Formulating Infrared Coatings for Defence Applications

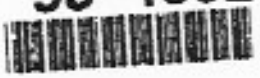
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Abstract

Relevant physical laws governing the response of coatings to solar and infrared radiation have been reviewed. The reflection of infrared radiation by a paint is controlled primarily by the refractive index and particle size of the pigments in the coating. Pigments have been evaluated for reflectance, transparence and hiding power in the near infrared region, and guidelines for pigment selection for various applications given in terms of their optical properties in the near infrared region. Raw materials selection, manufacture and evaluation of coatings have been discussed with respect to tailoring infrared reflectance. By employing the principles developed herein and using pigments with appropriate properties, organic coatings have been developed which are consistent with the visible colour requirements of the Australian and US Navies. Significant increases in the reflection of infrared radiation have been demonstrated by the new formulations. The need for a very clear understanding of the threat systems and the operational conditions of service platforms has been emphasised. It is only with this understanding that optimum paint schemes can be devised. However, it can be stated that the use of the solar infrared reflecting paints 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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1. Introduction

The short electromagnetic wavelengths which characterize near and thermal infrared radiation permit the use of thin coatings to control absorption and reflection of radiation in these regions. Paints can be designed which increase the reflection of incident solar radiation while retaining the visible properties of colour and gloss. The increased reflection reduces heating and lowers the energy requirements for cooling. In other instances, paints may be required to reduce the emission of thermal infrared radiation and shift infrared emissions to different wavelengths, thus reducing the likelihood of detection. Coatings may also be formulated to combine reduced emissions in the thermal region with reduced reflection in NIR bands used for laser detection.

Requirements to control infrared properties of coatings arose after the development of infrared photography. This need led to changes in paint formulation aimed at reducing reflection in the near infrared (NIR) region between 720 and 900 nm. With the increasing use of infrared detectors, paint specifications have retained the requirement for low infrared reflection. However, low NIR reflecting paints strongly absorb the NIR component of solar radiation. As such, they increase thermal infrared (TIR) signatures and the likelihood of TIR detection as well as adding to the cooling requirements. At the present time, the optimum balance for NIR or TIR signatures has received little attention.

This report examines mechanisms influencing the reflection, transmission and absorption of visible and infrared radiation by paint coatings. The report details a number of new paint formulations to meet defence coating requirements which significantly reduce thermal emissions. Consideration is also given to the selection of formulations to meet different combinations of threats and environments.

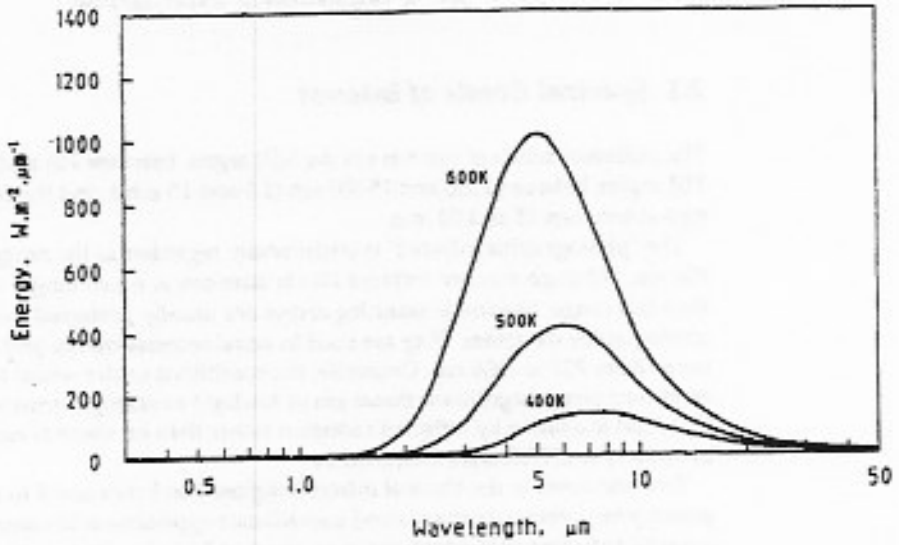


Figure 1: Radiation energy at three temperatures.

When Equation 1 is integrated over all wavelengths, the Stefan-Boltzmann Law (Equation 2) is obtained

$$W = \alpha T^4 \qquad (2a)$$

(in which α is the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}).

