BMDO MATERIALS TESTING IN THE EOIM-3 EXPERIMENT

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SUMMARY

The NASA Evaluation of Oxygen Interactions with Materials-3 (EOIM-3) experiment served as a testbed for a variety of materials that are candidates for Ballistic Missile Defense Organization (BMDO) space assets. The materials evaluated on this flight experiment were provided by BMDO contractors and technology laboratories. A parallel ground-based exposure evaluation was conducted using the Fast Atom Sample Tester (FAST) atomic-oxygen simulation facility at Physical Sciences, Inc. The EOIM-3 flight materials were exposed to an atomic oxygen fluence of approximately 2.3×10^{20} atoms/cm^2. The ground-based exposure fluence of $2.0 - 2.5 \times 10^{20}$ atoms/cm^2 permits direct comparison with that of the flight-exposed specimens. The results from the flight test conducted aboard STS-46 and the correlative ground-based exposure are summarized here. A more detailed correlation study is presented in the JPL Publication 93-31 entitled "Flight- and Ground-Test Correlation Study of BMDO SDS Materials: Phase I Report." In general, the majority of the materials survived the AO environment with their performance tolerances maintained for the duration of the exposure. Optical materials, baffles, and coatings performed extremely well as did most of the thermal coatings and tribological materials. A few of the candidate radiator, threat shielding, and structural materials showed significant degradation. Many of the coatings designed to protect against AO erosion of sensitive materials performed this function well.

INTRODUCTION

NASA provided a tray to the BMDO SEE Program for conducting O-atom exposure aboard NASA's EOIM-3 Platform flown on Shuttle Atlantis as part of the STS-46 mission. A group of 82 strategic materials of relevance to the BMDO was tested to determine material performance and reliability under hyperthermal atomic oxygen (AO) exposure characteristic of a low-Earth-orbit (LEO) space environment. The experimental data obtained from this program have allowed an assessment of the performance and longevity characteristics of a number of important materials that had not previously been flight qualified. The experiment was a cooperative effort between JPL and nineteen co-investigators from industry and government organizations, who provided test materials for both the flight and ground-based elements. The industry and government partners performed the bulk of the

laboratory evaluations of material properties to determine the effect of interaction of the materials with the AO environment on functional properties. The data was provided to JPL for insertion into the BMDO Space Environment and Effects (SEE) database. JPL identified a flight opportunity, organized the test, integrated the materials into the space flight mission, and directed the ground-based exposure. JPL also performed some pre- and post-exposure characterization of the materials.

EXPERIMENT

Materials and Sample Identification

Engineering materials relevant to the BMDO SDS Program were selected for studying AO exposure effects (see Table 1). The BMDO EOIM-3 Passive Tray design provided space for 82 disk-shaped samples: 27 one-inch diameter disks and 55 one-half-inch diameter disks. Six samples of each selected material were provided by the co-investigators. The six samples included a sample for flight, one for ground-based testing, a control sample, and three spares. A four-character code was used to identify each sample. The code identifies the sample diameter, the co-investigator's company or agency, the material number (for co-investigators who provided more than one material), and the sample type. The code was scribed onto the sample containers.

Sample Handling

At JPL, material samples were handled by personnel wearing vinyl, lint-free Class 100 clean room gloves. Samples were maintained in individual Fluoroware containers consisting of polypropylene wafer shippers with polyethylene springs. The containers protected the samples from damage and contamination during shipping and storage. The containers were cleaned with Soxhlet-extracted cloths wet with an azeotrope of 1,1,1-trichloro-ethane (75%) and ethanol (25%). Both the cloths and the solvent were supplied by Thermal Analytical, Inc. and certified by them to have a low non-volatile residue (NVR) of 4 ppm and 2 ppm, respectively. A final rinse with the solvent was used after wiping.

