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REQUIREMENTS AND TEST RESULTS FOR THE QUALIFICATION OF THERMAL CONTROL COATINGS

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ABSTRACT

Paint type coatings are often used as engineering materials in critical satellite temperature control applications. The functional features of coatings used for temperature control purposes must remain stable throughout the satellite manufacturing process and the satellite mission. The selection of a particular coating depends on matching coating characteristics to mission requirements. The use of paint coatings on satellites, although having an extensive history, requires that the paint be qualified to each application on an individual basis. Thus, the qualification process through testing serves to ensure that paint coatings as engineering materials will fulfill design requirements.

INTRODUCTION

The complexity and size of current and future spacecraft, the rigors of spacecraft manufacture and long mission life requirements impose increasing demands on paint type coatings used for spacecraft temperature control. Paint type coatings used on spacecraft hardware can be categorized into several general types. All of these coatings use inorganic pigments of a semiconductor or dielectric nature. The binder systems used are based on silicate, silicone or urethane chemistry. Coatings based on silicate binders, although among the most space stable, require absolute substrate cleanliness before coating application, are brittle, porous and are sensitive to environmental conditions during the coating process. Elastomeric silicone coatings are cleanable, flexible and relatively easy to apply, but are easily notched during routine assembly procedures. The silicone-alkyd and urethane coatings, while being durable, easily applied and easily maintained have unacceptable stability towards the space environment for long-term missions.

White thermal control coatings are used primarily for their properties of space stable, low solar absorptance, high emittance and relative ease of incorporation into hardware manufacturing processes. However, other coating properties are often considered during the coating selection and qualification procedure. As an example, the coating selection criteria for the Cosmic Background Explorer (COBE) satellite are generally more stringent than for other spacecraft due to added requirements for low surface particulates, high emittance at low temperature and a reasonable degree of conductivity for electrostatic discharge.

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While none of the paints evaluated for COBE were found to meet all of the criteria, low outgassing elastomeric silicone paints, pigmented with silicate treated zinc oxide, were found to have the greatest combination of desirable features. Test data and an outline of the qualification test procedures followed are presented for one of these coatings. This coating, designated as TW-1300, was found to be acceptable for use on the COBE satellite.

SYMBOLS

α_s = solar absorptance

$\Delta\alpha_s$ = change in solar absorptance

ε_1 = emittance of test specimen

ε_2 = emittance of standard

ε_H = hemispherical emittance

V_1 = voltage output, specimen

V_2 = voltage output, standard

C_p = heat capacity of block

m = mass of block

$\Delta T/\Delta t$ = rate of temperature change

σ = Stefan-Boltzman Constant

T = temperature of the sample

T_o = shroud temperature

$\dot{Q}_{tc}$ = heat loss due to thermocouple

$\dot{Q}_{gas}$ = heat loss due to residual gas

A = total area of block

COATING SELECTION CRITERIA

NASA Specification No. MSFC-PROC-1384 (Reference 1) outlines the basic requirements for a low outgassing, white silicone spacecraft temperature control coating. These requirements are dictated to ensure the quality and functionality of spacecraft temperature control coatings of this type. The requirements for low outgassing, solar absorptance, emittance, adhesion and ultraviolet stability are imposed to ensure that the coating, used as an engineering material to minimize solar load, meets all design and performance expectations. Paint type coatings used as engineering materials must also be incorporated into satellite manufacturing processes and schedules. Requirements for these practical realities include pot-life, shelf-life, sprayability and cure time. The basic requirements of MSFC-PROC-1384 apply to typical satellite requirements and are based on the experience of many satellite programs. Each program or mission however, contributes new demands on the performance of these coatings.

The selection of white paint for the exterior surface of the COBE satellite was based primarily on coating thermal properties. A liquid helium dewar and two instrument packages operate at a surface temperature between 140°K and 150°K. Paints can typically have an emittance in this temperature range which is 0.1 less than the emittance at room temperature. Therefore, a paint with the highest possible emittance was desired. Other important thermal properties include stable solar absorptance in a circumpolar orbit at 900km above the surface of the earth and good adhesion over varying thermal conditions.

Secondary selection criteria were low surface contamination and a high enough conductivity to minimize on-orbit surface charging and discharging to the satellite structure. A surface cleanliness rating of Level 300 or better was required in order that the coating would not produce particulate contamination. The cleanliness rating, as outlined in Reference 2, describes surface contaminant size, distribution and numbers. A rating for a typical silicate paint is 750, while urethane or silicone paints have ratings between 200 and 250. The coating conductivity requirement allowed a degree of latitude since the maximum electron flux and energy for satellites at the COBE altitude and inclination occur for only tens of seconds. The resulting peak differential charge, on the order of 200 volts, would therefore dissipate shortly after passing over the polar region.[1]

TYPICAL PROPERTIES

The requirements and typical properties for the TW-1300 coating are summarized in Table 1. The specific test methods and detailed procedures followed to determine the properties listed in Table 1 may be found in References 3 through 7.

SOLAR ABSORPTANCE AND REFLECTANCE

Solar absorptance was determined from absolute hemispherical spectral reflectance measurements performed in accordance with ASTM Standard Test Method E903-82. The measurements were performed using a Beckman DK-2A Spectrophotometer with a center mounted integrating sphere of the 'Edwards' type (Figure A1.2 of E903-82). Total reflectance measurements were obtained in the entire solar spectrum from 280 nm to 2400 nm wavelength at an incident angle of 7°. The measurements are properly denoted as being 'absolute hemispherical spectral reflectance'.