For non-ideal systems, the total radiative emissions are proportional to the emittance, ε, of the surface and the equation describing the total power W radiated by a body becomes

$$W = \alpha\varepsilon T^4 \qquad (2b)$$

The emittance, ε, of a surface is the ratio of its emission to that of an ideal black body at the same temperature and can vary from 0 to 1. The emittance of metals such as aluminum and nickel as well as treated metal surfaces with thin oxide coatings is typically in the range from 0.05 to 0.15 and these materials are inefficient radiators of energy. As well as being poor radiators of thermal radiation, polished metal surfaces are good reflectors of incident radiation. The emittance of organic materials such as plastics and most organic coatings is high (0.85 to 0.95). When the ratio of the spectral emission of a surface to that of a black body is constant with wavelength, the surface is known as a grey body. In most cases, the emissivity varies with wavelength and the coating is said to be a selective radiator.

it leaves in all directions. Diffusion of radiation arises from a large number of essentially random scattering events and in paint technology, the overall diffusion process is simply termed "scattering".

The selection of pigments largely determines the thermal control provided by coatings. The most important aspects of these are the solar absorptance, α_s, in the NIR and the emittance, ϵ, in the TIR regions. Examples of specific thermal requirements include (i) high solar absorptance to reduce photographic or NIR laser detectibility, (ii) low solar absorptance to keep illuminated equipment cool in hot environments or, (iii) low emittance to reduce thermal detectability. Coatings may combine low emittance properties with either high or low levels of solar absorptance.

Camouflage of defence equipment in the visible waveband is usually achieved by the use of dark coloured low gloss paints. Dark coloured paints, e.g. navy greys, are commonly formulated with carbon black which is a strong absorber of solar radiation and reduces photographic and laser detectibility in the NIR. However, paints formulated with carbon black have high emissivities and strongly emit thermal radiation. A number of metal oxide coatings applied to metal substrates combine high solar absorption with low emissivity in the TIR as thin oxide layers absorb short wavelength radiation but are transparent in the longer wavelength infrared region. These absorption characteristics act to reduce the chance of detection in both TIR and NIR regions. However, as these coatings strongly absorb solar radiation, heat build-up may be a problem. By replacing carbon black or the black metal oxides with organic perylene blacks which absorb weakly in the NIR, paints can be formulated in the same colours to reduce solar heating. Like the metal-metal oxide paints, the perylene black paints are selective absorbers, however, whereas the metal-metal oxide paints absorb strongly in the NIR and poorly in the TIR, the perylene black coatings absorb weakly in the NIR region and strongly in the TIR region. Low emittance paints may also be formulated with metal flakes, e.g. aluminium, which provide strong reflection across the visible and infrared spectrum.

The reduced thermal exitance resulting from either lower temperatures or low emittance reduces the chances of thermal infrared detection. However, when the detector system has both near and thermal detecting elements, such as in some of the air borne systems, the requirements involved in paint selection are more complex. Under normal conditions, the laser system has greater range than the TIR detectors. This imbalance permits active rangefinding well outside passive acquisition range. The use of solar reflecting paints will accentuate the imbalance by reducing the acquisition range while further increasing the active NIR rangefinding capability. Under normal daylight conditions this will lower the detection range while having little effect at night. An alternative paint for this application would be the NIR absorbing, low emittance metal-metal oxide paints. However, their use under Australian conditions, particularly in northern Australia, would result in considerable heat build-up.

It should be appreciated from the above examples that paints may be formulated which provide either (i) absorption across the NIR and TIR regions, (ii) reflection across the NIR and TIR regions, or (iii) absorption in the NIR and reflection in the TIR region or vice versa.

Equation 6 is in close agreement with experimental observations [5]. It is seen that the emittance of conducting materials decreases as the wavelength increases and, in practice, paints with low thermal emissivities are usually formulated with metal pigments. Flaked metal pigments are commonly chosen because they have large flat surfaces which maintain high reflectivity compared with smaller metal particles.

2.5.2 *Scattering of Radiation*

Scattering of visible and infrared radiation is a single stage process and is commonly referred to as being either elastic or inelastic. Scattering in which the radiation retains the same quantity of energy and momentum and hence with an unchanged frequency is considered to be elastic. Rayleigh scattering is such a process. Scattering in which the energy is exchanged with the scattering object is termed inelastic and is referred to as Raman scattering. It is much weaker than Rayleigh scattering. In Raman scattering, the energy is shifted by an amount equal to the change in vibrational energy of the material through which the radiation is passing.