During shipping, the containers, with or without samples inside, were double-bagged in 3M-2110E antistatic reclosable bags. Handling and shipping instructions were provided to each co-investigator to standardize the packaging and shipping methods and to minimize the risk of contamination or damage to the samples.

Photography

All specimens were photographed at JPL in a Class 100 clean room. Initially, the samples were photographed in their as-received condition prior to any thermal vacuum conditioning or characterization. For a direct comparison, close-up photographs of each flight-exposed sample adjacent to its control were taken. A third set of photographs was taken of each ground-exposed sample side-by-side with its control.

Electron Spectroscopy for Chemical Analysis

The surface chemistry of each control sample was analyzed with the use of Electron Spectroscopy for Chemical Analysis (ESCA), also known as X-ray Photoelectron Spectroscopy (XPS). The spectra were collected in a low-resolution mode of operation. This procedure ascertained material surface cleanliness and chemical composition.

Weight Measurement

The difference in sample weight before and after exposure provided a method to determine AO effects. A weight loss may indicate erosion. Weight increases may also be observed and could indicate water absorption, contamination, or a more complex interaction such as oxidation.

The flight, ground, and control samples were weighed before and after thermal vacuum conditioning. To minimize moisture absorption effects, the materials were conditioned in a 50% relative humidity chamber at room temperature for 24 hours prior to weighing, per ASTM E-595 procedures. A saturated calcium nitrate solution was used to maintain the humidity.

Weight measurements were made on a Mettler AE 163 Balance, which has a 0.01 mg sensitivity. The weighing procedure consisted of removing a sample from the humidity chamber and placing it in the balance immediately. The weight was recorded when the reading stabilized, which typically was less than one minute. After weighing, the sample was promptly returned to its Fluoroware container.

Thermal Vacuum Conditioning

Materials were subjected to a thermal-vacuum conditioning to remove any surface molecular contamination and to reduce the potential of outgassing during space flight or during ground-based testing. The thermal-vacuum conditioning environment was 65°C at 10^{-6} torr for a minimum of 48 hours per NASA Johnson Space Center (JSC) requirements.

Materials were vacuum-baked in two separate lots. Lot one contained only optical and non-polymeric materials. Lot two contained the balance of the samples including polymeric materials. Each sample set included the flight, ground, and control specimens.

A residual gas analyzer (RGA) monitored the outgassing products during the thermal-vacuum conditioning. Mass numbers greater than 60 (indicating possible hydrocarbon contaminants) were detected at the beginning of the conditioning at a pressure of 3×10^{-6} torr. There was an order of magnitude decrease of all mass peaks in the RGA by the end of the bake-out.

A Temperature-controlled Quartz Crystal Microbalance (TQCM) monitored the progress of the outgassing during the bake-outs. The amount of outgassing products deposited on the TQCM crystal at 0°C was measured and found to decrease gradually with time.

Post-thermal-vacuum ESCA results showed no significant evidence of contamination. The sensitive ultra-clean optics served as witnesses for contamination. They showed evidence of slight amounts of hydrocarbon accumulation on the surface (~10-20 Å), which should be removed with a fluence of $<10^{17}$ O atoms/cm^2 exposure and therefore were not considered to be detrimental.

