

DURABILITY OF SOLAR SELECTIVE COATINGS IN A SIMULATED SPACE ENVIRONMENT

Donald A. Jaworske
NASA Glenn Research Center
Cleveland, OH 44135

ABSTRACT

Solar selective coatings are being considered for heat engine and thermal switching applications on minisatellites. Such coatings must have the combined properties of high solar absorptance and low infrared emittance. High solar absorptance is needed to collect solar energy as efficiently as possible while low infrared emittance is needed to minimize radiant energy loss at operating temperature. These properties are achieved in sputter deposited thin films through the use of molecular mixtures of metal and dielectric. Solar selective coatings having a solar absorptance to infrared emittance ratio of 9 have been successfully deposited using a mixture of nickel and aluminum oxide. The space environment, however, presents some challenges for the use of materials on the exterior of spacecraft, including durability to atomic oxygen and vacuum ultraviolet radiation. To address these concerns, several candidate solar selective coatings were exposed to atomic oxygen in a plasma asher and to ultraviolet radiation in a vacuum facility equipped with calibrated deuterium lamps. The optical properties of the coatings were monitored as a function of time to evaluate their performance over long term exposure to the simulated space environment. Several coatings were found to be durable to both the atomic oxygen and the vacuum ultraviolet environments.

KEY WORDS: Solar Selective Coatings, Solar Absorbers

1. INTRODUCTION

Minisatellites designed for use in high radiation threat orbits will require robust space

This paper is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

This is a preprint or reprint of a paper intended for presentation at a conference. Because changes may be made before formal publication, this is made available with the understanding that it will not be cited or reproduced without the permission of the author.

power systems to achieve mission objectives. One vision for such a robust system is a heat engine powered by thermal energy captured by a small solar collector. To accomplish this, the captured solar energy must be successfully absorbed by the heat engine. A properly chosen solar selective coating applied to the heat input surface of the engine, located at the focus of the solar collector as shown in Figure 1, should provide a means to achieve this goal.

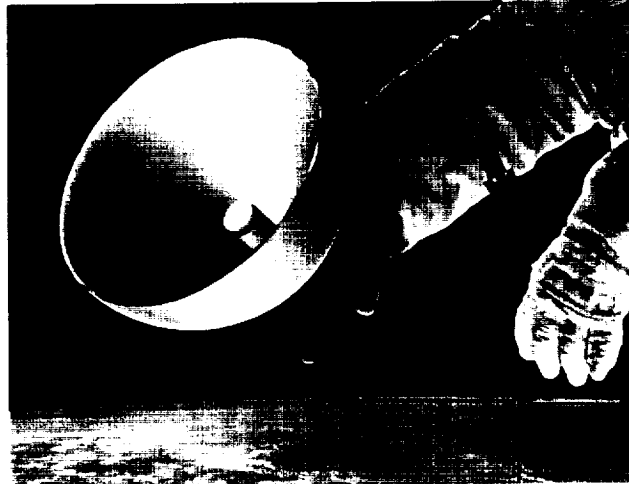


Figure 1. Artist's concept of a heat engine powered by solar energy.

Molecular mixtures of metal and ceramic have been shown to yield solar selective coatings that have the combined optical properties of high solar absorptance, and low infrared emittance. The ratio of solar absorptance, α , and infrared emittance, ϵ , serves as the figure of merit for solar selective coatings. Solar selective coatings manufactured from aluminum and aluminum oxide have been shown to have an α/ϵ ratio of 6 (1). Other coatings manufactured from molybdenum and aluminum oxide have been shown to have an α/ϵ ratio of 7.7 (2). Coatings of tungsten and aluminum nitride developed for terrestrial applications have been shown to have an α/ϵ ratio as high as 27(3). Additional high temperature coatings are currently under development.

Although much work has been done to identify molecular mixture combinations, additional research is needed to identify the durability of candidate solar selective coatings to the threats imposed by the space environment. Two such threats are atomic oxygen and vacuum ultraviolet radiation. The objective of this paper is to evaluate the durability of several candidate solar selective coatings in simulated atomic oxygen and vacuum ultraviolet radiation environments.

