Modelling The Heat Distribution In A Warship

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The adaptation of electrical transmission and increasing threats from infra red missiles has made thermal management on warships a hot topic. SURFCON is an established ship design tool and it has been adapted here to investigate the heat management problem. The heat distributions within four frigate sized vessel are compared, the vessel have different machinery configurations but are otherwise similar.

KEY WORDS
IFEP, infra red signature; ship design; SURFCON; thermal modelling; warship.

INTRODUCTION

Heat management on warships at a whole system level is a neglected area; research has tended to focus on components. This contrasts with terrestrial architecture and building design where the whole system approach is well developed. This paper discusses why the apparently similar problems are quite different. The SURFCON ship design tool is then developed to study the cooling load requirements for a ship. A baseline frigate model is then developed based on existing modern warships. The baseline frigate has conventional CODOG machinery fit. Three variants are then developed, one CODLAG and two IFEP, apart from the machinery fit the variants are kept as close to the baseline vessel as possible. The waste heat distribution and cooling loads of the four vessels are compared.

BACKGROUND

Architectural Approach

The whole system approach to thermal management is well developed in land based building design where the driver has been the desire to reduce temperature related running costs i.e. heating, ventilation and air conditioning (HVAC). For warships while the HVAC power requirements have been estimated to represent 25% to 40% of the auxiliary energy use (Timbrell 2005) this is still small compared to the total ship power requirement and so has not received much attention. This is not true for all ships, for example cruise liners where the air conditioning load can be many megawatts. The situation is now changing for warships driven by two factors, electrification and the desire to reduce overall IR signature.

The simplest solution would be to take the tools developed for buildings and apply them to ships, there are significant drawbacks with this approach. The shape of ships and their compartments are different from buildings. Construction materials are different. More significantly ships move so that their surrounding environments and orientation to the sun change rapidly and unlike buildings, ships have their main energy generating plant within them, not at some remote power station. Another significant problem is how to model the part immersion in water. For warships the differences are even more significant, warships are very compact and contain many energy intensive items. Finally buildings do not operate in a threat environment so there is no requirement to control their infra red (IR) radiation emissions from a signature reduction viewpoint.

Impact Electric Transmission

Warships are evolving from the traditional mechanical transmission with shafts and gearboxes to electrical transmission with converters and cables and the concept of integrated full electric propulsion (IFEP). IFEP offers many operational and layout advantages but these come at a cost of reduced transmission efficiency. A traditional mechanical drive system via a double reduction gearbox has a full load transmission efficiency of about 97% falling to perhaps 95% at part load measured from the prime mover output flange to the propeller flange. By comparison measured between the same two points an electrical transmission system (generator, converter and motor plus cabling) would be doing well to achieve 90% at full load with lower efficiency at part load. The flexibility of IFEP provides opportunities for this efficiency loss to be offset by gains elsewhere in the total propulsion system. The losses in most electrical machines consist of:

- I^2R losses which are cause by current flowing through the various parasitic resistances associated with electrical machines, voltages are kept high to minimise these losses but increasing the voltage introduces a new set of problems.
- Fixed Losses which include core losses such as hysteresis, eddy current losses and frictional losses.
- Switching Losses which happen in the power semiconductor as a result of the switching action of the power supply, for example as in modulation of a motor.

The 10% or greater energy loss must be removed by the ship's cooling plant, if it is not the system will rapidly overheat and fail. The lower the transmission efficiency the quicker it will overheat. The cooling system is therefore critical plant. An advantage of IFEP is that it permits more flexible positioning of prime movers, generators etc., not only longitudinally but also vertically. Placing machinery above the waterline reduces underwater noise transmission but it exacerbates the cooling problem, cable runs are longer and machinery is now further removed from the natural cold sink – the sea.

Gearboxes and shafts maintain high transmission efficiency at part load but some components of electrical transmission systems have noticeably lower efficiencies at part load. The operating profile of warships is such that although designed to operate at a high top speed they spend the majority of their time at part load at a cruise speed. It is quite possible for the maximum power loss for an electrical transmission system to occur at some part load and not full load. If a ship requires 10MW power delivered to the propeller at top speed and has a transmission efficiency of 90% the required brake power is 11.1MW and 1.1MW is lost and effectively has to be removed by the cooling system. Assuming the standard cubic power speed relationship 3MW power delivered to the propeller would propel the vessel at 2/3rd top speed. If the transmission system is only 70% efficient then the brake power required is 4.3MW and now 1.3MW is lost and effectively has to be removed by the cooling system. Figure 1 shows the efficiency curves for transmission systems that are 95, 90 and 85% efficient at maximum power and then maintain the same absolute power loss (measured in MW) across the entire power range, plotted against percentage brake power on the left and percentage maximum speed on the right. For each curve the same maximum delivered power and maximum speed are assumed.

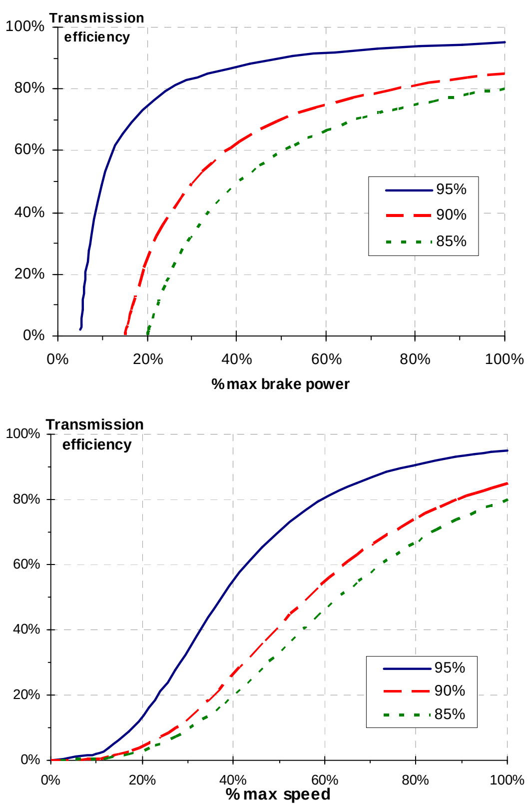


Fig. 1. Required part load efficiencies to maintain a constant transmission loss for full power transmission efficiencies of 95, 90 and 85%

