Advanced Cooling Methods for Naval Laser Directed Energy Weapons

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Synopsis

This paper reflects a research study that was undertaken on behalf of the UK Defence Science and Technology Laboratory (DSTL) to improve understanding of the cooling challenges posed by novel Laser Directed Energy Weapons (LDEWs) in the maritime domain. The aim was to characterise the thermal demands of near-term and future LDEW systems, identifying & comparing candidate cooling technologies and analysing the performance of the perceived best available cooling approaches.

This paper first provides comment on the scope of the near-term and future cooling challenge for LDEW integration. It then looks at the factors which affect the cooling methodology and considers potential design solutions that were developed as part of an options study. The study assessed the performance of current (High Technology Readiness Level) (TRL) and developing (Low TRL) cooling technologies, in order to provide recommendations for near-term cooling solutions, whilst also providing a roadmap for the technologies and manufacturing techniques which were considered to pose specific advantages in cooling the high-powered LDEW weapons of the future.

Finally the paper will consider a number of the developed concepts for LDEW cooling, discussing the feasibility of modular cooling approaches for configurable mission-bays and integrated cooling methods which utilise Thermal Energy Storage (TES) and Phase-Change materials (PCM) and the challenges associated with deploying these within in-service platforms.

Key Words;

LDEW, Cooling, Ship Integration, Thermal Storage, Modular.

1. Background: Why LDEWs?

The development of LDEWs poses a number of potential advantages within Naval Defence;

Low Cost per Shot – The use of energy as a weapon negates the requirement for costly projectiles.

'Effectively' Unlimited Ammunition – Availability of the weapon is limited only by the Ship's ability to provide energy and cooling. The question is therefore, how big are your fuel tanks?

Instantaneous Effector – The High Energy Laser moves at the speed of light; therefore the weapon system is highly accurate in targeting agile targets and challenging to defend against.

Safety – Whilst a LDEWs ammunition is dependent on fuel, it can negate the need for an explosives magazine in the upper deck region, reducing the risk posed to personnel.

LDEWs will therefore either be used in isolation, or alongside traditional Close-In Weapon Systems to counter key emerging threats where speed and endurance are both key.

Unlocking the capability of Naval LDEWs is dependent on the capacity of the host platform to provide power and cooling to the weapon. Integrating effective power and thermal management technologies is therefore as important as the development of the LDEW itself. Achieving effective thermal management of an LDEW presents a number of unique challenges when compared with traditional platform systems.

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 https://doi.org/10.24868/issn.2515-818X.2020.064

2. LDEW Cooling Assessment Methodology

Assessment of advanced cooling approaches for Naval LDEW systems was split into four stages. This enabled the scope to evolve at key decision points throughout the study;

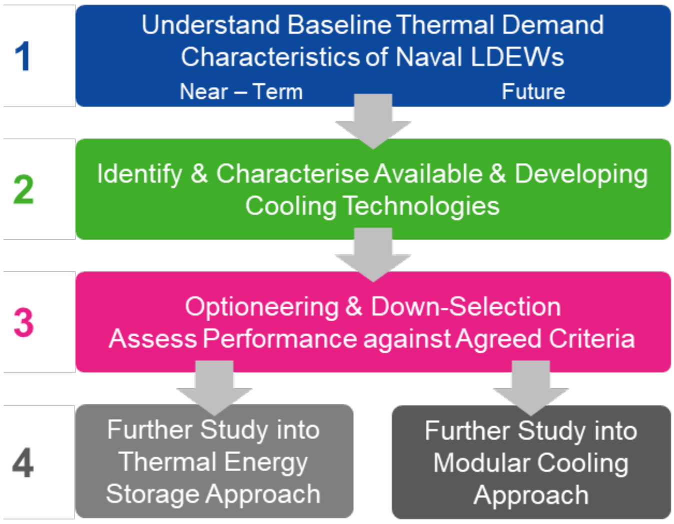

Figure 1: Research Methodology

3. Naval LDEWs – The Cooling Challenge

LDEWs present a requirement to manage of high, stochastic thermal energy (waste heat) outputs produced on testing or firing the weapon. Two sets of thermal energy outputs were proposed within this study;

The first set characterises a 'near-term' LDEW, expected to be realised within the next 10 years.

