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Optical Measurements on Solid Specimens of Solid Rocket Motor Exhaust and Solid Rocket Motor Slag

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Optical Measurements on Solid Specimens of Solid Rocket Motor Exhaust and Solid Rocket Motor Slag

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INTRODUCTION

Samples of rocket motor slag were investigated for the Earth science and Applications Division at Marshall Space Flight Center (MSFC). Optical measurements on space motor propellant exhaust and space motor propellant slag are provided for comparison with the optical property data of space refuse. In order to support a comparison with measurements derived from actual debris, readings were taken for both thermal emittance and solar absorbtivity. To determine the similarity between the samples and space motor exhaust or space motor slag, emittance and absorbance results were correlated with an examination of the specimen morphology.

SPECIMEN DESCRIPTION

Sample Location

Slag specimens were taken from slag entrained within a postfired solid rocket booster (SRB) and from samples obtained from subscale test motor firings. The specimen taken from entrained slag was provided by the Environmental Analysis Branch at MSFC. This sample was recovered from a retrieved space shuttle SRB at Kennedy Space Center (KSC) during refurbishment of the booster. During motor firing, slag tends to pool in the cavity created by the geometry of the submerged nozzle. One specimen was recovered from this portion of the motor during SRB refurbishment.

The alumina sample from the subscale motor firing was obtained after the horizontal test firing of a subscale motor, through a complete throat, and onto a material test section. The material test section sits at a low obtuse angle relative to the motor exhaust, and it was from this region that deposited exhaust, or slag, was obtained.

Sample History

The entrained slag retrieved from the postfired shuttle SRB was recovered after substantial exposure to sea water. An SRB is typically recovered 6 to 8 h after firing and towed back to KSC over an estimated 18 to 24 h. The sample surface was smooth, contoured, and of a uniform mottled gray appearance. Some of the smooth appearance may be attributed to the agitation of the sea water during splashdown and the associated retrieval operation.

The sample from the subscale motor firing was the result of direct exhaust deposition on the material test section. This sample showed two distinct surfaces, a lower surface adjacent to the material test section, and an upper surface exposed only to motor exhaust. The side referenced as the open side refers to the upper side facing away from the test section. This side is representative of alumina from the propulsion stream which might coalesce in space without

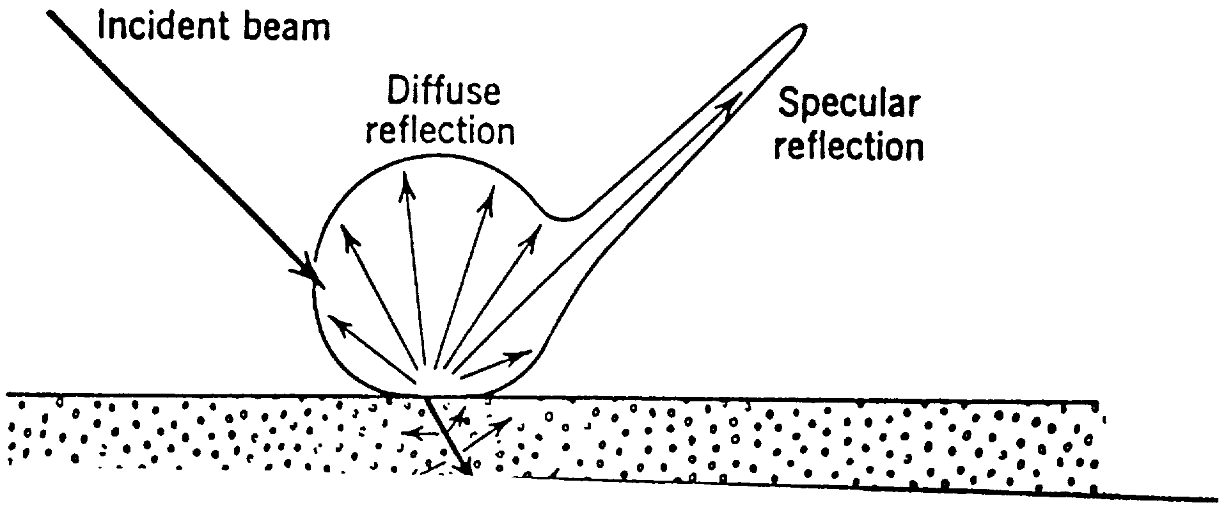


Figure 1. Diffuse and specular reflection components.

contact with a space nozzle. The side referenced as the nozzle side refers to the side facing the material test section. This side is more representative of alumina which initially adheres and detaches at a later time, or which erodes a portion of the nozzle as it is ejected from the throat region.

TEST METHODS

Solar Absorbance

Solar absorbance measurements were performed with a Cary spectrophotometer, model 2390, using a diffuse reflectance attachment. In the spectrophotometer, a focused beam is reflected off the sample surface at 3° 20'. The beam intensity is divided between absorption, transmission, and reflection.

$$\text{Absorption} + \text{transmission} + \text{reflection} = 1 \; . \tag{1}$$

The reflected beam has a diffuse component and a specular component (fig. 1) which are added by the integrating sphere at the detector. The simultaneous measurement of both the specular and the diffuse components of the reflectance gives an intensity measurement virtually insensitive to the surface topography. This total reflected intensity is compared with the intensity of the original beam. The ratio of initial versus reflected intensity is then compared with a similar ratio using a reference mirror giving, finally, a sphere-corrected reflectance.