Air Mass Zero solar absorptance, α_S, was determined using the solar spectral distribution from Johnson (Reference 8). Reflectance data for 48 selected equal energy ordinates, corresponding to 2% increments of the distribution, were averaged as a fraction and subtracted from unity. Measurement data between 295 nm and 2400 nm were used and account for 96% of total solar radiation. As seen in Figure 1, a nominal 8-10 mil coating thickness provides an optimal solar absorptance of less than 0.20.

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[1] "Selection of White Thermal Paint for COBE Exterior Surfaces," COBE Systems Engineering Memorandum. October 20, 1987.

Hemispherical spectral reflectance measurements were also used to evaluate the effects of surface roughness and were conducted in accordance with ASTM Standard Test method E-903-82. The measurements were performed with a Beckman DK-2A Spectrophotometer using an integrating sphere as shown in Figure A1.3 of ASTM E-903-82. This detector-baffled, wall mounted sample integrating sphere precludes the necessity of using a reference standard, except when defining the instrument's 100% line. The reflectance measurements were obtained in the solar spectrum from 280nm to 2400 nm wavelength at an incident angle of 20°. The diffuse hemispherical reflectance measurements were made using a light trap as shown in Figure A1.3 of ASTM E-903-82. The total hemispherical spectral reflectance measurements were made using the integrating sphere with a continuous sphere coating by employing a sphere-completing segment.

The paint test panels used for the measurements were chosen on the basis of their having strikingly different visual surface texture while having approximately the same coating thickness. The test panel prepared from paint Lot No. 169-8 was produced by spray painting in such a way as to produce a pebble grained surface. The test panel prepared from paint Lot No. 1-0028 had a surface typical of the egg-shell finish resulting from normal spray painting procedures. The average total solar reflectance, and the average diffuse reflectance were calculated using the same 48 selected energy ordinates used to determine solar absorptance. Specular reflectance was calculated by taking the difference between the total reflectance and the diffuse reflectance. These data are shown in Table 2.

The reflectance data presented in Table 2 indicate that the surface roughness of the coating has little effect on diffuse reflectance. Indeed, the solar absorptance and average reflectance values exhibited in Table 2 suggest that the two coating samples are identical. It should be noted that the light trap used with the 8 in. diameter integrating sphere intercepts about 0.8% of the diffusely reflected flux from the sample. The 0.4% specular reflectance obtained for both samples is approximately equal to the uncertainty in the measurements, thus, the coatings are essentially as close to being perfectly diffusing surfaces as can be designed into organic coatings.

TOTAL EMITTANCE

Total emittance measurements were performed with a Devices and Services Company emissometer Model AE, Adaptor Model AE-AD1, equipped with a Model RD-1 scaling digital voltmeter. The detector portion of the emissometer is heated to 150°F so that the sample does not have to be heated. The detector responds only to radiation heat transfer and is designed to have an output linear with emittance. Being a differential thermopile with sensing elements of aluminum foil and black paint, the detector has a near-constant response to thermal wavelengths from 3 to 30 microns.

The test specimens and a flat black standard of known emittance (0.90) were placed on a heatsink and allowed to stabilize to ambient conditions. The detector was placed on the flat black standard for approximately one and one half minutes and the voltage output recorded. The detector was then placed on the test specimen for approximately one and one half minutes and the voltage output recorded.

The total emittance was calculated as follows in Equation 1 and found to meet the requirements of 0.90 ±0.05 for nominal thickness.

$$\varepsilon_1 = \frac{V_1}{V_2} (\varepsilon_2) \tag{1}$$

In equation 1, where ε_1 = Emittance of test specimen,

ε_2 = Emittance of black standard,

V_1 = Voltage output for test specimen, and

V_2 = Voltage output for black standard.

ADHESION

Thermal shock tests were conducted using liquid nitrogen immersions, oven exposures and controlled rate temperature changes in an environmental chamber. The liquid nitrogen immersion temperature tests ranged between either 254°C or ambient temperature and liquid nitrogen temperature. An environmental chamber was used to cycle samples between 60°C and -70°C using a 0.5°C/min rate of temperature change. TW-1300 was evaluated on aluminum substrates primed with TW-1300 primer on both abraded and unabraded aluminum.

The aluminum substrates used for the 254°C - liquid nitrogen immersion tests were prepared by cleaning with Methyl Ethyl Ketone before applying TW-1300 primer and paint. Test samples were allowed to cure under ambient laboratory conditions for more than 40 hours before thermal cycling. After curing, the test samples were placed in a 254°C oven for 5 minutes. After 5 minutes the samples were immersed in liquid nitrogen until vigorous boiling ceased. At this point the samples were returned to the 254°C oven. This cycle was then repeated. None of the samples tested exhibited any change from their original appearance or condition.

The same cycles were used to test TW-1300 samples prepared on abraded and primed aluminum substrates. These substrates were prepared by scrubbing the substrate surface with a mixture of Comet cleanser, carborundum grit, and water. The substrates were thoroughly rinsed with water and allowed to air dry before applying primer and paint. These samples also did not exhibit changes from their original condition, after two cycles between 254°C and liquid nitrogen temperature.

