

Post-flight assessment of the OSIRIS-REx Sample Return Capsule (SRC) for organic and other potential contaminants

Scott A. SANDFORD^{1*}, Jason P. DWORKIN², Kevin RIGHTER^{3,4},
Feargus A. J. ABERNETHY⁵, Romain ALOSIUS⁶, José C. APONTE², James BALL⁶,
Eve L. BERGER³, Denise K. BUCKNER^{2,7}, Henner BUSEMANN⁶, Simon J. CLEMETT⁸,
George CODY⁹, Jamie ELSILA², Dionysis I. FOUSTOUKOS¹⁰, Ian A. FRANCHI⁵,
Daniel P. GLAVIN², Monica M. GRADY⁵, Heather V. GRAHAM², Philipp R. HECK^{11,12},
Amy E. HOFMANN¹³, Yongsong HUANG¹⁴, Bumsoo KIM⁸, Daniela KRIETSCH⁶,
Nicole G. LUNNING³, Colin MADEN⁶, Hannah L. McLAIN², Angel MOJARRO^{2,7},
Michel NUEVO¹, Philippe SCHMITT-KOPPLIN^{15,16,17}, Ewerton SANTOS¹⁴,
Maria SCHÖNBÄCHLER⁶, Christopher J. SNEAD³, Kathie L. THOMAS-KEPRTA¹⁸,
Alexander B. VERCHOVSKY⁵, Harold C. CONNOLLY Jr.^{19,20,21}, and Dante S. LAURETTA¹⁹

¹NASA Ames Research Center, Moffett Field, California, USA

²NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

³NASA Johnson Space Center, Houston, Texas, USA

⁴Department of Earth and Environmental Science, University of Rochester, Rochester, New York, USA

⁵School of Physical Sciences, Open University, Milton Keynes, UK

⁶Institute of Geochemistry and Petrology, ETH Zurich, Zurich, Switzerland

⁷NASA Postdoctoral Program, Oak Ridge Associated Universities, Oak Ridge, Tennessee, USA

⁸Amentum/JETS II Contract, NASA Johnson Space Center, Houston, Texas, USA

⁹Molecular Organic Analysis Laboratory, Geophysical Laboratory, Carnegie Institution for Science, Washington, DC, USA

¹⁰Earth and Planets Laboratory, Carnegie Institution for Science, Washington, DC, USA

¹¹Robert A. Pritzker Center for Meteoritics and Polar Studies, Negaunee Integrative Research Center, Field Museum of Natural History, Chicago, Illinois, USA

¹²Department of the Geophysical Sciences, University of Chicago, Chicago, Illinois, USA

¹³Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

¹⁴Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, Rhode Island, USA

¹⁵Center for Astrochemical Studies, Max Planck Institute for Extraterrestrial Physics, Garching, Germany

¹⁶Technical University Munich, Freising, Germany

¹⁷Research Unit Analytical Biogeochemistry, Helmholtz Munich, Neuherberg, Germany

¹⁸Barrios/JETS II Contract, NASA Johnson Space Center, Houston, Texas, USA

¹⁹Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona, USA

²⁰Department of Geology, Rowan University, Glassboro, New Jersey, USA

²¹Department of Earth and Planetary Science, American Museum of Natural History, New York, New York, USA

*Correspondence

Scott A. Sandford, NASA Ames Research Center, Moffett Field, CA, USA.

Email: scott.a.sandford@nasa.gov

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Abstract—Regolith samples from the carbonaceous asteroid Bennu were stowed and delivered to Earth in the *OSIRIS-REx* spacecraft's Sample Return Capsule (SRC). We applied multiple analytical techniques to study the components of the post-flight SRC, with a focus on assessing the conditions and any contaminants to which the Bennu samples were exposed. Examination of the passive temperature sensors placed inside the SRC, in combination with thermal modeling results, indicate that the samples were not heated

above the 75°C limit imposed by *OSIRIS-REx* mission requirements. The sample canister air filter was found to contain Bennu particulates that had escaped from the sample collector, as well as a range of contaminants likely associated with the original filter component materials. No indications of terrestrial soils were found in the filter. Isotopic analyses of organic compounds and noble gases trapped in the filter show values consistent with terrestrial origins, and there are no indications of trapped asteroidal volatiles. Organic compounds found in the flight filter that were not present in a non-flight control filter include aromatic hydrocarbons, alkylated aromatic hydrocarbons, phenolic-related compounds, aliphatic hydrocarbons, and alcohols. The abundances of these organic compounds typically decrease from outer layers of the filter toward the canister interior, suggesting that they are external contaminants. We conclude that the majority of these organic compounds are chemical byproducts associated with outgassing of the SRC heatshield and backshell following the ablation portion of SRC atmospheric entry. Overall, our findings show that the *OSIRIS-REx* SRC performed excellently in containerizing the asteroidal samples obtained at Bennu, delivering them safely to the ground at the UTTR, and preventing most, though perhaps not all, external contaminants from reaching them. We discuss lessons learned from the flight and recovery of the *OSIRIS-REx* SRC that can benefit future sample return missions.

INTRODUCTION

On September 24, 2023, the *OSIRIS-REx* (Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer) mission returned regolith samples from near-Earth asteroid (101955) Bennu after a 7-year round-trip journey (Lauretta et al., 2015, 2017, 2023a, 2024). Bennu is a small (~0.5 km diameter) B-type asteroid that has a carbonaceous composition and contains prebiotic organics and volatiles of the type that may have contributed to the habitability of the early Earth (Glavin et al., 2025; Sandford et al., 2025).

Central to the success of the mission was the *OSIRIS-REx* spacecraft's Sample Return Capsule (SRC) (Lauretta et al., 2017). Figure 1 shows an exploded view of the components that make up the SRC. The regolith samples, housed within the sampler head of the Touch-and-Go Sample Acquisition Mechanism (TAGSAM) (Bierhaus et al., 2018), were stowed in the sample canister of the SRC (Figure 2a) during transport back to Earth. The SRC served to protect the samples from potential contaminants and extremes of temperature, and ultimately deliver them to the surface of Earth.

The SRC was released from the main *OSIRIS-REx* spacecraft early in the morning of September 24, 2023. The spacecraft then executed a divert maneuver that put it on a trajectory for a new mission as *OSIRIS-APEX* (*OSIRIS-Apophis Explorer*), in route to a rendezvous with asteroid (99942) Apophis in April 2029 (DellaGiustina et al., 2023). The SRC continued on a trajectory that reached the Earth's atmospheric interface at 14:42 UTC; visible and infrared video footage

suggested a nominal atmospheric entry through the hypersonic phase (Francis et al., 2024). However, the SRC's drogue parachute deployed more than 3 min late and was immediately followed by the main parachute (Williams et al., 2025) (Figure 2b). Fortunately, despite this off-nominal parachute sequence, the SRC's descent ended in a safe touchdown at 14:52 UTC at the Utah Test and Training Range (UTTR) in Dugway, Utah (Lauretta et al., 2024) (Figure 2c).

After recovery of the SRC and parachutes, they were transported by helicopter longline to a UTTR temporary cleanroom. Once there, a gaseous nitrogen (GN₂) purge was established on the sample canister as soon as possible (18:51 UTC). The SRC was then partially disassembled under controlled conditions to remove the sample canister with the enclosed TAGSAM head. This disassembly was performed by Lockheed Martin (the primary contractor for the mission) personnel assisted by curation and team members. The sample canister, SRC heatshield, SRC backshell, and environmental samples and materials from the recovery site were then packaged in separate containers for transport to the curation facility at NASA's Johnson Space Center (JSC). Most packaged SRC components were transported to Ellington Air Force Base via airplane the next day and then by truck from Ellington to JSC, where the sample canister was taken into the *OSIRIS-REx* cleanroom (Richter et al., 2023) for subsequent processing.

The GN₂ purge established on the canister at UTTR was maintained until just before the canister was placed in its bespoke glovebox (also under GN₂ purge) in the cleanroom.

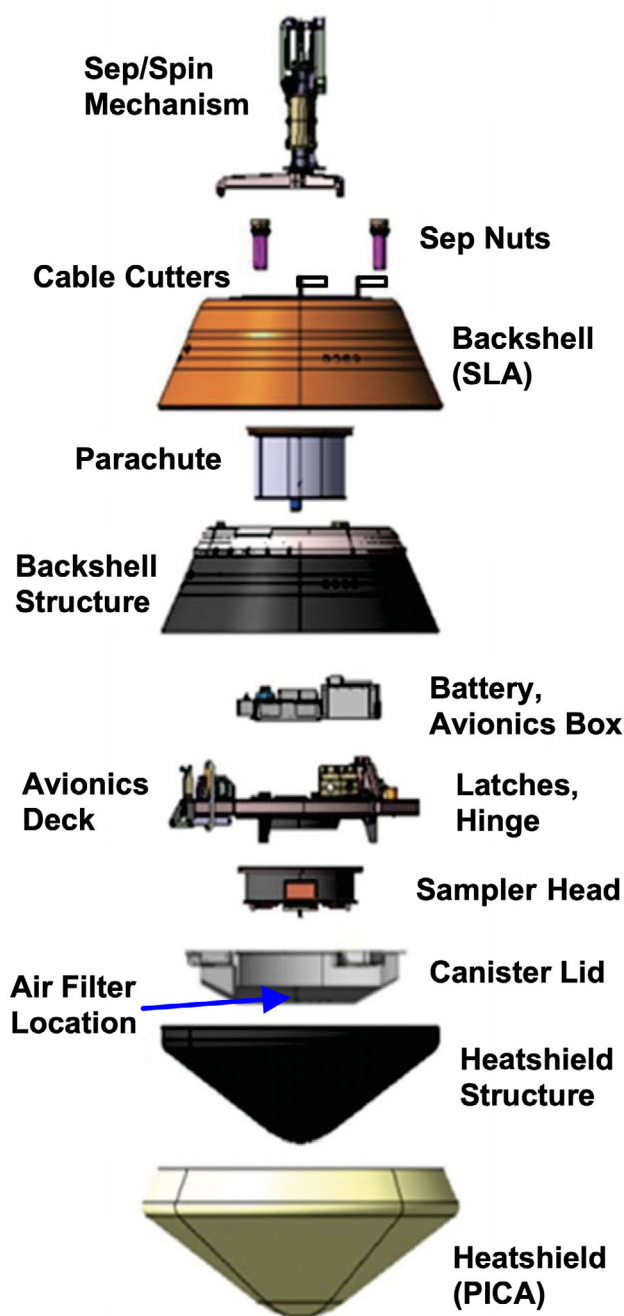


FIGURE 1. An exploded view of the *OSIRIS-REx* SRC and the separation/spin mechanism, cable cutters, and separation nuts that released it from the *OSIRIS-REx* spacecraft for Earth reentry. The structures from the backshell downwards were contained within the SRC that was returned to Earth [Figure adapted from Ajluni et al., 2015].

The transportation environment of the SRC from recovery at UTTR to arrival at JSC was monitored via a MadgeTech Ultrashock 3-axis data logger strapped to the SRC handling fixture. The logger recorded shock,

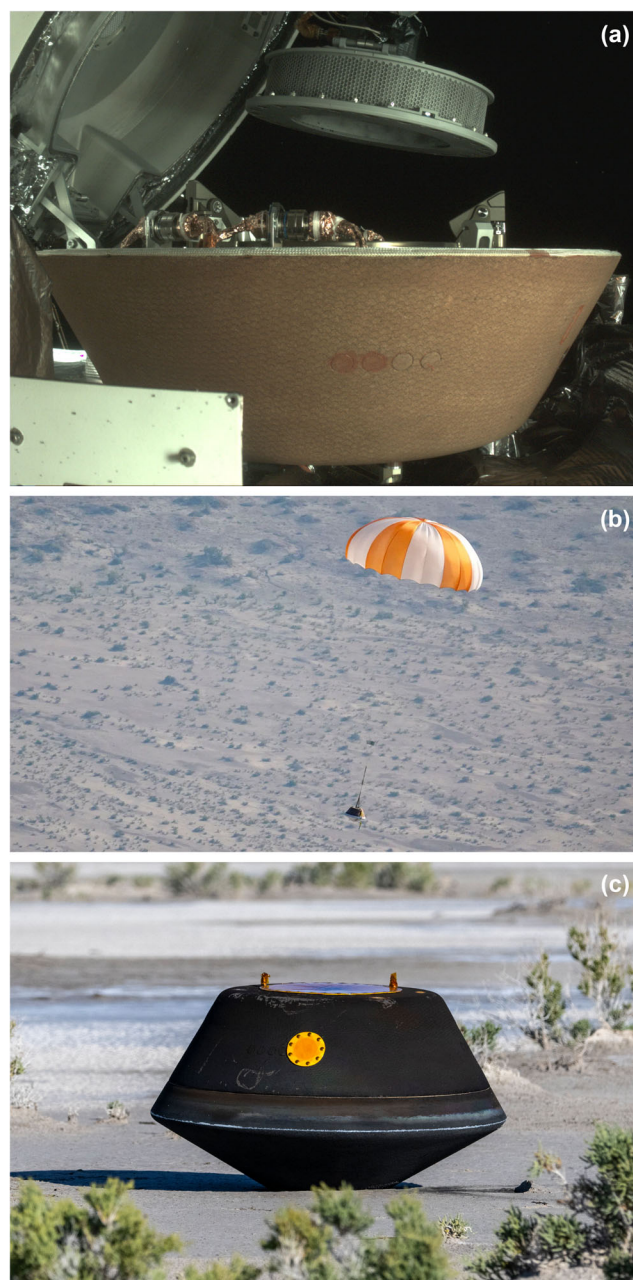


FIGURE 2. (a) StowCam image taken in flight on October 28, 2020, showing the open SRC with the TAGSAM head (containing Bennu regolith samples) positioned in the canister. (b) The SRC during descent to Earth on September 24, 2023, with the main parachute deployed. (c) The SRC at its landing site at the Utah Test and Training Range. The SRC hit the ground nearly vertically, bounced or dipped slightly to the side and onto its rim (the imprint of the rim in the ground can be seen on the right), and then righted itself back into the depression made by its original impact. The orange circle on the SRC backshell was added by recovery personnel to cover the opening of one of the backshell air vents to prevent the entry of contaminants. Image credits: (a) NASA/Goddard/University of Arizona/Lockheed Martin; (b, c) NASA/Keegan Barber.

temperature, relative humidity, and pressure at a resolution of 0.2 g, 0.1°C, 0.1%, and 0.05 mbar, respectively, every 10 s. Whereas variations in pressure, temperature, and humidity stemming from the change of location were evident, vibrations during the helicopter, airplane, and truck transportation were below the detection limits of the shock recorder.

