AD NUMBER

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NAWCWD/CL ltr, 15 Feb 2005

(2)

NAWCWPNS TP 8147

Comparative Sand and Rain Erosion Studies of Spinel, Aluminum Oxynitride (ALON), Magnesium Fluoride, and Germanate Glass

by
Daniel C. Harris
Research Department

AUGUST 1993

NAVAL AIR WARFARE CENTER WEAPONS DIVISION
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FOREWORD

This report summarizes sand and rain erosion studies of spinel, aluminum oxynitride (ALON), polycrystalline magnesium fluoride, and a germanate glass. The purpose of this study was to evaluate alternative materials to magnesium fluoride for infrared-transparent domes for missiles.

This work was carried out in the Optical and Electronic Materials Branch of the Chemistry Division of the Research Department. Portions of this work were done by Linda F. Johnson, Karl Klemm, Phil Archibald, and David A. O'Connor. The report was reviewed for technical accuracy by William Haight, Linda F. Johnson, and Donald L. Jones.

Approved by
R. L. DERR, *Head*
Research Department
4 August 1993

Under authority of
W. E. NEWMAN
RAdm., U. S. Navy
Commander

Released for publication by
S. HAALAND
Deputy Commander for Research and Development

NAWCWPNS Technical Publication 8147

Published by........................Technical Information Department
Collation........................Cover, 13 leaves
First printing........................155 copies

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
August 1993

3. REPORT TYPE AND DATES COVERED
FY 1992

4. TITLE AND SUBTITLE
Comparative Sand and Rain Erosion Studies of Spinel, Aluminum Oxynitride (ALON), Magnesium Fluoride, and Germanate Glass (U)

5. FUNDING NUMBERS

6. AUTHOR(S)
Daniel C. Harris

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Air Warfare Center Weapons Division
China Lake, CA 93555-6001

8. PERFORMING ORGANIZATION REPORT NUMBER
NAWCWPNS TP 8147

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12A. DISTRIBUTION/AVAILABILITY STATEMENT
C statement; critical technology; 26 July 1993

12B. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

(U) Comparative studies of erosion resistance were performed with Alpha Optical Company spinel, Raytheon aluminum oxynitride (ALON), Bausch and Lomb polycrystalline magnesium fluoride, and Corning 9754 germanate glass. Materials were tested on their bare surfaces, or with two different midwave infrared (3-5 µm wavelength) antireflection coatings. Magnesium fluoride was only used as the bare material. In sand erosion experiments, spinel and ALON performed best, with little impact damage and no loss of infrared transmission. Coatings on spinel and ALON were readily removed by sand erosion, and magnesium fluoride was readily eroded. (Germanate glass was not tested.) In rain erosion, ALON was nearly undamaged. Magnesium fluoride and spinel both suffered very slight impact damage, but differences in the level of damage could not be distinguished with the limited exposure in this test. Antireflection coatings were readily eroded by rain. The germanate glass, with or without coatings, was seriously damaged by raindrops. Magnesium fluoride has a midwave infrared optical scatter near 1%. The infrared optical scatter of spinel, ALON and germanate glass are 0.5%, 1-3%, and 0.2%, respectively. ALON will be of limited use at elevated temperature because of midwave infrared emission.

14. SUBJECT TERMS
Erosion
Domes
Missile domes
Spinel
Aluminum oxynitride
Magnesium fluoride
Germanate glass
Sand erosion
Rain erosion
Coatings
Antireflection coatings
Infrared window

15. NUMBER OF PAGES
23

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
UNCLASSIFIED

18. SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

19. SECURITY CLASSIFICATION OF ABSTRACT
UNCLASSIFIED

20. LIMITATION OF ABSTRACT
SAR

CONTENTS

SUMMARY AND RECOMMENDATIONS

Tests were conducted to evaluate alternate materials to magnesium fluoride (MgF_2) for midwave (3 to 5 micrometer (µm)) infrared (IR)-transmitting missile domes. Comparative sand and rain erosion experiments were performed with polycrystalline MgF_2, aluminum oxynitride (ALON), spinel, and Corning 9754 germanate glass. Materials were tested without coatings and with two different commercially available antireflection coatings. Coating O is silica-based, and coating D is fluoride-based without thorium. MgF_2 was uncoated in all experiments.

MgF_2 and spinel transmit adequately through the entire 3- to 5-µm region, while ALON has significant absorption between 4 and 5 µm. Germanate glass absorbs near 3 µm and is similar to spinel near 5 µm. Antireflection coating D improved the transmittance by ~5% throughout the 3- to 5-µm range when applied to one surface of ALON, spinel, or germanate glass. Coating O had a narrower antireflection bandwidth and is not adequate for a 3- to 5-µm seeker. MgF_2 scatters ~1% of incident light at a wavelength of 3.39 µm. Spinel samples scattered ~0.5%, and ALON scattered 1 to 3%. Corning 9754 glass scattered just 0.2% of incident radiation. Antireflection coatings had no significant effect on IR scatter.

Sand erosion tests were carried out under conditions simulating aircraft takeoff and landing (149- to 177-µm-diameter particles at 77 meters per second (m/s)) and aircraft cruising (<38-µm-diameter particles at 206 m/s) environments, with a 90-degree angle of incidence. (Corning 9754 glass was not included in these tests.) Uncoated ALON and spinel exhibited no loss of midwave IR transmission up to highest sand loads tested (300 milligrams per square centimeter (mg/cm^2)). However, microscopic examination showed some pitting, with more damage to ALON than to spinel. MgF_2 had significant loss of transmission and was extensively pitted. Both antireflection coatings on ALON and spinel delaminated locally at sand impact sites.

Rain erosion experiments carried out at the Wright-Patterson/University of Dayton Research Institute, Ohio, whirling arm facility used 2-millimeter (mm)-diameter water drops at a 25.4 mm/h rainfall rate with an incident speed of 210 meters per second (m/s) at a 90-degree impact angle. Uncoated ALON was the most durable material, with little damage after 10 minutes of exposure. MgF_2 and uncoated spinel both suffered slight damage but could not be distinguished from each other with the limited exposure received in this experiment. (One of the two MgF_2 disks broke during the test. However, since the MgF_2 was only 3.4 mm thick, while the spinel was 5.1 mm thick, no conclusions were drawn from this observation.) Antireflection coatings suffered localized delamination at impact sites. Uncoated and coated Corning 9754 glass was extensively damaged, with no coating delamination evident.