There are other phenomena which involve a two stage process of absorption and reradiation of the energy after a delay. These are termed luminescence, fluorescence or phosphorescence, depending on the delay time, however they are not considered to be scattering.

Elastic and inelastic scattering processes result from electromagnetic radiation perturbing the electronic cloud surrounding the molecules of the irradiated material. Weakly bound electrons are most able to respond to the fields of the radiation with increased delays at higher frequencies. The electrons attempt to screen the alternating electric field of the incoming beam. This field can induce an energy transition in the material with a corresponding energy change of the infrared photon. Inelastic scattering of this kind is called the Raman effect in condensed media.

Rayleigh scattering occurs in the presence of small independent particles commonly present in colloidal and other suspensions containing particles with sizes comparable to or larger than the wavelengths involved. Such scattering, which is nearly wavelength independent, is called "white scattering" and is also known as the Tindall Effect. Rayleigh scattering has been extended by other authors to particles of any size provided that the refractive index is nearly unity. As Scott [8] has pointed out, a more complete theory was developed earlier by Mie which covers the deficiencies in Rayleigh Theory.

The scattering of visible and infrared radiation by a pigment is a function of the refractive indices of the pigment and the resin in which it is dispersed. The refractive index of commercial pigments varies between 1.4 and 2.8. The scattering power m of a pigment for white light is calculated by dividing the refractive index of the pigment by that of the resin. Hiding pigments have values of m well above 1; they hide the substrate and modify the reflectance curve of the coating. Red iron oxide and titanium dioxide, which are among the most effective hiding pigments, have m values of 1.9. Extender pigments, i.e. achromatic pigments of low refractive index, such as barytes, talc, and silica have values of m below 1.1; they scatter light poorly, do not alter the shape of the reflectance curve but do modify the reflectivity.

infrared spectral absorptions from symmetric molecules, e.g. nitrogen and oxygen. Water vapour and carbon dioxide, on the other hand, are responsible for most of the absorption of radiant energy by the earth's atmosphere.

Table 1: Constants used to calculate the scattering power of pigments

Pigment	Refractive Index	Scattering Power[a] (m)	κ
Diatomaceous silica	1.43	0.97	-
Amorphous silica	1.55	1.05	5.86
Magnesium silicate	1.58	1.07	4.20
Barium sulfate	1.64	1.11	2.70
Chromium oxide	1.90	1.28	1.10
Zirconium dioxide	2.20	1.49	0.67
Yellow iron oxide	2.30	1.89	0.42
Red iron oxide	2.80	1.89	0.42
Titanium dioxide	2.81	1.90	0.42

[a] In an alkyd resin having a refractive index of 1.48.

3. Raw Materials

3.1 Measurement of Near Infrared Properties of Pigments

Pigments exert the principal influence on the optical and NIR properties of coatings [14]. Pigments used in infrared coatings are chosen because of their diffuse and specular reflectance, absorptance and transparence in the infrared region. A knowledge of the behavior of pigments in the infrared region is a critical factor in formulating coatings to specific requirements. The particular pigments required will depend on the intended application.

Compilations of absorption spectra of prime pigments, i.e. pigments possessing good hiding power, and of extender pigments are available for the thermal [15, 16] and far [17] infrared regions. They provide information about the position and intensity of absorption bands. Most published measurements, which have been made on pressed pure pigments in powder or tablet form, give no information on the refractive index nor of pigment-volume concentration (PVC). Preparation of a pigment for measurement of its spectrum may reduce its particle size; absorption would not be modified but scattering would be influenced as discussed in paragraph 2.5.2. In addition, dispersion of a pigment in an alkali metal halide matrix, a common sample handling technique for obtaining infrared absorption spectra, creates refractive index differences which are not found in paint films. Thus they are of little use in the design or prediction of NIR reflection of paint films.

