The Meteoritical Society

Meteoritics & Planetary Science 58, Nr 4, 572–590 (2023)
doi: 10.1111/maps.13973

Curation planning and facilities for asteroid Bennu samples returned by the OSIRIS-REx mission

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(Received 09 December 2022; revision accepted 08 March 2023)

Abstract–NASA's OSIRIS-REx spacecraft collected samples from carbonaceous near-Earth asteroid (101955) Bennu on October 20, 2020, and will deliver them to the Earth on September 24, 2023. The samples will be processed at the NASA Johnson Space Center (JSC), where most of the sample collection will be subsequently curated in a new cleanroom suite. The spacecraft collected loose regolith two ways: in a bulk sample chamber capable of holding up to 2 kg, and on industrial Velcro "contact pads" intended to collect small particles at the surface. Included in the JSC collection will be the bulk sample, the contact pads, contamination-monitoring witness plates, and supporting hardware. Planning for the curation of the samples and hardware started at the earliest phase of proposal development and continued in parallel with project development and execution. Because a major mission goal is characterization of organic compounds in the Bennu samples, extra effort was spent in the design stage to ensure a clean curation environment. Here, we describe the preparations to receive the sample, including the design, construction, outfitting, and monitoring of the cleanrooms at JSC; the planned recovery of the sample-containing capsule when it lands on Earth; and the approach to characterizing and cataloging the samples. These curation efforts will result in the distribution of pristine Bennu samples from JSC to the OSIRIS-REx science team, international partners, and the global scientific community for years to come.

INTRODUCTION

The OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, Security Regolith Explorer) mission launched a spacecraft to the B-type, near-Earth asteroid (101955) Bennu (formerly 1999 RQ36) in 2016 and plans to deliver sample collected at the surface to the Utah desert in 2023 (Lauretta et al., 2015, 2017, 2021). A major science goal of the mission is to investigate the organic compounds on this carbonaceous asteroid and assess their relevance to the origins of the solar system and life. Connecting asteroids and meteorites by spectral analysis is hindered by very few opportunities for ground

[Correction added on 17 May 2023, after first online publication: The copyright line was changed.]

truthing. The extensive laboratory analyses of the samples, combined with the context of remote sensing data from the spacecraft encounter and laboratory analyses of meteorites, are expected to aid interpretation significantly (e.g., Nakamura et al., 2011; Yokoyama et al., 2022).

The OSIRIS-REx spacecraft arrived at Bennu in December 2018 and performed detailed observations and identification of potential sampling sites (Lauretta et al., 2021). While in proximity to Bennu, OSIRIS-REx mapped the global and local geology, mineralogy, chemistry, and topography via its cameras, spectrometers, and altimeter (e.g., Jawin et al., 2022; Kaplan et al., 2020, 2021; Lauretta et al., 2017, 2019, 2021; Simon et al., 2020; Walsh, Bierhaus, et al., 2022). The data collected in orbit were used to select the sampling site location with an acceptable level of spacecraft risk. The selected sampling site, known by the team as Nightingale, is located within Hokioi crater in Bennu's northern hemisphere (Lauretta et al., 2021, 2022). This site presented an opportunity to sample Bennu in a location with a variety of particle reflectances suggestive of different lithologies (Lauretta et al., 2022), a relatively recent exposure age (DellaGiustina et al., 2020), and a low peak surface temperature (Rozitis et al., 2022), increasing the likelihood of sampling volatile- and organic-rich material. Sampling was accomplished on the first attempt on October 20, 2020 (Lauretta et al., 2022; Walsh, Ballouz, et al., 2022), and the spacecraft departed Bennu on May 10, 2021, for a 28-month return journey back to the Earth. The spacecraft will release the Sample Return Capsule (SRC) over Earth, which will re-enter the Earth's atmosphere and land in the Utah Test and Training Range (UTTR), to be recovered on September 24, 2023. The SRC will be transported to NASA Johnson Space Center (JSC) within a few days of recovery, where a new dedicated curation cleanroom and supporting facilities have been constructed especially for asteroid sample return.

One of the mission science foci is organic geochemistry, and in particular molecules of potential prebiotic interest. This emphasis required attention to potential contamination sources and contamination knowledge from the outset of the mission (Dworkin et al., 2018). For example, amino acids were monitored throughout the mission stages (e.g., spacecraft build, launch, operations, and curation cleanroom construction) because they are not only relevant for organic geochemistry (e.g., Elsila, Aponte, et al., 2016) but can serve as an indicator of biological and industrial organic contamination. Some known industrial contaminants such as nylon 6 (or polycaprolactum) which can hydrolyze to ε-amino-*n*-caproic acid (Glavin et al., 2006) were eliminated from spacecraft operations, cleanroom construction materials, and allowable materials within the cleanrooms.

OSIRIS-REx has benefitted from lessons learned from previous sample return missions such as Apollo (Allen et al., 2011), Genesis (Burnett, 2013), Stardust (Elsila, Callahan, et al., 2016; Sandford et al., 2010; Zolensky et al., 2008), Hayabusa (Yada et al., 2014), and Hayabusa2 (Abe, 2021) The philosophy that curation should be involved from the onset of the mission was exemplified by the Genesis mission, when the spacecraft was assembled in the International Organization for Standardization (ISO) 4 curation cleanroom during ATLO (assembly, testing, and launch operations; Burnett et al., 2003). Archived materials and contamination knowledge from previous missions helped identify procedures that could be improved (e.g., Karouji et al., 2014; Sandford et al., 2010) and cost-controlled approaches that could be followed by future missions (Dworkin et al., 2018). Lessons learned from previous missions informed the planning for cleanroom designs, environments, and processes (Yada et al., 2014, 2020; Zolensky et al., 2008). Sample recovery planning has benefitted from two previous sample return recoveries in Utah (Genesis and Stardust; Barrow et al., 2007; Burnett et al., 2003) and two in Woomera, Australia (Hayabusa and Hayabusa2; Tachibana et al., 2021; Yamada et al., 2010). This knowledge base, as well as curation and analysis of Apollo lunar samples, Antarctic meteorites, cosmic dust, and asteroid particles have informed the planning for the OSIRIS-REx asteroid samples, the majority of which will be curated at JSC.

The curation team was integrated with mission design and operations from the beginning, as early as 2004 (Timeline of Preparations section). That integration allowed curation-specific needs such as contamination knowledge to be incorporated into the mission design early, when adjustments had minimal cost impact. Not only did this early integration inform planning for sample characterization, cataloging, allocation, and the development of detailed sample handling and containment approaches; it was also an investment in the longer term needs of the community. Here, we describe these preparations for OSIRIS-REx, as a reference for sample scientists and curators and as a model for future sample return missions.

WHAT WAS COLLECTED AND WHAT WILL BE CURATED?

OSIRIS-REx's sampling apparatus, the Touch-and-Go Sample Acquisition Mechanism (TAGSAM; Bierhaus et al., 2018), consists of a robotic arm with a sample collection head at the end. The head collects samples (a) in a toroidal chamber that can hold up to

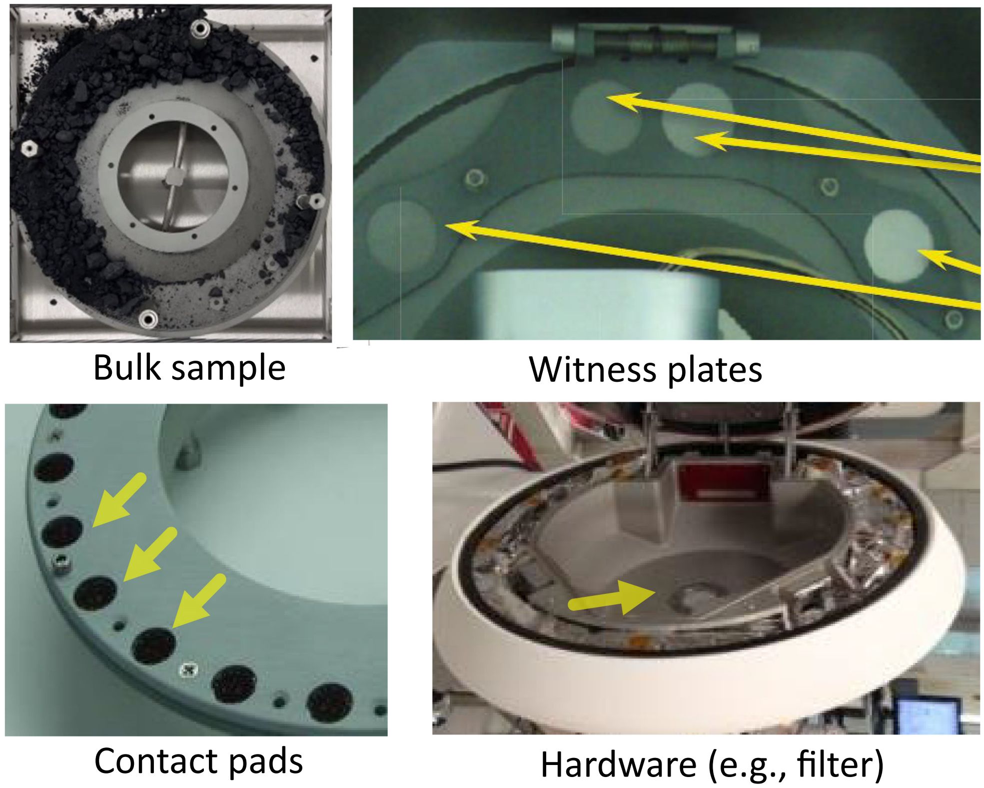


FIGURE 1. Flight-like representations of the OSIRIS-REx materials that will be curated at JSC. The "bulk sample" shown is a mineral simulant resembling the Tagish Lake meteorite (Hildebrand et al., 2015) in a TAGSAM replica from a 2021 rehearsal. Other items to be curated include witness plates (two TAGSAM plates are shown as examples), stainless steel contact pads (three are indicated out of a total of 24), and various hardwares related to samples or contamination knowledge (the canister air filter is shown as an example).

