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United States and Russian Thermal Control Coating Results in Low Earth Orbit

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Both the United States and Russia have conducted a variety of space environment effects on materials flight experiments in recent years. Prime examples are the long duration exposure facility, which spent 5 years and 9 months in low Earth orbit from April 1984 to January 1990, and the removable cassette container experiment, which was flown on the Mir orbital station from Jan. 11, 1990 to April 26, 1991. Thermal control coating materials data generated by these two missions are evaluated by comparing environmental exposure conditions, functionality and chemistry of thermal control coating materials, and pre- and postflight analysis of absorptance, emittance, and mass loss due to atomic oxygen erosion. These are noticeable differences in the United States and Russian space environment measurements and models, which complicates comparisons of environments. Nevertheless, the results of both flight experiments confirm that zinc oxide and zinc oxide orthotitanate white thermal control paints in metasilicate binders are the most stable upon exposure to this space environment. Russian flight materials experience broadens to the use of silicone and acrylic resin binders whereas the United States relies more heavily on polyurethane.

Introduction

CURRENT international cooperative efforts in space are highlighted by the ongoing Shuttle–Mir docking program. Future efforts are aimed at developing an international space station. One subject of interest on long term missions is the stability of exterior thermal control coating (TCC) materials. To date, the United States has conducted an extensive program of flight testing as highlighted by NASA's long duration exposure facility (LDEF). Similar programs have been conducted in Russia as part of the removable cassettes container (RCC) program. This paper presents the first comparison of these thermal control coating results that is available to the international community. The objective is to identify similarities and differences in the thermal control coating methodologies and results.

NASA's LDEF was a free-flying, 12-sided cylindrical spacecraft that was designed to expose a variety of technology experiments to a low-Earth-orbit (LEO) environment, Fig. 1.[1] The LDEF was three-axis stabilized, to ensure highly reliable predictions of environmental exposure conditions, and carried experiments in areas such as: materials, coatings, thermal systems, power, propulsion, space science, electronics, and optics. Most of the experiments were passive, with the majority of the data resulting from postflight analysis. As the indirect result of the Challenger accident, the LDEF remained in LEO for 5 years and 9 months before being returned in January of 1990 by the Shuttle Columbia. Postflight analysis of the LDEF has generated a wealth of data on the interaction of materials and systems with the LEO environment. These data have been presented at three dedicated postretrieval symposiums and integrated into the Materials and Processes Technical Information Service (MAPTIS) database.[2–6] Because the LDEF provides the largest and most complete United States space environment effects on materials database, LDEF data will serve as the United States benchmark for comparison to similar Russian results.

In parallel with the United States efforts a number of space environment effects on materials experiments have been conducted by the Russians aboard the Salyut and Mir orbital stations (OS). Eight experiments containing about 300 samples of various types of materials and TCCs have been tested in the last 10 years. The material samples were exposed to the space environment via removable cassettes that were carried aloft interior to the spacecraft during resupply missions, placed on the exterior of the station by cosmonauts, retrieved at a later date, and returned to Earth for analysis. Two types of cassettes, the FM-110 and the RCC, have been utilized. The Russian materials data presented in this paper were obtained by the RCC-1 experiment that was delivered to the Mir station on Aug. 24, 1989, exposed to the space environment for 470 days between Jan. 11, 1990 and April 26, 1991, and returned to the ground on May 20, 1991. The RCC-1 was installed on the transfer compartment body of the Mir station, as depicted in Fig. 2. The normal to the material samples was perpendicular to the Mir station surface. During the flight the Mir was in LEO with an apogee in the range 380–430 km, perigee in the range 360–390 km, (for an average altitude of 385 km), and an inclination of 51.6 deg.

Orbital Exposure Conditions

A standard measure of solar activity is the solar output at 10.7-cm wavelength, commonly known as the F10.7 value. As shown in

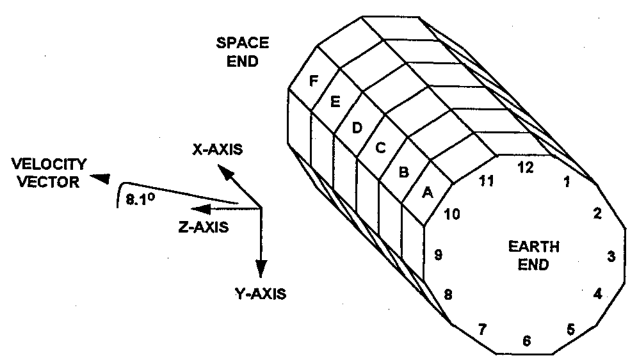

Fig. 1 Long duration exposure facility.

