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NONELECTRONIC COUNTERMEASURES FOR INFRARED GUIDED MISSILES

PART II - USE OF FLOOR AS A COUNTERMEASURE

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ABSTRACT

The properties and performance of an "ideal" FLOOR as a countermeasure against free-falling infrared guided missiles are considered in detail to show that the use of FLOOR as a countermeasure technique cannot be considered a satisfactory solution to the countermeasure problem.

PROBLEM STATUS

This is an interim report; work on the problem is continuing.

AUTHORIZATION

NRL Problem 32C09-05D, originated at the request of BuOrd (reference BuOrd ltrs. Re9h-HOB/gip S78-1(26)004352 dated 24 July 1947 and (Re9h) SS/jgb 004768 dated 18 November 1947 to Director, NRL) in connection with BuOrd Project No. PSO-171.

NO 119-008

NONELECTRONIC COUNTERMEASURES FOR
INFRARED GUIDED MISSILES

PART II - USE OF FLOOR AS A COUNTERMEASURE

INTRODUCTION

In a previous report (1) the general problem of providing countermeasures for free-falling missiles equipped with passive infrared homing devices such as the DOVE was considered, and it was concluded that decoy techniques offer the only generally effective means for achieving adequate protection. The present report presents a detailed analysis of the use of FLOOR, which is the most widely known form of the "cold" decoy, but does not concern "hot" decoys, which are treated in a separate report (2).

FLOOR has been defined, rather loosely, as a reflecting film on water. As such, it takes advantage of the low radiant temperature of the sky, relative to that of the sea, and therefore functions as a "cold" source rather than as a heat decoy. Since passive detectors such as the DOVE respond to either "warm" or "cold" targets, the use of FLOOR is, in principle, equally as effective as a heat decoy and in addition does not require that energy be supplied to or by the decoy.

Although the use of FLOOR is not new, its performance is known only from the results of field tests made under certain specific conditions. For example, field measurements have been made under clear and cloudy skies in the daytime, but not at night. While the usefulness of FLOOR could, of course, be evaluated conclusively by such additional field tests as might be required, it seems more desirable first to calculate as accurately as possible the expected performance of an ideal FLOOR under any particular conditions of interest, and to compare insofar as possible the results with available field measurements.

IDEAL FLOOR

Consider an area of the sea covered with FLOOR. The functional requirement as a countermeasure is that the radiant energy from this surface area toward zenith be a minimum. This energy consists of (a) that transmitted by the FLOOR from the water below, (b) that emitted by the FLOOR itself, and (c) sky radiation reflected by the FLOOR. The ideal FLOOR, therefore, is one which is opaque and which has zero emittance and zero reflectance in the infrared region. But since emittance is related to reflectance by $E = 1 - R$, this ideal FLOOR cannot exist. If the reflectance of FLOOR is made to approach zero, the emittance will then approach that of a black body and the radiant properties of the FLOOR will be essentially those of the sea itself. But if the emittance is made to approach zero, so that total reflectance is realized, the radiant energy leaving an opaque FLOOR will be numerically equal to that received from the cold sky and the FLOOR will exhibit maximum thermal contrast against the sea. The only ideal FLOOR which can exist, therefore, is one which is opaque and has zero emittance; it can be described uniquely as a surface which exhibits perfect reflectance.

The reflectance as used in defining an ideal FLOOR is the hemispherical reflectance, i. e., the ratio of reflected to incident radiant energy integrated over a solid angle of 2π steradians. The term reflectance is usually encountered and impulsively associated with mirror-like or specular reflection. Although there is a similar tendency to think of a reflecting film on water in these terms, it is clear that an ideal FLOOR can be either specular or diffuse. The relationship between a specular and diffuse FLOOR is identical with that between a mirror and a photographic projection screen.

EFFECTIVENESS OF FLOOR

The relative merits of each type of ideal FLOOR can be estimated by comparing the radiant energies reflected from unit areas toward zenith, for a standard set of conditions. It will be assumed for the standard conditions that (a) the sea is perfectly smooth (so as to emphasize any differences between specular and diffuse reflection), (b) that the zenith sky has a radiant temperature of 220° K (-50° C), a reasonable value for clear weather conditions, (c) that the effective radiation is that within the 8-12 μ region, i. e., the region which corresponds roughly to the most important atmospheric transmission window, and (d) that the sea temperature is 20° C. Further, the comparison will be made on the basis of radiation toward zenith emitted by an equivalent black body, rather than that reflected by FLOOR, and will be computed relative to the radiant flux from the sea as background. For black-body comparisons, the radiant energy emitted into a hemisphere may be used instead of the radiant energy per unit solid angle (per steradian) toward zenith.

Consider first a perfect specular FLOOR on a perfectly smooth sea. The reflected radiant flux toward zenith will correspond to the energy emitted by a black body at the radiant temperature of the zenith sky. Assuming a radiant sky temperature of 220° K (-50° C), the black-body emissive power in the spectral interval 8-12 μ is approximately 2.20 watts/sq ft.[1] This is to be compared with the emissive power of the sea at ambient temperature, say 20° C, which is approximately 95 percent of that for a black body at the same temperature (3) or 9.7 watts/sq ft for the 8-12 μ interval. A net difference of -7.5 watts/sq ft relative to background is therefore obtained for an ideal specular FLOOR under the assumed conditions.