The second set of thermal outputs characterises a speculated 'future' LDEW. This represents expected scaling-up of near-term LDEW technologies to produce higher-power laser weapon in the 10 > 20 years range.

As today's Naval Platforms can be expected to operate for over 30 years, the potential for future higher-power LDEW systems must be considered today in order to understand and mitigate scalability constraints imposed by current platform cooling system design.

3.1 Near-Term LDEW Thermal Demands;

- Produces a High-Energy Laser Output of < 100 KW,
- Imparts a thermal demand of < 200 KW onto the platform throughout test & firing,
- Directly cooled using fresh water,
- For laser stability, the temperature must be maintained within a narrow band, therefore requiring a high flow rate of water coolant,
- Size of laser effector is approximately $25m^3$,
- Mass of laser effector is approximately 10Te.

 https://doi.org/10.24868/issn.2515-818X.2020.064

3.2 Future LDEW Thermal Demands;

- Produces a High-Energy Laser Output of > 100 KW,
- Imparts a thermal demand of circa. 400 KW onto the platform throughout test & firing,
- May be cooled using either water or an alternative coolant technology,
- For laser stability, the temperature must be maintained within a narrow band, therefore requiring a high flow rate of water coolant,
- Size of weapon system is approximately 25m³,
- Mass of weapon system is approximately 12Te.

3.3 Weapon Duty Cycle Effects

The weapon duty refers to the availability requirement from the LDEW system and can be defined as;

$$Duty\ \% = \frac{Engagement\ Time\ \times 100}{\begin{matrix}Engagement\\Time\end{matrix} + \begin{matrix}Time\ between\\Engagements\end{matrix}}$$

Figure 2: Weapon Duty Definition

Duty requirements for LDEWs are influenced by a number of complex operational factors;

- Number of targets,
- 'Hardness' of targets,
- Target velocity,
- Engagement range,
- Atmospheric conditions.

As the effect of these variables on Naval LDEW duty is not yet fully understood within an operational context, a weapon system which is capable of unlimited operation is preferred.

The Size, Weight and Power (SWAP) costs attached to both powering and cooling an unlimited duty weapon will inform the feasibility of this approach.

To provide a basis for SWAP comparison of cooling approaches, it was agreed that a nominal 20% Duty Cycle would also be investigated. It is important to note that by applying a duty constraint, TES approaches may be investigated as a method of achieving thermal damping, reducing the required capacity of cooling as described within Figure 3.

