA-0106	Support Materials	tape lift from TAGSAM Qual head	Tape Lift from TAGSAM Qual head	

OR-MA-0107	TAGSAM	Flight TAGSAM Head TVAC residue	NVR; chamber pre-cert - blank	2" round Al pan
OR-MA-0108	TAGSAM	Flight TAGSAM Head TVAC residue	NVR; chamber pre-cert	2" round Al pan
OR-MA-0109	TAGSAM	Flight TAGSAM Head TVAC residue	NVR; TAGSAM bakeout - blank	2" round Al pan
OR-MA-0110	TAGSAM	Flight TAGSAM Head TVAC residue	NVR; TAGSAM bakeout	2" round Al pan
OR-MA-0111	TAGSAM	Washer coupon	Stainless steel; CRES NAS620C8L	5/16" diam
OR-MA-0112	SRC	sapphire coupon, pre-open	Sapphire	1.2" x 0.8"
OR-MA-0113	Support Materials	polyester lacing tape	Polyester	~ 4" long
OR-MA-0114	Support Materials	Ultratape 1110 (Orange glove tape)	Polyethylene; tape, acrylic adhesive	1.5 x 3 "
OR-MA-0115	TAGSAM	TAGSAM rivit, POGO arm assembly	Stainless Steel; A286 CRES	0.388"
OR-MA-0116	Launch Container	launch container base coupon	Aluminum 6061-T651; A286 stainless steel	10 cm^2
OR-MA-0117	SRC	Washer, capture ring assembly	Stainless Steel; CRES; NAS1149EN232R	0.25" diam.
OR-MA-0118	SRC	SRC avionics deck connector bracket	Aluminum 7050-T7451	10 cm^2
OR-MA-0119	SRC	SRC aluminum witness plate coupon post-open	Aluminum	1.2" x 0.8 "
OR-MA-0120	Support Materials	Kimtech nitrile glove NxT	nitrile butadiene rubber	~ 8" long
OR-MA-0121	Support Materials	TX1009 AlphaWipe	Polyester 100%	9" x 9"
OR-MA-0122	Support Materials	shipping container dessicant DESI-PAK	tyvek packet; bentonite clay	8" x 5" bag
OR-MA-0123	REXIS	TiNi switch washer	Ti Al-4V, 302SS, Ag/Cu wire, Tetzel	2 7/8" x 5/8"
OR-MA-0124	REXIS	Frangibolt Ti bolt	Titanium 6Al-4V	1.33" x 0.183"
OR-MA-0125	REXIS	Frangibolt Housing Iridite	Iridite [Henkel Alodine 1132 Touch-n-prep pen]	4 1/8" x 7/8"
OR-MA-0126	REXIS	Torlon standoff	Polymer - Torlon 5030	1.058" x 0.394"
OR-MA-0127	OLA	Solithane 113	Epoxy - urethane pre-polymer	1/2 of 3" pan
OR-MA-0128	OLA	CV-2646	Polymer - electrically conductive RTV silicone	1/2 of 3" pan
OR-MA-0129	OLA	CV-2646	Polymer - electrically conductive RTV silicone	1/2 of 3" pan
OR-MA-0130	OLA	CV-2646	Polymer - electrically conductive RTV silicone	1/2 of 3" pan
OR-MA-0131	OLA	Hysol EA 934NA	Epoxy adhesive	1/2 of 3" pan
OR-MA-0132	OLA	Hysol EA 934NA	Epoxy adhesive	1/2 of 3" pan
OR-MA-0133	OLA	Solithane 113	Epoxy - urethane pre-polymer	1/2 of 3" pan
OR-MA-0134	OLA	Solithane 113	Epoxy - urethane pre-polymer	1/2 of 3" pan
OR-MA-0135	OLA	Solithane 113	Epoxy - urethane pre-polymer	1/2 of 3" pan
OR-MA-0136	OLA	Solithane 113	Epoxy - urethane pre-polymer	1/2 of 3" pan
OR-MA-0137	OLA	Solithane 113	Epoxy - urethane pre-polymer	1/2 of 3" pan
OR-MA-0138	OLA	Solithane 113	Epoxy - urethane pre-polymer	1/2 of 3" pan
OR-MA-0139	OLA	Solithane 113	Epoxy - urethane pre-polymer	1/2 of 3" pan
OR-MA-0140	OLA	Solithane 113	Epoxy - urethane pre-polymer	1/2 of 3" pan
OR-MA-0141	OLA	Hysol EA 934NA	Epoxy adhesive	1/2 of 3" pan
OR-MA-0142	TAGSAM	TAGSAM shim	Aluminum foil	3 cm dia
OR-MA-0143	SRC	SRC sapphire witness plate coupon, post-open	Sapphire	1.2" x 0.8"
OR-MA-0144	SRC	SRC aluminum witness plate coupon, always	Aluminum	1.2" x 0.8"

OR-MA-0145	SRC	SRC sapphire witness plate coupon, always	Sapphire	1.2" x 0.8"
OR-MA-0146	SRC	SRC screw coupon	Stainless Steel; CRES	0.053" long
OR-MA-0147	SRC	SRC Cam coupon	Aluminum; 7050-T7451	10 cm^2
OR-MA-0148	SRC	Flap coupon, SRC deployable witness plate assembly	Aluminum	10 cm^2