The introduction of IFEP not only increases the cooling load on a ship but it makes the HVAC, chilled water and seawater cooling systems critical systems which must be designed with survivability and redundancy built in. The replacement of many auxiliary systems with electrical actuation only adds to this requirement. New sensors and weapons systems will further increase the cooling load. On the Royal Navy's Type 45 frigate the Sampson radar located over 30m above sea level imposed significant pressures on the chilled water system. In the near future pulsed weapons and electromagnetic launch systems for UAV's will be new customers for cooling. The introduction of high temperature super conducting motors and the cryogenic storage of gases for fuel cells will add a new dimension to on board thermal management.

Infra Red Signature

A number of ongoing ship programs (US DDG-1000, Spanish F100, Norwegian Nansen Frigate) have specified IR signatures as part of their overall requirement (Vaitekunas et al. 2000). Whilst the majority of anti-ship missiles are radar guided there is a small but significant number of missiles that are either IR guided or contain a combination of guidance systems such as radar and IR. IR detection is passive which makes it more difficult to detect an incoming missile and it cannot be jammed. Decoys can be deployed but this takes time. With improvements in Electronic Warfare it is likely that there will be increasing numbers of IR guided missiles in service. There is also likely to be a significant number of less complicated short range IR homing missile that could be used in an asymmetric threat environment.

Infra red radiation is attenuated by environmental conditions and detection range is limited even in good weather. The two main transmission bands for maritime conditions are the near and far infra red radiation bands; the NIR band has a wavelength of 3.2 to 4.8μm, and in the FIR band 8 to14μm (Gates 1986). For a warship the NIR band usually corresponds to the very hot parts of the ship and the ship appears as a few point sources, see Fig. 2a. The exhaust plume clearly has the largest IR signature and is the easiest to lock onto. Sensors tracking this band are also the easiest to confuse with decoys and high temperature counter measures.

The not so hot parts of the ship such as the machinery rooms will radiate in the FIR band, while these regions have a lower signal strength than the exhaust efflux they emit from a much larger area so more of the ship's details can be discerned, see Fig. 2b. Sensors operating in the FIR band are more difficult to deceive with decoys and the image can also be used for target recognition.

Exhaust gases have produced the significant IR signature of ships and considerable effort has been expanded in reducing this signature especially for gas turbines. The most advanced systems use an eductor diffuser system and inject a fine mist of water into the exhaust. This will dramatically reduce the plume temperature and hence the NIR signature but water injection increases the mass of the plume and signature in the FIR band (Thompson et al. 2002). The drives to reduce emissions and increase efficiency by use or advanced cycle gas turbines, exhaust gas scrubbers and waste heat recovery systems have also significantly reduced exhaust gas temperatures. Some new diesel driven ships have submerged exhausts. The result is that emissions in the FIR band are now as important, if not more so, than in the NIR band and it has become important to control the whole ship temperature profile.

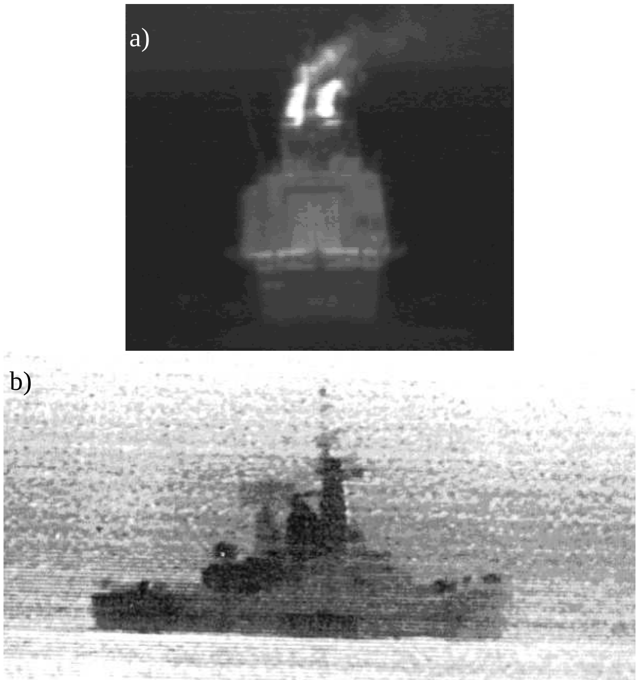


Fig. 2. Thermal Images of Warships, a) NIR band (Thompson et al. 2002) b) FIR band (Gates 1986).

SHIP MODELS

A CODOG machinery fit (baseline vessel) and three variants (CODLAG, IFEP – compact and IFEP - dispersed) were developed using SURFCON. Each vessel is a fully balanced design and the only significant difference between them is the main machinery fit and the consequential changes this forces. Where possible all other features are kept the same including the weapon fit, superstructure and crew numbers.

SURFCON and the Design Building Block Technique

SURFCON is a tool within Graphics Research Corporation's PARAMARINE ship design suite, which uses the UCL Design Building Block approach to incorporate an architectural description as the core to initial ship design. The DBB approach, described by Andrews and Dicks (1997), focuses on calculating the ship's key characteristics from the spaces required by the key components. This is very different to the traditional method of ship design where the hull envelope, damage stability and structural continuity produce a hull envelope in which the general arrangement is developed.