The heatshield, parachute, battery, and avionics box were sent directly to the Lockheed Martin facility in Littleton, CO, for testing and characterization of the engineering performance. These items were sent to JSC two weeks later for permanent curation.

In addition to flight materials, NASA JSC curates an *OSIRIS-REx* contamination knowledge collection that includes coupons of materials used in the making of the spacecraft, SRC, and canister (e.g., steel, aluminum, epoxy, paint), and materials related to the environments of launch, cleanroom construction, and recovery (Dworkin et al., 2018). Items not constrained by ITAR considerations can be requested from the NASA Astromaterials Acquisition and Curation Office (<https://curator.jsc.nasa.gov/osirisrex/requests.cfm#>).

In this paper, we describe the results of multiple analyses designed to establish the extent and nature of contaminants to which the Bennu samples may have been exposed during the flight and recovery of the SRC. We analyzed key components of the flown SRC, archival samples of materials used to make the SRC, and environmental samples associated with the construction and flight of the SRC. This work builds on experience from previous sample return missions and provides lessons learned for such missions in the future.

THE *OSIRIS-REx* SAMPLE RETURN CAPSULE

The blunt-nosed *OSIRIS-REx* SRC was based on that of NASA's *Stardust* mission (Brownlee et al., 2003) and was composed of five principal components: a heatshield, a backshell, a sample canister, a parachute system, and avionics (Lauretta et al., 2017) (Figure 1). Early in mission planning, a requirement was established providing for the post-flight analysis of the recovered SRC and its components, with the aim of assessing both the potential for contaminants in the asteroid samples and the engineering performance of the SRC. To this end, a plan was developed that included analysis of the following items addressed in this manuscript: asteroidal regolith materials found inside the SRC but outside the sample canister, the sample canister itself, the sample canister air filter, the SRC heatshield and backshell, and air and gas associated with the SRC landing site and the UTTR cleanroom. These items are described directly below and are followed by descriptions of the results of the analyses.

Asteroidal Regolith Materials Found Outside the Sample Canister

After the spacecraft collected the samples, particles were observed escaping from the TAGSAM (Lauretta et al., 2022). Such particles could have been trapped inside the capsule, but outside the sample canister when the TAGSAM head was stowed (Figure 2a). Indeed, as soon as the SRC was opened in the UTTR cleanroom, loose, possibly asteroidal materials were observed outside the canister. Materials that could be easily mobilized during subsequent transport were collected and containerized by curation personnel prior to packaging SRC components for delivery to JSC (Lauretta et al., 2024). Some potential asteroidal materials were left in place for removal after transport to JSC.

Sample Canister

The sample canister was designed to hold the collected sample in a controlled space that prevented contamination from outside sources once the SRC was closed. The design prevented air from entering or leaving the canister except through a dedicated air filter mounted on the canister lid. The location of the sample canister within the SRC is shown in the exploded view of the SRC found in Figure 1. Images of the inside of the canister lid can be seen in Figures 2a and 3a, the first taken during stowage of the TAGSAM head after sample collection and the second after opening of the canister lid in the JSC cleanroom. Figure 3a–d show portions of the interior of the canister after it was opened in the JSC cleanroom, and Figure 3e shows the interior face of the air filter mounted on the canister lid.

During the return cruise phase and reentry, the SRC was closed and the sample canister lid was sealed against the bottom of the canister. During these periods, all volatiles entering or leaving the canister had to pass through the air filter mounted on the canister lid. The canister lid seal remained intact through reentry, touchdown, and subsequent transportation to the UTTR cleanroom.

As previously noted, the sample canister was under GN₂ purge in the UTTR cleanroom and during transportation, until just before it was placed in its GN₂-purged glovebox at JSC (Righter et al., 2023). During the brief period between purge connections, the tortuous path created by the sealed canister lid likely prevented air from contacting the enclosed Bennu samples.

Results from *Hayabusa2* (Imae et al., 2024) underscored the significance of humidity exposure to sample integrity. Part of the procedure for transferring the sample canister from the GN₂-purged shipping

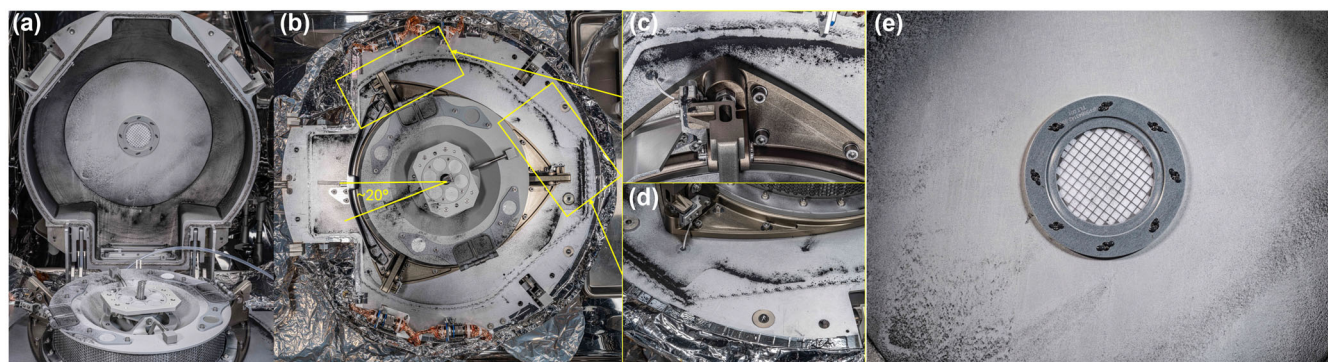


FIGURE 3. (a) Dust coating the inside of the canister lid. (b–d) Distribution of asteroid particles on the avionics deck. In (b), yellow boxes highlight concentrations along the canister seal, which are shown in zoomed view in (c) and (d). Panel (b) also shows a TAGSAM head rotation of $\sim 20^\circ$ (angle measure in yellow) from its initial stow position at Bennu. (e) Interior face of the SRC air filter mounted to the canister lid, showing Bennu particles adhering to both the lid and filter.

container to the GN_2 -purged glovebox in the JSC cleanroom involved a brief exposure to air. To minimize the duration of possible air exposure, the fasteners on the canister catches had been removed at UTTR, and the canister lid was held in place by its own weight during transportation to JSC. This decision saved the samples from exposure to humidity, which could have compromised the detection of deliquescent salts in the sample (McCoy et al., 2025). However, it provided the means for loose material on the avionics deck to migrate under the seal around the edge of the sample canister owing to vibration or movements of the SRC.

When the canister lid was opened in the cleanroom glovebox, asteroidal dust was observed to be widespread within and around the canister, including on the inside of the canister lid, on the avionics deck on which the canister lid rested, and under the canister lid seal (Figure 3a–d; Lauretta et al., 2024). These materials were photo-documented and removed according to the procedures described in Righter et al. (2023). The details can be found in the curation plan, which is publicly available at: <https://nspires.nasaprs.com/external/solicitations/summary.do?solId=%7B18ABFFE3-786E-8BA4-75CD-D137ADAD55F1%7D&path=&method=init>.

It was also apparent that the TAGSAM had been rotated $\sim 20^\circ$ counterclockwise relative to the avionics deck between being stowed in the SRC at Bennu and the canister lid being opened in the JSC cleanroom (Figure 3b). Rotation of the TAGSAM and dust migration to the seal may have occurred during the zero-gravity Earth-return cruise phase, during SRC movement and vibration during Earth reentry, during subsequent handling and transportation to the JSC cleanroom, or any combination of the above. The concentration of material against the canister lid seal could have several possible causes, including the rotation

of the SRC when it was released from the *OSIRIS-REx* spacecraft, movements of the SRC as it nutated prior to deployment of the main parachute, and movement caused by GN_2 purge gas flow from the sample out to the seal during transport to JSC.

Sample Canister Air Filter

The design of the sample canister air filter was based on that used successfully for the *Stardust* mission (Brownlee et al., 2003; Sandford et al., 2010). The filter (Figure 4), which was mounted on the canister's lid, consists of a cylindrical structure containing layers of filter material sandwiching active absorbing materials (a mixture of activated carbon and zeolite) (Dworkin et al., 2018).

The purpose of the air filter was to prevent gas-phase and particulate contaminants from entering the sample canister when closed, particularly during launch site processing, atmospheric entry, and ground recovery. It was designed to be a 2-way filter that can trap particulate, humidity, and organics moving into or out of the canister. Because the air entering or exiting the canister passes through this filter, its contents would provide critical information about the nature of any molecular and particulate contaminants to which the canister was exposed. Some of these contaminants could be relatively volatile. The filter could also have captured sample outgassing products or small loose particles during the return cruise from Bennu.

Because air passed through the filter in different directions at different times of the mission (outward during launch, inward during reentry, minor movement in and out during SRC ablation heatsoak and cooling after reentry), it was desirable to analyze each of the filter's layers independently. This allowed for a search for gradients in detected molecules and particulates within

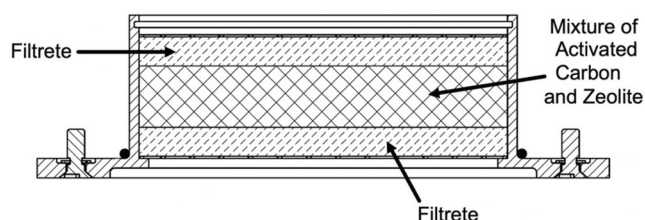


FIGURE 4. Cross section of the sample canister air filter showing the alternating layers of filtrete material and active absorbing materials. The materials from each of these separate layers are curated and portions of each analyzed in this study.

the vertical structure of the filter that could provide information concerning whether the filter-trapped materials were leaving the canister (escaping asteroidal materials) or entering the canister (external contaminants).

Disassembly of the flight air filter was carried out at the JSC Curation Facility and is described in detail in the SOM.

Heatshield and Backshell

The heatshield and backshell—made of PICA (Phenolic Impregnated Carbon Ablator) and SLA (Super-Lightweight Ablator), respectively (Tran et al., 1996, 1997; Venkatapathy, 2019)—provided thermal protection of the SRC during atmospheric reentry. The seal between them protected against heat leaks. Two vents on the side of the backshell allowed depressurization during ascent at launch in 2016 and re-pressurization during descent at Earth return in 2023 to preclude unacceptable pressure loads within the SRC.

Potential sources of contamination associated with the SRC heatshield and backshell include: (i) outgassing associated with the SRC during flight (Sandford et al., 2020) and (ii) production of ablation products during atmospheric reentry.

During the outbound cruise, Doppler tracking of the spacecraft detected a small but measurable acceleration when the SRC was first placed in sunlight (Sandford et al., 2020). Subsequent analysis determined that outgassing from the SRC was the most likely cause for the acceleration. This outgassing received combined engineering and scientific attention because it had potential implications both for spacecraft navigation performance and for contamination of the collected samples. Thermal modeling, laboratory studies of SRC materials, and monitoring of the acceleration were all found to be consistent with H_2O as the main component of the outgassing. Dedicated in-flight campaigns continued to expose the SRC to sunlight until the acceleration dropped to the acceleration noise floor and

any residual amounts of H_2O outgassing were not considered to be a hazard with regard to mission operations or pristine sample acquisition (Sandford et al., 2020). The sample stow procedure was then updated to ensure that no direct line of sight existed between any residual outgassing and the samples during future operations. Once the sample canister was sealed with the Bennu samples inside, sample exposure to additional outgassing would have also been restricted by the air filter. Thus, sample contamination associated with H_2O outgassing from the SRC heatshield and backshell was limited. Only one SRC sunlight exposure was performed after sample stow to minimize sample heating while reducing the outgassing acceleration after SRC separation for Earth entry.