The concepts of scattering and opacity are useful throughout the infrared spectrum as well as the visible spectrum. The combination of diffuse reflection

Table 2: Diffuse reflectance values (in percent) of paint films applied over white (R_w) and black (R_b) backgrounds.[a,b]

Pigment		Wavelength (nm)									
		400	500	600	700	800	900	1000	1100	1200	1300
Barytes	R_w	56	81	88	90	90	88	88	88	84	81
	R_b	5	5	5	5	0	0	5	5	2	0
Carbazole Dioxazine Violet	R_w	3	3	3	7	25	40	62	75	75	80
	R_b	3	3	3	7	7					
Chromium Oxide	R_w	11	9	8	18	50	47	40	42	42	38
	R_b	11	9	8	18	50	47	40	42	42	38
Heliogen Black	R_w	4	4	4	5	50	80	85	88	84	88
	R_b	4	4	4	5	6	9	21	29	30	28
Iron Oxide, Red	R_w	2	2	14	28	25	12	30	45	42	37
	R_b	2	2	14	28	25	12	35	45	42	37
Iron Oxide, Yellow	R_w	3	7	37	35	37	24	22	38	65	73
	R_b	3	7	37	35	37	12	20	29	27	22
Iron Oxide, Lt. Brown	R_w	6	7	16	18	17	13	11	7	4	1
	R_b	6	7	16	18	17	13	11	7	4	1
Iron Oxide, D. Brown	R_w	3	3	4	4	4	4	0	0	0	0
	R_b	3	3	4	4	4	4	0	0	0	0
Iron Oxide, Black	R_w	5	5	5	5	0	0	0	0	0	0
	R_b	5	5	5	5	0	0	0	0	0	0
Paliogen Black	R_w	3	3	3	25	67	67	67	66	64	64
	R_b	3	3	3	10	10	8	4	4	4	4
Silica Amorphous, 25 µm	R_w	62	81	86	90	89	88	87	87	85	85
	R_b	5	5	6	6	3	3	4	5	4	3
Silica Amorphous, 22 µm	R_w	51	73	78	82	94	92	89	87	85	85
	R_b	5	5	5	5	4	4	4	3	2	1
Silica Amorphous, 16 µm	R_w	60	81	86	90	92	92	90	88	83	85
	R_b	5	5	5	5	5	1	3	3	0	0
Silica, Diatomaceous	R_w	57	83	89	91	97	94	94	94	90	90
	R_b	6	6	6	6	0	0	0	0	4	8
Talc	R_w	39	53	53	53	92	92	91	90	87	87
	R_b	6	9	10	11	2	0	0	0	0	0
Titanium Dioxide, 0.2 µm	R_w	30	94	94	94	94	92	89	87	85	85
	R_b	30	94	92	88	84	75	70	64	58	53
Titanium Dioxide, 10 µm	R_w	10	67	71	75	83	84	85	86	85	86
	R_b	10	42	41	39	31	29	27	25	23	23
White Background	R_w	72	84	88	90	92	90	89	89	86	86
Black Background	R_w	0	0	0	0	2	3	4	5	5	5

[a] Measurements are relative to a pressed white poly(tetrafluoroethylene) powder which was assigned a value of 100%.

[b] Changes in filters and detectors at 800 nm produced a discontinuous baseline at that point.

Table 3: Near infrared (730 to 890 nm) reflectance data for pigments

Pigment	R_w	R_b	CR_{ir}
Barytes	99	1	1
Carbazole dioxazine violet	26	3	11
Chromium oxide	45	44	99
Hellogen black	52	6	13
Paliogen black	73	9	12
Iron oxide, red	33	33	100
Iron oxide, yellow	56	56	100
Iron oxide, lt brown	16	16	100
Iron oxide, dk brown	0	0	100
Iron oxide, black	0	0	100
Silica, amorphous, 25µm	95	1	1
Silica, amorphous, 22 µm	96	2	2
Silica, amorphous, 16 µm	95	2	2
Silica, diatomaceous	99	2	2
Talc	96	1	1
Titanium Dioxide, 0.2 µm	100	93	93
Titanium Dioxide, 10 µm	91	40	44
White card	99		
Black card	1		

$$CR_{ir} = \frac{R_{black} \times 100}{R_{white}} \qquad (10)$$

By means of these measurements, each pigment was classified according to its reflectance and contrast ratio into one of six categories as shown in Table 4. Each pigment was found to be either highly reflective, highly absorbent, transparent, or intermediate in behavior between any two of these categories. When R_W greatly exceeds R_B, the pigment is transparent and has little or no hiding power, but similar values of R_W and R_B denote high contrast ratios. Values of R_W and R_B which are similar and high indicate that hiding is principally achieved by diffuse reflectance, whereas values which are similar and low indicate that hiding is caused by absorption; in both of these cases the contrast ratio is high, usually above 0.90.

