STUDY OF INFRA RED REFLECTING COATINGS FOR MARINE APPLICATIONS

ABSTRACT

Solar energy is essential for human race. It spreads itself thin on the entire surface of the globe. The summer season in the Indian subcontinent lasts up to 08 months in a year. The peak summer results in temperatures in the range of 35-45 degrees Celsius causing illnesses, epidemics and even death. The solar radiations heat the exposed surfaces and increase temperatures of enclosed spaces such as residential buildings, commercial spaces, ships and structures at sea etc. More than 50% of the total surface area of the ships deployed at sea, is exposed to direct radiations from the sun. For a naval ship, ship sides, exposed decks and superstructures are continuously heated by Infra Red Solar Radiations both at sea and shore.

Consequently, the volumes enclosed by these exposed surfaces face a drastic increase in temperature due to thermal conduction through steel hull. This leads to a tremendous increase in heat load for the ship installed air conditioning system causing immense discomfort and hampering the efficiency of man and machinery. Published literature reveals that Infrared Reflective coatings which can reflect the Infra Red radiations from the sun and minimize the heat transfer to the substrate (steel), have been designed, formulated and developed. It is emphasized that a significant drop in temperatures (05-10ºC) from exterior to enclosed spaces and energy savings up to 30% can be achieved by application of such coatings.

While significant benefits have been demonstrated by such new formulations, a very clear understanding of the threat systems and the operational conditions of naval platforms is mandatory for exploitation. It is only with this understanding that optimum paint schemes can be designed. This paper studies the basics of solar spectrum and Infra-Red emissions and assesses the utility of Infrared Reflecting paint coatings for marine applications. The application and suitability of such coating system for naval platforms has also been discussed.

Introduction

1. According to the National Oceanic and Atmospheric Administration (NOAA), 2018 is on pace to be the fourth hottest year on record. Only three other years have been hotter: 2015, 2016 and 2017. Further, NOAA has revealed that the average global temperature has increased by about 0.8 ˚C over the past 100 years. This rise in average temperature will have far-reaching effects on the earth's climate patterns and

on all living things. In a series of heat wave calamities, Chicago was hit by an intense Heat Wave in 1995 (739 Deaths), European Heat Wave in 2003 caused as many as 30,000 Deaths and Moscow-Centered Heat Wave in 2010 lead to 10,000 Deaths. In 2016, the Indian subcontinent heat wave saw maximum temperatures surge to 51˚C and cause over 1600 deaths and countless casualties. This tremendous rise in temperatures and intense heat is proving fatal not just for humans but for animals, birds and endangered species too.[1]

2. India is currently the world's seventh largest consumer of energy and the sixth largest source of greenhouse gas (GHG) emissions and second in terms of annual GHG emissions growth. Due to increased requirements of energy and electricity, the emissions per capita have been projected to rise from the levels of 1.7 tons/capita in 2012 to 3.7 tons/capita in 2030 [2]. Consequent to rapid change in living pattern besides adverse climate changes and swift economic development, the energy use in buildings and installations is continuously rising and would be many folds in future. Hence, use of energy efficient technologies and energy conservation in buildings and installations is becoming one of the prime focuses for the designers and researchers. About 40% of global energy consumption is attributable to the building sector where a substantial portion of the global energy is used to maintain room temperature within the comfort range of 20–22˚C [3, 4]. With the rising anomalies in the weather conditions across Indian subcontinent, the energy requirements in buildings and installations for heating, air conditioning and ventilation (HVAC) is bound to rise sharply over the coming decades.

3. The Roof of a buildings and installations experience the maximum amount of radiations from the sun and in summers the roof-surface temperature may rise up to 65˚C [5]. Traditionally, white washing the roofs using lime and chalk is one common practice, and act to reduce heat gain from roofs, among other energy conservation strategies that are prevalent in India [6]. Such roofs that are designed to reduce the heat gain into the enclosed spaces because of the increased roof solar reflectance are called as cool roofs.

4. Most of the marine structures today, both fixed and floating, are made up of steel. Steel is an excellent conductor of heat and gets heated very rapidly. Steel has fairly low emissivity of about 0.2-0.32 which results in it cooling very slowly. In essence, steel hull of ships at sea exposed to solar radiation tends to absorb solar heat very quickly and radiates it out very slowly. This leads to heating of compartments of enormous volumes contained within the ship and consequent increased requirement of air conditioning and ventilation in the tropical waters. The severity of the problem increases many folds in case of passenger and naval ships which have larger exposed superstructures, shipside and deck areas enclosing huge volumes.