It is more difficult to calculate the approximate radiant energy reflected from an ideal diffuse FLOOR on a perfectly smooth sea because of the facts that (a) radiant energy from the entire sky, rather than from only the zenith sky, is reflected diffusely toward zenith, and (b) the radiant temperature of the sky varies with zenith angle for any given conditions. The measurements of Sanderson, Lamberson, and Smith (4) show that the apparent radiant temperature of a 220° K (-50° C) zenith sky increases with increasing zenith angle, i. e., toward the horizon, approximately as indicated in Figure 1. Variation of sky temperature with azimuth angle is relatively small and unimportant in the present considerations. Now in computing the radiant energy falling on unit area of sea (or FLOOR) the radiant flux of the sky must be integrated over the hemisphere. Elsasser (3) has shown that in this integration the effect of both the horizon and the zenith sky is zero due to a factor $\sin\theta\cos\theta$ in the calculations, where θ is the zenith angle, and that the integrated flux from the hemisphere is equivalent to that which would be obtained if the sky had a uniform radiant temperature corresponding to the actual value at 45° zenith angle. Due to the nature of diffuse reflection, however, energy incident upon the FLOOR from zenith angles greater than 60° will contribute little to the reflection towards zenith.

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[1] Radiated into a hemisphere. See Appendix.

As far as radiation toward zenith is concerned, the effective radiant temperature of the hemisphere will be less than that of the 45° zenith sky, and will correspond more nearly to the sky temperature at about 30° zenith angle.

It therefore follows from Figure 1, that for a zenith sky at -50° C the radiant energy reflected vertically by an ideal diffuse FLOOR on a perfectly smooth sea will be numerically equivalent to that emitted by a black body at about -46° C, the radiant temperature of the sky at 30° zenith angle. The energy emitted in the 8-12 μ region by a black body at this temperature is 2.48 watts/ft^2 or -7.22 watts/ft^2 relative to water at 20° C.

These calculations indicate that under ideal conditions corresponding to an average clear nighttime sky (no solar radiation) the radiant energy into a hemisphere from ideal specular and diffuse FLOORS will be 2.20 and 2.48 watts/ft^2, respectively, and that the net radiation relative to a 20° C sea as a background will be -7.50 and -7.22 watts/sq ft for ideal specular and diffuse FLOORS, respectively. Thus, under the assumed conditions, an ideal diffuse FLOOR will be about 96 percent as effective as an ideal specular FLOOR.

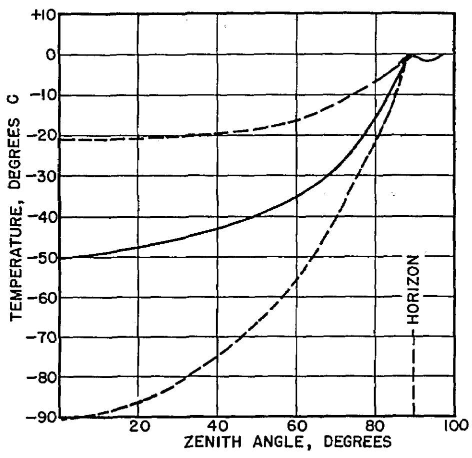

Figure 1 - Variation of radiant sky temperature with zenith distance in the 8-12 micron spectral region, (based on the data of Sanderson, Lamberson, and Smith, Reference (4)). This is a typical curve representing average values. Actual values of radiant temperature for low zenith angles vary between rather wide limits, as indicated by the dotted curves, depending upon prevailing conditions.

Effect of Rough Water

We may now remove the condition of a perfectly smooth sea, which is rarely if ever encountered. Considering first an area of sea small enough to be essentially flat, the average tilt may be taken to be approximately 15° (5). When covered with a perfect specular FLOOR, the average energy reflected from this small area toward zenith will be that from the 30° zenith sky, rather than that from the colder zenith sky. This is the condition which was previously used for a diffuse FLOOR, and which represents a decrease of 4 percent in effectiveness. Similarly, if the area were covered with a perfect diffuse FLOOR the effect of tilt would again be to decrease the net signal by about the same amount due to the increasing contribution of warmer skies at greater zenith angles. Since the effect of tilt will be the same for each of the small flat areas which go to make up the surface of the (rough) sea, it is clear that the roughness of the sea will decrease the effectiveness of both specular and diffuse FLOOR by a small amount of about 5 percent. Surface roughness, in effect, renders a specular FLOOR diffuse, and a diffuse FLOOR more diffuse, so far as total response to sky radiation is concerned.

Surface roughness will, in the case of specular FLOOR, produce a certain amount of thermal "noise." At any given instant radiation from different portions of the sky will be reflected from areas having different tilt, such as at the trough and near the crest of large waves, causing these areas to appear warmer or colder relative to one another. The thermal noise will not be so great as might be imagined, however, due to the fact that large waves are covered with smaller waves, or ripples, which render the reflection from the larger areas diffuse thereby decreasing the thermal contrast. In the case of diffuse FLOOR, where the variation of sky temperature with zenith angle is already averaged by the nature of the reflection, the tendency of the waves to produce noise will be less important.

