INFRARED SIGNATURES IN THE MODERN WARSHIP

(Reference No: IJME683, DOI No: 10.5750/ijme.v163iA2.762)

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KEY DATES: Submitted: 23/11/20; Final acceptance: 26/03/21; Published 12/07/21

SUMMARY

A key aspect in design of the modern warship from the point of view of energy efficiency is undoubtedly the selection of its propulsion system. A large part of the total Infrared (IR) radiation emitted by the ship will be originated from propulsion, because not all the energy generated will be transformed into effective work. The remaining energy will contribute directly to the IR signature of the warship as a whole, thus increasing its susceptibility and, therefore, its casualty. The aim of this article is to describe the main sources of IR signature on frigates and destroyers, current and future IR signature reduction countermeasures, and present the results of an Infrared Control Measures (IRCM) study in which the vessel's ability to dissuade aerial threats through the use of deception techniques, within a stated energy efficiency scenario, is analysed. In conclusion, electrical variants to warship propulsion systems are more efficient under the same operating conditions, and their associated reduction of waste energy contribute favourably to IR signature control. The activation of IRCM will further reduce the IR susceptibility of a warship.

NOMENCLATURE

CODAD	COmbined Diesel And Diesel
CODAG	COmbined Diesel And Gas turbine
CODELAG	COmbined Diesel ELectric And Gas turbine
CODELOG	COmbined Diesel ELectric Or Gas turbine
CODOG	COmbined Diesel Or Gas turbine
COEOD	COmbined Electric Or Diesel
COEOS	COmbined Electric Or Steam turbine
COGES	COmbined Gas turbine Electric And Steam
COGOG	COmbined Gas turbine Or Gas turbine
COGAG	COmbined Gas turbine And Gas turbine
COGAS	COmbined Gas turbine And Steam
CONAG	Combined Nuclear And Gas turbine
COSAG	COmbined Steam And Gas turbine
DE	Diesel Engines
GT	Gas Turbine
IFEP	Integrated full electric propulsion
IR	Infrared Range
NATO	North Atlantic Treaty Organization
ST	Steam Turbine

1. INTRODUCTION

It is believed that the Canadian Navy in the late 1930s was the first that cared about reducing the signature of its ships with diffuse light anti-illumination camouflage in the visible range. This honor is also often awarded to the German submarine U-480, as it had a rubber coating and a layer of airbags to remain undetected by the sonars of the allies.

Since then the reduction of the signature is a discipline of military tactics and passive countermeasures, covering a wide range of techniques used in air, naval and ground warships, reaching even the combatants themselves. The objective is to have a camouflage that provides stealth, for example, in different ranges of the electromagnetic spectrum, so as not to be detected with radar, infrared, sonar, etc., devices.

In the case of the infrared (IR) range, it is considered a band between the visible eye and the microwaves, i.e. of wavelengths between 0.75 and 1000 μm. As IR radiation has a number of specific characteristics related to heat emission and transmission, it is used in multiple defense applications, in particular in anti-ship missile detection and guidance cameras. Countering this threat will require reducing the ship's signature by reducing heat emissions.

Currently it is common for the Armed Forces of NATO countries to specify emission levels in the IR spectrum, as part of the set of program requirements through the use of NATO standard IR signature (ShipIR/NTCS) programs and models to predict and evaluate both the signature and vulnerability of their new ship designs, under different environmental conditions, signature suppression levels and even for the design of countermeasures such as flares and tactics for their deployment (Vaitekunas et al, 2000).

In relation to the IR susceptibility, the warship will be strongly conditioned by the efficiency of its propulsion system and the number of measures designed to mitigate the emission of IR energy outdoors. Good design will reduce the detection capability of certain sensors, providing an edge in anti-aircraft warfare scenarios by making it difficult for them to detect, classify, and track targets. Life cycle costs (up to 75% are for operating and support activities) and emissions into the atmosphere (mainly NO_X and SO_X) will also be reduced according to voluntary compliance with Annex VI warships of the MARPOL Convention.

This article will describe the main sources of IR signatures on frigate/destroyer warships, current and future IR signature reduction countermeasures, ending with a study in which, depending on the countermeasures selected, the vessel's ability to dissuade aerial threats through the use of deception techniques, within the energy efficiency scenario considered. The relationship of this issue with the aspects of Operational Energy Security according to the NATO doctrine enables approaching the subject of influencing energy optimization without a detrimental effect on the stealth.

2. THEORETICAL BACKGROUND

2.1 HISTORY OF WARSHIP PROPULSION

In 1893, when the James Watt steam engine was routinely used in both the general industry and the propulsion of ships, the engineer Rudolf Diesel registered in the *"Kaisenlichen Patentant"* of Berlin the patent of his invention, which among other points indicated: *"that the working plunger compresses so much pure air in a cylinder that the temperature resulting from the compression is considerably higher than the temperature of inflammation of the fuel it is to be used, after which the gradual introduction of fuel is carried out, from the deadlock..."* (Casanova, 2001).

At a time when the steam engine dominated ship propulsion, with yields ranging from 15 to 18%, Rudolf Diesel discovered a path that could lead to yields of around 40%. Starting in 1902, the application of the diesel engine shows constant increases. While in 1925 only 4% of the world's tonnage has diesel propulsion, in 1939 it increased to 24%. Currently, about 90% of vessels above 2000 tonnes of gross registration (TRB) use the diesel engine for propulsion (Casanova, 2001).

Related to gas turbines, more than two and a half centuries have elapsed from the first designs based on the principle of *"action-reaction"* (Newton's third law), to the arrival of designs in which air is compressed in a compressor, from which it comes out at the temperature corresponding to its pressure and is introduced into the combustion chamber, where fuel is sprayed by injectors and the resulting gases are expanded and output into the atmosphere. In this case, a part of the thermal energy stored in the flue gases is used to move the compressor (Casanova, 2001).

The Royal Navy first used a gas turbine on one of the three shafts of the MGB-2009 ship in 1947. Subsequently, from modifications made to aircraft gas turbines, the first generation of ship gas turbines, known as *"marinized gas turbines"*, was born. The main feature that differentiates them from aviation is that the expansion of gases, once the compressor is moved, is carried out in another turbine called *"power turbine"* (Casanova, 2001).