3.2 *Selecting Pigments for Applications in the Near Infrared*

A wide variety of useful NIR properties are obtained when pigments are dispersed in films. Titanium dioxide pigments reflect NIR radiation very well, as indicated by their high value of m. Different particle sizes have optimum reflectances in different parts of the spectrum, as shown in Equations 7 and 8. Conventional titanium dioxide with a mean particle size of 200 nm reflects well between 400 and 1700 nm, and is used where reflectance in the visible region is most important.

Conventional extender pigments such as barytes, amorphous and diatomaceous silica, and talc are transparent and nonreflective throughout the visible and NIR regions. These pigments are valuable where transparency in the NIR is needed, and they do not interfere with the performance of other pigments.

Carbon black absorbs strongly throughout the NIR and TIR regions [19]. When used in small amounts it is effective in decreasing the level of infrared reflectance without greatly affecting visible colour. However, should the required reflectance of the paint in the NIR or TIR be low, the amount of carbon black necessary to bring the reflectance down to this level will have a substantial effect on the visual appearance of the paint.

In addition to spectral factors, conventional coating considerations also play a part in the selection of pigments. These include can-stability, resistance to formation of a friable powder on the surface on exposure (chalking), resistance of flat coatings to polishing to a higher gloss (burnishing), and durability. In modern high solids coatings, pigments having the lowest possible product of oil absorption and specific gravity are valued, as they require less resin and are relatively free of settling problems.

3.3 Selecting Pigments for Applications in the Thermal Infrared

The technique of using large pigment particles to promote scattering is restricted in the TIR region. For example, in order to scatter radiation at 12 μm, titanium dioxide particles 5 μm in diameter are required, and particles of this size, i.e. Hegman 7.5, (the Hegman scale is a measure of the fineness of dispersion of a pigment, larger numbers indicating larger particles) are large enough to affect the gloss of a coating. If radiation at 12 μm is to be effectively scattered by a pigment with a low value of m, such as talc, a 50 μm-particle would be required. A particle 50 μm in diameter, i.e. Hegman 4, is the largest that could be tolerated; it would make a coating visibly coarse and would affect colour uniformity, dirt retention, and other important performance properties [25].

In addition, most inorganic pigments have strong, broad absorption bands in the TIR region. For example, carbonates absorb near 7 μm, silicates around 9 μm, and oxides between 9 μm and 30 μm. Organic pigments such as the perylene blacks, phthalocyanine blues and greens, and carbazole dioxazine violet show strong, sharp absorption bands throughout the TIR region, but principally between 6 and 11 μm. Thus, properties of coatings will be influenced by the pigments used and will be strongly wavelength dependent, and grey body approximations are likely to lead to considerable error.

For this reason, metallic pigments, particularly metal flake pigments, are preferred in the TIR region. They absorb TIR energy poorly, but scatter and reflect efficiently throughout this region. Hagen-Rubens [26] first attributed the high infrared reflectance of metals as being due to their high density of conduction electrons. Coatings filled with metallic pigments, particularly leafing pigments, do not demonstrate appreciable wavelength dependence, and so grey-body approximations can be used.

4.2 *Control of Colour*

The colour of a coating (i.e., its visible reflectance spectrum) is normally established for cosmetic or camouflage requirements, and the opportunity to alter the amount of visible light reflected or its wavelength distribution is severely restricted. Two avenues of approach to colour matching are available. First, a pigment which is transparent in the visible region but highly reflective in the infrared can raise the infrared reflectance without affecting the visible colour, and a nonmetameric match to the desired colour can be made. An example of an appropriate pigment for this is the large particle size titanium dioxide discussed in paragraph 3.2.

Alternatively, pigments employed for visual colour match which absorb strongly in the infrared can be removed and replaced with pigments which show similar absorptions in the visible but reflect or are transparent in the infrared. This is seldom a simple matter, and additional pigments will have to be added to duplicate the desired colour. As an example, carbon black can be replaced by an organic perylene black such as Paliogen Black [30] or Heliogen Black [31]. When used as tints, the former has a green shade and the latter has a violet shade. A colorant such as red or yellow iron oxide, respectively, must be added to reestablish a true black or grey shade. The colour thus produced will be metameric to the original colour, and the old and new colours may not match under all types of illumination or observation.