OR-MA-0149	OVIRS	Braycote 601 EF lubricant	Lubricant; Braycote 601 EF	> 10 g
OR-MA-0150	OVIRS	Z93C55 conductive white paint	Paint; Z93C55 conductive white silicate paint	two 2" x 2" surfaces
OR-MA-0151	OVIRS	EPOTEK 353 solar mesh epoxy	Epoxy; EPOTEK 353	1/4" x 3 inch syringe
OR-MA-0152	OVIRS	EPOTEK 353ND epoxy - cured 1/4" x 3" syringe	Epoxy; EPOTEK 353ND epoxy - cured	>10 g
OR-MA-0153	REXIS	Braycote 601EF lubricant	Lubricant; Braycote 601EF	~ 3 g
OR-MA-0154	REXIS	Hysol EA 934 NA	Epoxy - Hysol 934 on REXIS Main Electronics Board	~ 1.5 cm plug
OR-MA-0155	Support Materials	LF8900C ziplock bag	Polyethylene with fire retardant additives - Sb2O3 and ethane	16" x 16"
OR-MA-0156	Support Materials	TAGSAM simulant	Tagish Lake simulant from A. Hildebrand	10 g
OR-MA-0157	TAGSAM	washer, Sampler Head U-joint Subassembly	Stainless Steel; CRES NAS620C10L	0.354" od
OR-MA-0158	Spacecraft	Solar Cell Coupon, Solar Array	Smart ZTJ material	3" diameter
OR-MA-0159	Spacecraft	Hydrazine Dry Down #1	NVR; hydrazine dry down	
OR-MA-0160	Spacecraft	Hydrazine Dry Down #2	NVR; hydrazine drydown #2	
OR-MA-0161	Spacecraft	Hydrazine Dry Down #3	NVR; Hydrazine Dry Down #3	
OR-MA-0162	Spacecraft	Hydrazine Dry Down #4	NVR; Hydrazine Dry Down #4	
OR-MA-0163	Spacecraft	Hydrazine Dry Down blank	NVR; Hydrazine Dry Down blank	
OR-MA-0164	Spacecraft	Hydrazine Dry Down blank	NVR; Hydrazine Dry Down blank	
OR-MA-0165	Spacecraft	Hydrazine Dry Down unused vial	NVR; Hydrazine Dry Down unused teflon vial	
OR-MA-0166	OCAMS	OCAMS CDA motor	motor for all 3 OCAMS imagers	3"x2"x1"
OR-MA-0167	Support Materials	End cap nylon bag from Lufkin AC	nylon	8" x 8"
OR-MA-0168	SRC	Manniglas MLI SRC	MLI blanket	6" x 6" + braid
OR-MA-0169	TAGSAM	Reinforced black Kapton blanket	kapton, adhesive, kapton tape	8" x 8"
OR-MA-0170	TAGSAM	Diffuse PTFE film	PTFE film, diffuse	8" x 8"
OR-MA-0171	SRC	Avionics deck coupon	Honeycomb, aluminum + facesheet	~ 5" long
OR-MA-0172	SRC	Batt Blanket Coupon	Kapton, braid, solder	6" x 6"
OR-MA-0173	OLA	Black aluminum foil	Aluminum foil, flat black epoxy	~ 1 ft2
OR-MA-0174	SRC	thermocouple coupon, SARA installation	copper-constantin wire; PFA insulation	~12" long
OR-MA-0175	Spacecraft	RTV adhesive - solar arrays LM-BF10898A-0100	Epoxy - adhesive, silicone RTV	1.5" Al pan
OR-MA-0176	Support Materials	Braycote TAGSAM gas delivery system	Lubricant; braycote 601EF	~ 1 g
OR-MA-0177	TAGSAM	Flight head build sponge count	miscellaneous	~ 20" bag
OR-MA-0178	Support Materials	gloves from TAGSAM flight head installation (see note)	nitrile gloves	~ 20 " bag
OR-MA-0179	Support Materials	swabs from baffle/optical cleaning	cotton swabs	~12" bag
OR-MA-0180	Support Materials	Braycote 601 EF; s/c transport SVIP purge system	Lubricant; braycote 601 EF	2 oz tube (empty)
OR-MA-0181	SRC	avionics box pressure transducer, insulation; 8530C-15M41-SRC-BK	miscellaneous; avionics box pressure transducer, trimmed insulation	12" long pieces
OR-MA-0182	Support Materials	Contamination event, soldering tool	glass-filled nylon; soldering tool	~ 6" long

OR-MA-0183	SRC	molybdenum disulfide, MMSN399A100	Lubricant; braycote 602EF	~ 1 g
OR-MA-0184	Support Materials	epoxy for fairing doors	Epoxy - CHO-BOND 1030-55	1.5 x 1.5 x 1 cm
OR-MA-0185	Support Materials	Entegris filter	filter for purge gass on MLP/VIF	~ 8" x 3" cylinder
OR-MA-0186	TAGSAM	convoluted tube - T section	stainless steel	~ 12"
OR-MA-0187	TAGSAM	convoluted tube - inlet side	stainless steel	~ 16" length