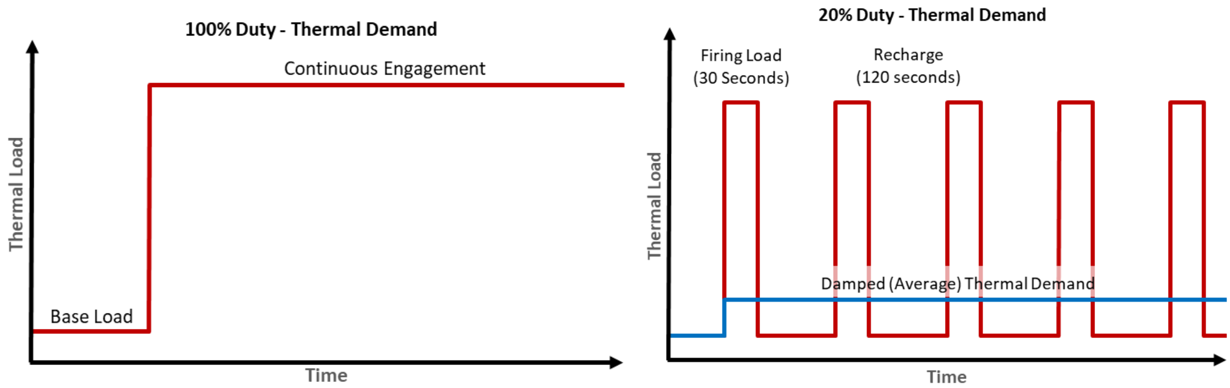

Figure 3: Weapon Duty Effects on Thermal Demand

 https://doi.org/10.24868/issn.2515-818X.2020.064

3.4 How Many LDEWs?

Understanding the required number of LDEW systems is key to confirming total cooling demand. Table 1 details an initial posited number of LDEWs across different platform types. These numbers were estimated to shape further cooling systems assessment only and not to accurately represent the future roll-out of such systems;

Table 1: Posited Number of LDEW Systems at Increasing Platform Size &/ or Complexity

OPV	Small Frigate	Large/ Modern Frigate	Destroyer	Amphibious	Auxiliary	Aircraft Carrier
1		2				3
No. of LDEWs						

No. of LDEWs	Max. Potential Cooling Capacity (Near-Term)	Max. Potential Cooling Capacity (Future)
1	200 KW	400 KW
2	400 KW	800 KW
3	600 KW	1200 KW

Other considerations which will drive LDEW cooling system requirements include;

Cooling Configuration & Redundancy;

Dependent on the cooling method used and survivability requirements, several cooling system configurations could be adopted in the case of multiple weapon systems;

1. Separate – System providing dedicated cooling for each LDEW system,
2. Combined – Shared cooling resource feeding multiple LDEWs,
3. Separate but Interconnected – Dedicated systems for each LDEW, with inter-connecting pipework and appropriate margins, favoured for providing greater survivability.

 https://doi.org/10.24868/issn.2515-818X.2020.064

4. Advanced Cooling Methods – Options Study

Market research was completed to identify and assess cooling technologies. Within this research we identified current cooling technologies utilised within the maritime domain and developing cooling technologies within academia. A TRL number of 1 to 9 was assigned to each technology to identify the current state of development.

4.1 Near-Term Cooling Options;

The near-term LDEW cooling options were limited to technologies within the medium-to-high TRL range of 6 (demonstrated in laboratory environment or representative demonstrator) to 9 (proven in active operations) in order to align with the time-frame for LDEW roll-out;

Option 1 – Air cooled Chilled Water Plant (CWP) (TRL 7),

Option 2 – Salt-water cooled CWP (TRL 7),

Option 3 – Ship's chilled-water cooled CWP (TRL 9),

Option 4 – Use of extant CWP only (TRL 9),

Option 5 – Dedicated salt-water cooled CWP (TRL 9),

Option 6 – Absorption chiller (TRL 7),

Option 7 – TES using cold water storage tanks (TRL 7),

Option 8 – TES using bulk storage of ice for latent heat effect within phase change (TRL 6),

Option 9 – TES using paraffin wax for latent heat effect within phase change (TRL 6).

4.1.1 Options Study Approach for Near-Term Candidates;

Several options studies were completed to assess the performance of available near-term cooling options in different operational scenarios. Performance criteria were agreed by a panel of stakeholders and assigned a weighting of 1-5 based on their relative importance;

Operational Scenarios;

1. Short-Term Capability Demonstrator – Retrofitted to an in-service platform, for initial capability demonstration, to minimise complexity of integration and cost,
2. Operational Solution for Retrofit – Option which provides capability to meet long-term operational demands for retrofit to current Naval Platforms,
3. Solution for Future Ships – Fully integrated cooling considered within ship design & build.

4.1.2 Evaluation Criteria;

Cooling Capability – Ability of solution to meet required cooling capacity and duty demands,

SWAP Cost – Size, weight and power costs of new systems and equipment where required, can it feasibly be retrofitted to current platforms?

