Iranian Journal of Chemical Engineering
Vol. 6, No. 2 (Spring), 2009, IAChE

Comparative Study on Space Qualified Paints Used for Thermal Control of a Small Satellite

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Abstract

A satellite with a passive thermal control system mainly uses thermal coatings and paints to maintain temperatures within safe operating limits. Satellite coatings, exposed to harsh space environments such as ultraviolet (UV) radiation and atomic oxygen (AO), undergo physical damage and thermal degradation, which must be considered by the satellite thermal designer for design optimization and cost reduction. In this paper, we have briefly reviewed the effects of space environment effects on degradation of satellite coatings. To study the consequences of paints degradation on the thermal performance of satellites with passive thermal control, a small cubical satellite in Low Earth Orbit (LEO) has been considered. The satellite's bottom surface faces the Earth, and the top surface faces deep space. The satellite's lateral sides are covered with solar panels, and the top surface, which acts as the satellite radiator, is covered with white paint. The satellite orbit is sun-synchronous with an inclination angle of 99º. Three radiator coatings (Chemglaze A276 and SG121FD white paints, and AZW-11LA ceramic white coating) have been used in turn, and the satellite has been thermally analyzed for each case. In these analyses, beginning-of-life and end-of-life optical properties have been used to predict the satellite temperatures, before and after degradation of the coatings. The analyses results show the importance of stability of optical properties of the thermal coatings for the long-term thermal control of satellites. On considering the rate of thermal performance degradation, lower production cost, and ease of application on satellite surfaces, SG121FD white paint is recommended as a suitable satellite radiator paint for use in satellite thermal control applications, with the same design requirements, mission life and orbital parameters as the satellite considered in this study.

Keywords: *Thermal control, Radiator, Degradation, Atomic oxygen, Ultraviolet radiation*

1. Introduction

An orbiting satellite is exposed to varying amounts and forms of thermal energy, namely solar radiation, albedo (solar radiation reflected off the earth surface), earth-emitted infrared (IR) rays, and the heat generated by onboard equipment. In addition, the satellite experiences extreme shifts in

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temperatures, as it repeatedly passes through day and night, a scenario referred to as "thermal cycling". A satellite in *low-earth orbit* (LEO), for example, must survive temperature swings from -80 to +80 ^{o}C, approximately every 90 minutes. This happens not once, but thousands of times during its operational lifetime, all while continuing to perform its mission [1]. Hence, a well-designed and properly operating thermal control system is essential to ensure optimum performance when satellite equipment is operating, and avoid damage when not in use.

The energy absorbed by a satellite depends on the thermal characteristics and area of its external surfaces, its orientation with respect to the source of thermal radiation, and the characteristics of the thermal radiation source. Since satellite coatings and surfaces are spectrally responsive to the radiation source, the spectral distribution of the energy source becomes particularly important in the design of a satellite thermal control system (see Fig. 1).

Passive and active methods are used for thermal control of satellites. A passive thermal control system mainly uses coatings and paints (black & white), multilayer insulation (MLI) and radiators to achieve the required control action. Active thermal control systems by comparison, use heaters and mechanical refrigerators for their operations. The passive thermal control method is used when simplicity, cost and reliability are the key design factors [2].

Paints are passive thermal control hardware, used to alter optical properties of satellite surfaces such as radiators and electronic boxes, as required by the thermal design. The optical properties of paints, namely solar absorptance (α_s) and emittance (ε), are fixed at the time of application, and are functions of the raw materials used and the processing techniques employed in applying them to the space hardware [1].

The satellite radiator presents the interface of the satellite with the outer space, and radiatively couples it to the space environment. To maximize heat rejection and limit heat absorption from the surroundings, most satellite radiators are coated with white paints of low (α_s/ε) ratios, or combinations of black and white paints in various proportions, to provide different shades of gray with high emittance and a range of solar absorptance values [3]. However, in order to select suitable thermal paints and coatings for satellite radiators, it is necessary to understand the effects of space environment on the performance of such thermal hardware.