OR-MA-0188	Support Materials	fluoroclean dry down #1	NVR; fluoroclean HE-27152-AEBT	Al pan 2"
OR-MA-0189	Support Materials	payload fairing amino acid foil witness plates	Aluminum foil; amino acid witness plates	12" x 12"
OR-MA-0190	Support Materials	payload fairing particle plates filter paper - left	filter paper	~2" circles
OR-MA-0191	Support Materials	payload fairing particle plates filter paper - right	filter paper	2" paper disc
OR-MA-0192	Support Materials	fluoroclean dry down #2	NVR; fluoroclean HE-27152-AEBT	Al pan 2"
OR-MA-0193	SRC	Epoxy used on sep/spin mechanism repair LM-AE10782A	Epoxy - Scotch Weld EC-2216	~ 1 g
OR-MA-0194	SRC	Epoxy used on SRC avionics deck - connector bracket re-work LM-AE10782A	Epoxy - Scotch Weld EC-2216	~ 1 g
OR-MA-0195	SRC	Epoxy used on avionics deck LM-AE10490A	Epoxy - Henkel Loctite EA9394	~ 1 g
OR-MA-0196	SRC	Epoxy used on avionics deck LM-AE10490A	Epoxy - Henkel Loctite EA9394	~ 1 g
OR-MA-0197	SRC	Epoxy used on avionics deck LM-AE10490A	Epoxy - Henkel Loctite EA9394	~ 1 g
OR-MA-0198	SRC	Epoxy used on avionics deck LM-AE10490A	Epoxy - Henkel Loctite EA9394	~ 1 g
OR-MA-0199	SRC	Epoxy used on avionics deck LM-AE10490A	Epoxy - Henkel Loctite EA9394	~ 1 g
OR-MA-0200	SRC	Epoxy used on avionics deck LM-AE10490A	Epoxy - Henkel Loctite EA9394	~ 1 g
OR-MA-0201	SRC	Epoxy used on avionics deck LM-AE10490A	Epoxy - Henkel Loctite EA9394	~ 1 g
OR-MA-0202	SRC	Epoxy used on avionics deck LM-AE10490A	Epoxy - Henkel Loctite EA9394	~ 1 g
OR-MA-0203	SRC	SRC pushoff fitting re-work; LM-BF10316B	Epoxy; RTV 566 silicone adhesive Momentive	~ 1 g
OR-MA-0204	SRC	SRC R&R assembly; LM-BF10316B	Epoxy; RTV 566 silicone adhesive Momentive	~ 1 g
OR-MA-0205	SRC	SRC backshell pushoff removed, replaced with 203; LM-BF10316B	Epoxy; RTV 566 silicone adhesive Momentive	~ 1 g
OR-MA-0206	SRC	SRC harness install; LM-BF10316B	Epoxy; RTV 566 silicone adhesive Momentive	~ 1 g
OR-MA-0207	SRC	SRC backshell parachute seal; LM-BF10316B	Epoxy; RTV 566 silicone adhesive Momentive	~ 1 g
OR-MA-0208	SRC	SRC Catch Can install; LM-BF10316B	Epoxy; RTV 566 silicone adhesive Momentive	~ 1 g
OR-MA-0209	SRC	SRC backshell inner seal; LM-BF10316B	Epoxy; RTV 566 silicone adhesive Momentive	~ 1 g
OR-MA-0210	SRC	SRC backshell outer seal; LM-BF10316B	Epoxy; RTV 566 silicone adhesive Momentive	~ 1 g
OR-MA-0211	SRC	SRC backshell vents; LM-BF10316B	Epoxy; RTV 566 silicone adhesive Momentive	~ 1 g
OR-MA-0212	SRC	SRC sep/spin thermal test cable; LM-BF10316B	Epoxy; RTV 566 silicone adhesive Momentive	~ 1 g
OR-MA-0213	SRC	SRC harness potting; LM-BF10316B	Epoxy; RTV 566 silicone adhesive Momentive	~ 1 g
OR-MA-0214	SRC	SRC backshell fitting installation; LM-BF10316B	Epoxy; RTV 566 silicone adhesive Momentive	~ 1 g
OR-MA-0215	SRC	SRC backshell seal emulsion; LM-BF10316B	Epoxy; RTV 566 silicone adhesive Momentive	~ 1 g
OR-MA-0216	SRC	SRC test seal, providing just in case; LM-BF10316B	Epoxy; RTV 566 silicone adhesive Momentive	~ 1 g
OR-MA-0217	SRC	SARA cable fitting to test cable; LM-BF10316B	Epoxy; RTV 566 silicone adhesive Momentive	~ 1 g
OR-MA-0218	SRC	epoxy used on SRC filter assembly LM-AE10490A	Epoxy; Henkel Loctite EA9394	~ 1 g
OR-MA-0219	SRC	epoxy used on SRC filter assembly LM-AE10490A	Epoxy; Henkel Loctite EA9394	~ 1 g

OR-MA-0220	SRC	epoxy used on SRC backshell pin plate	Epoxy; Henkel Loctite EA9394	~ 1 g