~2 kg of Bennu regolith mobilized by nitrogen gas jets, and (b) on 24 contact pads made of stainless steel Velcro encircling its base plate (Figure 1). The contact pads were designed both to serve as a backup sampling mechanism if regolith failed to mobilize into the chamber, and to ensure the collection of materials exposed at the surface for direct comparison with the data obtained by the spacecraft.

During the sampling operation, the TAGSAM head was immersed in loose regolith to a depth of nearly 50 cm and collected a substantial estimated bulk sample of 250 ± 101 g (Lauretta et al., 2022). Post-sampling imaging showed particles adhering to the contact pads and, unexpectedly, wedged in the Mylar (biaxially oriented polyethylene terephthalate) flap meant to keep material inside the chamber. Sample leaking through the partially open flap led the mission team to stow the TAGSAM head in the protective SRC on an expedited timeline to preserve as much material as possible, at the expense of less precision on the mass of material to be returned.

In addition to the contact pads and bulk sample, witness plates from the TAGSAM head, wrist, and SRC canister interior will be curated as part of the OSIRIS-REx collection at JSC (Figure 1). Some hardware items, such as the SRC canister's air filter and irreversible temperature sensor strips, will be used to help interpret the thermal and degassing history of the sample, as could sampling and analysis of exhaust gas from the sample gloveboxes. The air filter may contain volatiles liberated from the bulk sample, offering a third type of asteroid material for analysis. Finally, the collection includes non-flight contamination knowledge samples such as witness plates deployed in various ATLO and cleanroom environments, as well as an archive of materials and components of the spacecraft (Contamination Control and Knowledge section).

TIMELINE OF PREPARATIONS

The OSIRIS mission concept to collect and return a sample from a carbonaceous asteroid began with the Discovery class mission proposal in 2004, with preliminary sample curation planning occurring in association. Curation plans included in the Discovery Concept Study Report (2007) were already well defined

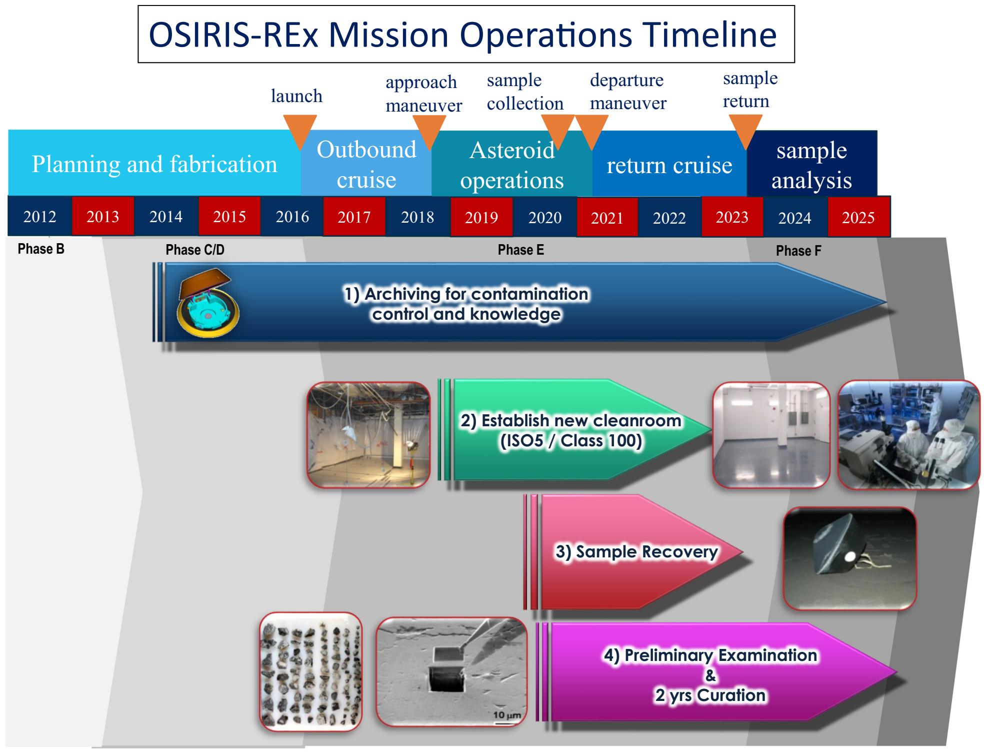


FIGURE 2. Timeline of four major curation activities over OSIRIS-REx mission phases C–F. Sample recovery and preliminary examination start in ~2020 to reflect preparatory activities leading up to those events. The 2 years of curation indicated in activity (4) refers to the 2 years of curation costs borne by the mission; curation will continue indefinitely after 2025, supported by the Astromaterials Curation office.

and costed at this early stage, allowing a solid foundation upon which to build more detailed subsequent plans. When OSIRIS was not selected as a Discovery mission, it was renamed OSIRIS-REx and conceptually expanded to meet the greater science goals of New Frontiers 3 (NASA, 2009). The curation plan from OSIRIS was further developed in the OSIRIS-REx New Frontiers Step 1 proposal in July 2009 and then the New Frontiers Concept Study Report in January 2011. The mission was selected for full funding in May 2011, with a 14-year schedule that included development, launch, cruise, operations, return, recovery, and sample analysis (Figure 2; Lauretta et al., 2017, 2021). The curation-related activities fall into four major categories: (i) materials archiving for contamination knowledge, (ii) establishment of a new sample cleanroom, (iii) recovery operations, and (iv) preliminary examination of the returned samples and hardware.

Even though curation does not contain the traditional flight elements, curation planning was part of all mission life cycle reviews as an essential component of the project, as well as subsystem reviews specific to sample return missions (e.g., entry–descent–landing, contamination control and knowledge), and status reporting with other mission elements at project management reviews (Figure 3). Curation rehearsals were carried out at key stages of mission planning and preparation (see also 7.2.1 below). Rehearsal #1 in June 2013 involved disassembly of a mock sample canister containing bulk sample (asteroid simulant), occurred on a table in a conference room, and helped to inform the budget and schedule planning for all curation activities. Rehearsal #2 in 2021 kicked off a series of more focused activities rehearsing aspects of sample return, transport to JSC, SRC canister and TAGSAM disassembly, and bulk sample handling and characterization. Rehearsal #3 in mid-2023 will be a high-fidelity activity with a clean flight-like SRC canister, TAGSAM head, and outfitted gloveboxes.

CONTAMINATION CONTROL AND KNOWLEDGE

Contamination control—that is, the strategy for limiting contamination to the sample—was achieved using several approaches, such as careful selection of materials that will be in direct or indirect contact with the sample, monitoring the sample environment after collection to identify contamination threats, and defining appropriate cleanroom operation and sample handling

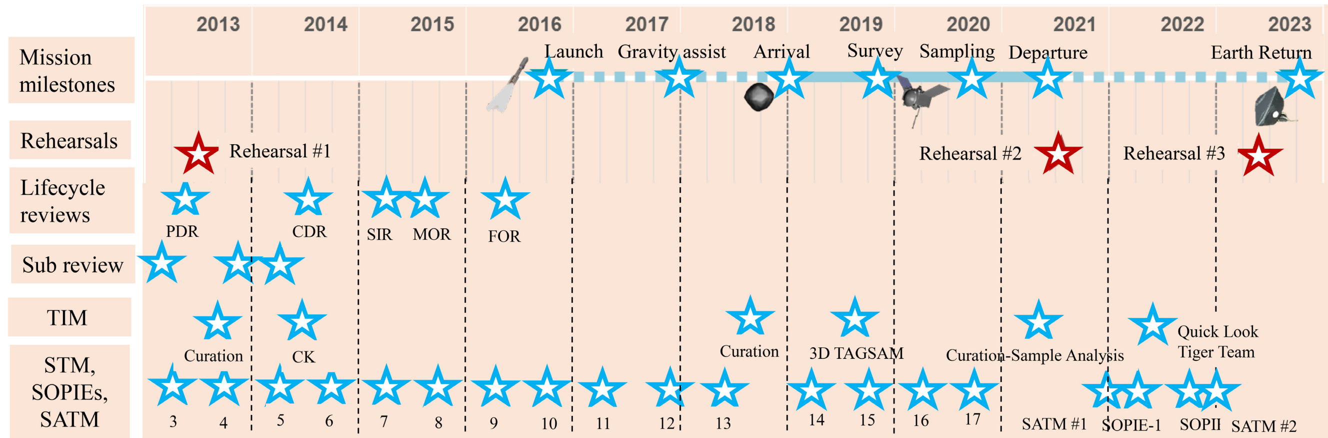


FIGURE 3. Curation was integrated with OSIRIS-REx mission planning from the beginning. Stars indicate curation-relevant events and milestones during the 14-year mission schedule, including curation rehearsals, mission lifecycle reviews (preliminary design review (PDR), mission definition review (MDR), critical design review (CDR), system integration review (SIR), mission operations review (MOR), flight operations review (FOR)), subsystem reviews, technical interface meetings (TIMs), science team meetings (STMs), science operational proficiency integrated exercises (SOPIEs), and sample analysis team meetings (SATMs). Curation rehearsal #1 involved a design concept of the TAGSAM head containing a simulant with materials similar to the Tagish Lake meteorite, all contained within a mock sample canister. Curation rehearsal #2 utilized a TAGSAM qualification unit with Tagish Lake simulant and 3-D printed plastic canister lid and avionics deck, whereas curation rehearsal #3 will use an empty flight-like TAGSAM and aluminum canister lid and avionics deck to be materials compliant for the cleanroom.