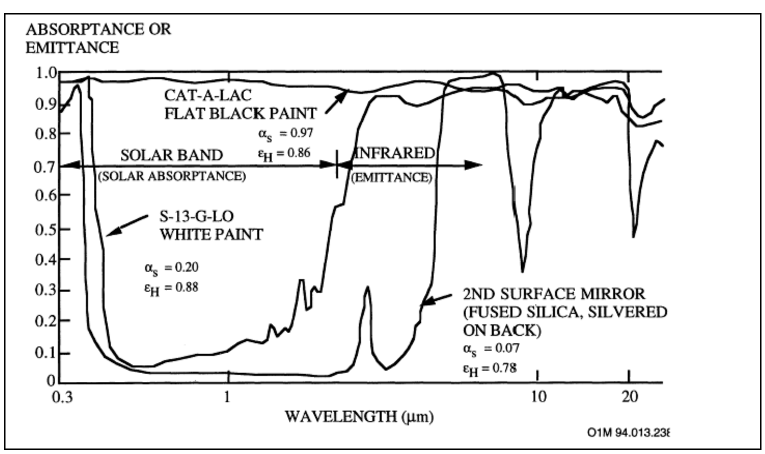

Figure 1. Spectral absorptance/emittance of several materials and coatings [2]

The primary change that occurs to paints in service is degradation of physical and optical properties due to the harsh space environment. This degradation varies as function of time and the satellite orbit [2]. This is not desirable, because satellite radiators must be sized to account for the substantial increase in absorbed solar energy due to degradation over the mission life. These radiators, which are oversized to handle the high solar loads at the *end-of-life* (EOL), cause the satellite to run much cooler in the early years of its mission, sometimes requiring heaters to avoid under-temperatures of electronic components. For example**,** changing the solar absorptance from 0.2 to 0.4 over the life of a satellite increases the needed radiator area from 35 m^2 to 56 m^2 for a 10 KW satellite [4]. However, emittance (ε) of the white coating does not change much during the satellite life (remaining almost constant). Therefore, satellite thermal designers must account for the *end-of-life* properties by overdesigning components such as radiators. However, increased area translates into extra weight. The degradation also affects the number, sizes and positions of the satellite radiators for any particular satellite application [5].

Various thermal control paints are used for satellite applications, including polyurethanes, silicones, and silicates. Polyurethanes tend to be cheaper, but suffer from greater degradation due to the space environment. The silicates are more stable, but are also more expensive, more brittle, and harder to apply [3]. Paints are very susceptible to physical damage and thermal degradation caused by exposure to the harsh ultraviolet (UV) radiation, atomic oxygen (AO), and outgassing due to outer space high vacuum level. Reference [3] presents a thorough study on the space environmental effects on materials used in *Low Earth Orbits (LEO).*

Change in the solar absorptance of thermal control paints goes from the initial values of 0.15 -0.20 to final values in the vicinity of 0.4, after five to seven years of service [1]. However, the satellite thermal control is designed to provide full protection to the satellite for the entirety of its service life. Therefore, satellite designers must account for the extent to which the protective capabilities of the thermal control paints degrade over that time, and size the thermal control system based on the predicted properties at the *end-of-life*. This means that for long in-service life, the satellite thermal control system must be designed for the higher absorptance values in excess of 0.4, resulting in a thermal control design, which is large, heavy and expensive to build.

The high intensity UV radiation of the space can damage organic chemical bonds. In addition, UV radiation can lead to dislocations in polymeric materials and ceramics (e.g. glasses), which change the solar absorptance of materials. Ultraviolet radiation is particularly damaging to white paints used on the external surfaces of satellites. UV radiation causes significant increase in the solar absorptance of white paints, while it decreases the absorptance of black paints due to bleaching effects [3].

Atomic oxygen is produced in the upper atmosphere when UV radiation from the sun is absorbed by oxygen molecules, and causes them to dissociate into negatively charged ions. Atomic oxygen is prevalent in orbits between 100 and 650 kilometers. The atmospheric density at these altitudes depends highly on both orbit and solar activity. While the density is small, the ionic flux encountered is high given the satellite's velocity of orbit. For 250 km to 300 km orbits, a density of 10^9 atoms/cm^3 yields a flux of $8*10^{14}$ atoms/cm^2s [1]. The high velocity of orbit also gives AO roughly 5 electron volts (eV) impact energy per ion [4]. The carbon bonds of many organic materials are susceptible to impact energies of this magnitude.

Atomic oxygen erosion of the paint binder results in a fragmented surface, which could cause particulate contamination to other areas of the satellite. It also causes the emittance to increase gradually while the absorptance decreases gradually [3]. The degree of surface degradation is directly proportional to AO fluence (total integrated flux), which in turn is determined by several factors, including satellite orbit altitude, orbital inclination, mission duration, and solar activity [6].