To get the solar absorbance, the solar spectrum is divided into 50 equal energy increments. Reflectance measurements are then taken at the wavelengths which separate the energy increments. The average of these reflectance values gives the sphere corrected average solar reflectance.

For the alumina slag samples, it is possible to assume that there is no light transmitted through the sample due to the sample thickness. This allows one to set the transmitted intensity to zero and directly relate the measured reflectance with the solar absorbance.

$$\text{Solar absorbance} = 1 - \text{sphere corrected solar reflectance} \; . \tag{2}$$

Thermal Emissivity

Thermal emissivity measurements were taken with a Gier Dunkle DB 100 in the range of 5 to 25 microns. For this measurement, the sample is alternately irradiated from a warm and a cold chamber where both chambers have been constructed to approach the ideal of black-body radiation.[1] The difference between these signals is read at the detector as:

$$KS = \int_5^{25} p_\lambda E_{\text{hot}\lambda} d\lambda - \int_5^{25} p_\lambda E_{\text{cold}\lambda} d\lambda , \tag{3}$$

where KS is the signal read at the detector, p is the reflectance, and E is the emissive power at the respective chamber. The measurements are compared against a signal derived from the wall of the two black bodies.

$$KS_{100} = \int_5^{25} E_\lambda d\lambda - \int_5^{25} E_\lambda d\lambda . \tag{4}$$

This ratio provides the measured reflectance of the sample. Again the transmitted component is assumed to be zero, and the reflectance, therefore, can be used to obtain the specimen absorbance through equation (2). Furthermore, it can be shown that the absorbance and the emittance are equal in magnitude,[2] and one is able to derive the thermal emissivity for the range of 5 to 25 microns.

Average thermal emissivity = 1 – reflectance .

SAMPLE ANALYSIS

Specimen Morphology

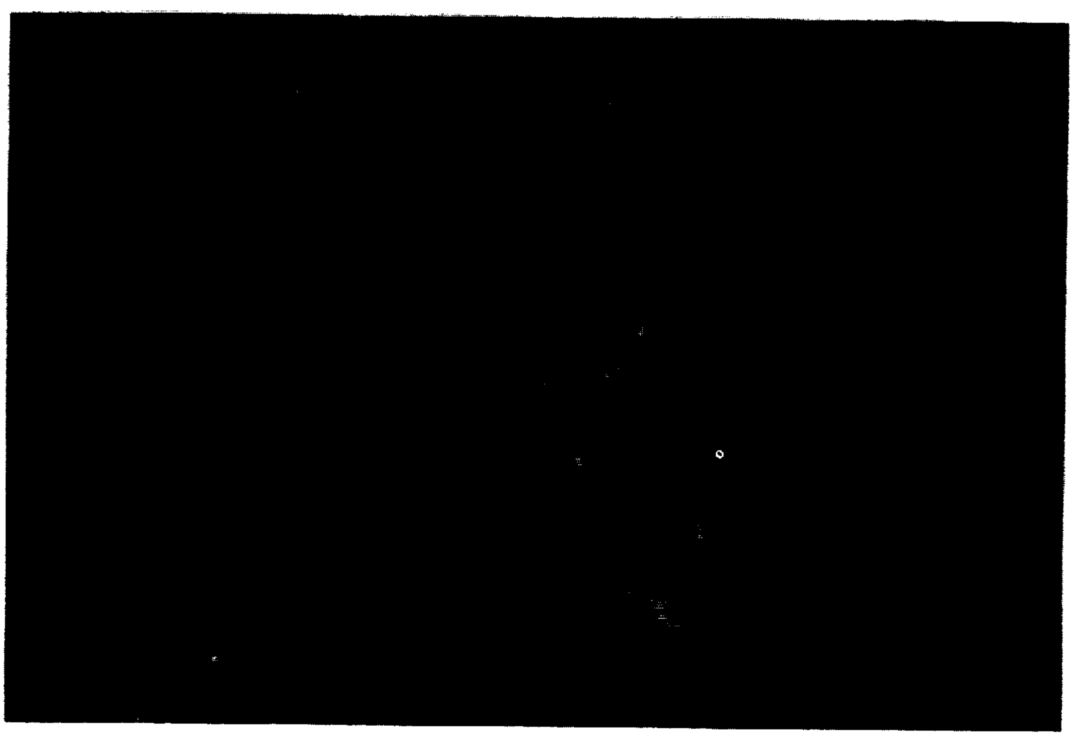
There were two features of interest on the entrained slag specimen. The first was a stalactite-stalagmite column (join), and the second was a trapped portion of charred sheet.

The view in figure 2A is down into a cavity in the specimen showing the join in the center of the photo. The presence of the cavity indicates that during solidification of the sample a large air pocket was trapped. The column indicates that the sample had to be still molten to some degree during this process in order to allow the formation of the column.

Figures 2B and 2C show a nodule which has trapped a charred sheet against the main body of the sample. This is particularly visible in figure 2C. The trapped sheet is thought to be charred insulation. This insulation came off during firing to become trapped between two molten pieces of slag. The charred insulation would provide a source of carbon for the alumina slag to mix with in order to produce the gray color of the entrained sample. For a space motor, residue of this absorbance is therefore possible, given some insulation char during actual firing of the motor.