Figure 1– Ships at Sea Exposed to Solar Radiations

5. The concept of Infrared reflective or cool roof coatings in residential buildings for various climatic conditions revealed that increasing the roof reflectance reduces the cooling load by 18–93% and peak cooling demand in air-conditioned Building by 11–27% [7]. Akbari et al. {Lawrence Berkeley National Laboratory (LBNL), USA} in 2008 had estimated that permanently retrofitting urban roofs and pavements in the tropical and temperate regions of the world with solar-reflective materials would offset 44 billion tonnes of emitted CO_2, worth $1.1 trillion at $25/tonnes. Considering the benefits, Indian Green Building Council (IGBC) has mandated that roofs of buildings and offices be constructed using materials with high solar reflectivity [8]. There are several research laboratories throughout the globe which emphasize and experiment in this field of cool roof coating. Metallurgical Engineering and Material Science Department of IIT Bombay and Centre for IT in Building Science, IIIT Hyderabad, are two of the main labs working on cool roof coatings and related fields in India. Several white and dark coloured coating formulations for application on concrete as well as steel substrates have been developed by these laboratories.

6. A Paint Coating mainly comprises pigments, resins (binder), solvent and additives. The manner in which pigments and resins contribute to the spectral properties of paint coatings is of considerable importance in formulating coatings to control reflectance and radiation emission in desired spectral regions. Coatings may be required to: -

(a) Reduce excessive heating of equipment from absorption of solar radiation.

(b) Reduce detection by decreasing radiation in either the visible or infrared regions.

(c) Absorb the maximum amount of solar radiation and re-emit the minimum amount of thermal infrared radiation, e.g. solar heating systems.

(d) Transmit visible light while preventing the transmission of other infrared wavelengths, e.g. heat through architectural glass [9].

The Solar Spectrum

7. The sun's energy is generated in the thermonuclear reaction, the energy radiation to the surface of the earth is about 1.77×10^7 J/s. Figure 2 shows the solar radiation spectra for direct light at sea level. The visible region of the solar spectrum is commonly considered to be the wavelength range between 0.4-0.7 μm. The ultraviolet region relevant to solar radiation is considered to be the region between 0.3-0.4 μm. The radiation bands of interest are the NIR region between 0.7 and 2.5 μm.

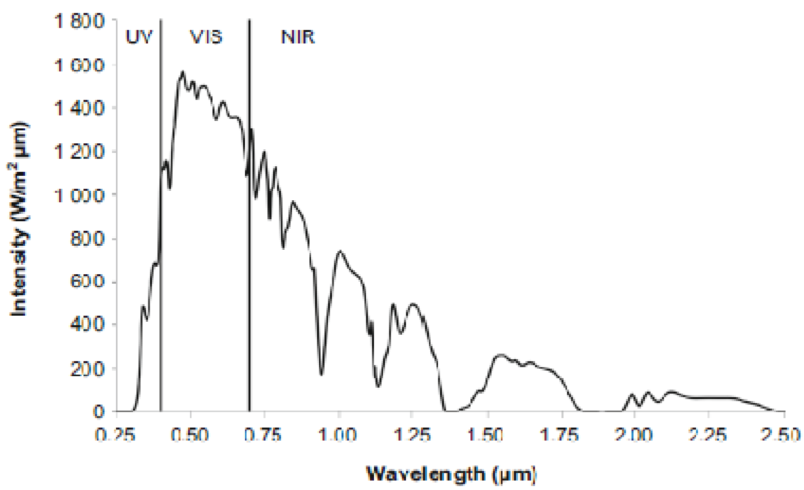

Figure 2 – Solar Energy Distribution [10]

8. When light impinges an object's surface, it will be reflected, absorbed or transmitted as shown in figure 3. The process of scattering, as a special form of reflection in case of non-smooth surface, is included in reflection. Light absorption results in energy increase of an object. In the case of non-luminescent materials, the absorbed light will be mainly converted to heat resulting in temperature increase. Absorption of NIR light is the main source of heat gain of an object as NIR totals 52% of the available solar energy.

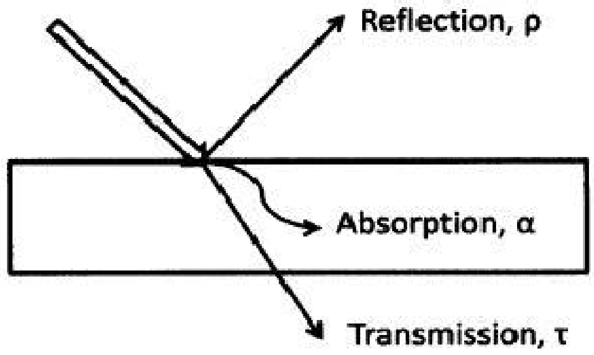

Figure 3 – Light Incident on an Object Undergoes Reflection, Absorption and Transmission

9. The sum of energy from three components equals the incident light. The equation below shows the relationship among reflectance (ρ), absorbance (α) and transmittance (τ).

$$\rho + \alpha + \tau = 1$$

10. When the surface of the object is opaque, transmittance (τ) is zero. This reduces the equation to $\rho + \alpha = 1$. Materials with high reflectance must have low absorbance and/or transmittance. There are three modes of heat transfer: conduction, convection and radiation. Conduction is a heat transfer process that takes place through material surfaces with different temperatures when adjacent atoms vibrate against one another, or as electrons move from one atom to another. Conduction is the most significant means of heat transfer within a solid or between solid objects in thermal contact.