Although the near-Earth space environment, namely AO and UV, can have extremely damaging effects on materials, more detrimental to the satellite are the synergistic effects that arise when a material is exposed to these factors simultaneously. The thermal designer or material developer should keep this in mind, because these synergistic effects can reduce satellite performance much faster than predicted. For example, optical properties (solar absorptance and thermal emittance) may change due to AO bleaching or UV radiation darkening, polymeric films may peel due to thermal cycling, which in turn opens new surfaces that can be attacked by AO or AO + UV, and finally the electrical conductivity of a material may be affected by AO, resulting in spacecraft charging [3].

The extreme conditions in the space environment and the high cost associated with placing satellites in orbit require that satellites be thoroughly tested prior to deployment in their respective orbits. Every satellite program must address the effect of the space environment on their hardware. Additionally, all new materials must be space flight qualified prior to use. Ground-based testing [7, 8] offers the flexibility to study multiple materials in simulated space environmental conditions without the extreme cost and limited availability of space flight testing.

Reference [1] presents research work on the improvement of performance of passive thermal control coatings through weight reduction, improved *end-of-life* properties, and formulation changes of existing material combinations. Extensive work is being done to reduce film thickness and lower the specific gravity (i.e., density) of coatings. Researchers are also working to improve *end-of-life* solar reflectance properties by using materials with lower overall solar absorptance, and good resistance to degradation when exposed to the space environment. Improvements in *end-of-life* properties will lead to additional satellite weight reductions, mainly due to the smaller thermal radiator surface area required for a given heat duty.

In this paper effects of degradation of coatings on the thermal control of a satellite with passive thermal control have been studied through the comparison of thermal performance of some space qualified thermal paints and coatings, having different *beginning-of-life* and *end-of-life* optical properties. The satellite considered is a small cubical satellite in Low Earth Orbit (LEO). The top surface of the satellite, which acts as the satellite radiator, is covered with white coating. Three radiator coatings (Chemglaze A276 and SG121FD white paints, and AZW-11LA ceramic white coating) have been used in turn, and the satellite has been thermally analyzed to predict its temperatures, before and after degradation of the radiator thermal coatings.

2. Systems of thermal coatings considered in this study

Thermo-optical properties and the effects of space environment on degradation of the coatings under study are presented in Tables 1 through 3. The Chemglaze A276 white paint (Table 1) is a polyurethane paint, used on many short-term space missions. It is formulated for space applications requiring high reflectivity and low outgassing, and provides excellent gloss and color retention. A276 is known to degrade moderately under long term UV exposure and to be susceptible to Atomic Oxygen (AO) erosion [3]. SG121FD white paint (Table 2) provides excellent thermo-optical properties and high resistance to space adverse environment (AO, UV and charged particles such as electrons and protons), and can withstand very low temperatures (-170°C) [9]. AZW-11LA (Table 3) is a white ceramic coating, which incorporates a stabilized pigment system with a silicate binder. This coating is suitable for use in the harshness of the space environment, because it has a low rate of degradation [10].

Table 1. Thermo-optical properties and degradation effects for Chemglaze A276 white paint

Paint	Chemical Composition	Description	Solar Absorptance (α_s)	IR Emittance (ε)
Chemglaze A276 white paint	Pigment: • Titanium dioxide Binder: • Polyurethane	No degradation	0.28	0.88
		After 15000 hrs exposure to UV in LEO, With no atomic oxygen exposure	0.60	0.88
		After 15000 hrs exposure to UV in LEO, with atomic oxygen exposure	0.35	0.88

Table 2. Thermo-optical properties and degradation effects for SG121FD white paint

Paint	Chemical Composition	Description	Solar Absorptance (α_s) or Solar Absorptance Increase ($\Delta\alpha_s$)	IR Emittance (ε)
SG121FD white paint	Pigment: • Encapsulated zinc oxide Binder: • Silicon Solvent: • Aromatic and aliphatic	No degradation	0.20 ±0.04	0.88±0.03
		Variations of solar absorptance due to the effect of UV alone	$\Delta\alpha_s$ = + 0.01 for 1000 esh	-
		Variations of solar absorptance due to the combined effect of UV, electrons and protons (1 year operation in GEO orbit)	$\Delta\alpha_s$ = + 0.09	-

Table 3. Thermo-optical properties and degradation effects for AZW-11LA ceramic white coating