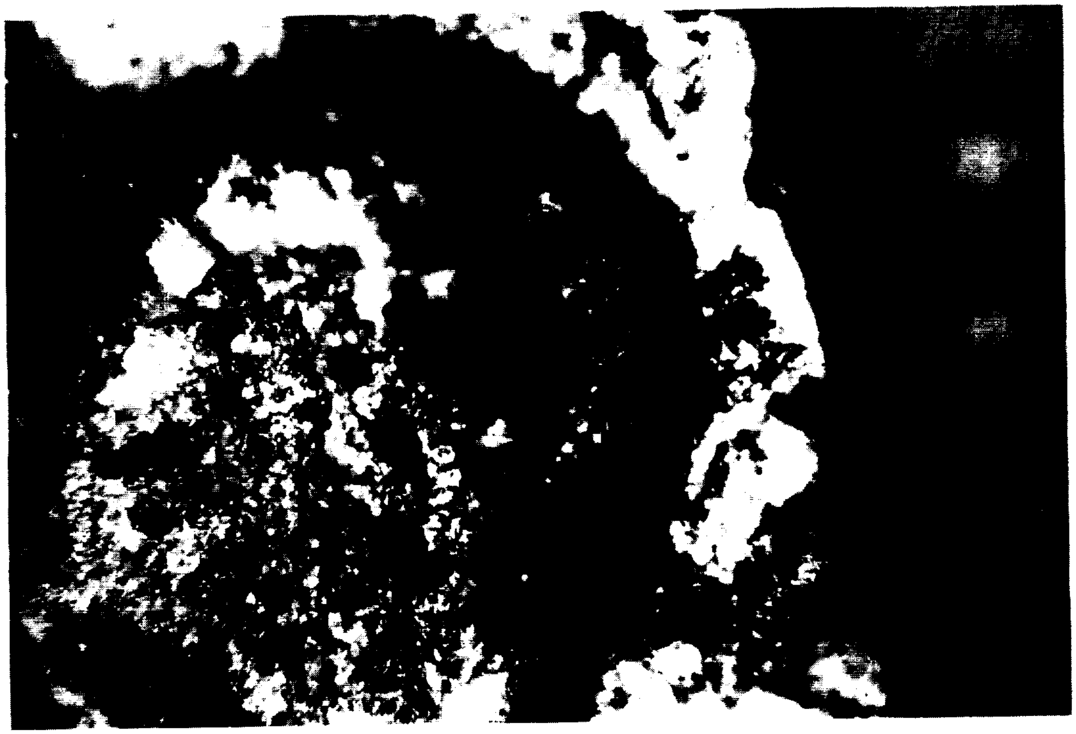
Figures 2D, 2E, and 2F show the open side, nozzle side, and downstream edge of the test motor sample, respectively. The higher carbon content and the more porous structure can be

A. Entrained slag specimen showing join.



B. Entrained slag specimen showing nodule.

Figure 2. Entrained slag specimens and subscale test motor specimens.