procedures (Dworkin et al., 2018; McCubbin et al., 2019; Sandford et al., 2010). Contamination control efforts generally do not identify the chemistry of a contamination, merely the quantity, and on a cost-capped mission, contamination control cannot identify all potential sources. Thus, contamination knowledge complements contamination control efforts by helping to identify contaminants and permitting researchers to mitigate their scientific impact. Contamination knowledge comes from materials coupons of hardware that could pose a contamination risk and witness plates deployed in a sample-specific environment. Contamination knowledge has played a role in interpreting data from many sample collections including Apollo, Genesis, Stardust, Hayabusa, and Hayabusa2 (Allton, 1999; Burnett, 2013; Calaway et al., 2014; Sandford et al., 2010; Sugahara et al., 2018). Contamination control and knowledge can be optimized and integrated to yield the most useful information for each mission (Dworkin et al., 2018). Like curation planning, contamination control efforts for OSIRIS-REx started early in mission formulation.

Materials Archive and Witnesses

OSIRIS-REx planned proactive measures to understand the sample environment, including, for example, materials used in the construction of the spacecraft and cleanroom. This approach required science and engineering teams to work together on the spacecraft design and build and look for ways to minimize or eliminate contamination sources while staying within the mission resource profile. To understand potential contamination sources, mission scientists and engineers identified hundreds of spacecraft and ground support materials with a reasonable pathway to the sample and archived them during ATLO. Archiving efforts continued with the JSC cleanroom construction and will also include items related to recovery at the UTTR (e.g., soil and air samples, UTTR cleanroom materials, witness plates) and subsequent curation at JSC. The OSIRIS-REx materials archive is housed in an ISO 7 cleanroom at JSC in dedicated purged gaseous nitrogen (GN_2) desiccators. Prior to use, the desiccator internal environment was periodically characterized by witness plates over the course of a year to ensure that it was free of organic contaminants (e.g., Dworkin et al., 2018).

The spacecraft and sampling mechanism experienced multiple environments during ATLO, including assembly cleanrooms and acoustics, vibration, and vacuum testing at Lockheed Martin, followed by payload assembly cleanrooms and the launch pad at Kennedy Space Center. These environments were recorded by (i) deploying witness plates designed for particle analysis (four silicon wafers) and non-volatile residues (four aluminum foils), and (ii) collecting air samples for prompt gas chromatography–mass spectrometry analyses at JSC. One of each witness plate was analyzed by the science team after collection (Dworkin et al., 2018; Regberg et al., 2020), with the remaining three archived for future study. These same approaches are being applied to understanding the environments at recovery and in the sample cleanrooms. As with the materials archive, the witness plates are housed in dedicated cabinets in an ISO 7 cleanroom at JSC.

NEW CLEANROOM FACILITIES

JSC Cleanroom Suite Design

In the baseline plan from the earliest design until just after critical design review (CDR) in 2014, the sample cleanroom design was a modular design based on the Stardust cleanroom to be constructed within an existing room on the second floor of the Astromaterials Research and Exploration Science building (a.k.a. Building 31) at JSC. The cleanroom design and construction schedule were tied to the timing of the 2020 sample collection and 2021 departure milestones. Several developments after CDR resulted in substantial changes to the schedule and plan. First, a Memorandum of Understanding (MOU) between the Japan Aerospace Exploration Agency (JAXA) and NASA was created involving exchange of sample material from the former's Hayabusa2 mission to asteroid Ryugu (10% of bulk sample to NASA) and the OSIRIS-REx mission Bennu (0.5% of bulk sample to JAXA). Because the Ryugu sample for NASA is a significant mass of material, a separate sample cleanroom was planned. Like Bennu, Ryugu is carbonaceous, and the science goals for the Ryugu sample allocation are similarly focused on organic geochemistry and volatile elements. Thus, as the curation environments are nearly identical, the decision was made to colocate these two new sample cleanrooms on the second floor of Building 31. In parallel with this development came an opportunity from NASA Headquarters (HQ) to upgrade and modernize the advanced curation and cleaning facilities, in part with unused funds from the New Frontiers 3 Agency Baseline Commitment for OSIRIS-REx held by NASA for risk reduction outside the mission cost cap.

The Stardust-like module design has a limited lifespan, and though it would meet OSIRIS-REx project requirements, it would require expensive refurbishment over time. Thus, NASA HQ advised the construction of a permanent cleanroom integrated into the building with a lower lifetime cost instead of the module with a lower upfront cost. Space on the first floor of the building, immediately below the proposed new sample cleanrooms, was identified for these new advanced curation and cleaning facilities, thus broadening the scope of construction to include nearly half of Building 31. The combination of these two major changes led to a larger scale design.

In March 2016, the design firm Reynolds, Smith & Hills (RS&H) was competitively selected to design the asteroid cleanroom suite for the second floor of Building 31. JSC's Curation Team completed 30%, 60%, and 90% design reviews in cooperation with representatives from OSIRIS-REx, Hayabusa2, and NASA HQ, culminating with a February 2017 100% design meeting and a completed design in March 2017. This new design modified the cost and tied the schedule to the Hayabusa2 sample return in December 2020 and sample exchange with NASA in December 2021. The earlier start to the design process offered an advantage for OSIRIS-REx: Planning would start much earlier than originally scheduled, allowing attention to details which would likely lead to a more robust curation approach by the time of sample return in 2023. RS&H was subsequently tasked to design the new advanced curation and cleaning cleanrooms on the first floor, which started in June 2017. That design also went through 30%, 60%, 90%, and 100% design reviews, culminating with a completed issued for construction design in August 2018.

OSIRIS-REx Cleanroom Design

The mission science emphasis on characterization of organic compounds on Bennu, and the desire to process Bennu samples in a pristine environment, motivated the need for an ISO 5 cleanroom rating. Sample processing in GN_2 glovebox cabinets in the main sample cleanroom is necessary to eliminate terrestrial contaminants and prevent alteration due to hydration and oxidation. In addition to the sample cleanroom, spaces were also designed for general staging (ISO 7), ultra-microtomy (ISO 7), and thin section preparation (not a cleanroom) (Figure 4). The ISO 5 cleanroom environment also stipulated temperature requirements of 22°C ± 1°C, relative humidity 50% ± 5%, positive room pressure (air velocity >0.2 m s^{-1}, 37 Pa relative pressure per ISO 14644 cleanroom standard, Part 1, 2, and 4, 2015), acoustics not to exceed noise criterion (NC) 45, lighting no less than 500 lux (in all spaces). In addition, GN_2 (99.995% curation grade nitrogen gas, MIL-PRF-27401G, 2013) plumbing was extended to multiple drops in the sample cleanroom, electrical panels were expanded to support all the new cleanroom suites, and a new climate control system was tied into the centralized monitoring and control system. Sample security implementation includes controlled access and local and centralized alarming and monitoring.

Material selection for the cleanroom was a detailed and careful process for contamination control and followed the relevant spacecraft contamination control requirements (Dworkin et al., 2018, Material S1, and references therein). Many materials were prohibited for

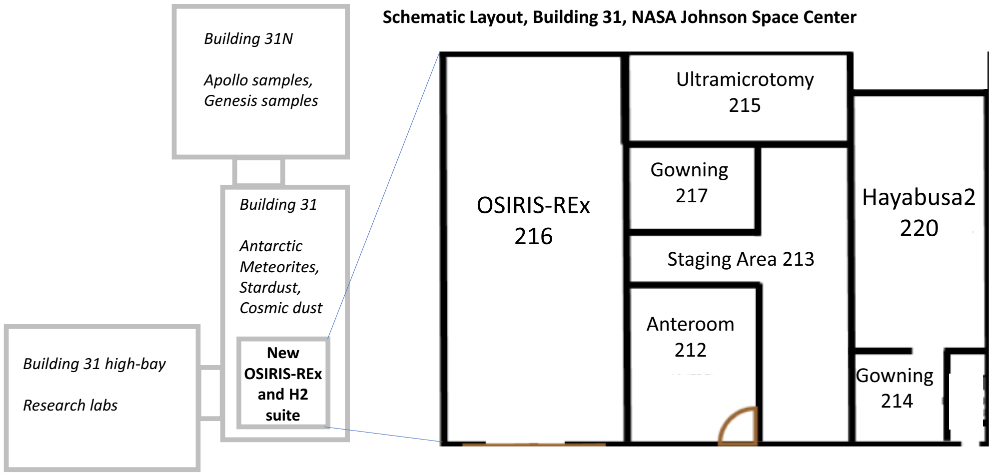


FIGURE 4. Floor plan of the facilities at Building 31, JSC, including the OSIRIS-REx and Hayabusa2 cleanrooms, microtomy lab, staging, gowning, and anteroom areas. (Color figure can be viewed at wileyonlinelibrary.com.)

use such as latex, nylon, polyamides, open solder, and mercury-containing lights (light-emitting diode, LED was used instead). Others were minimized or avoided as feasible, such as magnetic materials, silicones, foams, most paints, metal oxides, bare (untreated) aluminum, iron, non-corrosion-resistant steel, and shedding materials (or those with thin films) that erode, crack, or flake, and pose particulate contamination risk.