Possible contamination from ablation products associated with atmospheric reentry of the SRC was of greater concern. Ablation of the surfaces of the SRC occurred during the hypersonic phase of atmospheric reentry, which proceeded nominally (Francis et al., 2024). During this phase, the SRC was oriented nose-first and preceded by a shock front, and very little air entered the SRC through its backshell vents. Consequently, during this period, ablation products consisting of gases and some small particles largely streamed around the capsule. However, when the SRC's drogue parachute did not deploy as it should have to stabilize the SRC prior to main parachute deployment (Williams et al., 2025), the SRC did not remain nose cone-forward and instead was able to nutate or tumble. This led to a period of more chaotic air flow around the capsule than expected, which probably led to air entering the SRC earlier, at higher temperatures, and at a faster initial rate than planned. Also, there may have been times when the backshell vents were in the ram direction (i.e., direction of SRC motion). This increased the chances of contaminant gases and particles from the exterior of the SRC getting inside through the vents.

To examine the possible impact of this source of contamination, we took archival samples of the materials used to make the *OSIRIS-REx* heatshield, pyrolyzed them to simulate atmospheric ablation, and analyzed the resulting products so they could be directly compared to materials detected within the sample canister air filter.

Temperature Strips

Multiple irreversible thermal indicators (temperature strips) were placed inside the SRC heatshield and backshell to verify that the interior of the SRC complied with the mission requirement to maintain the asteroidal samples at $<75^\circ\text{C}$ from collection through curation. Locations of the various temperature strips are shown in Figure S10. Thus, the maximum temperatures recorded

by these sensors were of interest both for evaluating SRC performance and for scientific reassurance that the samples were not heated beyond what was expected during and after SRC reentry.

Unfortunately, the temperature strips on the backshell were exposed to temperatures that tripped them prior to launch, during an unplanned extra thermal-vacuum cycle that was required to reduce unexpected backshell outgassing. It was decided that replacement of these strips could result in a launch delay, so the loss of these strips was an acceptable trade. These strips now serve as a positive control, together with the negative control of the strips from the materials archive, when comparing the color of the remaining flight temperature strips from the SRC. On their own, the remaining active strips on the flight SRC are insufficient to accurately constrain the actual temperatures of the SRC's interior. Post-flight analysis of the temperature strips by Lockheed Martin personnel determined that the heatshield structure did not exceed 82°C and the backshell did not exceed 132°C. Thermal models of the SRC carried out by Lockheed Martin using conservative boundary conditions for atmospheric entry predict that the TAGSAM temperature remained below 50°C during the entire reentry sequence, including the thermal soakback that occurs after reentry as heat generated at the SRC's outer surface conducts deeper into the capsule. Given that the model shows more than 25°C of margin on the SRC temperature requirement, we are confident that the TAGSAM remained well below 75°C during and after reentry.

After SRC disassembly, the temperature strips placed inside the SRC were photo-documented in the UTTR cleanroom by Lockheed Martin personnel so their maximum attained temperatures could be noted and recorded. These strips have been archived at JSC and can be requested for science or engineering analyses via standard hardware request processes.

ENVIRONMENTAL SAMPLES

Because the SRC landing site was on open ground at the UTTR, the terrestrial environment posed potential contamination risks to the Bennu samples. To address this possibility, we planned for a systematic sampling of environmental materials around the SRC landing site, including soil, standing water (if any), vegetation (if necessary), and air.

The ancient lakebed in which the SRC landed is composed largely of very fine carbonate muds that are remnants of the Pleistocene Lake Bonneville (Williams, 1962). The water table is very close to the surface, and the groundwater has high concentrations of dissolved salts. As a result, the surface soils contain a

variety of evaporites. When wet, these materials can form a cloying mud (Sandford et al., 2010).

Fortunately, the SRC landed in a controlled fashion in a location where the ground consisted of a thin layer of dry soil over a sublayer of slightly damp soil. There was no standing water in the vicinity, and the SRC did not come into contact with any vegetation during or after landing, so it was not necessary to acquire either of these types of environmental samples from the landing site. We did collect samples of soils that had been contacted by the SRC (as evidenced by surface traces of ablation soot) as well as nearby pristine soils.

At the moment of ground impact, the SRC was nose-down and in a nearly vertical descent. As a result, the SRC came down on its nose, bounced or tipped onto its side, and then righted itself in the depression created by its initial impact, forming two depressions at the site of original impact (Figure 2c). This contrasts significantly with the *Stardust* SRC, which came down on a muddy surface in a crosswind, bounced at least three times while tumbling, and then rolled on its rim for a substantial distance before finally coming to a stop on its side (Sandford et al., 2010).

As a result of this favorable landing, the SRC suffered no damage on contact with the ground, and the seal between the heatshield and backshell was not compromised, eliminating any concerns about contamination associated with a breach of the SRC. Because the soil was not wet and only a few areas of the SRC touched it, very little material adhered to the SRC exterior. There was a very minor possibility that a small amount of the adhering material could have entered the SRC through the backshell vents; however, there is no evidence that the backshell vents ever came into direct contact with the ground. Furthermore, because the SRC did not tumble or roll after touchdown, if any soil did manage to enter through the backshell vents, it would not have had an opportunity to find its way to the external surface of the sample canister air filter.

Thus, contamination of the asteroidal samples by soils at the landing site was deemed not to be a risk. For this reason, although soil samples were collected as planned, they were not analyzed. All the collected soil samples were stored at JSC in a cleanroom, separate from the asteroidal samples. They are available by request from JSC.

Samples of air were taken at the SRC landing site, as well as in the UTTR cleanroom (near SRC vents, adjacent to the filter, and ambient) and in the rotorwash of the transport helicopter outside the high-bay that enclosed the UTTR cleanroom during approach and departure. Samples of the N₂ gas used for purging the canister were also collected. All air samples were subsequently consumed during analyses using procedures previously described (Dworkin et al., 2018).

Details about the collection and analysis of the air samples can be found in the SOM, and the results are summarized in Table S15. In brief, the air samples, including controls, contained only trace amounts of a few compounds. Toluene and benzene, detected adjacent to the SRC vents, were the only compounds not found in any of the controls. These compounds were only observed when the SRC was in the UTTR cleanroom, possibly after being liberated by the SRC ablation heatsoak. It was important to determine whether they originated from asteroidal material or the SRC, so they were specifically targeted in the SRC air filter analyses (next section).

AIR FILTER ANALYSES

In this section, we report the results of analyses of the sample canister's flight air filter and non-flight filter controls, as well as the pyrolysis products from the heatshield and backshell needed to help interpret the filter results. All samples were analyzed single-blind to minimize the potential for bias.

In addition to the flight air filter, Lockheed Martin produced a number of filter prototypes for testing. Once a final design for the air filter was selected, Lockheed Martin constructed the flight air filter as well as five spare air filters and two air filter housings. These spares were stored in polypropylene bags in a safe and clean storage environment at Lockheed Martin before being archived at JSC in 2015. At JSC, the archive filters and filter housings are kept in a continuously purged dry nitrogen container. One of the spare filters, OR-MA-0019-0, was removed in August 2023 for subdivision for use as control filter material.

The methods and equipment used to disassemble and study the flight filter and a non-flight control filter are detailed in the SOM. As part of *OSIRIS-REx* sample return preparations (Lauretta et al., 2023b), testing was performed on an engineering filter unit, which demonstrated the utility of the analytical techniques selected for use on the flight filter and confirmed that planned allocations of filter subsamples (components and amounts) were adequate. Allocations of filter subsamples and the techniques applied to each filter component are summarized respectively in Tables S1 and S2. In the subsections that follow, we report (i) particulates, (ii) noble gases, and (iii) organic compounds found within the flight and non-flight filters.

Particulates

Particles were searched for and measured in flight and non-flight air filters using scanning electron microscopy (SEM).

Materials from three filters were allocated for this study: (1) OR-MA-0233-28, a non-flight test filter; (2)

OR-MA-0019, a non-flight air filter assembly; and (3) OREX-103001, the *OSIRIS-REx* flight canister air filter. We analyzed ~1-cm² samples of filter layers (Figure 4) from the exterior (outward-facing) and interior (canister-facing) sides of the filters. We also analyzed samples of activated carbon and zeolite grains from the middle layer of the filters (Figure 4) as follows: (i) exterior layer (carbon exterior (CE)/zeolite exterior (ZE)); (ii) center layer (carbon center (CC)/zeolite center (ZC)); and (iii) interior layer (carbon interior (CI)/zeolite interior (ZI)). Details of the individual samples are summarized in the SOM, and filter assembly arrangements are shown schematically in Figures S1 and S10.

Analyses of zeolites from the non-flight test assembly (OR-MA-0233-28) show that they are composed of aluminosilicate particles ranging from sub-millimeter to ~10 mm in size, with considerable intraparticle chemical heterogeneity (Figures S11 and S12). This chemical complexity of the zeolites complicates the interpretation of the composition of particles collected by the substrate. Minor amounts of foreign materials were detected on zeolite surfaces of the non-flight filter assembly (OR-MA-0019) (Table S3). These include evaporite minerals, mainly NaCl and KCl; Al ± O; metals such as stainless steel; and a variety of other phases including Na- and Ca-sulfates, oxides (chromite and, possibly, rutile), and carbonates. Most of these terrestrial particles differ markedly in composition from local UTTR soil and from Bennu fine-grained matrix minerals that are composed of Na, Si, Al, Mg, S, Ca, Fe, and occasionally Ni with the modal mineralogy dominated by fine-grained phyllosilicates, a mixture of serpentine and saponite minerals typically containing nanophase Fe-sulfides and magnetite (Keller et al., 2024; Lauretta et al., 2024; Zega et al., 2025). Evaporite minerals have also been detected in Bennu sample; however, they are dominated by Na-bearing phosphates and Na-rich sulfates/carbonates primarily associated with Mg phyllosilicates (McCoy et al., 2025). These terrestrial particles were found throughout both non-flight filters examined (OR-MA-0233-28 and OR-MA-0019), indicating that they represent materials introduced during manufacturing and/or filter assembly. The biggest difficulty is associated with distinguishing the presence of any terrestrial phyllosilicates that are compositionally similar to Bennu coarse-grained phyllosilicates. However, the lack of sulfides and Na, common in the Bennu fine-grained matrix, can be used as markers to distinguish asteroidal materials from terrestrial clays (Figure S13).

Comparison of the non-flight filter materials from OR-MA-0233-28 and OR-MA-0019 with materials from the flight filter (OREX-103001) demonstrates that the flight filter contained both Bennu and terrestrial particles similar to those in the non-flight filters (Table S3). The

majority of Bennu particles (particles with compositions consistent with those reported in the Bennu fine-grained matrix in Laurretta et al., 2024 and Zega et al., 2025) were detected on the innermost filter layer that faced the interior of the sample canister (Figure S14). Rare Bennu particles were also identified in the center and outermost layers of the activated carbon/zeolite layer of the flight filter. This distribution indicates that the *OSIRIS-REx* air filter assembly was successful in mitigating any loss of asteroidal particles from the sample canister into the interior of the SRC. Further details about the results from the individual filter samples can be found in the SOM.

Noble Gases

Noble gases are among the more volatile components that might have escaped the Bennu samples during the *OSIRIS-REx* Earth-return cruise phase. Details concerning the equipment and methods used to search for noble gases in the activated carbon and zeolite of flight and non-flight filters can be found in the SOM.

He and Ne in all the filter samples studied (flight and non-flight controls) were found to be isotopically consistent with a terrestrial air composition at a 2σ uncertainty level (Table S4), as shown in the Ne three-isotope plot (Figure 5). If Bennu dust from inside the sample canister found its way into the filter, it might be discernible in the innermost filter layer by a deviation of the released Ne from the terrestrial air isotopic composition, namely a shift toward cosmogenic, solar, or presolar (HL) Ne isotopic compositions. Such signatures were generally not found, indicating that only minor amounts of Bennu dust got into the filter, consistent with the SEM studies described above.

We also assessed the potential production of cosmogenic ^{21}Ne in zeolite. Three of the flown zeolite filter samples show a small offset from the Ne terrestrial air isotopic composition (Figure 5, arrow), perhaps suggesting a small ^{21}Ne excess, which could in principle suggest the presence of extraterrestrial material in the filter or cosmogenic *in situ* production within the zeolite during the 7 years for which the *OSIRIS-REx* spacecraft was in space. However, the similar excess in one of the *non-flight* activated carbon filter samples rather suggests that this excess is due to a small release of memory ^{21}Ne from the Mo crucible wall during a reaction with the melting filter material (see SOM for more details). We nevertheless determined a rough production rate for the zeolite (see methods in the SOM; Table S8). The production of the excess cosmogenic ^{21}Ne in the three samples would require nominally $\sim 700\text{--}2300$ yrs of exposure of the zeolite to galactic cosmic rays and can thus be excluded.