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Table 1 LDEF environmental exposure conditions

Row	Angle off ram, deg	Sun exposure, h	AO fluence, atoms cm^{-2}
1	111.9	7,400	2.92×10^{17}
2	141.9	9,600	1.54×10^{17}
3	171.9	11,100	1.32×10^{17}
4	158.1	10,500	2.31×10^{05}
5	128.1	8,200	9.60×10^{12}
6	98.1	6,400	4.94×10^{19}
7	68.1	7,100	3.39×10^{21}
8	38.1	9,400	7.15×10^{21}
9	8.1	11,200	8.99×10^{21}
10	21.9	10,700	8.43×10^{21}
11	51.9	8,500	5.61×10^{21}
12	81.9	6,800	1.33×10^{21}
Earth	90.8	4,500	3.33×10^{20}
Space	89.2	14,500	4.59×10^{20}

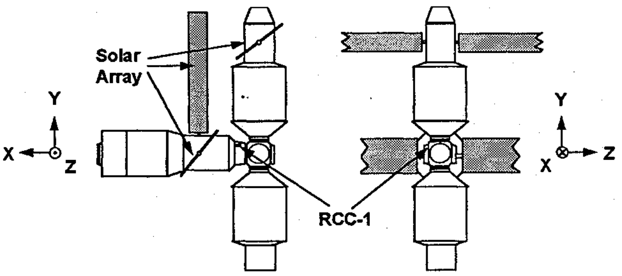

Fig. 2 Mir orbital station (OS).

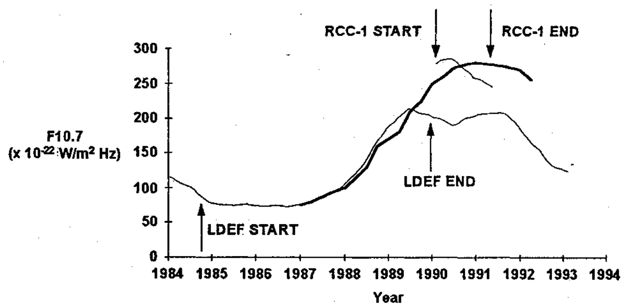

Fig. 3 Solar F10.7 vs time.

Fig. 3, the LDEF was launched just before solar minimum and remained in orbit until just before solar maximum. Conversely, the RCC-1 experiment took place during solar maximum.

The LDEF sun and atomic oxygen (AO) exposure is indicated in Table 1. Because of the duration of the experiment, 5 years and 9 months, the sun exposure for all LDEF surfaces are in the thousands of hours. Conversely, the RCC-1 solar exposure is estimated at no more than 20–25 equivalent solar days, 480–600 h, at least one full order of magnitude less than the LDEF. The sun exposure is a significant measure of a materials stability in that photons having energy in the range 5–10 eV, the solar uv, are capable of severing molecular bonds and altering materials properties.

It is well established that variations in solar activity induce changes in the local atmospheric density at spacecraft orbital altitudes.[5] Knowledge of F10.7 variations during the LDEF mission provides detailed knowledge of atmospheric density that when coupled with knowledge of the LDEF attitude yield the AO fluence indicated in Table 1.

For RCC-1, the AO fluence was calculated using a Russian atmospheric model based on knowledge of the Mir OS attitude control modes. Analysis showed that the integrated fluence of AO to the RCC-1 was estimated at 5.36×10^{22} cm^{-2} as shown in Table 2. Consequently, the RCC-1 AO exposure exceeds the exposure of any LDEF surfaces by at least a factor of five.

Note that there is disagreement between the neutral density as predicted by the United States and Russian atmospheric models used to obtain AO fluence as highlighted in Fig. 4. Using the AO

Table 2 Solar activity and atomic oxygen flux during the RCC-1 experiment

Exposure time, h	Solar activity, F10.7	AO flux, cm^{-2} s^{-1}
0	279	1.50×10^{15}
1,000	284	1.6×10^{15}
2,000	285	1.65×10^{15}
3,000	286	1.7×10^{15}
4,000	281	1.6×10^{15}
5,000	275	1.5×10^{15}
6,000	269	1.4×10^{15}
7,000	264	1.3×10^{15}
8,000	259	1.2×10^{15}
9,000	255	1.15×10^{15}
10,000	250	1.0×10^{15}
11,000	246	0.8×10^{15}
11,280	245	0.75×10^{15}
Average	267.5	1.32×10^{15}
Integrated fluence = 5.36×10^{22} cm^{-2}		