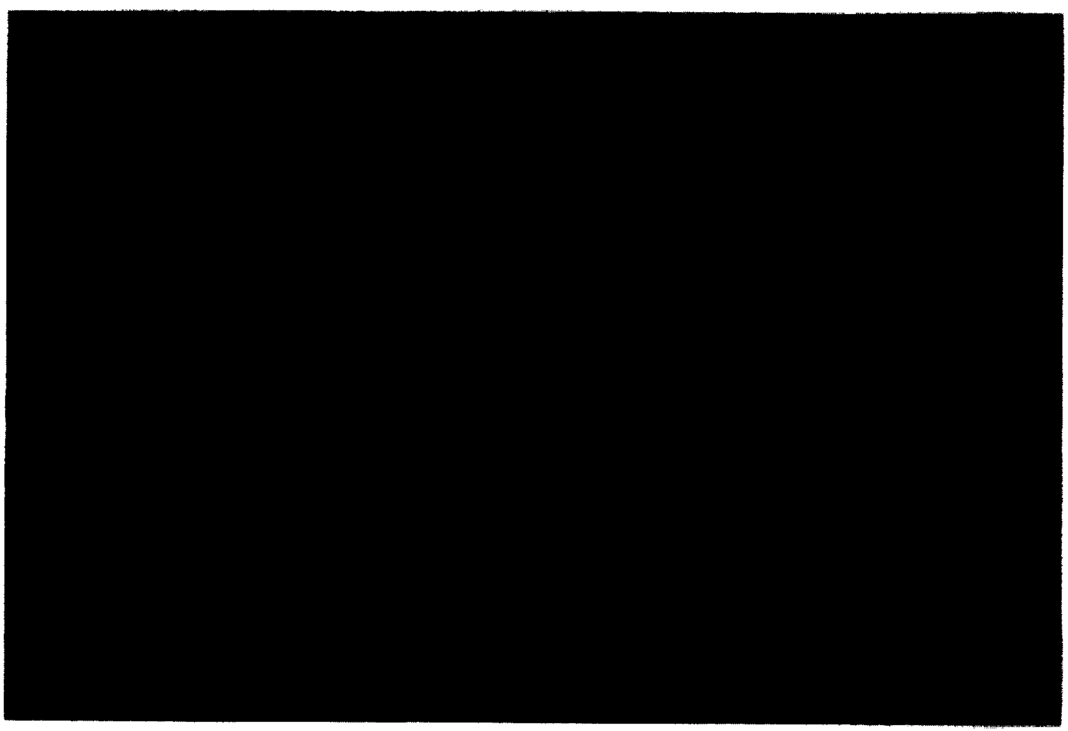


C. Entrained slag specimen showing nodule and trapped sheet.

D. Subscale test motor specimen showing open surface.

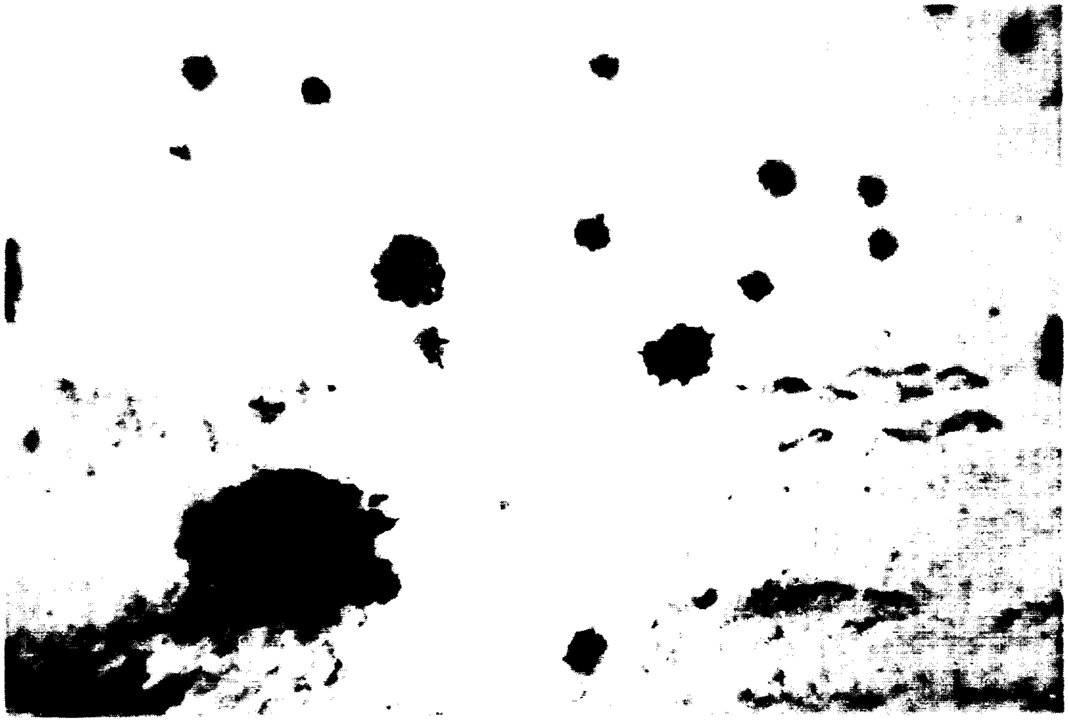
Figure 2. Entrained slag specimens and subscale test motor specimens (continued).

E. Subscale test motor specimen showing material test section or nozzle side.

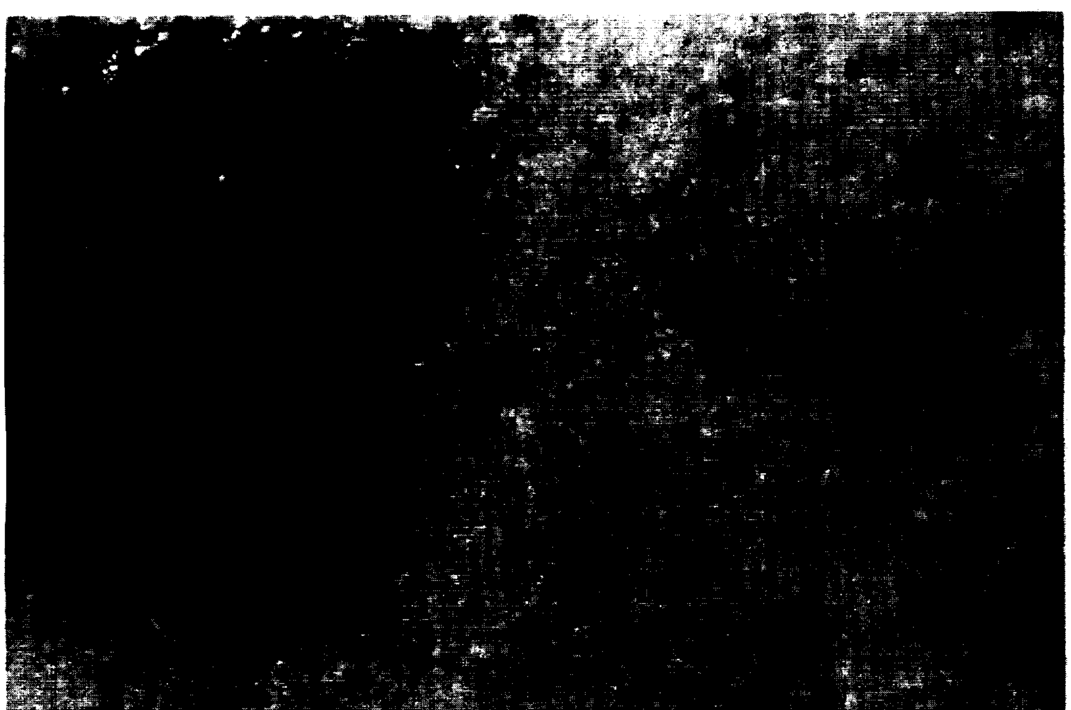


F. Edge of subscale test motor specimen.

Figure 2. Entrained slag specimens and subscale test motor specimens (continued).