Effect of Solar Radiation

FLOOR is most effective in clear weather, and since under this condition the atmosphere is transparent to solar radiation in the 8-12 μ region, the reflection of solar radiation by FLOOR must be considered. It is clear that for a smooth specular FLOOR the sun will have no effect until it approaches the zenith sky, whereupon its image will come within the field of view of a freely-falling missile. The reflected solar radiation will then cause the FLOOR area (or a portion of it) to function as a heat decoy, i. e., as a warm target rather than as a cold target. This has been confirmed experimentally at Tonopah, Nevada (6), where it was found that specular reflection of solar radiation from sheet metal covering a portion of an air field runway produced a positive signal relative to background whereas negative signals were produced when the metal sheet was viewed from any other direction. It is also clear, from previous discussion, that roughness of the sea will cause a specular FLOOR to reflect solar radiation more or less diffusely. In actual practice, therefore, the sun at all positions well above the horizon will effect the performance of specular FLOOR, and this effect will be to decrease the negative signal from the FLOOR and perhaps to create "noise," depending upon the nature of the waves.

A diffuse FLOOR, on the other hand, will reflect toward zenith a portion of the solar radiation for all positions of the sun except at, or very near, the horizon. To estimate the maximum value of reflected solar radiation, we may consider the sun at true zenith position. The intensity of total solar radiation (all wavelengths) reaching the earth's atmosphere (known as the solar constant) is 1.9 cal/cm^2/min (7) or 120 watts/ft^2. Assuming, for calculation, that the sun radiates as a black body at 6000° K, the radiant energy in a one-micron interval at 10 μ is 2.16×10^{-4} times the total energy. The solar radiation in the 8-12 μ interval reaching the earth's atmosphere is therefore approximately $4 \times 2.16 \times 10^{-4} \times 1.31 \times 10^6 = 1.12 \times 10^3$ ergs/cm^2/sec. Even if there were no attenuation by atmospheric absorption—which there most certainly is—the 8-12 μ solar radiation from a zenith sun would amount to only 0.10 watt/sq ft at the surface of the ocean. The reflected solar radiation in the 8-12 μ region is therefore seen to be small compared either to the radiant flux above background for a battleship (approx. 5 watts/sq ft) (8) or to that calculated for an ideal FLOOR (approx. -7 watts/sq ft).

The effect of 8-12 μ solar radiation upon the use of FLOOR as a countermeasure will therefore be twofold. First, it will decrease the negative signal from the FLOOR relative to the sea by a small amount, as just explained. Second, due to surface heating and reflection it will increase the (positive) signal from naval targets relative to the sea as a background. Both effects tend to decrease the effectiveness of FLOOR, but the latter will probably be the more important since the 8-12 μ emissive power of a black-body naval target will increase approximately 0.16 watt/sq ft for each degree (centigrade) temperature rise of the target whereas the change in total radiant flux reflected from FLOOR due to 8-12 μ insolation will not be more than 0.1 watt/sq ft. If this temperature rise does not exceed a few degrees, however, the combined effects of 8-12 μ solar radiation cannot effect appreciably the performance of an ideal FLOOR on actual (rough) sea under the assumed conditions.

For missiles which do not operate exclusively within the 8-12 μ spectral region, however, the effect of solar radiation cannot be dismissed. Moreover, since none of the filters so far proposed for guided missile use are perfect, it must be assumed that all missiles, and certainly those equipped with the DOVE, will exhibit some response to radiation in other atmospheric windows. Further, it is certain that reflected solar radiation can in certain instances produce large thermal signals, since it has frequently been observed that unfiltered thermal detection equipment is "blinded" by reflected sunlight.

The intensity of solar radiation increases rapidly on going to wavelengths shorter than 8 μ, whereas the intensity of radiant energy emitted by the sea or naval targets decreases rapidly. It is for this reason that heat-homing missiles must respond to 8-12 μ radiation if they are to detect naval targets, and it is also for this reason that radiation of shorter wavelengths is important only in solar radiation effects. In Table 1 the calculated intensity of solar radiation at sea level is given for several spectral windows beyond 0.7 μ.[2] It is seen that the solar intensity (for zenith sun) through all of the windows above 1.5 μ may amount to 5.8 watts/sq ft, i. e., a value approximately equal to the net flux calculated for perfect FLOOR. If the window at 1 μ is included, the intensity increases to about 38 watts/sq ft, and if shorter wavelengths are included the intensity may amount to as much as 100 watts/sq ft.

Since solar radiation would be completely reflected by ideal FLOOR, whereas only a fraction of it would be reflected by the sea or naval targets, it is evident from the calculated data in Table 1 that ideal FLOOR (either specular or diffuse) may function in the presence of strong solar radiation as an effective hot decoy, rather than a cold decoy, against a missile operating on total radiation. Furthermore, since FLOOR acts as a hot decoy, under certain daytime conditions and by night as a cold decoy, there must be intermediate times (when the sun is at greater zenith angles) when FLOOR thermally blends with the sea and affords no protection whatsoever. In addition, if the sun should be intermittently obscured by an isolated cloud, FLOOR might appear alternately as a hot and cold decoy, and again be ineffective during the transitions.