Figure 3 shows an example of the Design Building Block approach when applied to the initial design of a generic frigate. The calculation of the space and weight requirements of each of the main blocks will drive the size requirements of the overall ship. SURFCON was developed as part of the PARAMARINE computer aided ship design suite and allows the user to design the ship using the building block methodology. The use of SURFCON has been particularly useful in investigating IFEP systems where the system layout may not be similar to the classical machinery location and configuration an example is provided .Andrews et al. (2004) study of monohull frigates.

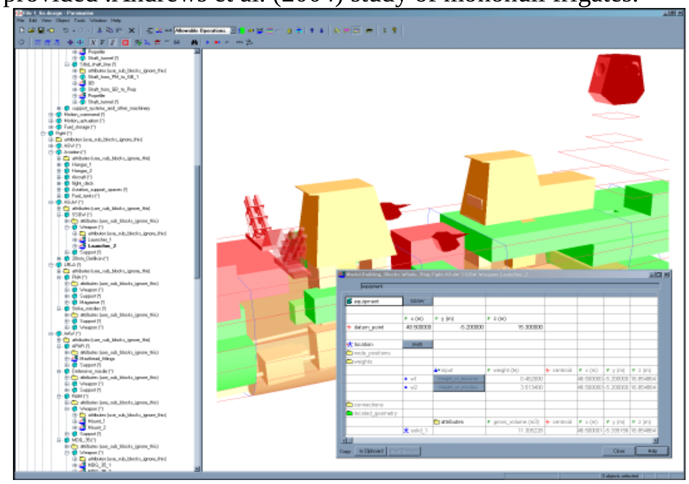


Fig 3. Design Building Block approach (Andrews et al. 2004).

One of the advantages of SURFCON is it allows easy manipulation of the ship's configuration. This is because the dimensions of the blocks themselves can be linked to either the surrounding blocks or in some cases the bulkheads. This is done by creating a framework of key dimensions. So it would be possible to move around a complicated system of smaller blocks as part of a much larger block defining a machinery system. One of the unique aspects of SURFCON when using the UCL ship design procedure is that the compartments space and weight requirements can be related to the ship's overall geometry and complement. Thus changing the overall length of the ship can automatically scale both the size of the blocks and their demands of weight, systems etc. SURFCON also allows a property with most common units to be associated with a specific Design Building Block, categorised as supply or demand. The audit function within PARAMARINE can then be used to assess the supply against demand for any particular property, such as chilled water or electrical power. The ability to assign any property to a Design Building Block makes SURFCON a good candidate for configuration based heat management. Each compartment can be considered as a block but compartments like the engine room can contain sub blocks, which can be used to define individual main machinery items.

Heat Loss Calculation

Each design building block where heat loss could be identified was included in the SURFCON model. For each compartment values for heat loss such as lighting were assigned to the relevant compartment design building block and any losses associated with equipment to the relavent equipment block. Heat losses were divided into different categories:

- Thermal convective/radiant waste heat, this is given off by all equipment and personnel.
- Low pressure salt water (LPSW) heat, this is heat given off to the LPSW system through heat exchangers which effectively covers all forms of coolant within the ship.
- Chilled water (CW) heat, this is heat given off to the chilled water system. This overlaps with the LPSW system as the CW plants use LPSW heat exchangers.

Non Propulsion Machinery. For the auxiliary systems data was taken from manufacturer's published information where available. In these cases efficiencies were assumed and losses were calculated based on the power requirements of the system. For shafting and gearbox loss calculations efficiencies were estimated and then losses calculated using the power transmitted to each shaft. For water cooled systems it was assumed that the coolant acquires 90% of the waste heat and the other 10% is given off as radiant heat. For the weapon systems little information was available in the public domain and the data was taken from the UCL ship design data book (UCL 2008). Where heat losses or coolant requirements were not available these were based on similar systems.

Engine/Generator Losses. The calculation of the engine heat losses was done on an energy basis. Knowing the energy content of the fuel and the specific fuel consumption of the engine, the losses and efficiency can be calculated. For Wartsila diesel engines the heat losses to the different coolant circuits and the radiant heat loss are specified, so the heat loss to exhaust can be calculated from this. For the gas turbine engines it is assumed that they are housed in a thermal enclosure and are naturally air cooled. Due to the ventilation of the thermal enclosure the vast majority of the lost energy will exit through the exhaust and ventilation systems. However despite its insulation some waste heat will transfer through the enclosure, it was assumed that 1% of the total energy lost escapes through the enclosure, BHEL-GE (2008) would seem to support this. To calculate generator losses the electrical output from the manufacturer specification sheet was subtracted from the shaft output of the engine. It was assumed 10% of the heat loss is waste heat and 90% is lost to the charge air cooling system.

IFEP System Losses. For motors, converters and other IFEP equipment losses were calculated based on assumed efficiencies for known powers with 90% of the heat transferred to the cooling system and 10% as waste radiant heat. It was assumed that all I^2R losses generated by cabling became lost heat, although it is likely that some of these losses manifest themselves in other ways such as noise their contribution is likely to be tiny. Only the losses from the main busbar were calculated as the other lower power losses will be small in comparison.

Minor contributors. The heat loss data for personnel was calculated based on the data in ISO 7547; the contribution by personnel was not assigned to any specific block but it was assigned at a system level, to allow for total load demand. The heat gain from lighting and office equipment was taken from ISO 7547; however there were only a limited number of classifications of rooms in this standard. For example it did not include a gain for the Ops room, so this was based on a high technology office specified in ISO 13791. ISO 13791 specifies heat gains for buildings but this should be similar to the heat gains on a ship. Similar approximations were made for other compartments where no suitable value from ISO 7547 was available.