Recommendations resulting from this study follow:

1. Spinel and ALON are durable alternatives to MgF_2 for midwave IR missile domes.

2. The optical performance of spinel in the 3- to 5-μm region is similar to that of MgF_2, while ALON has a reduced transmission window. At high speeds, ALON cannot be used because it will have too much midwave IR emission. Further optical analysis is required to estimate the upper useful speed and temperature for ALON.

3. Spinel and ALON are greatly superior to MgF_2 in resisting sand erosion. Neither spinel nor ALON show any loss of transmission under the most severe conditions tested. However, spinel showed slightly less impact damage than ALON under microspcopic examination. ALON is greatly superior to MgF_2 in resisting rain erosion. With the limited extent of the present experiments, the rain erosion resistance of spinel could not be distinguished from that of MgF_2.

4. Typical commercial antireflection coatings that are currently available should not be used on the outer surfaces of spinel or ALON because the coatings are easily eroded by sand and rain. (Current work on more durable coatings for ALON and spinel could allow external antireflection coatings in the future.)

5. Antireflection coating D is recommended for the inside surface of a dome. Thermal shock testing is necessary to verify that the coating does not delaminate.

6. Corning 9754 germanate glass, with or without antireflection coatings, is too easily eroded to be a serious candidate for a missile dome.

INTRODUCTION

The purpose of this study is to evaluate the erosion resistance of commercially available midwave (3 to 5 μm) IR-transmitting materials that are candidates to replace MgF_2 in missile domes (References 1, 2, and 3). One of the deficiencies of MgF_2 is that it is eroded by impact with rain and dust during captive carry under the wing of an aircraft. For example, Sidewinder missiles deployed in the Persian Gulf War suffered severe sand erosion.

In this work we sought to compare the performance of different dome materials in side-by-side sand and rain erosion tests with MgF_2. The materials tested were aluminum oxynitride (ALON), spinel, and Corning 9754 germanate glass. Each specimen was tested in bare form with two different commercial antireflection coatings. MgF_2 was not coated because it is not used with a coating. This report describes optical characteristics of the uncoated and coated samples and reports the results of erosion tests.

MATERIALS

All samples were disks with a diameter of 22.2 mm. Some specimens were coated on one side with a 3- to 5-µm antireflection coating. **Coating O** is a multilayer silica-based coating, while **coating D** is a fluoride-based material not containing thorium.

Magnesium fluoride (MgF_2) was obtained by core drilling of Bausch and Lomb, Rochester, N.Y., production-quality, hot-pressed, polycrystalline MgF_2 domes fabricated from MgF_2 powder produced by Mallinckrodt Chemical Co., St. Louis, Mo. Flat disks with a thickness of 3.4 mm were machined and polished from the cores. The surfaces were generally smooth but had obvious polishing streaks that were millimeters or centimeters in length and visible to the naked eye.

ALON (aluminum oxynitride, $9Al_2O_3 \cdot 5AlN$) is a polycrystalline, optically polished material with a thickness of 5.1 mm and was purchased from Raytheon Research Division, Lexington, Mass. (Reference 4).

Spinel (magnesium aluminum oxide, $MgAl_2O_4$) is a polycrystalline, optically polished material with a thickness of 5.1 mm and was purchased from Alpha Optical Systems, Ocean Springs, Miss. (Reference 5).

Corning 9754 germanate glass was obtained as optically polished material with a thickness of 4.4 mm from Corning Glass Works, Corning, N.Y. (Reference 6).

OPTICAL CHARACTERISTICS

Figure 1 compares the IR transmission spectra of uncoated ALON, spinel, and MgF_2. The wavelength of the IR cutoff increases in the order ALON<spinel<MgF_2. The transmittance in the flat "window" region of each material is limited by Fresnel reflection (Table 1). The sharp absorption spike near 3 µm in the spectrum of MgF_2 is attributed to OH^- impurity.

Figures 2 through 4 show the IR transmission of antireflection-coated samples. The maximum theoretical transmittance of a sample coated on one side will be halfway between that of the uncoated material and 100%. Coating D gives good broadband performance on all three materials. Coating O has a narrower effective bandwidth and did not increase the transmittance of spinel; in this case, we suspect that the coating was misapplied.

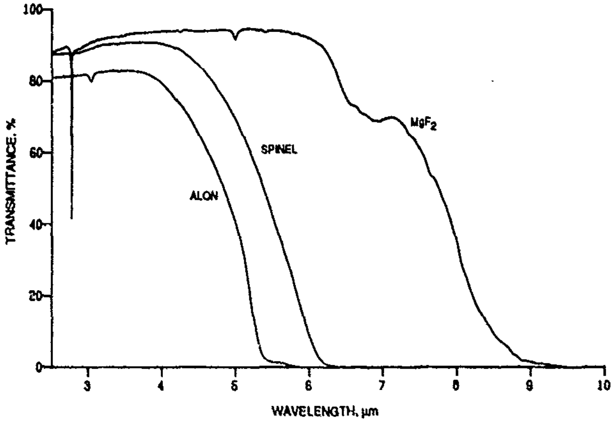


FIGURE 1. IR Transmission Spectra of Uncoated ALON, Spinel, and MgF_2. ALON and spinel are 5.1 mm thick, while MgF_2 is 3.4 mm thick.

TABLE 1. Refractive Index and Theoretical Transmission.

Materials	Refractive index near 4 µm[a]	Theoretical transmittance[b]
MgF_2	1.36	0.95
Spinel	1.66	0.88
ALON	1.72	0.87

[a] Data obtained from Reference 7.

[b] Transmittance = $2n/(n^2+1)$, where n = refractive index.