If the missile is equipped with a filter opaque to all wavelengths shorter than 5 μ, it is clear that diffuse FLOOR cannot then appear as an effective heat decoy. If the filter transmits 1 percent below 8 μ, however, the effective solar intensity at sea level may still amount to as much as 1 watt/sq ft. This amount, when added to the reflected flux above background (-7 watts/ft^2) calculated for ideal FLOOR, brings the total within range

TABLE 1
Intensity of Solar Radiation

Spectral Window	Intensity* (watts/sq ft)	Water		Naval Targets		Ideal Floor	
		Average Reflectance(9)	Reflected† Solar Radiation	Average Reflectance‡	Reflected† Solar Radiation	Average Reflectance	Reflected† Solar Radiation
0.7 - 1.1	32.3	.02	.65	.10	3.2	1.0	32.3
1.5 - 1.7	2.6	.02	.05	.10	.26	1.0	2.6
2.1 - 2.3	1.5	.02	.03	.10	.15	1.0	1.5
3 - 4	1.6	.03	.05	.05	.08	1.0	1.6
8 - 12	0.1	.01	---	.05	.01	1.0	0.1
Total§	38.1		.77		3.70		38.1

* At sea level (calculated values)
† Watts/sq ft reflected into a hemisphere
‡ Approximate values for 20B standard deck paint
§ The total for all wavelengths is approximately 100 watts/sq ft (average)

2 These values were obtained in exactly the same way as described previously for the 8-12 μ solar radiation. The transmission has been assumed to be 100 percent for each window interval.

of radiant flux from naval targets (5-6 watts/ft^2), and may therefore have an important effect upon the performance of FLOOR. It is clear, then, that the effects of solar radiation upon the use of FLOOR can be dismissed only in the case of missiles which are equipped with filters transmitting practically no short-wave radiation. A transmission of 0.1 percent would in most instances reduce the effects of solar radiation to a tolerable level, but a much lower transmission would be required to render them undetectable.

It may be noted that solar radiation tends to increase the (positive) signal from naval targets, first, by increasing the emission due to surface heating, as mentioned previously, and second, by reflection, as indicated by the approximate values in the sixth column of Table 1. Therefore, the effects of solar radiation upon FLOOR and upon targets do not cancel. As the positive signal from a target is increased, the negative signal from the FLOOR is decreased, as is the protection. Hence, even small solar radiation effects tend to become important, particularly in the case of missiles equipped with imperfect filters. Further, since surface heating (by all wavelengths) of naval targets increases their 8-12 μ emissive power, this effect exists regardless of filters.

Effect of Clouds

The radiant temperature of clouds and overcast may be either warmer or colder than that of the sea, but they are always warmer than the blue sky and hence reduce the thermal contrast between FLOOR and sea. The apparent radiant temperature of the sky therefore varies over wide limits depending upon atmospheric conditions, as indicated roughly by the dotted lines in Figure 1. The lower the radiant sky temperature and the higher sea temperature (in degrees Kelvin), the greater will be the effectiveness of FLOOR. For example, if the sky could achieve radiant temperatures as low as absolute zero, the 8-12 μ radiant flux from a perfect FLOOR could vary between -11.4 and 0.0 watts/sq ft relative to background as shown in Table 2.

TABLE 2
Relation of Sky and Sea Temperature to the 8-12 μ Radiant Flux Above Background for Ideal "Floor"

Sea Temperature (° C)	Radiant Flux* from Ideal "Floor" for Effective Radiant Sky Temperatures of:				
	-273° C	-100° C	-50° C	0° C	+25° C
0	- 6.9	- 6.6	-4.7	+0.3	+4.2
10	- 8.2	- 7.9	-6.0	-1.0	+2.9
20	- 9.7	- 9.4	-7.5	-2.5	+0.9
30	-11.4	-11.1	-9.2	-4.2	-0.9

*Watts/sq ft relative to sea as background, calculated for the 8-12 μ region by black-body radiation laws. Emissivity of sea water is assumed to be 0.95.

Variation in sea temperature is mainly seasonal and geographical, and is slow in time. Except for conditions created by a ship's wake, and perhaps at the boundaries of certain ocean currents (such as the Gulf Stream), the sea exhibits by emission a uniform thermal background. But sky radiation, like solar radiation, may vary rapidly with time in cloudy weather. For example, total daytime radiation during high fog has been observed (11) by means of a hemispherical radiometer to change from 350 to 250 Btu/hr/sq ft in a period of five minutes. Although 8-12 μ radiation may or may not fluctuate so greatly, percentagewise, it must certainly change similarly with time. Since this can occur only when the intensity varies rapidly over small adjacent surface areas, (at sea level), clouds and overcast may under these conditions cause FLOOR to produce an appreciable amount of thermal noise. Such noise will of course be averaged out to some extent by surface roughness, and will be less for a diffuse FLOOR than for specular FLOOR.