Paint	Chemical Composition	Description	Solar Absorptance (α_s) or Solar Absorptance Increase ($\Delta\alpha_s$)	IR Emittance (ε)
AZW-11LA ceramic white paint	Pigment: • Stabilized pigment system Binder: • Silicate	No degradation	0.08 ±0.02 (for thickness > 10 mils)	0.91 ± 0.02
		Variations of solar absorptance due to the combined effect of UV and atomic oxygen exposure (NASA Experiments)	$\Delta\alpha_s$ = 4% for 7.4*10^{20} atomic oxygen exposure and 832 hours UV exposure	$\Delta\varepsilon$ = 1%
		Variations of solar absorptance after 9 months exposure to space environment (on Optical Properties Monitor (OPM))	$\Delta\alpha_s$ = + 0.02	-

3. The satellite modeling

To study the consequences of degradation, a satellite with passive thermal control has been modelled and analyzed. The satellite model considered is cubic in shape, in which the bottom surface faces the Earth, and the top surface faces deep space. The satellite's lateral sides are covered with solar panels, and the top surface, which acts as the satellite radiator, is covered with white thermal coatings. The main internal units of the satellite include an electronic box (E-Box), two telemetry units (UHF, VHF), and two battery packs. The satellite is positioned in an orbit of circular sun-synchronous near polar type. Fig. 2 shows the satellite model considered for analyses, and the satellite when positioned in its nominal orbit.

The modeling process begins with construction of a geometrical mathematical model (GMM) (shown in Fig. 3). Thermal Desktop software has been used for this purpose. The GMM consists of sub-models such as E-Box, telemetry units, batteries, structural elements and the solar panels. In the next step a thermal mathematical model (TMM) has been constructed. The complete TMM consists of a network of thermal nodes, linear and radiation conductors between different units, and modeling of internal heat dissipations in the satellite.

Linear conductors transport heat in direct proportion to the difference in nodal temperatures: $Q_{1-2} = G(T_1 - T_2)$, where $Q_{1\text{-}2}$ is the heat flowing from node 1 to node 2 through a conductor of value G, T_1 is the current temperature of node 1 and T_2 is the current temperature of node 2. On the other hand, radiation conductors transport heat according to the difference in the fourth power of absolute temperature: $Q_{1-2} = G(T_1^4 - T_2^4)$.

More than 1000 thermal nodes of arithmetic and diffusion types have been considered in these analyses. The satellite radiator has been considered with a white coating, allowing it to have suitable thermal emission to the outer space through the radiative conductors. The internal surfaces have been considered black to facilitate radiative heat exchange between various surfaces and the internal satellite units.

Outputs from the GMM, including view factors of the satellite surfaces exposed to the space environment, and the environmental heat fluxes (Earth albedo, direct solar flux, and Earth emitted IR), have been used in the thermal mathematical model.

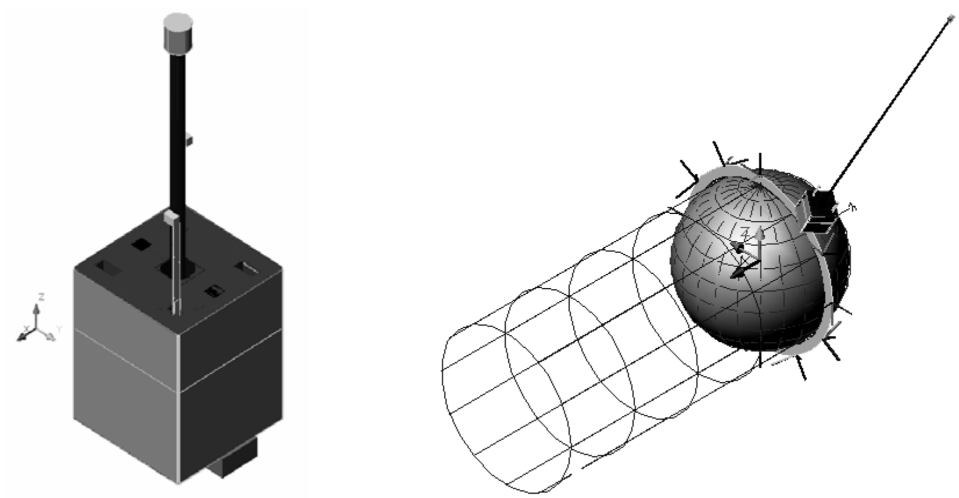

Figure 2. The satellite model under consideration (left), satellite in its nominal orbit (right) (colors are for demonstration only)