Where reflectance is important, the amount of hiding pigments which absorb should be just sufficient to meet the requirements for hiding. The balance of the pigmentation should be made up of extender pigments with optimized infrared reflectance.

4.3 *Control of Emissivity in the Thermal Infrared*

The emissivity of a coating contributes directly to its signature in the TIR region, and emissivity as well as reflectance must be controlled in order to achieve the performance desired. Organic resins are strong emitters in the thermal infrared region, particularly at the wavelengths which are found in their absorption spectra. Oxide, carbonate, and silicate pigments show selective emission; for example, titanium dioxide emits near 8 μm.

Finely dispersed metallic pigments such as aluminum flake have low emissivity and are used to decrease the emissivity of organic coatings. Bright aluminum foil has a reflectance of about 95 percent for black body radiation from a source at 50°C; the maximum energy from such a source is emitted at 9 μm. Aluminum paints show reflectivity as high as 82 percent and emissivity as low as 18 percent [32].

Clean or polished metallic substrates radiate heat poorly, but their emissivity can be enhanced by a wide range of black or dark oxide, phosphate, chromate and other coatings applied by chemical or electrochemical processes [33]. When cooling of a coated object is important, high emissivity coatings are used. On the other hand, coatings with low emissivity are used to retain heat within, for example, steam pipes or boilers.

Solar reflective coatings have been formulated in either of two ways. 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 possess some absorption. Also, for uniform visual appearance the film thickness has to be consistent; this is not always easy when the coating is applied outside a factory. Maintenance is a problem because topcoat and undercoat must be applied at proper thicknesses and intercoat intervals to retain properties, and the cost of a two coat system exceeds that of a single coat.

In so far as visible colour permits, pigments which strongly absorb in the infrared should be avoided in the topcoat of a two coat system. As the near infrared absorptance of the topcoat increases, reflectance from the undercoat is diminished because less energy reaches the undercoat. It is essential to pay particular attention to pigment volume concentration in the topcoat under these conditions.

A 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.

5.3 *Thermal Infrared Reflecting (low emissivity) Coatings*

These coatings are designed to reduce thermal emission and to reflect incident TIR radiation. Metallic pigments, particularly aluminium flakes, reflect strongly across the TIR region and are the principal active ingredient in these coatings. The best aluminium paints for this purpose are those made with extra brilliant grades of aluminium flake which have larger particle sizes. Pigments which overlap in a systematic manner, known as leafing pigments, have been shown to produce greater reflectance than nonleafing pigments [32], and this has been ascribed to the complete hiding of the resin by the leafing metal flakes in the matrix. Aluminium paints reflect thermal infrared with greater efficiency than they reflect white light. Black coatings are commercially available [34] which offer low solar reflectance and high thermal reflectance (0.9), i.e. thermal emissivities of 0.1. It is understood that these materials have been trialled on NATO tanks, however the high solar collection efficiency of this material would require that its use in tropical and subtropical environments be closely engineered.

Table 5 shows the temperature transfer properties of a steel panel coated on the illuminated side with the standard Australian Navy grey paint compared to one painted on the illuminated side with a leafing aluminium paint.

5.4 *Camouflage Coatings*

Camouflage coatings adjust the normal reflectance of an object so that it resembles its immediate environment, thus making it nearly indistinguishable from its surroundings under natural as well as artificial illumination. Camouflage coatings must reflect both visible light and infrared radiation to the same degree as their surroundings. For terrestrial applications, the most important environments where concealment is desired are foliage and desert regions.

Most specifications for camouflage coatings require a sharp rise in reflectance between 700 and 720 nm, and require that the average reflectance in the 700 to 900 nm region exceeds the average reflectance in the 600 to 690 nm region. Such coatings approximate the reflectance spectrum of chlorophyll and appear in the NIR to have the same reflectance as natural vegetation.

Many green pigments resemble the colour of chlorophyll but, unlike chlorophyll, show strong absorption in the NIR. Chromium trioxide is green in colour and possesses a reflectance curve similar to that of chlorophyll, and was the principal pigment in early NIR camouflage paints. For some specifications which do not call for reflectance to rise rapidly in the NIR, chromium trioxide tinted to the desired visual shade can still be used as the basic pigment. When infrared photography or modern detection methods are used, however, these pigments are readily detected as dark shadows against a light background of natural vegetation.