FLIGHT EXPERIMENT

Atomic Oxygen Environment

The AO fluence for EOIM-3 has been estimated to be $2.2 - 2.5 \times 10^{20}$ atoms/cm^2. Three methods provided estimates of the EOIM-3 atomic oxygen fluence. The first method used the Mass Spectrometric and Incoherent Scatter (MSIS-86) Thermospheric model along with the National Oceanic and Atmospheric Administration's (NOAA's) reported solar 10.7 cm (F10.7) flux and magnetic indices (Ap, Kp), and the estimated densities for various atmospheric species, including AO. The fluxes were computed with the MSIS-86 model. Fluences were calculated by multiplying number densities by orbiter velocity and integrating for the exposure periods. Depending on the period for which the solar and magnetic indices were sampled, the estimated AO fluence varied from 2.0×10^{20} atoms/cm^2 to 2.2×10^{20} atoms/cm^2. The second AO fluence estimate was based on the erosion of Kapton polyimide film. Numerous Kapton samples were located on various passive trays on the EOIM-3 pallet. Erosion was determined by mass loss, Scanning Electron Microscopy (SEM), and profilometry measurements. Based on a reaction efficiency of 3.0×10^{-24} cm^3/O atom, the EOIM-3 fluence was calculated to be between 2.3×10^{20} atoms/cm^2 and 2.5×10^{20} atoms/cm^2. The weight losses varied with sample location and gave rise to the calculated fluence range. The third AO fluence estimate was based on data from the Air Force Phillips Laboratory mass spectrometer. The on-board spectrometer provided a mission fluence estimate of $2.2 \pm 0.4 \times 10^{20}$ atoms/cm^2.

Solar UV Environment

NASA JSC provided the EOIM-3 solar UV exposure estimate. Their estimate is based on integration of the sun angle, orbiter attitude, and ephemeris over the entire mission. The estimate does not account for shadowing from payloads and orbiter structure but is thought to be accurate within ±20%. The estimate is 22 equivalent solar hours' (ESH) exposure.

Thermal Environment

The EOIM-3 pallet provided twelve temperature sensors as part of the state-of-health and engineering data system. One of the temperature sensors was mounted on an aluminized Kapton film bonded on a thin aluminum disk. During the EURECA operations, the payload bay was held in a solar inertial attitude for approximately 12 hours. The Kapton film reached a temperature in excess of 70°C during this period. Later, during the EOIM-3 exposure phase of the mission, the same sensor temperature cycled between +20°C and +45°C. The BMDO Passive Tray (N-11) temperature excursions were damped considerably as compared to the aluminized Kapton specimen temperature excursions. The peak temperature during the solar inertial phase reached +55°C, and temperatures cycled between +5°C and +20°C during the EOIM-3 exposure period.

Flight Contamination

After the mission, surface chemical analyses revealed a small percentage of silicon present on all flight samples. Materials readily eroded by atomic oxygen contained 2-3 atom percent silicon on the surface. The more stable or resistant materials contained 9-12 atom percent silicon on the surface. The stoichiometry indicated that a thin film of SiO_2 had formed on these specimens. For the stable materials, which had received a heavier accumulation of silicon, this film was on the order of 20 Å thick. The extent of contamination witnessed on EOIM-3 was lower than that experienced on parts of LDEF. The amount of contamination (silicates and hydrocarbon compounds) found on LDEF trays varied from a few monolayers to as much as 20μm, depending on tray location and substrate characteristics (Ref. 1).

The Naval Air Warfare Center (NAWC) polycrystalline diamond on silicon (5M1A) flight sample contained a visibly distinct "crescent" feature on the surface near the tray retaining lip. ESCA showed the crescent region to be completely free of silicon. The rest of the sample surface had nearly 10 atom percent silicon. The sample contained a gold strip which was visible in tray photographs. The strip oriented the crescent area with respect to the tray and the orbiter. From a geometrical analysis of the crescent feature and the height of the retainer lip, it was determined that the contamination source was located in the aft portion of the orbiter and could not extend more than 30° above the plane of the BMDO EOIM-3 tray top surface. The contamination source was either at the top of the aft bulkhead surface or extended along the entire aft bulkhead surface.

It is not clear whether the forward surfaces of the OMS pods were in the field-of-view of the NAWC sample. Since a silicone-based waterproofing agent is applied to the shuttle thermal protection system (TPS) tiles, the tiles are a potential source of silicone contamination. The aft bulkhead is covered with a multi-layer insulation blanket with an outer layer of Beta-cloth. Beta-cloth is a woven glass fabric encapsulated in a fluorocarbon resin. In the manufacturing process, the glass fabric is treated with a silicone oil prior to encapsulation to improve the handling characteristics of the material. In the thermal vacuum environment of space, this silicone oil can slowly diffuse from within the fabric, migrate to the surface, and desorb. Yellowing of the Beta-cloth liner is commonly observed and is associated with environmental aging of the silicone film. Silicone oil could outgas and be transported via line-of-sight to all EOIM-3 surfaces.