Several components deserve special attention owing to their custom design to minimize contamination. The fan filter units (FFUs) were specially designed with custom seals, aluminum motor parts, stainless steel housings, and an integrated LED lighting strip to minimize off-gassing and material contamination. The air handling system keeps the cleanrooms at constant temperature by varying the volume of air cycled through them. The plenums above and between the cleanroom spaces were kept as clean as possible and sealed off and finished with as few materials as possible, such as a low-off-gassing cleanroom caulk, and epoxy paint was used on all untreated surfaces. The walls and ceilings were made of low-off-gassing aluminum frames and panels, whereas the flooring was coated in low-off-gassing epoxy paint, with a customized coving at the floor and wall interface. Testing of various wall, flooring, and adhesive products for off-gassing informed the selection of final materials for the cleanroom (Calaway et al., 2019; Calaway & McQuillan, 2022).

Construction

After a competitive bidding process, Advon Corporation was awarded the contract for cleanroom construction in February 2019, with construction starting that spring. The construction project was met with two major challenges: (i) discovery of significant pre-existing (but unknown) conditions in Building 31 that needed attention during the construction and (ii) the SARS-CoV-2 global pandemic. These two factors delayed the main construction completion dates from February 2020 to March 2021. These spaces underwent testing and balancing of the cleanroom environments, a several month period of monitoring, and ultimately ISO certification to permit outfitting and occupation in October 2021.

Pre-existing conditions that were discovered during the course of the project and subsequently addressed were numerous. Ceiling spaces in both floors required asbestos abatement as the building dates to 1966. Establishing a temporary air handling system to allow the abatement to proceed added 6 weeks to this process. Floor drain systems on the first floor were discovered to be decayed beyond repair, requiring new ones to be designed and constructed after the initial demolition phase of the project. Cracks in the foundation slab and numerous unplanned small cavities on the flooring surface due to removed electrical boxes (tombstones) fed by an old electrical chase in the existing slab that was filled in with concrete, made it necessary to add a vapor barrier, then finish and smooth the surface before application of the final epoxy flooring. The new air handling system installation on the roof of Building 31 required additional structural support (above the original design) as well as the recognition of local deterioration of aging roof surfaces and materials.

The pandemic effects were initially related to construction crew staffing and access to JSC, which took several months to resolve. The other major issues were related to delays in manufacturing and supply chains. In some cases, multicomponent systems were delayed waiting on one final component to arrive even though all others were ready for installation.

During the construction phase, JSC curation worked with the contractor to identify problematic materials that could compromise the mission science. In such instances, JSC Curation, with input from the mission's curation contamination control working groups, chose alternative materials that satisfied mission and construction requirements. In several cases, lack of adequate material substitutions necessitated archiving of items or materials as part of the contamination knowledge collection (Contamination Control and Knowledge section). For example, various sprinkler heads were considered, and the head selected contains 316 L stainless steel and a Be-Ni spring, rather than other stainless steel components or titanium metal. Similarly, duct heaters utilized stainless steel and polycarbonate for metal and plastic components and had stainless steel enclosures around the $Ni_{80}Cr_{20}$ heating elements.

Cleanroom Monitoring

The curation cleanroom was ISO 5 certified in November 2021, allowing a multiple month period of monitoring to establish a baseline for interpreting long-term changes in particle counts, relative room air pressures, organics, and inorganics, as well as microbial and fungal counts (e.g., Regberg et al., 2022). Particle counts (taken weekly) for the cleanroom spaces fall well within the ISO class ratings (Figure 5a). The cascade of positive pressure from room to room was designed to be from 12 to 7 Pa, where the cleanest rooms have the highest pressure and cascade to the relatively dirty hallway. Preliminary witness plate and air characterization of the OSIRIS-REx cleanroom indicated lower concentrations by a factor of several of identified organics and plasticizers from sealants, gaskets, paints, and epoxies than are typical in NASA curation cleanrooms (Figure 5b). These very low levels, especially at this early stage of characterization, indicated that the careful design and selection of cleanroom materials and infrastructure contributed to an exceptionally clean sample environment. The organic, inorganic, microbial, and fungal monitoring will continue on a regular cadence to establish a baseline, with the frequency to be determined based on early findings. Any departure from the baseline values can be detected and remediated as quickly as possible.

Post-Construction Adjustments

Several issues were identified at the end of construction that are being resolved; none of these have affected the overall cleanliness of the cleanroom (Cleanroom Monitoring section) but have relevance to longer term operation. Nitrogen exhaust lines will be expanded with a new separate roof exhaust to handle the nitrogen volumes used in the second floor cleanrooms. FFU velocities need to be balanced against noise levels and particle count loads to satisfy cleanliness and work environment requirements (e.g., ISO 14644 cleanroom standard, Part 1, 2, and 4, 2015). Chilled water pumps were not adequate to provide temperature control as installed, and replacements were made. Remote monitoring of the cleanrooms required optimization for local control of the temperature, humidity, lighting, and other environmental aspects.

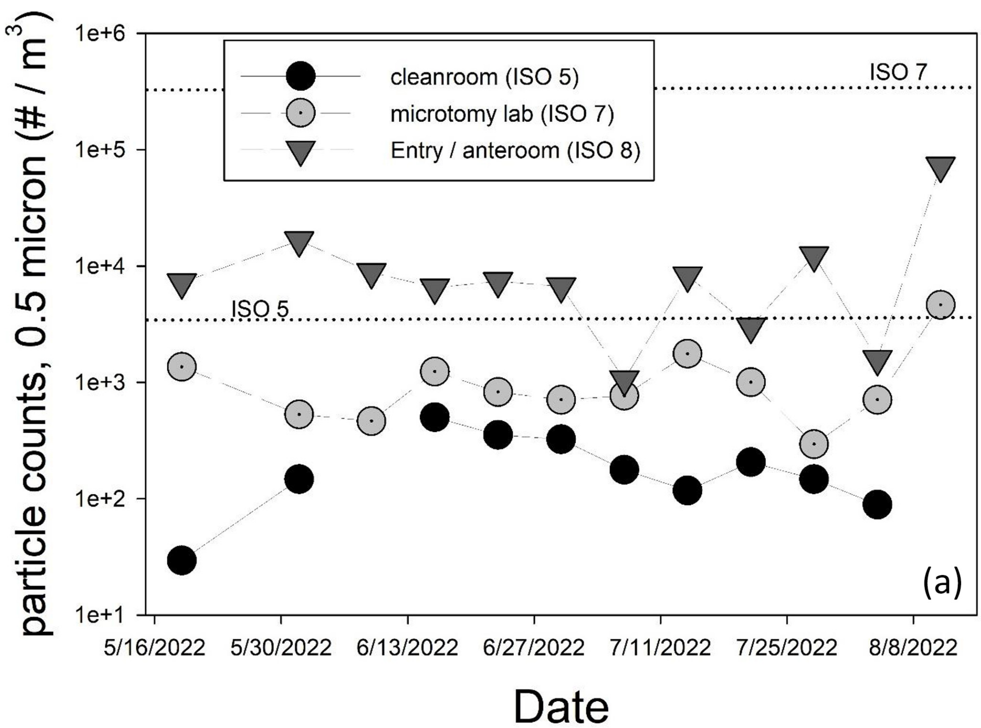
CLEANROOM OUTFITTING

Cleanroom outfitting encompasses all the items that will be curated in the OSIRIS-REx collection. The two largest and most significant items—both of which need to be handled in a clean and inert environment—are the sample canister from the SRC, and the TAGSAM head inside it. Accordingly, two large gloveboxes were designed for handling and disassembly of these items to provide access to the sample materials within. Two additional gloveboxes (for contact pads and witness plates) and several storage desiccators are also planned for the cleanroom (Figure 6).

First, the SRC canister glovebox was designed to have access on both sides of its length, so that multiple people may assist with disassembly steps. It also has extra space for items to be removed, as well as tools, containers, bags, stands or fixtures, and a balance. After the canister is opened and the TAGSAM head removed, the glovebox can be utilized for activities such as witness plate removal and measurements of bulk or hardware samples.

Second, the TAGSAM disassembly glovebox was designed to accommodate the removal of contact pads, any loose Bennu material, witness plate hardware, and finally the bulk Bennu sample from the TAGSAM head. The TAGSAM glovebox also has access from both sides of its length and includes windows and extra space at the end that are optimized for multistep imaging of the sample and hardware. A sliding and rotating stage within the glovebox allows the TAGSAM head to be moved to facilitate the disassembly.