Older formulations based on lead chromate (chrome yellow), basic lead chromate (chrome orange) and molybdated lead chromate (moly orange), and tinted with blue and red pigments, produce camouflage coatings in a variety of green shades [37], but their use has been curtailed in the United States because of their extremely high lead content.

A range of visual colours is used for modern camouflage coatings. Each colour is specified by its brightness Y and its chromaticity coordinates x and y. These parameters are defined by the International Commission on Illumination, known as CIE from its name in French, Commission Internationale d'Eclairage. The desired colour is plotted as a point on a chromaticity diagram, and colour tolerance is stipulated by a boundary on which lie all points which differ from the target colour by the same visual difference. The boundary normally takes the form of an ellipse, as shown in Figure 3 for US forest green camouflage paint [38]. In this case the visual difference is stipulated by the obsolescent NBS [for (US) National Bureau of Standards] unit, which is computed using complex equations from the Y, x and y values of the standard and sample colours [39].

Infrared reflectance is specified in various ways. British Material Specification DTD 5618 [40] stipulates minimum values of reflectance at 700, 800, 900, 1000, 1400 and 2000 nm for each of eleven colours. In the United States, the infrared reflectance is specified by a narrow range of permissible values as shown in Figure 4. Chromium oxide alone cannot meet this requirement. Cobalt chromite spinels containing small amounts of zinc and titanium are the most effective pigments for this purpose and are tinted to the desired spectral properties with iron and chromium oxides and organic yellows, browns and violets. The optical brightness (Y), the average reflectivity in the 600 to 900 nm band, and the reflectivity ratio of the band at 700 to 900 nm to the band at 600 to 690 nm are also specified for forest green camouflage paint [39].

A solar heat reflecting lusterless olive drab enamel conforming to Australian Specification 7650/ADE(M) 146-1 [41] has been produced in the present study from some of the pigments in Table 4. This coating has a reflectivity of 42% at 800 nm and a gloss of 1. The formulation of this coating is given in Table 6.

Table 6: Solar heat reflecting olive drab camouflage enamel

Ingredient	Oil Absorption	Specific Gravity	Kilograms	Litres
Chromium Oxide[a]	22	5.12	64.20	12.58
Red Iron Oxide[b]	18	4.90	3.72	0.76
Yellow Iron Oxide[c]	36	4.03	10.55	2.65
Titanium Dioxide, 10 µm[d]	17	3.90	51.86	13.32
Magnesium Silicate[e]	45	2.75	37.14	13.51
Silicone Alkyd Resin, 70%[f]		0.96	85.37	85.31
Cobalt Octoate, 6%[g]			0.60	0.67
Calcium Octoate, 20%[h]			2.44	2.65
Zirconium Octoate, 20%[i]			0.50	0.45
Methyl Ethyl Ketoxime[j]			4.00	3.80
White Spirit[k]		0.79	20.93	25.25
TOTAL			281.31	160.95

[a] Chrome oxide G8599, Commercial Minerals Ltd.
[b] Red iron oxide RO-4097, Commercial Minerals Ltd.
[c] Yellow iron oxide YO-2087, Commercial Minerals Ltd.
[d] Tiona VC, SCM Chemicals Ltd
[e] Talc TSF, Commercial Minerals Ltd.
[f] Kemsil 2425/70, Kemrez Chemicals Division, ICI Aust. Ltd.
[g] Hardadri cobalt, Colours & Chemicals Pty Ltd.
[h] Hardadri calcium, Colours & Chemicals Pty Ltd.
[i] Hardadri zirconium, Colours & Chemicals Pty Ltd.
[j] Exkin number 2, A.C. Hatrick Chemicals Pty Ltd.
[k] White spirit, Shell Chemicals (Australia) Pty Ltd.

5.4.2 *Coatings for Desert Regions*

For these regions, natural sand and earth colours in a range of grey, orange, red, yellow and earth colours must be reproduced. For desert colours and woodland browns and black, iron oxides ranging from red to yellow to black are used. Carbon black absorbs strongly throughout the infrared and is usually proscribed in camouflage coatings, although trace levels (0.01%) can sometimes be used to bring the infrared reflectance down into specified levels. In recent times, formulations have been prepared to increase NIR reflectances to match higher reflectances in specific desert regions.

5.4.3 *Coatings for Ocean Environments*

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 topweight to the ship.

