Evaluation of infrared signature suppression of ships

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ABSTRACT

Reduction of the infrared signature of warships helps to increase their survivability. Two methods to reduce the infrared signature are discussed: the cooling of exhaust gases and the application of low emissivity paint. The infrared signature of a generic frigate has been calculated with and without signature reduction. The signature values are used to determine the lock-on range of four generic infrared seeker heads of anti ship missiles ranging from hot spot seekers to imaging seekers. From the reduction in lock-on range the reduction in hit probability is calculated. The results show that both exhaust gas cooling and low emissivity paint contribute to the survivability of a warship.

Key words: Infrared signature, Exhaust gas radiation, low emissivity paint, infrared guide missiles, anti surface ship missiles, hit probabilities, survivability.

1. INTRODUCTION

Infrared signatures of warships have been of interest since several decades. Improved design and the use of special paint on these ships may significantly reduce the infrared signature. However, rather than the reduction of the signature itself, the final goal is an increase in ship survivability. The interest in signature reduction must be related to the defense of ships against infrared threats. Apart from signature reduction also other countermeasures (CM) as infra red decoys and jammers, can provide protection against infrared threats. In some cases a combination of signature reduction and other CM is required to counter a threat successfully.

Against this background there is an ongoing discussion on how to balance the efforts and costs of infrared signature reduction with expenses for other infrared countermeasures. Basically one would like to measure the increase in survivability of a ship according to objective standards. This paper will not try to provide these standards and will deal with all elements which determine the effectiveness of infrared signature reduction.

In the first part of this paper the infrared signature aspects in general will be discussed. The second section will define four generic infrared guided missile threats. In the remainder of this paper the effect of signature reduction measures on the hit probability by these missiles will be discussed. Two signature suppression methods are discussed: cooling of the exhaust gases and application of low emissivity paint. This paper is based on a study on signature reduction for a generic frigate, built according to the design rules of the late 1980's.

2. INFRARED SIGNATURES

The amount of infrared energy emitted and reflected by a ship is highly variable. For example it depends on the power dissipated on board and the meteorological conditions. Roughly one can divide the infrared sources in the stack and the hot gases from the engines on the one hand and the superstructure and the hull of the ship on the other hand.

The hot exhaust gases of the engines are important contributors to the signature of the ship. The amount of hot gases depends on the power setting of the engines. The gases emit mainly in the 3 to 5 µm band. At short ranges they are the dominant factor in this band. At longer ranges (above a few miles) the atmosphere absorbs the plume radiation strongly. The radiation of the gases is calculated using the same approach as NIRATAM (NATO Infrared Air Target Model)[1] which provides a rigorous treatment of the radiation of exhaust gases. The model uses a correlated treatment for the emission and the absorption of exhaust gases in the plume and in the atmosphere. Therefore, for each different range a new calculation had to be done.

Apart from the emission by the gases themselves, a second effect of the hot exhaust gases is that heat is transferred to the stack and to parts of the superstructure of the ship by radiation and convection. These parts become hot spots and

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contribute significantly to the signature in both atmospheric windows (3-5 μm and 8-12 μm). Another effect of the hot gases is that they might degrade the performance of infrared sensors and possibly other sensors as well.

The infrared emission of the hull and the superstructure is governed by the temperature and the emissivity of the surface. For a well insulated ship the outside temperature of a ship is determined to a large extent by the temperature of the ambient air. The emissivity (emission coefficient) of the surface determines the ratio between emission and reflection at the surface. When the emissivity is 100%, the surface emits as a blackbody source. When the emissivity deviates from unity, radiation from the background is partially reflected at the surface. This can already be observed for normal paints with emissivities between 0.90 and 0.95, where two surfaces with exactly the same temperature can look different in the infrared due to different reflected backgrounds e.g. "cold" sky and "warm" sea.

Instead of defining all parameters in a very detailed way for a detailed calculation, the signature is approximated by calculating the blackbody radiation of a block like structure. Figure 1 gives a schematic drawing. To simulate a "hot" and a "cold" environment the ship surface temperature is set at +10°C and +2°C above the sea water temperature. Negative temperature differences may occur at night. A special case of 0°C contrast between ship and background is also considered. The transmission losses in the atmosphere are calculated using LOWTRAN7[2]. The construction of the stack is such that the top of the stack is in a horizontal plane and will therefore in first approximation not allow sea skimming missiles to see any hot parts of the uptake.