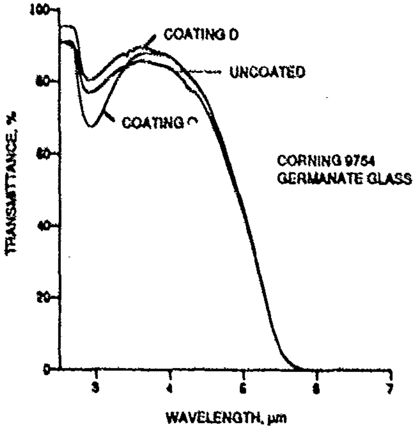


FIGURE 2. IR Transmission Spectra of Uncoated and Antireflection-coated Corning 9754 Germanate Glass With a Thickness of 4.4 mm.

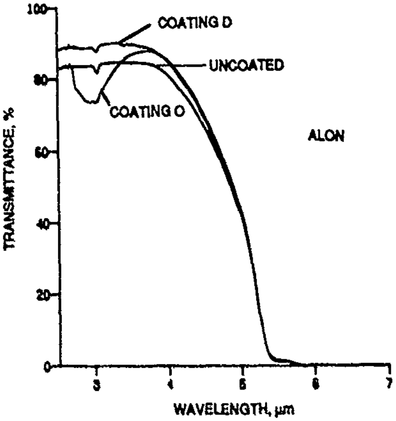


FIGURE 3. IR Transmission Spectra of Uncoated and Antireflection-coated ALON.

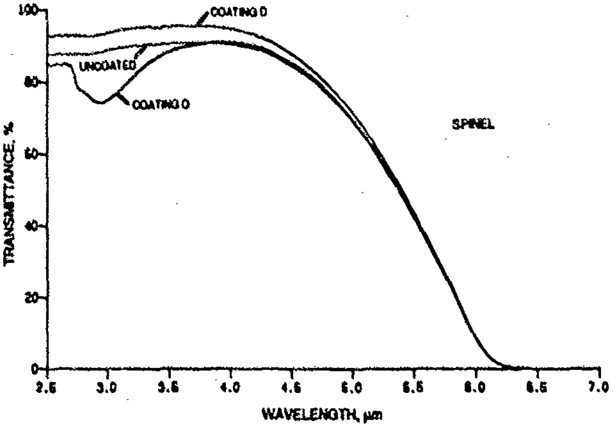


FIGURE 4. IR Transmission Spectra of Uncoated and Antireflection-coated Spinel.

IR and visible optical scatter are shown in Table 2. The most important number is the total integrated scatter in the forward hemisphere at 3.39 µm wavelength, because this is representative of the optical scatter in a midwave IR seeker. New, production-quality MgF_2 domes scatter ~1% of midwave IR light (as measured in 1978) (Reference 8). The scatter is increased in domes that have been in service. Spinel samples in the current work scatter ~0.5%, ALON samples scatter ~2%, and Corning 9754 germanate glass scatters ~0.2%. In the past, we have measured IR scatter at 3.39 µm as low as 0.1% on Alpha Optical spinel and as low as 0.05% on Raytheon ALON. Table 2 shows that neither antireflection coating changes the scatter to a significant extent.

TABLE 2. Total Integrated Scatter.

Material	Scatter at 3.39 µm, %[a]		Scatter at 0.63 µm, %[b]
	Forward hemisphere	Back hemisphere	
MgF_2, polycrystalline	1.3 ± 0.2[c]	...	...
MgF_2, single crystal[d]	...	...	0.001-0.002
MgF_2, mosaic crystal[d]	...	...	0.001-0.002
Spinel, S1, uncoated	0.53 ± 0.02	0.073 ± 0.005	3.4
Spinel, S1, coating O	0.59 ± 0.02	...	...
Spinel, S2, uncoated	0.39 ± 0.06	0.034 ± 0.009	...
Spinel, S2, coating O	0.32 ± 0.03	...	...
Spinel, S3, uncoated	0.44 ± 0.05	0.057 ± 0.004	...
Spinel, S3, coating D	0.52 ± 0.03	...	...
Spinel, S4, uncoated	0.33 ± 0.02	0.030 ± 0.003	3.5
Spinel, S4, coating D	0.35 ± 0.04	...	...
ALON, A1, uncoated	2.6 ± 0.1	0.29 ± 0.01	4.1
ALON, A1, coating O	2.8 ± 0.1	...	...
ALON, A2, uncoated	1.9 ± 0.1	0.22 ± 0.02	...
ALON, A2, coating O	2.1 ± 0.1	...	...
ALON, A3, uncoated	3.0 ± 0.1	0.31 ± 0.01	...
ALON, A3, coating D	3.5 ± 0.1	...	...
ALON, A4, uncoated	1.2 ± 0.1	0.12 ± 0.01	2.1
ALON, A4, coating D	1.5 ± 0.1	...	...
Corning 9754, C1, uncoated	...	...	0.7
Corning 9754, C1, coating O	0.16 ± 0.01	...	...
Corning 9754, C4, uncoated	...	...	0.5
Corning 9754, C4, coating D	0.17 ± 0.01	...	...

[a] Measured with a Coblentz sphere collecting all light between 2.5 and 70 degrees from the incident direction (Reference 8). Each measurement is an average for several points in the specimen.

[b] Derived from integration of the bidirectional transmittance distribution function between 2.5 and 70 degrees from the incident direction in the forward hemisphere (Reference 9).

[c] Average for 18 unused domes measured in 1978 (Reference 8). No measurements of polycrystalline MgF_2 were made in the present work.

[d] Single crystal and mosaic crystal (polycrystalline material with millimeter-to-centimeter-sized crystals) MgF_2 were not used in the erosion experiments in the present work.

Optical scatter was measured prior to, but not after, erosion tests. Past experience with rain erosion indicates that scatter increases significantly only at the isolated, damaged impact sites (Reference 10). Because rain erosion damage was very light in the present experiments, we anticipated no change in the optical scatter. In sand erosion tests, where the surface is uniformly and significantly "sand blasted," scatter increases substantially. This scatter is partly measured by the decrease in transmittance, which is reported later in this document.