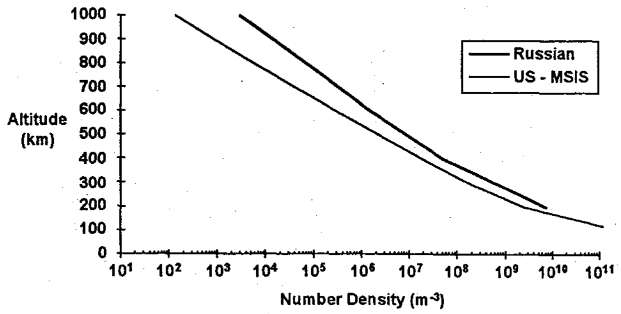

Fig. 4 Comparison of United States and Russian atmospheric density for F10.7 = 100.

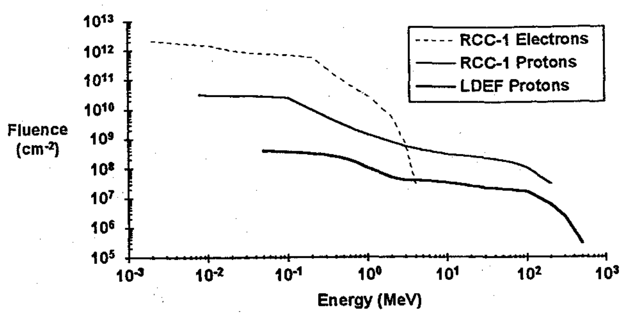

Fig. 5 Proton and electron belt fluence predictions for the LDEF and RCC-1 experiments.

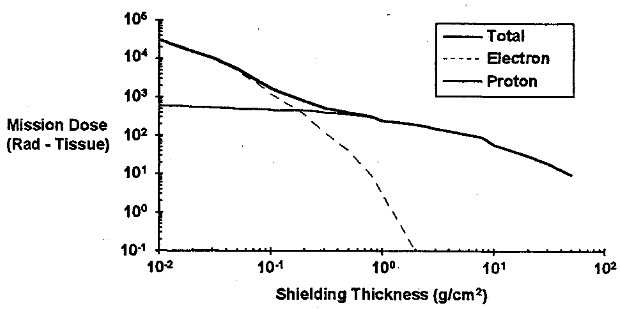

Fig. 6 Comparison of LDEF and RCC-1 radiation dose.

density values predicted by the United States Mass Spectrometer Incoherent Scatter model at F10.7 = 200 would reduce the RCC-1 AO fluence by a factor of 5. This would bring the RCC-1 fluence into general agreement with the exposure seen by rows 9 and 10 on LDEF.

During the course of the LEO experiments, the sample materials were subjected to radiation from the trapped radiation belts, solar protons, and galactic cosmic rays. Because of their low altitude, both the LDEF and the RCC-1 were below most of the trapped radiation belts save for the region referred to as the South Atlantic anomaly. This phenomena provided most of the ionizing radiation that the LDEF and RCC-1 were exposed to as the Earth's magnetic field effectively screened the majority of the solar protons and galactic cosmic rays.

The flux of electrons and protons to both spacecraft was calculated based on two separate isotropic flux distribution models. The radiation belt fluences for both the LDEF and RCC-1 missions are illustrated in Fig. 5. Note that even though the RCC-1 mission was of a signficantly shorter duration than the LDEF, its fluence is greater because of its higher orbital inclination.

The LDEF radiation dose values have been well studied and are on the order of 3×10^4 rad as illustrated in Fig. 6. The placement of the RCC-1 cassette provided partial shielding of the TCC samples to the direct effect of the Van Allen belt (VAB) particle fluxes. Performing a Monte Carlo simulation indicated that 26% of the overall VAB flux fell on the working side of the RCC-1 samples, with the remaining 74% of the flux impinging the opposite side of the spacecraft. The radiation does absorbed by the RCC-1 samples is estimated at 8×10^5 rad as shown in Table 3.

The LDEF and RCC-1 orbital exposure conditions are compared in Table 4. As shown, the RCC-1 AO fluence is approximately equal to that seen by rows 9–10 of LDEF when determined using United States models. The RCC-1-uv exposure is only about $\frac{1}{20}$ of rows 9 and 10 of LDEF and the RCC-1 radiation dose is a factor of 25 higher. As a result, the RCC-1 experiment would not be expected to witness uv degradation in materials if the time scale associated with the degradation process were longer than ~500 h. Conversely, the RCC-1 materials would be more susceptible to radiation damage. Since these levels of radiation are not close to the usable limits for most materials, however, the main difference will be the uv exposure value.