OR-MA-0221	SRC	epoxy used on SRC filter assembly LM-AE10490A	Epoxy; Henkel Loctite EA9394	~ 1 g
OR-MA-0222	SRC	epoxy used on SRC septum bushing LM-AE10490A	Epoxy; Henkel Loctite EA9394	~ 1 g
OR-MA-0223	TAGSAM	epoxy used on TAGSAM N2 system temp sensors LM-AE10490A	Epoxy; Henkel Loctite EA9394	~ 1 g
OR-MA-0224	SRC	epoxy used on SRC hinge assbly - spools, shunt insert LM-AE10490A	Epoxy; Henkel Loctite EA9394	~ 1 g
OR-MA-0225	SRC	epoxy used on SRC filter assembly LM-AE10490A	Epoxy; Henkel Loctite EA9394	~ 1 g
OR-MA-0226	SRC	epoxy used on SRC stepper motor assbly - heater wire bonding LM-AE10490A	Epoxy; Henkel Loctite EA9394	~ 1 g
OR-MA-0227	SRC	epoxy used on SRC filter assembly LM-AE10490A	Epoxy; Henkel Loctite EA9394	~ 1 g
OR-MA-0228	SRC	epoxy used on SRC avionics deck assembly - nut plate install LM-AE10490A	Epoxy; Henkel Loctite EA9394	~ 1 g
OR-MA-0229	SRC	epoxy used on SRC bathtub fitting (attaches backshell to deck) LM-AE10490A	Epoxy; Henkel Loctite EA9394	~ 1 g
OR-MA-0230	SRC	epoxy used on avionics deck inserts LM-AE10490A	Epoxy; Henkel Loctite EA9394	~ 1 g
OR-MA-0231	SRC	epoxy used on Detent insert installation LM-AE10490A	Epoxy; Henkel Loctite EA9394	~ 1 g
OR-MA-0232	SRC	epoxy used on avionics deck various locations LM-AE10490A	Epoxy; Henkel Loctite EA9394	~ 1 g
OR-MA-0233	SRC	SRC filter unit	Aluminum, filter, epoxy	~9.5 round x 2.5 cm high
OR-MA-0234	SRC	epoxy used on sample canister hinge assby - new insert installation LM-AE10490A	Epoxy; Henkel Loctite EA9394	~ 1 g
OR-MA-0235	SRC	epoxy used on sample canister hinge assby - new insert installation LM-AE10490A	Epoxy; Henkel Loctite EA 9394	~ 1 g
OR-MA-0236	SRC	epoxy used on SRC filter assembly LM-AE10490A	Epoxy; Henkel Loctite EA9394	~ 1 g
OR-MA-0237	TAGSAM	epoxy used on TAGSAM N2 gas assembly LM-AE10490A	Epoxy; Henkel Loctite EA9394	~ 1 g
OR-MA-0238	SRC	epoxy used on SRC lap shear testing LM-AE10490A	Epoxy; Henkel Loctite EA9394	~ 1 g
OR-MA-0239	SRC	epoxy used in an unknown location	Epoxy; Henkel Loctite EA9394	~ 1 g
OR-MA-0240	SRC	Nusil 2599 LM-AH10314A SRC temp sensor replacement	Epoxy; Nusil 2599 silicone adhesive	~ 1 g
OR-MA-0241	SRC	Nusil 2599 LM-AH10314A SRC temp sensor replacement	Epoxy; Nusil 2599 silicone adhesive	~ 1 g
OR-MA-0242	SRC	Nusil 2599 LM-AH10314A sep/spin installation - temp sensor	Epoxy; Nusil 2599 silicone adhesive	~ 1 g
OR-MA-0243	TAGSAM	Nusil 2599 LM-AH10314A TAGSAM wrist motor thermal assmy	Epoxy; Nusil 2599 silicone adhesive	~ 1 g
OR-MA-0244	TAGSAM	Nusil 2599 LM-AH10314A TAGSAM shoulder drive thermal control - temp sensor installation	Epoxy; Nusil 2599 silicone adhesive	~ 1 g
OR-MA-0245	SRC	Nusil 2599 LM-AH10314A SRC stepper motor sensor bonding	Epoxy; Nusil 2599 silicone adhesive	~ 1 g
OR-MA-0246	TAGSAM	Nusil 2599 LM-AH10314A TAGSAM shoulder drive thermal control - temp sensor install	Epoxy; Nusil 2599 silicone adhesive	~ 1 g
OR-MA-0247	TAGSAM	Nusil 2599 LM-AH10314A TAGSAM wrist motor temp sensor install	Epoxy; Nusil 2599 silicone adhesive	~ 1 g
OR-MA-0248	SRC	Nusil 2599 LM-AH10314A SRC avionics and battery temp sensor install	Epoxy; Nusil 2599 silicone adhesive	~ 1 g
OR-MA-0249	SRC	Nusil 2599 LM-AH10314A sep/spin installation - sep nut thermal install	Epoxy; Nusil 2599 silicone adhesive	~ 1 g
OR-MA-0250	Spacecraft	Nusil 2599 LM-AH10314A NavCams temp sensor installation	Epoxy; Nusil 2599 silicone adhesive	~ 1 g
OR-MA-0251	TAGSAM	contact pad coupon	stainless steel velcro; aluminum	~ 5/8" dia.