SAND EROSION

Sand erosion experiments were performed by PDA Engineering, Costa Mesa, Calif. Sand with a density near 2.75g/cm^3 (measured by liquid displacement), obtained from Whitehead Brothers Co., Florham Park, N.J., was sieved to obtain particles in the size ranges of 149 to 177 µm and 0 to 38 µm. Sand from a screw feeder system was accelerated by a 6-mm-diameter compressed-air jet and directed at an impact angle of 90 degrees onto a flat specimen holder that could hold as many as 16 25-mm-diameter samples (Figure 5). Sand mass flow rate and velocity were established by prior calibration. The square specimen holder was rastered in a uniform manner so its full 310-cm^2 area was exposed to the jet twice in 2 minutes. Exposure was measured in terms of milligrams of sand per cm^2 of sample area. After a mild initial exposure to 1 mg/cm^2, successive loadings were chosen to produce significant damage.

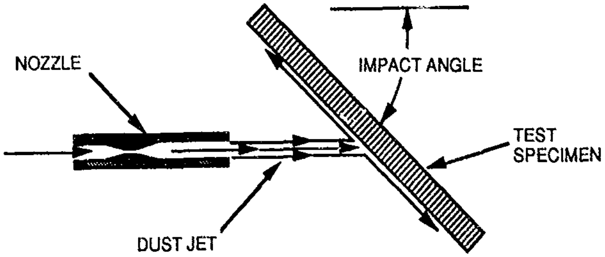


FIGURE 5. Test Configuration for Sand Erosion Experiments.

A speed of 77 m/s (150 knots) was chosen for relatively large particles (149 to 177 µm) to simulate the environment of an aircraft during takeoff and landing. A speed of 206 m/s (406 knots) was chosen for small particles (<38 µm) to simulate aircraft cruising conditions. Seven samples (Table 3) were exposed simultaneously to the low-speed conditions, and seven samples (Table 4) were exposed simultaneously to the high-speed conditions.

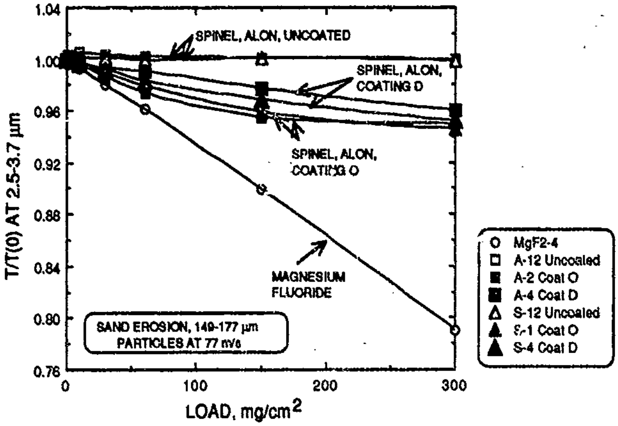
The average IR transmission in the wavelength range 2.0 to 2.5 μm and 2.5 to 3.7 μm was recorded after each exposure. Figures 6 and 7 show transmission resulting from the 14 samples designated in Tables 3 and 4, respectively. A 200X optical micrograph (Figures 8 through 10) was also taken after each exposure, using bright-field, reflected illumination. Corning 9754 glass was not included in the sand erosion tests.

TABLE 3. Sand Erosion by 149- to 77-μm-Diameter Particles at 77 m/s at 90-Degree Incidence.

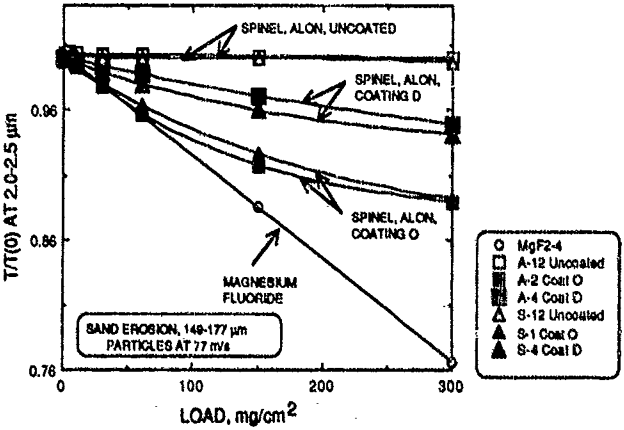
Cumulative sand load, mg/cm^2	Percent Transmittance Averaged from 2.5 to 3.7 μm Wavelength						
	MgF_2, uncoated No. 4	ALON, uncoated No. 12	ALON, coating O No. 2	ALON, coating D No. 4	Spinel, uncoated No. 12	Spinel, coating O No. 1	Spinel, coating D No. 4
0	87.31	82.38	78.04	89.74	86.58	78.64	91.28
1	86.99	82.61	77.94	89.65	86.78	78.72	91.29
4	87.05	82.61	77.92	89.64	86.70	78.55	91.21
10	86.72	82.79	77.72	89.49	86.63	78.35	90.96
30	85.55	82.62	76.97	89.13	86.68	77.78	90.53
60	83.95	82.53	76.02	88.88	86.50	77.02	89.71
150	78.53	82.46	74.53	87.71	86.62	75.42	88.41
300	69.05	82.37	74.09	86.13	86.46	74.37	86.89
	Percent Transmittance Averaged from 2.0 to 2.5 μm Wavelength						
0	83.87	81.08	82.15	88.16	84.01	81.60	88.16
1	83.59	81.30	82.06	87.98	84.07	81.48	88.04
4	83.54	81.38	82.00	88.07	84.05	81.43	88.04
10	83.13	81.31	81.58	87.93	84.10	81.05	87.80
30	82.02	81.19	80.33	87.57	83.99	79.88	87.11
60	80.16	81.21	78.59	87.02	83.96	78.59	86.35
150	74.29	81.16	75.41	85.57	83.97	75.59	84.60
300	64.24	81.00	73.09	83.69	83.73	72.77	83.00

TABLE 4. Sand Erosion by <38-μm-Diameter Particles at 206 m/s at 90-Degree Incidence.