Scalability – Applicability of solution across multiple platform sizes, ability of the solution to be scaled for multiple LDEWs, or higher power future systems,

Integration Complexity – Associated with the scale and distribution of required new equipment, requirements for reconfiguration of existing systems,

Effect on Platform Operations – Knock on effects to platform operations, usability & signature,

Availability of Solution – Required level of development, commercial off-the-shelf equipment availability & cost implications,

Safety – Introduction of new health & safety hazards posed by solution,

Survivability/ Resilience – Ability of the solution to offer redundancy and/or low risk of damage/ unavailability.

 https://doi.org/10.24868/issn.2515-818X.2020.064

4.1.3 Results of Near-Term Options Study;

The options study highlighted TES methods as being particularly advantageous across the demonstrator, operational retrofit and future ship design scenarios. The use of containerised chilled water systems was also raised as a potentially effective method of meeting short-term demonstrator and retrofit requirements at a relatively low cost and complexity.

Table 2: Scenario 1 - Short-Term Capability Demonstrator;

Rank	Option
1	Thermal Storage using Water Tanks
2	Containerised Fan Cooled Unit and Heat Exchange System Connected to Extant Chilled Water System
3	Containerised Air Cooled CWP

Table 3: Scenario 2 – Operational (Long-Term) Solution for Retrofit;

Rank	Option
1	Thermal Storage using Water Tanks
2	Thermal Storage using Wax PCM
3	Containerised Fan Cooled Unit and Heat Exchange System Connected to Extant Chilled Water System

Table 4: Scenario 3 – Solution for Future Ship Designs;

Rank	Option
1	Thermal Storage using Water Tanks
2	Thermal Storage using Wax PCM
3	Thermal Storage using Ice

The outcomes of the Near-Term LDEW options study were used as the basis to scope our next stage of development, considered alongside our customer's research aims and operational goals.

 https://doi.org/10.24868/issn.2515-818X.2020.064

4.2 Future Technologies;

The future technologies section of the cooling options study was focused on developing technologies within the low-to-medium TRL range. Within this remit we had more scope to investigate alternative refrigerants and improvements to the heat exchange interfaces within the weapon system itself (in accordance with Section 3.2).

The future technologies section is targeted at developing solutions with the potential to offer cooling performance improvements for future LDEWs. It should be noted that many of the identified technologies apply to improving steps in a cooling process and would therefore be used alongside other (traditional) cooling technologies;

Option 10 – Cooling using alternative PCMs (TRL 3 - 5)

Option 11 – Heat Exchange Utilising Miscibility Gap Alloy (TRL 3)

Option 12 – Cooling utilising Metal Hydride Heat Exchange (TRL 5),

Option 13 – Weapon Incorporating Internal PCM (Wax Based) Heat Sink (TRL 4),

Option 14 – Pumped Two-Phase Cooling utilising Latent Heat of Vaporisation (TRL 5),

Option 15 – Hybrid Two-Phase Cooling utilising two sub-loops (TRL 5),

Option 16 – Heat Exchange utilising Confined Jet Impingement (TRL 4),

Option 17 – Pool boiling thermos-syphon cooling - Immersion of weapon power electronics for two-phase cooling using vaporisation (TRL 5),

Option 18 – Heat exchange utilising advanced heat pipes (TRL 5 - 7),

Option 19 – Cryogenic cooling utilising liquid helium (TRL 5).

Table 5 shows a Red-Amber-Green (RAG) study, used to summarise the overall performance of the future LDEW cooling options at high-level. Against each criteria; Green = Benefits, Amber = Neither Benefits or Drawbacks, Red = Drawbacks.