For detection purposes one is not only interested in the emission of the target itself, but a certain minimum contrast level is required for detection. Depending on the position of the sensor the ship is seen either against a sea background or a mixture of sea and sky background. As for the surface of the ship, the radiation from the surface of the sea depends on the temperature and surface conditions. Again both sea water temperature and surface structure vary with meteorological conditions. Apart from the absolute radiance of the sea surface which determines the ships contrast, also variations in the background radiance must be considered. This clutter is defined here as the variations in sea surface radiance with spatial frequencies which match the instantaneous field of view of the seeker. Fluctuations are either due to temperature differences or emissivity variations. Medium clutter is defined as a contrast fluctuation over the sea surface with an amplitude ΔT of 2°C. This is typically the case for sea surface with waves which curl over. Maximum clutter shows fluctuations with $\Delta T =$ 10°C. Maximum clutter will occur only in extreme cases such as sun glint. It must be noted that the clutter defined here ignores temporal and spatial correlation of the wave motions and ignoring variations in the emissivity at sea surfaces.

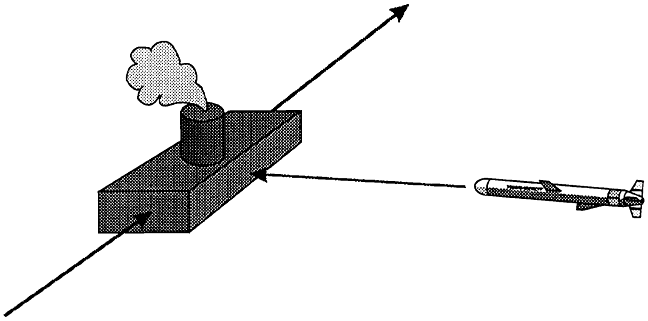

Figure 1 : Schematic drawing of ship and threat

3. INFRARED THREATS

In this paper four generic missile threats will be considered. The characteristics are given in table 1. Each threat represents a class of missiles. Class I and II represent the first and second generation of infrared seekers respectively. Class III and IV represent "state of the art" technology for imaging seekers.

For this study the lock-on range is only determined by the irradiance threshold. For the spot seekers no other detection criteria which require signal processing are taken into account. The imaging seekers require at least a closed area of 10 pixels on the target before the seeker locks-on; the ship intensity is assumed to be distributed homogeneously over this area.

In the ideal case, for a homogeneous background without clutter, the irradiance threshold is only limited by the sensor noise level. In the case of a cluttered background the maximum detection range is limited by the background clutter. The assumed instantaneous field of view and the resulting detection thresholds with clutter are also listed in table 1.

All infrared guided anti surface ship missiles (ASSM) considered here are assumed to be sea skimmers. For this reason only the infrared signature for near horizontal aspects is of interest. Possible pop-up movements in the last part of the missile flight will not be considered because these take place after the seeker has locked on the ship. During the roll movement of the ship the top of the stack and the inner part of the uptake become visible. However, the roll angle is not permanent and a seeker will not be able to lock-on permanently on parts of the ship which become only visible during roll. Still, some lock-on range calculations have been performed for 5° elevation angle. The signature at this elevation might also be a good estimate for the signature as seen by surveillance aircraft at long range. However, one has to keep in mind that surveillance sensors will be in general more sensitive than seekers, which results in much larger detection ranges.

Table 1 Characteristics of the 4 generic seekers

Seeker Class	I	II	III	IV
Category	Spot	Spot	Imaging	Imaging
Detector type	PbS	InSb	InSb	CMT
Wavelength band (μm)	3-4	3-5	3-5	8-12
IFOV (mrad)	5	5	0.5	0.5
Irradiance threshold for detection (W/m^2)				
noise limited	2.0 10^{-6}	1.0 10^{-7}	5.0 10^{-9}	5.0 10^{-8}
med clutter limited	5.0 10^{-6}	2.5 10^{-6}	2.5 10^{-8}	2.5 10^{-7}
max clutter limited	7.5 10^{-6}	1.0 10^{-5}	1.0 10^{-7}	1.0 10^{-6}
Search area				
horizontal (°)	20	20	20	20
vertical (°)	4	4	4	4
Lock-on area				
horizontal (°)	1	1		
vertical (°)	1	1		
pixel area			10 pixels	10 pixels
Missile speed (m/s)	300	300	300	300
Flight altitude (m)	30	30	30	30