TW-1300 was also evaluated on abraded and primed aluminum substrates, by cycling between ambient temperature and liquid nitrogen temperature. Test samples were allowed to "equilibrate" at each temperature before continuing the cycle. Samples tested in this manner exhibited no change from their original condition even after more than 40 such cycles.

TW-1300 applied to abraded and primed aluminum substrates with various thicknesses of primer were subjected to the liquid nitrogen immersion test and to a cyclic temperature test in an environmental chamber. Environmental chamber test samples were soaked for 6 hours at 24°C with 80% RH followed by another soak at 24°C with 50% RH for 1 hour prior to cycling temperature between 40°C with 50% RH and -70°C using a 0.5°C/min. temperature change rate. No adhesion loss, cracking or other signs of failure were noted after 100 cycles.

Additional test samples were subjected to thermal vacuum tests at 10^{-6} torr. 90 cycles with a 2°C/min. rate of temperature change were conducted between -130°C and 60°C and followed by a liquid nitrogen immersion. There was no apparent loss of adhesion after this testing.

COATING HANDLING PROPERTIES

The sprayability and resulting appearance of the TW-1300 coating are subject, in part, to paint preparation and spraying technique. The paint is applied using typical spray painting procedures and equipment in successive wet coats of uniform thickness, allowing just enough time between coats for solvent evaporation in order to avoid runs. The paint is air dried at room temperature generally for not less than 64 hrs. before conducting critical tests such as outgassing, ultraviolet degradation or thermal/vacuum tests. However, hardware or samples can be handled after 8 hrs. since nearly 100% of the mechanical strength of the film is developed in this time period.

The resulting paint coating is soft and subject to tearing when compared to polyurethane coatings. However, these characteristics are inherent to the coating material. Evaluation tests were conducted on the paint as a function of film thickness and as a function of temperature and humidity conditions during application and cure to determine optimum spray painting conditions. The results of this testing indicated that the greatest film strength is obtained with an 8-10 mil thick film cured at 70°F with relative humidity in the range between 25% and 45%. Softer paint films generally resulted when high humidity conditions were used during the cure time.

Other paint characteristics related to sprayability and handling include weight per gallon, shelf-life, pot-life and viscosity. Typical values for these characteristics are shown in Table 1 and are determined at the time of manufacture as part of quality assurance procedure.

SPACE STABILITY PROPERTIES

OUTGASSING PROPERTIES

Outgassing tests in accordance with ASTM E595 were conducted on paint samples which were applied to release films. The samples were allowed to cure under ambient conditions for a minimum of 5 days prior to the outgassing test. No elevated temperature cure or baking cycles were used. As shown in Table 1 Total Mass Loss (TML) averaged 0.35% and Collected Volatile Condensable Material (CVCM) averaged 0.01%.

ULTRAVIOLET STABILITY

The ultraviolet stability of new spacecraft coatings with respect to changes in solar absorptance must be verified. Ultraviolet exposure and reflectance measurements must be performed invacuo and at nominal spacecraft operating temperature. Solar absorptance was determined in air prior ultraviolet exposure from reflectance measurements made in accordance with ASTM E-903 over the wavelength region between 290nm and 2400nm. Test samples were then mounted in a vacuum chamber and maintained at 25°C throughout the test. The samples were subjected to a total exposure of 1000 equivalent sun hours (ESH) at a one sun intensity using an X-25 airmass zero xenon source. The vacuum chamber was operated at 10^{-6} torr during the test and was not interrupted for reflectance measurements. Reflectance measurements were made in-situ through a quartz window at 0, 50, 100, 200, 500 and 1000 ESH. Although measurements made in this manner do not yield absolute solar absorptance values, relative changes in solar absorptance can be determined. Changes in solar absorptance using this technique can be determined within ± 0.02.

Catalyst type, handling and storage effects on the ultraviolet stability of TW-1300 were determined during several ultraviolet degradation tests. The solar absorptance data shown in Table 3 indicates that the TW-1300 is quite stable to ultraviolet radiation when handled properly. The detrimental effects of surface contamination on reflectance, and thus solar absorptance, is shown by comparing the reflectance spectra in Figure 2 for an uncontaminated sample to the spectra in Figure 3 for a sample handled with latex rubber gloves.

CHARGED PARTICLE STABILITY

The differential energy spectrum of electrons in the COBE mission environment exhibits two flux density peaks at relatively low energies. The lowest energy electrons occur between 6 and 30 eV and have a flux of approximately 2×10^7 electrons/$\mathrm{cm}^2 \cdot \mathrm{sr} \cdot \mathrm{eV} \cdot \mathrm{s}$. The higher energy electrons are typically on the order of 1 KeV but could be as high as 20 KeV. The 1 KeV electrons have a flux of approximately 5×10^5 electrons/$\mathrm{cm}^2 \cdot \mathrm{sr} \cdot \mathrm{eV} \cdot \mathrm{s}$.