Table 5: Scenario 3 – Future Cooling Technology Options; RAG Study;

Option	Size	Weight	Power	Scalability	Integratability	Availability	Cooling Ability	Survivability	TRL
Pumped 2 - Phase Cooling									5
Weapon Internal PCM									4
Hybrid 2 - Phase Cooling									5
Jet Impingement									4
Advanced Heat Pipes									7
Alternative PCMs									3 - 5
Pool Boiling Thermosyphon									5
Miscibility Gap Alloy									3
Metal Hydride HX									5
Cryogenic Cooling									5

 https://doi.org/10.24868/issn.2515-818X.2020.064

5. Assessment of Down-Selected Options

The scope of this phase of work was to develop a number of the top-performing options identified within the Options Study including;

- Deliver concept level schematics,
- Assessment of cooling performance and capacity,
- Specifications for major commercial off the shelf (COTS) components,
- Investigate ship interfaces & highlight platform integration complexities,
- Estimates for cost, size and mass.

The aim of this further assessment was to provide a greater understanding of the opportunities and challenges posed by the concepts, particularly in terms of cooling performance and platform integration and therefore enable recommendations to be made on future development and demonstrator activities to de-risk future LDEW platform integration.

In order to align with likely future requirements for both a ‘Test & Trials’ solution for LDEW cooling and a long-term operational solution for LDEW cooling to be retrofitted to current near-term (design mature) ships, the assessment was split in to two sub-tasks;

Task 1 – Development of Integrated Cooling Concepts utilising Thermal Energy Storage;

Within the Options Study, cooling solutions which utilise the ship’s tank spaces to provide a bulk store of coolant (Thermal Energy Store) were found to be advantageous for both the operational retrofit scenario (2) and future ships scenario (3). Further concept development and assessment was therefore completed to compare the following approaches;

- TES Utilising a Cold-Water Storage Tank,
- TES Utilising a PCM.

Task 2 – Investigation of Modular Cooling Approaches;

Task 2 was undertaken to assess the feasibility and SWAP characteristics of modular LDEW cooling solutions for use within a ship’s mission bay. The development of modular cooling concepts is focused on reducing the complexity of LDEW integration and reducing the reliance of the weapon system on existing platform technologies (e.g. Chilled Water Plant and Power Generation).

The use of modular cooling approaches primarily relates to a ‘Test and Trials’ operational scenario (1), but additionally has the potential to negate constraints imposed by the ship’s power and cooling supply margins. A modern Frigate was used as the exemplar platform for this part of the study, in order to provide understanding of the constraints imposed by the design of a Mission Bay and its interfaces.

 https://doi.org/10.24868/issn.2515-818X.2020.064

6. Task 1 - Integrated Cooling Approaches utilising Thermal Energy Storage

This task investigated the cooling performance and integration challenges associated with managing LDEW thermal demands using TES, providing a summary of the advantages and disadvantages of various configurations and the use of water vs. a wax PCM. An in-depth review of the capabilities of TES to provide cooling on Ships is described within the related study "The Potential of Thermal Storage Tanks to Assist in Managing Peak Heat Loads on Naval Ships [Dawe T, 2020]. Our paper therefore only provides a summary of the performance of the investigated TES options.

An exemplar in-service Naval Ship was used as the design basis of the study, to determine both tank architecture and Chilled Water availability. At a worst case scenario of maximum system demand (daytime tropical conditions), it was estimated that 100 kW of spare cooling capacity exists within the existing chilled water system.

Repurposing of one of the Ship's tank spaces is used as the basis for housing the Thermal Energy Store. Options of repurposing Fresh Water or Diesel tanks were considered and are examined in full within the [Dawe T, 2020] paper. A 35m^3 tank, with an insulated tank boundary producing an overall heat transfer coefficient (U value) of 5.5 W/m^{2}K and thermal gain of 8.2 kW was used as the basis of the TES performance calculations.

The following TES configurations were assessed, both to understand the complexity and integration challenges of the design solution and to determine the available TES cooling endurance under LDEW thermal demands;

1. Water tank with plate heat exchangers located outside of the tank space, connected to both Chilled Water Plant and LDEW,
2. Fresh water tank with an internal array of dimple heat exchangers for direct LDEW interface,
3. Wax PCM modules within a fresh water tank to enable direct LDEW cooling.