Constructing the CODOG Model

The baseline ship is a generic combatant based on the performance characteristics of three recent generation warships, the Dutch De Zeven Provinciën, the French La Fayette and the South African Valour class frigates. The hull shape is based on the UK Type 23 Frigate. The weapon fit is listed in Table 1 and provides the baseline vessel with a capability similar to the De Zeven Provinciën class. The hangar and flight deck are sized for a Merlin helicopter. Payload details were taken from the UCL ship design data book (UCL 2008). The compliment was fixed at 200 and includes space for air crew and compliment margins.

Table 1 Chosen Weapons Fit, data taken from UCL Ship Design Data Book (UCL 2008).

Group 6: Payload		Mass Mg	Vol. m^3
61	Weapon Control Systems		
	Command System	15.00	200
62	External Communication		
	Communications I	34.10	354
63	Sonars		
	Hull Mounted Sonar	21.10	99
	Towed Array Sonar	30.20	310
64	Radars		
	"A" Navigation Radar	0.20	7
	MFR	12.00	224
	Search Radar	7.80	183
65	Electronic Warfare System		
	EW System	4.50	30
66	Weapon Systems		
	155mm Gun	24.50	428
	Chaff	1.20	0
	20mm Guns	8.00	0
	Magazine Torpedo Launch System	25.00	283
	Harpoon *8	17	31
	Aster	12	140
	Hangar (Merlin)		998
	Totals	212.6	3287

Using the UCL approach it was possible to calculate some initial dimensions shown in Table 2. This information permitted calculation of all the space requirements for the associated compartments using the UCL ship design data book [UCL 2008]. As the space requirements for each Design Building

Block using SURFCON can be linked in to the general characteristics of the ship, the approach was an iterative approach refining both the ship's dimensions and space requirements for each Design Building Block.

Table 2. Initial Sizing Calculations for CODOG vessel.

Initial Payload Volume	3287.00	m^3
Payload Volume Fraction	0.20	
Total Internal Volume,	16435.00	m^3
Assumed Overall Density	0.29	Mg/m^3
Displacement	4815.46	Mg
Displacement Volume	4698.00	m^3

A first estimation of resistance was obtained using Holtrop (1984) and this indicated that 39MW shaft power would deliver a top speed of 30kts. A space and services audit was conducted and it was confirmed that the ship met the intact damage stability criteria due to a damage length of 15% of the waterline length (MoD 2000). For the resultant design the powering calculations were refined and the design iterated until the design balanced. The design was validated against the type 23 Frigate by comparing the weight groups and checking for any significant deviations. Figure 4 shows the final profile and machinery configuration for the CODOG vessel. A similar process was applied to the three variants.

The CODOG (baseline) design is similar to the De Zeven Provinciën class with a mechanical transmission CODOG configuration. The CODLAG variant has a machinery installation in some ways similar to the Royal Navy Type 23. The last two options both have IFEP and identical machinery fit installed, in the IFEP – compact variant the machinery is concentrated in the traditional engine room area while in the IFEP – dispersed variant full use has been made of the flexibility of IFEP and the main machinery is widely dispersed about the ship. Table 3 summarises the features of the four vessels. The cruise speed of the CODOG vessel is only 15kt compared to 20kt for the other three, this compromise was used to keep the size and total installed power of each vessel similar. Even so the total installed power in the CODOG variant is 47MW compared to 44MW for the rest. To achieve a cruise speed of 20kts the CODAG variant would require at least 53MW installed power and this would have resulted in a bigger ship. As the following analysis is for the worst case scenario, i.e. at top speed and maximum activity load, the lower cruise speed of the CODOG vessel has no direct input on these results.

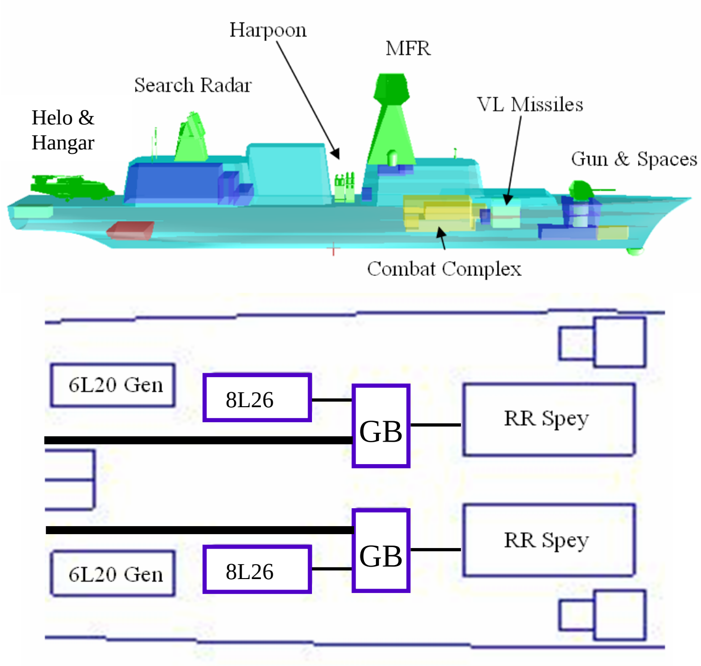


Fig. 4. Details of the CODOG vessel.

THERMAL ANALYSIS

The data available from SURFCON consisted of the total heat gain and loss per building block for each of the characteristics defined and the (x, y, z) co-ordinates of the centre of gravity for each block. This information was combined to form the output data based on the compartment layout, remembering that in this particular design blocks can be major machinery items not just whole compartments.

Table 3. Key characteristics of ship options.