Cumulative sand load, mg/cm^2	Percent Transmittance Averaged from 2.5 to 3.7 μm Wavelength						
	MgF_2, uncoated No. 3	ALON, uncoated No. 11	ALON, coating O No. 1	ALON, coating D No. 3	Spinel, uncoated No. 11	Spinel, coating O No. 2	Spinel, coating D No. 3
0	87.67	79.34	76.73	84.88	82.69	81.93	88.70
1	87.47	79.43	75.16	84.30	82.60	79.74	87.56
2	86.72	79.70	73.99	84.09	82.88	78.67	86.45
4	86.29	79.74	72.92	83.30	82.98	77.57	85.47
8	84.47	...	71.32	79.76	...	76.58	82.10
30	...	79.55	...	...	82.77	...	...
50	...	79.43	...	...	82.84	...	...
100	...	79.38	...	...	82.70	...	...
	Percent Transmittance Averaged from 2.0 to 2.5 μm Wavelength						
0	83.90	77.84	80.92	83.17	80.28	81.93	88.70
1	82.93	77.82	78.27	82.32	79.82	79.74	87.56
2	81.77	77.81	75.76	81.51	79.83	78.67	86.45
4	81.39	78.01	73.13	80.57	80.22	77.57	85.47
8	79.02	...	69.88	76.86	...	76.58	82.10
30	...	77.93	...	...	80.04	...	...
50	...	77.90	...	...	80.06	...	...
100	...	77.85	...	...	79.98	...	...

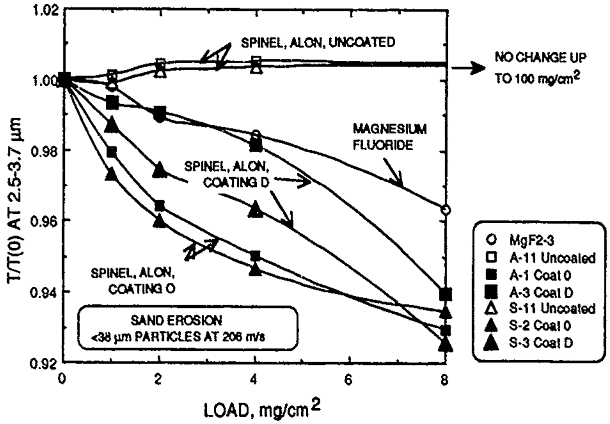


(a) Average transmittance for wavelength interval of 2.5 to 3.7 µm.

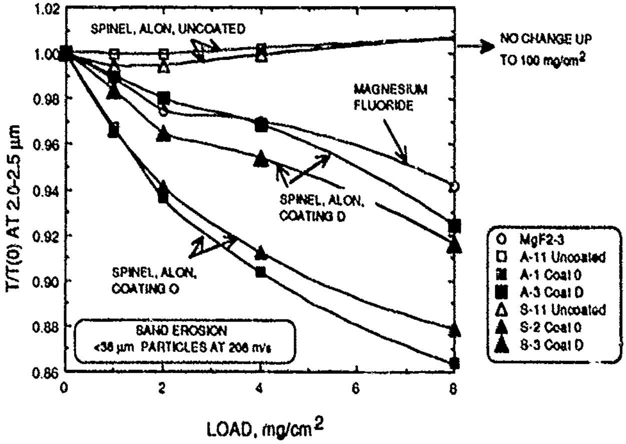


(b) Average transmittance for wavelength interval of 2.0 to 2.5 µm.

FIGURE 6. IR Transmittance as a Function of Sand Load in Experiments Simulating Takeoff and Landing Erosion Conditions (Table 3). Transmittance is expressed as a fraction of the initial transmittance of the uneroded sample.

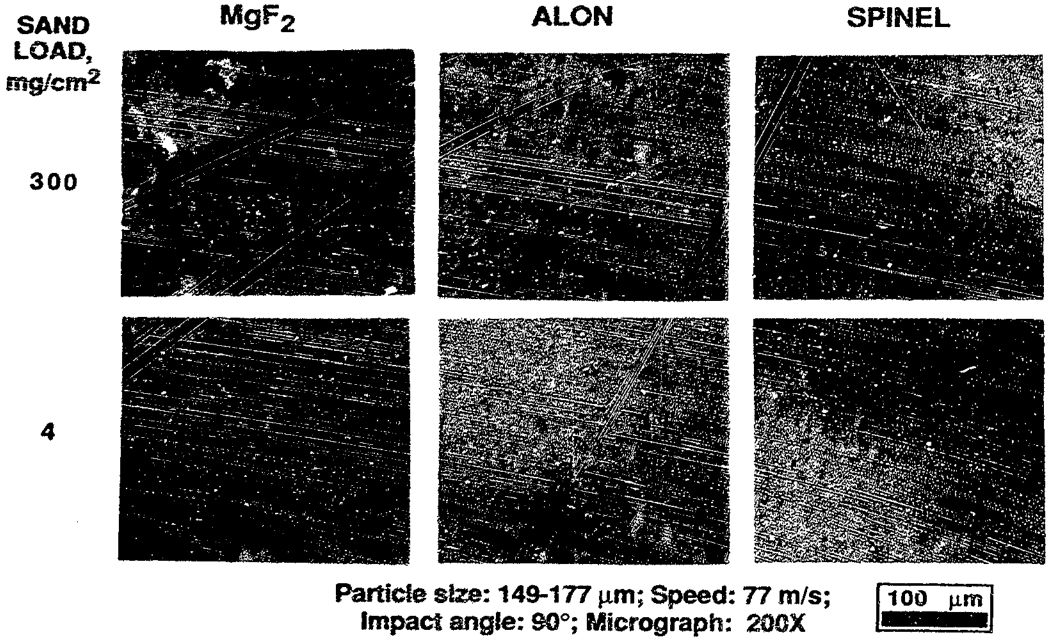


(a) Average transmittance for wavelength interval of 2.5 to 3.7 µm.