11. Convection is heat transfer process taking place in liquid or gas through diffusion and advection, the movements of fluids. Both conduction and convection are driven by temperature differences and the heat transfer requires a medium. The energy transferred is a function of temperature, geometry and thermal constants. In terms of heat blocking, conduction and convection can be reduced by using heat insulation materials with low thermal conductivity.

12. Radiation, the third heat transfer mode, is energy emitted via electromagnetic waves. The magnitude of energy transferred by radiation is a function of temperature to the 4th power, geometry and emissivity. The emissivity (e) of a material is a relative ability of its surface to emit energy by radiation. It is the ratio of energy radiated by a material to the energy radiated by a black body at the same temperature. The true black body would have $e = 1$ while any real object would have $e < 1$. Radiation does not require medium to transfer energy. Sunlight is a source of radiation whose electromagnetic spectrum ranges from ultraviolet to visible and up to NIR region.

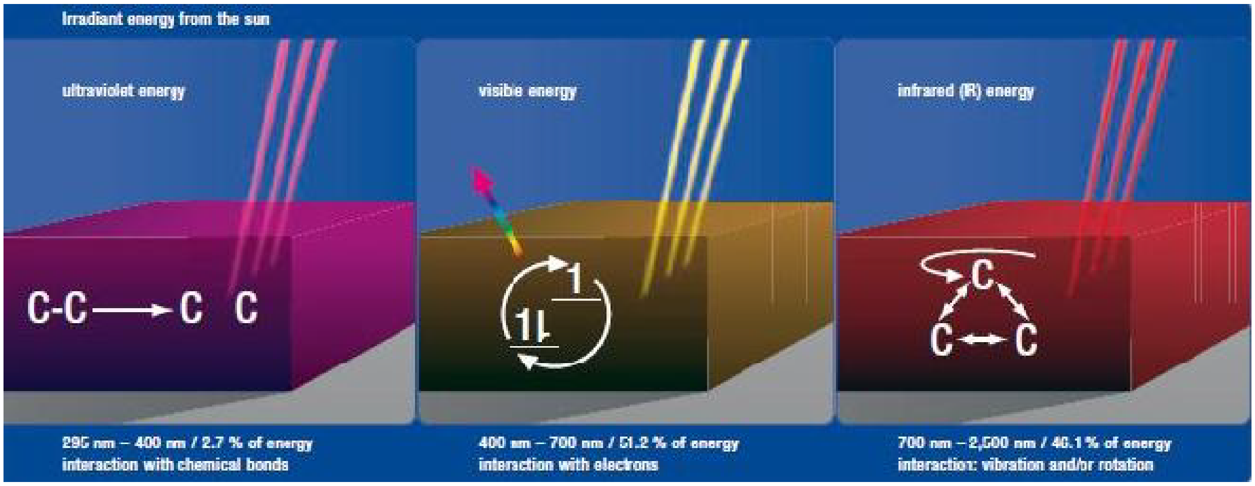

Figure 4 – Forms of Solar Energy

13. Absorption of light occurs when light energy promotes electrons from one bonding state to another. If light of a different wavelength is used to cause this energy transition, it will not be absorbed. This means there are electronic transitions responsible for absorbing light with wavelengths of energy from 400-700 nm. Light of lower energy (> 700 nm) is not absorbed. In this case, a beam of light with a wavelength of 1500 nm is too low in energy to cause any electronic transitions in the material. Thus it will not be absorbed. Instead the 1500 nm light beam is refracted, reflected and scattered, leading to the diffuse reflection of NIR light. There is no method to predict the NIR reflectivity of an inorganic or organic compound. When a beam of light falls on a powdered sample, reflection, transmission, and absorption can occur. If the sample is optically thick enough, the transmitted light is negligible.