POTENTIALITY OF FLOOR

The potentiality of FLOOR as a countermeasure may now be estimated by comparing the radiant energy above background from perfect FLOOR surfaces to that from naval targets. Since actual FLOOR surfaces cannot be assumed to be perfect, calculated rather than experimental values must be used. Those given in Table 2 are satisfactory for this purpose if the comparison is made on the basis of radiation at sea level within the 8-12 μ spectral interval. The fact that the wavelength limits and transmission of the atmospheric window in this region are somewhat different will not affect the argument, since the signals produced at altitude (at the missile) by FLOOR and by target will be scaled equally in accordance with atmospheric transmission, thus preserving the comparison.

Using the black-body radiation laws, and assuming that the average radiant temperature of naval targets may be as much as 20° C above that of the sea, radiant flux values of from 0.0 to +6.0 watts/sq ft (in the 8-12 μ region) relative to background are calculated, depending upon the emittance of the ship and the thermal difference between it and the sea. A negative value from naval targets may also occur (as has been observed experimentally) when the ship is cooler than the sea, or when a ship having a low surface emittance is at the same or lower temperature than the sea, and may amount to as much as -5.0 watts/sq ft. Therefore, naval targets may in general be expected to emit from -5.0 to +6.0 watts/sq ft (usually a positive value) relative to background. It may be noted that this is in good agreement with the experimental value of 5 watts/sq ft for a battleship (8).

The 8-12 μ radiant flux computed for perfect FLOOR, on the other hand, ranges from 0.0 to -9.5 watts/sq ft relative to background (this should be decreased by approximately 5 to 10 percent to allow for the effect of rough water and diffuse reflection), and in no case may exceed -11.5 watts/sq ft (Table 2), the value calculated for a nonradiating sky and a 30° C sea.

It is seen, therefore, that at best the radiant flux above background for a decoy composed of FLOOR will exceed that for a good naval target by only 1 to 3 watts/sq ft (16 to 50 percent). This means that under optimum conditions a FLOOR area 66 to 86 percent that of the target is required to produce an equivalent signal, and an equal or larger area would be required for positive protection. However, since increasing the area of a decoy beyond that of the target offers no additional protection against missiles having adequate resolution, it appears desirable both for functional and for tactical reasons that the area of the decoy should be comparable to (or preferably slightly smaller than) that of the target. It is evident, therefore, that the protection offered some ships by FLOOR under optimum conditions will constitute only a small margin of safety.

When the effect of clouds and solar radiation, both of which decrease the effectiveness of FLOOR as a cold decoy and at times render it completely ineffective, are taken into consideration it becomes clear that FLOOR can offer protection to some ships only a fraction of the time they are at sea, and even then with only marginal safety. Therefore, it cannot be considered an adequate countermeasure technique for general use against heat-homing missiles. For targets which do not give very strong signals, proper use of an ideal FLOOR could confidently be expected to afford adequate protection on clear nights, and probably under most clear daytime skies, and might be recommended for use at such times if tactical considerations (maneuverability, etc.) permit.

ACTUAL FLOOR MATERIALS

If there were no alternative to the use of FLOOR as a countermeasure, a serious attempt to evaluate both by laboratory and field measurement the properties of actual FLOOR materials in terms of ideal materials would of course be justified. But in view of the apparent advantages of heat decoys (2), it appears both unnecessary and inadvisable, at least at this time, to direct further effort toward evaluating or increasing the effectiveness of FLOOR as a technique for the general solution of the countermeasure problem. Nevertheless, since FLOOR may have some value for restricted use a brief qualitative description of actual FLOOR materials is pertinent. Since the margin of safety offered by ideal FLOOR appears to be rather small, actual materials must not deviate too far from ideal if they are to have any value at all as a countermeasure.

The functional criteria for a FLOOR material require that it have high reflectance (low emittance) and that it float as a coherent opaque film on water. The best infrared mirrors, prepared by evaporating an aluminum film onto a mirror blank, reflect up to 98 percent of the incident radiation over a considerable wavelength range extending from the ultraviolet far out into the infrared. Other pure metals also have high reflectivity in the infrared (Table 3), although many are unsuitable for use as mirrors because of the formation of low-reflective coatings on the surface.

TABLE 3
Fraction of Normally Incident Infrared Radiation
Reflected by the Polished Surfaces of Various Metals*

Metal	Wavelength in Microns					Metal	Wavelength in Microns				
	4	7	9	10	12		4	7	9	10	12
Aluminum	.92	.96	--	.98	.98	Palladium	.88	.94	--	.97	.97
Antimony	.68	--	.72	--	--	Platinum	.92	--	.95	--	--
Bronze (68 Cu 32 Sn)	.88	--	.93	--	--	Rhodium	.92	.94	--	.95	--
						Silicon	.28	.28	--	.28	--
Cadmium	.96	.98	--	.98	.99	Silver (chem. dep.)	.99	--	.99	--	--
Cobalt	.81	.93	--	.97	.97	Speculum Metal	.89	--	.92	--	--
Copper	.97	--	.98	--	--	Steel	.88	--	.93	--	--
Gold	.97	--	.98	--	--	Stellite	.83	--	.88	--	--
Graphite	.48	.54	--	.59	--	Tantalum	.93	.94	--	--	.95
Iridium	.94	.95	--	.96	.96	Telurium	.57	.68	--	--	--
Iron	.89	--	.94	--	--	Tin	.72	.81	--	.84	.85
Magnesium	.83	--	.93	--	--	Tungsten	.94	--	.95	--	--
Molybdenum	.90	.93	--	.94	.95	Vanadium	.79	.88	--	--	--
Nickel (elec.)	.91	--	.96	--	--	Zinc	.97	.98	--	.98	.99