4. LOCK-ON RANGE REDUCTION BY COOLING OF EXHAUST GASES

One of the methods to reduce the infrared signature of a ship is to cool the exhaust gases. Here we analyze the effect of cooling of the gases first by calculating the resulting signature reduction and subsequently calculating the lock on range for the four seekers. As a basis for the calculations we take a generic frigate. This ship has two diesel and two gas turbine engines. By mixing air at ambient temperature into the exhaust flow, it is assumed that the gases are cooled from 340°C to 220°C for the diesel exhaust and from 420°C to 250 °C for the gas turbine plumes. This is at the cost of a larger volume of exhaust gases.

The radiation contrasts as a function of range in the relevant threat bands for plume and ship are added and converted into irradiance levels. When the irradiance rises above the detection thresholds for the spot seekers in table 1 a lock-on is assumed. Figure 2 gives a typical example for the case of gas turbine propulsion for class II. The resulting lock-on ranges from this plot and all other cases, are listed in table 2 and 3 for the diesel and gas turbine exhaust respectively. As expected, the largest change in lock-on range is observed for the "cool" ship and the gas turbine exhaust case. To test the effect of plume signature suppression the case of $\Delta T = 0°C$ is added.

To test the effect of roll the same calculations were done for an elevation angle of 5°. Here the hot metal parts of the upper part of the uptake become visible for the seekers. In the case for the cooled gases the uptake metal will be at ambient temperature. The calculations are only performed for the "cool" ship. The resulting lock-on ranges are listed in table 4.

Another benefit of cooling of the exhaust gases is the reduction in indirect heating. The hot gases of the plume will heat other parts of the ship as the mast and sensors. Heating of the radar antennas and other sensors may have detrimental effects on the lifetime and performance of the sensors. This is difficult to express in a quantitative way, but a reduction in the temperature of the imminent gases will certainly help. Another effect which has to be considered is the effect of the hot plume on the performance of an Infra Red Search and Track (IRST) sensor on the top of the mast. When the exhaust plume is in the field of view of this sensor, the performance may be reduced in this part of the field of view. Although cooling of the exhaust gases will not completely suppress the IRST performance degradation due to the plume, it will certainly reduce the effect.

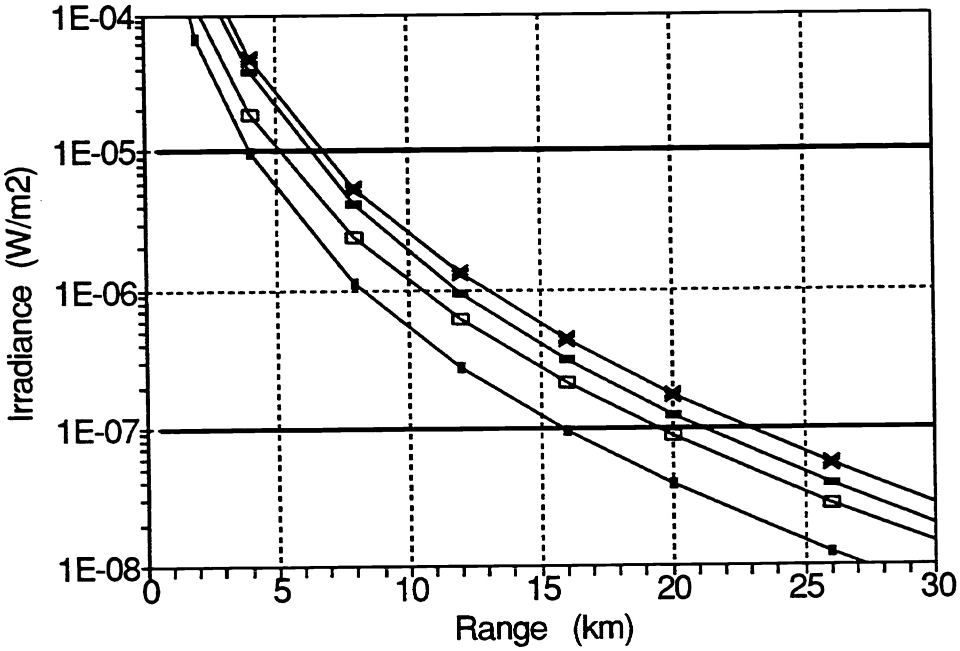

Figure 2: Irradiance levels as a function of range for a ship with gas turbine plume as "seen" by a Class II missile: . hot ship+cool plume, x hot ship+hot plume, l cool ship+cool plume and - cool ship+hot plume. The threshold levels for noise limited and max clutter limited detection are indicated.