GROUND-BASED EXPERIMENT

Seventy-seven material samples, identical to those flown on the BMDO EOIM-3 passive tray, plus ten witness samples, were exposed to atomic oxygen in the ground-based facility located at Physical Sciences, Inc. (PSI) in Andover, MA (Ref. 2). Although the passive tray contained 82 samples, three samples, 5P5, 1K8, and 1K9, were one-of-a-kind, and two were Kapton and magnesium fluoride control samples. While no spare samples of magnesium fluoride existed, numerous Kapton witness samples accompanied the ground-based materials during exposures to provide a good measurement of the Kapton-equivalent fluence. In addition, germanium-coated Kapton samples, which do not erode significantly upon exposure to atomic oxygen, were included in the ground-based test as monitors of the contamination levels in the chamber and in the O-atom beam. PSI weighed the samples before and after exposure. The samples were exposed in two batches. After exposure, samples were returned to JPL. Photographs were taken of the exposed and control samples together. The control samples had been in storage at JPL. Survey ESCA analyses were carried out on the exposed samples. The samples were then returned to the co-investigators for further analyses and comparison to the flight samples.

Environment

Four Kapton witness specimens were exposed in each batch. Based on the weight loss of these samples and a Kapton reactivity of 3.00×10^{-24} cm^3/atom, the average fluences of each batch were 2.46×10^{20} atoms/cm^2 and 1.97×10^{20} atoms/cm^2, respectively. The fluence variation across the sample pallet for the first batch was 2.30-2.78×10^{20} and that for the second batch was 1.88-2.13×10^{20}. Both batches were exposed for the same amount of time, 25 hours, at a 3 Hz pulse rate. The fluence difference for the two batches provides an idea of the ability to control the fluence from test to test without an in situ monitor. The target fluence was 2.0×10^{20} atoms/cm^2, which was the best estimate of the EOIM-3 mission fluence at the time of the ground-based exposure. Subsequent estimates adjusted the EOIM-3 flight fluence upward to $\sim 2.5 \times 10^{20}$ atoms/cm^2. Given the uncertainties in the EOIM-3 fluence and in the ability to predict an actual ground-based exposure fluence, the ground-based exposures can be considered to be equivalent to the EOIM-3 fluence.

Survey ESCA analyses were performed on all samples subjected to ground-based exposure. The objectives of the analyses were to determine if the surface chemistry was the same for both ground and flight samples and to assess the contamination generated by the facility on the samples that were exposed in the ground-based facility.

Germanium-coated Kapton (Ge/K) witness samples accompanied both batches of samples. ESCA analyses of these witness samples were performed at JPL before shipping them to PSI. Although the germanium coating can oxidize, it has been shown to erode negligibly, if at all. Therefore, Ge/K can serve as a valid witness for contamination that is deposited on a surface and does not erode away.

The first exposure batch contained a Ge/K sample that sampled the ambient environment of the vacuum chamber. It was placed out of the direct line of sight of the O-atom beam. The only changes observed were in the relative amounts of carbon and oxygen on the surface. The increase in atom percent of O is likely the result of increased oxidation on the surface from scattered O-atoms in the chamber. There is no evidence for contamination arising from the ambient chamber environment.

One Ge/K sample (5P7C) served as the witness sample in the beam for the first batch. Two spots were examined after exposure. Again, the relative oxygen content of the surface increased, presumably as a result of oxidation. In addition, there is evidence for contamination arising from the exposure. In particular, the surface acquired silicon (Si), fluorine (F), copper (Cu), and sodium (Na). The fluorine is generated from laser ablation of the Teflon poppet in the pulsed valve in the source, and the copper comes from ablation of the adjacent copper nozzle. The origins of the Si and Na are unclear.