Since the 1980s, warship propulsion systems have evolved from traditional mechanical transmissions based on shaft and gear transmission assemblies to electrical transmission systems with converters and wires, all coupled with the concept of *"integrated full electric propulsion"* (IFEP). These electric propulsion control systems bring together many advantages from the point of view of operational control, albeit at the cost of loss of efficiency throughout the transmission. Even so, the flexibility of IFEP compensates for potential transmission losses with improved efficiency in other sections of the propulsion assembly (Greig, et al. 2009).

2.2 SPECIALITIES OF MODERN WARSHIP PROPULSION

Due to the need for fuel savings and, ultimately, the improvement in the energy efficiency of warship power plants, Navies have initiated and strengthened solutions in the search for improved economy, both in reducing consumption and the hours of operation, through the use of redundant propulsion systems. From the combination of diesel engines and gas turbines (and in some cases steam turbines and nuclear power), the following propulsion systems appear:

Table 1: Warship´s Propulsion Systems.
Source: Casanova, 2001; Casanova, 2009; Seijo, 2013

Acronym	System
CODAD	COmbined Diesel And Diesel
CODOG	COmbined Diesel Or Gas turbine
CODAG	COmbined Diesel And Gas turbine
COGOG	COmbined Gas turbine Or Gas turbine
COGAG	COmbined Gas turbine And Gas turbine
COSAG	COmbined Steam And Gas turbine
COGAS	COmbined Gas turbine And Steam
CONAG	Combined Nuclear And Gas turbine

Respect to the table 1, COGAS plants can also be called STAG “Steam And Gas Turbine” or RACER “Rankine Cycle Energy Recovery” (Casanova, 2001).

In addition to the above combinations of diesel engines (hereinafter DE), gas turbines (hereinafter GT), steam turbines (hereinafter ST) and nuclear power, based on an optimal power and efficiency solution, there are other combinations based on the integration of electric propulsion within a mixed propulsion system. In this case, the vessel's low speed range is covered by much more efficient electric propulsion, while high speeds are reserved for other systems. In this sense, the most commonly used systems for ship propulsion are as follows:

Table 2: Warship´s Electric Propulsion Systems.
Source: Casanova, 2001; Casanova, 2009; Seijo, 2013

Acronym	System
CODELAG	COmbined Diesel ELectric And Gas turbine
CODELOG	COmbined Diesel ELectric Or Gas turbine
COEOD	COmbined Electric Or Diesel

COEOS	COmbined Electric Or Steam turbine
COGES	COmbined Gas turbine Electric and Steam

The modern warship needs high power to reach operational top speeds, even though most of its active life it will sail at economic speed. From experience it is known that it will operate about 85% of its active life at the approximate cruising speed, which will usually be achieved at 79% of the maximum speed and correspond to 50% of the maximum continuous power in COGAG and CODAD installations; and 58% of the maximum speed, which will correspond to 20% of the maximum continuous power in COGOG, CODOG and ST installations. Due to the above, the study of the operating economy at cruising speed will be of particular importance during the development of the warship project, from which range and its influence on the cost of the life cycle will be deducted (Casanova, 2009).

2.3 CODOG/CODAG AND CODELOG/CODELAG ELECTRICAL VARIANTS PROPULSION SYSTEMS

Since 1975, when the GT began replacing the ST, until the present day, 461 frigates have been commissioned worldwide (excluding countries such as Russia and China). The following figure shows the number of vessels commissioned, over five-year periods, by the type of propulsion and average displacement. Ships of the same class are counted in the year of commissioning of the first. GT propulsion includes a GT with or without DE, while DE propulsion includes only DE-powered vessels.

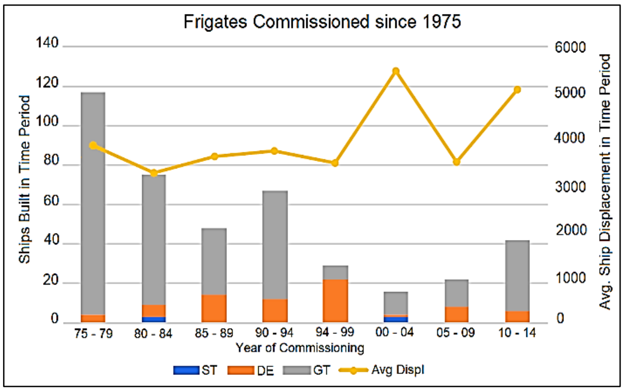

Figure 1: Frigate Propulsion Type and Displacement versus Time. Source: GE Marine Solutions, 2018

The following figure summarizes a list of GT-powered frigates grouped by displacements from which data is available, where it can be seen that the average displacement of vessels prior to 1999 is 3500 t, increasing since to 5700 t. The maximum speed can also be verified between 28 and 30 kn, excluding the LCS in the United States, whose top speed is above 40 kn.

3000 - 3999 T					
Displ (T)	Frigate	N. Built	Year First Commision.	Propulsion Type	Max. Speed (kn)
3600	Anzac	8	1993	CODOG	27
3680	F122	8	1982	CODOG	30
3320	Karel Doorman	8	1991	CODOG	30
3700	Valour MEKO	4	2006	CODAG	28
3261	FFX Batch 1	6	2013	CODOG	30
3600	LCS Freedom	5	2008	CODAG	> 40
3105	LCS Independence	5	2010	CODAG	> 40
4000 - 4999 T					
Displ (T)	Frigate	N. Built	Year First Commision.	Propulsion Type	Max Speed (knots)
4110	Adelaide	6	1980	COGOG	29
4770	Halifax	12	1992	CODOG	30
490	F123	4	1994	CODOG	29
4000	Hatsuyuki	12	1982	COGAG	30
4169	Cheng Kung	8	1993	COGOG	29
4200	Oliver Perry	71	1977	COGOG	29
4900	Type 23	16	1987	CODLAG	28
5000 - 5999 T					
Displ (T)	Frigate	N. Built	Year First Commision.	Propulsion Type	Max Speed (knots)
5800	F124	3	2003	CODAG	29
5290	Nansen	5	2006	CODAG	31
5300	Type 22	16	1988	COGOG COGAG	30
6000 - 7200 T					
Displ (T)	Frigate	N. Built	Year First Commision.	Propulsion Type	Max Speed (knots)
6000	FREMM	10	2012	CODLOG	27
7299	F125	4	2017	CODLAG	26
6700	FREMM	10	2012	CODLAG	30
6050	De Zeven	4	2002	CODAG	30
6400	Alvaro de Bazan	5	2002	CODOG	29