Once removed from the TAGSAM head, contact pads will be moved to a dedicated glovebox for characterization and removal of individual particles (Figure 6). This will be accomplished with a combination of x-y-z translation stages and micromanipulation devices that will allow tools to be applied to move particles. Thumb forceps (tweezers) can be used to remove particles from the contact pad hooks, after which containers for storage and allocation can be moved to them. The



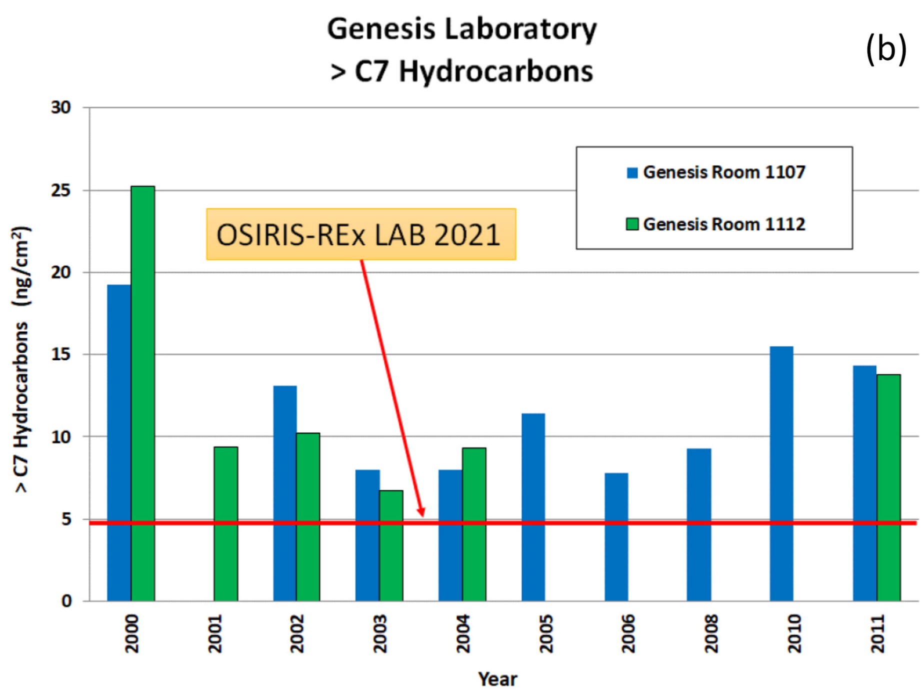


FIGURE 5. a) Counts of 0.5 μm particles, May–July 2022, demonstrating that each of the spaces is well within the ISO rating. ISO 5 and ISO 7 limits for 0.5 μm sized particles are shown as horizontal dashed lines. Counts have been averaged over several sampling locations within each space. The apparent gap in cleanroom counts corresponds to no counts detected that day. b) Levels of organic compounds with mass > C7 (nanograms per square centimeter) after cleanroom construction in October 2021 (red line, 5 ng cm^{-2}), compared to the levels measured in the ISO 4 Genesis cleanroom suite (Rooms 1107 and 112) between 2000 and 2011.

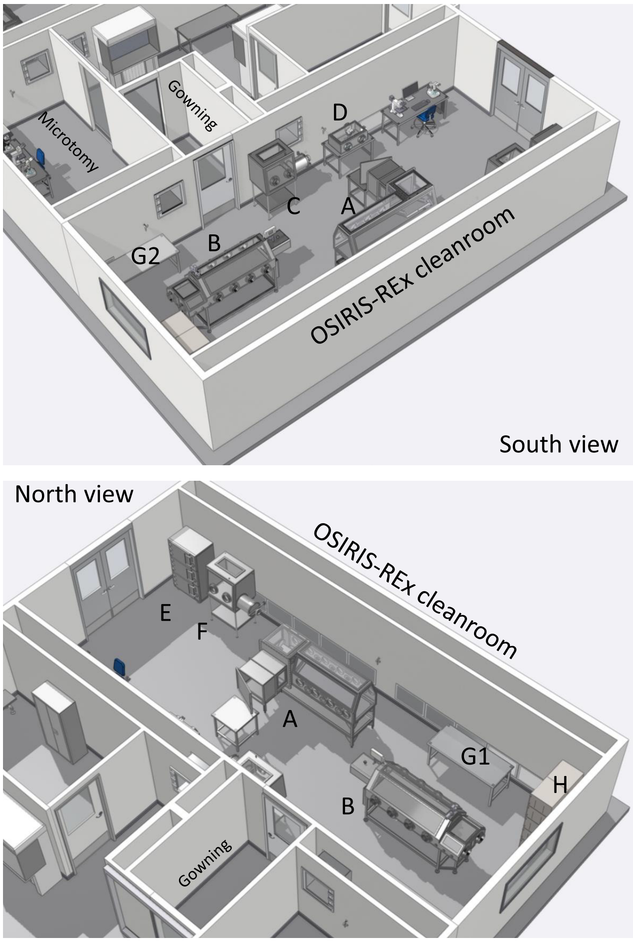


FIGURE 6. Schematic layout of the OSIRIS-REx cleanroom looking north (top) and south (bottom), with canister glovebox (A), TAGSAM disassembly glovebox (B), witness plate glovebox (C), contact pad glovebox (D), isolating desiccator for storage (E), returned sample cabinet (F), tables (G1, G2), and double triple desiccator for storage (H). Also indicated are the gowning entry area and the microtomy room shared with Hayabusa2. (Color figure can be viewed at wileyonlinelibrary.com.)

aluminum and sapphire witness plates will be moved to a dedicated glovebox where they will be handled and can be subdivided using blades or shears (aluminum), cleaved by scoring, or broken along predefined orientations (sapphire; e.g., Lauer Jr et al., 2013). The possible generation of particles during these events requires the use of a dedicated witness plate glovebox.

Curated materials will be stored in GN_2 cabinets and desiccators, depending on the type of materials. Pristine Bennu bulk sample—that portion of the bulk that has never left the JSC GN_2 curation environment—will be stored in GN_2 desiccators using a combination of stainless steel or polytetrafluoroethylene (PTFE, a.k.a. Teflon) containers and PTFE bags, and it will be processed as needed in the TAGSAM disassembly cabinet. As with Apollo, samples that are returned to the collection after study by scientists will be stored separately and handled either on a flow bench or a dedicated return sample processing GN_2 cabinet. Hardware samples will be stored in dedicated GN_2 desiccators as well and will be processed in a contamination knowledge cleanroom. In addition to these storage and processing cabinets, there will be stations for imaging, an ISO 5 compatible flow bench, cabinets, and other supporting furniture (tables and chairs) for the cleanroom activities (Figure 6).

FUTURE PLANNING

Recovery

Personnel from Lockheed Martin, NASA Goddard, JSC Curation, the mission science team, and the UTTR will recover the SRC when it lands on September 24, 2023. The science and curation teams will characterize the local environment by collecting samples of soil, air, and other materials from the UTTR landing site that could be potential contaminants. Coordination meetings with all parties involved in recovery (including curation) were held at the UTTR on July 6, 2017, and September 20, 2022, and will continue until recovery, thus allowing regular curation input.

The SRC recovery procedure and training exercises will be based on experience gained through the Genesis and Stardust missions. Genesis had to enact a contingency plan owing to the off-nominal landing of its SRC, including extended curation efforts at the recovery site (Burnett 2013). Stardust SRC recovery was nominal, but the program had developed plans and procedures for numerous contingency situations (Barrow et al., 2007), knowledge of which can benefit OSIRIS-REx in the event of an off-nominal return. Recovery and contingency planning for OSIRIS-REx is being developed in detail in the year leading up to recovery.

The recovered SRC will be transported via helicopter to a temporary ISO 7 cleanroom (Figure 7) that will be established at the UTTR in Dugway hangar Building 1012, Avery Complex, Michael Army Airfield. Particle counts equivalent to ISO 7 will be verified upon completion of the build, and the cleanroom air will be monitored for possible organic and inorganic contaminants, as was done for the Stardust and Genesis missions (Stansbery et al., 2001; Zolensky et al., 2008). Within the cleanroom, a GN_2 purge on the sample canister will be initiated and verified, canister extracted from the SRC, and the SRC and sample canister triple-bagged in PTFE and prepared for transport to JSC by aircraft. Additional items, including the SRC parachutes, avionics box, battery, irreversible temperature recording