*From "Handbook of Chemistry and Physics," Chemical Rubber Publishing Co. (1949)

Metallic powders, such as are used in aluminum and bronze paints, are available commercially in a form which will float on water with a tendency to spread over the surface in a more or less continuous film. Because of their high visibility in sunlight these powders can be used in rescue work for air identification of personnel forced down at sea (12). These same powders, in particular those composed of aluminum, are the only materials so far proposed and tested (13, 14, 15, 16) for use as FLOOR (1).

Commercial metallic powders are made of various pure metals, or of various alloys, and have different particle size distributions. The shape of the particles also varies, the larger particles usually being flattened or leaf-like due to the process used in their preparation. The particles are also coated with various chemicals, chiefly polar hydrocarbon derivatives, to prevent "welding" during manufacture, and it is the hydrophobic property of this chemical coating which causes the particles to spread out and float on the water surface. Since a single monolayer can render a surface hydrophobic, the attenuation of infrared radiation by the coating will be negligible if the thickness of the coating is not excessive.

A photomicrograph of a typical film of commercial aluminum powder on water is shown in Figure 2. Such films appear to be nearly opaque, and this is borne out by experiment. For example, a film picked up from the water surface on a sheet of silver chloride without disturbing the particle orientation, transmitted less than 5 percent (forward scattering) throughout the visible and infrared spectral range (to 15 μ). Only a small fraction of the radiant energy emitted by water is transmitted by a film of close-packed metallic particles, therefore, and may be neglected.

It is also evident from Figure 2 that only the larger particles are very much flattened, and that even these do not lie flat on the water surface. Radiation reflected from such a surface may therefore be expected to be predominantly of a diffuse nature, rather than specular. This was confirmed by a simple laboratory experiment. When films were prepared from a series of commercially available aluminum powders and the reflection at 45° incidence compared to that of a plane reference mirror in an experimental arrangement for specular reflection,[3] the values obtained for the specular reflectance fell within the range 2 to 10 percent for radiation peaked at 2 μ, and were slightly higher (10 to 20 percent) for radiation in the 8-13 μ region. The actual distribution of the reflected radiation over a hemisphere was not measured, but is probably intermediate between that for a specular and a diffuse (cosine law) reflector. This is of minor importance, however, since it has already been shown that there can be very little difference in the effectiveness of specular and diffuse FLOOR, except for the effects of solar radiation. Of greater importance is the value of either the hemispherical reflectance or emittance, neither of which are accurately known.

Some idea of the effectiveness of aluminum FLOOR can be formed from available field measurements, but these measurements do not permit an evaluation in terms of an ideal FLOOR. This could be done, for example, by comparing the radiant temperature of the zenith or near zenith sky as determined at sea level, first, by direct observation of the sky, and second, after reflection from FLOOR. In making the latter observation, however, sky radiation must not be blocked off from the FLOOR by the observation equipment, and this difficulty has not been eliminated in reported measurements. If the measurements are made at an altitude rather than at sea level, so that the size of the observer becomes unimportant, there must then be taken into account the variable and uncertain transmission of the atmosphere.

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[3] The area ($\sim 1\ cm^2$) of the reflecting surface was masked so that the angle subtended by the detector included only the source.

Figure 2 - A microphotograph of a typical FLOOR film on smooth water
Magnification approximately 40x

Sanderson (13) on one occasion measured (at sea level, with a 7.5-10 μ transmission filter on the detector) a radiant temperature of -11^{0} C for aluminum FLOOR on a clear day, but reported no direct measurement of the radiant sky temperature for comparison. The sea temperature was 19^{0} C, and the total flux (all wavelengths) above background leaving the FLOOR area was calculated to be -12.5 watts/ft^2. At these temperatures approximately one-fourth of the total radiant flux, or about -3 watts/ft^2, falls within the 8-12 μ spectral interval. On a "partly cloudy" day the radiant temperature of FLOOR was 2^{0} C, that of the sea was 17^{0}C, and the calculated total flux relative to background was -7 watts/ft, of which less than -2 watts/ft would be in the 8-12 μ interval. On a completely overcast day the radiant temperature of the FLOOR was the same as that of the sea, and the FLOOR was completely ineffective with respect to 7.5 to 10 μ radiation.