Table 2. Lock-on ranges in kilometers for a ship in approximately 90° side aspect with diesel exhaust plumes, 0° elevation.

		"Hot" ship ΔT = 10°C		"Cool" ship ΔT = 2°C		ΔT = 0°C	
		Uncooled	Cooled	Uncooled	Cooled	Uncooled	Cooled
Class I	No clut	4.5	4.5	2.7	2.4	1.2	0.7
	Med clut	3.2	3.2	1.7	1.6	0.9	0.5
	Max clut	2.5	2.5	1.3	1.2	0.7	0.4
Class II	No clut	17.5	17.5	12.0	11.5	8.0	6.5
	Med clut	7.3	7.3	4.2	3.8	3.0	2.0
	Max clut	4.3	4.3	2.6	2.3	1.8	1.2
Class III	No clut	32.0	32.0	25.0	24.0	18.0	14.5
	Med clut	25.0	25.0	17.2	16.9	12.0	9.0
	Max clut	17.0	17.0	12.0	11.7	8.0	6.5
	10 pixels	21.0	21.0	14.5	13.7	10.0	8.0
Class IV	No clut	32.0	32.0	26.5	26.5	8.5	7.0
	Med clut	27.0	27.0	18.5	18.5	5.5	4.2
	Max clut	20.0	20.0	13.0	13.0	3.5	2.8
	10 pixels	23.0	23.0	16.0	16.0	4.5	3.4

Table 3. Lock-on ranges in kilometers for a ship in approximately 90° side aspect with gas turbine exhaust plumes, 0° elevation.

		"Hot" ship ΔT = 10°C		"Cool" ship ΔT = 2°C		ΔT = 0°C	
		Uncooled	Cooled	Uncooled	Cooled	Uncooled	Cooled
Class I	No clut	6.2	5.0	5.5	3.5	5.0	3.0
	Med clut	4.5	3.5	4.0	2.3	3.8	2.0
	Max clut	3.4	2.7	3.8	1.8	3.3	1.8
Class II	No clut	23.0	19.5	21.5	16.0	21.0	15.0
	Med clut	10.0	8.0	9.5	6.5	8.0	5.0
	Max clut	6.8	5.2	6.4	4.0	7.0	3.5
Class III	No clut	36.0	36.0	36.0	32.0	36.0	30.0
	Med clut	31.0	27.0	28.5	22.0	28.0	21.0
	Max clut	23.0	19.5	21.0	16.0	18.0	14.5
	10 pixels	26.5	23.0	24.5	18.5	24.0	17.5
Class IV	No clut	36.0	36.0	29.0	28.0	23.0	17.0
	Med clut	27.5	27.1	20.8	19.0	16.0	12.0
	Max clut	20.0	20.0	14.5	13.5	12.0	8.0
	10 pixels	23.0	23.0	17.0	16.0	13.5	9.5

Table 4. Lock-on ranges in kilometers for a "cool" ship in approximately 90° side aspect at 5° elevation.

		Diesel		Gas turbine	
		Uncooled	Cooled	Uncooled	Cooled
Class I	No clut	3.0	2.2	7.2	3.5
	Med clut	2.3	1.7	5.5	2.2
	Max clut	1.6	1.1	3.2	1.8
Class II	No clut	13.0	11.5	23.0	16.0
	Med clut	5.0	3.9	11.0	7.0
	Max clut	3.0	2.5	7.0	3.8
Class III	No clut	27.0	24.5	36.0	32.0
	Med clut	18.5	17.0	31.0	22.0
	Max clut	13.5	12.0	23.0	16.0
	10 pixels	15.5	13.5	26.0	18.5
Class IV	No clut	26.5	26.5	29.5	27.5
	Med clut	18.5	18.5	21.5	18.7
	Max clut	13.0	13.0	15.0	13.5
	10 pixels	16.0	16.0	18.0	16.0

5. LOCK-ON RANGE REDUCTION BY USE OF LOW EMISSIVITY PAINT

Infra-Red Low Emissivity Paint (IRLEP) has a low emission coefficient and will therefore reduce the thermal emission of a surface compared to the same surface covered with normal paint. However, connected with the low emissivity is a high reflectivity, which increases the reflected fraction of the radiation incident on the surface.