G. Subscale test motor specimen showing open side.



H. Subscale test motor specimen showing carbon wetting of slag.

Figure 2. Entrained slag specimens and subscale test motor specimens (continued).

I. High magnification of slag edge.

Figure 2. Entrained slag specimens and subscale test motor specimens (continued).

seen in the nozzle side (fig. 2E). The open side (fig. 2D) shows a speckled surface with regions of carbon entrapment. Figures 2G and 2H show enlargement of the carbon entrapment. Specifically figure 2H shows a region where the carbon has "wet" the alumina slag and surrounds a region of apparently glassy carbon.

An enlargement (fig. 2I) of the edge region (fig. 2F) shows areas of higher carbon content moving outward along the flow path. The presence at the end of the flow path of higher carbon concentrations is somewhat puzzling. One suggestion is that there is a substantial amount of carbonaceous material in the flow stream, however, the heavier alumina falls out of the flow stream at an earlier stage, therefore producing the observed gradations in the sample surface.

Test Results

The thermal emissivity values for all samples stayed within the range of 15 to 30 percent (fig. 3A) emissivity. The average value for each sample set was within 21 to 25 percent (fig. 3B) well within the standard deviations of the sample sets (fig. 4A, B, C, and D).

The solar absorbance results show a critical difference between the nozzle side of the test motor sample and the open side of the same sample. The variance of the test results are 0.002 (figs. 5A, B, and C) for the solar absorbance readings. There is a difference of 30 percent total reflectance between the open and the nozzle side of the test sample and a difference of 25 percent between the open side of the test motor sample and the entrained sample from KSC. The solar absorbance for the open side falls significantly outside the standard deviation ranges for the other samples (fig. 6A).

X1 : Thermal Emissivity KSC slag side #1

Mean:	Std. Dev.:	Std. Error:	Variance:	Coef. Var.:	Count:
.216	.027	.016	.001	12.735	3
Minimum:	**Maximum:**	**Range:**	**Sum:**	**Sum of Sqr.:**	**# Missing:**
.185	.238	.053	.647	.141	6

(A)

X2 : Thermal Emissivity KSC slag side #2

Mean:	Std. Dev.:	Std. Error:	Variance:	Coef. Var.:	Count:
.247	.029	.017	.001	11.71	3
Minimum:	**Maximum:**	**Range:**	**Sum:**	**Sum of Sqr.:**	**# Missing:**
.229	.28	.051	.74	.184	6

(B)

X3 : Thermal emissivity TM Nozzle side

Mean:	Std. Dev.:	Std. Error:	Variance:	Coef. Var.:	Count:
.211	.048	.021	.002	22.57	5
Minimum:	**Maximum:**	**Range:**	**Sum:**	**Sum of Sqr.:**	**# Missing:**
.162	.272	.11	1.053	.231	4

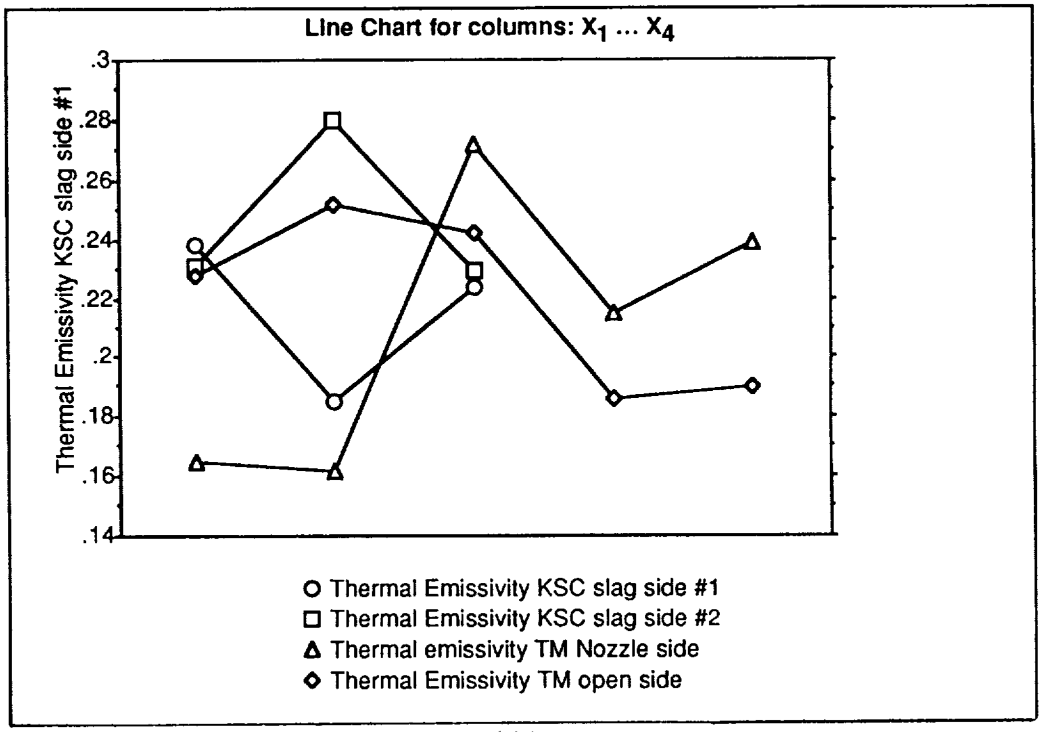
(C)