Table 3 Radiation dose values for the RCC-1 experiment

Source	Dose, rad
Trapped protons	2.7×10^5
Trapped electrons	5.3×10^5
Total	8.0×10^5

Table 4 Comparison of the LDEF and RCC-1 environmental exposure conditions

	LDEF		RCC-1	
	Row 9	Row 10	RM[a]	UM[b]
UV exposure, h	11,200	10,700	~600	—
AO fluence, $\times 10^{21}$ cm^{-2}	8.99	8.43	53.6	~10
Dose, krad	30	30	800	—

[a]Russian atmospheric model.
[b]United States atmopsheric model (MSIS).

Finally, it is important to note that the absorptance in space of environmentally exposed samples can be significantly less when reintroduced to air. This bleaching can be very pronounced for certain materials, particularly some of the pigments used in the white paints. For this reason, the data reported in this paper is best suited for relative comparisons, rather than design.

Summary of RCC-1 Flight Test Results

The Russian RCC-1 TCC experiment contained 14 separate materials, as listed in Table 5. As indicated, only two United States materials, Z93 and YB71, bear chemical similarity to their Russian counterparts despite full functional similarity. Tests were conducted on the RCC-1 materials to measure their optical, mass loss, and chemical properties. A visual inspection of the TCC samples was conducted to assess the external appearance of the samples.

The visual inspection of the TCC samples showed some significant changes in the external appearance of many of the samples, as illustrated in Table 6. The AK-512-w, KO-5258, and 40-1-12-88 reflectors changed from white to various shades of yellow. The unprotected absorber AK-243 changed from black mat to grayish blue. This is probably due to AO erosion of the acrylic resin binder. The grayish blue could be easily rubbed out but surface mat color loss was observed. The FP-5246 coating changed from black to grayish white. The protected absorbers showed no change in color or state. The AK-512-g changed from dark green to emerald green with more mat surface. All other materials showed no visible change.

Magnified images of four of the coatings were obtained with the use of an electron microscope. Investigation of the surface structure indicated that the ceramic and paint coatings vary in surface relief. Before the flight the enamels had a rather flat surface with a small number of pores. After exposure to space, the paint coating

Table 6 Visual inspection of the RCC-1 thermal control coating materials

Class	Reference	Final appearance
Reflectors	AK-512-w	gray yellow
	KO-5191	no change
	KO-5258	gray yellow
	TP-co-2	no change
	TP-co-10M	no change
	TP-co-11	no change
	TP-co-12	no change
	TP-co-90	no change
	40-1-12-88	bright yellow
Absorbers	AK-243[a]	grayish blue
	FP-5246[a]	grayish white
Other	AK-512-g	initial: dark green final: emerald green
	AMΓ 6 (w)	no change
	AMΓ 6 (b)	no change

[a]Samples protected by quartz glass did not exhibit a change in surface color.

Table 5 Thermal control coating materials exposed on the RCC-1 experiment

			U.S. equivalent	
Class	Reference	Chemical nature	Chemical	Functional
Reflector	AK-512-w	TiO_2+ ZnO/acrylic resin	—	A276, S13G
	KO-5191	ZnO/silicone resin	—	YB-71, Z93
	KO-5258	ZnO + TiO/silicone resin	—	
	TP-co-2	ZnO/potassium metasilicate	Z93	
	TP-co-10M	ZnO/asbestos	—	
	TP-co-11	ZnO/orthotitanate—potassium metasilicate	YB71	
	TP-co-12	ZnO/potassium metasilicate	Z93	
	TP-co-90	Zr Titanate/potassium metasilicate	—	
	40-1-12-88	ZrO_2/silicone resin	—	
Absorber	AK-243	deep black pigment/acrylic resin	—	Z302, Z306
	FP-5246	deep black pigment/fluoroplastic solution	—	
Other	AK-512-g	CrO/silicone resin—green	—	N/A
	AMΓ 6 (w)	acid anodized aluminum—white	—	Same
	AMΓ 6(b)	acid anodized aluminum—black	—	Same