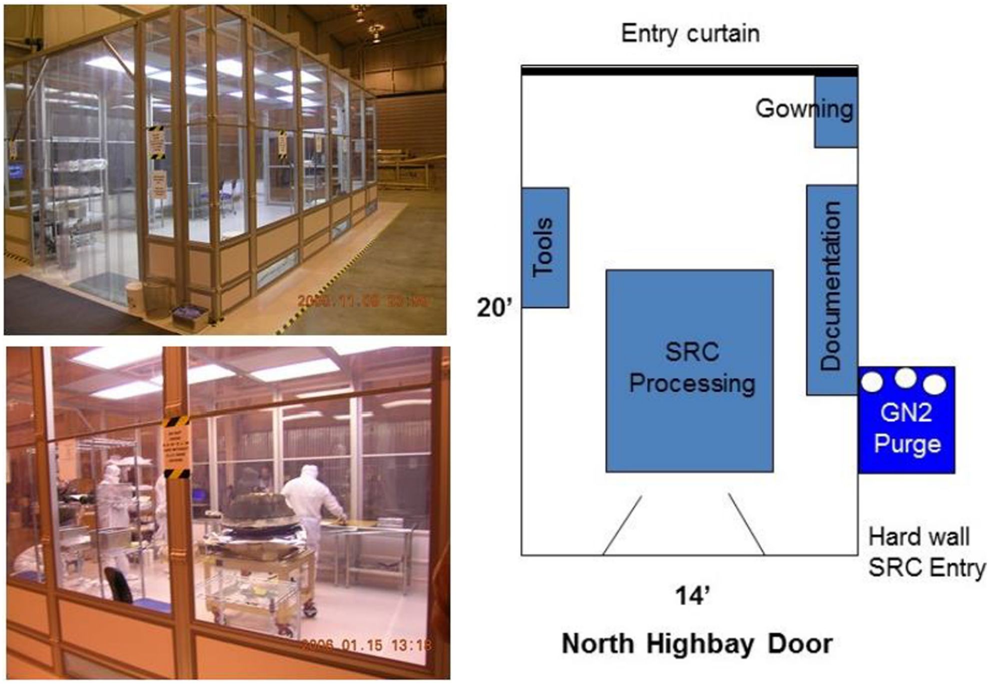


FIGURE 7. Photos and floor plan of the Stardust ISO 7 portable cleanroom established at the UTTR for SRC recovery. High-purity nitrogen in size K compressed gas cylinders was used to purge the canister before transport to JSC. Air from the hangar building was supplied to the cleanroom and filtered by a group of FFUs designed to maintain ISO 7 cleanliness. This portable cleanroom provided a clean and secure space for necessary disassembly steps for the SRC before shipping to Houston, served as clean space for contingency processing in case of an off-nominal landing, and will provide the basis on which the OSIRIS-REx recovery cleanroom will be established.

strips, and possibly the drogue parachute's unexpended NASA Standard Initiator, will also be removed and prepared for transport to JSC, or temporarily to Lockheed Martin for nondestructive characterization. In the nominal plan, the SRC and hardware will be prepared and transported to JSC the day after recovery. However, there are several off-nominal scenarios including the possible presence of a hurricane or other weather events near JSC at the time of return. These scenarios would require an SRC hold or delay at the UTTR until JSC is deemed safe for sample reception. The safety and integrity of the sample are the top concern; thus, the temporary cleanroom needs to be sufficient for longer storage.

The unopened sample canister assembly will be transported to JSC, maintaining a continuous GN_2 purge, first by flight from the UTTR to Ellington Field Joint Reserve Base ~6 miles north of JSC, and then by temperature-controlled truck from Ellington Field to Building 31 on the JSC campus. The sample canister assembly will be removed from the shipping container, disconnected from purge, transferred to an ISO 7 cleanroom on the first floor for outer bag removal, and rebagged (returning to triple-bagged configuration). Then, the canister will be taken to the OSIRIS-REx cleanroom, and the outer surface of the outer bag will be removed before entering. The other SRC contents (exclusive of the sample canister assembly) will be received, disassembled, documented, and curated in an ISO 7 cleanroom in Building 31 designated for space-exposed hardware.

Preliminary Examination

Preliminary examination of the OSIRIS-REx sample has four main goals. First is the disassembly of the sample canister and removal of samples, witness plates, and space-exposed hardware to be curated. Second is selection of representative sample splits for international agencies (4 wt% to the Canadian Space Agency (CSA) and 0.5 wt% to JAXA), remote storage at White Sands Complex (New Mexico, USA), and hermetically sealed and cold storage. The purpose of the hermetically sealed sample is to control the potential loss of volatile species. In the process of analyzing Stardust comet-exposed aluminum foils, it was observed that there was an apparent decrease in measured levels of glycine since recovery of the samples of roughly 0.1% per day

(~60 pmol cm^{-2} day^{-1}) (Elsila et al., 2009; Sandford et al., 2010). While at JSC, these samples had been stored at room temperature in a cabinet under flowing GN_2, and volatiles may have been lost gradually by evaporation. Third is selection of sample splits by the mission science team for early characterization and hypothesis testing per the mission science goals (including destructive and nondestructive analyses; up to 25 wt%). Fourth is the characterization of the bulk sample using nondestructive methods (Initial Characterization and Selection of Samples and Catalog sections below) and isolation of splits for the generation of a sample catalog. The online published catalog will include sufficient detail about each sample split for members of the scientific community to make informed requests of materials to conduct their investigations.

Disassembly of Sample Canister and TAGSAM

To inform the disassembly strategy, the mission conducted a series of rehearsals and related exercises over the decade preceding sample return. The first such rehearsal was held on June 17, 2013 (Figure 3), in a conference room at JSC. It involved a design concept of the TAGSAM head containing a simulant with materials similar to the Tagish Lake meteorite (Hildebrand et al., 2015), all contained within a mock sample canister. This rehearsal enabled the maturation of the curation plan and the integration of small but important changes to the hardware by Lockheed Martin to facilitate the disassembly and tracking of TAGSAM components. An additional exercise with a printed plastic model of the flight TAGSAM head was held at JSC on July 29, 2019, to facilitate the design of custom tools for disassembling and manipulating the TAGSAM head.

The second curation rehearsal was held in November 2021 at JSC with input and participation from Lockheed Martin, science team leadership, and international partners. Flight-like models of the canister and TAGSAM head loaded with Tagish Lake simulant were disassembled in a glovebox mock-up. Lessons learned from this rehearsal, science team-led exercises in February and August 2022 (Figure 3), and a series of mini-rehearsals at JSC focused on removing the canister lid, witness plates, contact pads, and bulk sample, all led to a detailed disassembly procedure with joint input from the science and curation teams and international partners.

Disassembly will start with the removal of the canister hinge fasteners and lid, in the canister disassembly cabinet. Bulk sample inside of the sample canister but outside of the TAGSAM head may also be collected here, as anticipated from both curation rehearsals; a small amount will be analyzed for quick characterization by the mission sample analysis team. Next, the TAGSAM witness plates will be removed, a stand installed, and the TAGSAM head mass measured. The known mass of the empty TAGSAM head will be subtracted from the total mass to obtain the mass of bulk sample within the TAGSAM head. This mass will be added to the mass of material collected from the capture ring and avionics deck to obtain the total mass of bulk Bennu collected. The TAGSAM head (with witness plates removed) will then be transferred to the TAGSAM disassembly cabinet. There, the 24 contact pads will be removed, and the bulk sample will be uncovered and poured into a set of trays for characterization. Finally, the canister filter and the additional witness plates in the canister lid will be removed in the canister disassembly cabinet.

Initial Characterization and Selection of Samples

Sampling handling, characterization approaches, and storage will depend to some extent on the sample particle sizes. Observations of Bennu's surface and the TAGSAM head taken before, during, and after sample acquisition (e.g., Lauretta et al., 2022; Walsh, Ballouz, et al., 2022; Walsh, Bierhaus, et al., 2022) showed particles ranging from dust to gravel. The centimeter-scale stones wedged in the TAGSAM flap indicate strength of individual particles, but Bennu's thermal inertia indicates weak, porous rocks (Rozitis et al., 2022). It is unknown to what extent the particles might be disrupted during atmospheric entry, descent, and landing. As a result, the curation team is preparing for a wide range of possible sizes.

A small number (likely 8–20) of the largest stones will be picked out with forceps from the bulk material for handling and sample preparation techniques that are appropriate for larger objects (e.g., thin sectioning or XCT scanning; Coarse Particles section). Some of the large particles separated at the very beginning of sample processing will be further characterized (Figure 8A,C). The procedures for how to allocate and characterize them will be based on how many large particles are present, their masses relative to the bulk sample mass, sizes relative to each other, and apparent lithologic diversity. Curatorial procedures will be developed for a range of anticipated large-particle scenarios.