Figure 2: Notable Frigate Ship and Propulsion Information by Displacement.
Source: GE Marine Solutions, 2018

The sequential combinations of GT and DE or CODAG and CODOG propulsion, and the electrical variants CODELOG (or CODLOG) and CODELAG (or CODLAG) are a standard in the propulsion of warships, from small corvettes to large destroyers or DDGs. According to the data collected in Figure 2, of the total ships delivered for which data are available, 56% have CODOG/CODAG or CODELOG/CODELAG propulsion (39 and 17% respectively).

The typical configuration of a CODOG drive plant consists of two shaft lines that operate two controllable pitch propellers respectively. Each of these lines is connected, by means of a self-synchronizing gear, to a DE and a GT respectively, forming a double CODOG propulsion system:

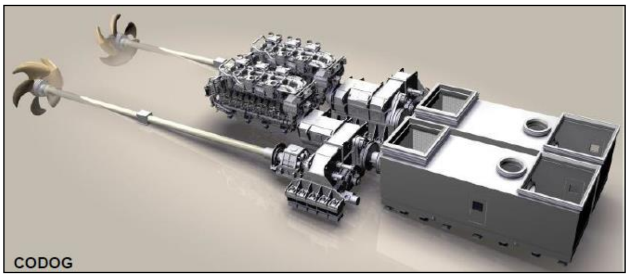

Figure 3: Dual Configuration of a Propulsion System CODOG. Source: Ohmayer, 2012

In the electrical variant CODELAG, the DE move electric generators that produce the electrical power needed to power the electric drive motors, while the GT is connected directly to the shaft lines through the gearbox. In cruise mode, the vessel is powered by the DE electric system, while for operations requiring maximum speed, the GT is coupled.

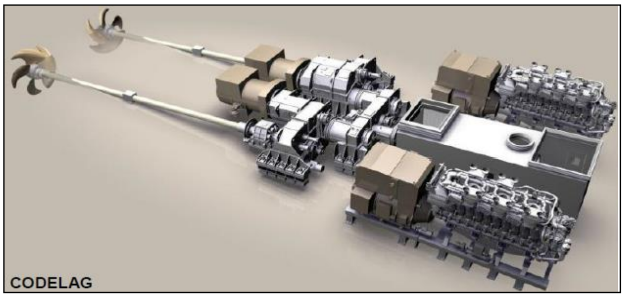

Figure 4: Dual Configuration of a Propulsion System CODELAG. Source: Ohmayer, 2012

2.4 SURVIVAL OF THE WARSHIP

To assess the survival capacity of the current warship, consideration should be given to the susceptibility or inability of the unit to avoid certain sensors. Susceptibility depends, in turn, on the spectrum of energy emitted and/or reflected and the modification of physical parameters, being intrinsically related to the signatures of the warship.

To assess the survival capacity of the warship during the design process, the following aspects should be considered (Villa, et al. 2015):

- Susceptibility. Chance of impacts. It will depend on the spectrum of energy emitted and/or reflected.
- Vulnerability. Degree of deterioration achieved after an attack. It will depend on the level of compartmentalization, type of structure, etc.
- Recoverability. Ability to restore damaged functions after being hit.
- Casualty. Chance of destruction after taking an impact.

The susceptibility, vulnerability and recoverability concepts will directly contribute to the casualty and survival of the ship as follows (Piperakis, Andrews, 2014):

Casualty= Susceptibility . Vulnerability . Recoverability
Survival = 1 – Casualty

In order to achieve low susceptibility or detectability, the amount of energy emitted and/or reflected by the warship will have to be minimized in order to reduce its influence on the environment - thus appears the concept of signature.

The main signatures or physical fields of the warship are (Valdés, et al. 2012):

- IR signature, corresponding to the electromagnetic radiation emitted in the infrared range of the spectrum.
- Radar signature, related to electromagnetic type energy reflected by the superstructure of the warship.
- Acoustic signature, relating to the vibrating energy of the machinery transmitted from below the waterline to the sea.
- Magnetic signature, associated with the magnetic fields generated by the structure of the warship.

Stealth technology consists of the installation of countermeasures onboard warships in order to make them invisible to radar detectors, IR, etc. The stealth degree achieved during the warship design stage will depend on the threat level and cost. The stealth condition forces shipyards and equipment manufacturers to devote efforts to I+D in order to reduce the susceptibility of new units.

Of the previous warship signatures, the IR signature will have a negative impact on the warship's survival by becoming a source of IR missile guidance, further allowing its detection, classification and tracking.

2.5 CHARACTERISTICS OF THE INFRARED SIGNATURE (IR) IN WARSHIPS

Any object at a temperature greater than 0 ºK emits energy in the IR region of the electromagnetic spectrum, being able to be represented as a wavelength and temperature function according to Planck's law. From this law, by integration with respect to wavelength, Stephan-Boltzman's law is obtained, being represented as follows:

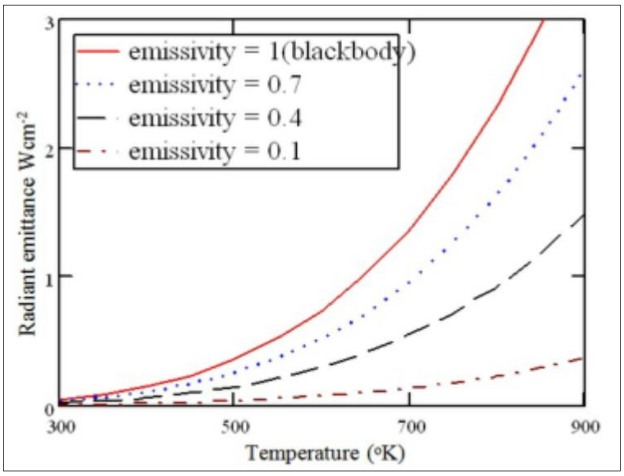

Figure 5: Emission Curves.
Source: Ab-Rahman, Hassan, 2009

In the particular case of warships, the atmosphere will have a mitigating effect on the emitted IR energy, absorbing its entirety throughout the spectrum except in certain bands also called atmospheric windows and located in the band of 3 to 5µm or medium wavelength IR (MWIR) and in the band of 8 to 12µm or long wavelength IR (LWIR), both characterized by high transmittance values due to low attenuation values.