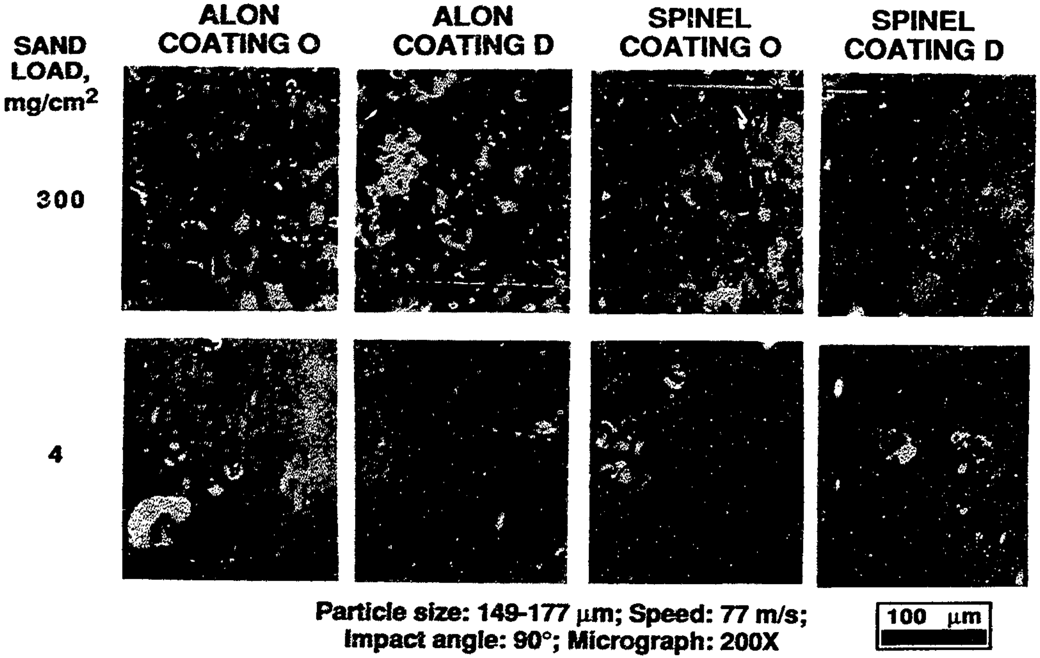
(b) Average transmittance for wavelength interval of 2.0 to 2.5 µm.

FIGURE 7. IR Transmittance as a Function of Sand Load in Experiments Simulating Aircraft Cruising Conditions (Table 4). Transmittance is expressed as a fraction of the initial transmittance of the uneroded sample.



Particle size: 149-177 µm; Speed: 77 m/s;
Impact angle: 90°; Micrograph: 200X

FIGURE 8. Typical Surfaces of MgF_2, Uncoated ALON, and Uncoated Spinel After Exposure to 4 mg/cm^2 and 300 mg/cm^2 in Sand Erosion Tests Simulating Takeoff and Landing Conditions.



Particle size: 149-177 µm; Speed: 77 m/s; Impact angle: 90°; Micrograph: 200X

FIGURE 9. Typical Surfaces of Antireflection-coated ALON and Spinel After Exposure to 4 mg/cm^2 and 300 mg/cm^2 in Sand Erosion Tests Simulating Take-off and Landing Conditions.

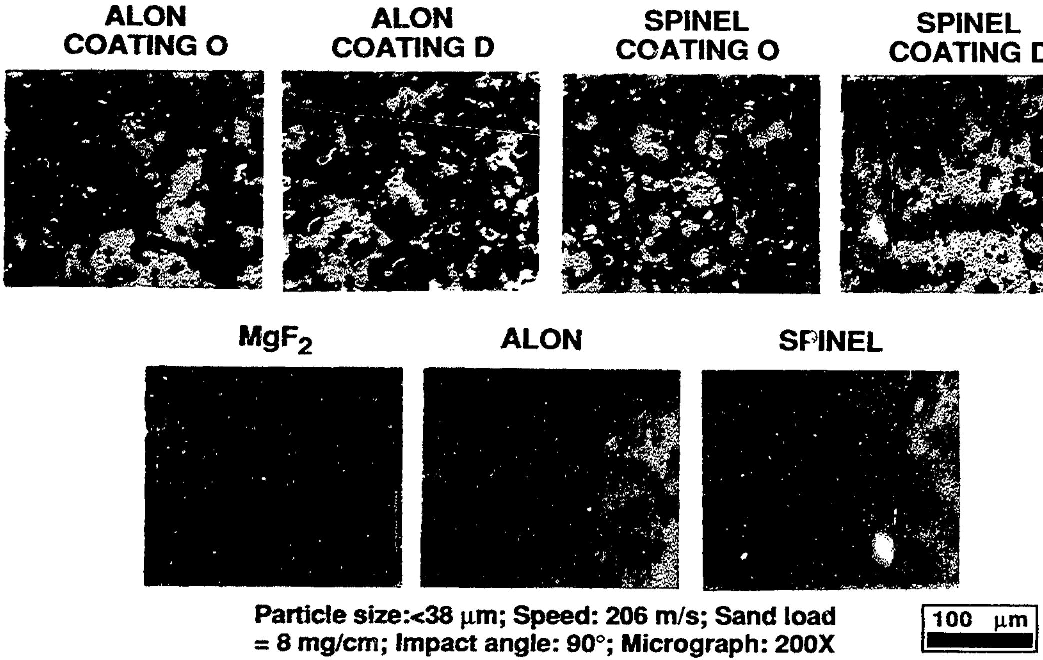


FIGURE 10. Typical Surface Regions of Specimens After Exposure to 8 mg/cm^2 in Sand Erosion Tests Simulating Aircraft Cruising Conditions.

Both sand erosion environments gave qualitatively similar results:

1. Uncoated spinel and ALON showed no loss of IR transmission up to the most severe conditions encountered (Figures 6 and 7). The ALON results are consistent with previous work (Reference 11) in which ALON showed no loss of transmission at wavelengths of 1.0, 2.0, or 3.0 µm when impacted by 53- to 74-µm sand particles at 76 m/s up to a cumulative loading of 250 mg/cm^2. There was a 1.6%T loss at 0.350 µm wavelength in the previous work.