	CODOG	CODLAG	IFEP - compact	IFEP - dispersed
Length (m)	129.8	129.9	130.0	133.9
Beam (m)	18.2	18.2	18.2	18.2
Draught (m)	5.1	5.3	5.2	5.4
Displacement full (Mg)	4039	4650	4725	5077
Top speed (kts)	30	29.5	29.5	29.25
Cruise speed (kts)	15	20	20	20
Complement	200	200	200	200
Propulsion	CODOG	CODLAG	IFEP compact	IFEP dispersed
Installed Power (MW)	2 x 19 GT 2 x 2.6 D 4 x 1.0 DGen	1 x 30 GT 2 x 5.0 DGen 3 x 1.3 DGen	1 x 30 GT 2 x 5.0 DGen 3 x 1.3 DGen	1 x 30 GT 2 x 5.0 DGen 3 x 1.3 DGen
Gear Box	2 double reduction	1 cross couple dbl reduct	-	-
Motors	-	2x5 AIM	2x20 AIM	2x20AIM

CODOG baseline

Figure 5 displays the waste heat distribution within the baseline CODOG ship, and the eleven zones into which the ship has been dived for thermal analysis. The diameters of the circles represent the amount of heat given off, and the circles are centred at the centre of gravity of each block. Further discrimination can be achieved by colour coding the circles to float, move, fight and infrastructure functionalities. The output from the funnel and exhaust plume has been omitted as they would swamp the rest of the data. A similar approach is used for Fig. 6 and Fig. 7 which show the CW weapons demand LPSW demands in the ship. As each variant has the same weapons fit the CW weapons demand is similar for all four variants. From Fig. 5 it can be seen that the primary sources of heat come from within the main machinery space, however these are larger than first appear as this view can be misleading. The figure is only a 2D representation of a 3D model and the output from the port machinery line is obscured by that of the starboard line. An alternative representation of the data is shown in the graph in Fig. 8 where the total waste heat from each main longitudinal subdivision is displayed; the vertical axis is kW/m so that integrating the curve produces the total radiant heat output which is 2.3MW. A simpler version of this approach can also be used for displaying supply and demand; an example is given in Fig. 9. This shows the magnitude and relative position of the CW demand in each section permitting a clear overview of the system distribution to be established, the two supply units are also shown.

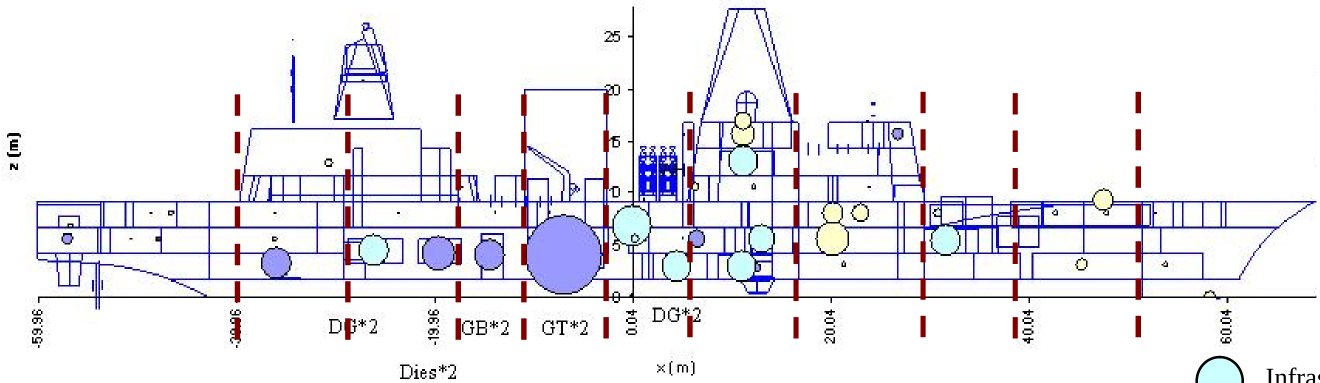
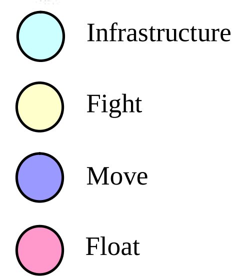