2. MATERIALS AND METHODS

Four samples were evaluated for their atomic oxygen durability and vacuum ultraviolet exposure durability. Two of the samples were prepared utilizing ion beam sputter

deposition. To accomplish this, custom made cylindrical targets consisting of metal and dielectric were made, such that a gradually changing composition of metal and dielectric could be deposited by rotating the cylinder under the beam during the sputter deposition process (1). Aluminum disks, 2.54 cm in diameter and diamond turned to a mirror finish, were used as the substrates to minimize infrared emittance. One target, installed in the ion beam sputter deposition facility, is shown in Figure 2. The rate of rotation under the beam during sputter deposition determines the change in metal and dielectric composition through the thickness of the as-deposited coating. The as-deposited coatings were typically metal rich at the substrate coating interface and dielectric rich at their surface. The metals used were either aluminum or nickel, and the dielectric used was aluminum oxide. One sample, consisting of tungsten and aluminum nitride was prepared by the University of Sydney using a proprietary process (3). The fourth sample was a diamond turned aluminum substrate with no coating at all.

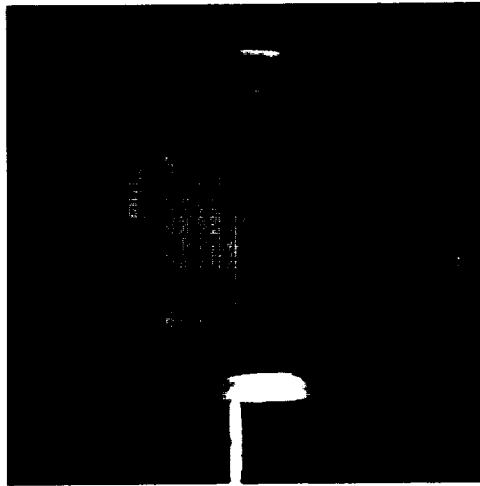


Figure 2. Cylindrical target used for ion beam sputter deposition.

The cylindrical target used during sputter deposition allows for an infinite number of variations in metal and dielectric combinations through the thickness of the cermet coating. For the aluminum/aluminum oxide sample, equal sputter deposition time was spent on eleven discrete positions around the cylindrical target, yielding a gradual linear transition from metal to oxide through the thickness of the cermet coating. For the nickel sample, less time was spent on the first few metal rich positions and extra time was spent on the last few oxide rich positions yielding a non linear transition from metal to oxide through the thickness of the coating.

The solar absorptance of each sample was evaluated utilizing a Perkin-Elmer Lambda-19 spectrometer equipped with a 15 cm diameter integrating sphere. Total reflectance was obtained for each sample in the wavelength range of 250 to 2500 nanometers. The reflectance value at each wavelength was subtracted from unity to yield absorptance at that wavelength and the absorptance values were weighted with respect to the air mass zero solar spectrum to yield solar absorptance, α . With this approach, it should be noted that solar absorptance is temperature independent. The infrared emittance of each sample

was evaluated utilizing a Surface Optics Corporation SOC-400t portable infrared reflectometer. Infrared reflectance was obtained for each sample in the wavelength range of 2 to 25 micrometers. The reflectance value at each wavelength was subtracted from unity to yield emittance at that wavelength and the emittance values were weighted with respect to two black body spectra, one at 25°C and one at 450°C, to yield the infrared emittance, ϵ , at that temperature. Although emittance at both temperatures is reported, values at 450°C are more representative of the envisioned heat engine application. With this approach, it should be noted that infrared emittance is temperature dependent.

Atomic oxygen exposure was obtained utilizing a Plasma Prep II RF plasma asher operating on air. Samples were placed on a glass shelf in the plasma asher, along with a 2.54 cm diameter Kapton H[®] polyimide disk purposely dehydrated under vacuum and weighed just prior to atomic oxygen exposure. Samples were removed periodically for optical properties evaluation, and were returned to the plasma asher to continue cumulative exposure. Kapton H[®] mass measurements after each atomic oxygen exposure were used to calculate atomic oxygen effective fluence. A freshly weighed Kapton H[®] disk was added, as needed, to achieve the desired cumulative atomic oxygen exposure.

Vacuum ultraviolet exposure was obtained utilizing a cryo-pumped vacuum chamber equipped with a calibrated deuterium lamp (4). The chamber computer monitored lamp output as a function of time, making small changes in the distance between lamp and sample to allow for near uniform illumination of the samples as a function of time. The vacuum ultraviolet intensity from the lamp was estimated to be approximately 1.5 times that of the sun just outside the Earth's atmosphere. Samples were removed periodically for optical properties evaluation, and were returned to the chamber to continue cumulative exposure.