2. Even though uncoated spinel and ALON exhibited no loss of IR transmission in these experiments, Figure 8 shows that both materials do suffer some impact damage at high sand loading. Spinel suffers less damage than ALON.

3. Both antireflection coatings were readily eroded in both environments, with coating D showing less transmission loss than coating O (Figures 6 and 7).

4. Uncoated MgF$_2$ was also readily eroded. Uncoated MgF$_2$ showed more rapid transmission loss than coated ALON and spinel in the takeoff/landing environment (Figure 6) and was comparable to the coated samples in the cruising environment (Figure 7).

RAIN EROSION

Rain erosion experiments were carried out at the Wright-Patterson/University of Dayton Research Institute (Ohio) whirling arm facility. Samples at the ends of a propeller blade were spun at 210 m/s inside a chamber in which 2-mm-diameter water drops falling at a rainfall rate of 25.4 mm/h were impacted at normal incidence (90 degrees). After an exposure of 2.5 to 5 minutes the samples were removed, and their condition was observed under a microscope. Specimens were run one time or more until microscopic damage was noticeable. At the conclusion of the experiment, an inexperienced observer would consider these samples to be essentially undamaged; however, trained personnel can discern very slight damage. If we were to repeat these experiments, all samples would be run for longer times (20 minutes) to create more distinct damage.

Results of the rain erosion tests are shown in Table 5 and Figures 11 through 13. The general observations follow:

1. Uncoated ALON is the most durable material, being nearly undamaged (Figure 11). This result is consistent with previous work (Reference 10) in which ALON was undamaged after 40 minutes of exposure under the same conditions at the same test facility.

2. MgF$_2$ and uncoated spinel performed worse than ALON and better than the coated materials and the Corning 9754 glass. There is no clear distinction between MgF$_2$ and spinel. One MgF$_2$ sample broke during a test, perhaps because the MgF$_2$ samples were the thinnest of all the specimens (3.4 mm) or because there were significant polishing scratches (straight lines in Figure 11). Both materials showed slight impact damage (Figure 11). The structure at the impact site in spinel in Figure 11 is probably related to

(Figure 11). The structure at the impact site in spinel in Figure 11 is probably related to grain structure. In previous work, uncoated spinel from Coors (the predecessor to Alpha Optical) was also more heavily damaged than uncoated ALON under the same conditions (Reference 10).

3. Antireflection coatings on ALON delaminate upon raindrop impact. Coating D adheres better than coating O (Figure 12).

4. Antireflection coating D on spinel also delaminated upon raindrop impact (Figure 12). Coating O on spinel in Figure 12 did not appear to delaminate, even though the underlying spinel was damaged. Unfortunately, this coating had no optical antireflection performance in Figure 4. We do not know how well properly applied coating O on spinel would perform under water-drop impact.

5. Corning 9754 germanate glass exhibited the worst performance. Damage shown in Figure 13 is in the underlying glass, with no evidence of delamination of either coating. Corning 9754 glass is too easily eroded to be considered for missile dome applications.

TABLE 5. Rain Erosion by 2-mm-Diameter Drops at 210 m/s at 90-Degree Incidence at 25.4 mm/h Rainfall Rate.

Sample	Time, minutes	Description of damage
MgF_2 No. 1	2.5	Subsurface ring fractures/(erosion damage)
MgF_2 No. 2	2.5	Sample broke; subsurface ring fracture/pitting/cratering/internal fracture/(erosion damage)
ALON No. A9	5	Very slight pitting
	10	Pitting/(erosion damage)
ALON No. A10	5	Very slight pitting
	10	Pitting/(erosion damage)
Spinel No. S9	5	Pitting/slight cratering/(erosion damage)
Spinel No. S10	5	Pitting/slight cratering/(erosion damage)
ALON No. A5, coating O	5	No apparent damage
	10	Slight pitting/localized coating removal/(erosion damage)
ALON No. A6, coating O	5	No apparent damage
	10	Slight pitting/localized coating removal/(erosion damage)
ALON No. A7, coating D	5	Very slight pitting
	10	Slightly increased pitting/localized coating removal/(erosion damage)
ALON No. A8, coating D	5	Very slight pitting
	10	Slight increased pitting/localized coating removal/(erosion damage)
Spinel No. S5, coating O	5	Slight pitting
	10	Pitting/(erosion damage)
Spinel No. S6, coating O	5	Slight pitting
	10	Pitting/(erosion damage)
Spinel No. S7, coating D	5	Pitting/localized coating removal/(erosion damage)
Spinel No. S8, coating D	5	Pitting/localized coating removal/(erosion damage)
Corning 9754 No. C5	5	Subsurface ring fracture/surface microcracks/pitting/cratering/(erosion damage)
Corning 9754 No. C6	5	Subsurface ring fracture/surface microcracks/pitting/cratering/(erosion damage)
Corning 9754 No. C2, coating O	5	Subsurface ring fracture/surface microcracks/pitting/cratering/(erosion damage)
Corning 9754 No. C3, coating D	5	Subsurface ring fracture/surface microcracks/pitting/cratering/(erosion damage)