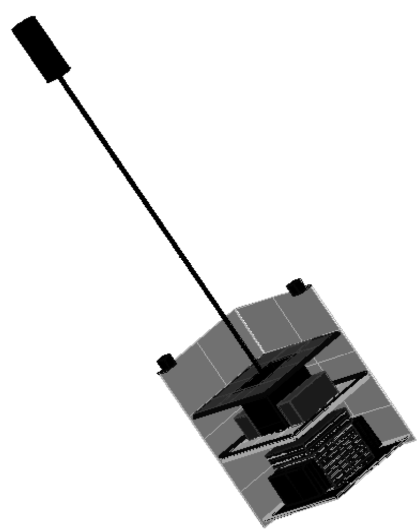

Figure 3. Geometrical mathematical model of the satellite (colors are for demonstration only)

The satellite system under consideration is transient, and hence, a transient thermal analysis, based on numerical implicit Forward-Backward method, has been used. A standard thermal software [11] has been used to determine the temperatures of various satellite surfaces and units. The heat balance for a diffusive thermal node is given as [11]:

$$\frac{2C_i}{\Delta t}\left(T_i^{n+1}-T_i^n\right) = 2Q_i + \sum_{j=1}^{N}\left[G_{ji}\left(T_j^n-T_i^n\right)+\hat{G}_{ji}\left\{\left(T_j^n\right)^4-\left(T_i^n\right)^4\right\}\right] + \sum_{j=1}^{N}\left[G_{ji}\left(T_j^{n+1}-T_i^{n+1}\right)+\hat{G}_{ji}\left\{\left(T_j^{n+1}\right)^4-\left(T_i^{n+1}\right)^4\right\}\right] \quad (1)$$

T_j Temperature of thermal node *j* at current time *t*

T_j^{n+1} Temperature of thermal node j at current time *t+Δt*

G_{ji} Linear conductor for connecting the diffusion thermal node *j* to thermal node *i*

$\hat{G}_{ji}$ Radiative conductor for connecting the diffusion thermal node *j* to thermal node *i*

C_i Heat capacitance of the diffusion thermal node *i*

Q_i Heat Source/Heat Sink for diffusion thermal node *i*.

4. Results and discussion

Fig. 4 presents the radiator temperatures, predicted *before* the degradation of the three radiator coatings (α_s and ε are BOL values). As the absorptance value for A276 white paint is higher than the other two coatings, and the absorptance value for AZW-11LA is the lowest among the three, the maximum radiator temperatures occur for A276 white paint, and the lowest temperatures are predicted for AZW-11LA white ceramic coating. Temperatures of the radiator coated with SG121FD white paint lie between the corresponding values for the other two coatings.

Fig. 5 presents the radiator temperatures, predicted *after* the degradation of the three radiator coatings (α_s and ε are EOL values). As shown, the temperature trends for the three coatings remain the same, however, the maximum temperature values are higher than the corresponding values in Fig. 4. The reason for this relative increase in temperature values is the increase in the absorptance values due to the thermal degradation of the three coatings. Out of the three coatings, A276 paint shows the maximum increase, because it undergoes the maximum degradation in comparison to the other coatings (see Tables 1 through 3). The SG121FD white paint comes second, while AZW-11LA white ceramic coating has the least degradation, and hence, the least increase in temperature of the radiator covered with this coating. However, due to the low absorptance of AZW-11LA white ceramic coating, compared to the other two white paints, the radiator temperatures for the cold orbital condition are lower than the corresponding temperatures for the other paints. As a result, the main satellite components in the vicinity of the radiator (e.g., battery) will experience lower temperatures, even needing heaters to heat them up during certain periods in orbit. This is not desirable, because it results in an increase in the satellite power budget. On the other hand, application of SG121FD white paint does not result in critical thermal situations in either cold or hot orbital cases, or any increase in satellite power budget, making it more suitable than AZW-11LA white ceramic coating for the case under consideration.

Fig. 6 presents the radiator temperatures, predicted *before* and *after* the degradation of A276 paint. As shown, the degradation has resulted in about 12 ºC increase in the radiator temperature, which is not desirable. Since the heat dissipation from internal satellite units and the environmental heat loads (solar, earth albedo and emitted IR) are reradiated to the space by the satellite radiator, any increase in the radiator temperature due to increased environmental heat loads, will result in reduced temperature gradient between the radiator and the dissipating units, and hence, reduced heat rejection capability. The consequence is a rise in temperatures of the dissipating units, which in some instances, even exceeds their safe operating temperatures. Therefore, it is advisable to keep the radiator temperature at a reasonably low temperature by using coatings with less thermal degradation.