Mechanism of Reflection

14. In classical electrodynamics, light is considered as an electromagnetic wave, which is described by Maxwell's equations. Light waves incident on a material induce small oscillations of polarization in the individual atoms (or oscillation of electrons, in metals), causing each particle to radiate a small secondary wave in all directions, like a dipole antenna. According to the Huygens–Fresnel principle, All these waves add up to give specular reflection and refraction.[11]

15. In the case of dielectrics such as glass, the electric field of the light acts on the electrons in the material, and the moving electrons generate fields and become new radiators. The refracted light in the glass is the combination of the forward radiation of the electrons and the incident light. The reflected light is the combination of the backward radiation of all of the electrons. In metals, electrons with no binding energy are called free electrons. When these electrons oscillate with the incident light, the phase difference between their radiation field and the incident field is π (180°), so the

forward radiation cancels the incident light, and backward radiation is just the reflected light.

16. The interaction of light (electromagnetic waves) with any material is hidden in the frequency dependence of the material's complex dielectric function (derived from the interaction of light and free electrons in conduction band and the bound electrons that transit from valence band across energy gap to the conduction band when these electrons have energy greater than energy gap). Properly designed materials are known to produce high reflection or high absorption factors. The reflectivity of a surface is a measure of the amount of reflected radiation. The reflectivity depends on the angle of incidence, the polarization of the radiation, and the electromagnetic properties of the materials forming the boundary surface. These properties usually change with the wavelength of the radiation.

Design of Infrared Reflective Coatings

17. The most effective way to produce a solar heat reflecting coating is to maximize the reflectance of solar energy in the near infrared region of the spectrum. An Infrared reflecting pigment or a combination may be chosen based on requirements and dispersed uniformly in the binder (polyurethane/ epoxy/ acrylic etc) to achieve optimum pigment volume concentration (PVC) for the coating formulation. Pigments are powders that are mixed into materials to impart color.

18. A pigment's color is due to its selective absorption/reflection of visible light. There are several types of pigments and each has its unique shade based on its specific pattern of reflectance/absorbance of visible light. Likewise, each pigment has distinct IR-reflective characteristics. The efficiency of an Infrared reflecting pigment is evaluated by solar reflectance index (SRI), which incorporates both solar reflectance and emittance in a single value. SRI measures the pigment's ability to reject solar heat, defined such that a standard black (reflectance 0.05, emittance 0.90) is 0 and a standard white (reflectance 0.80, emittance 0.90) is 100. Using one or more pigments having high SRI, coating designer can achieve the required results and colour for the formulations.

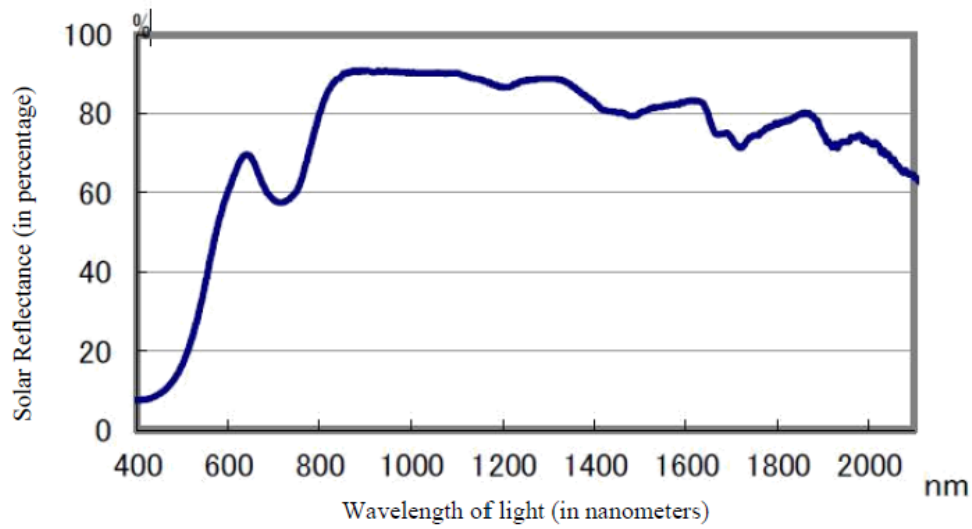

Figure 5 – Solar Reflectance Spectrum of Yellow Infra-Red Reflecting Pigment (Ti-Cr-Sb, TSR 62% (300-2100nm range) & 86% (800-2100nm range)

19. Infrared reflective inorganic pigments are complex inorganic color pigments (CICP), which reflect the wavelengths in infrared region in addition to reflecting some visible light selectively. Infrared reflective paint coatings based on single layer solar reflecting topcoat with IR reflecting pigments such as metal nanoparticles [12] complex inorganic color pigments (CICP) [13] and rare earth metal oxides have been developed [14]. The general benefits of IR-reflective pigments are: longer potential life-cycle due to less polymer degradation and thermal expansion due to lower temperature, aesthetically pleasing color and improved system durability and less thermal degradation [15].