The total radiation of a surface as seen by an infrared sensor consists of two components. The first component is the thermal emission at the surface of the material. This emission is determined by the temperature of the surface and its emissivity (ε). The second component is the reflection at a surface. It is usually diffuse and the reflected radiation component will therefore originate from all parts of the environment of the surface under consideration. All these different contributions are averaged by background radiation at an "average" temperature T_{env}. For discussion it is convenient to define the apparent temperature T_{app} of a surface as the temperature that a surface would have if the emission coefficient were equal to 1, while this surface emits the same amount of energy as emitted and reflected components together. It must be noticed that T_{app} can only be defined if the wavelength band of interest is defined. For normal paints, ε is approximately 0.90 to 0.95. However, even for 5 to 10 percent reflection, the apparent temperature of a surface can be decreased by a few degrees compared to the real surface temperature due to reflection of "cold" sky radiation. For IRLEP, ε can be as low as about 0.50. Any value between 0.5 and 0.95 can be obtained by tuning the paint composition.

An ideal IRLEP should have a very high reflectively in the near infrared (0.7-3.0 μm). This will strongly suppress solar heating. In the visual range the color (which is also determined by the reflectivity) should of course match the requirements for the area of operation.

In general IRLEP can be applied in three ways: 1) Treatment of small hot spots, 2) Painting large parts of the ship and 3) Painting of the complete ship. Since 1) and 2) in general do not have a large effect on the lock-on range, only 3) will be considered here.

To reduce the total contrast of the ship the entire ship (possibly except the decks) must be coated with IRLEP. Due to the higher reflectivity, the signature of the ship will be more dependent on its environment. Under complete overcast conditions this option will reduce the contrast signature of the ship. Under clear sky conditions the apparent radiation of the ship might drop below the background radiation level, resulting in a negative contrast. In principle future infrared homing seekers can lock as easily on a negative contrast, as on a positive contrast. In the future one might think of adaptive coatings which compensate for the varying environmental conditions resulting in a minimized contrast independent of the environment. This type of coating would also allow dynamic changes of the contours of the ship, causing break-lock of seekers using contour recognition.

Some estimates have been made for the reduction in lock-on range. For the calculation cases have been chosen for the diesel propulsion, where the hull and superstructure of the ship dominate the signature. A typical example is given in figure 3. The largest effect is then to be found for a "hot" ship, which is solar heated. However, this is very unlikely under overcast conditions. The results given in table 5 are calculated for ε = 1.0, 0.5 and 0.1.

It has already been mentioned that the signature of an IRLEP coated ship becomes strongly dependent on the environment of the ship. Therefore, also the actual effect of the application of IRLEP will be strongly dependent on this environment. This suggests the application of specific IRLEP paint schemes for different areas of operation.

One has to be aware that the application of more reflective surfaces on a ship can cause hot spots when the ship is illuminated by the sun or by a CO2 laser. In this case low emissivity paint will have a negative effect on the survivability of the ship. However, this is the case only for those positions of the observer (seeker) and the sun, where specular reflection occurs. The same is true for reflections of decoy radiation off the ship. Here also the momentary signature increase of the ship due to the reflections depends on the geometrical positions of decoy, ship and seeker.