The effect of degradation of A276 white paint on the satellite battery temperature is shown in Fig. 7. The maximum temperature of the satellite batteries, *before* and *after* the degradation of A276 paint, shows an increase of about 8.5 ºC. It is important to note that any increase in the operating temperature of the battery, which is a critical unit with tight temperature requirements, will result in reduced efficiency and reduction of the battery's useful life over the mission.

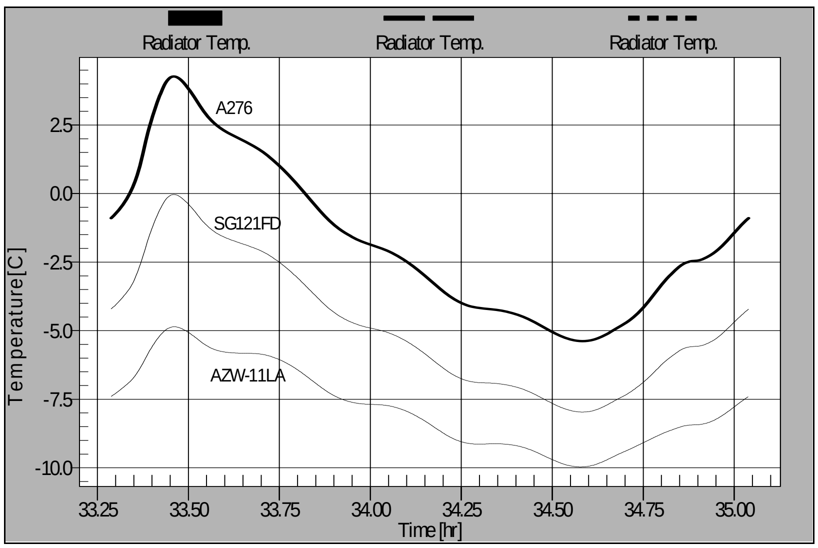

Figure 4: Temperatures of radiator coated with the three selected coatings (no degradation)

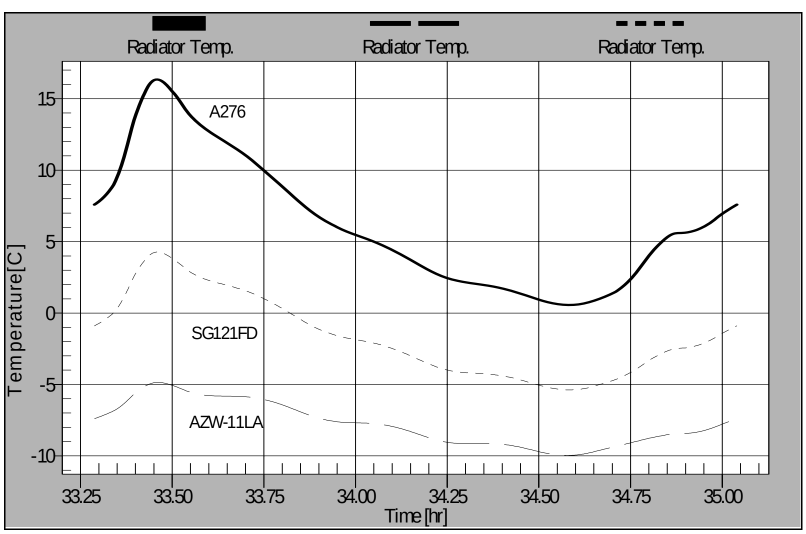

Figure 5. Temperatures of radiator coated with the three selected coatings (after degradation)