The Ge/K witness in the beam for the second exposure batch showed similar results. For this sample, three areas on the surface were examined by ESCA after the exposure, thus providing a good indication of the variability of the surface. Although the fluorine contamination appears to be lower for the second batch, examination of the test samples shows that both batches had similar fluorine contamination levels. It appeared that sample surfaces acquired an extra 3 to 20 atom percent F as a result of the exposure. The wide variability suggests that the measurement is strongly dependent on the area of the surface that is examined. Contamination from the other three elements, Si, Cu, and Na, did not appear to be so severe, as they were typically present at atom percentages of 5 or less.

RESULTS

The materials, the thermal-vacuum conditioning and the sample handling procedures were chosen to minimize any risk of contamination on the samples. The result was a nominally clean atomic oxygen exposure experiment. The measured mass loss of Kapton agrees with estimates based on the MSIS-86 predictions. Different erosion rates for various materials were observed, as expected. It is

important to recall that the total amount of silicone contamination is considered to be small, but it was sufficient to affect the optical performance of some of the optical test samples.

The BMDO samples that were exposed in a ground-based atomic oxygen testing facility experienced an **average** flux of O-atoms about twice that encountered on EOIM-3. The nominal O-atom velocity and the velocity distribution were close to on-orbit O-atom velocities. The O-atom fluence to which all the samples were exposed was the same as the EOIM-3 fluence within the uncertainties associated with measurement of the ground and space fluences for the respective exposures (~20 percent). Although low levels of contamination were observed on most of the witness samples, these levels should have no bearing on conclusions reached about the correlation of the ground- and space-based exposures. Any differences observed between the EOIM-3 flight samples and the identical samples that were exposed at PSI should reflect a fundamental difference between the nature of the FAST-1 and LEO environments and not an experimental artifact associated with the ground-based test.

The 82 samples flown by BMDO on the EOIM-3 experiment cover a broad range of material types for a number of specific applications. There was a broad range of atomic oxygen effects from "no effect" to highly deleterious. EOIM-3 experienced a much lower atomic oxgyen fluence (2.3×10^{20} atoms/cm^2) than LDEF's 9.0×10^{21} atoms/cm^2 (Ref. 3). Given this diversity, only a limited number of general conclusions can be drawn. One of these, which is consistent with previous atomic oxygen testing, is that carbon-containing materials, such as graphite, organic polymers, and carbon fiber composites, are extremely susceptible to erosion, while metals and refractory inorganics are not. For example, structural materials show significant erosion of bare carbon-carbon and P-100 fiber-reinforced MR56-2 bismaleimide composites. A significant result derived from the BMDO experiments, however, is that protective coatings aimed at protecting these potentially important classes of materials from atomic oxygen work very well. The tungsten-coated and titanium-carbide-coated carbon-carbon composites were resistant to erosion, unlike the bare materials. Similarly, plasma-sprayed alumina effectively protected PEEK composites, while epoxy-terminated silane materials were ultimately protected by the formation of silicon dioxide coating. Interestingly, for some materials such as the Martin Black and boron carbide on graphite optical baffles, removal of carbon occurred without any significant compromise in their primary performance characteristics as indicated by the invariance of their reflectance and BRDF parameters.

Within the specific classes of materials, some generalized comments can also be made. As mentioned previously, the optical baffle materials showed no performance changes even though erosion was observed. Some classes of materials showed no significant change when exposed to atomic oxygen, due to the chemical nature (i.e., relative inertness) of their composition. Among these are the optical materials including the Naval Air Warfare Center reflectors and the mirrors and coatings provided by other co-investigators, which with a few minor exceptions noted elsewhere, showed no degradation either in their physical or performance characteristics. Similarly, silicon carbide optical substrates showed no changes, though a small amount of oxidation was observed. Of the optical materials investigated, the most notable changes were observed for some of the protective coatings such as the diamond films. Likewise, ceramic copper oxide high temperature superconductor materials tested were also unaffected by AO.