OR-MA-0252	TAGSAM	wire mesh screen coupon	stainless steel	3 cm
OR-MA-0253	SRC	NAS1352N08-6; SRC top assembly witness plate screws	Stainless Steel; heat resistent steel; NAS1352N08-6	~ 0.375"
OR-MA-0254	SRC	razor blade, detent pin cleaning	steel	~ 1.5"

OR-MA-0255	SRC	retainer clip, fixed coupon top assembly witness plate	Stainless steel - CRES	~ 10 cm^2
OR-MA-0256	TAGSAM	Braycote 602 EF + Mo disulfide; sine vibe test preparations	Lubricant; Braycote 602 EF (Castrol) + MoS2 (Dow)	~ 1 g
OR-MA-0257	Support Materials	witness plate stand frame	Aluminum 6061-T6	~ 12" long
OR-MA-0258	SRC	red primer, PR-1200RTV; LM-CJ-10894A-0013	Silane; used for SRC battery and avionics temp sensors	~ 1 g
OR-MA-0259	TAGSAM	gloves used by Jim Harris for witness plate fit check	nitrile, butadene rubber; NxT	1 large size glove
OR-MA-0260	TAGSAM	screw coupon, sampler head subassembly	Stainless steel - CRES; NAS1152E7	~ 1.5 cm long
OR-MA-0261	TAGSAM	Spring coupon, sampler head subassembly	stainless steel	0.5" diam.
OR-MA-0262	SRC	SRC dust cover caplugs	Polyethylene polymer conductive	~ 1" diam.
OR-MA-0263	Support Materials	nitrile glove used in SSL	nitrile glove blue	1 glove (M)
OR-MA-0264	TAGSAM	Washer coupon, sampler head subassembly	Stainless steel - CRES; NAS620C8L	5/16" diam.
OR-MA-0265	TAGSAM	washer coupon, sampler head subassembly	Stainless steel - CRES; NAS620C8	0.304" diam.
OR-MA-0266	TAGSAM	Sampler Head diaphragm coupon	Mylar	10 cm^2
OR-MA-0267	TAGSAM	cap screw coupon, sampler head subassembly	Stainless steel - CRES; NAS1352N08-10	~ 0.75" diam.
OR-MA-0268	TAGSAM	screw coupon, sampler head subassembly	Stainless steel - CRES; NAS1102E08-10	1.5 cm long
OR-MA-0269	TAGSAM	Washer coupon, TAGSAM, W3-50-TI	Titanium 6AL-4VTI	0.5" dia.
OR-MA-0270	TAGSAM	screw coupon, sampler head subassembly NAS1152E8	Stainless steel - CRES; NAS1152E8	2 cm long
OR-MA-0271	TAGSAM	nut coupon, sampler head subassembly	steel; silver plated; hexagonal nut	0.75 cm od
OR-MA-0272	TAGSAM	restraint coupon, sampler head sub-assembly	Titanium	6 cm long
OR-MA-0273	SRC	Al witness plate, pre-open coupon	Aluminum	1" x 0.75"
OR-MA-0274	Support Materials	ESD wrist strap used by ATLO personnel	metallic, painted	0.75" long
OR-MA-0275	SRC	washer coupon, SRC tang assembly	Stainless steel - CRES; NAS620C2	0.149" od
OR-MA-0276	Support Materials	particle fallout plate PFOP unused	polystyrene; HVWP filter	47 mm diam. filter
OR-MA-0277	TAGSAM	washer coupon, U-joint sub-assembly	Stainless steel - CRES; NAS1149EN632R	0.375" od
OR-MA-0278	Support Materials	connector used for wire splicing	glass filled nylon	1.25" long
OR-MA-0279	TAGSAM	screw coupon, sampler head top assembly	Stainless Steel; heat resistent; NAS1351N08-12	2.25 cm long
OR-MA-0280	TAGSAM	spring spacer coupon, witness plate assembly	Aluminum alloy 6061-T651	~ 0.86 g
OR-MA-0281	SRC	Silicone adhesive hardness coupon; microchip installation	Epoxy - adhesive, silicone RTV-142	~ 1 g
OR-MA-0282	SRC	LH torsion spring coupon, capture ring assembly	stainless steel	~ 2 " long
OR-MA-0283	SRC	LH Spring coupon, SRC top assembly	stainless steel	~ 2" long
OR-MA-0284	SRC	RH Spring coupon, SRC top assembly	stainless steel	~ 2" long
OR-MA-0285	TAGSAM	detent pin coupon (-006) DUPLICATE; wrist drive assembly	Stainless steel; A386-CRES	~ 2 cm long
OR-MA-0286	SRC	Washer coupon DUPLICATE, SRC top assembly	Stainless steel; 300 CRES - NAS620C8L	~0.5 cm OD
OR-MA-0287	TAGSAM	Washer coupon, DUPLICATE, TAGSAM, W3-50-TI	Titanium 6AL-4VTI	0.5" dia.