As for the IR radiation sources of warships, classified according to the MWIR and LWIR bands, the following exist (Greig, et al. 2009):

- Exhaust gases, with a very significant contribution in the MWIR band, due to the presence of carbon dioxide and water vapour at high temperature.
- Hull, superstructure and deck elements, due to the incidence of the sun and insufficient insulation in machinery compartments. The main contribution will be in the LWIR band.
- Exhaust ducts and other surfaces heated by exhaust gases, contributing to both bands (MWIR and LWIR).

Therefore, it can be established that the IR signature of the warship has an internal and an external component. The internal component includes heat released by motors and equipment, engine exhaust products, air ventilation systems and heat loss from internal spaces, highlighting the contribution of the engines and electric generators. The external component will be the result of the radiation absorbed and/or reflected from the environment of the ship by its outer surfaces, the main sources of radiation being the sun, the glare of the sky and the sea.

Figure 6 illustrates different ways in which heat from the ship's main machinery manifests itself in the form of IR emissions, identifying the hot hull sections (location of the engine room), the exhaustducts through which the engine exhaust gases escape, the top of the exhaust ducts heated by exhaust gases when leaving the exhaust ducts (greater contribution as an internal IR source due to the high position and temperature reached), the gases leaving the ship (mainly CO_2 and water vapour) and the communications mast heated by the gases when leaving the ship.

Figure 6: Infrared Image of a Typical Unsuppressed Ship. Source: Thompson, et al. 2000a

Due to the composition and high temperature of the column formed by the exhausting gases, it will radiate within the spectral band from 4.1 to 4.6μm. Although much of this radiation will be rapidly absorbed by the atmosphere, a portion will reach 10km or more of penetration through the atmosphere, thus becoming a major contributor to the ship's IR signature. Figure 7 shows the spectral emission diagram corresponding to a GT LM2500 at different distances.

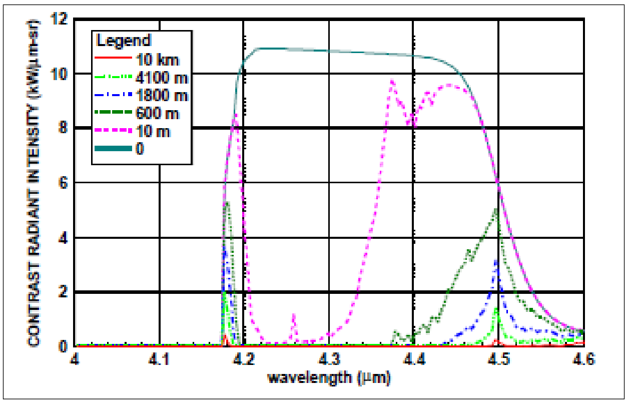

Figure 7: Spectral Emission of 75kg/s at 500 ºC plume. Source: Thompson, et al. 2000a

Figure 8 shows two IR images of a vessel turning with sun on the side. Despite the small degree of rotation between the two pictures (from 2 to 4 degrees) the ship behaves in the second picture in a highly reflective way. This feature can be leveraged by designers of missile guiding systems.

Figure 8: Solar Glint from Typical Navy Grey Paint. Source: Thompson, et al. 2000a

Figure 9 represents a simulation of the IR signature of a frigate from an observer located 500m away facing down at an angle of 15 degrees. The vessel sails at 30kn with two GT LM2500s and lacks IR signature suppression systems. The sun strikes from starboard at an angle of 30 degrees. In this case, the IR signature is dominated by the component corresponding to the last section of the exhaust. In addition, the contribution of exhaust gas plumes is of the same order of magnitude as that for sun-heated outdoor surfaces.

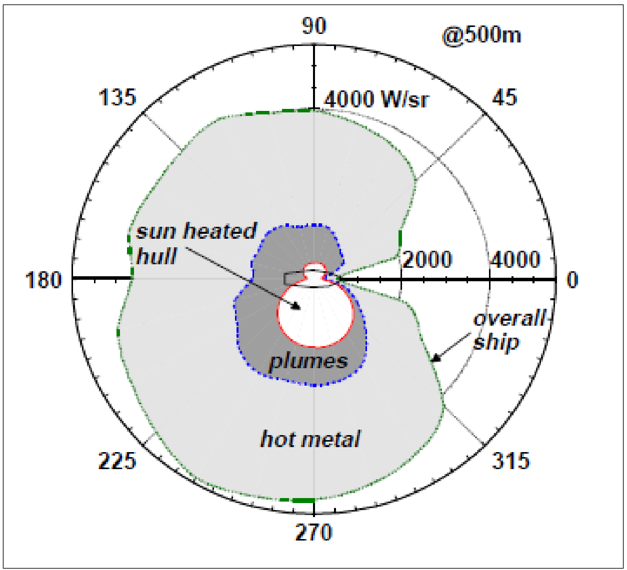

Figure 9: Breakdown 3-5μm band signature as predicted by ShipIR/NTCS. Source: Thompson, et al. 2000a

2.6 IR THREATS AND COUNTERMEASURES OF THE MODERN WARSHIP

Depending on the MWIR and LWIR bands, IR threats can be classified as follows (Greig, et al. 2009):

- Passive self-guided IR missiles, in the MWIR and LWIR bands.

- Detection and monitoring with FLIR thermal cameras in the LWIR band.