The presence of extraterrestrial material would also lead to an elevated $^3\text{He}/^4\text{He}$ ratio well above that of air ($\sim 1.4 \times 10^{-6}$), as all trapped He components have $^3\text{He}/^4\text{He}$ ratios that are much higher (two orders of magnitude: $\sim 1\text{--}4 \times 10^{-4}$). Such excesses were not detected in the filters. Only two samples, both from the flight filter—one from the exterior and one from the center of the activated carbon/zeolite layer—contained both detectable ^3He and ^4He . Adopting a small concentration of ^3He of $2.4 \times 10^{-8} \text{ cm}^3/\text{g STP}$ detected in a Bennu grain (Barnes et al., 2025), we can exclude the presence of a Bennu dust particle of more than $900 \mu\text{g}$ in any filter sample. Several other samples, including non-flight samples, show very small but detectable amounts of ^3He , suggesting these are instrumental “memory” artifacts associated with residual gas from the instrument. Adding the isotopic constraints, it can be concluded that neither extraterrestrial He- and Ne-bearing grains nor gases are present at detectable levels in the flight filter samples.

The $^{40}\text{Ar}/^{36}\text{Ar}$ ratio in terrestrial air is close to 300, whereas it is $\ll 10$ in most extraterrestrial (K-poor) carbonaceous chondrite-like materials (e.g., CIs/CYs, CMs, Ryugu, and Bennu) (Barnes et al., 2025; King et al., 2019; Krietsch et al., 2021; Okazaki et al., 2023). All $^{40}\text{Ar}/^{36}\text{Ar}$ ratios detected in the filters scatter around 300 (Table S5). Likewise, $^{129}\text{Xe}/^{132}\text{Xe}$ is close to the terrestrial Xe value of 0.9832 ± 0.0001 , whereas the minimum ratio found in meteorites is 1.042 ± 0.002 (phase Q; Busemann et al., 2000); the ratio can be higher if radiogenic ^{129}Xe from the decay of now extinct ^{129}I is present (Tables S6 and S7). In summary, we find no evidence for the presence of extraterrestrial noble gases in the filter materials.

Organic Compounds

One of the primary goals of the *OSIRIS-REx* mission was to understand the nature of organics in the Bennu samples, particularly those of astrobiological interest. Because organic compounds are ubiquitous on Earth, the unequivocal detection of intrinsic organics in extraterrestrial materials requires that meticulous care be taken with identifying possible sources of contamination. For this reason, considerable effort was made to identify any organics captured in the sample canister air filter and to establish whether they represented outside contaminants attempting to enter the sample canister or volatile organics derived from the asteroidal material trying to leave.

To this end, filter materials were examined for a wide variety of organic compounds (including aromatic, aliphatic, and phenolic compounds and alcohols) using a host of analytical techniques (Table S1). Details about the instruments, methods, and results can be found in the



Thus, both EA-IRMS and stepped heating studies demonstrate that the sample canister flight filter contained excess C and N relative to the non-flight control filters.

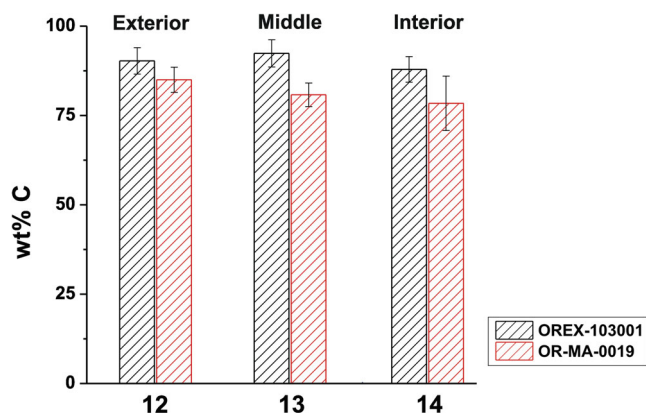


FIGURE 6. Weight-percent carbon in activated carbon from flight filter subsamples OREX-103001-12, OREX-103001-13, and OREX-103001-14, and non-flight filter splits OR-MA-0019-12, OR-MA-0019-13, and OR-MA-0019-14. Uncertainties correspond to a 1σ deviation, which is determined based on either replicate analyses of standards or analyses of at least two aliquots of individual samples, whichever is the larger.

Several techniques were used to identify the molecular nature of the organics trapped in the flight filter: microprobe two-step laser mass spectrometry ($\mu\text{L}^2\text{MS}$), two-dimensional gas chromatography-high-resolution mass spectrometry (GCxGC-HRMS), pyrolysis gas chromatography mass spectrometry (pyGC-MS), thermal desorption pyrolysis with GC-MS (TD-pyGC-MS) and gas chromatography isotope ratio mass spectrometry (GC-IRMS). These analyses show that the organics trapped in the filter consist of a complex population of compounds that include aromatics, alcohols, aliphatics, and phenols discussed in turn below.

Aromatic Compounds

$\mu\text{L}^2\text{MS}$ analyses demonstrated that activated carbon and zeolite samples from both the non-flight and flight filters contain various aromatic molecules. In the non-flight filter samples, aromatics showed no correlation with location (*i.e.*, whether a given sample came from the exterior, center, or interior of the filter assembly). The SOM and Figures S16, S32–S35 provide more details about the nature of aromatics associated with the non-flight filter samples.

Aromatic species in the flight samples were present at higher abundances than in their corresponding non-flight controls and did show a correspondence to sample location within the filter assembly (Figures 8 and 9, S37–S39). In activated carbon and zeolite samples, the total observed polycyclic aromatic hydrocarbon (PAH) mass abundance generally decreased from the interior to the exterior of the filter assembly, and this gradation was most prominent for the lower-molecular-weight species. For example, the single-ring aromatic species toluene ($\text{C}_6\text{H}_5\text{CH}_3$; 92 m/z) and phenol ($\text{C}_6\text{H}_5\text{OH}$; 94 m/z) are

present at abundances up to 20 times those observed in the respective non-flight samples and are most abundant in the interior of the filter assembly (see Figure S17). Although these results would appear to indicate an outward-pointing PAH concentration gradient (*i.e.*, higher concentrations of PAHs in the portion of the filter facing into the canister and lower concentrations in the portions facing out of the canister). This concentration gradient is the reverse of that seen using many other analysis techniques on the filter materials. However, it should be kept in mind that these observed relative concentrations may not be significant because $\mu\text{L}^2\text{MS}$ analyses involve the measurements of very small surface areas ($\sim 2000 \mu\text{m}^2$ per sample) whose exposures to air may be dominated by small-scale, local air flow within the filter. Rather than relative concentrations, the overall higher loading of aromatic species in the flight samples is the more pertinent finding, indicating that gas infusion and trapping of volatile organics did occur in the flight filter assembly during the mission.

GCxGC-HRMS, pyGC-MS, and TD-pyGC-MS pyrolysis coupled to GC-MS/GC-IRMS all confirmed the presence of aromatic compounds in the filter samples, including alkylated benzenes and naphthalenes, larger PAHs, and abundant toluene (Figures 10–12, SOM, Figures S21–S26, and S28–S32).

Aliphatic Compounds and Alcohols

GCxGC-HRMS, pyGC-MS, and thermal desorption pyrolysis with GC-MS/GC-IRMS show the flight filter also contains branched and straight-chain alkane and alkene compounds and alcohols, alky-alcohols, and fatty alcohols (Figures 10–12, SOM, Table S14, Figures S19, S20, S25, S26 and S37–S39).

Phenolic Compounds

Phenolic compounds detected in the flight filter include abundant phenol and a variety of alkylated phenolic compounds (Figures 8–12, Table S14, Figures S28 and S37–S39). The abundant phenolic compounds are of interest given that the SRC's heatshield was made from PICA; thus, the heatshield and its ablation products are potential sources of these species.

Potential Source(s) of Organics in the Flight Filter

Possible sources of the organics found within the flight filter include volatile release from the Bennu samples within the sample canister and outgassing from the SRC's heatshield and backshell.

Bennu Samples

The most direct way to address the possibility that the flight filter contains extraterrestrial organics derived

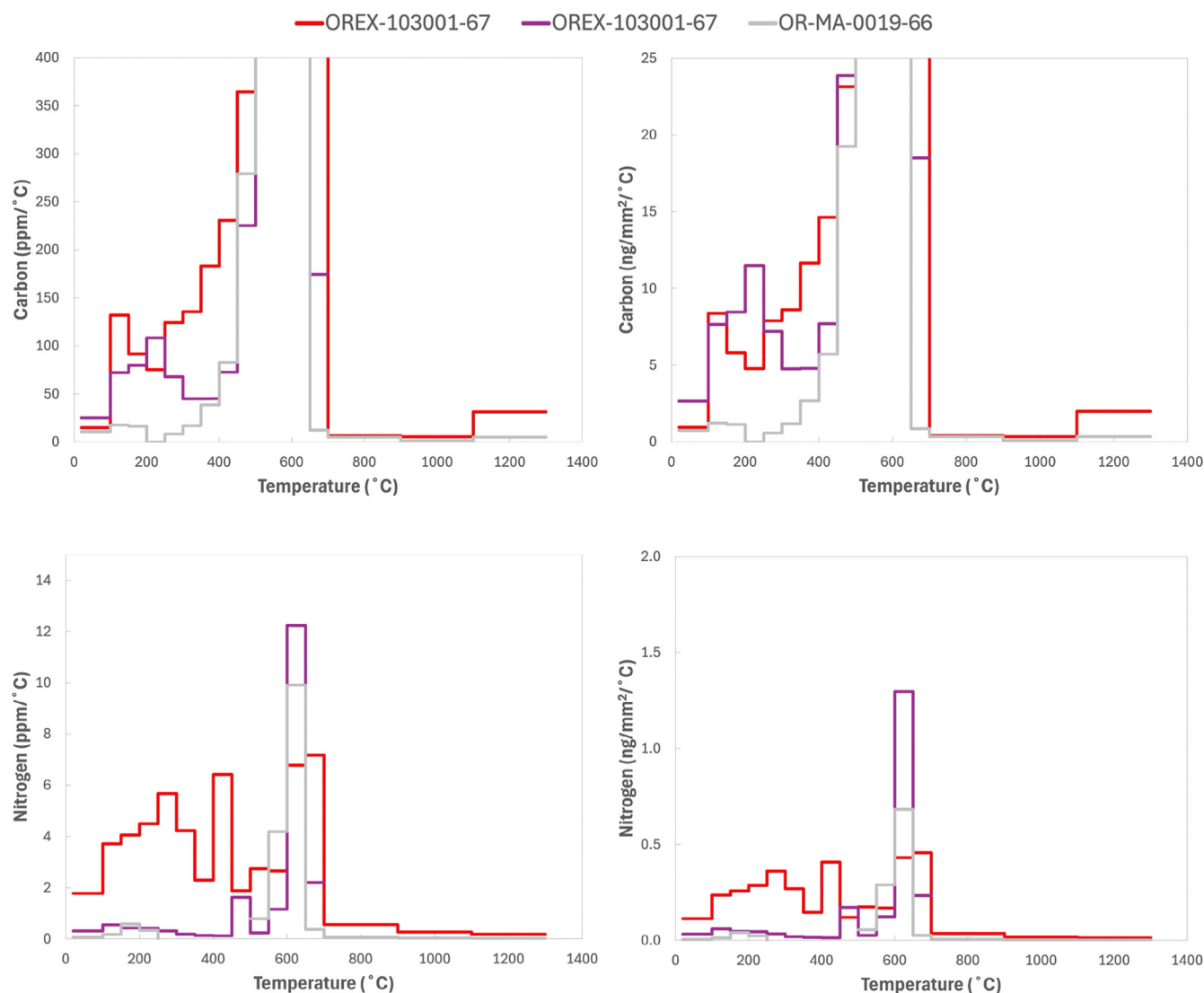


FIGURE 7. Comparison of the C and N release profiles from activated carbon particles in the interior and exterior layers of the flight filter (OREX-103001-67 and -21) compared to that from an activated carbon particle from the middle layer of a non-flight filter (OR-MA-0019-66). Panels on the left show C and N abundance as parts per million by weight. Panels on the right show C and N yield as a function of particle surface area assuming spherical particles with density 0.5 g cm^{-3} . Carbon yield axes adjusted to show details of the release profile below 500°C .

from the Bennu samples is to look for isotopic anomalies in C and N. The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ compositions of activated carbon samples from flight filter samples (OREX-103001-12, -13, -14) and a non-flight control filter (OR-MA-0019-12, -13, -14) determined by EA-IRMS, were nearly identical to each other—approximately -22‰ and $+4\text{‰}$, respectively, except for a higher $\delta^{15}\text{N}$ composition in the middle section of the flight filter ($\sim 6\text{‰}$; Table S9). The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ compositions of the zeolite samples were similar, approximately -14‰ and $+2\text{‰}$, respectively, and likewise showed a marginally higher $\delta^{15}\text{N}$ composition in the middle section of the flight filter ($\sim 4.8\text{‰}$; Table S9). These values are substantially different than those of bulk

Bennu samples (Lauretta et al., 2024; Glavin et al., 2025). Thus, the EA-IRMS results provide no indication of Bennu organics in the flight filter.