OR-MA-0288	TAGSAM	silicone adhesive LM-AH10314A; Qual shoulder drive assembly	Epoxy; Nusil silicone adhesive	~ 1 g
OR-MA-0289	TAGSAM	Nusil silicone adhesive; LM-AH10314A; SCV1-2599; qual N2 gas system temp sensor install	Epoxy; Silicone adhesive	~ 1 g
OR-MA-0290	TAGSAM	Nusil silicone adhesive; LM-AH10314A; SCV1-2599; qual wrist drive assembly - non-flight	Epoxy; Silicone adhesive	~ 1 g

OR-MA-0291	TAGSAM	Nusil silicone adhesive; LM-AH10314A; SCV1-2599; qual shoulder drive assembly - non-flight	Epoxy; Silicone adhesive	~ 1 g
OR-MA-0292	SRC	backshell coupon	SLA-561V	3" x 3"
OR-MA-0293	Launch Container	epoxy adhesive, sealant for amphenol connector	Epoxy - UAH 6190	> 1 g
OR-MA-0294	Launch Container	Blanket repair tape, payload fairing	extruded PTFE; silicone adhesive	~ 2" long
OR-MA-0295	Spacecraft	ACS Thruster Assembly NFP30708100	Valves - Stainless steel 300 series, Thruster Chamber - Inconel, Catalyst - iridium coated aluminum	8” x 1.75”; Flight mass: 0.36
OR-MA-0296	SRC	Tombstone coupon, SRC top assembly	Aluminum alloy 7050-T7451	10 cm^2
OR-MA-0297	TAGSAM	Sampler Head Mass Simulator (aluminum hat)	Aluminum, clear anodized	3.2 kg
OR-MA-0298	TAGSAM	stepper motor, SRC and TAGSAM	heater, temperature sensor, motor	flight mass 0.39 kg
OR-MA-0299	SRC	pica coupon	PICA	unknown, flight mass 9.94 kg
OR-MA-0300	Support Materials	unknown foil put in Jamie's cabinet	unknown	6" x 6"
OR-MA-0301	SRC	washer coupon, capture ring assembly	stainless steel CRES; NAS620C6	0.267" o.d.
OR-MA-0302	TAGSAM	baseplate coupon, sampler head subassembly	Aluminum 6061-T651	10 cm^2
OR-MA-0303	TAGSAM	Convoluted tube, feedline assembly	stainless steel	1 tube
OR-MA-0304	SRC	stow guide bracket sample assembly, left	Aluminum / Stainless steel	10 cm^2
OR-MA-0305	TAGSAM	sampler head air tube	Aluminum alloy; 6061-T651	~ 2.25" long
OR-MA-0306	TAGSAM	Sampler head surface plate coupon	Aluminum alloy; 6061-T7451	10 cm^2
OR-MA-0307	TAGSAM	Bolt restraint coupon, sampler head subassembly	Aluminum alloy 6061-T651	10 cm^2
OR-MA-0308	TAGSAM	Fan support plate coupon, sampler head subassembly	Aluminum alloy 6061-T651	10 cm^2
OR-MA-0309	TAGSAM	Standoff coupon, sampler head subassembly	Aluminum 6061-T651 and CRES MS21209C0815	5.5 cm long
OR-MA-0310	TAGSAM	Cover plate coupon, sampler head subassembly	Aluminum alloy 6061-T651	10 cm^2
OR-MA-0311	TAGSAM	screw coupon, sampler head subassembly	stainless steel CRES NAS1102E08-6	1 cm long
OR-MA-0312	TAGSAM	contact pad spool coupon	stainless steel CRES 304L	0.75" o.d.
OR-MA-0313	TAGSAM	screen coupon, air filter assembly	stainless steel CRES 304L	10 cm^2
OR-MA-0314	TAGSAM	sapphire witness plate coupon, post-stow	Sapphire	1" diam.
OR-MA-0315	TAGSAM	self-locking nut coupon, U-joint subassembly	silver plated CRES	~0.33" o.d.