Fig. 5. CODOG (baseline) waste radiant heat



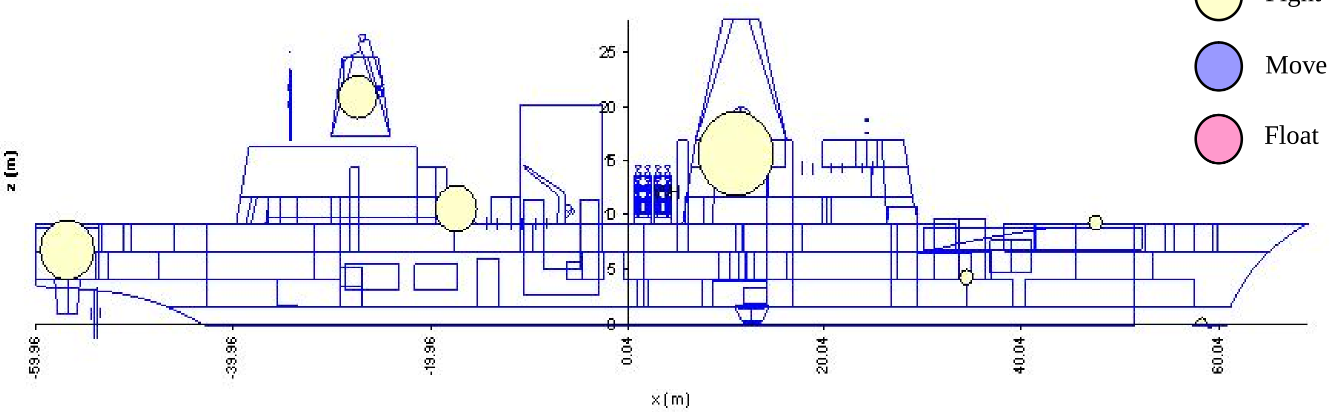


Fig. 6. CODOG (baseline) distribution of CW weapons demand

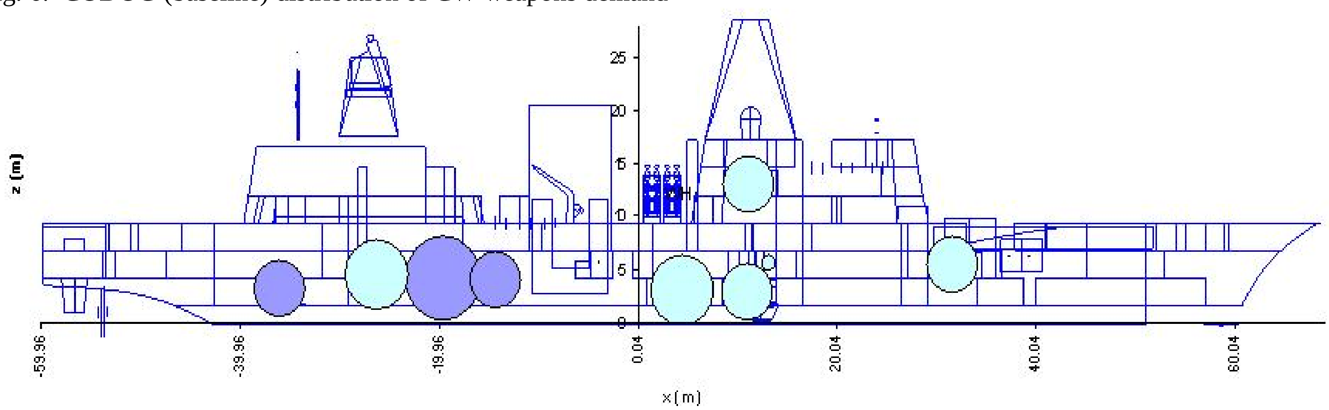


Fig. 7. CODOG (baseline) distribution of LPSW.

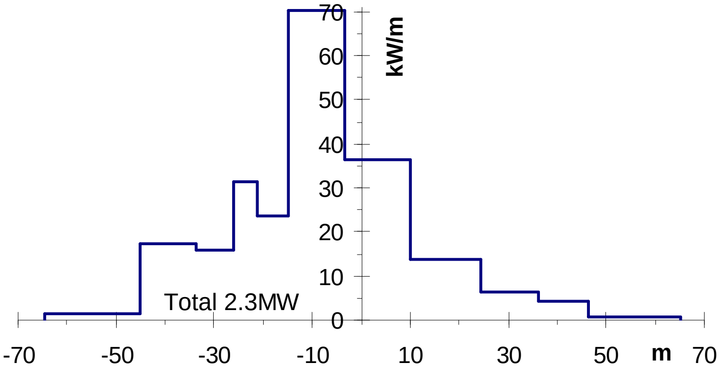


Fig. 8. CODOG waste radiant heat longitudinal distribution.

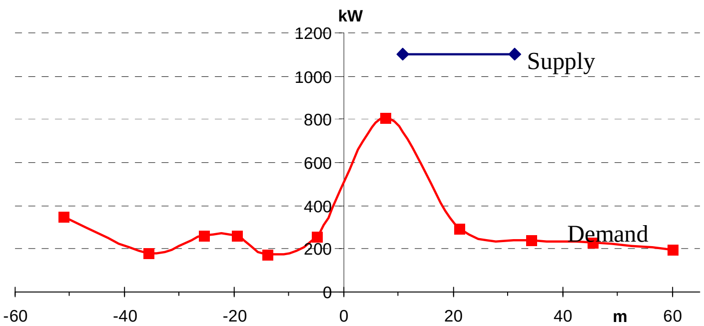


Fig. 9. Chilled water supply and demand for CODOG ship.

CODLAG Variant

The CODLAG variant consists of one GE LM2500+ (30MW) driving twin shafts via a cross coupled gearbox. 5MW Advanced Induction Motors (AIM) are mounted on the shafts. To power the motors and provide electrical service power two 16v26 Wartsila generators are included to take up the maximum load, whilst three Wartsila 8L20 generators are provided to allow for base service load and low speed patrolling. These smaller generators are mounted on 3 deck above the waterline to enable quieter running for submarine patrol operations.

The CODLAG propulsion system is slightly longer than the baseline CODOG system. This is largely due to the increased power provision of the diesel engines. The forward diesel generators now require two decks and rearrangement has forced the gas turbine further forward. This in turn has forced the main funnel forward requiring the Harpoon be relocated in-between the funnel and hanger. There is more space above the gas turbine as the exhaust system is smaller, but now requires a different configuration on 2 deck due to the central location of the exhaust.

The main machinery room is still in a centralised location and is still somewhat restricted by the shaft, but a degree of flexibility is created by the use of electric motors. By using large diesel generators forward of the gas turbine, the thermal profile of the ship has been smoothed slightly as can be seen in Fig.10. However the total waste heat output has increased to 2.6MW which is largely due to the decreased efficiency of a complex cross-coupled gearbox, and the introduction of electric motors and their associated equipment.

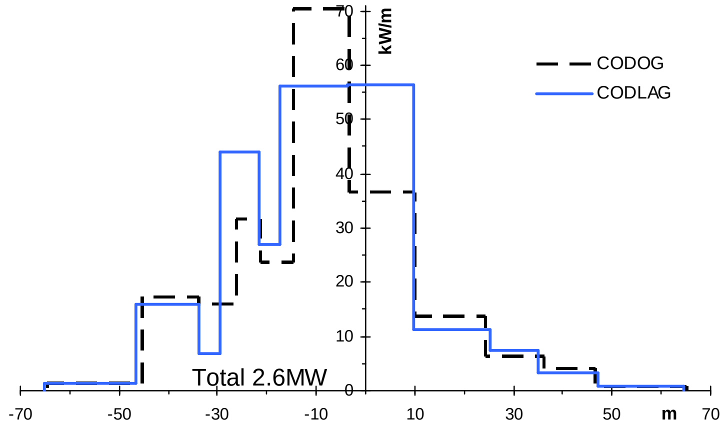


Fig. 10. CODLAG waste radiant heat longitudinal distribution.