Figure 4 presents data for separate but consecutive 1 MeV electron and proton exposures each with a total fluence of 10^{14} particles/cm^2. The results of the high energy electron irradiation indicates significant damage in the near infrared region and is not untypical. However, results obtained from tests conducted on a similar coating using more realistic energy levels were found to be considerably less dramatic (References 9 and 10). Further, a comparison of the effects of 20 KeV electrons to 80 KeV electrons also on a similar coating reported on in Reference 9 suggests that the electron energy dependent damage effects are generally less than the energy ratio. Therefore the $\Delta\alpha_s = 0.04$ measured after the 1 MeV exposure is not considered inordinate. This is especially true since the 10^{14} electron fluence is approximately two times greater than the total fluence predicted for the COBE mission.

The interpretation of the effects of the proton irradiation, conducted subsequent to the electron irradiation is less straight forward since both the electron and proton energy levels used exceed the threshold levels at which incipient damage can be observed in silicate treated zinc oxide systems. Therefore, the additional significant damage in the near infrared region occuring after the proton irradiation could be due to a synergistic effect of the prior damage caused by the electron irradiation. Low energy proton testing is planned for the very near future in order to further characterize the TW-1300 coating performance in the charged particle environment.

LOW TEMPERATURE EMITTANCE

The hemispherical emittance of many materials is temperature dependent. Therefore, it was necessary to characterize the temperature dependency of emittance for the coatings used on COBE. Coating samples were evaluated using a transient calorimetric technique where a metallic block of known mass and heat capacity was coated with the test material and suspended in a liquid nitrogen cooled shroud inside a vacuum chamber (Reference 11). Sample temperature was monitored while the sample radiatively cooled under these conditions. Heat loss by conduction in the vacuum chamber was minimized by maintaining a pressure less than 10^{-6} torr. Heat loss through the thermocouple lead was calculated and accounted for in each temperature interval.

The thermal balance of the test chamber is described by Equation 2, where:

m = mass of block

C_p = heat capacity of the block

$\Delta T/\Delta t$ = rate of temperature change

A = total area of the block

ε_H = hemispherical emittance

T = sample temperature

T_o = shroud temperature

$\dot{Q}_{tc}$ = heat loss from the thermocouple

$\dot{Q}_{gas}$ = heat loss due to residual gases

σ = Stefan-Boltzman Constant

$$-mC_p(\Delta T/\Delta t) = A\sigma\varepsilon(T-T_o) + \dot{Q}_{tc} + \dot{Q}_{gas} \tag{2}$$

Hemispherical emittance was calculated using Equation 3 by rearranging Equation 2 and neglecting the heat loss to the chamber, Q_{gas}.

$$\varepsilon_H = \frac{-mCp(\Delta T/\Delta t)-\dot{Q}_{tc}}{A\sigma(T-T_o)} \tag{3}$$

This technique has been found to be reliable for determining hemispherical emittance as a function of temperature for temperatures as low as 120°K with an accuracy of ± 2%. Emittance data for the TW-1300 coating is shown in Figure 5 and ranges from 0.90 at +363°K to 0.75 at -123°K.

SUMMARY

The results of qualification tests conducted on a white thermal control coating have been presented. The test results show that this coating is acceptable for use on the exterior surfaces of the COBE satellite. The coating meets specific requirements for low solar abosrptance, emittance, cleanliness and space stability. The physical features and handling characteristics of the coating tested were also found to meet requirements for sprayability, adhesion, pot-life and storage-life, thus allowing the coating to be easily incorporated into the satellite manufacturing and assembly process. The resistance of this particular coating to degradation by the effects of ultraviolet, electron and proton bombardment was found to be not unlike similar coatings that have been well characterized and which have a long history of use in satellite temperature control applications. The analysis of NASA Specification MSFC-PROC-1384 and the specific requirements of the COBE satellite clearly suggests the suitability of the TW-1300 coating investigated for many satellite applications in addition to the COBE mission.

REFERENCES

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4. "Total Mass Loss and Collected Volatile Condensible Material from Outgassing in a Vacuum Environment." ASTM Number: E 595.

5. "Elongation of Attached Organic Coatings with Conical Mandrel Apparatus." ASTM Number: D 522.

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TABLE 1
Summary of Coating Properties and Test Results

Test	Requirement	Result
Total Emittance (ε_1)	0.90 ± 0.05	0.93
Emittance vs. Temperature (ε_H)	123°K to 363°K Stability	0.75 - 0.90
Solar Absorptance (α_s)	Less than 0.22	0.18
Ultraviolet Stability ($\Delta\alpha_s$)	Less than 0.02 after 500 ESH	Less than 0.02 after 1000 ESH
Adhesion		
- Thermal Shock	No loss of adhesion	No loss of adhesion
- Conical Mandrel	No loss of adhesion	No loss of adhesion
- Thermal/Vacuum	No loss of adhesion	No loss of adhesion
Coating Weight		
- As Manufactured	11.3 to 12.5 lbs./gal.	11.8 lbs./gal.
- Dry Film	Not specified	0.03g/mil-in.^{2}
Pot-Life	45 minutes minimum	Greater than 45 minutes
Paint Shelf-Life	6 month minimum when refrigerated	Greater than 6 months when refrigerated
Catalyst Shelf-life	6 month minimum when refrigerated	Greater than 6 months when refrigerated
Viscosity at Time of Manufacture	25 to 31 seconds No. 4 Ford Cup	25 to 31 seconds No. 4 Ford Cup
Outgassing-No Oven Cure or Bake	TML - 1.0% CVCM - 0.1%	TML - 0.35% CVCM - 0.01%
Self-Generated Particulate Contamination	Not Specified	Better than Level 300