Passive self-guided missiles will depend only on the target as a source of radiation, being independent of the launch pad. In addition to the use of the MWIR band, the new generations will recognize the MWIR and LWIR bands, so not only the ship's hottest spots but also its entire surface will constitute a source of guidance. In terms of detection and monitoring, warships will be detected by the IR signature divided on a seabed and a skybed, in the LWIR band, through the use of FLIR type thermal imaging cameras. Detection will therefore be easier the greater the contrast between the two signatures.

It is known as the infrared countermeasures (IRCM) to those aiming to reduce the temperature of the ship's surfaces and the exhaust gases of internal combustion engines. Within the set of IRCM available on ships to achieve stealth condition, the most important are (Vílchez, Sierra, 1999) (Thompson, et al. 2000b):

- Insulation in machinery chambers and other spaces where heat can be dissipated.

- Paints with low absorption coefficient.

- Washdown seawater distribution systems, through sprinklers arranged along the ship for temperature reduction on the weather deck, external bulkheads and sides.
- Eductors/diffusers to cool both ducts and exhaust plumes of internal combustion engines.

As seen above, the external surfaces of the ship will have a significant contribution to the IR signature, only behind that corresponding to the final section of the exhaust ducts. Due to the size of the exposed area, small temperature contrasts have a significant impact. During the night, on ships with good internal insulation, the surface of the hull is in balance with the air and sea temperature. But during the day, as the sun rises, the temperature of the hull increases rapidly. Sun elevations greater than 10 degrees may mean a temperature contrast greater than 10 ºC. Due to the large area involved and the wide range of environmental factors to consider, it is quite common to use paints with a low coefficient of sun absorption.

As for seawater distribution systems, these basically consist of a set of sprinklers arranged throughout the ship for temperature reduction on decks, bulkheads and outer sides. For cooling to be effective, the system must be able to reduce the temperature contrast between the hull and the environment to less than 5 ºC in a short period of time (usually less than 10 minutes). The following figure shows the effect of the spray system on a horizontal panel painted with *"Canadian marine grey"* paint and oriented towards the sun, with a flow of 0.22 $m^3/m^2/h$. In this case, the system is able to reduce the panel temperature variation to below 5 ºC in approximately 7 minutes.

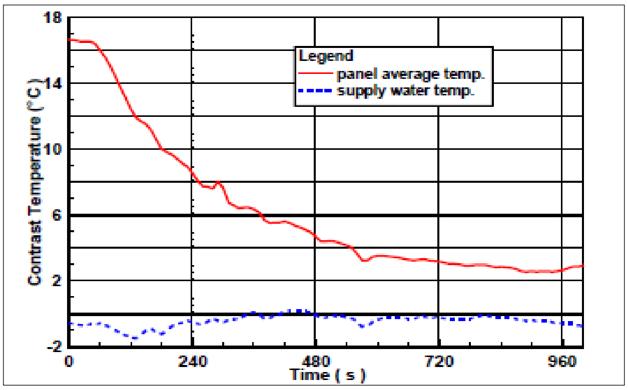

Figure 10: Cooling Time of a Water Washed Panel. Source: Thompson, et al. 2000b

With regard to exhaust gas cooling systems, they are usually passive systems composed of an eductor, a mixing tube and a diffuser (Cho, Y-J., Ko. D-E., 2017a) and are responsible for cooling the exhaust ducts and gases of internal combustion engines, maintaining an average metal temperature in the multiple ring diffuser below 25ºC from the ambient air temperature, with a dilution rate of exhaustion gases of 50% in the eductor. The diffuser reduces the temperature of the metal by forming an air film thanks to the pressure difference between exhaust gases and outside air. Recent studies confirm that the operation of the diffuser is affected by variations in the number of rings (Cho, Y-J., Ko. D-E., 2017b).