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Good results were obtained for a majority of the thermal control materials. Coatings for thermal control applications, including ceramic coatings on various composite substrates (7 samples), and several classes of coating materials (4 samples), such as Kapton-based materials showed no significant change in their performance parameters. Their measured absorptivity and emissivity did not change as a function of atomic oxygen exposure. Of the three thermal control blankets, the Beta-cloth and the glass fiber/Teflon composite were unaffected, but the Kapton HN showed the expected erosion.

The advanced radiator, threat shielding, and structural materials showed the most significant degradation. This was especially obvious for unprotected materials with a large organic chemistry component such as bare carbon-carbon composites. Two tribological materials, MoS_2/Ni and MoS_2/SbO_x, were also tested, with the latter giving the superior performance in the space environment.

Overall, the ground and flight correlation was excellent with the exception of fluorocarbons and the plasma-sprayed Beta-alumina on carbon/carbon composite samples. Details about individual materials and their correlative functional properties can be found in JPL Publication 93-31 (Ref. 4). In general, many of the materials tested showed a good resistance to atomic oxygen degradation. As a number of these have no prior flight history, this should facilitate their integration into future flight hardware. More importantly, the ability to duplicate the essential responses of the space-exposed materials with ground-based testing has provided a valuable step toward reliable ground-based testing. The results obtained from both the flight- and ground-based exposures provided input for a ground-based testing protocol (Ref. 5). This protocol provides a framework for more consistent and reliable ground-based testing in the future. Finally, all data collected in these experiments will be incorporated into a database that will be available to design engineers.

ACKNOWLEDGEMENTS

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Table 1. BMDO EOIM-3 passive tray materials list.

Material ID Code	Material
1A1	MoS_2-Ni lubricant on steel, Ovonic
1A2	MoS_2-Ni lubricant on steel, Ovonic
1A3	MoS_2-SbO_x lubricant on steel, Hohman
1A4	MoS_2-SbO_x lubricant on steel, Hohman
1B1	SiO_2-doped Al_2O_3/SiO_2 multilayer on fused SiO_2
1B2	TiN (1000 Å) on fused SiO_2
1K3	Four coatings* on Al/PVDF: A: Ni/PbTe B: Ni/Si/SiO_2 C: Ni/SiO_2 D: Ni/ZnS/PbF_2/ZnS
1K4	Four coatings* on Al/PVDF: A: Mo/Si/SiO_2 B: Ni/TiO_2/Al_2O_3/TiO_2 C: Mo/TiO_2/Al_2O_3/TiO_2 D: Bare
1K8	Al_2O_3/Carbon foil on sapphire, Al holder
1K9	SiO_x/Carbon foil on sapphire, Al holder
1L1	TiC-coated carbon/carbon
1L2	Glass fiber/Teflon composite
1M9	CVD diamond brazed to a ZnS window
1M10	$(SiC/SiO_2)^6$/Si, MWIR-tuned reflector
1M11	$(Si_3N_4/Al_2O_3)^6$/Ag/fused silica, beam splitter
1M12	Al_2O_3/Al half-coated on β-SiC
1M13	Uncoated HIP I-70 beryllium, broadband reflector
1M14	$(Si_3N_4/Al_2O_3)^2$/Al/Si, MWIR-tuned reflector
1M15	AlN/SiH/CVD diamond/ZnS
1M16	$(Si/SiO_2)^4$/Al/Si, MWIR-tuned reflector

* A=upper right, B=lower right, C=lower left, D=upper left.

Table 1. BMDO EOIM-3 passive tray materials list (continued).