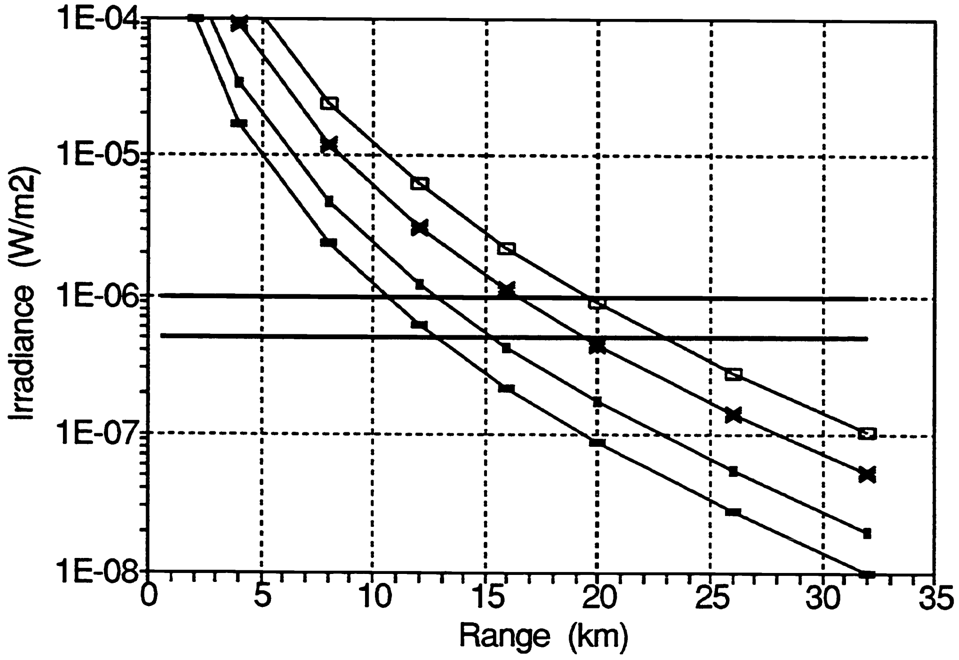

Figure 3: Irradiance levels as a function of range for a ship with cool diesel plume as "seen" by a Class IV missile: . hot ship, x hot ship+IRLEP, I cool ship and - cool ship+IRLEP. The threshold levels for 10 pixel (noise) limited and max clutter limited detection are indicated.

Table 5. Effect of IRLEP on lock-on ranges in kilometers for a ship with diesel propulsion in approximately 90° side aspect.

		"Cool" ship			"Hot" ship		
		ε = 1.0	ε = 0.5	ε = 0.1	ε = 1.0	ε = 0.5	ε = 0.1
Class I	No clut	3.5	2.7	1.6	4.5	3.5	1.8
	Max clut	2.0	1.5	0.9	2.9	2.0	1.1
Class II	No clut	12.0	9.5	7.5	18.0	15.0	10.0
	Max clut	2.5	1.9	1.5	4.5	3.5	2.0
Class III	10 pixels	14.0	10.0	8.5	21.0	18.0	12.0
	Max clut	12.0	9.5	7.5	17.5	15.0	10.0
Class IV	10 pixels	15.5	13.0	8.0	23.0	19.5	13.0
	Max clut	13.0	11.5	7.0	19.0	15.5	11.0

6. REDUCTION OF HIT PROBABILITY

The reduction in the lock-on range alone does not give an indication of the reduction of the probability that the ship is hit by a missile. After all, when the lock-on range is reduced, but the missile flies in the correct direction, the only effect will be that the ship will be acquired by the seeker later in its flight. Eventually the ship will still be hit.

A relative reduction of the hit probability can be defined. One approach is to define the hit probability proportional to the area of a circle with a radius equal to the lock-on range. This definition assumes that the missile is fired completely at random and is therefore not very realistic. According to this definition the hit probability reduces proportional to the square of the lock-on range. In the following to this definition will be referred as "quadratic area" definition.

It seems better to relate the hit probability to the maximum inaccuracy in the bearing in which the missile is fired. Then the hit probability is proportional to the maximum area in horizontal direction in which the missile can acquire the ship. This area is equal to the product of the sine of the search angle and the lock-on range.

According to this definition the hit probability reduces proportional to the lock-on range. In the following to this definition will be referred as "linear bearing angle" definition.

The effective areas for the two definitions are shown in figure 4. In reality the distribution of the inaccuracy in bearing will not be random. Large errors in bearing will be less probable than small ones. However, no real data are available on such a probability distribution and this issue is not included in the treatment of the hit probability.

The reduction due to exhaust gas cooling of the hit probability according to the two definitions above for the various seekers and combinations of engine type and ship temperature in 0° elevation are summarized in tables 6 and 7. 0% indicates that signature reduction has no effect, 1005 indicates that lock-on is no longer possible at any range. For the three different threshold levels, the reduction in hit probability does not vary much, and therefore only the average value is given. Note that in these calculations the missile dynamics are not taken into account. Table 8 shows the reduction in hit probability in the 5° elevation case. Both linear and quadratic definition are combined in this table. Again the values are averaged over the three threshold levels. Table 9 shows the reduction in hit probability due to the application of infrared low emissivity paint (IRLEP).