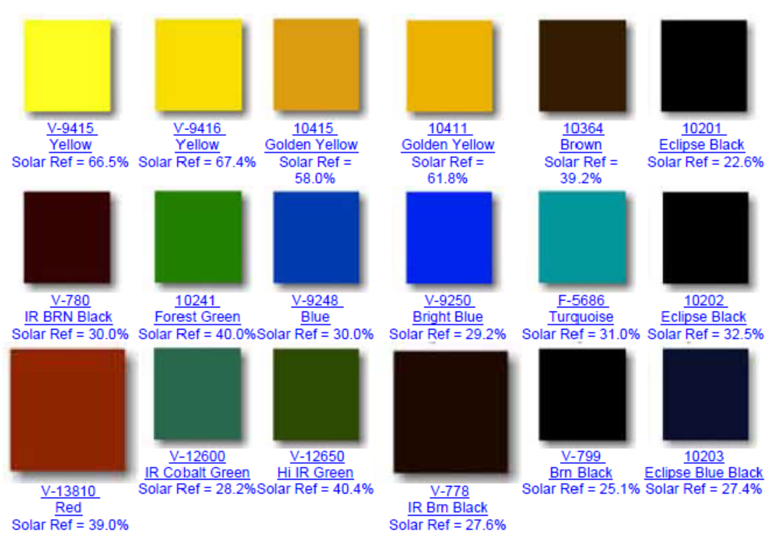

Figure 6 –Infrared reflecting pigments[16]

20. Solar reflective coatings can be formulated as a single or two coat formulation. In the first case, it is possible to produce solar reflective coating systems comprising a highly reflective undercoat and a topcoat which can be coloured with pigments transparent to NIR radiation. The topcoat provides the desired visual colour but does not absorb NIR radiation. The topcoat must be as thin as possible for it will always have

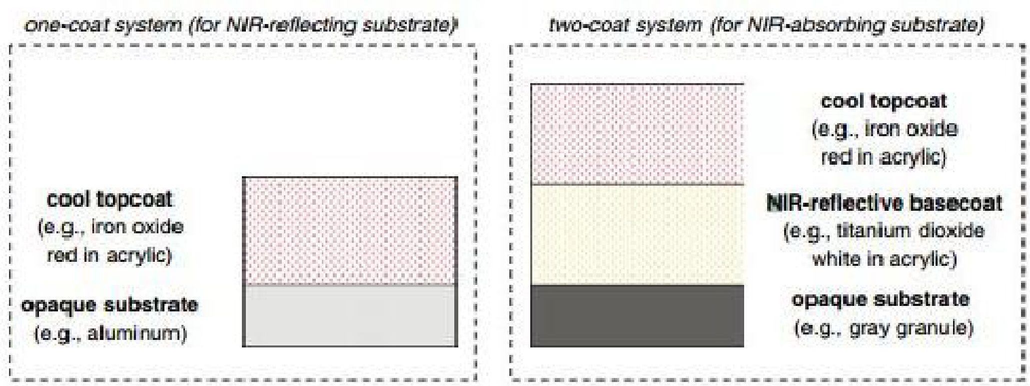

Figure 7 – Schematic of One coat and Two-coat Systems [17]

some absorption. The second and preferred solution is to use pigments which are reflective in the NIR to produce a single coating. Blending reflective and transparent pigments gives much flexibility in tailoring infrared properties, and the difficulties of a two-coat system are avoided. The main approaches used individually or in combination are to: -

(a) Select pigments to match visible colours using pigments that also naturally reflect more infra-red radiation,
(b) Utilise hollow silica/ceramic microsphere/ nanoparticle additives that reflect the longer wavelength solar radiation and
(c) Improve the ability to radiate any heat build-up out to the sky.

21. These Infrared (IR) reflective paint coating formulations reduce the absorption of infra-red radiation at surfaces exposed to sunlight without changing the visible colour. Using such paint coatings, it is also possible to create black paints and near black paints with judicious use of combined ‘infra-red reflecting’ pigments that absorb across the visible. This is done whilst reflecting moderately well in the infra-red instead of absorbing right across the spectrum like traditional paints based on carbon black pigment. An example of Dulux paint coating company using this approach is presented in figure 8.