Table 2

Solar Reflectance and Solar Absorptance of TW-1300 Samples Having Different Surface Roughness

Sample	α_s	Total Reflectance (%)	Diffuse Reflectance (%)	Specular Reflectance (%)
169-8	0.190	81.0	80.6	0.4
1-0028	0.190	81.0	80.6	0.4

TABLE 3

TW-1300 ULTRAVIOLET/VACUUM EXPOSURE TEST RESULTS

Sample Description	Initial α_s In Air	Initial α_s In Vacuum	α_s After 50 ESH	α_s After 100 ESH	α_s After 200 ESH	α_s After 1000 ESH	$\Delta\alpha$ After 1000 ESH
TW-1300	0.19	0.19	0.19	0.19	0.19	0.19	Less than 0.02
TW-1300 After Storage in Clean Room Bag	0.18	0.18	0.18	0.18	0.18	0.18	Less than 0.02
TW-1300 Contaminated After Handling with Latex Rubber Gloves	0.20	0.21	0.22	0.22	0.21	0.23	0.03
TW-1301 (Organometallic Catalyst)	0.20	0.20	0.20	0.20	0.20	0.20	Less than 0.02
TW-1301 (Organometallic Catalyst)	0.19	0.19	0.19	0.19	0.19	0.19	Less than 0.02