Similarly, C and N isotopic analysis of organics released during stepped heating show no evidence for Bennu-like C or N in the trapped organic population. Figure 13 shows the temperature release pattern and the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of material released from a Bennu sample compared with organics released from the flight and non-flight filters. The material released from the flight filter differs from that released by the Bennu sample and is consistent with a terrestrial origin.

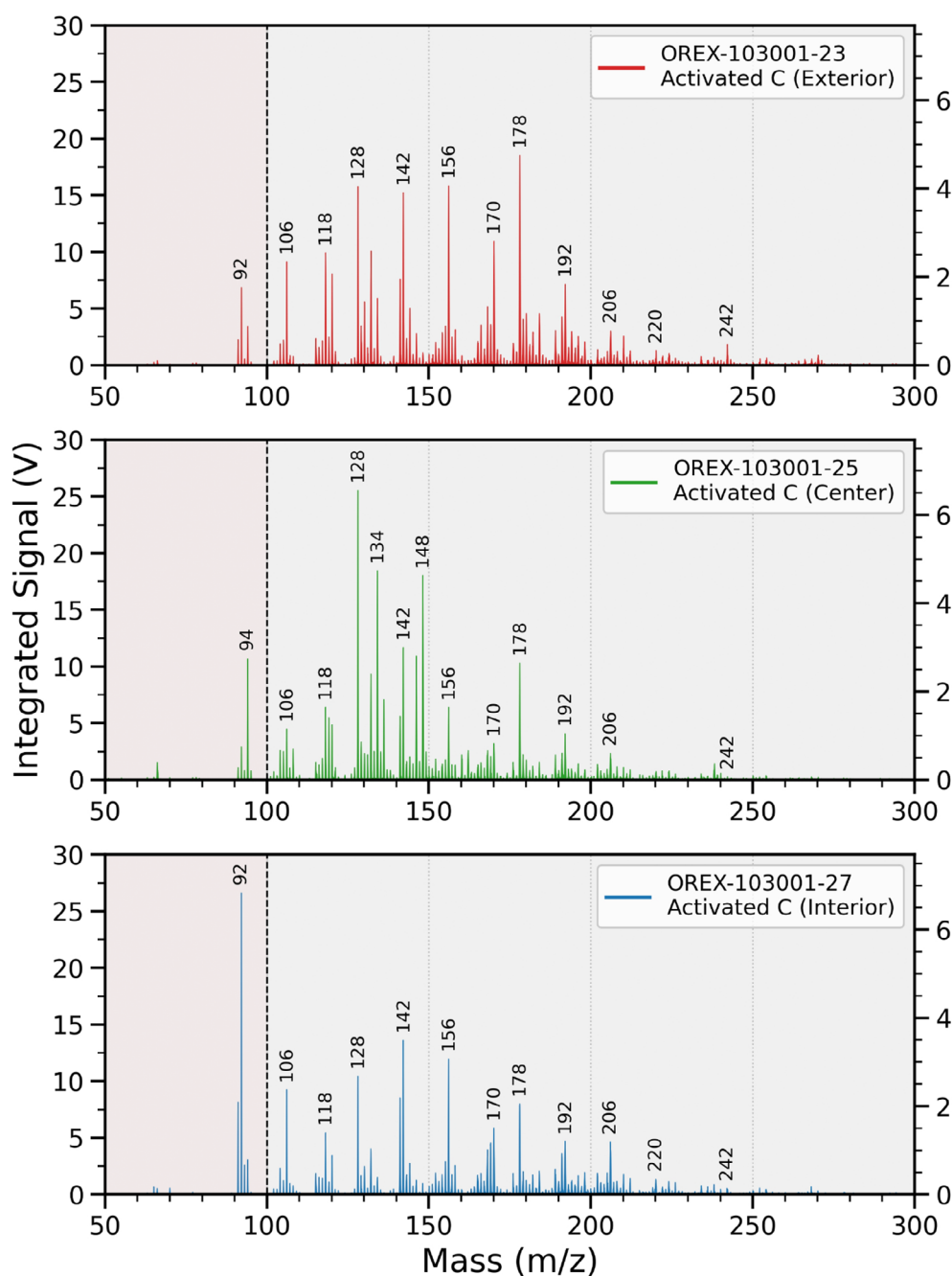


FIGURE 8. $\mu\text{L}^2\text{MS}$ mass spectra of activated carbon samples from the exterior (OREX-103001-23), center (OREX-103001-25), and interior (OREX-103001-27) of the flight filter assembly. To take account of the large dynamic range of peak intensities, each mass spectrum is divided into two sections with different vertical axis scaling. The scale for the lower-mass region (50–100 m/z) is on the left, and the scale for the high mass region (100–300 m/z) is on the right.

Compound-specific carbon isotope data obtained using thermal desorption pyrolysis with GC-MS/GC-IRMS demonstrated that all measured compounds in the flight filter have typical terrestrial carbon isotopic ratios (Figure S30).

Given toluene's high abundance in the organics found trapped in the flight filter (Figure S31), its isotopic nature was of considerable interest. GC-MS/GC-IRMS analysis gave δD values ranging from -73.1 to -120.4‰ . Similarly, thermal desorption pyrolysis

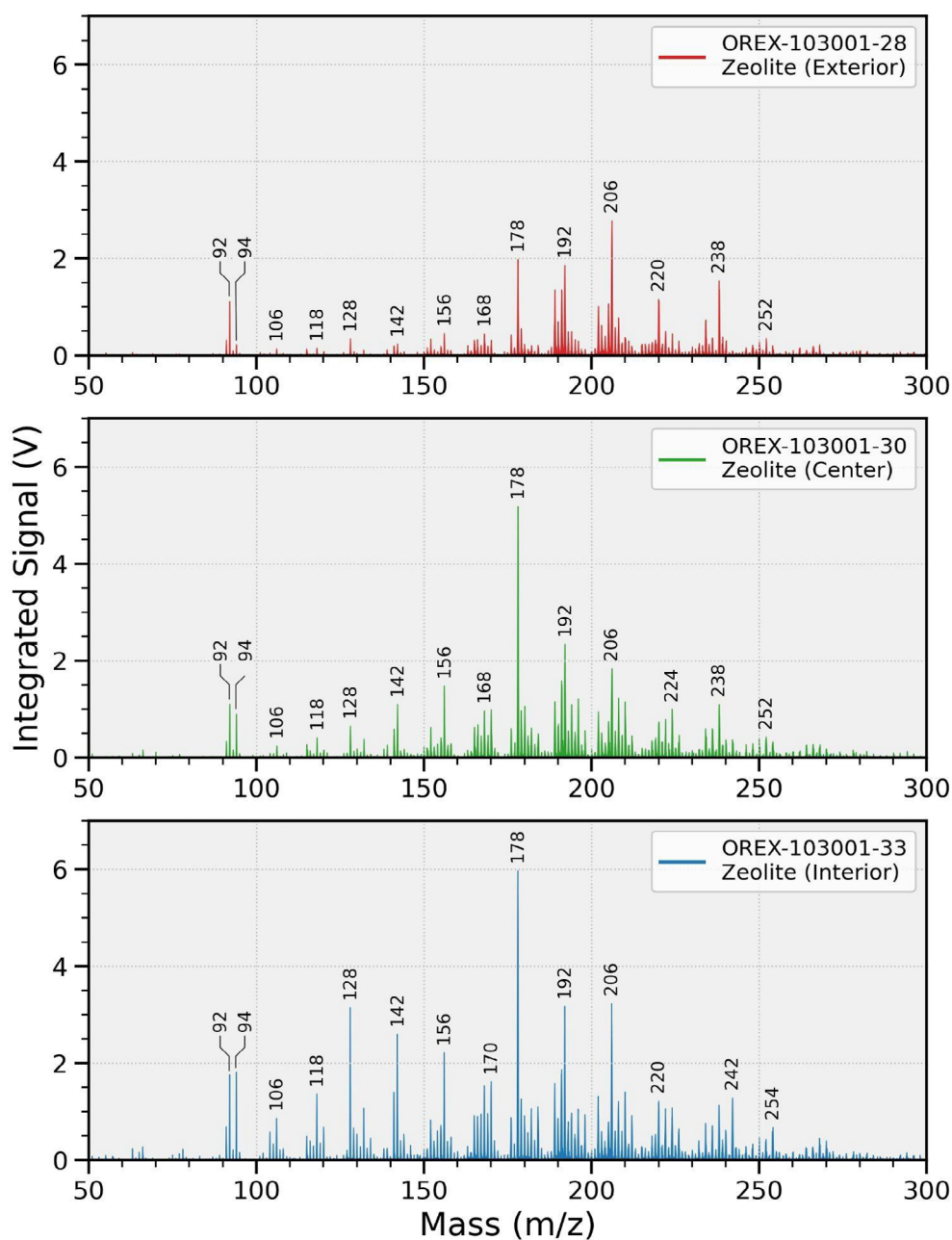


FIGURE 9. $\mu\text{L}^2\text{MS}$ mass spectra of zeolite samples from the exterior (OREX-103001-28), center (OREX-103001-30), and interior (OREX-103001-33) of the flight filter assembly.

with GC-MS/GC-IRMS yielded δD values ranging from -76 to -86‰ (SOM). The δD values for terrestrial toluene range between -13 and -40‰ (Kikuchi & Kawashima, 2013), whereas the values for toluene found in the Murchison meteorite (which has a similarly carbonaceous, hydrated composition to Bennu) measured after pyrolysis/GC is $+806 \pm 14$ (Wang et al., 2005). Therefore, the δD and $\delta^{13}\text{C}$

isotopic analyses suggest a terrestrial origin for the toluene found in the SRC filter.

Finally, as described in more detail in the SOM, although the flight filter materials do contain many of the molecules detected in the CM2 chondritic IOM from Mighei (Alexander et al., 2017), there are considerable differences in the distributions of relative abundances and some notable absences (Table S14, Figure S36).

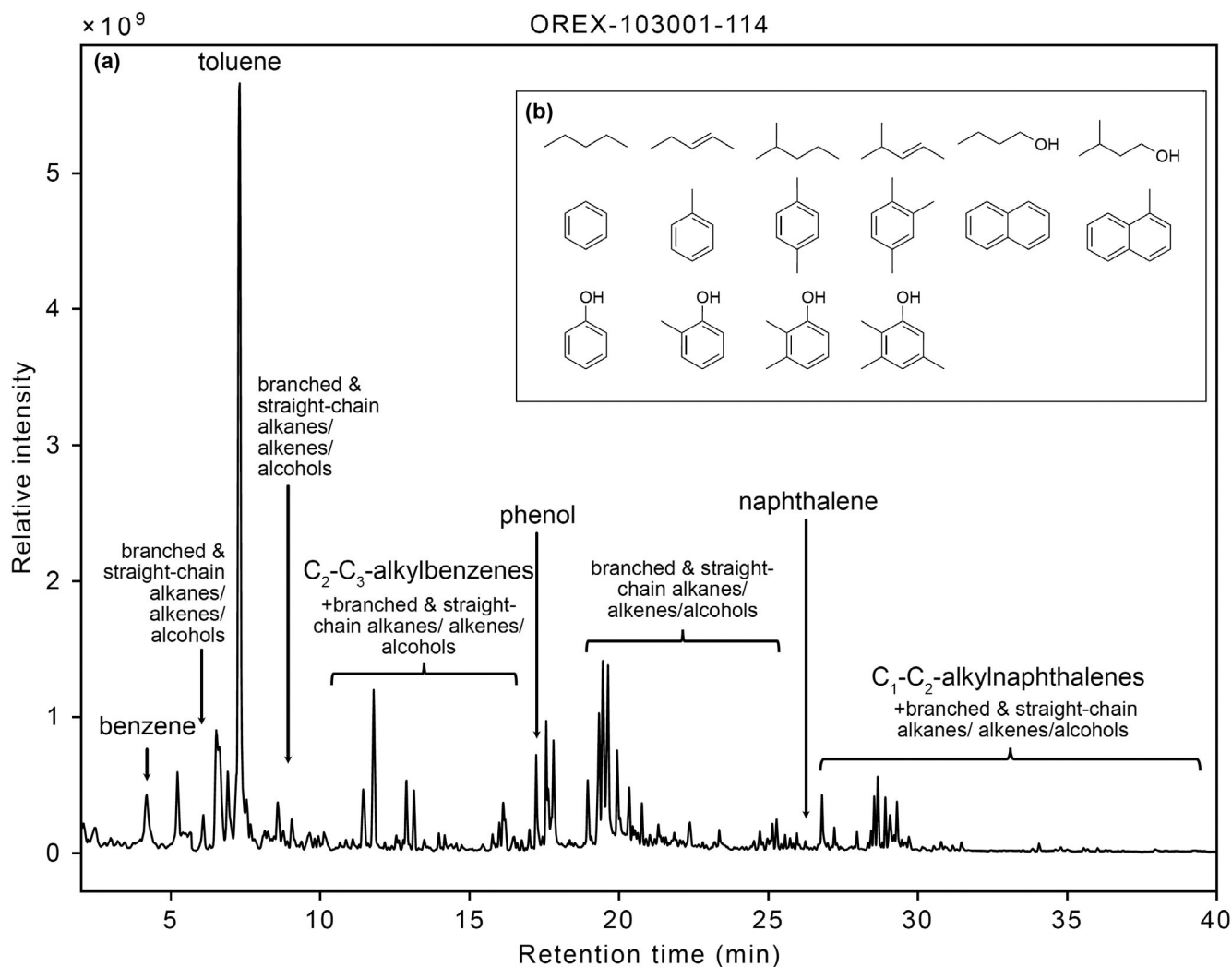


FIGURE 10. (a) Pyrolysis of split from OREX-103001-114 (OREX-103001-9 activated carbon). The flight carbon filter component is primarily characterized by a major toluene peak and PAHs including their C_1 – C_4 alkylated homologous series and C_n -branched and straight chain alkanes, alkenes, and alcohols. OREX-103001-114 is a representative example for the entire activated carbon component. (b) Representative molecular structures for major pyrolysis products of the activated carbon filter component are shown in the upper right of the figure.