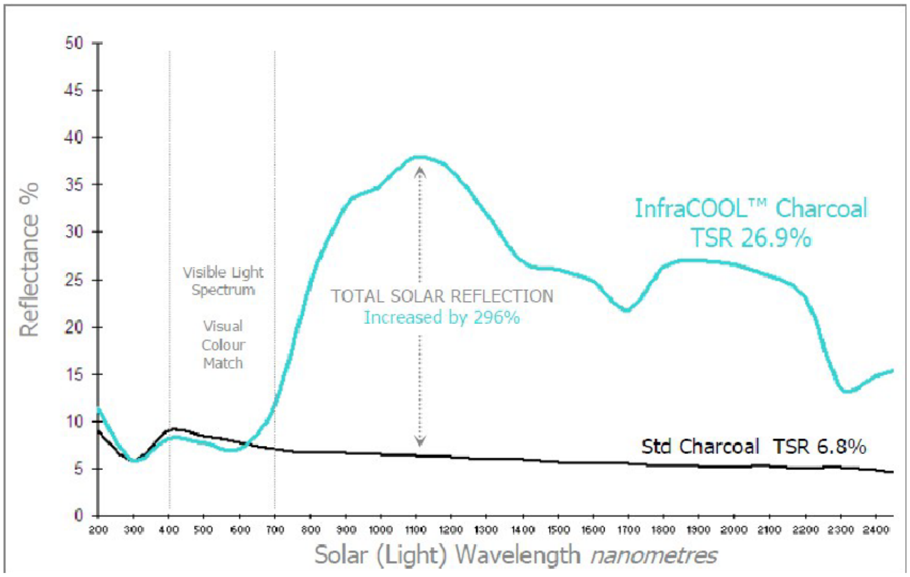

Figure 8 – A comparison of Standard and IR reflective Charcoal coating [18]

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Infrared Reflective Coatings for Marine Environments

22. The surface area exposed to solar radiation in case of warships and passenger ships generally tends to be more than half of the total external surface area. The cargo ships such as oil tankers, general cargo ships and container ships have lesser exposed areas in comparison. Considering the complement and the quantum of solar exposure, the problem of effectively air-conditioning the enclosed spaces is more severe in case of warships and passenger ships.

23. Heating, air conditioning and ventilation (HVAC) system onboard ship is a vital system that enables the crew and passengers to perform their everyday mission and maintain a high level of operational readiness. It provides comfort and odor control and is essential in protecting personnel from indoor air quality (IAQ) contaminants and chemical, biological, and radiological (CBR) contaminants. Shipboard HVAC systems supply and remove air to and from spaces throughout the ship. In doing so, these systems control quality of breathing air and protect personnel and sensitive equipment from hazardous airborne contaminants, fires, explosions, and excessive heat. This ensures the maintenance of a crew that is physically and mentally fit. Failure to provide effective ventilation systems in the design stage can create costly obstacles to safe and efficient ship operation and maintenance, which ultimately presents a threat to personnel safety and health and to mission readiness.

24. The most widespread HVAC problem aboard a ship is controlling heat and humidity. High heat and humidity lead to conditions that are both uncomfortable and reduce personnel productivity. This has an indirect, but potentially very significant effect on cost over the life of the ship, because of reduced productivity and the need for additional manpower to perform a given set of tasks.

25. Various Classification Society and Naval standards define the requirements governing the overall design of HVAC systems. They specify environmental control required to be achieved throughout the full spectrum of ambient conditions for which the ship is to be designed. With the steady rise in global temperatures, the load on HVAC system is bound to increase with time. Accordingly, paint coating firms like M/s Akzonobel, Nippon Marine have recently introduced IR Reflecting coatings for marine applications. These marine coatings can withstand harsh marine corrosion and provide smooth finish on exposed surfaces such as decks, superstructure and ship side. A wide variety of coloured coatings having infrared reflective properties are available for application for marine vessels. Full scale trials conducted by the manufacturer have shown that surface temperature drop of the coated surface can be as high as 28 degree Celsius in comparison with conventional coatings. The infrared reflective coating can be easily applied by crew or mainteners using conventional methods and requires standard surface preparation. Considering the requirements and operational profile of merchant ships, these coatings are bound to gain importance in the future.

Stealth and Application of IR Reflecting Coatings onboard Naval Ships

26. Unlike merchant ship, a warship has a prime requirement of performing role of a "Stealth Platform". The Stealth is ability of a warship of not being detected. The methods of detection (signature) of a ship can be visual, acoustic, magnetic, infrared etc. [19] Area of interest here is Infrared Reflective signatures of a ship. A ship's IR signature is made up from two main components: internally generated sources, and externally generated sources. Internally generated signature sources include rejected heat from engines and other equipment, exhaust products from engines, waste air from ventilation systems and heat losses from heated internal spaces. Externally generated sources result from the surfaces of a ship absorbing and/ or reflecting radiation received from its surroundings (ie. radiation from the sun, sky and sea) [20].

27. Beyond the small, hot sources (high radiance) of IR such as engine exhausts, the only other major contributor to a ship's signature is from its external surfaces; hull, decks, and super-structure bulkheads. Typically ship surface temperatures are much lower than that of exhaust uptakes and plumes. However, because of the large area

even very small contrast temperatures can result in a significant signature. This is especially true under solar heating conditions. [21-23]

28. Figure 9 shows a polar plot of contrast radiant intensity for the generic frigate model. The ship is travelling in the same environment as used for Figure 10, at 30 knots on two LM2500 engines, with no engine suppression. The sun is positioned directly of the starboard beam, at an elevation of 30˚. The plot is made for an observer 500 m away, looking down on the ship at a 15˚ angle.