Solar absorptance and infrared emittance data were plotted as a function of cumulative atomic oxygen or vacuum ultraviolet exposure, to display any changes in the optical properties as a consequence of simulated space environment exposure.

3. RESULTS AND DISCUSSION

The initial optical properties of the four samples exposed to atomic oxygen attack are summarized in Table 1. Of the four samples, the tungsten/aluminum nitride sample had the highest α value alone, however, the nickel/aluminum oxide sample had the highest α/ϵ ratio.

The effective cumulative atomic oxygen fluence was found to be 7.54×10^{21} atoms/cm², based on the as-measured Kapton H[®] mass loss. Figures 3-6 summarize the durability of the optical properties of the four samples as a function of effective fluence. The aluminum/aluminum oxide combination actually exhibited an increase in α as a function of atomic oxygen exposure, changing from 0.890 initially to a value of 0.932 at the conclusion of atomic oxygen exposure. The nickel/aluminum oxide combination also

Table 1. Summary of optical properties prior to atomic oxygen exposure.

Sample	α	ϵ 25°C	ϵ 450°C	α/ϵ 25°C	α/ϵ 450°C	Thickness
Aluminum/Aluminum Oxide	0.890	0.178	0.284	5	3	283 Nanometers
Nickel/Aluminum Oxide	0.894	0.104	0.203	9	4	178 Nanometers
Tungsten/Aluminum Nitride	0.934	0.119	0.225	8	4	Not Available
Bare Aluminum, Diamond Turned to a Mirror Finish	0.106	0.030	0.031	4	3	Not Applicable

exhibited an increase in α , changing from 0.894 initially to a value of 0.947. The α of the tungsten/aluminum nitride combination declined slightly, from 0.934 to 0.925. The bare aluminum sample used as a “blank” changed slightly, from 0.106 to 0.155. The ϵ of all samples was found to remain essentially constant as a function of atomic oxygen exposure.

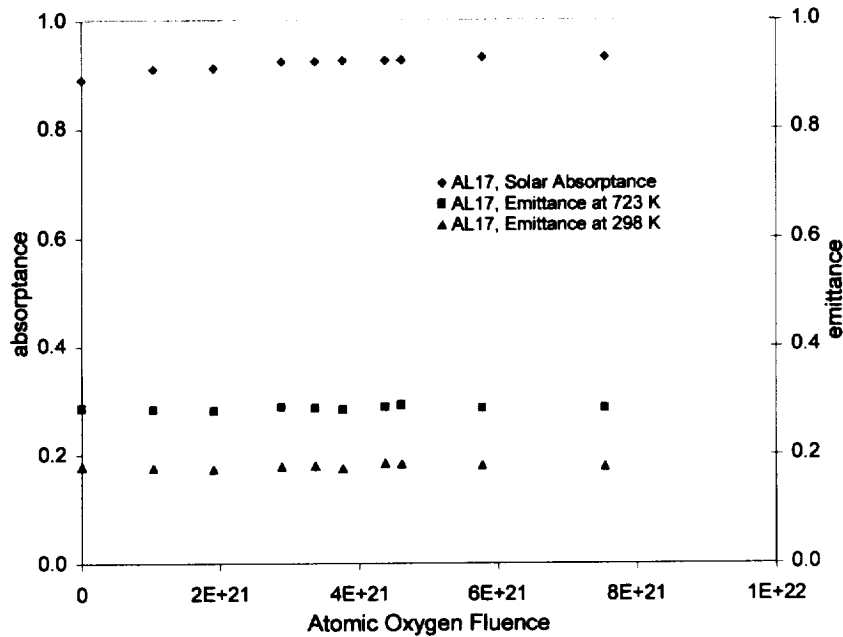


Figure 3. Solar absorptance, α , and infrared emittance, ϵ , of a cermet coating composed of aluminum and aluminum oxide, as a function of effective atomic oxygen fluence.