The remaining bulk, termed "bulk sample*", will be divided into aliquots by tray and separately containerized. The reasons for doing this are to limit the exposure time to GN_2 flow within the glovebox and allow future study or allocations to be done without reopening the entire bulk sample*. Because this process needs to be done rapidly to protect the sample from volatile loss, the total number of aliquots will need to be small, on the order of ten. Before containment, high-resolution macro-scale photographs will be taken of (i) each aliquot as a

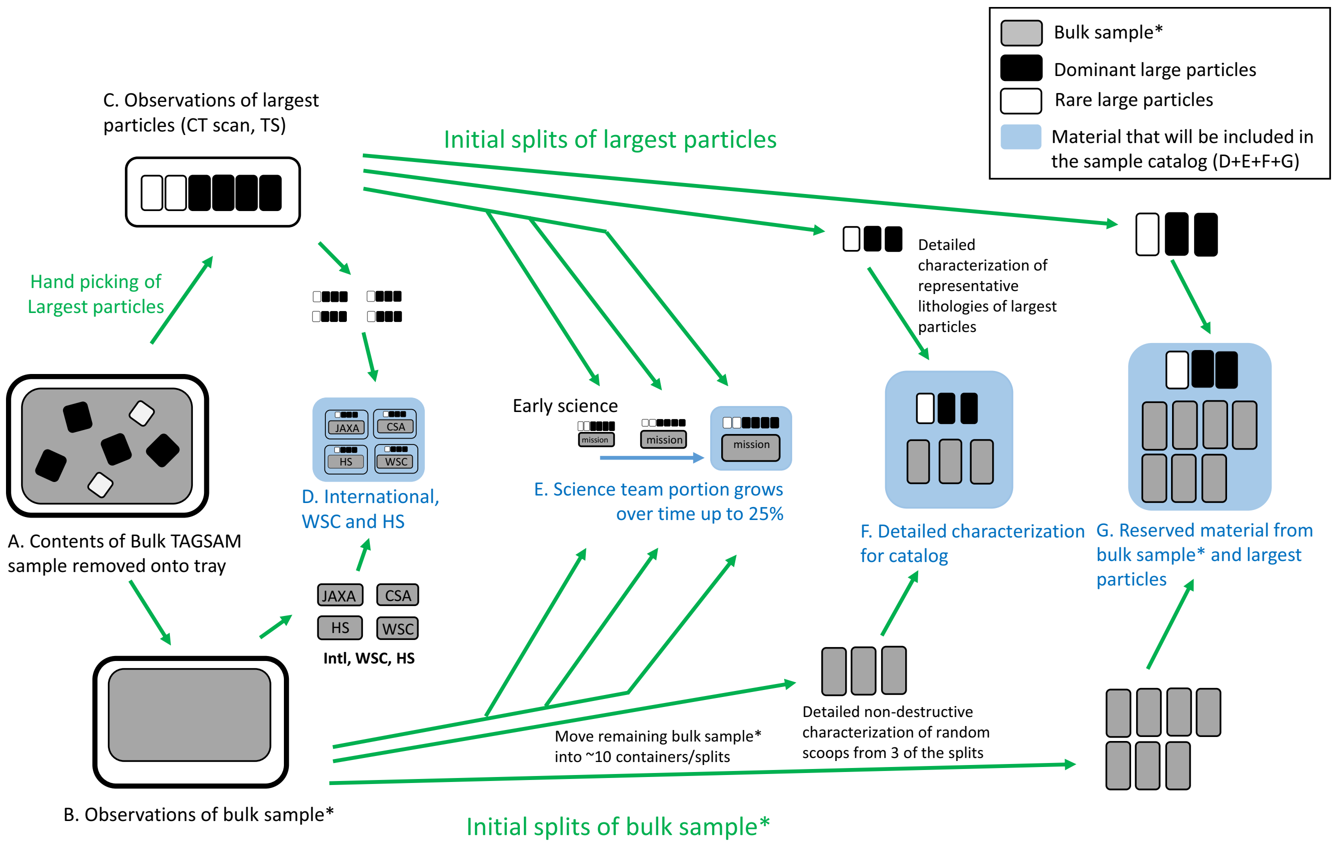


FIGURE 8. Flow diagram of sample characterization and allocation to international partners (Intl), White Sands Complex (WSC) for remote storage, hermetic sealing (HS), mission science, and cataloging.

pile of loose material and (ii) that aliquot with the remaining (not yet containerized) bulk sample*, to record its position relative to the other aliquots. Thus, basic information for each aliquot will include several images, a macroscopic description, and a mass measurement.

A subset of the separated clasts and remaining bulk sample* will initially be characterized using optical and spectral imaging (i.e., Fulford et al., 2022) and other nondestructive and minimally destructive measurements (e.g., Fourier-transform infrared [FT-IR] spectroscopy, X-ray computed tomography [XCT], scanning electron microscopy [SEM]). All required techniques are available at JSC in Building 31 to minimize sample handling, transport, and loss. These measurements, coupled with observations of colors, textures, and physical characteristics, will be used to select representative samples for the science team, JAXA, and CSA, as well as NASA remote storage and a hermetically sealed sample (Figure 8). The mission science team may opt not to select their full 25 wt% allocation during this period, so that analysis of the initial selections can inform later ones. These activities will all take place within a 6-month period, culminating with the production and release of a catalog in late March 2024 (Figure 9).

Catalog

The sample catalog must be publicly available and searchable online, and it must allow requests of specific types of samples in a manner efficient for the scientific community, and curators. The catalog will encompass all objects and samples that were documented during preliminary examination: all asteroidal samples, including splits and separated particles, whether taken from the bulk or elsewhere; individual contact pads and witness plates; and hardware items, including any individually separated components such as the SRC filter, backshell, heatshield, and TAGSAM head. At a minimum, the catalog will contain for each object or sample a unique catalog name; the photographic documentation and complete description recorded during preliminary examination; the form of the material (e.g., aggregate, particle, chip, thin section, etc.) in the case of asteroid samples; its original and remaining size or mass; the conditions to which it was exposed; its parentage with respect to other entries in the catalog; a description of any

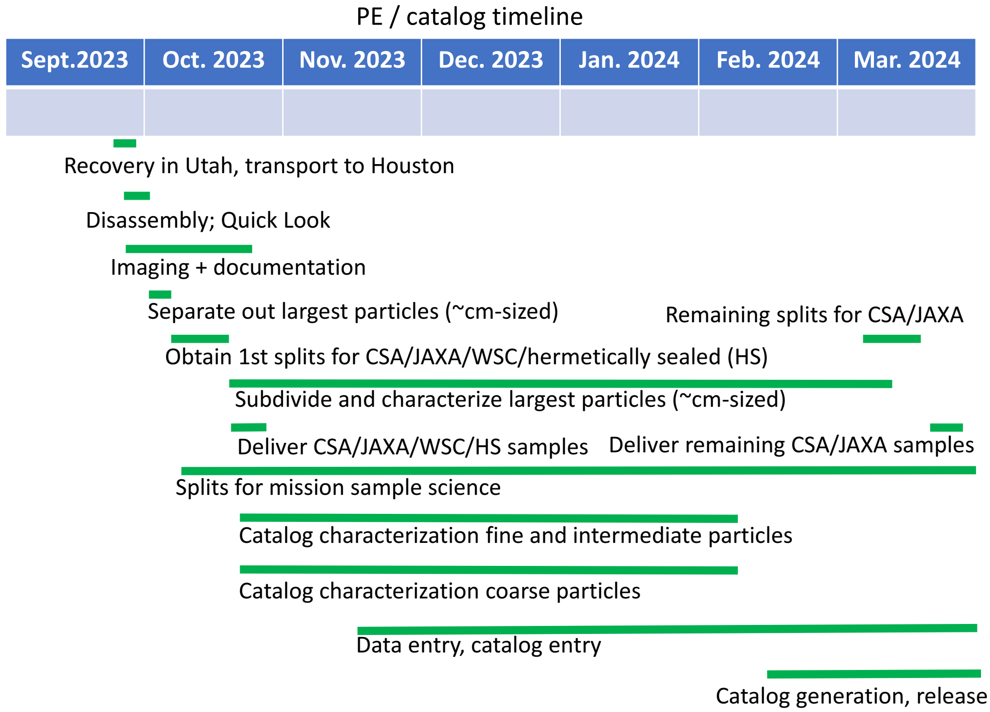


FIGURE 9. Detailed timeline of the expected curation activities within the 6-month period of preliminary examination.

adhering asteroidal material in the case of hardware and components; notes on detected or suspected contamination; and whether it can be requested for analysis. The catalog will include basic information about the NASA, science team, and international partner samples. For the contact pads, witness plates, and hardware items, the catalog will include information to place them in the context of their location and orientation on the SRC or TAGSAM head and correlate them with the images of the TAGSAM head on the surface of Bennu and in space.

A fraction of asteroidal samples will be characterized in the catalog beyond the minimum level of detail during PE to allow the science team and sample analysis community to make more informed sample requests, while being conservative of irreplaceable sample mass. Approximately three of the bulk sample* aliquots will be selected for additional characterization. The selected aliquots will be chosen to represent noncontiguous spatial areas within the original bulk sample*, so the catalog may capture any unrecognized variations within the visually representative subdivisions of the bulk sample*. A subset of particles from each of the selected aliquots will be characterized using nondestructive or minimally destructive techniques: optical microscopy (color, texture, mineralogy), multispectral imaging, and other analyses as necessary such as FT-IR, UV fluorescence, SEM, Raman spectroscopy, μ-XCT scanning, or μ-X-ray fluorescence (μ-XRF). These analyses will be incorporated into the sample catalog.

Because some of the rock fragments might be friable, and thus transformed even by simple handling, only small portions of each aliquot will be analyzed. Characterization techniques used will depend on the sizes of particles (Table 1).

Fine to Intermediate Particles

In cases where organic-rich and organic-poor materials are finely interspersed and difficult to differentiate, it will be necessary to use an array of techniques ordered from least destructive to more destructive. For example, all the approaches listed in Table 1 for fine particles may have to be used and, in that case, the FT-IR and UV would be least destructive and used first, whereas SEM and/or μ-XRF would be more destructive due to potential beam damage and therefore used last.

For Stardust and Hayabusa samples, two kinds of characterization were performed, depending on whether they were organic-rich or organic-free/poor, and these approaches will be implemented for OSIRIS-REx. Organics-bearing samples (identified using FT-IR or multispectral imaging, e.g., Fulford et al., 2022; Zolensky et al., 2008) will be mounted on a chemical vapor deposition (CVD) diamond platelet and analyzed using FT-IR spectroscopy to characterize the mineralogy and

TABLE 1. Potential particle sizes and the corresponding analytical techniques that may be used during preliminary examination.