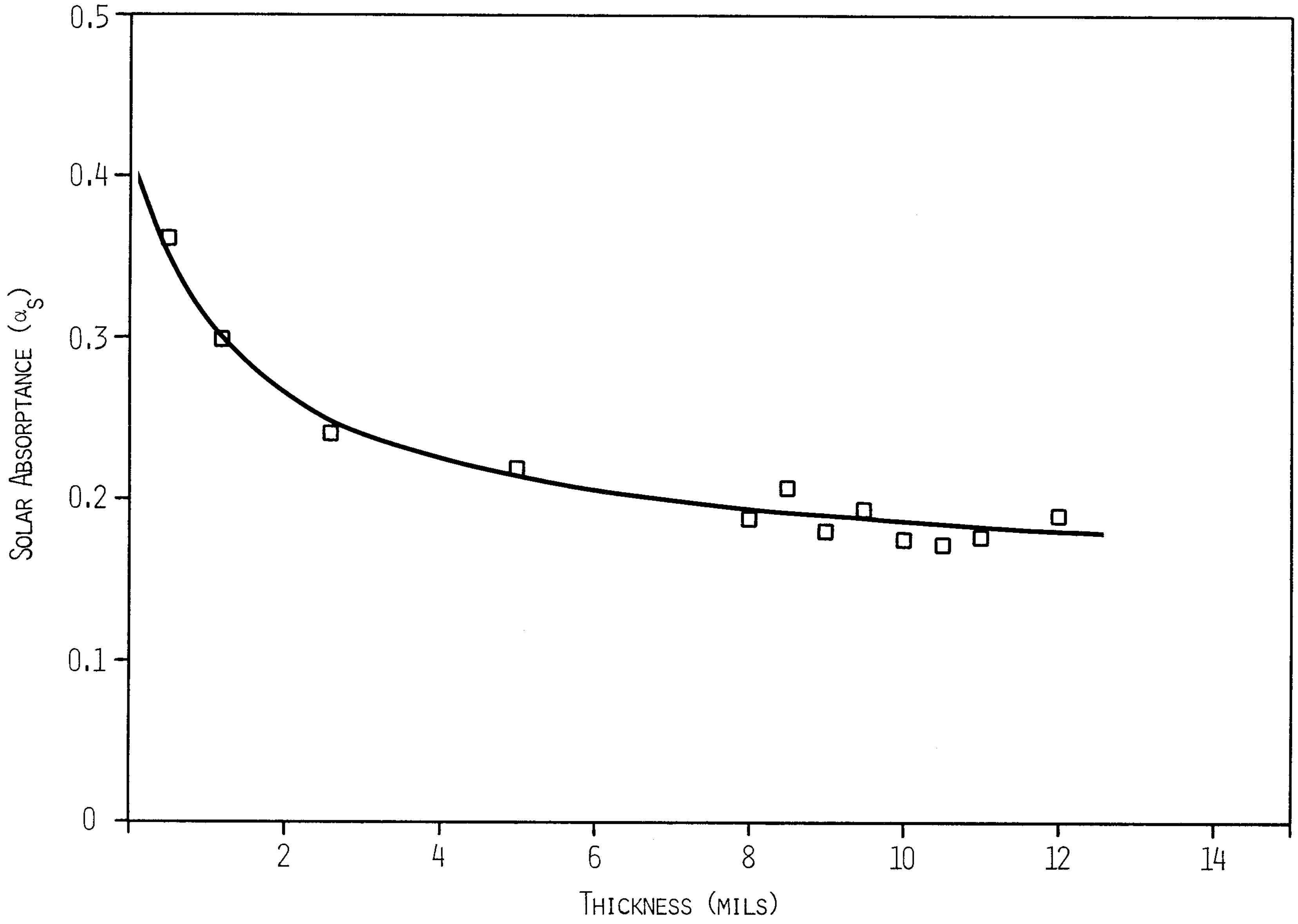

Figure 1. TW-1300 Solar Absorptance vs. Thickness

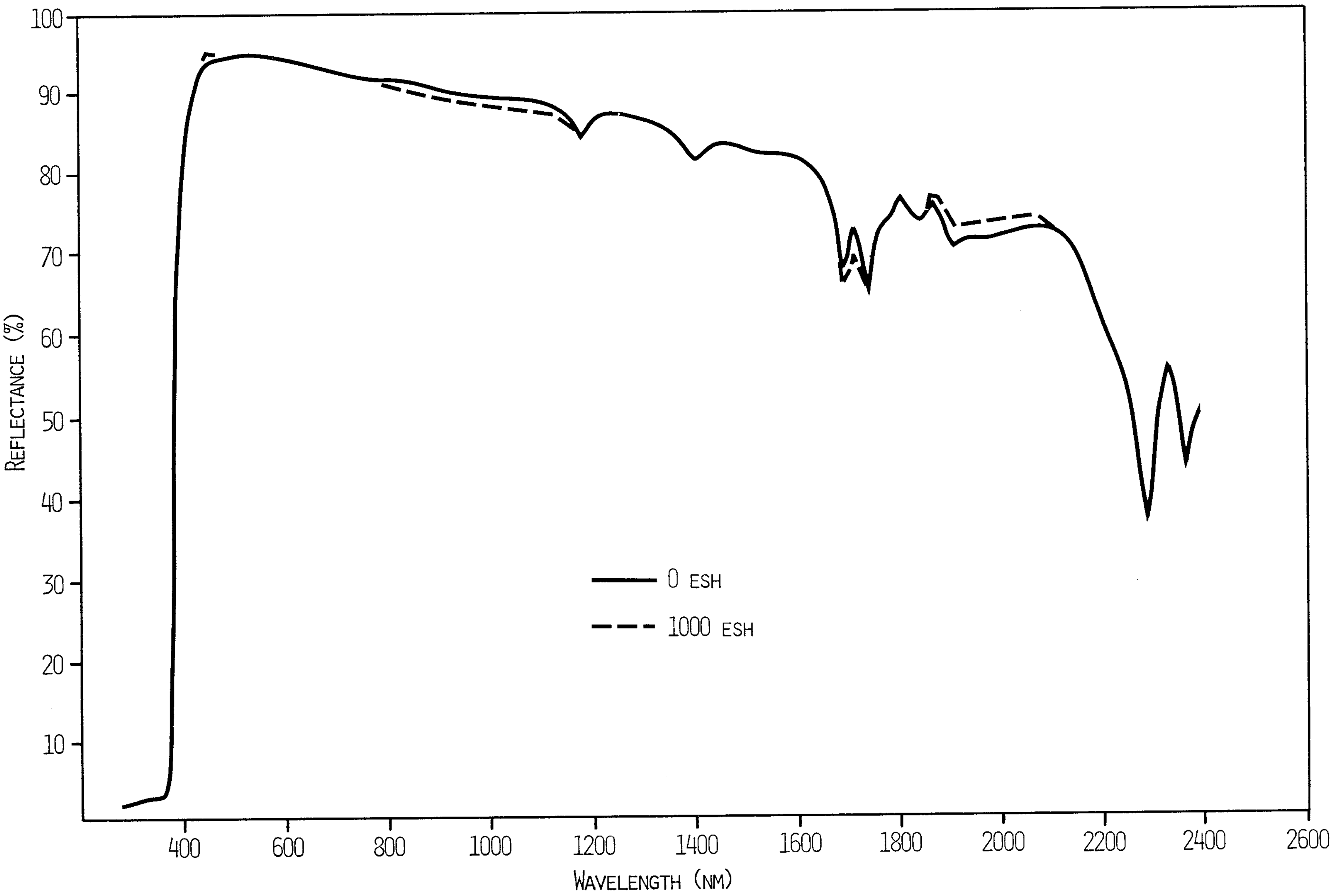

Figure 2. Ultraviolet Stability