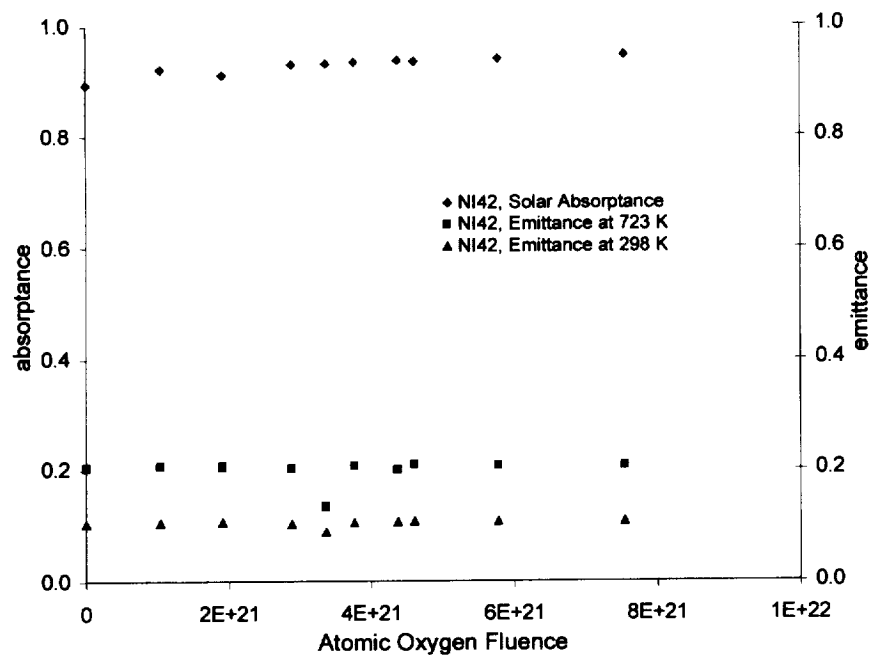


Figure 4. Solar absorptance, α , and infrared emittance, ϵ , of a cermet coating composed of nickel and aluminum oxide, as a function of effective atomic oxygen fluence.

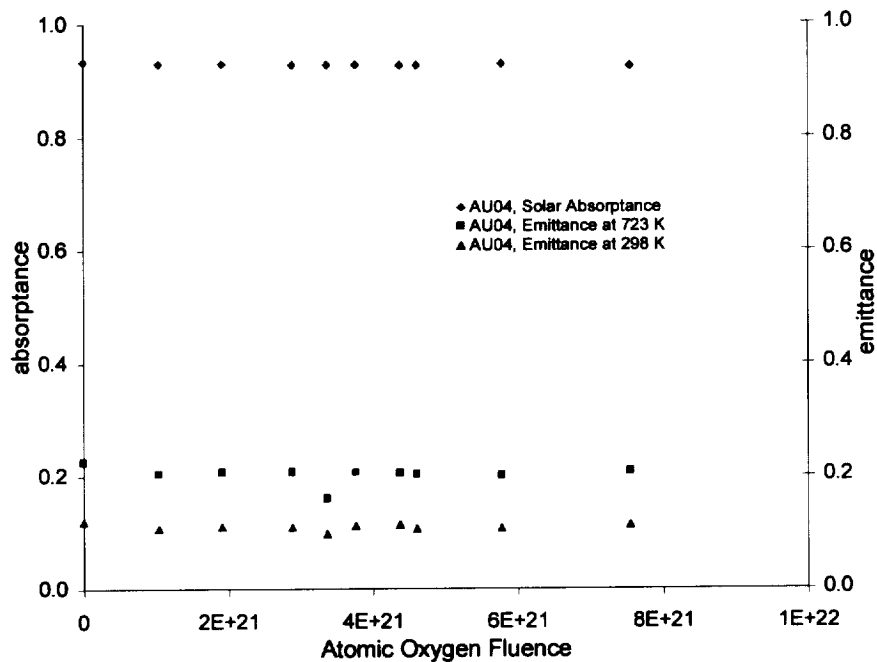


Figure 5. Solar absorptance, α , and infrared emittance, ϵ , of a cermet coating composed of tungsten and aluminum nitride, as a function of effective atomic oxygen fluence.