X4 : Thermal Emissivity TM open side

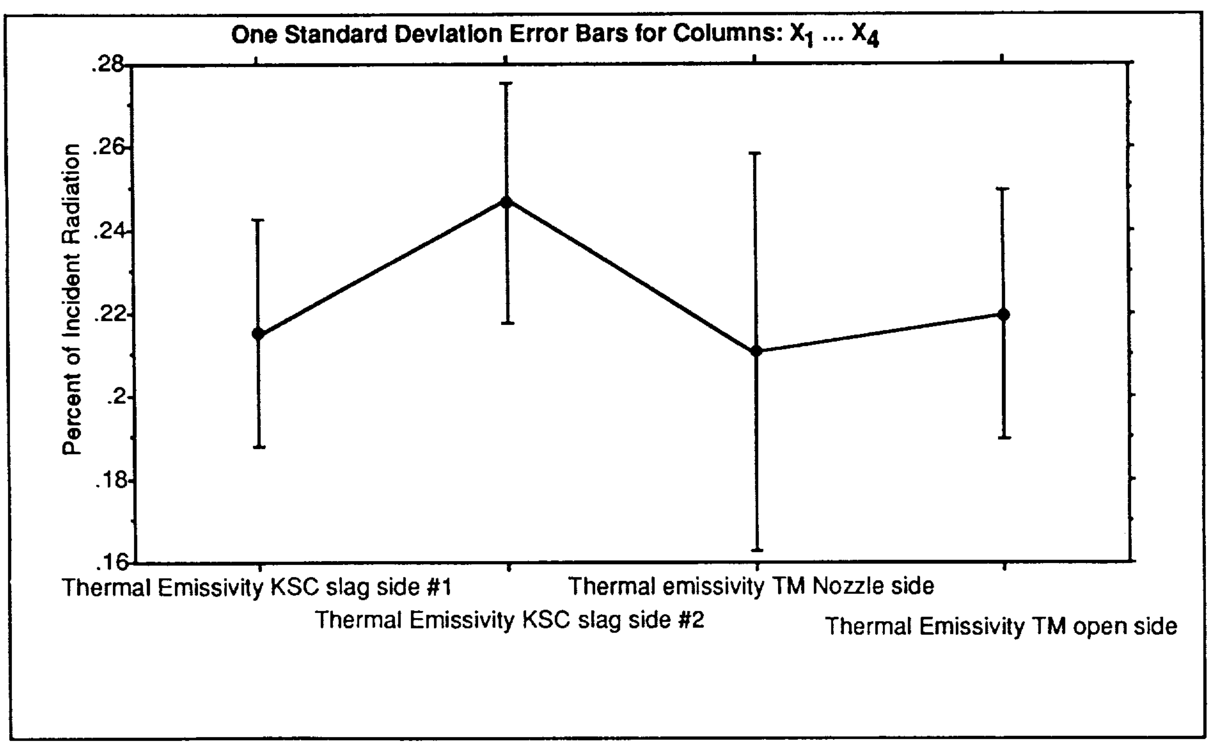
Mean:	Std. Dev.:	Std. Error:	Variance:	Coef. Var.:	Count:
.22	.03	.013	.001	13.713	5
Minimum:	**Maximum:**	**Range:**	**Sum:**	**Sum of Sqr.:**	**# Missing:**
.186	.252	.066	1.098	.245	4

(D)

Figure 3. Thermal emissivity and solar absorbance for KSC and test motor Al_2O_3 slag.



(A)



(B)

Figure 4. Thermal emissivity for KSC and test motor Al_2O_3 slag.

X5 : Solar Absorbance KSC slag

Mean:	Std. Dev.:	Std. Error:	Variance:	Coef. Var.:	Count:
.837	.048	.016	.002	5.698	9
Minimum:	**Maximum:**	**Range:**	**Sum:**	**Sum of Sqr.:**	**# Missing:**
.779	.886	.107	7.531	6.32	0

(A)

X6 : Solar Absorbance TM slag Nozzle side

Mean:	Std. Dev.:	Std. Error:	Variance:	Coef. Var.:	Count:
.888	.017	.007	2.730E-4	1.86	6
Minimum:	**Maximum:**	**Range:**	**Sum:**	**Sum of Sqr.:**	**# Missing:**
.874	.914	.04	5.329	4.734	3