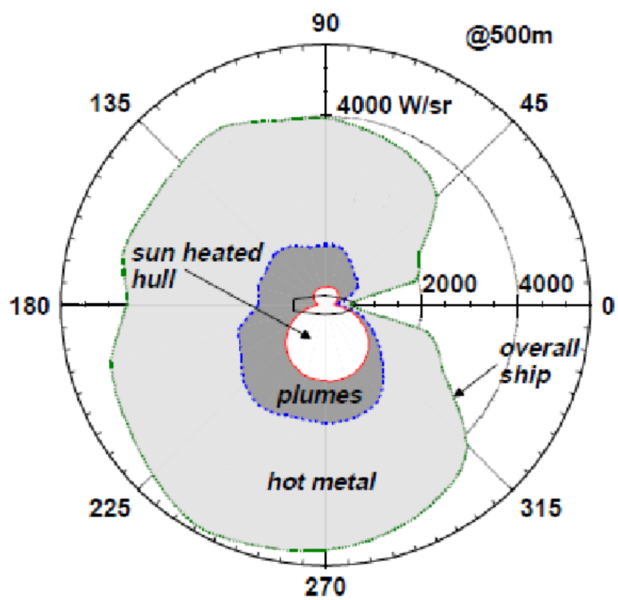

Figure 9 – 3-5 µm Polar Plot of Signature Components [24]

29. The figure suggests that the ship's signature is dominated by visible uptake metal. The figure also suggests that the contribution made by the plumes is of the same order of magnitude as the sun heated hull, at this range. The shape of the curve in Figure 9 is indicative of typical ships. The hull radiance distribution is dependant on visible area, resulting in a "figure 8" shape. Meanwhile, the uptake metal and plumes have a roughly circular distribution, with a dip in radiance appearing for views from ahead of the ship. This dip is a result of the mast and superstructure obscuring the engine exhausts.

30. At night-time, if a ship's hull is well insulated, a ship's surface is at equilibrium somewhere between air and sea temperature. As the sun rises in the sky, the ship's surface temperature quickly heats up to a large contrast with ambient. Suppression of an excessive hull temperature is regarded as a difficult, if not impossible task. The large surface areas involved, and wide range of environmental factors influencing ship skin temperatures pose an interesting challenge. Three solutions have been proposed at

present:

(a) Use low solar absorbtivity/ thermal emissivity paints to reduce surface heating and IR emission;
(b) Wash solar heated surfaces with sea water; and
(c) Blanket entire ship in a cloud of heavy water mist.

31. Paints now used on the hulls and superstructures of warships often exhibit relatively high solar absorption because of the grey colours required for visual camouflage. These colours may vary from bluish to greenish grey depending on the waters in which the vessel is likely to operate, and have reflectances near 30%, High solar absorption necessarily results in high surface temperatures which reduce the comfort of the crew, increase cooling requirements and, more significantly, amplify the emission of thermal radiation. Other methods of cooling hot exposed surfaces, such as using water spray, reduce thermal emissions but add power requirements and top weight to the ship.

32. Historically, naval coatings have contained significant amounts of carbon black [17]. An early attempt to formulate without carbon black produced solar heat reflecting coatings and low emittance coatings containing 15% of powdered aluminium. These coatings had poor weatherability and colour retention because antimony sulfide, a black pigment used in place of carbon black, is unstable and reacts with air to form white antimony oxide on prolonged exposure.

33. Effective solar heat reflective coatings have now been made in the grey shades established for warships. Carbon black has been replaced by an organic perylene black which absorbs strongly in the visible region but is transparent throughout the infrared. The formulation for a full gloss Australian naval coating conforming to Light Grey 631 has been developed. This coating reflects 77% of solar radiation at 800 nm in comparison to the standard coating which reflects 33%. A similar formulation has also been developed for a semigloss solar heat reflecting coating for U.S. naval warships which has a haze grey colour. The spectral reflectance from 380 to 2300 nm is shown in Figure 10 for this coating and for the conventional coating. The reflectance of the new coating is approximately twice that of the older coating in the region from 720 to 2300 nm. The reflectance in the visible region between 380 and 720 nrn indicates that the new colour is metameric to the older colour; this is a consequence of substituting phthalocyanine blue and red iron oxide for carbon black [17].