OR-MA-0316	SRC	witness plate bracket coupon	Aluminum alloy 7050-T7451	10 cm^2
OR-MA-0317	TAGSAM	torsion spring RH coupon, witness plate assembly	stainless steel 17-7	~ 3 cm long
OR-MA-0318	SRC	Connector bracket enable coupon, SRC top assembly	Aluminum alloy 7050-T7451	10 cm^2
OR-MA-0319	TAGSAM	witness plate retaining pin coupon	stainless steel CRES A286	~0.1 g
OR-MA-0320	TAGSAM	U-joint yoke, sampler head subassembly	Aluminum alloy 6061-T651	10 cm^2
OR-MA-0321	SRC	cap screw coupon, SRC top assembly	Stainless Steel; heat resistant steel, NAS1351N3-8	1.75 cm long
OR-MA-0322	SRC	septum bushing coupon	Aluminum alloy 6061-T651	10 cm^2
OR-MA-0323	TAGSAM	perforated plate coupon, air filter assembly	stainless steel CRES 304L	~ 1 in2
OR-MA-0324	TAGSAM	witness plate baseplate	Aluminum alloy 6061-T651	10 cm^2
OR-MA-0325	TAGSAM	screw coupon, sampler head top assembly	Stainless steel - CRES NAS1102E04-5	~0.75 cm
OR-MA-0326	TAGSAM	shaft coupon, witness plate assembly	stainless steel CRES A286	4.01 g
OR-MA-0327	TAGSAM	U-joint fan support fitting assembly coupon	Aluminum alloy 6061-T651	10 cm^2

OR-MA-0328	SRC	septum retainer coupon, SRC top assembly	Stainless Steel; heat resistant steel, NAS1351N6-14	1" long
OR-MA-0329	SRC	Bolt coupon, SRC hinge assembly	stainless steel CRES	#10 x 0.4375"
OR-MA-0330	TAGSAM	Airframe bearing, inner POGO assembly	steel	0.0375" od
OR-MA-0331	Support Materials	ESD packaging, non-flight consumable	Dunshield ESD, used in LC firing to catch the lid - ATLO test	~ 3" x 3"
OR-MA-0332	SRC	screw coupon, SRC top assembly	stainless steel CRES	~0.5" long
OR-MA-0333	SRC	bolt coupon, SRC hinge assembly	n/a	0.688" long
OR-MA-0334	SRC	latch fitting, avionics deck assembly	Aluminum alloy 7075-T7351	10 cm^2
OR-MA-0335	TAGSAM	witness coupon retainer coupon, U-joint subassembly	Aluminum alloy 6061-T651	10 cm^2
OR-MA-0336	TAGSAM	screw coupon, U-joint subassembly	n/a	~ 1" long
OR-MA-0337	TAGSAM	feedline Tee coupon, sampler head subassembly	stainless steel CRES 316L	1.5" long
OR-MA-0338	TAGSAM	feedline elbow, sampler head subassembly	stainless steel CRES 316L	1.25" long
OR-MA-0339	Launch Container	launch container cover coupon, cover assembly	Aluminum alloy 6061-T651	10 cm^2
OR-MA-0340	TAGSAM	contact pad velcro loop pad coupon	stainless steel velcro	0.75" od
OR-MA-0341	TAGSAM	wrist joint restraints, sampler head subassembly	Titanium	~ 2.5" long
OR-MA-0342	TAGSAM	U-joint arm fitting, sampler head subassembly	Aluminum alloy 6061-T651	10 cm^2
OR-MA-0343	TAGSAM	bolt head capture cleat coupon, sampler head subassembly	Aluminum alloy 6061-T651	10 cm^2
OR-MA-0344	TAGSAM	witness plate shaft coupon, witness plate assembly	stainless steel CRES A286	4.01 g
OR-MA-0345	SRC	cotter pin coupon, capture ring assembly	stainless steel CRES; MS24665-151	0.5" long
OR-MA-0346	TAGSAM	torsion spring LH coupon, sampler head witness plate assembly	stainless steel CRES	~1.25" long
OR-MA-0347	TAGSAM	witness plate post-stow coupon, witness plate assembly	Aluminum 99.999%	~1: diam.
OR-MA-0348	TAGSAM	U-joint arm fitting coupon, U-joint subassembly	stainless steel CRES A286 Cadmium plated MS51830CAL102L	0.134" diam.
OR-MA-0349	SRC	washer coupon, SRC top assembly	stainless steel CRES; NAS1149CN832R	0.875" od
OR-MA-0350	TAGSAM	screw coupon, sample head U-joint subassembly	stainless steel CRES; NAS1151E6	0.375" od
OR-MA-0351	TAGSAM	nut coupon, sampler head U-joint subassembly	stainless steel CRES A286; MS21043-06N	0/168" od
OR-MA-0352	TAGSAM	feedline tube coupon, sampler head subassembly	stainless steel CRES 316L	~0.122 kg
OR-MA-0353	TAGSAM	witness plate launch coupon, witness plate assembly	Aluminum 99.999%	~ 1" diam.