Test Results – Uncontaminated Sample

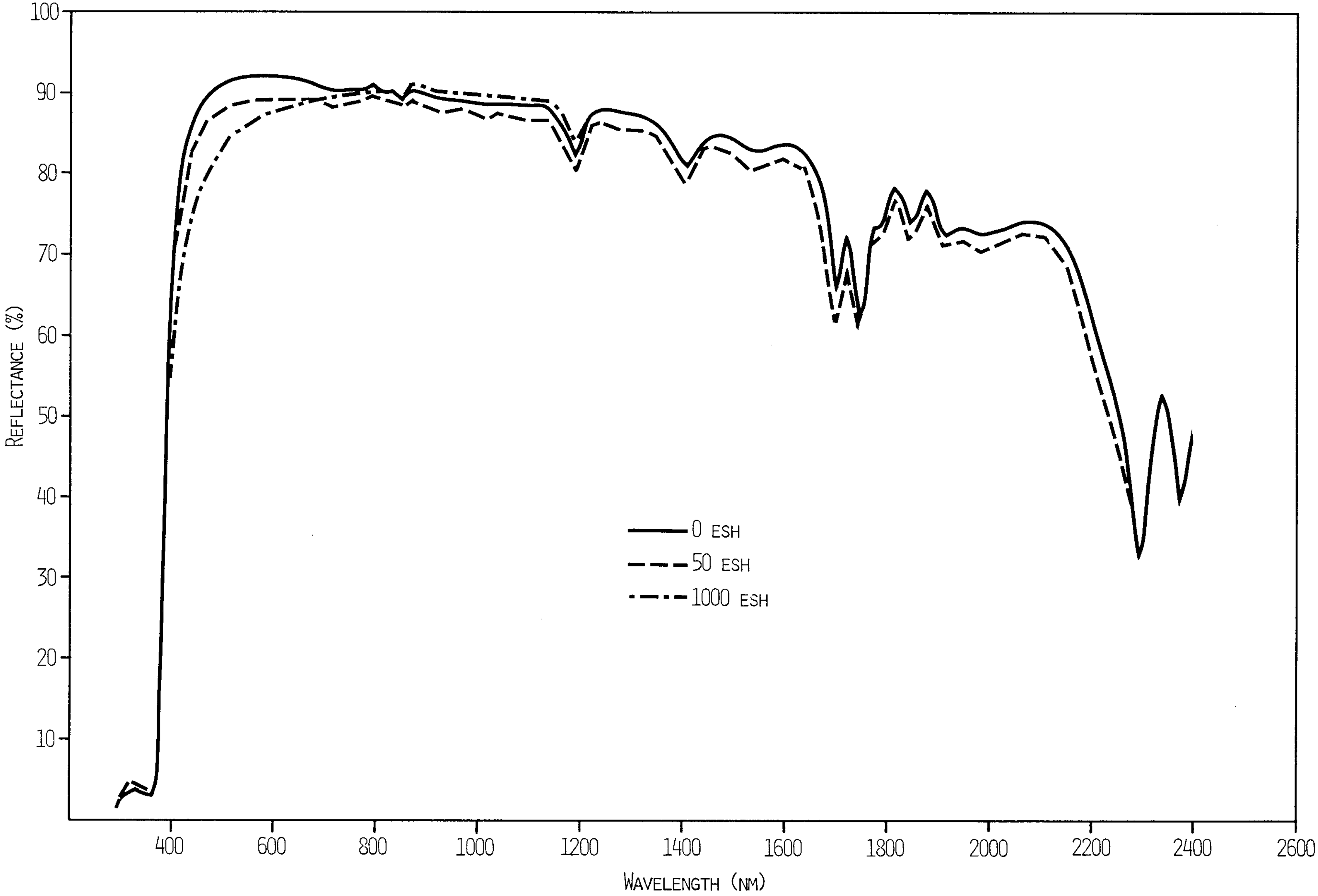

Figure 3. Ultraviolet Stability Test Results - Contaminated Sample