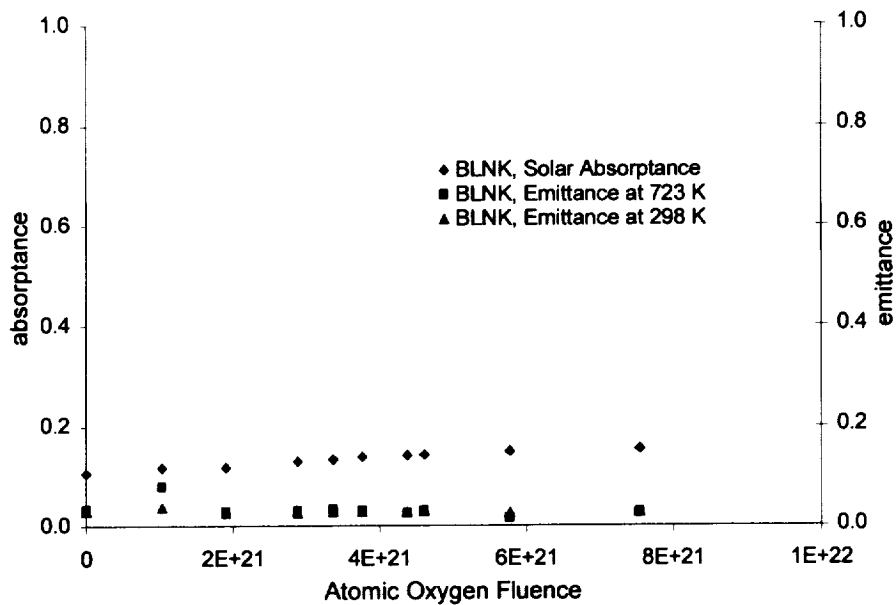


Figure 6. Solar absorptance, α , and infrared emittance, ϵ , of a bare aluminum substrate diamond turned to a mirror finish, as a function of effective atomic oxygen fluence.

The initial optical properties of the four samples exposed to vacuum ultraviolet radiation are summarized in Table 2. Of the four samples, the tungsten/aluminum nitride sample had the highest α value alone. Again, the nickel/aluminum oxide sample had the highest α/ϵ ratio.

Table 2. Summary of optical properties prior to vacuum ultraviolet exposure.

Sample	α	ϵ 25°C	ϵ 450°C	α/ϵ 25°C	α/ϵ 450°C	Thickness
Aluminum/Aluminum Oxide	0.901	0.175	0.277	5	3	271 Nanometers
Nickel/Aluminum Oxide	0.899	0.095	0.194	9	5	178 Nanometers
Tungsten/Aluminum Nitride	0.936	0.104	0.205	9	5	Not Available
Bare Aluminum, Diamond Turned to a Mirror Finish	0.121	0.025	0.015	5	8	Not Applicable

The cumulative dose of vacuum ultraviolet radiation exposure in the facility was found to be 381 hours, based on the as-measured lamp exposure time recorded by the computer monitoring vacuum ultraviolet exposure. Figures 7-10 summarize the durability of the optical properties of the four coatings as a function of vacuum ultraviolet radiation exposure. Much like the samples exposed to atomic oxygen, some of the vacuum ultraviolet exposed samples also showed improvements in optical properties. The aluminum/aluminum oxide combination had an increase in α , changing from 0.901 initially to a value of 0.919. The nickel/aluminum oxide combination also had an

increase in α , changing from 0.899 initially to a value of 0.910. The α of the tungsten/aluminum nitride combination declined slightly, from 0.936 to 0.928, and the α of the bare aluminum sample changed from 0.121 to 0.159. Again, the ϵ remained essentially constant as a function of vacuum ultraviolet exposure.

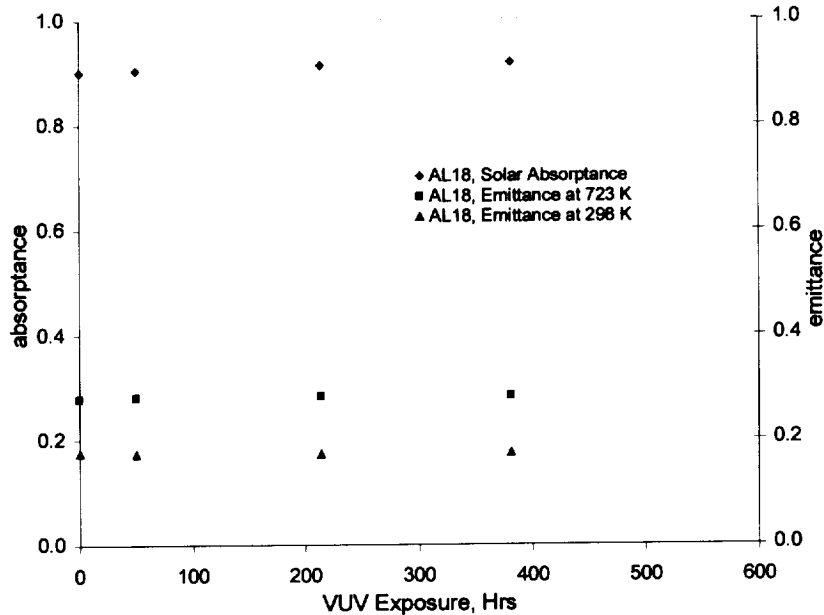


Figure 7. Solar absorptance, α , and infrared emittance, ϵ , of a cermet coating composed of aluminum and aluminum oxide, as a function of vacuum ultraviolet exposure.