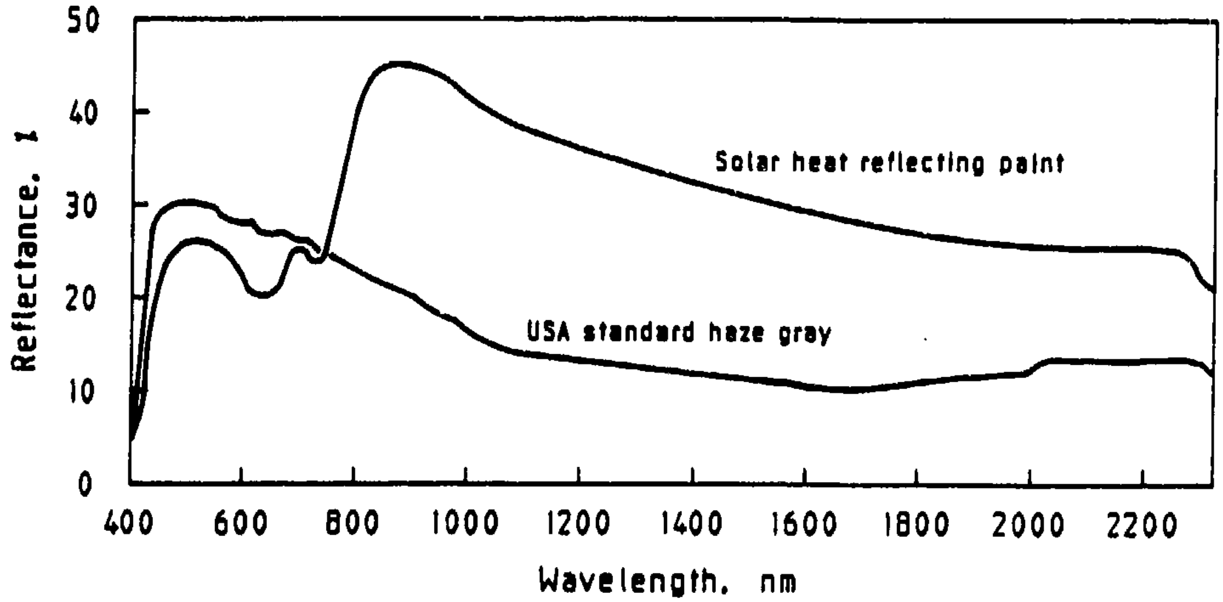

Figure 10 – Infrared reflectances of two Haze Grey formulations [17]

34. The selection of special paints is a very complex issue and there is no single correct answer. There will always be a tradeoff between the best solution for sunny conditions versus the best solution for night time or cloudy day conditions. For example, under sunny conditions, a hull paint should not absorb solar radiation below 3 μm wavelength (i.e. low emissivity to short wavelength); and absorb all radiation above 3 μm (i.e. high emissivity to mid and long wave) [24].

35. With this type of surface the hull would heat up less due to the sun, but it would not reflect the sun in the important 3-5 and 8-14 μm wavebands. However, low reflection means high emission, and if the hull is heated above the ambient it will emit strongly in the 3-14 μm range. This type of spectral paint is available but is expensive and its effectiveness can be dramatically reduced by surface contaminants such as oxidation, dirt, etc.

36. Under overcast conditions it would be desirable to have low emission paints (or "low Ɛ"). In this case the ship would emit less and reflect its surroundings more. Little unclassified data on the in service experience of ships that use special low Ɛ paints has been available. At the time of this paper, no report could be found that compares the overall susceptibility of ships with typical paints vs ships with special paints. Without extensive field trials and signature measurements it is not possible to recommend an alternate surface finish with confidence. Therefore, standard navy grey paint is assumed to be a reasonable trade-off between low emission/ absorption and low reflection.

Conclusion

37. IR-reflective paints are a radiative barrier minimising surface heating rather than providing an insulating layer that reduces conductive heat flow. These paints can lead to a reduction of exterior surface temperatures, and heat load, on buildings, external electrical and electronic equipment, pipes transporting oil or water and hulls of ships. They could contribute to reduced peak electricity requirements for air-conditioning on very hot summer days and reduce greenhouse gas emissions caused by air-conditioning. Due to such benefits, solar-reflective coatings and materials are beginning to be used in industrial and architectural applications to give significant cost savings through reduced energy use for temperature control. Using IR reflecting pigments and optimum formulation, tailored infrared reflectance can be obtained. Such formulations have now been developed for marine applications and would tremendously help in improvising the efficacy of the HVAC system fitted onboard. In the naval context, a very clear understanding of the threat systems and the operational conditions of service platforms is mandatory for designing such coatings. However, it can be stated that the use of the suitably designed and experimented solar infrared reflecting coatings described herein would reduce conspicuity of isolated platforms to surveillance and seeker systems operating in the mid and far infrared without detriment to visual camouflage characteristics.

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