Particle size	Diameter (μm)	Organic techniques	Inorganic techniques	Analog
Fine	1–100	FT-IR, UV	FT-IR, μ-XRF	Stardust, cosmic dust
Intermediate	100–500	FT-IR, UV	SEM, μ-XRF, Raman	Cosmic dust, micrometeorites
Coarse	500–5000	FT-IR, UV, VIS	SEM, optical	Apollo coarse fines (2–10 mm)
Largest	~10,000	FT-IR, UV, VIS	SEM, optical	Antarctic meteorites

organic groups (aliphatic hydrocarbons, polycyclic aromatic hydrocarbons, etc.). This approach affects samples minimally and avoids a sticky substrate that could be a potential contaminant. The CVD platelet does not particulate, so it will not be a source of microdiamond contamination, which was a problem for Stardust aerogels samples (e.g., Nakamura-Messenger et al., 2011). Organics-bearing samples can also be mounted by pressing fine particles into Au foil (Nevill et al., 2019), a contamination- and volatile-free substrate. Organics-poor samples are mounted on amorphous carbon substrate and analyzed using SEM and EDX spectroscopy. Not using a carbon coat creates a risk of losing material but maintains the pristine state of the sample. A light coat (<5 nm) can be used with minimal effect on future inorganic analyses.

For the fine particle size fraction (Table 1), we will characterize 200–300 particles, as was done with Hayabusa samples (Yada et al., 2014). For intermediate-sized particles, we will select ~100 particles. Characterization of fine and intermediate size particles by FT-IR and optical microscopy analysis allows ~15 particles per day, and by SEM–EDX analysis 15–25 particles per day. Thus, during the first several months of preliminary examination, hundreds of particles can be characterized using these approaches.

Coarse Particles

For the Apollo samples, "coarse fines" (4–10 mm) were photographed, described (color, texture, coherence, other notes), and in some cases thin-sectioned (mineralogy and texture) to allow preliminary mineralogical identification using optical microscopy or SEM; such approaches will be used on thin and/or polished sections of Bennu samples. However, there are nondestructive techniques available to OSIRIS-REx that were not available during Apollo times, such as μ-XRF and μ-XCT. 3-D information about samples can be obtained using the μ-XCT scanner now at JSC; the distribution of minor components (metal, vesicles, chondrite components, unusual clasts) can be observed and documented to aid in cutting or subsampling. Micro-XRF can provide generally nondestructive chemical information from geological and meteorite samples, and JSC has a Nikon XTH 320 μ-XCT that will be utilized for the OSIRIS-REx samples. Although X-ray-based techniques like XCT and XRF have been demonstrated not to alter amino acid abundances beyond analytical errors (Friedrich et al., 2016, 2019), the impacts of X-ray techniques have not yet been explored for other classes of organic compounds. In preparation for sample return, the OSIRIS-REx science team is performing a blind study of meteoritic powder exposed to X-rays for a range of compounds. The results of this work will be used to determine whether the X-rays are sufficiently nondestructive for widespread use.

About 25 coarse particles from each aliquot can be characterized using imaging and observations similar to that used for Apollo's coarse fines (4–10 mm; Marvin, 1972). The characterization process will be limited by time, but the analyses described above are expected to be achievable in the first 6 months.

Sample Preparation Techniques

All the techniques for subdivision of fine-, intermediate-, and coarse-sized particles are on hand to achieve the goal of initial studies, and the planned preparation techniques are different for each particle size class, as explained below.

Microtomy and FIB for Fine and Intermediate Particles

Fine and intermediate size particles (Table 1) can be mounted in epoxy and sliced using microtomy techniques (e.g., Zolensky et al., 2008). The microtomy lab for the OSIRIS-REx samples, located adjacent to the sample cleanroom (Figure 6), will include a flow bench, microscopes, microtome, and supporting equipment. Pass-throughs allow direct transport of small particles from the sample cleanroom to the microtomy lab for ease of operations and efficient sample flow. Small particles will be subdivided using microtomy on individual grains. The lab suite will be equipped with a vacuum oven for sulfur or epoxy embedding. Microtoming allows multiple sections or slices (for organic studies) to be prepared from the same stub or butt (off-cut epoxied sample). The microtomy lab will benefit from extensive experience with small particle sample preparation at JSC that has been gained from the Stardust and cosmic dust experience (e.g., Snead et al., 2018; Zolensky et al., 2008). The focused ion beam instrument at JSC can be used to prepare targeted small samples (e.g., Berger & Keller, 2015).

Thin Sectioning and Other Mounts for Coarse and Large Particles

The thin section lab will host a variety of sample preparation techniques for intermediate and large size fraction materials (Table 1). Such techniques cannot be implemented in an ISO 5 cleanroom, because grinding and polishing materials can create potential contaminants to cleanroom surfaces and spaces. Some analytical techniques can utilize 1″ (2.54 cm) round thin or thick sections for detailed analyses such as most e-beam techniques. Samples can be mounted in epoxy, cut, ground flat, epoxied to 1″ (2.54 cm) round glass slides, then cut and polished for thick or thin section mounts. Larger samples (>~2 mm) can be mounted in epoxy, or if friability is not a factor, cut directly using a wire saw or cut-off saw, as has been done for lunar samples and meteorites. The saw kerf (loss of material during a cut) will be minimized by using either the cut-off saw or wire saw, depending on the nature of the sample and the desire to precisely control the location of the cut (Uesugi et al., 2014). Saw fines will be recovered and preserved for study. Wire saws at JSC are used without a lubricant, which reduces contamination, but can enhance heating near the cutting interface; heating can be minimized or even eliminated by making slower cuts. (However, organic contamination control in epoxy-mounted samples is of limited importance.) Extensive JSC curation experience with thin section production of Apollo and Antarctic meteorite samples provides a strong foundation on which to build successful Bennu thin and thick sectioning approaches (e.g., Harrington & Righter, 2013, 2017; Lunning et al., 2021).

Some bulk techniques require crushing and powdering. Homogeneous powders may be prepared following the protocol defined for meteorites by the Smithsonian Institution (e.g., Jarosewich et al., 1987) with possible adaptation to a GN2 atmosphere. FT-IR spectroscopy can measure such samples by pressing pellets into a substrate such as potassium bromide. Intermediate-sized materials may be analogous to micrometeorites where 100–500 μm sized particles can be mounted on some specific substrate like diamond plate, Au foil, or carbon nanotube. Some analyses by secondary ion mass spectroscopy (SIMS) and NanoSIMS require that samples are mounted by pressing into indium. Additionally, intermediate-sized particles or areas could be prepared using ion milling, which typically uses Ar ions to remove material from the surface of a sample; ion milling can be controlled to remove large portions of material from a slice or section.

SUMMARY

Curation planning for the OSIRIS-REx asteroid sample return mission began in 2004, during the earliest stage of mission formulation. Curation scientists were closely associated with mission design, engineering, and science throughout development and execution of the project. Custom facilities were built at JSC to process and store the samples returned from asteroid Bennu, as well as the associated spacecraft hardware and contamination knowledge materials. The curation strategy, which is informed by previous sample return missions, is focused on preserving the OSIRIS-REx samples of asteroid Bennu in a pristine, uncontaminated state. This will support not only the near-term science goals of the mission particularly with respect to organic chemistry but also future generations of scientists testing ongoing or yet-to-be-posed hypotheses. The latter has proven important for lunar and planetary science, with samples collected decades ago (e.g., Apollo, Luna, Stardust, Genesis, meteorites) being used to address newly defined science questions.

Acknowledgments—Curation planning for the OSIRIS-REx mission has benefitted from the eyes of many associated with the project since the early 2000s: E. Stansbery, C. Evans, C. Allen, M. Zolensky, J. Allton, F. McCubbin, A. Regberg, and C. Schwarz (JSC); R. Jenkens, J. Loiacano, M. Donnelly, R. Burns, M. Moreau, R. Mink, V. Elliot, J. Rogers, M. Crigger, D. Bradel, D. Sallitt, and A. Bartels (Goddard Space Flight Center); H. Enos and E. Beshore (University of Arizona); M. McGee and J. Harris (Lockheed Martin); and J. Grossman, M. Morris, M. Lindstrom, and K. Vander Kaaden (NASA HQ). We are grateful to C. Wolner for editorial suggestions, and the journal reviews of K. Tait and an anonymous reviewer, all of which improved the manuscript substantially. We thank RS&H and their design team (A. McCain, M.P. Vascellaro), NASA Project Manager T. Pryor, and the construction team for working with us to meet our cleanliness requirements. We also thank review committees from 2013 (M. Grady, C. Herd, G. Flynn, M. Anderson) and 2020 (CAPTEM, now ExMAG). We are grateful to the entire OSIRIS-REx team for making sample return from Bennu possible. This material is based on work supported by NASA under Contracts NNH09ZDA007O and NNM10 AA11C issued through the New Frontiers Program and NNH06ZDA0010 issued through the Discovery Program.

Data Availability Statement—The data that support the findings of this study are available from the corresponding author upon reasonable request.

Editorial Handling—Dr. Christian Koeberl

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