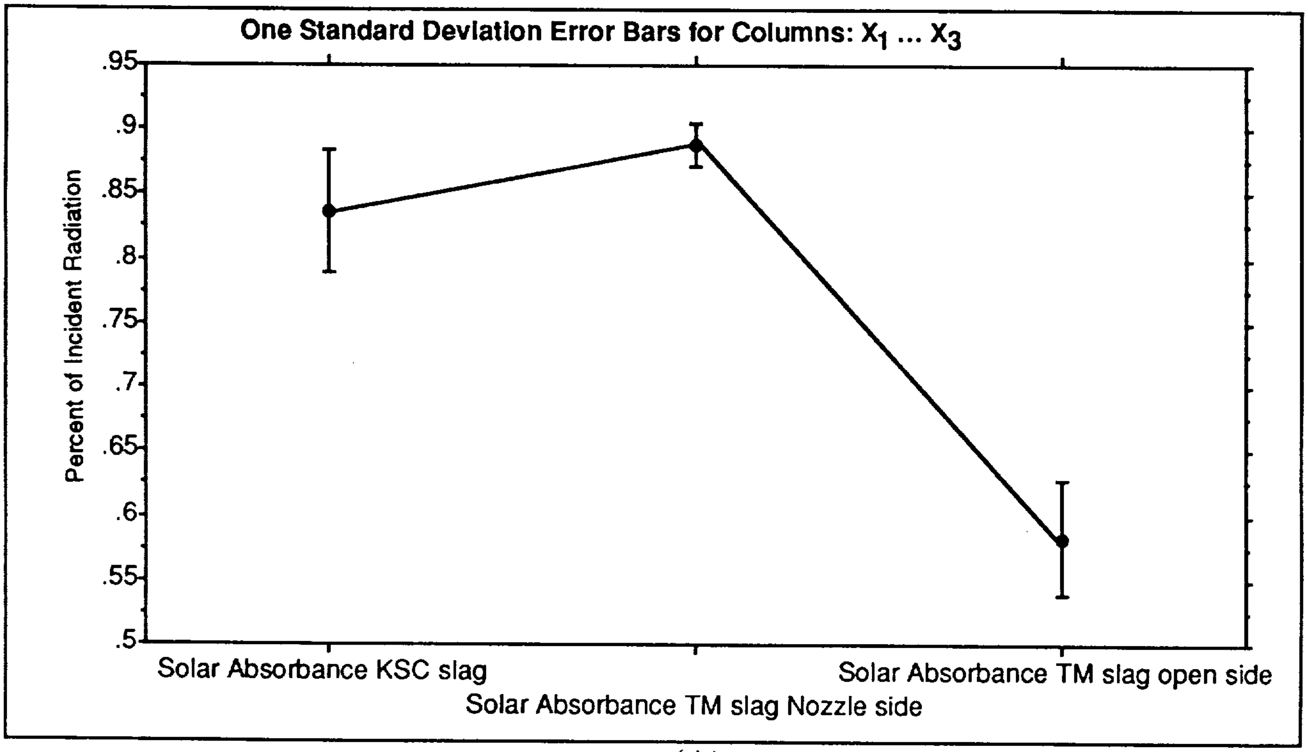
(B)

X7 : Solar Absorbance TM slag open side

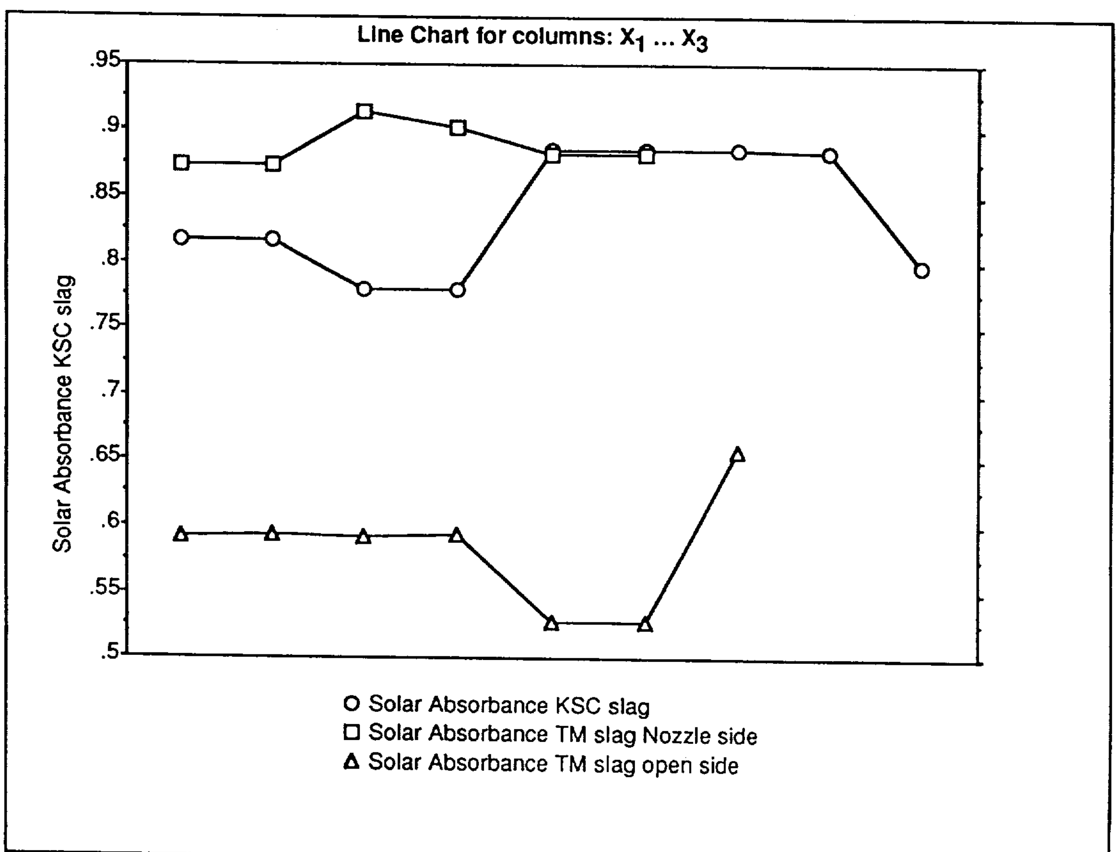
Mean:	Std. Dev.:	Std. Error:	Variance:	Coef. Var.:	Count:
.583	.045	.017	.002	7.661	7
Minimum:	**Maximum:**	**Range:**	**Sum:**	**Sum of Sqr.:**	**# Missing:**
.527	.656	.129	4.08	2.39	2

(C)

Figure 5. Statistical summary.