Table 7 Full-scale test results of the RCC-1 thermal control coating materials

Reference	Absorptance Preflight	Absorptance Postflight	Δα	Emittance Preflight	Emittance Postflight	Δε	Mass, g Preflight	Mass, g Postflight	Δm, mg
AK-512-w	0.30	0.30	0.00	0.88	0.88	0.00	4.3844	4.3837	−0.7
KO-5191	0.18	0.20	0.02	0.89	0.89	0.00	4.5258	4.5258	0.0
KO-5258	0.27	0.31	0.04	0.90	0.89	−0.01	4.6203	4.6206	0.3
TP-co-2	0.18	0.18	0.00	0.97	0.94	−0.03	4.6200	4.6197	−0.3
TP-co-10M	0.20	0.20	0.00	0.84	0.84	0.00	4.6992	4.6973	−1.9
TP-co-11	0.14	0.14	0.00	0.93	0.91	−0.02	4.5807	4.5807	0.0
TP-co-12	0.19	0.19	0.00	0.96	0.94	−0.02	4.5260	4.5271	1.1
TP-co-90	0.15	0.15	0.00	0.95	0.94	−0.01	4.6095	4.6068	−2.7
40-1-12-88	0.21	0.28	0.07	0.92	0.91	−0.01	4.6222	4.6223	0.1
AK-243	0.98	0.92	−0.06	0.95	0.94	−0.01	4.3839	4.3784	−5.5
AK-243[a]	0.98	0.97	−0.01	0.95	0.95	0.00	4.3619	4.3608	−1.1
FP-5246	0.98	0.96	−0.02	0.92	0.91	−0.01	4.3783	4.3717	−6.6
FP-5246[a]	0.98	0.98	0.00	0.92	0.91	−0.01	4.4102	4.4099	−0.3
AK-512-g	0.83	0.75	−0.08	0.91	0.91	0.00	4.4623	4.4586	−3.7
AMГ 6 (w)	0.19	0.22	0.03	0.78	0.78	0.00	3.9240	3.9241	0.1
AMГ 6 (b)	0.94	0.94	0.00	0.92	0.91	−0.01	3.9563	3.9559	−0.4

[a]Protected by quartz glass.

surface appeared rougher and the number of pores increased. Before flight, the ceramic coatings already had a large number of cracks on their surfaces. After flight both the number and dimension of cracks were observed to have increased, probably due to thermal cycling. The surface relief of the coating TP-co-10M, which showed no evidence of a contaminant layer, did not vary. The egress of pigment particles on the surface of coatings TP-co-90 and 40-1-12-88 was easily seen. In this case the degree of the surface filling with such particles is insignificant. This fact correlates with the results of chemical analysis of these TCC that shows a decrease in surface pigment and an increase in surface binder.

Laboratory measurements of solar absorptance, emittance, and mass loss for the TCCs are given in Table 7. The reader is cautioned when using the solar absorptance values to note that in-space- and ground-based numbers may vary because in-space values may show the effects of oxygen bleaching upon exposure to AO. This bleaching may fade with continued exposure to oxygen on return to Earth. All semiconductor pigments like ZnO or TiO_2 exhibit substantial bleaching of the reflectance degradation, (from uv exposure in high vacuum), after a few months of re-exposure to air. Except for the in-flight data from LDEF experiment S0069, the results are from specimens exposed to air for several months, and bleaching has occurred.

A number of TCC materials did not experience any significant changes in solar absorptance or emittance and showed no significant mass changes. This proves the stability of these coatings under exposure to the space environment. The TP-co-2, TP-co-11, and TP-co-12 coatings are the most stable, whereas KO-5191 exhibited the highest increase in solar absorptance (0.02), due to the degrading effect of the solar uv.

White paint 40-1-12-88 turned out to be the least stable material studied. This material is based on ZrO_2 and is known to be very sensitive to uv radiation. Because this material exhibited no practical mass change it can be concluded that it is relatively immune to AO attack, thereby preventing any cleaning erosion effect. Conversely, the coatings TP-co-10M and TP-co-90 showed a mass decrease but no change in optical properties. The mass loss is consistent with the fact that the optical stability of these materials was maintained by AO erosion on the exterior surface. No significant changes in emittance were observed for any of the materials.

Mass loss was observed on the majority of the samples due to erosion by AO. The greatest mass loss was observed on the black paint FP-5246 and is related to the carbon content in the coating pigment binder that is susceptible to AO. KO-5191 and TP-co-11 demonstrated no mass changes, whereas the porous ceramic coating TP-co-12 demonstrated a significant increase of 1.1 mg. It is believed that this increase is due to contamination from the Mir OS condensing on the materials surface when cooled by the Earth's shadow. For coatings that exhibited a mass increase, the contamination deposition effect obviously prevailed over the AO erosion effect.