IFEP – Compact Variant

This option uses the same prime movers as the CODLAG option and where possible has kept them in similar locations. The LM2500+ now drives a generator and the main gearbox has been eliminated. The AIM's are increased to 20MW size with consequential increase in converters, filters and switch gear. This increase in size has forced two of the smaller generators to be moved alongside the LM2500+ generator, but still on the same higher level. The length of the machinery fit has also increased.

Analysis of Fig. 11 shows that moving two of the smaller generators alongside the gas turbine has increased the severity of the heat spike at amidships. Where as the compartment that had the smaller generators in has maintained its level of heat generation due to the addition of larger converters and motors.

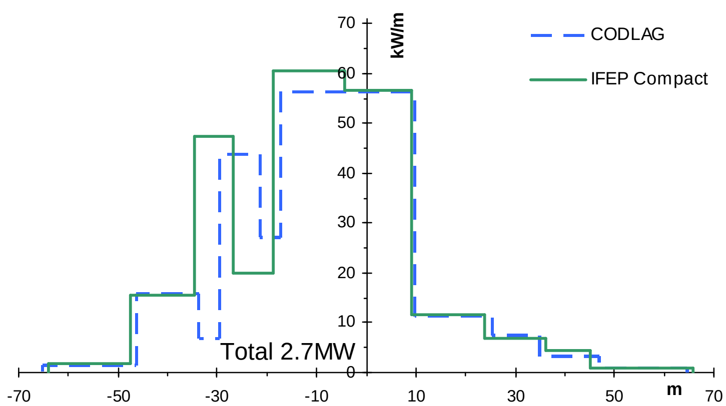


Fig. 11. IFEP-compact variant waste radiant heat longitudinal distribution.

The total amount of heat generated is now 2.7MW, only slightly higher than the CODLAG option. The IFEP option gains heat from the addition of bigger converters, motors and the addition of a generator to the gas turbine but this is offset by the removal of the complex gearbox. In this option the electrical wiring is starting to generate significant amounts of heat due to the increasing power of the main busbars.

IFEP – Dispersed Variant

The final variant uses the same IFEP propulsion system as the previous option, but the main components are dispersed about the ship making full use of the flexibility offered by IFEP, the layout can be seen Fig. 12. The vertical launch missile silo (VLS) was moved to the centre of the ship, this creates more space forward for the smaller diesel generators. The main diesel generators are unaltered as are the AIMs and their associated equipment. The gas turbine is now located to the very rear of the ship. The exhaust system vents over the stern similarly to the Valour class frigate. In order to fit both the gas turbine and its exhaust trunking in the ship the overall ship height was increased along with the heights of 2 and 3 deck. To accommodate all these changes the overall length of the ship was also increased. This arrangement removes the requirement for a main funnel. Whilst the central location of the VLS breaches 1 deck the hole is only slightly larger than that formed by the exhaust.

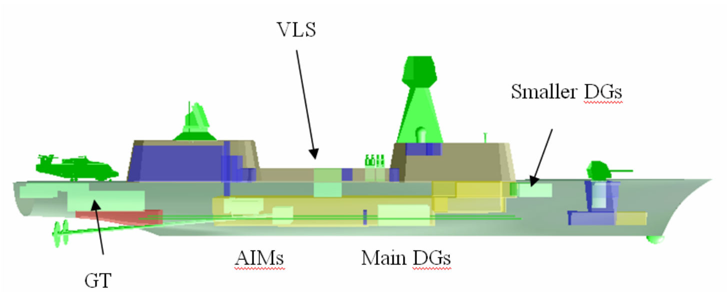


Fig. 12. Dispersed IFEP variant machinery locations.

The thermal profile has changed significantly as seen in Fig 13 but as the same equipment is still being used the overall magnitude is little altered, it has increased slightly due increased cable losses. A large peak still remains amidships due to the main diesel generators while a smaller peak now appears forward due to the two small diesel generators located there.

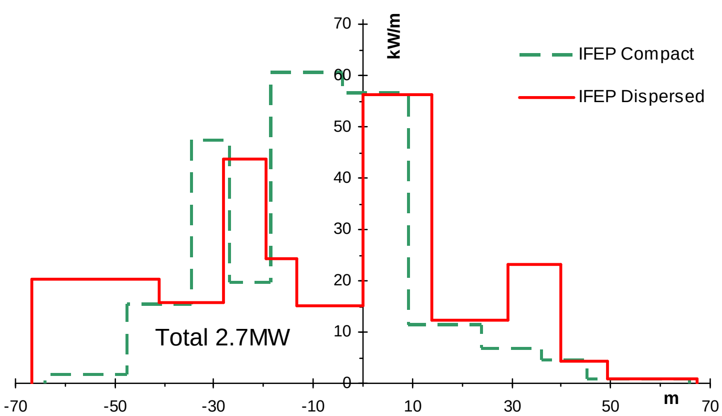


Fig. 13. IFEP-dispersed variant waste radiant heat longitudinal distribution.

By spreading out the amount of heat generated by the prime movers this design has created a new dilemma about which compartments to ventilate mechanically and which to use air conditioning. Whereas other designs have the entire main machinery space mechanically ventilated the subdivision of the machinery space may cause other problems. The gas turbine compartment at the rear of the ship will still be mechanically ventilated. The compartment overlaps with the hanger slightly so the ventilation system will probably have to use the hanger superstructure as the exhaust is vented over the stern and the flight deck is right above it. The inclusion of a gas turbine directly below the flight deck could cause survivability issues in event of a helicopter crash, but this will have to be factored in to the design of the flight deck.