In summary, we find no indications of organics in the flight filter being derived from the Bennu samples. This implies that these organic compounds are contaminants stopped by the filter.

Heatshield and Backshell

Given that the *OSIRIS-REx* SRC's heatshield is made from PICA (Tran et al., 1996, 1997; Venkatapathy, 2019), the presence of abundant phenolic compounds in the organic population found in the filter suggests that the organics seen in the sample canister filter are derived from its ablation products. We carried out pyrolysis experiments (details in the SOM) on *OSIRIS-REx* archival samples of heatshield (PICA) and

backshell (SLA) materials to compare them to previously published results for ablation products and the population of organic compounds seen in the flight filter.

Previous experimental studies of the heating of PICA and SLA showed that the main ablation products fall into three categories— H_2O , “permanent gases” (H_2 , CO , CO_2 , and CH_4), and volatile organic species (principally phenol derivatives and aromatics like xylene, phenol, cresol, dimethylphenol, trimethylphenol, benzene, and toluene, plus 1-propanol and 2-propanol)—with the permanent gases dominating the yield (Bessire & Minton, 2017; Wong et al., 2015, 2016; and references therein). At temperatures $>800^\circ C$, light hydrocarbons like C_2H_4 , C_2H_6 , C_3H_6 , and C_3H_8 are also produced, albeit at



The results of thermal desorption pyrolysis with GC-MS/GC-IRMS of the archival heatshield and backshell

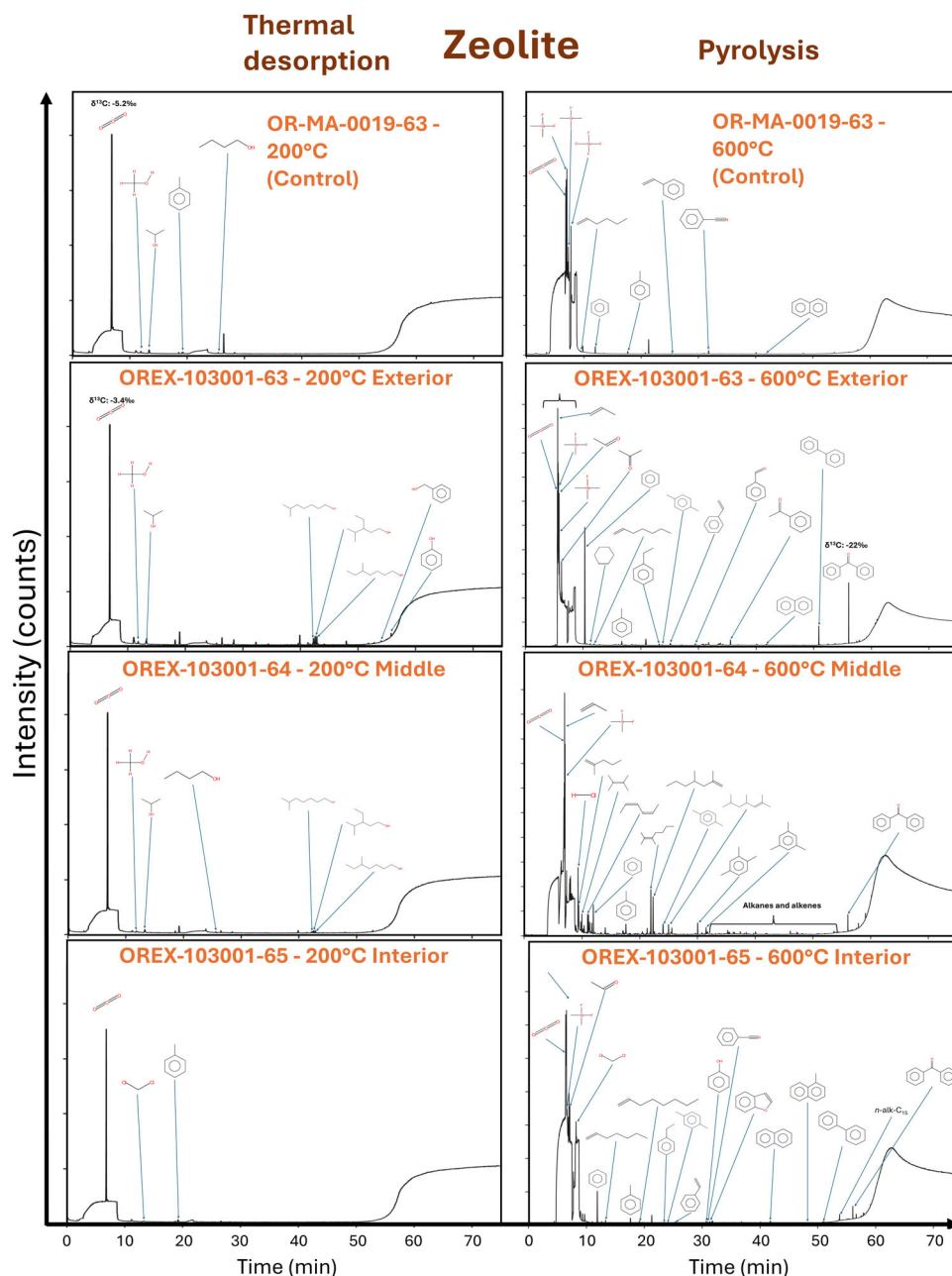


FIGURE 12. Total-ion chromatograms of thermal desorption and pyrolysis of zeolite from non-flight (OR-MA-0019-63) and flight (OREX-103001-63, -64, -65) filter samples.

materials are shown in Figure 15. Few compounds are found in 200°C thermal desorption, confirming that 200°C is insufficient to break down these materials. However, at 600°C, large amounts of substituted benzene, including toluene, are found in both types of materials. The backshell material also released numerous linear alkyl compounds during pyrolysis at 600°C. These data suggest that the substituted benzenes found in flight

filters are likely derived from heating of the PICA heatshield and SLA backshell.

In summary, in terms of the types of compounds produced, our pyrolysis studies of the heatshield and backshell archival samples are qualitatively similar to previous studies of their constituent materials and show strong resemblances to the compounds found in the flight filter. There are differences in the details between the

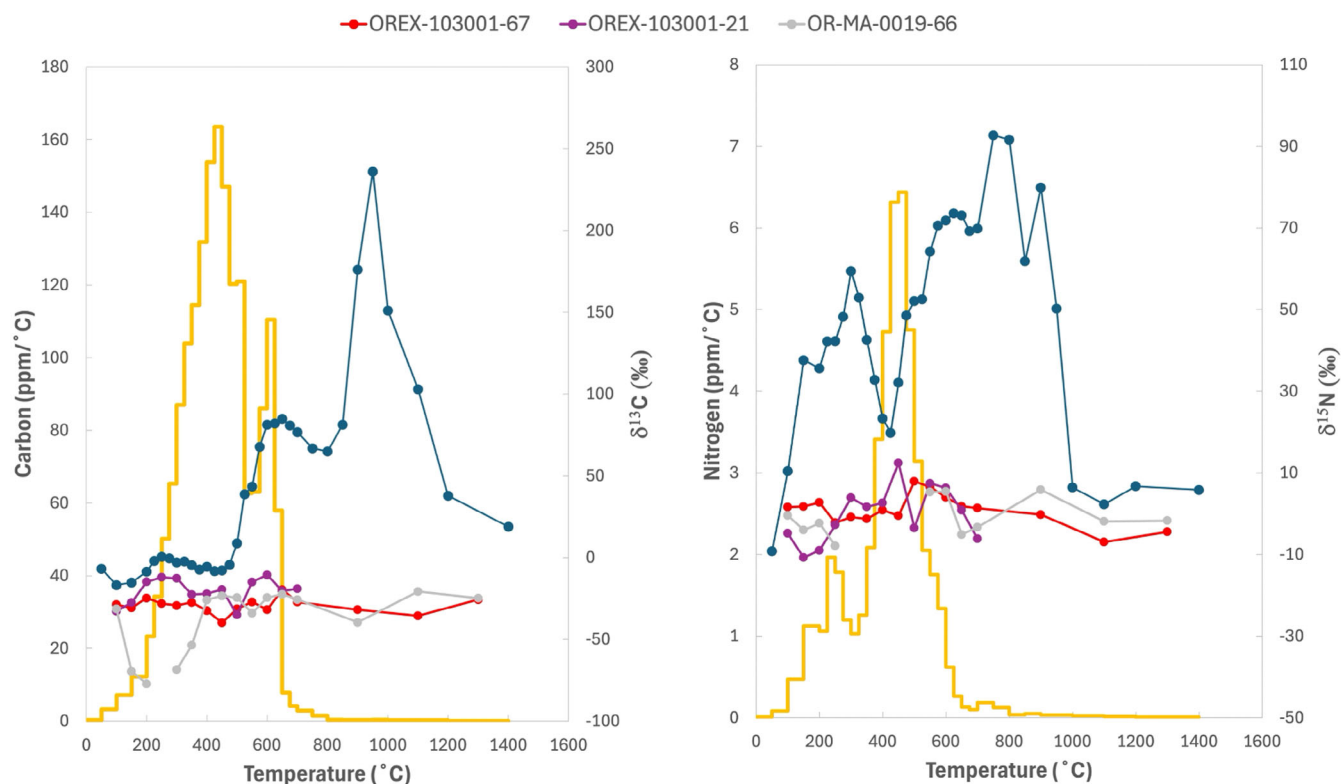


FIGURE 13. Comparison of the C and N isotopic composition of gas released from the activated carbon particle samples from the SRC flight filter and non-flight control filter with the release profile from Bennu sample OREX-803058-0 (yellow line = yield, blue line and dots = isotopic composition; Bennu sample data from Barnes et al. (2025)). Isotopic composition of flight and non-flight filter samples are shown for comparison: OREX-103001-67 (interior) = red, OREX-103001-21 (exterior) = purple, and OR-MA-0019,66 (non-flight) = gray).

three data sets, but given the strong temperature dependence of what products are made (Bessire & Minton, 2017; Wong et al., 2015, 2016), these differences are probably primarily due to variations in the experimental conditions.

These findings suggest that the bulk of the organics found in the flight filter are ablation products. However, during the hypersonic (ablative) phase of atmospheric reentry, very little air would have entered the SRC owing to the shock wave leading the capsule and the low atmospheric pressure at high altitude. Significant amounts of air could only have entered the SRC after the peak of ablation was over and the SRC descended at subsonic velocities. Thus, the filter should have been exposed to very little in the way of direct ablation products of PICA and SLA.

Instead, the majority of air passing through the filter would have been exposed to a somewhat different population of compounds outgassing from the cooling SRC heatshield. The nutation of the SRC caused by late deployment of the drogue parachute increased the

chances for these outgassing products to enter the SRC through the backshell vents. Products from outgassing, rather than ablation, could explain the differences between the compounds found in the filter and those produced by pyrolysis of the archival materials. There is no evidence from the analyses of Bennu samples (Lauretta et al., 2024; Glavin et al., 2025) that these compounds were introduced to the asteroidal material in the canister interior.

CONCLUSIONS AND LESSONS LEARNED

We applied multiple analytical techniques to study components of the *OSIRIS-REx* SRC post-flight, with a focus on assessing the potential for contamination of the Bennu regolith samples that the SRC carried. The use of multiple techniques frequently allowed for synergistic comparisons that helped with the interpretation of the results.