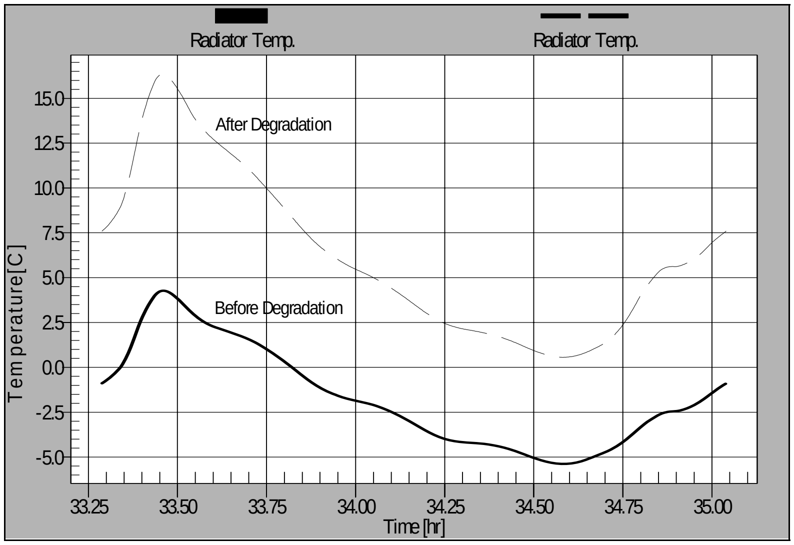

Figure 6. Radiator temperatures, before and after degradation of A276 white paint

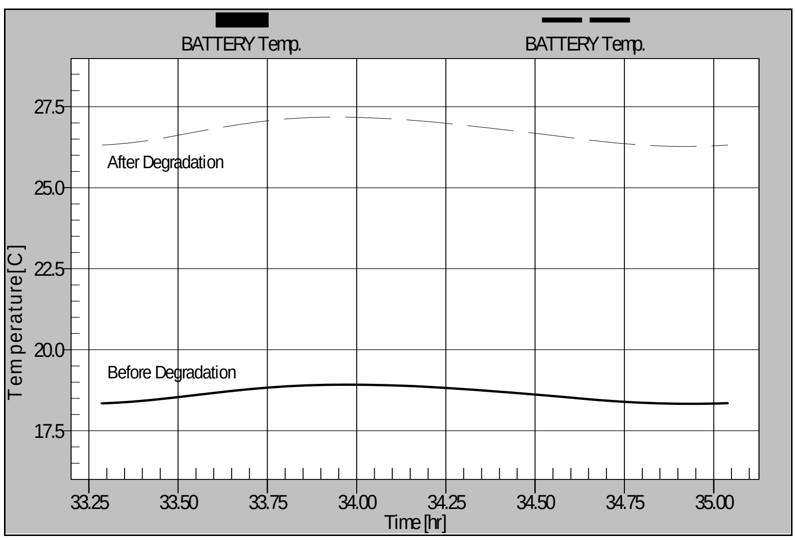

Figure 7. Effect of degradation of A276 white paint on the battery temperatures

Fig. 8 shows temperatures of the telemetry unit (UHF), predicted *after* the degradation of the three radiator coatings (α_s and ε are EOL values). The increase in temperature of the telemetry unit, due to the degradation of the three coatings, is clearly shown in this figure. Again, the maximum increase is predicted for A276 paint, which has the highest rate of degradation among the three coatings.

Temperatures of the electronic box (E-Box), predicted *after* the degradation of the three radiator coatings (α_s and ε are EOL values) is shown in Fig. 9. Here also, the coating with the highest rate of degradation (A276 white paint), produces the maximum increase in the satellite electronic box (E-Box) temperature.

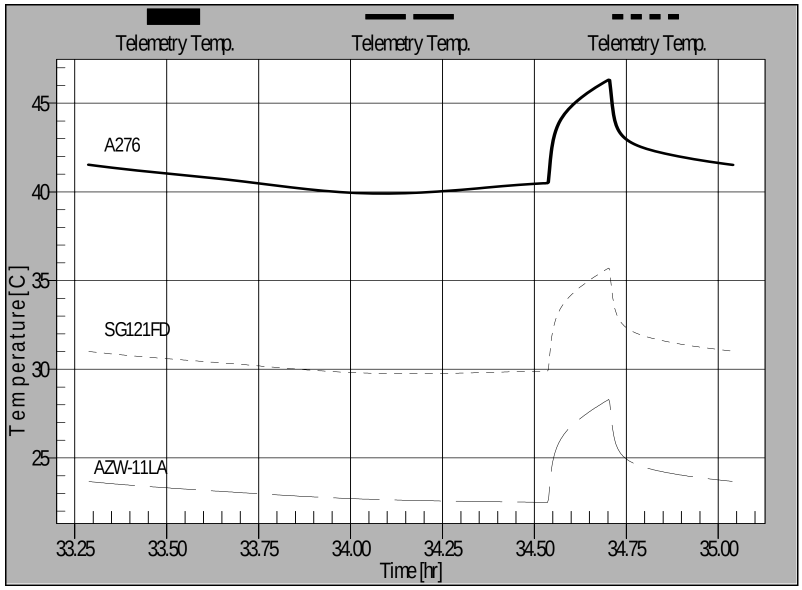

Figure 8. Effect of degradation of the three coatings on temperatures of telemetry unit