The hit probabilities as defined here, only take into account the situation where the ship will not maneuver or activate countermeasures. In the case the ship will use decoys the hit probability will be further reduced. A reduction of the lock-on range will increase the success rate of decoys. It is a critical factor in the success of a decoy, whether the decoy is used in the seduction (after lock-on) or distraction (before lock-on) mode. When the lock-on range is reduced, more time will be available to use the decoy in the distraction mode. In the distraction mode the success rate is much higher than in the seduction mode, resulting in a clear benefit of a reduced lock-on range.

Table 6 Reduction of hit probability due to cooling of the exhaust gases in
the 0° elevation aspect situation according to the linear bearing angle definition.

	Diesel			Gas turbine		
	ΔT = 10.0	ΔT = 2.0	ΔT = 0.0	ΔT = 10.0	ΔT = 2.0	ΔT = 0.0
Class I	0.0 %	6.6 %	42.0 %	20.9 %	42.0 %	45.0 %
Class II	0.0 %	7.5 %	30.0 %	20.4 %	31.1 %	38.0 %
Class III	0.0 %	2.7 %	21.0 %	9.4%	19.2 %	23.0 %
Class IV	0.0 %	0.0 %	22.0 %	0.5 %	6.3 %	25.0 %

Table 7 Reduction of hit probability due to cooling of the exhaust gases in
the 0° elevation aspect situation according to the quadratic area definition.

	Diesel			Gas turbine		
	ΔT = 10.0	ΔT = 2.0	ΔT = 0.0	ΔT = 10.0	ΔT = 2.0	ΔT = 0.0
Class I	0.0 %	12.8 %	68.0 %	37.3 %	66.0 %	70.0. %
Class II	0.0 %	14.3 %	50.0 %	36.6 %	52.3 %	50.0 %
Class III	0.0 %	5.4 %	37.0 %	17.4 %	17.4 %	37.0 %
Class IV	0.0 %	0.0 %	39.0 %	1.0 %	12.2 %	39.0 %

Table 8 Reduction of hit probability due to cooling of the exhaust gases in the 5° elevation aspect situation according to the linear bearing angle definition and the quadratic area definition.

	Linear		Quadratic	
	Diesel engine	Gas turbine	Diesel engine	Gas turbine
Class I	28 %	52 %	47 %	76 %
Class II	16 %	37 %	30 %	60 %
Class III	11 %	25 %	19 %	48 %
Class IV	0 %	10 %	0 %	20 %

Figure 4: Effective search area according to the two definitions of hit probability. Above (4a) "quadratic area", Below (4b) "linear bearing angle" definition.