Material ID Code	Material
1N4	Beryllium (black-etched) on beryllium foam
1N5	Boron (plasma sprayed) on beryllium
1N6	Martin Black on aluminum
1P2	Tungsten/graphite cloth/carbon foam
1P5	Solar cell
K	Kapton HN
MgF_2	MgF_2 on Al mirror, glass substrate
5C1	T300/934 composite, LDEF trailing edge
5C2	T300/934 composite, adjacent to 5C1 on LDEF
5C4	Polyethylene ring/anodized aluminum cover on silver oxide coated aluminum base
5C5	Polyethylene ring/anodized aluminum cover on anodized aluminum base
5D1	3M Y9469 acrylic transfer tape
5E1	HRG-3/AB epoxy silane (HAC)
5E2	HRG-3/AB epoxy silane (vendor)
5F1	Diamond film on silicon wafer
5F2	Diamond film on silicon wafer
5G1	β-cloth, graphite interwoven
5H1	SiC/Al composite, $CaZrO_3$ coating
5H2	SiC/Al composite, Al_2O_3 coating
5H3	IM7/PEEK, Al_2O_3 coating
5H4	IM7/PEEK, BN/Al_2O_3 coating
5K5	Vendor aluminum electrode/PVDF film
5K6	Y-Ba-Cu-O High temperature superconductor, oxygen deficient
5K7	Y-Ba-Cu-O High temperature superconductor, fully oxygenated

Table 1.   BMDO EOIM-3 passive tray materials list (continued).

Material ID Code	Material
5L3	β-alumina (.002") coated aluminum
5L4	Silicon carbide ceramic
5L5	Carbon/carbon composite
5L6	Calcium zirconate coated carbon/carbon
5L7	β-alumina on carbon/carbon
5L8	Copper indium diselenide-photovoltaic
5L9	Niobium beryllide, high temperature alloy
5L0	P75/magnesium vacuum cast composite
5M1	CVD diamond on silicon
5M2	$(SiC/SiO_2)(SiH/SiO_2)^5/Si$, MWIR-tuned reflector
5M3	$(Si_3N_4/SiO_2)^6/Si$, MWIR-tuned reflector
5M4	$(AlN/Al_2O_3)^6/Si$, visible-wavelength-tuned reflector
5M5	$(Si/SiO_2)^5/Si$, MWIR-tuned reflector
5M6	$(SiH/SiO_2)^5/Si$, MWIR-tuned reflector
5M7	$(BN/SiO_2)(SiH/SiO_2)^5/Si$, MWIR-tuned reflector
5M8	Unprotected aluminum on silicon, broadband reflector
5N1	Beryllium, diamond turned, on beryllium
5N2	Beryllium, conv. polished, on beryllium
5N3	Beryllium/silicon/silicon carbide
5O1	P-100 fiber/MR 56-2 composite

5P1	Two coatings on Vit-C/SiC substrate
	    upper: Si/Al_2O_3
	    lower: Si/Al_2O_3/enhanced MLD

5P3	CVD TiC/graphite cloth/carbon foam
5P4	Alumina on aluminum substrate

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Table 1. BMDO EOIM-3 passive tray materials list (continued).

Material ID Code	Material
5P6	Al_2O_3/graphite composite
5P7	Germanium/Kapton
5P8	Indium tin oxide/Teflon/VDA/Kapton
5P9	Microsheet/Ag/Y966/Al
5P0	$(Si/SiO_2)/(TiO_2/SiO_2)$/Kapton
5Q1	Aluminum, textured
5Q2	Aluminum, textured
5Q3	Beryllium, textured, 100 μm, on aluminum
5Q4	Beryllium, textured, 100 μm, on aluminum
5Q5	Beryllium, black etched, on beryllium
5Q6	Beryllium, black etched, on beryllium
5Q7	Boron carbide on graphite
5Q8	Boron carbide on graphite
5Q9	Magnesium oxide on beryllium
5Q0	Magnesium oxide on beryllium