As the main diesel compartment will require exhaust and inlet trunking anyway, it seems sensible to mechanically ventilate this compartment. The pulse width modulator converter compartment in the compact IFEP option was supplied with air conditioning, so it now seems sensible to supply air conditioning for the whole of this compartment. The chilled water demand can be seen in Fig. 14, the magnitude of the spikes at the two radar locations are still the same height but the drop off either side has now been reduced. Compare this with the chilled water demand for the CODOG variant in Fig. 9. It should also be noted that the chilled water demand now does not reach the stern of the ship due to the location of the gas turbine compartment. This may be beneficial to the air conditioning and chilled water system due to the reduction of the length of the zone which requires supply. With this in mind the chilled water plants were placed near the spikes of the demand. The overall demand has increased to 2.1MW; this is largely due to the inclusion of the AIMs within the air conditioning boundary.

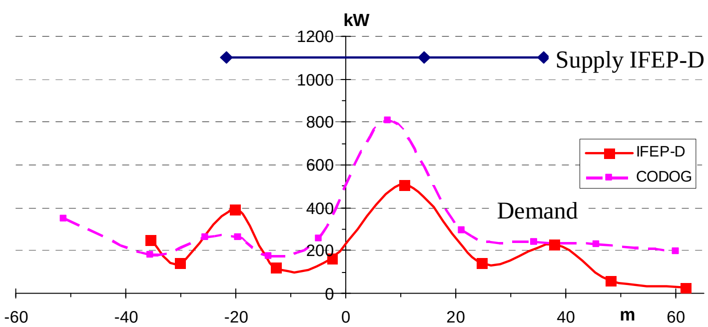


Fig. 14. Comparison of chilled water demands for CODOG and IFEP-dispersed variants.

CONCLUSIONS

The SURFCON tool had been adapted to help model the thermal profile using its building block approach and its ability to assign attributes to blocks. The exercise has demonstrated the flexibility of SURFCON but for more detail analysis modifications of the model would be required.

Heat management is going to become an increasingly important subject for ships and especially warships. Warships are relying increasingly on electrical transmission systems not only for main power but also for auxiliaries and in the future weapons. While electric transmission offers many advantages electrical transmission systems and machines are not prefect and do have losses. They losses manifest themselves as heat and for main propulsion electrical systems have higher transmission losses than simple mechanical systems. The result is that more cooling is required and maintaining reliable cooling is becoming more critical. The flexibility that electrical distribution systems offer exacerbates the cooling problem because the equipment that needs to be cooled is more widely distributed about the ships, not only horizontally but also vertically.

The primary purpose for developing the tool was for a better understanding of heat management, to show heat is generated in compartments and how some of the main auxiliary systems to remove and control heat are distributed around a ship. A secondary use for this tool is for assisting in the control of the infra red signature. The infra red signature of warships, especially in the far infra red, is also gaining in significance. The type of threat is evolving and as counter measures become more successful against active sensors passive sensors are again being exploited, the successes in reducing the infra red signature of the funnel and exhaust plume have now made the signature of the remainder of the ship more significant. While this tool will assist in controlling the IR signature, full understanding of the IR signature can only be achieved by including other factors such as solar radiation, radiation and conduction to the external environment.

For comparison purposes the four variants had the same payloads, crew numbers and similar displacement and installed power. There is scope for further refinement of the designs, for example taking in to consideration the size of the ME department and fuel capacity required for each the machinery installations. Much of the data was taken from the UCL data book or approximated so while valid for comparison purposes absolute values should be treated with caution. The results discussed above were all for the ships travelling at full speed with maximum connected activity load. This is considered the worst possible case, except that no allowance has been made for operating in an NBCD environment. In a high threat situation the ventilation might be greatly reduced due to an NBCD threat environment. This would raise the internal temperature of the ship, especially machinery spaces. The resulting vulnerability of the ship due to the increased IR signature of the ship hull would have to be balanced against any emergent NBCD threat.

There is considerable scope for further analysis including for cruise, loiter and stealth conditions or optimising designs for minimal signature. Ironically the drive to reduce the FIR signature could put diesels back below the waterline.

REFERENCES

Andrews DJ Dicks C (1997). "The Building Block Design Methodology Applied to Advanced Naval Ship Design", *Proc. IMDC, Newcastle: International Marine Design Conference (IMDC)*

Andrews D Greig A and Pawling R (2004). "The implications of an all electric ship approach on the configuration of a warship". *I.Mar.E.S.T. 7th Intl. Naval Engineering Conf. (INEC), Proc. IMarEST part D*, pp. 132-146 Amsterdam, March, 2004.

BHEL-GE (2008). BHEL-GE Gas Turbine Collaboration Status, available from www.scribd.com/doc/2909125/GAS-TURBINE-3 (cited Sept 2008).

Gates P (1986). "Infra-red Signatures of Warships", *J Naval Engineering*, Vol 30 1986-87.

Holtrop J (1984), "A Statistical Re-Analysis of Resistance and Propulsion Data", *International Shipbuilding Progress*, Vol.31, No.363, Delft, Netherlands: TUDelft

Ministry Of Defence, (2000). "Stability Standards for Surface Ships", Defence Standard 02-109 (NES 109) Issue 1, Glasgow: MoD

Timbrell I (2005). "Energy Efficiency of Warship Auxiliary Systems", MSc thesis, Dept. Mech. Eng., UCL Sept 2005.

Thompson J, Vaitekunas D and Brooking B (2002). "Signature Management – The Pursuit of Stealth Lowering Warship Signatures – Electromagnetic and Infrared", WR Davis Engineering Limited, Ottowa, Canada, www.davis-eng.on.ca (cited Sept 2008).

UCL (2008) "Master Course Ship Design Data Book"; Department of Mechanical Engineering; UCL; 2008

Vaitekunas D, Thompson J and Reid F (2000). "IR Vulnerability of Modern Warships using SHIPIR/NTCS", Defence Research Establishment, Valcartier, Quebec, Canada.