On another occassion Sanderson (15) measured[4] the radiant temperature of both FLOOR and sky, as observed from shipboard at angles within ±15° from the horizon. However, in this instance the sky and sea temperatures differed by only 1 to 4^{0} C, so that a difference by this amount in the observed radiant temperature of FLOOR under these conditions would represent the difference between 100 percent effectiveness and zero

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[4] With an instrument having 1/2° square field of view and equipped with a filter opaque below 2.3 μ and transmitting 70 percent in the 8-13 μ region.

effectiveness of FLOOR. The radiant temperatures observed for the aluminum FLOOR were actually a degree or two below, rather than above, the corresponding radiant temperatures of the sky. Although a summary of the results (16) indicated that the radiant temperature of aluminum FLOOR can be assumed to be essentially that determined by direct observation of the sky, the main conclusion reached on the basis of the measurements was that 8-13 μ radiant energy at low angles of incidence was reflected diffusely by aluminum FLOOR (either because of the nature of the metallic film or because of the surface roughness of the sea), thereby accounting for the low radiant temperatures observed for the FLOOR.

The radiant temperature of the zenith sky on this occasion (not a clear day) was +6.5°C, a rather high value. If this value is assumed for the radiant temperature of the FLOOR as viewed from zenith, the total radiant flux relative to the sea at 27° C is calculated to be -10.5 watts/ft^2 of which about -2.6 watts/ft^2 is within the 8-12 μ region.

The performance of aluminum FLOOR is also known in terms of the signals produced at 10,000 ft altitude (14, 15). A summary of the results (15) states that in clear weather, and at a viewing angle of 30°, signals of about -1.5 erg/cm^2/sec above background are produced by 10,000 ft^2 of FLOOR. On an overcast day corresponding signals of from -0.2 to 0.4 ergs/cm^2/sec were observed. In both cases the detectors were equipped with far infrared filters, so that the observed signals represent energy transmitted mainly through the 8-13 μ atmospheric window. These signals may be compared with those from naval targets measured in the same way. The average value of the latter is reported (6, 16) to be about +0.4 ergs/cm^2/sec above background for each 10,000 ft^2 of target surface. From these data it would appear that for equal areas of decoy and target, aluminum FLOOR will offer adequate protection[5] for the average naval target in clear weather, but not in the presence of overcast skies.

Since aluminum has such high reflectivity, and since specular and diffuse FLOOR may be expected to exhibit very nearly equal effectiveness, there appears little to be gained in seeking other FLOOR materials. With regard to the effects of solar radiation, some improvement might be achieved by treating the aluminum or by using a different material which would make the FLOOR absorbent at short wavelengths without decreasing the reflectance in the 8-12 μ window. If it should ever be established for any reason that specular FLOOR has significant advantages over diffuse FLOOR, some improvement in aluminum FLOOR might be achieved by controlling the particle size and shape, and/or the hydrophobic coating so as to obtain greater flatness of the film. It is doubtful, however, that metallic powders can ever function effectively as a specular FLOOR. It appears more likely that this could be achieved by using a confetti-like material, i. e., a FLOOR composed of larger, flat, thin sheets or discs coated with a reflective material and made hydrophobic by an adsorbed chemical film. For example, glass can be blown out into thin films, broken and sieved for particle size, and silvered en masse to obtain smooth, thin, relatively flat, mirror-like flakes which can be made to float as a film. Other materials such as mica or even plastic might be used, and can be covered with a reflective coating of aluminum or other material which would not be attacked by sea water. Since close packed circular discs cover approximately 90 percent of the surface, an efficient specular FLOOR could probably be prepared from high-reflective materials in this form.

A possible alternative to metallic or metallic-coated materials for use as effective FLOOR may be found in crystalline materials which exhibit selective reflection (residual or restrahlen bands) in the region of 8-12 μ. Apophylite (3) and quartz, for instance,

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[5] Against heat-homing missiles operating within the 8-13 μ atmosphere window.

have a region of high reflectivity (approaching 100 percent) in this region. A layer of crystals or mixture of crystals floating on water should therefore serve as a reflecting film over a limited spectral interval, provided, of course, that the crystals have appropriate size, shape, etc. Crystalline materials do not appear to offer any advantages over metallic FLOOR, however, and should not be considered seriously. The volume and weight of crystalline FLOOR required to cover a given area, for example, would greatly exceed that of a metallic FLOOR.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of previous experimental data and the results of the present approximate calculations it is concluded that:

1. An "ideal" FLOOR consists of an opaque film which exhibits 100 percent reflectance in the infrared. An ideal FLOOR may be either specular or diffuse, depending upon whether incident radiation if reflected specularly or diffusely. The effectiveness of an ideal diffuse FLOOR will be nearly equal, but less than, that of an ideal specular FLOOR as a countermeasure against free-falling infrared guided missiles.

2. For average clear weather conditions the radiant flux which may be expected from an ideal FLOOR relative to sea water at 20° C is of the order of -6 to -7 watts/sq ft for the 8-12 μ spectral interval. Cloudy or overcast skies, rough water, and the presence of solar radiation tend to decrease the effectiveness of FLOOR and (in the case of missiles not equipped with filters for operation within the 8-12 μ atmospheric window) may render it completely ineffective.

3. Since the radiant flux values expected from ideal FLOOR exceed those from strongly emitting naval targets, e. g., battleships, by only 1 to 3 watts/sq ft (for the 8-12 μ region), the protection offered by FLOOR under optimum conditions will be marginal, i. e., the safety factor will be small. And since under less favorable conditions the protection offered by ideal FLOOR will be inadequate, the use of FLOOR cannot be considered a satisfactory technique for the general solution of the countermeasure problem.