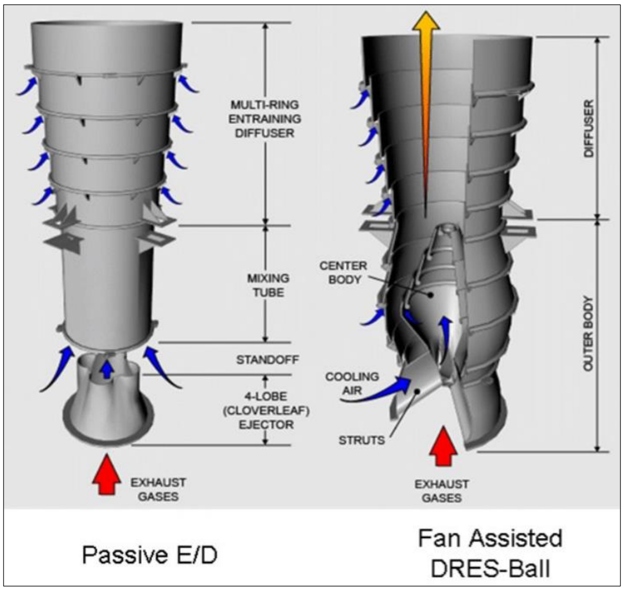

Figure 11: Stack Infrared Suppression Systems.
Source: Vaitekunas, Kim, 2013

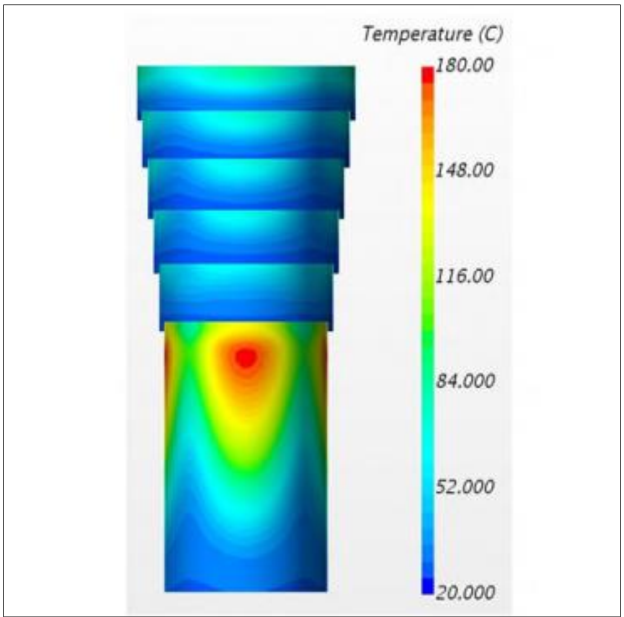

Figure 12: Temperature of the metal surface.
Source: Cho, Ko, 2017b

3. RESEARCH OBJECTIVE AND BEHAVIOR

The objective of this technical paper will be to demonstrate that both the efficiency in the propulsion system used and the installation of IR signature control technologies (IRCM) aboard modern warships will have a huge impact on the susceptibility of the entire hull forms and, therefore, on its survival in high-intensity scenarios.
Depending on the type of propulsion used, the warship will move in two different scenarios. Although it must have high power in order to achieve peak speeds in those scenarios and situations where it was operationally required, for most of its active life it will sail at an economic cruising speed, speed that will have a special importance in the study of the operating economy, from where range will be deduced and its influence on the cost of the life cycle.

In order to improve the energy efficiency of power plants, solutions have been strengthened to reduce their consumption, through redundant propulsion systems predominantly through the combination of diesel engines (DE) and gas turbines (GT). In this case, a CODOG system and its electrical variant CODELOG will be analyzed from data extracted from the different bibliographic sources consulted. Because propulsion makes a large contribution to the resulting IR signature (mainly in the MWIR band), the efficiency of the propulsion plant will directly influence a reduction in its contribution to the IR signature. In this sense, there is an intrinsic link between energy efficiency and stealth of the warship, so that Operational Energy Security translates into multiple advantages, not just in terms of energy.

The Opertional Energy Security concept and requirements lead to adjusted solutions taking into consideration the following particular items: special rules to be applied and technical requirements of the sector and the project (i.e. particular conditions for habitability, protection and logistics), accurate adjustment of equipment and procedures into the operational needs of facilities' locations and mission deployments (i.e. manoeuvrability of military units), proper flexibility, scalability (i.e. in case of extended missions), technological compatibility and electronic connectivity (for management systems), situation awareness of an operational framework under adverse conditions (i.e. extreme climate, combat stress and asymmetric warfare, NBQ scenario), parameters of autarchy conditions and logistical difficulties (i.e. energy supplies cut), requirement of minimum response terms from the supplier´s side facing technical incidences of the customer (i.e. accident, sabotage, attack), security of information and technical details related to equipment items.

When studying the impact of IRCM technology on susceptibility, levels such as hierarchy will be identified in which countermeasures are added in order to reduce the impact of the sources on the resulting signature, and then assess its impact on IR susceptibility and, ultimately, the time available to deploy decoys in order to divert air threats.

The impact on susceptibility will be analyzed from simulations of references consulted, in which the case of a warship is studied sailing at maximum power with GT and DE, countermeasures based on eductors/diffusers for GT and DE exhaustion gases and hull washdown system. The results will apply to MWIR and LWIR sensors located at different heights relative to the sea.

The aim is that using the polar radiation emission diagrams, and depending on whether or not the IRCM systems are activated, their impact on the extent of the IR radiation emitted both in the MWIR and LWIR bands can be verified in order to be able to compare the possible benefits of their activation and which advantages contribute to the type of threat assessed.

As susceptibility is intimately related to the inability of warships to avoid certain sensors (MWIR and LWIR), knowing the response of the ship based on operating regime conditions, climatics, etc., and the availability and type of IRCM on board, will give an advantage when operating in scenarios where threats predominate based on self-guided IR missiles (based on MWIR sensors), classification and tracking, in which the use of LWIR type sensors associated with night vision systems based on FLIR thermal cameras will prevail.

4. RESULTS AND DISCUSSION

4.1 CODOG AND CODELOG PROPULSION FROM THE POINT OF VIEW OF ENERGY EFFICIENCY

For the analysis from the point of view of the energy performance of a CODOG type propulsion system, the following configuration per shaft line has been selected based on widely used commercial standards in ship propulsion:

- One (1) GT General Electric LM2500 (GE Technical Manual, 1999).
- One (1) DE Caterpillar C280-16 (Caterpillar C280 Marine Project Guide, 2010).

The GT GE LM2500 is a 17.5bMW *"marine turbine"* of continuous maximum power, developed from the GE CF6 aviation engine. From the 1960s to the present, its use has been popularized in frigate and destroyer ships, and can be combined with diesel engines in CODAG, CODOG, COGAG, COGOG, CODLAG and CODLOG propulsion systems (GE's Marine Solutions, 2018).

With regard to the DE CAT C280-16, it is a four-stroke, 16V cylinder, non-reversible, direct-injection, turbocharged and charge air cooling system. The maximum continuous power is 5650bkW to 1000r.p.m., measured under standard conditions. It is an IMO/EPA MARINE TIER II certified engine (Caterpillar C280 Marine Project Guide, 2010).

The previous CODOG propulsive scheme will allow a frigate or DDG type ship of approximately 6000t to be moved at an approximate cruising speed (transit) of 20kn with the two active shaft lines at 80% of the maximum continuous power of the DE, power matching 20% of the maximum continuous power installed on board, reaching a maximum speed of approximately 30kn with the two active shaft lines at 100% of the maximum continuous power of the GT (GE's Marine Solutions, 2018).

With regard to the efficiency of a thermal machine, as is the case of the GT and DE considered, it is defined as the ratio between the energy produced by the machine in the form of mechanical work (in an operating cycle) and the energy supplied to the machine. In the case of the GT, the operation is in line with the development of the *"Brayton cycle"*, whose performance is (Casanova, 2001):

$$\eta_B = 1 - \frac{1}{\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}}$$

where P_1 and P_2 are the pressures at the inlet and outlet of the GT compressor and γ the adiabatic constant of the air, which shows that the thermal efficiency of the *"Brayton cycle"* depends on the ratio between the discharge and intake pressures of the GT compressor.

As for the DE, the efficiency will be obtained directly from relating the energy produced by the machine, or power in relation to the unit of time, to the equivalent of fuel consumption for each regimen (Caterpillar C280 Marine Project Guide, 2010).