Table 7: Solar heat reflecting Light Grey camouflage enamel

Ingredient	Oil Absorption	Specific Gravity	Kilograms	Litres
Titanium dioxide, 200 nm[a]	17	4.00	9.20	2.30
Titanium dioxide, 10 µm[b]	17	3.90	84.15	21.65
Magnesium silicate[c]	45	2.75	10.34	3.74
Yellow iron oxide[d]	36	4.03	0.31	0.07
Paliogen black[e]	37	1.43	1.76	1.24
Silicone alkyd resin, 70%[f]		0.96	112.53	113.66
Cobalt octuate, 6%[g]			0.73	0.83
Calcium octoate, 20%[h]			2.95	3.21
Zirconium octoate, 20%[i]			0.60	0.53
Methyl ethyl ketoximej			3.35	3.33
White spirit[k]		0.79	13.06	15.78
TOTAL			237.98	166.34

[a] Ti-Pure R-960, duPont Australia Ltd.
[b] Tiona VC, SCM Chemicals Ltd.
[c] Talc TSF, Commercial Minerals Ltd.
[d] Yellow iron oxide YO-2087, Commercial Minerals Ltd.
[e] Paliogen black L0084, BASF Australia Ltd.
[f] Kemsil 2425/70, Kemnez Chemicals Division, ICI Australia Ltd.
[g] Hardadri cobalt, Colours & Chemicals Pty Ltd.
[h] Hardadri calcium, Colours & Chemicals Pty Ltd.
[i] Hardadri zirconium, Colours & Chemicals Pty Ltd.
[j] Exkin number 2, A.C. Hatrick Chemicals Pty Ltd.
[k] White spirit, Shell Chemicals (Australia) Pty Ltd.

5.4.4 *Coatings for aircraft*

Strict countershading principles are used by the U.S. Navy on maritime reconnaissance aircraft which involve the darkest colour on top, intermediate on the sides and lightest shade underneath. This system is used as detection from above will involve the aircraft against a sea background which has a reflectance factor to sunlight of less than 3% [49]. Viewed against a clear sky, the relative effect of paint schemes is related to the direction of view to the sun. White aircraft appear lighter than the sky when viewed down sun so light grey colours are employed. The thermal load from insolation into the P3-C aircraft painted with the U.S. Navy grey paint (which is a low infrared reflecting paint) has been determined to be 1.7 kW more than that for the same aircraft with white top half fuselage and all other surfaces grey which is the RAAF 1990 colour scheme [50]. The air temperature for this comparison was 33°C. The infrared reflectances of the high NIR reflecting paints were compared to those of standard paints of the same visual colours and are shown in Table 9. In theory, these grey colours should reduce the heat load by 50% compared to painting in standard grey colours.

6. Summary

Relevant physical laws governing the response of coatings to solar and infrared radiation have been reviewed. The reflection of infrared radiation by a paint is controlled primarily by the refractive index and particle size of the pigments in the coating. Pigments have been evaluated for reflectance, transparence and hiding power in the near infrared region, and guidelines for pigment slection for various applications given in terms of their optical properties in the near infrared region. Raw materials selection, manufacture and evaluation of coatings have been discussed with respect to tailoring infrared reflectance. By employing the principles developed herein and using pigments with appropriate properties, organic coatings have been developed which are consistent with the visible colour requirements of the Australian and US Navies. Significant increases in the reflection of infrared radiation have been demonstrated by the new formulations. The need for a very clear understanding of the threat systems and the operational conditions of service platforms has been emphasised. It is only with this understanding that optimum paint schemes can be devised. However, it can be stated that the use of the solar infrared reflecting paints 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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Relevant physical laws governing the response of coatings to solar and infrared radiation have been reviewed. The reflection of infrared radiation by a paint is controlled primarily by the refractive index and particle size of the pigments in the coating. Pigments have been evaluated for reflectance, transparence and hiding power in the near infrared region, and guidelines for pigment selection for various applications given in terms of their optical properties in the near infrared region. Raw materials selection, manufacture and evaluation of coatings have been discussed with respect to tailoring infrared reflectance. By employing the principles developed herein and using pigments with appropriate properties, organic coatings have been developed which are consistent with the visible colour requirements of the Australian and US Navies. Significant increases in the reflection of infrared radiation have been demonstrated by the new formulations. The need for a very clear understanding of the threat systems and the operational conditions of service platforms has been emphasised. It is only with this understanding that optimum paint schemes can be devised. However, it can be stated that the use of the solar infrared reflecting paints 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.