Examination of the passive temperature sensors placed inside the SRC, in combination with thermal

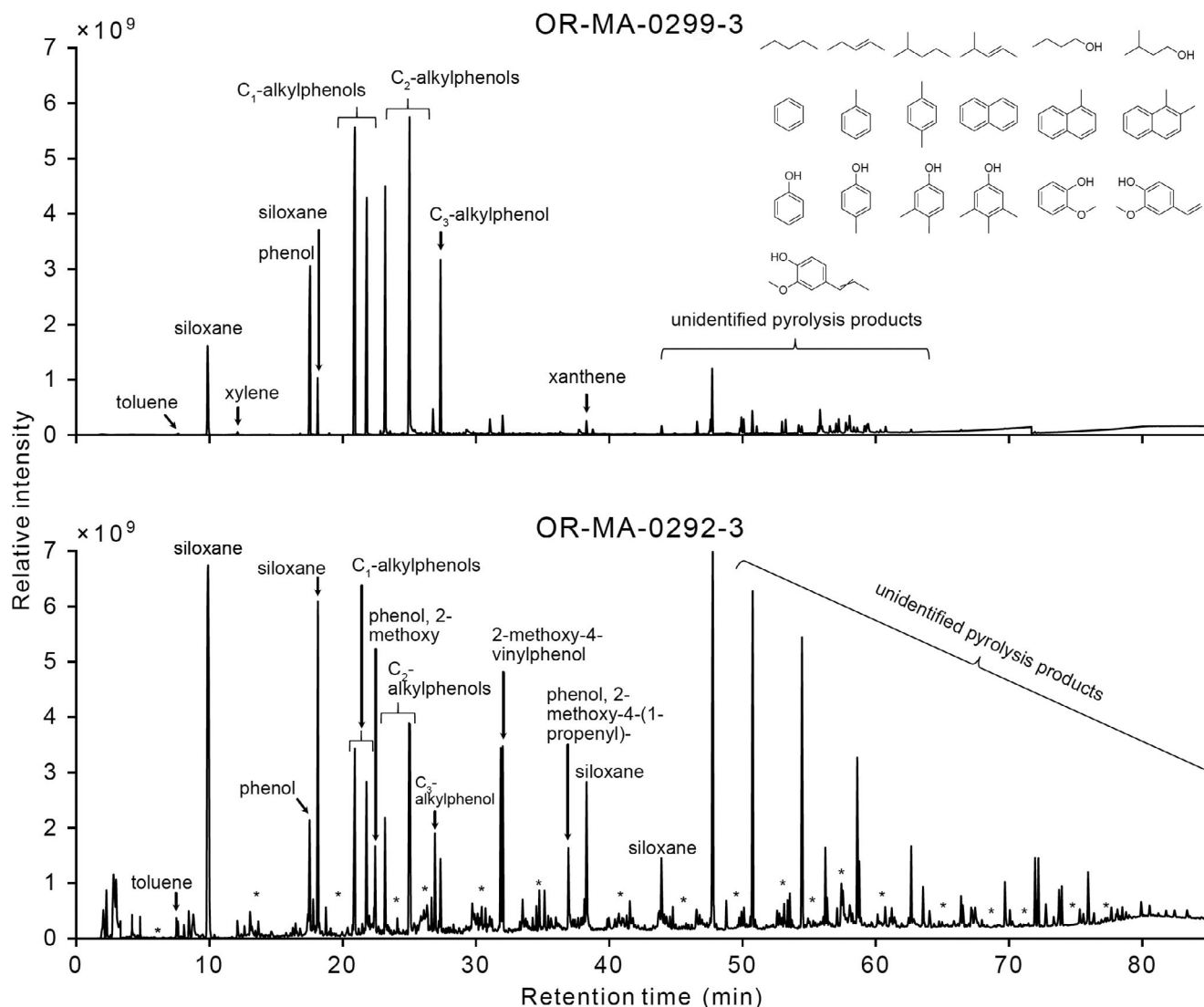


FIGURE 14. Pyrolysis products of archival heatshield and backshell material. Pyrolysis of OR-MA-0292-3 primarily reveals C_{1-3} alkylphenols, C_{1-4} alkylated methoxy phenols, and minor toluene. Asterisks denote a series of straight-chain and branched alkanes, alkenes, and alcohols.

modeling results, indicates that the samples were not heated above the 75°C limit imposed by *OSIRIS-REx* mission requirements.

Some fine-grained Bennu material escaped the TAGSAM and migrated around the interior of the sample canister. Not surprisingly, the sample canister air filter was found to contain Bennu particles, which were largely concentrated in the innermost filter layer (Figure 3e).

The filter also contained additional particulates of varying composition. These were found in all layers of the flight filter and non-flight control filters and most likely represent the original materials from which the filter was made, not contamination from an external source.

Isotopic analyses of organic compounds and noble gases trapped in the filter all show values consistent with terrestrial origins. We find no indication of asteroidal volatiles escaping from the Bennu samples.

No indications of the presence of terrestrial soils were found in the filter, which is consistent with the favorable landing geometry of the SRC at the UTTR. The nose-down landing involved no rolling or bouncing of the SRC onto its backshell, and the backshell vents through which air enters the interior of the SRC never came into contact with UTTR soils.

The flight air filter contained a diverse population of organic molecules that were not present in a non-

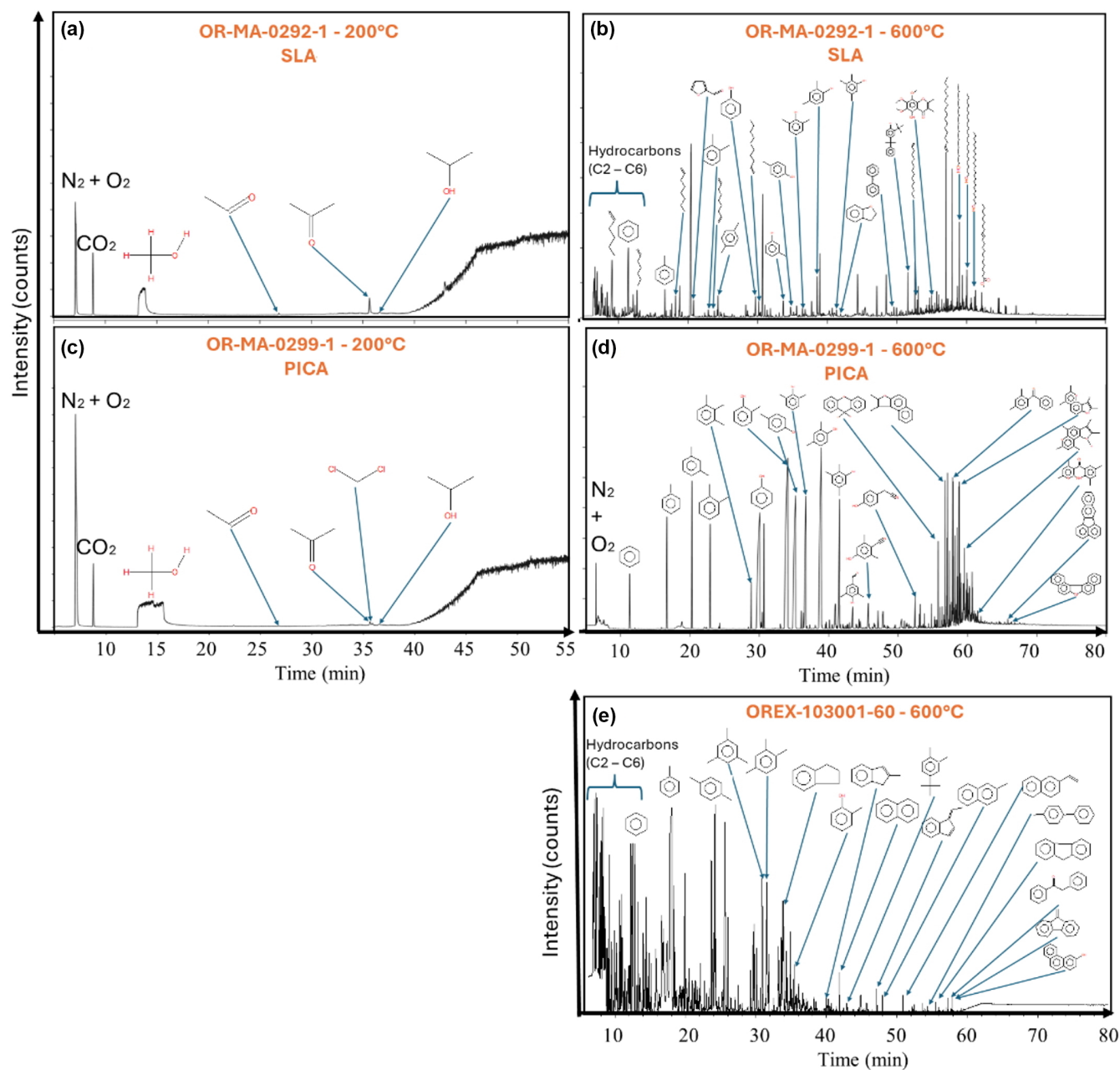


FIGURE 15. Total-ion chromatograms of thermal desorption and pyrolysis for PICA and SLA samples. Panels are paired as follows: OR-MA-0292-1—SLA thermal desorption and pyrolysis (a, b). OR-MA-0299-1—PICA thermal desorption and pyrolysis (c, d). OREX-103001-60—flight filter thermal desorption and pyrolysis (e).

flight control filter, including a variety of aromatic hydrocarbons, alkylated aromatic hydrocarbons, aliphatic hydrocarbons, and alcohols. The most abundant organic molecule detected was toluene; phenol and a variety of phenolic-related compounds were also common. The abundances of these organic compounds typically decreased from outer layers of the filter toward the canister interior (observed exceptions may be due to movement of individual granules of activated carbon and

zeolite within the filter structure). This gradient suggests that these organic molecules are contaminants that entered the SRC from outside. The observation of this organic contamination in the filter components nearest the canister interior indicates that at least some of this organic contamination could have penetrated into the canister interior. This should serve as a cautionary note for measurements of organic compounds in the Bennu samples. However, no evidence of such contamination

has been observed in organic analyses of the Bennu samples to date.

We conclude that majority of these organic compounds are chemical by-products associated with the ablation of the PICA heatshield. The populations of organic molecules detected in previous PICA ablation studies, our own pyrolysis studies of *OSIRIS-REx* archival heatshield and backshell materials, and the flight filter are highly similar. All include aromatic compounds (particularly toluene), phenol derivatives, alkanes, and alcohols. However, the putative timing of their entry into the SRC during its descent and minor differences between the archival heatshield pyrolysis products and the organic molecules in the filter suggest that the organics in the filter are not direct ablation products but rather species that outgassed from the cooling heatshield after ablation was complete.

Overall, our findings show that the *OSIRIS-REx* SRC was appropriately designed and built so that it safely housed the asteroidal samples obtained at Bennu, delivering them safely to the ground at the UTTR and preventing most, if not all, external contaminants from reaching the precious returned samples.

Lessons learned from the performance and analysis of the *OSIRIS-REx* SRC, as well as the *Stardust* SRC that came before it, apply to virtually any future sample return mission. First, it must be remembered that the SRC is a returned sample, just like its cargo. Understanding the returned capsule is critical to understanding its performance and assessing the purity of the samples it contains. With this in mind, it is critical to plan for the curation and analysis of SRC components from the earliest stages of mission design and throughout manufacture, testing, and flight.

Materials used in the construction of the SRC (and any spacecraft materials that could come into contact with the samples) must be archived. Documentation to ensure SRC materials are made available in a timely manner for analysis is necessary. All of this requires early engagement of personnel from the science team, the landing site, the curation facility, and the funding institution. Once a plan is in place, it is essential to rehearse curatorial and analytic plans using appropriate analogs, as the *OSIRIS-REx* team did. This familiarizes key personnel with planned tasks.

The collection of environmental samples is a necessary precaution for monitoring the nature of potential terrestrial contaminants at the landing site. In addition to sampling soil and, if applicable, water and vegetation at the landing site, it is also crucial to obtain air samples throughout the manufacture, testing, recovery, and curation of the capsule.

An air filter in the sample canister is critical for any returned samples that are not hermetically sealed. This

filter is the main line of defense against the introduction of contaminants during launch, flight, reentry, and recovery. It also provides insights into the nature of possible contaminants, and it serves as a potential trapping site for volatiles released by the extraterrestrial samples. Once a filter design is tested and approved for use, the mission should manufacture and archive additional filters of the same design and materials as the flight filter. These are needed for rehearsals of filter disassembly and analysis and as controls for comparison to the flight filter. For example, in 2014, *OSIRIS-REx* archived three filters for humidity, particulate, and organics trapping tests, two full filters and two housings for disassembly rehearsals (one of which also served as an analytical and procedural blank), and one filter for the archive collection.

The findings we have presented demonstrate that the *OSIRIS-REx* SRC's air filter was effective in protecting the returned samples from all or most of the organic contaminants that arrived with incoming air during reentry, with none of the compounds detected in the filter having appeared as clearly anomalous detections in the Bennu samples. However, because organic contaminants were found in the innermost part of the filter, future filter designs need to be at least as capable as *OSIRIS-REx*'s for the return of carbonaceous samples, and even more capable if the returned samples are expected to be less carbon-rich than Bennu.

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Data Availability Statement—The instrument data supporting the experimental results in this study will be available via astromat.org at the DOIs given in Table S16 and/or within the manuscript and its Supplementary Information file.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article.

Figure S1. (Left) Photograph of the filter being removed from the canister lid in the canister glovebox at NASA-JSC on October 6, 2023.

Figure S2. (Right) Filter with fasteners, C-clips, and O-ring removed, and Teflon caps taped with Kapton to cover each side of the filter for the lathing steps.

Figure S3. Lathing setup showing the chuck jaw pieces and cutting tools that were precision-cleaned before use.