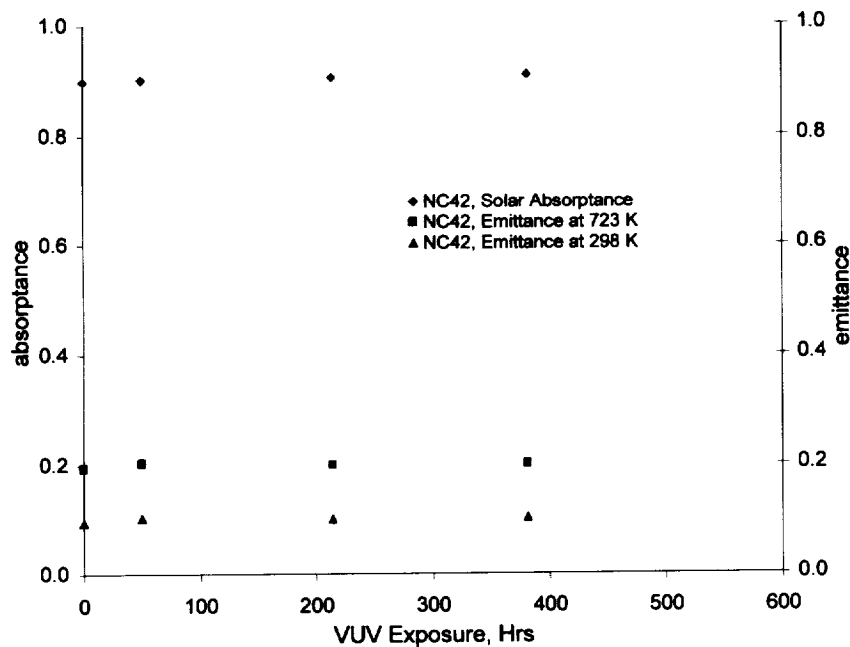


Figure 8. Solar absorptance, α , and infrared emittance, ϵ , of a cermet coating composed of nickel and aluminum oxide, as a function of vacuum ultraviolet exposure.

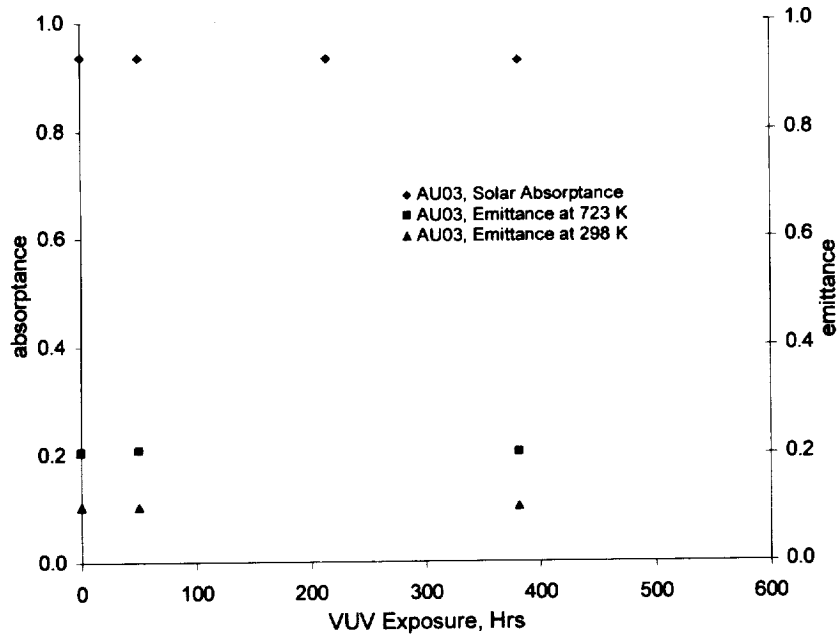


Figure 9. Solar absorptance, α , and infrared emittance, ϵ , of a cermet coating composed of tungsten and aluminum nitride, as a function of vacuum ultraviolet exposure.