4. Available experimental data is not sufficient to show that aluminum powders now available for use as FLOOR have the properties of an ideal diffuse FLOOR material. However, none of the other metallic, metallic-coated, or crystalline materials which are suggested as possible alternatives for aluminum FLOOR appear to offer any advantage.

It is accordingly recommended that:

1. Future work toward the solution of the countermeasure problem should be directed toward the use of "hot" decoys (heat-forming materials) rather than toward the evaluation or improvement of existing or new FLOOR materials.

2. FLOOR should be considered for only restricted use as a countermeasure technique. For naval targets which have relatively small thermal signals its use may be recommended only during clear weather (preferably at night), and then only when tactical criteria (limitation of target maneuverability, etc.) permit.

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APPENDIX A
Black-Body Radiation

A body which absorbs all incident radiation, and reflects none, is called a black body. Because of the relation $E = 1 - R$, where R is the reflectance, a black body has unit emittance and is, by definition, a perfect emitter of radiant energy. The rate at which energy of all wavelengths is emitted by unit area of surface into a hemisphere, called the hemispherical emissive power, is given by the Stefan-Boltzmann law, $E = \sigma T^4$, where σ is a constant and T is the absolute (Kelvin) temperature. The value of $\sigma = 5.709 \times 10^{-5}$ gives E in ergs/cm²/sec, and $\sigma = 5.309 \times 10^{-9}$ gives E in watts/ft². The total hemispherical emissive power of a black body is given in the third column of Table 4 for several temperatures mentioned in this report.

TABLE 4
Black-Body Radiation

Temperature		Total Hemispherical Emissive Power	Spectral Emissive Power at 10 μ	Emissive Power (8-12 μ)
°C	°K	Watts/ft²	Watts/ft²	Watts/ft²
-273	0	0	0	0
-100	173	4.76	0.08	0.34
- 50	223	13.14	0.55	2.20
- 46	227	14.10	0.62	2.48
0	273	29.50	1.81	7.24
+ 10	283	34.10	2.16	8.64
+ 20	293	39.20	2.56	10.24
+ 25	298	41.80	2.78	11.12
+ 30	303	44.80	3.00	12.00

The spectral emissive power of a black body at wavelength λ and temperature T is given by Planck's law

$$E_\lambda = \frac{C_1 \lambda^{-5}}{e^{C_2/\lambda T} - 1}.$$

If λ and T have units of microns and degrees Kelvin, then $C_1 = 3.48 \times 10^7$ watts/ft²/micron and $C_2 = 14{,}384$ micron-degrees gives E_λ in watts/ft²/micron at wavelength λ. Values of E_λ at 10 μ are given in column 4 of Table 4. In the last column are given values of the emissive power in the 8-12 μ region, assuming that the average spectral emissive power over this region is that at 10 μ; for temperatures near 300° K the correct values are slightly less than those given.

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APPENDIX B
Relationship Between Radiant Flux Emitted and Radiant Flux Signal

If a body at sea level is emitting (or reflecting, or transmitting) energy into a hemisphere at a given rate per unit exposed area (watts/ft^2) it is necessary to know the angular distribution of the flux over the hemisphere in order to compute the signal (the flux incident upon unit area) at a given distance and angle from the emitting surface. For a point source, the total radiant flux is distributed uniformly over the surface of a sphere (a solid angle of 4π steradians) having the source at its center. For a point source, then, the radiant flux per unit solid angle (per steradian) is $1/4\pi$ x the total radiant flux, or $1/2\pi$ x the total radiant flux into a hemisphere, and is independent of angular direction. But for an actual surface, the emitted flux per steradian will not be independent of angular direction.

The radiant flux from many surfaces follows closely the cosine law which states that, for emission or for reflection at normal incidence, the radiant flux per steradian along a direction θ degrees from the surface normal is equal to $\cos\theta$ x the radiant flux per steradian along the normal. For this case it may easily be shown that the radiant flux per steradian along the normal is $1/\pi$ x the total radiant flux into a hemisphere. Values of the radiant flux into a hemisphere given in this report should therefore be divided by π to obtain the radiant flux per steradian toward zenith. Thus, a target which emits 5 watts/ft^2 into a hemisphere, emits $5/\pi$ watts/ft^2/steradian toward zenith.

The radiant flux incident upon unit area at a distance λ from a source is given by the flux per unit solid angle emitted in that direction x the solid angle subtended by unit area. Thus, if one sq ft of source area is emitting 5 watts into a hemisphere, or $5/\pi$ watts/steradian toward zenith, the signal produced at 10,000 ft altitude is $5/\pi \times 1/10^8$ watts/ft^2 or $1.07 \times 10^4 \times 5/10^8\pi$ ergs/cm^2/sec, assuming no attenuation of radiant energy by the atmosphere. The total signal from a 10,000 ft^2 target emitting 5 watts/ft^2 is then $1.07 \times 5/\pi = 1.7$ erg/cm^2/sec at 10,000 ft. If the emission of the target is that relative to background, or in a particular spectral interval, the same conditions apply to the calculated signal.

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