Figure S4. Filter with thinned wall on Teflon pad with cutting tool. Right image shows the partially cut top

of filter lifted at an angle exposing the carbon-zeolite layer within.

Figure S5. Filter splits of top and bottom filter layers (OREX-103001-1 and –5; top row) and top, middle, and bottom carbon-zeolite layers (OREX-10300-2, –3, and –4; bottom row).

Figure S6. (Left) Example of carbon filter material in a glass vial with baked-out aluminum foil lining the screw cap lid.

Figure S7. (Right) Example of a filter piece in container made of aluminum with an aluminum/glass lid.

Figure S8. Schematic diagram of cross section of filter showing the five layers and the numbers and locations of splits taken for analysis.

Table S1. Allocation of filter splits.

Table S2. Summary of science analyses of air filter components and sample requirements.

Figure S9. Panel A: schematic of sample canister air filter components and associated labels (left) and an SEM/BSE image of the filtrate layer from OREX-103001-70 (right). Panel B: SEM/BSE image of the external zeolite component (left) and a C–Si–Al element map of that region showing it is predominantly composed of zeolite with infrequent C-rich (activated carbon) particles (right). Panel C: SEM/BSE image of the external carbon component (left) and a C–Na–Si–Al element map of that region showing it is composed primarily of carbon with occasional zeolite particles (right).

Figure S10. Left: BSE image of the zeolite component from the surface of the non-flight test filter OR-MA-0233-28. It is a composite of fine-grained particles ranging from sub-mm to ~10 mm in size. The region analyzed by EDX is outlined by the yellow box. Right: EDX spectrum, from the analyzed area shown at left, is composed of O, Na, Mg, Al, and Si, with minor Ca and Fe.

Figure S11. Upper: Low-magnification BSE image of a zeolite surface from the non-flight test filter OR-MA-0233-28. Lower: Element maps of the same region showing the interparticle heterogeneity of O, Na, Mg, Al, Si, and Ca.

Table S3. A summary of SEM results from non-flight (OR-MA-0019) and flight (OREX-103001-0) filter assemblies (a schematic representation of filter locations is shown in Supplementary Figure S9A).

Figure S12. BSE images and corresponding EDX spectra of siliceous particles (highlighted by arrows in the BSE views) from the non-flight components, activated carbon interior (OR-MA-0019-42; top) and zeolite exterior (OR-MA-0019-45; bottom). These particles have compositions similar to Bennu fine-grained matrix material but also show differences—the upper spectrum lacks significant S and Na typically found in fine-grained Bennu matrix, while the lower spectrum lacks S.

Figure S13. BSE images (left) and corresponding EDX spectra (right) of Bennu fine-grained matrix in the interior filtrate layer (OREX-103001-71) of the flight filter assembly. Panel A shows an aggregate phyllosilicate-rich particle (all spectra) in which micron-size carbonate grains are embedded (+Ca; green and blue spectra). Panel B shows a phyllosilicate-rich region (red spectrum) and a pyrrhotite grain embedded in phyllosilicate (blue spectrum). Panel C shows an aggregate phyllosilicate-rich particle with Mg-bearing carbonate, likely magnesite (circle corresponds to the red spectrum) and pyrrhotite (arrow; spectrum not shown). All these minerals have been identified in the Bennu fine-grained matrix (Lauretta et al., 2024; Zega et al., 2025).

Table S4. He and Ne concentrations (in $10^{-8} \text{ cm}^3 \text{ STP/g}$) and isotopic ratios in SRC filter materials: OREX-103001-0 flight filter, OR-MA-0019 non-flight filter, and OR-MA-0233 non-flight filter.

Table S5. Ar, Kr, and Xe concentrations (Ar in $10^{-8} \text{ cm}^3 \text{ STP/g}$; Kr, Xe in $10^{-12} \text{ cm}^3 \text{ STP/g}$) and isotopic ratios in SRC filter materials: OREX-103001-0 flight filter, OR-MA-0019 non-flight flight filter, OR-MA-0233 non-flight filter material. For full Kr and Xe isotopic ratios see Table S6.

Table S6. Kr and Xe isotopic ratios in SRC filter materials: OREX-103001-0 flight filter, OR-MA-0019 non-flight filter, OR-MA-0233 non-flight filter material (Xe continued in Table S7).

Table S7. Xe isotopic ratios in SRC filter materials. OREX-103001-0 flight filter, OR-MA-0019 non-flight filter, OR-MA-0233 non-flight filter material.

Table S8. Bulk chemistry of the filter zeolite determined in four samples of OREX-103001-58 (given first in oxide ppm, average, and then converted into element wt%, as input for the model) and cosmogenic production rate range for ^{21}Ne in zeolite (P21, in $10^{-8} \text{ cm}^3/(\text{g} \times \text{Ma})$), determined using the model calculations by Leya and Masarik (2009) (see text for details).

Table S9. Bulk C and N elemental and isotopic composition of contents and their stable isotopic compositions of the flight and non-flight filter samples. Measurements were conducted using EA-IRMS at the Carnegie Institution for Science (CIS). The masses of each subsample used for the measurements are also shown. Uncertainties correspond to a 1σ deviation, which is determined based on either replicate analyses of standards or analyses of at least two aliquots of individual samples, whichever is the larger.

Table S10. Summary of C and N abundance and isotopic composition of activated carbon non-flight and flight samples.

Figure S14. Carbon (left) and nitrogen (right) release profiles from activated carbon samples. Top row: OR-MA-0019-66 (non-flight). Middle row: OREX-103001-67 (flight interior). Bottom row: OREX-103001-21 (flight exterior). Yellow line = yield profile, blue line = isotope profile. Carbon yield axis is shown in logarithmic scale. Uncertainty for isotopic measurements is approximately $\pm 1\text{‰}$ (2σ).

Table S11. SART and flight filter assembly samples analyzed.

Figure S15. Averaged $\mu\text{L}^2\text{MS}$ mass spectra from activated carbon and zeolite SART filter samples acquired using 266-nm photoionization. Peaks corresponding to prominent polycyclic aromatic hydrocarbons (PAHs) and their homologous alkylation

series are indicated along with the molecular weights (m/z).

Figure S16. Plots of relative abundances of toluene and phenol abundances from activated carbon (left) and zeolite (right) samples as a function of sample location in flight filter assembly (exterior → interior). In each case, the abundance is relative to that observed from the corresponding SART filter sample. For each plot, the left vertical scale corresponds to toluene abundance and the right vertical scale corresponds to phenol abundance.

Table S12. Samples used for GC×GC-HRMS.

Figure S17. The solvent blanks and non-flight filter samples (zeolite component) were depleted in organic compounds relative to the flight materials.

Figure S18. Alcohols detected in samples of the procedural blank, non-flight sample (activated carbon component), and flight filter samples.

Figure S19. Alkanes detected in samples of the procedural blank, non-flight sample (activated carbon component), and flight filter samples.

Figure S20. Alkylated benzenes and PAHs detected in samples of the procedural blank, non-flight sample (activated carbon component), and flight filter samples.

Figure S21. Pyrolysis of OREX-103001-114 compared to archived non-flight material OR-MA-0019-9. The flight carbon filter material shows various compounds not detected in the archival material, which is primarily characterized by small carbon compounds (less than C_6) and trace toluene.

Figure S22. Outside-to-inside sampling transect of the flight filter carbon component. Pyrolysis of equal sample masses revealed a systematic decrease in signal response for larger molecular weight compounds eluting after ~10 min for 10C relative to 9C and after 11C relative to 10C. The overall trend indicates higher abundances in the outside portion of the filter relative to the inside. Toluene is observed to be the major compound in all samples.

Figure S23. a–c Pyrolysis of flight carbon powders compared to solvent-extracted residues. Identical molecular distributions were observed between raw powders and after solvent extraction suggesting the detected signal is primarily derived from an insoluble fraction (e.g., char).

Figure S24. Pyrolysis of OREX-103001-115 zeolite (top) compared to archived non-flight material OR-MA-0019-9 zeolite sample (bottom). The flight zeolite filter material shows minor siloxanes likely derived from column degradation and straight-chain alkanes (C_{max} at C_{27}) likely derived from anthropogenic emissions in the atmosphere. The archival zeolite material did not reveal additional compounds besides minor siloxanes.

Figure S25. Outside-to-inside sampling transect of the flight filter zeolite component. Pyrolysis of equal

sample masses revealed a decrease in alkanes between OREX-103001-115 and OREX-103001-117 zeolites. Sample OREX-103001-119 zeolite was not analyzed.

Figure S26. Frontier Lab 3030D TD, PY system with liquid nitrogen cryogenic focusing. A Frontier Lab MicroJet Cryo-Trap MJT 1030E operated with liquid nitrogen was used to immobilize the desorbed compounds on the GC column front during the thermal desorption.

Figure S27. Total-ion chromatograms of thermal desorption and pyrolysis for activated carbon samples (Batch 2), including non-flight (OR-MA-0019-77) and flight (OREX-103001-73 to -78) filter samples.

Figure S28. Bar plot of totals for Batch 1 samples with peak area normalized by sample mass (μg) of thermal desorption (top, blue bars) and pyrolysis (bottom, orange bars) analysis of *OSIRIS-REx* filter samples.

Figure S29. Bar plot of totals for Batch 2 samples with peak area normalized by sample mass (μg) of thermal desorption and pyrolysis analysis of *OSIRIS-REx* filter samples. Toluene is plotted alongside total compound abundances due to toluene's exceptionally high abundance.

Figure S30. $\delta^{13}\text{C}$ (VPDB, ‰) isotopic values of selected OREX filter samples analyzed for organic compounds. The top plot represents results from thermal desorption at 200°C, while the bottom plot shows data from pyrolysis at 600°C.

Figure S31. GC-IRMS chromatograms for compound-specific H isotope analysis of Batch 2 filter samples.

Table S13. Molecular abbreviations used in the text.

Table S14. Molecules detected via pyGC–MS.

Figure S32. PyGC-MS data (total ion current, TIC, versus retention time, RT) for Activated Carbon Control sample OR-MA-0019-6. The chromatogram is broken into three RT ranges, where changes in magnification (TIC scale) are specified. The peak identification abbreviations are explained in Table S13.

Figure S33. PyGC-MS data (total ion current, TIC, versus retention time, RT) for Activated Carbon Control sample OR-MA-0019-7. The chromatogram is broken into three RT ranges, where changes in magnification (TIC scale) are specified. The peak identification abbreviations are explained in Table S13.

Figure S34. PyGC-MS data (total ion current, TIC, versus retention time, RT) for Activated Carbon Control sample OR-MA-0019-8. The chromatogram is broken into three RT ranges, where changes in magnification (TIC scale) are specified. The peak identification abbreviations are explained in Table S13.

Figure S35. PyGC-MS data (total ion current, TIC, versus retention time, RT) for Activated Carbon Control

sample OR-MA-0019-7. The chromatogram is broken into three RT ranges, where changes in magnification (TIC scale) are specified. The peak identification abbreviations are explained in Table S13.

Figure S36. PyGC-MS data (total ion current, TIC, versus retention time, RT) for insoluble organic matter (IOM) from the CM2 carbonaceous chondrite, Mighei. The chromatogram is broken into three RT ranges, where changes in magnification (TIC scale) are specified. The peak identification abbreviations are explained in Table S13.

Figure S37. PyGC-MS data (total ion current, TIC, versus retention time, RT) for flown activate carbon filter material OREX-103001-6. The chromatogram is broken into three RT ranges, where changes in magnification (TIC scale) are specified. The peak identification abbreviations are explained in Table S13.

Figure S38. PyGC-MS data (total ion current, TIC, versus retention time, RT) for flown activate carbon filter material OREX-103001-7. The chromatogram is broken into three RT ranges, where changes in magnification (TIC scale) are specified. The peak identification abbreviations are explained in Table S13.

Figure S39. PyGC-MS data (total ion current, TIC, versus retention time, RT) for flown activate carbon filter

material OREX-103001-8. The chromatogram is broken into three RT ranges, where changes in magnification (TIC scale) are specified. The peak identification abbreviations are explained in Table S13.

Figure S40. PyGC-MS data (total ion current, TIC, versus retention time, RT) for samples of non-flight A) SRC backshell and B) heatshield. The peak identification abbreviations are explained in Table S13. For the back shell (A), peaks are predominantly alkyl phenols and polymethylsilicone oligomers. For the heat shield (B) the major peaks are polymethylsiloxane oligomers, trace alkyl phenols and a homologous series of unknown peaks (unk) are roughly identified by mass fragments as various poly methyl-phenyl siloxane oligomers.

Figure S41. The sum of all peak intensities from retention times (RT) of 3.5 up to 30 min (blue histograms) and the integral for toluene RT = 3.26 min (red histogram) for filter positions inner, middle, and outer (6, 7, and 8, respectively). Toluene is uniformly represented in each sample; however, the many other molecules vary considerably from exterior to interior positions.

Table S15. Summary of collected gas results, values are in parts per billion by volume (ppbv). Pre-launch results are shown and described in Dworkin et al. (2018).

Table S16. DOIs of sample analysis data products.