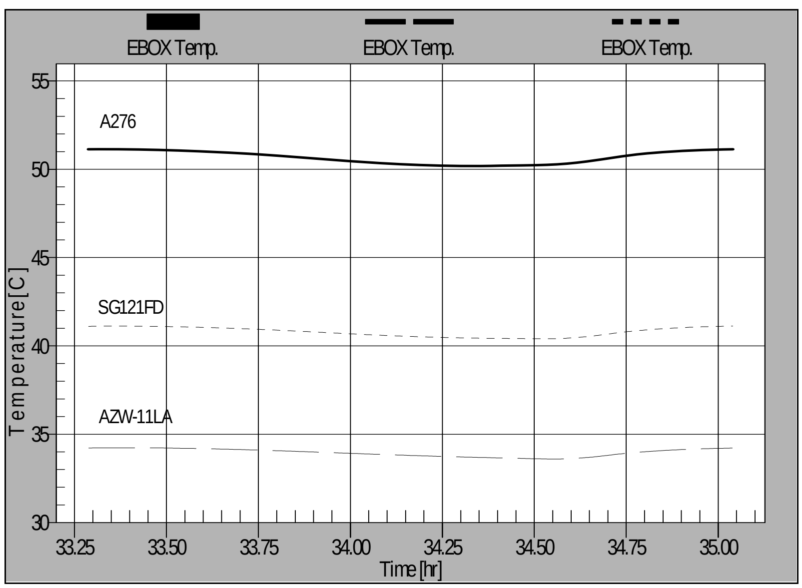

Figure 9. Effect of degradation of the three coatings on temperatures of the E-Box

4. Conclusions

Paints and other thermal coatings in satellites are influenced by adverse space environmental effects, namely atomic oxygen (AO) and ultraviolet (UV) radiation. These influences become more critical when the synergistic effects of AO and UV are taken into account. Consequently, thermal control paints and coatings degrade with time due to their extended exposure to environmental effects. This degradation, which directly affects the thermal control of sensitive satellite units, must be given due consideration when selecting thermal paints and coatings for any particular space application.

The three thermal control coatings analyzed in this paper show different behavior when exposed to environmental effects, resulting in different rates of degradation for each thermal coating. The analyses results for the case of a satellite with A276 white paint, which has the highest degradation rate (about 100%) and beginning of life absorptance value, show that the satellite radiator experiences a maximum increase in temperature of about 12 °C. This appreciable increase in the satellite radiator temperature suggests the need, at the design stage, for consideration of an appropriate margin for the beginning of life absorptance value (100% or more in certain instances), to account for the degradation of this paint at the end of the satellite mission. The results further show that the use of A276 white paint on satellites requiring precise thermal control on extended LEO missions should be avoided as far as possible. However, other factors such as low cost and ease of application, make this paint much more desirable for boosters and upper stage rockets that do not require long mission lifetimes.

The analyses results for SG121FD white paint, with a degradation rate of about 45%, show a maximum increase in the satellite radiator temperature of only about 4 °C. Further observation indicates that application of SG121FD white paint does not result in critical thermal conditions in either cold or hot orbital cases.

The results of analyses for AZW-11LA white ceramic coating, with the lowest degradation rate (about 25%) and beginning of life absorptance value, show negligible increase in the satellite radiator temperature. However, for the satellite under consideration, temperatures during the cold orbital conditions are lower than the allowable temperature limits for sensitive satellite units. This necessitates the use of heaters to warm up the the units to their safe operational temperatures during cold orbital conditions. From the point of view of satellite power consumption, this is not desirable because it increases the satellite power budget to compensate for the increased power usage in the heaters.

The two thermal coatings, SG121FD white paint and AZW-11LA white ceramic coating, with higher resistance to degradation due to space environmental effects, could be good candidates for use in missions lasting 3 years or more. However, considering the overall thermal performance degradation, lower production cost, and ease of application on satellite surfaces, SG121FD is recommended as a suitable satellite radiator paint candidate for use in satellite thermal control applications, having the same design requirements, mission life and orbital parameters as the satellite considered in this study.

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