Table 3. DE & GT efficiency versus power level (0 – 100). Source: Own Elaboration

POWER LEVEL	0	10	20	30	40	50	60	70	80	90	100
DE (%)	35	35	36	37	38	40	40	40			
GT (%)	0	3	9	16	22	29	34	40	44	48	51

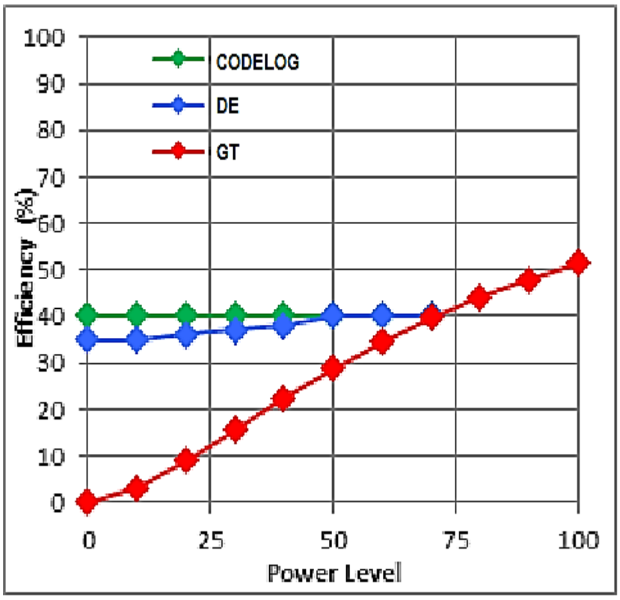

Figure 13: GT & DE efficiency versus power level. Source: Own Elaboration

Thanks to the CODOG propulsion scheme proposed, thermal efficiency over the entire speed range will range from 35 to 51% (figure 13). In this sense, the use of propulsion with GT should be restricted to short intervals where it is strictly necessary to navigate at high speeds by operational, tactical, maneuverability, navigation safety, or other important requirements, reserving DE propulsion for cruising speeds during transit requirements to operational scenarios.

In the same figure the electrical variant CODELOG efficiency curve has been represented (green color). Thanks to the use of electric diesel propulsion, the DE can work more or less constantly at an optimal rate in terms of efficiency (around 40%). All other non-propulsion energy is used by other consumers (auxiliary services, sensor and weapons systems, etc.). In this case it is easily verified that the electrical variant CODELOG shows more efficient behavior, allowing the vessel to work with an efficiency of 40 to 51% over the entire speed range.

4.2 IR SIGNATURE SUPPRESSION AGAINST AERIAL THREATS

The main goal will be to achieve an integrated solution that includes a balanced approach to signature reduction. It doesn't make sense to minimize the contribution of a component from a given source and leave other significant components untouched. Although it is impossible to make the warship disappear from the IR signature point of view, it can be transformed into a blurred target, which fades into the background clutter.
When establishing the degree of IR signature suppression applied to a naval warfare ship and its effect against aerial threats in terms of susceptibility, it is important to remember that IR signature sources can be grouped into two categories:

- Internal sources, mainly due to internal combustion engines (GT and DE).
- External sources, due to the incidence of the sun on the outer surfaces of the vessel.

In addition, as already indicated, for the control of the contribution in the IR signature of the previous sources, the following countermeasure systems are available:

- Eductors/diffusers to cool both visible metal and exhaust gases.
- Washdown systems to cool the outer surfaces of the ship.

Based on the experience of companies developing IR signature suppression systems on ships and aircrafts, it is concluded that the IR signature suppression schemes can be organized into a system consisting of four IRSS levels (Davis, Thompson, 2002):

- LEVEL I, no suppression (hull ship baseline).
- LEVEL II, basic cooling of the exhaust visible metal surfaces and exterior surfaces by activating the NBQ decontamination system (less extensive than the wash-down).
- LEVEL III, basic cooling of the exhaust visible metal surfaces, exhaust gases to be below 250 ºC and external surfaces by washdown system (greater extensive than NBQ system).
- LEVEL IV, basic cooling of the exhaust visible metal surfaces, exhaust gases to be below 150º C and external surfaces by means of washdown system.

To reduce the temperature of exhaust gases to below 150 ºC, the use of educators/diffusers is not sufficient. In this regard, there are hybrid systems based on seawater sprinklers together with the eductor/diffuser that manage to reduce the temperature of exhaust gases to below 150 ºC (Hiscoke, 2000). Recent studies confirm that the use of water mist allows, together with the eductor/diffuser effect, tthe reduction of the temperature of exhaust gases to below 150 ºC (Pernas, Riola, 2015a) (Pernas, Riola, 2015b).

From a 2400t frigate ship with CODOG propulsion composed of 2 GT of 20MW, 2 DE of 4 MW and 3 DEE of 1MW (Davis, Thompson, 2002), it can be established by simulation the contribution of the two IR signature components according to the IRSS suppression level adopted and the distance at which can be detected by an MWIR sensor (0.1º C NETD), located at a height of 10m above the sea level and under the worst solar condition. As can be seen in the following figure, as the IRSS level increases, the susceptibility of the warship is reduced in IR terms and, the time available for the release of IRCM increases.

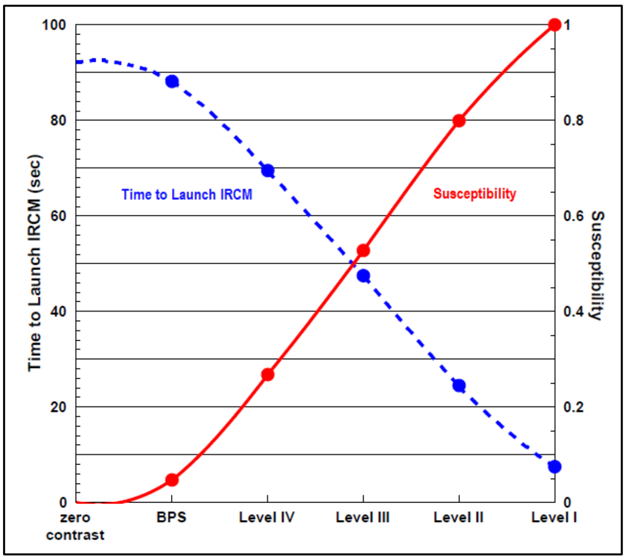

Figure 14: Real World Impact of IRSS.
Source: Davis, Thompson, 2002

The following table summarizes all the values of the variables put into play, i.e. IRSS levels and IRCM measurements and their impact on both IR susceptibility and the time available for the release of IRCM.