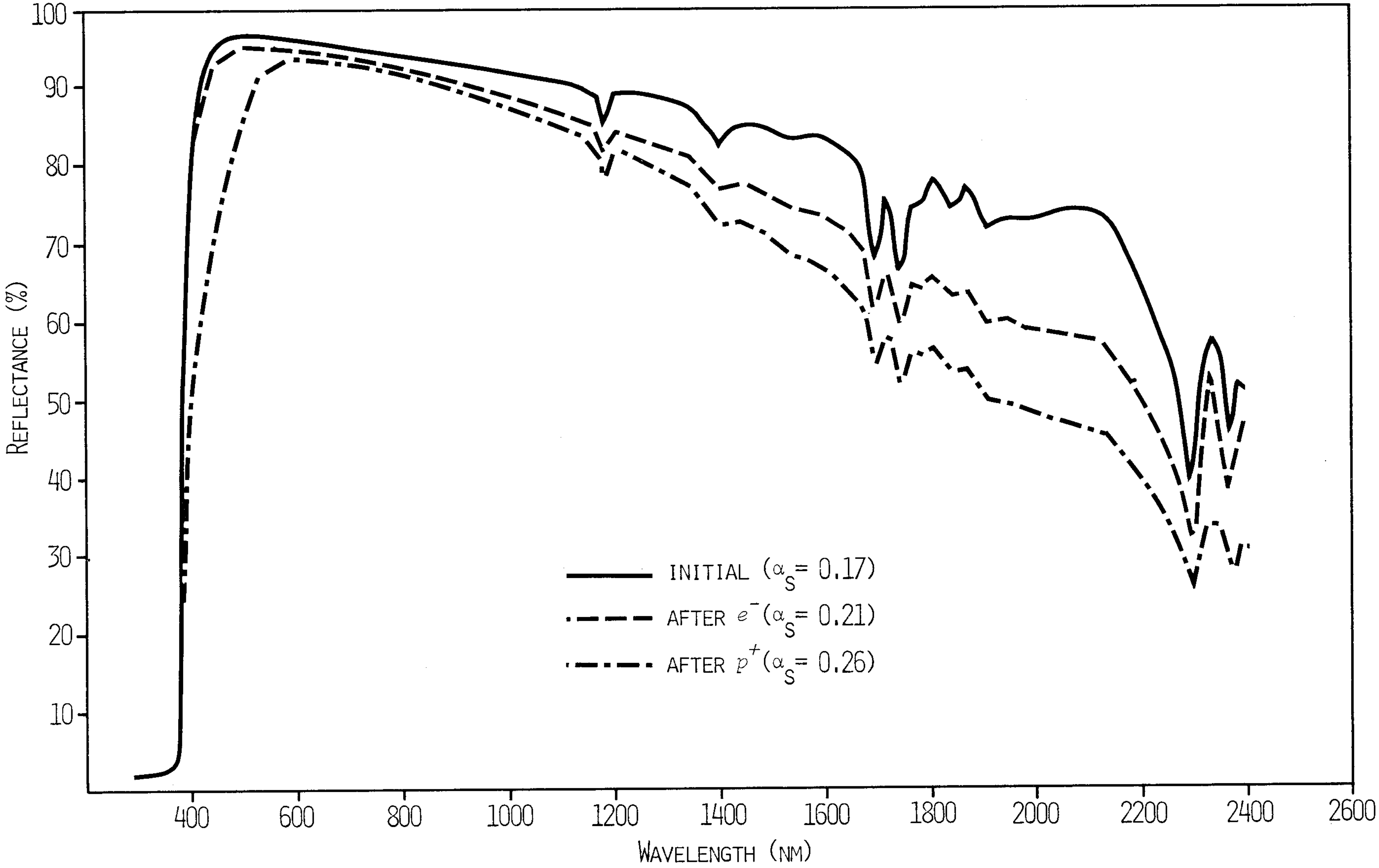

Figure 4. Charged Particle Stability Test Results

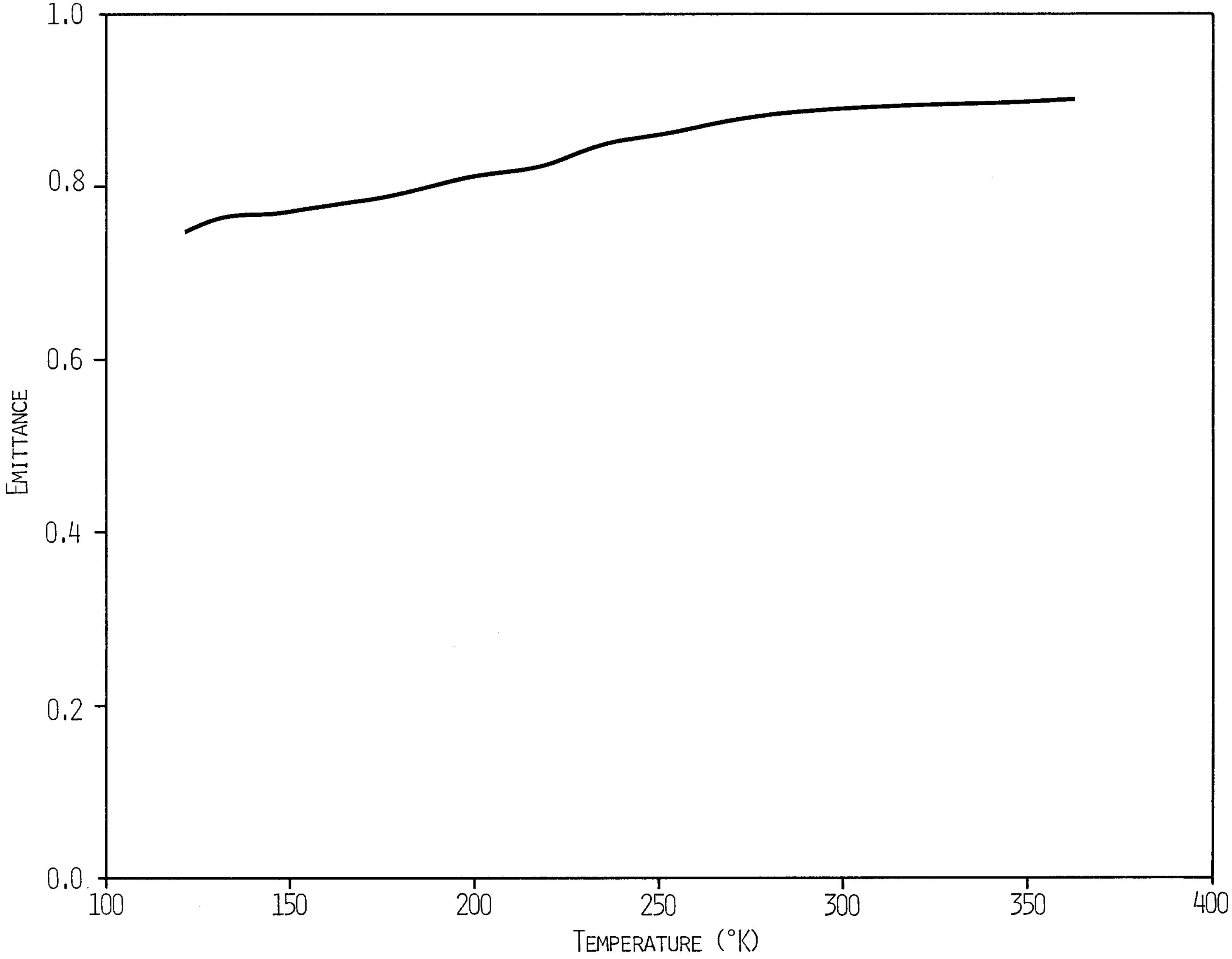

Figure 5. TW-1300 Emittance vs. Temperature