Table 8 RCC-1 key findings

The reflective TP-co-2, TP-co-10M, TP-co-11, and TP-co-12 ZnO- and Zn_2TiO_4-based coatings were the most resistant to space exposure. No changes in the visible or thermooptical properties, detectable mass loss, or chemical composition were observed.
The reflective paints coatings 40-1-12-88 and KO-5258 were the least resistance to space exposure. A minor increase in solar absorptance and a decrease of reflection spectra were noticed. The KO-5258 coating showed a more detectable increase in silicon content.
All absorber coatings were degraded by space environment exposure. These coatings revealed a significant decrease in solar absorptance, an increase in spectral reflection, and significant erosion due to AO. The AK-243 and FP-5246 coatings that were protected by quartz glass did not experience noticeable changes in their characteristics.
Surface morphology changes were detectable depending on the nature of the TCC. An increase in the number of pores and microcracks were detected, but the sizes of the pigment particles in the coatings showed little variation.

A chemical composition analysis data confirms an increase in contamination and a reduction in surface pigment base for all types of materials. The white and green AK-512 paints that exhibited a silicon decrease were the only exception. Of particular interest is a comparison of the study results for the black enamels FP-5246 and AK-243. The unprotected FP-5246 sample showed a twofold increase in silicon content and almost the same decrease in chlorine content. The unprotected AK-243 sample exhibited a decrease of silicon content and a significant increase in molybdenum that was not present in the coating before the flight. The chemical composition of the protected surfaces varied only moderately but did exhibit a decrease of silicon content. No changes in the chemical composition of the anodized aluminum coatings were detected. The key RCC-1 findings are summarized in Table 8.

Summary of LDEF Flight Test Results

The LDEF materials special investigation group conducted investigations of a variety of materials on the LDEF, including aluminum structures, polymers, composites, films, silvered fluoroethylene propylene (FEP) Teflon®, and a variety of thermal control coatings.[6–13] Because the Russian RCC-1 experiment was concerned exclusively with TCC, only the LDEF TCC results will be summarized here. A partial list of LDEF TCC materials is provided in Table 9. Because the LDEF contained numerous samples of each material and each may have been subjected to a different orbital environment, it is more appropriate to examine the conclusions for each material separately, before comparing directly with the Russian results. The absorptance and emittance properties of the LDEF TCC, which were measured in accordance with the American Society of Testing Materials (ASTM) E 424 and ASTM E 405, are listed in Tables 10 and 11, respectively.

Table 9 Partial list of thermal control coating materials on the LDEF

Class	Material Reference	Chemical nature
Reflector	White Tedlar	——
	A276	TiO_2/polyurethane
	Z93	ZnO/K silicate
	S13GLO	Zn_2TiO_4/silicone
	YB71	Zn Orthotitanate
	Silver Teflon	——
Absorber	D111	carbon/polyurethane
	Z302/Z306	TiO_2 + C/polyurethane
Other	Chromic Acid Anodized Al	——

Table 10 Solar absorptance values for LDEF thermal control coatings; thermal control surfaces experiment

	Solar absorptance		
Materials[a]	Preflight	Postflight	$\Delta\alpha$
Tedlar	——	——	——
A276	0.25	0.24	−0.01
w/RTV670	0.27	0.62	0.35
w/OI650	0.25	0.59	0.34
Z93	0.14	0.15	0.01
S13GLO	0.18	0.37	0.19
YB71	0.13	0.15	0.02
Silver Teflon	0.06	0.08	0.02
D111	0.98	0.99	0.01
Z302	0.97	0.98	0.01
w/RTV670	0.98	0.99	0.01
w/OI650	0.98	0.99	0.01
Cr Anodize	0.40	0.47	0.07

[a]Position: row 9, angle off ram = 8.1 deg, AO fluence, 8.99 × 10^{21} atoms cm^{-2}, sun h = 11,200.

Table 11 Emittance values for LDEF thermal control coatings; thermal control surfaces experiment

	Emittance		
Materials[a]	Preflight	Postflight	$\Delta\alpha$
Tedlar	——	——	——
A276	0.90	0.93	0.03
w/RTV670	0.91	0.88	−0.03
w/OI650	0.90	0.89	−0.01
Z93	0.91	0.92	0.01
S13GLO	0.90	0.89	−0.01
YB71	0.90	0.89	−0.01
Silver Teflon	0.81	0.78	−0.03
D111	0.93	0.90	−0.03
Z302	0.91	0.92	0.01
w/RTV670	0.91	0.90	−0.01
w/OI650	0.90	0.90	0.00
Cr Anodize	0.84	0.78	−0.03

[a]Position: row 9, angle off ram = 8.1 deg, AO fluence: 8.99 × 10^{21} atoms cm^{-2}, sun h = 11,200.