Table 4: IRSS & IRCM versus IR Susceptibility.

IRSS	IRCM	SUSCEPTIBILITY	MISSILE LOCKS ON SHIP TIME TO LAUNCH FLARES (s)
Level 1	No Wash	1.0	8
	No Stack Suppression		
Level 2	NBC Wash	0.8	25
	Passive Metal Cooling		
Level 3	Full Wash	0.52	50
	Passive Metal Cooling		
	Passive Plume 250 ºC		
Level 4	Full Wash	0.26	70
	Passive Metal Cooling		
	Passive Plume		
	Sea Water Injection		

Figures 15 and 16 show the results of simulations performed with IR signature prediction and analysis software on an unclassified destroyer model, taking into account the following considerations:

- Ship condition at full power (GT propulsion and power generation with DE).
- Main sources of IR signature (gases and exterior surfaces).
- IRCM (eductors/diffusers and full wash-down).
- Most unfavourable weather (during a sunny day).
- Sensors type MWIR and LWIR at different heights (10 and 270m from the sea level).

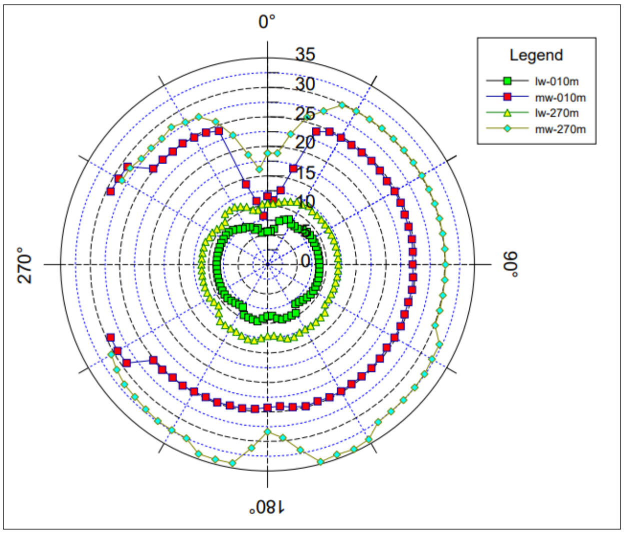

Figure 15: Detection Range (km) of Dark-Grey Destroyer at Full-Power with no Signature Treatment (Best Clear Day). Source: Vaitekunas, 2010

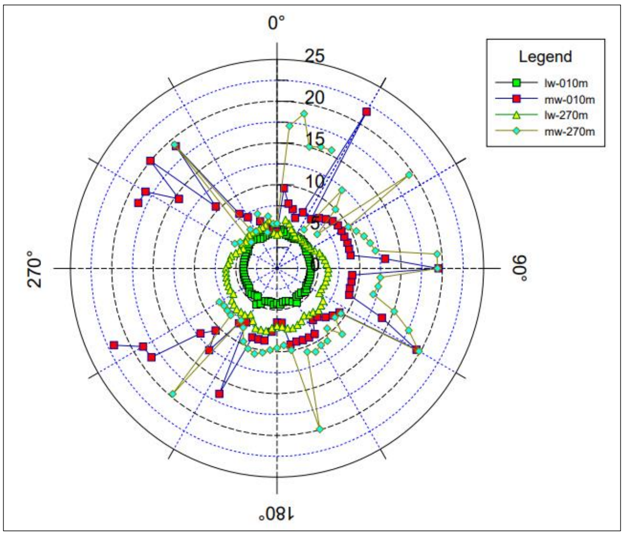

Figure 16: Detection Range (km) of Dark-Grey Destroyer at Full-Power with Stack Suppression and Hull Film Cooling (Best Clear Day).
Source: Vaitekunas, 2010

As can be seen in the above figure, the activation of IRCM have a great impact on the results, especially in the MWIR band, mainly by reducing the temperature of both the exhaust gases of the engines and the surfaces heated by them when leaving the ducts. There is also a slight impact on the LWIR band due to the reduced temperature of the outer surfaces of the ship by activation of the washdown system.

Therefore, the adoption of IRCM will provide a huge advantage, especially in quasi-passive or *"softkill"* defense scenarios, in the way that the ship will make use of decoys in order to divert the attention of aerial threats to false targets, which is commonly known as deception techniques.

5. CONCLUSIONS

Based on the results obtained in the previous pages, the following conclusions can be established:

- The CODELOG solution will be much more advantageous than the CODOG from the point of view of the thermal efficiency of the propulsion system. This will entail a number of advantages, such as improvements in consumption, range, the control of emissions to the atmosphere, and even maintenance.

- From the point of view of IR susceptibility, the CODELOG option will also be much more advantageous, since it will be able to transform a greater amount of heat into effective work that would otherwise be radiated to the outside of the ship with the negative impact on the IR signature.

- From the above conclusions it can be stated that electrical variants to warship propulsion systems, such as CODELAG, CODELOG, etc., are more efficient under the same operating conditions, which will be a clear advantage from the point of view of IR signature control.

- With regard to IRCM measurements, their activation will have a great impact on the MWIR band, mainly due to the cooling of both the exhaust gases and the diffuser effect on the last part of the GT and DE exhaust ducts. As far as the LWIR band is concerned, although there is a reduction in radiation, it is not as pronounced as in the case of the MWIR band. In addition, radiation in the LWIR band will be strongly influenced by both the time of day (day or night) and the weather conditions surrounding the ship.

- In any case, it is proven that activating IRCM reduces the susceptibility of a warship in terms of IR signature, making it difficult to detect, classify, and track. In addition, passive missile self-tracking capability will be hampered, increasing the time available for the deployment of IR decoys.

- In this case, the relationship between energy efficiency and stealth of the warship demonstrates the practical advantages of Operational Energy Security.

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