OR-MA-0354	TAGSAM	witness plate cover plate coupon	Aluminum alloy 6061-T651	10 cm^2
OR-MA-0355	SRC	cap screw coupon, SRC top assembly	Stainless Steel; NAS1352E06-6	0.75" long
OR-MA-0356	SRC	washer coupon, capture ring assembly	stainless steel CRES; NAS1149C0416R	0.500" od
OR-MA-0357	TAGSAM	witness plate always coupon, witness plate assembly	Aluminum 99.999%	~1" diam
OR-MA-0358	SRC	cap screw coupon, Tang assembly	stainless steel CRES	~0.25" long
OR-MA-0359	TAGSAM	U-joint fan support fitting, U-joint subassembly	stainless steel CRES 303 cadmium plated MS51830CA104L	0.134" diam
OR-MA-0360	TAGSAM	sampler arm wrist shim, Pogo assembly	laminated aluminum	6 cm long
OR-MA-0361	SRC	washer coupon, sample cansiter top assembly	stainless steel CRES; NAS620C6L	0.267" od
OR-MA-0362	Launch Container	launch container barrel coupon	Aluminum alloy 6061-T651	10 cm^2
OR-MA-0363	TAGSAM	cap screw coupon, TAGSAM top assembly	stainless steel CRES; NAS1352N08H6	~0.25" long
OR-MA-0364	Spacecraft	top deck blanket (+Z) spacecraft	kapton blanketing, kapton tape	4" x 3"

OR-MA-0365	Support Materials	nylon tape used to package TAGSAM TVAC NVR samples	nylon tape, rubber adhesive	2" wide
OR-MA-0366	Support Materials	swabbed particulate from flight TAGSAM head	unknown, collected with polyethylene swab	~100-200 microns
OR-MA-0367	Support Materials	pink polyethylene in cleanroom room 202	Polyethylene, anti-static	maybe 2 ft2
OR-MA-0368	Spacecraft	Spacecraft USB drive	metallic	~ 1.5" long
OR-MA-0369	Support Materials	TAGCAMS nylon camera covers	nylon	~2" diam (2)
OR-MA-0370	Support Materials	Faraday Cap - cable cutter mate	n/a	~0.5" long
OR-MA-0371	Support Materials	Crane Control panel residue; Cape	unknown	n/a
OR-MA-0372	TAGSAM	severed frangibolt fasteners TAGSAM	stainless steel	~2.25" long
OR-MA-0373	Support Materials	TAGSAM TVAC Si wafers	Silicon wafers, polyethylene cases	3" diam (5)
OR-MA-0374	Spacecraft	black kapton MLI blanketing	kapton, tapes, films, staples, etc.	8" x 8"
OR-MA-0375	Support Materials	tube cutter, qual TAGSAM head "decapitation"	n/a	~1.5" long
OR-MA-0376	Support Materials	epoxy used to stake tube cutter	Epoxy, Glass	~ 1 g
OR-MA-0377	SRC	temperature sensor assembly coupon	wire, tape, thread, etc.	~ 2 ft
OR-MA-0378	Support Materials	swabs from detent pin cleaning on SRC	Polyethylene swabs	~2" swabs
OR-MA-0379	Launch Container	PLA transducer cap - nylon	cap material unknown, nylon bagging	~0.5" long
OR-MA-0380	TAGSAM	Qual TAGSAM head insert	ultem, stainless steel fastener	~3" long
OR-MA-0381	Support Materials	insert pull throughs, SRC canister	silicone	~2" long
OR-MA-0382	Support Materials	TAGSAM test blanket	fiberglass re-inforced teflon	~ 2 ft long
OR-MA-0383	TAGSAM	wire coupon, TAGSAM ordnance installation	stainless steel CRES 302	0.20" diam
OR-MA-0384	SRC	Temperature strip coupon, SRC thermal installation	kapton	0.56" diam
OR-MA-0385	SRC	Temperature strip coupon, SRC thermal installation	kapton	0.38" x 1.5"
OR-MA-0386	SRC	Temperature strip coupon, SRC thermal installation	kapton	0.38" x 0.8"
OR-MA-0387	Spacecraft	Diode bonding adhesive coupon, solar array	Epoxy - RTV silicone LM-BF10898F	> 1 g
OR-MA-0388	Spacecraft	Diode bonding adhesive coupon, solar array	Epoxy - RTV silicone LM-BF10898B	> 1 g
OR-MA-0389	Spacecraft	wire coupon - red,blue - solar array	silver coated copper, kapton insulation	> 1 ft
OR-MA-0390	Spacecraft	wire coupon - green - solar array	silver coated copper, kapton insulation	> 1 ft
OR-MA-0391	Support Materials	Ultratape 1153 clean tent tape coupon, VIF	Polyethylene, rubber adhesive	~ 2"
OR-MA-0392	Support Materials	Ultratape 1154	Polyethylene, synthetic rubber adhesive	~2"
OR-MA-0393	Support Materials	ULA fairing adhesive	Epoxy - RTV silicone CV3-1142	>1g
OR-MA-0394	SRC	conformal coating coupon, sep/spin mechanism assembly	polyurethane (Arathane 5750)	>1 g
OR-MA-0395	TAGSAM	Qual TAGSAM head witness plates (3)	sapphire	~1" diam.
OR-MA-0396	TAGSAM	Qual TAGSAM head witness plate	sapphire	~1" diam.
OR-MA-0397	TAGSAM	Qual TAGSAM head witness plate + shim	sapphire	~1" diam.
OR-MA-0398	TAGSAM	Qual TAGSAM head witness plate	sapphire	~1" diam.
OR-MA-0399	TAGSAM	Qual TAGSAM head witness plate	sapphire	~1" diam.
OR-MA-0400	TAGSAM	Qual TAGSAM head witness plates (3)	sapphire	~1" diam.
OR-MA-0401	Support Materials	Contamination Control samples Box 1 Al foils	Aluminum foil	~ 1 cm x 2 cm

OR-MA-0402	Support Materials	Contamination Control samples Box 2 Al foils	Aluminum foil	~ 1 cm x 2 cm
OR-MA-0403	Support Materials	Contamination Control samples Box 3 Al foils	Aluminum foil	~ 1 cm x 2 cm
OR-MA-0404	Support Materials	Contamination Control samples Box 4 Al foils	Aluminum foil	~ 1 cm x 2 cm
OR-MA-0405	Support Materials	Contamination Control samples Box 5 Al foils	Aluminum foil	~ 1 cm x 2 cm
OR-MA-0406	Support Materials	Contamination control knowledge samples curation cabinet	Aluminum foil	~ 1 cm x 2 cm