White Tedlar

White Tedlar was expected to show the degrading effects of the solar uv over the course of the LDEF mission. Instead, the optical properties of this material actually showed slight improvement. The surface of the samples, which were located in row A9, remained diffuse and white, apparently as the result of AO erosion breaking loose the degraded surface layers, leaving a clean surface behind.

A276 White Paint

Chemglaze A276 is a white thermal control paint made with titanium dioxide pigment in a polyurethane binder that has been used on many short term space missions. It was known to degrade moderately under long term uv exposure and to be susceptible to AO erosion. Approximately 100 A276 disks were measured for absorptance and emittance making A276 one of the most extensively studied materials on the LDEF.

AO protected and trailing edge facing A276 samples underwent darkening, changing from a white color to tan and eventually dark brown after six years LEO exposure. This nonrecoverable darkening is due to a uv degradation of the polyurethane resin portion of the coating. Unprotected leading edge samples remained very white. Apparently, as the exposed A276 surfaces degraded they were also eroded by AO, leaving a fresh, undamaged surface. The AO eroded the polyurethane portion of the paint, leaving behind paint pigment particles. The total erosion depth was measured and found to be on the order of 10 μm. Preflight, in space, and post-flight measurements of solar absorptance indicate that both protective coatings prevented AO erosion but allowed the solar uv to degrade the A276. Unprotected A276 samples show only small amounts of degradation. The overcoated samples indicated cracking and peeling of the protective overcoat postflight, whereas the unprotected samples remained smooth.

Z93 White Paint

Z93 is a white thermal control paint made with zinc oxide pigment in a potassium silicate binder. Most Z93 samples were almost impervious to the 69 months of LEO exposure making it a leading candidate for Space Station applications. The Z93 samples showed an initial improvement in solar absorptance due to an increased reflectance above 1300 nm. This increase in solar absorptance above 1300 nm is offset by a very slow degradation below 1000 nm that results in an overall degradation of 0.01 in solar absorptance.

S13GLO White Paint

S13G and its low-outgassing version, S13GLO, are white thermal control paints made with zinc oxide pigment in a RTV602 silicone binder. Both leading- and trailing-edge samples of S13GLO were observed to degrade significantly during the LDEF mission. Unlike the A276, however, there is little difference in the surface morphologies between leading- and trailing-edge samples. Note that these tests were conducted on the early 1980s version of S13GLO. RTV602 has since been discontinued and the silicone used in the currently produced material has a slightly different formulation. More recent test results may vary from these flight data.

YB71 White Paint

YB71 is a white thermal control paint made from zinc orthotitanate. The YB71 coatings behaved similarly to the Z93 samples. A small increase in infrared reflectance early in the mission caused a decrease in solar absorptance. This decrease in solar absorptance was followed by a slow, long term degradation in reflectance resulting in a small overall increase in solar absorptance. Samples with YB71 applied over a primer coat of Z93 had a somewhat lower absorptance than did other YB71 samples.

Silver Teflon

These were a variety of silver Teflon materials flown on the LDEF. The thermal control surfaces experiment (TCSE) flew one 50-μm-thick silver FEP Teflon sample, and two 127-μm-thick (specular and diffuse) samples. The exterior surfaces underwent significant appearance changes where the surface color was changed to a diffuse, whitish appearance due to AO erosion. Although the visual appearance was noticeably changed, the solar absorptance of the 127-μm samples did not degrade significantly, and there was little change in emittance. The 50-μm sample had developed a brown discoloration, under the Teflon surface, and more than doubled the solar absorptance. Postflight analysis indicated that the brown discoloration was attributed to the application process that cracked the silver layer and allowed the adhesive to migrate through the cracks and be degraded by the solar uv. Only a small change in solar absorptance was measured over the first 16 months of exposure, however, an indication that the degradation occurred slowly over long space exposure.

Chromic Acid Anodized Aluminum

One sample of chromic acid anodized aluminum indicated significant degradation during the first 18 months of the mission. When the TCSE batteries were depleted at 19.5 months, one sample was left exposed to the environment, and the other was protected. These two samples had noticeably different appearances. The sample exposed for 19.5 months had an evenly colored appearance, except for several small surface imperfections. The sample exposed for 69.2 months was mottled and washed out in appearance. Both samples were contaminated with a silica/silicate contaminant, although the level of contamination was not enough to account for the physical or optical changes. Specimens in an adjacent tray that were anodized in the same batch as the TCSE specimens indicated only a 0.02 change in solar absorptance.

D111 Black

The D111 diffuse black ceramic samples performed very well, with little change in either visual appearance or optical properties during the LDEF mission. D111 is a nonspecular coating made of a carbonaceous pigment in a glass binder. Apparently, the glass binder adequately protects the pigment from AO attack.