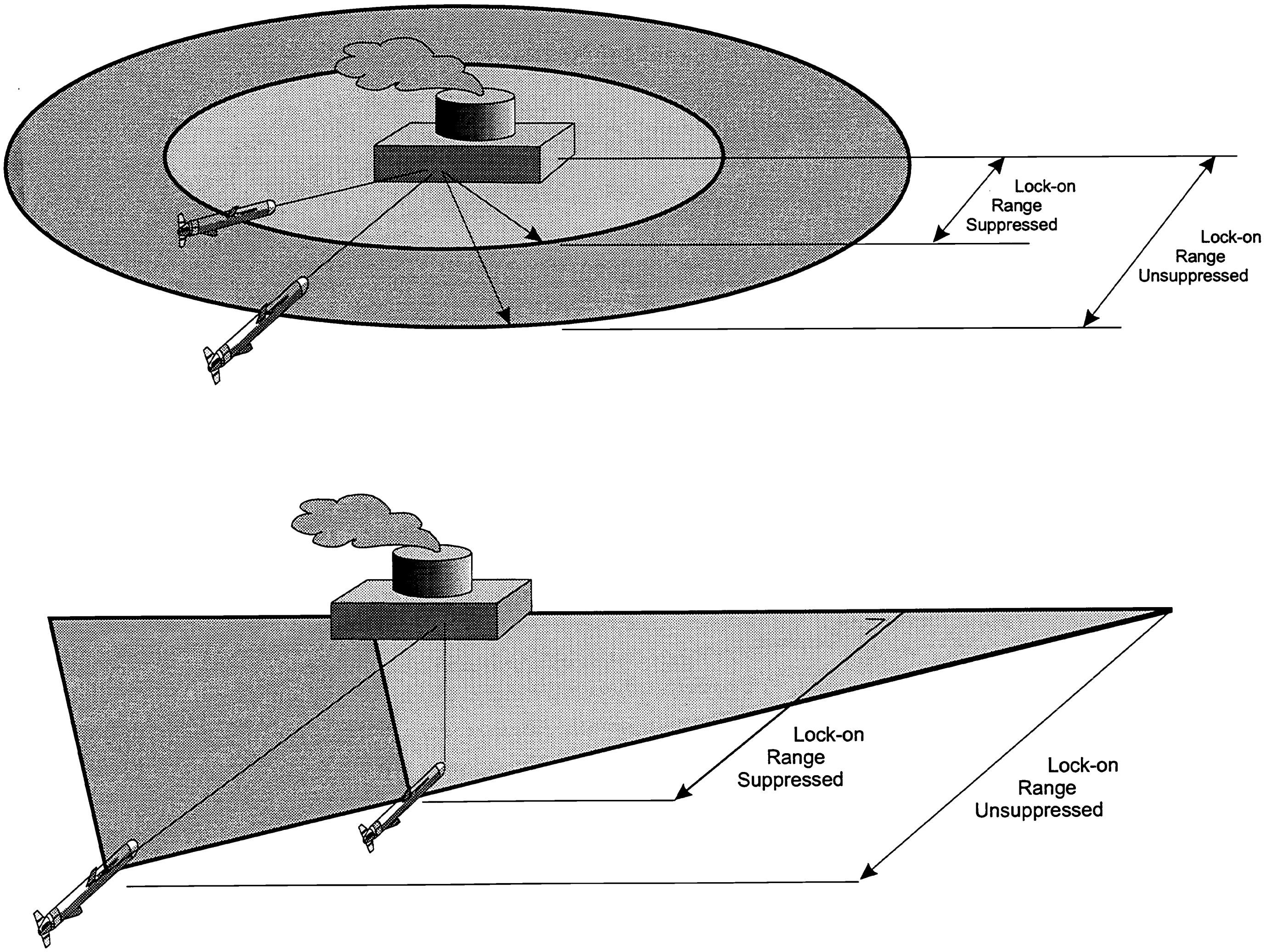

Table 9 Reduction of hit probability due to the application of IRLEP with $\varepsilon = 0.5$ and 0.1 respectively, according to the linear bearing angle definition and the quadratic area definition.

Missile class	Linear		Quadratic	
	Cool ship	Hot ship	Cool ship	Hot ship
$\varepsilon = 0.5$				
Class I	24 %	27 %	40 %	45 %
Class II	22 %	19 %	39 %	35 %
Class III	25 %	14 %	43 %	26 %
Class IV	14 %	17 %	25 %	31 %
$\varepsilon = 0.1$				
Class I	55 %	61 %	79%	84 %
Class II	38 %	49 %	63 %	75 %
Class III	38 %	44 %	67 %	68 %
Class IV	47 %	43 %	72 %	67 %

7. DISCUSSION AND CONCLUSIONS

Suppression of the temperature of the exhaust gases and the uptake pipe will in most cases reduce the lock-on range of the various seekers.

The application of IRLEP can contribute to the survivability of the ship. The various applications of IRLEP will reduce the lock-on ranges of threat missiles. In general the signature of an IRLEP coated ship will become strongly dependent on the environment and therefore the actual effect of the application of IRLEP strongly depends on this environment. The use of adapted IRLEP paint schemes for different areas of operation is therefore very beneficial.

Apart from this, the missile has to come closer to the ship to obtain lock-on, in which case the probability that the missile is detected by the sensors on board of the ship before lock-on increases. This will increase the possibility to deploy countermeasures in time.

To summarize this paper: it has been shown with some numerical examples that cooling of exhaust gases and the application of low emissivity paint can contribute to the survivability of a ship. One has to be aware that the numerical values for the decrease of the hit probability as quoted here, are based on a chain of assumptions, each of which is debatable, but anyway the paper presents a first attempt to "translate" infrared signature reduction quantitatively into an increase of survivability.

8. REFERENCES

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