(A)



(B)

Figure 6. Solar absorbance for KSC and test motor Al_2O_3 slag.

Two distinct ranges of solar absorbance values are observed as shown in figure 6B. One range of slag absorbance shows a reflectance of between 10 and 20 percent, the other range shows between 40 and 50 percent solar reflectance.

Representative sample reflectance curves are shown on figure 7A, 7B, and 7C. From these graphs, the reflectance difference is noted for the wavelengths above 300 microns. This agrees with the thermal emissivity results which show no significant difference in the 5- to 25-micron region.

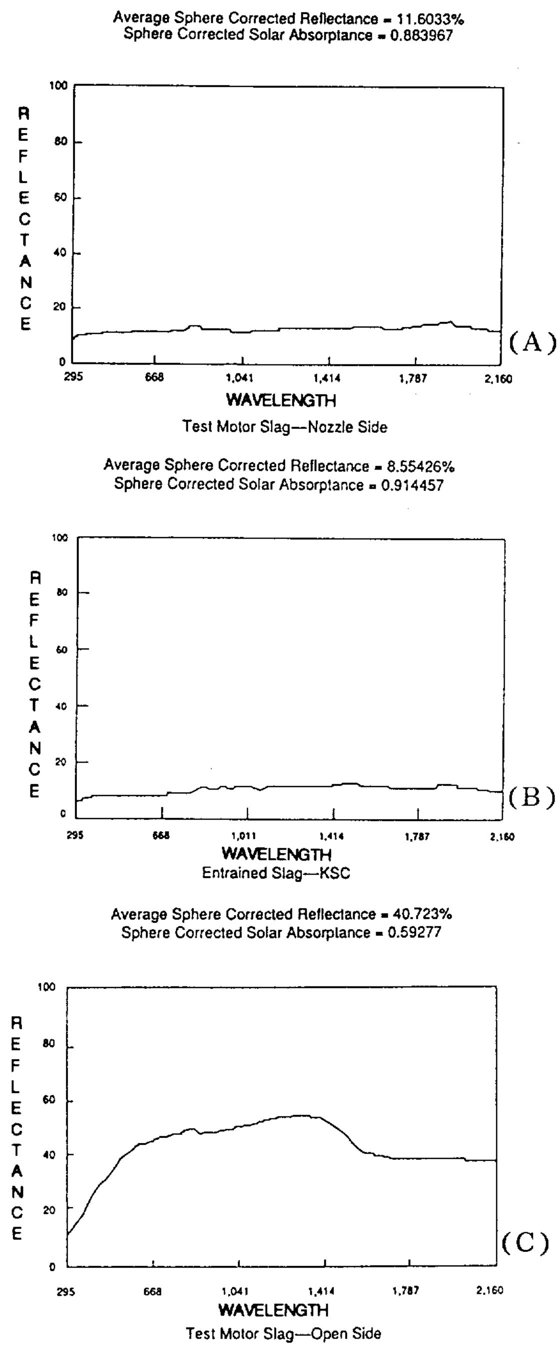


Figure 7. Test motor slag and entrained slag reflectance curves.

CONCLUSIONS

The data indicate uniform reflectance from a wavelength of 5 microns through a wavelength of 300 microns. Measurements above this wavelength show two distinct ranges of reflectance values.

The first range of reflectance at 40 to 50 percent correlates with the sample which was primarily in contact only with exhaust gases. This reflectance would seem to be applicable for clouds of particles and direct plumes from space motor exhaust. The figures 2G and 2H, however, indicate that there may be a direct carbon component present in the exhaust. This is supported by enlargement of the carbon entrapment, specifically (fig. 2H) the carbon has "wet" the alumina slag and is shown surrounding a region of glassy carbon trapped from the exhaust stream. Carbon in the flow stream is also supported by the presence at the end of the flow path of higher carbon concentrations as seen in the enlargement (fig. 2I) of the edge region (fig 2F). This suggests that there is a substantial amount of carbonaceous material in the flow stream which was noticed toward the end of the test motor deposited sample.

The second range of reflectance at 10 to 20 percent would more likely correspond to slag which has had substantial contact with either charred insulation or nozzle surfaces during expulsion. The possibility of refuse in this range is supported by the column shown in figure 2A indicating that the sample was still molten during formation of the column. The charred insulation of figures 2B and 2C provides a possible source of carbon for the alumina slag to mix with during firing. For a space motor, residue of this absorbance would be possible given some insulation char during actual firing.

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Samples of alumina slag were investigated to aid the Earth Science and Applications Division at Marshall Space Flight Center (MSFC). Alumina from space motor propellant exhaust and space motor propellant slag was examined as a component of space refuse. Thermal emittance and solar absorptivity measurements were taken to support their comparison with reflectance measurements derived from actual debris. To determine the similarity between the samples, and space motor exhaust or space motor slag, emittance and absorbance results were correlated with an examination of specimen morphology.

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