Z302 Black Paint

Z302 is a glossy black thermal control paint made from carbon black pigments in a polyurethane binder. Z302 is known to be susceptible to AO attack, and several samples were flown with protective overcoats of either OI650 or RTV670. Two unprotected samples that were exposed for the entire mission eroded down to the primer coat. Two other samples that were exposed for only 19.5 months eroded but still had good reflectance properties. As with the A276 overcoats, the overcoated Z302 was observed to contain cracks and peels during postflight analysis but showed little change in solar absorptance.

Z306 Black Paint

Chemglaze Z306 is a flat black thermal control paint made from titanium dioxide and carbon in a polyurethane binder. Z306 was the primary thermal control coating on all LDEF interior structural members and experiment tray bottoms. The Z306 on the interior surfaces, which were not subjected to AO or uv, showed good durability. On exterior surfaces and the leading-edge tray clamps, the Z306 was almost completely eroded away from the composite substrate to which it was applied. The red coloration characteristic of the primer pigment was visible, and significant erosion into the composite substrate was observed. Based on the coating thickness, the erosion rate of Z306 is estimated to be at least 5×10^{-25} cm^3/O atom.

LDEF Key Findings

Continuous monitoring of solar absorptance for the LDEF materials was not possible because 1) most experiments were passive, returning no data in flight, and 2) the LDEF batteries expired after about 1.5 years, leaving the majority of the mission without a means to capture data on the spacecraft. Because the LDEF was most of its AO fluence late in the mission, recovery effects due to AO may have altered some of the degrading effects of the solar uv. Nevertheless, some significant conclusions can be made about the LDEF findings as shown in Table 12.

Table 12 LDEF key findings

White thermal control paints Z93 and YB71 are stable, while A276 is degraded by both AO and uv radiation. Potassium silicate binders are stable, organic binders are not.
D111 black thermal control paint is stable.
Chromic acid anodized aluminum is stable.
UV accelerates AO erosion of Teflon and FEP erodes more rapidly than predicted. The silver Teflon blankets were eroded by AO but remained functional. On LDEF only 2.5 μm were eroded from the original 127-μm film. For longer lifetimes or higher AO fluences the functionality of silver Teflon blankets may be a concern.
Surface crazing was found in clear silicone coatings, reducing their usefulness as AO protective overcoats.

Comparison of Results

Several significant comparisons can be made as the result of this study. They are grouped into the areas of space environment models, materials chemistry, and materials exposure results.

There appear to be significant differences in the United States and Russian space environment measurements and models. Specifically, differences in Russian and United States measurements of F10.7 were noted and the neutral atmospheric density predicted by Russian models exceeds the corresponding United States value by a factor of 3–10, with the greater difference occurring at higher attitudes (1000 km). Finally, the Russian radiation models appear to predict a slightly greater radiation environment in comparison to United States models. Consequently, for the same spacecraft orbit, the Russian and United States models would predict significantly different environmental exposure conditions. This makes comparison of flight test results difficult and also complicates cooperation on future space missions as, pending resolution of these differences, United States and Russian designers would deduce different requirements for the same space vehicle. The disagreement in environmental models is a subject that warrants further investigation.

The most significant overlap in materials chemistry occurs for two types of white thermal control paint and for acid anodized aluminum. Both countries utilize zinc oxide and zinc oxide orthotitanate pigments in metasilicate binders. Russian experience broadens to the use of silicone and acrylic resins and asbestos paper whereas the United States relies more heavily on polyurethane.

Conclusions

The removable cassette container experiment confirms some of the more significant thermal control coatings findings made by the LDEF, minimizing the potential for materials incompatibility on future flights. Both flight tests confirm that zinc oxide and zinc oxide orthotitanate in metasilicate binders (Z93, YB71, TP-co-2, TP-co-11, and TP-co-12) are the most stable upon exposure to the space environment. These materials are leading candidates for use on future, international space ventures such as the space station. The solar absorptance and emittance values for these materials are very similar, indicating consistency of results. Even the diffuse reflectance spectra for TP-co-2 and TP-co-12 are in general agreement with the United States equivalent Z93. The same is true for TP-co-11 and YB71.

The analysis technique, however, highlights significant differences in space environment model development, making this a key area for further study. Whereas these results presented here are significant for the LEO environment, other orbits will require additional evaluation. High-inclination and geosynchronous orbits will have the added effects of charged particle radiation and a possible absence of AO. The synergism between the many effects of Earth orbits warrants continued attention.

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