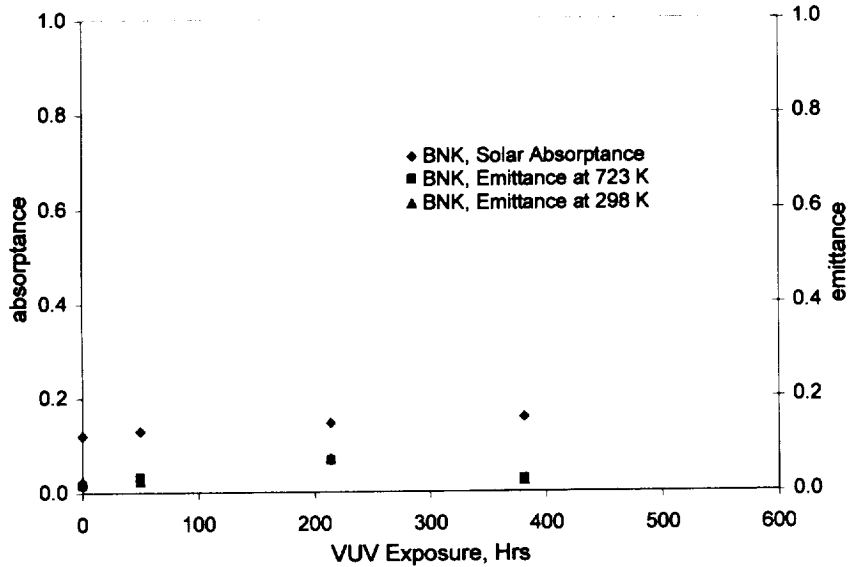


Figure 10. Solar absorptance, α , and infrared emittance, ϵ , of a bare aluminum substrate diamond turned to a mirror finish, as a function of vacuum ultraviolet exposure.

It is interesting that both atomic oxygen exposure and vacuum ultraviolet exposure lead to similar improvements in the α/ϵ ratio, for three out of four samples. The plasma asher environment is known to generate a vacuum ultraviolet component that is similar to the vacuum ultraviolet exposure facility. Perhaps atomic oxygen exposure purposely in the absence of a vacuum ultraviolet component would lead to slightly different observations.

Future work will encompass exposure to elevated temperatures, in an effort to identify candidate coating durability to likely end use temperatures. Although the current vision is to utilize sunlight concentrated by a factor of approximately 100 to yield a temperature in the vicinity of 450°C, the durability of candidate solar selective coatings may be evaluated at slightly higher temperatures to allow for accelerated testing of the material.

4. CONCLUSIONS

Several solar selective coatings having optical properties that are attractive for use in future space power applications were evaluated for their durability to two harsh environments: atomic oxygen and vacuum ultraviolet radiation. Of the three solar selective coating samples evaluated in both facilities, the aluminum/aluminum oxide and nickel/aluminum oxide cermets exhibited darkening upon atomic oxygen or vacuum ultraviolet exposure while the tungsten/aluminum nitride cermet exhibited a slight decrease in solar absorptance. All three samples had essentially no change in infrared emittance. Additional work is needed to identify the durability of these candidate coatings to elevated temperatures.

5. ACKNOWLEDGEMENTS

The author gratefully acknowledges Joyce A. Dever, NASA Glenn Research Center, for her help and guidance in the exposure of the samples to vacuum ultraviolet radiation, Qi-Chu Zhang, University of Sydney, New South Wales, Australia, for kindly providing the tungsten/aluminum nitride samples, and Terry Condrich, InDyne, Inc., for providing the artist's concept of the solar powered heat engine.

6. REFERENCES

1. D. A. Jaworske and J. Hornacek, 33rd International SAMPE Technical Conference, Seattle, WA, pp. 1573-1580 (2001).
2. R. E. Hahn and B. O. Seraphin in G. Hass and M. H. Francombe, eds, *Physics of Thin Films, Volume 10*, Academic Press, New York, 1978, pp. 55-57.
3. Qi-Chu Zhang, et al., *J. Vac. Sci. Tech. A*, 17(5), pp. 2885-2890 (Sept./Oct. 1999).
4. J. A. Dever, A. J. Pietromica, T. J. Stueber, E. A. Sechkar, and R. K. Messer, "Simulated Space Vacuum Ultraviolet (VUV) Exposure Testing for Polymer Films," AIAA Paper No. 2001-1054, American Institute of Aeronautics and Astronautics, January 2001.