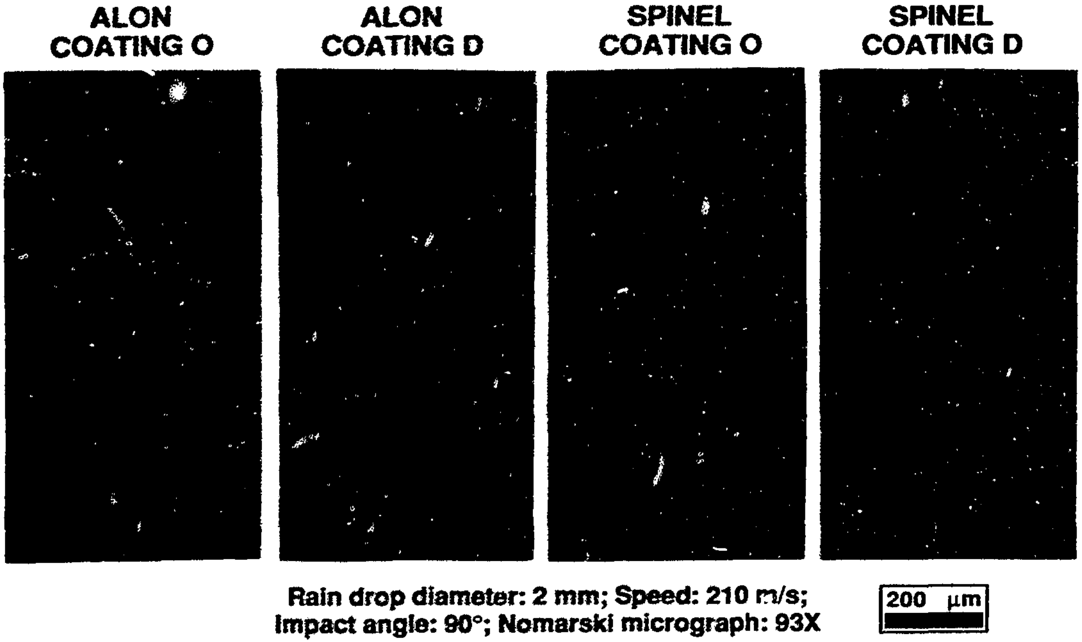


FIGURE 12. Water Drop Damage Sites on Antireflection-coated ALON and Spinel.

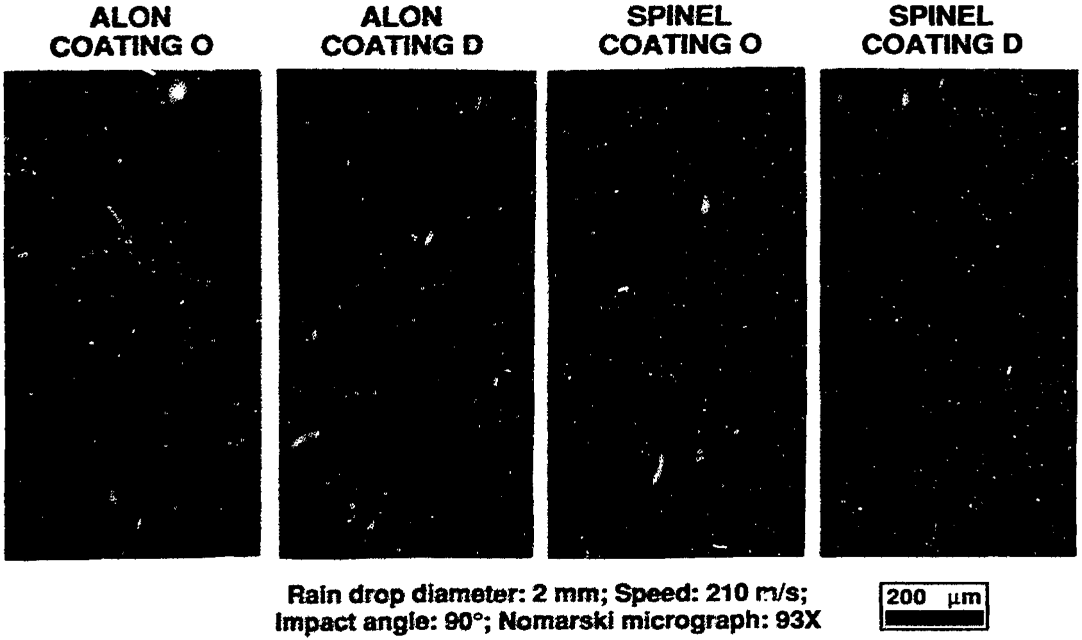
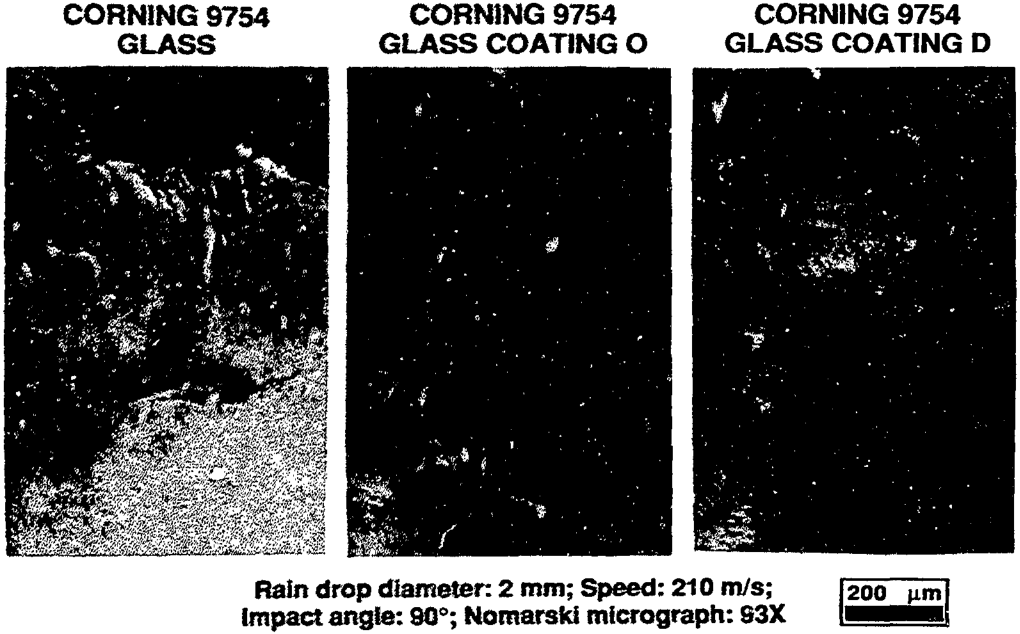


FIGURE 12. Water Drop Damage Sites on Antireflection-coated ALON and Spinel.



Rain drop diameter: 2 mm; Speed: 210 m/s;
Impact angle: 90°; Nomarski micrograph: 93X

FIGURE 13. Water Drop Damage Sites on Bare and Antireflection-coated Corning 9754 Glass.

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