Analysis of the options showed the following cooling performance when subject to near-term LDEW thermal demands;

Table 6: Cooling Endurance of TES Solutions under LDEW Thermal Demands

Option	Operating Temp. Delta	Cooling Endurance 1 LDEW with CW	Cooling Endurance 1 LDEW without CW
Option 1 – Water Tank with external Plate Heat Exchangers	3°c	1 hr 7 min	0 hr 21 min
Option 2 – Water Tank with Internal Dimple Heat Exchangers	7.5°c	2 hr 49 min	1 hr 29 min
Option 3 – Wax PCM Modules in Water Tank	7.5°c	10 hr 45 min	5 hr 32min

To melt the wax PCM from a cooled solid state, it would therefore take 10 hrs 45 min. with 100kw of CW available. TES solutions utilising a Wax PCM therefore offer revolutionary advantages for the cooling of LDEW weapons on Naval Ships, offering the capability to provide multiple weapon systems with sustained cooling and capitalising on the natural increase in CW margin overnight to enable the TES store to be 're-charged' efficiently.

 https://doi.org/10.24868/issn.2515-818X.2020.064

7. Task 2 – Modular Cooling Approaches for Ship's Mission Bays

Four main cooling solution concepts have been envisaged to produce the desired ~200kW of cooling. These can be summarised as:

Concept 1. Core equipment only, using the ships spare CWP and electrical generation capacity;
Concept 2. Water-cooled CWP combined with the core equipment, using the ships spare electrical capacity;
Concept 3. Water-cooled CWP combined with the core equipment and with a diesel generator (DG) fitted to supply electrical capacity.
Concept 4. Hybrid Cooling Approach utilising a Thermal Energy Storage Container.

7.1. Key Considerations for Modular Cooling

Research into the regulatory environment as well as the design of the Frigates' mission bay identified a number of limitations and constraints.

Regulatory Requirements – There is currently no defined British Standard or UK Defence Standard (DEFSTAN), therefore the regulatory approach for this concept design made use of the considerable offshore container experience, specifically the standard DNV 2.7-2 Containerised modules on offshore platforms [DNVGL, 2016] and the North Atlantic Treaty Organisation's (NATO) Naval Ship Code ANEP-77 [NATO, 2019]. Elements of the above codes were used to inform the concept designs.

Fire – According to ANEP-77, the spaces classify as auxiliary machinery spaces and therefore require an A-0 fire boundary, with fire detection integrated into the Ships' Mission Bay alarm system, with the ability to automatically shut fire dampers and trigger local alarms. If a DG is fitted which is greater than 110 kW in size, then this increases the requirements to A-60, and if it is >375 kW a fixed-firefighting system is necessary.

***Shock* -** To survive naval shock and blast standards it is recommended to build to DNV GL 2.7-1 structural standard [DNV GL, 2013], which utilises 4mm S355 steel compared to 1.6mm for the standard ISO 1496-1 container This increases the tare weight to ~4Te from the original ~2Te. The UK MoD is also developing a 'Pumpkin Mount' shock isolation system. This has been shown in to protect containers up to 12Te in mass.

Maximum Mass – The Frigates' Mission Bay Handling System can be expected to safely load/unload a 20ft ISO container from the dockside up to a mass of 15Te. Therefore the limiting weight factor for is determined by either the shock protection system or the ability for air transportation. In the UK only a C-17A Globemaster is capable of transporting a standard 20' ISO container using standard equipment, at a lower mass limit. If it is desirable to transport via an A400M Atlas then smaller 8' high containers must be used.

Electrical Supply – The maximum consumer size is limited by the two transformers present to isolate the earthed Mission Bay equipment from ships supply.

Chilled Water & Salt-Water Supply – There is no dedicated chilled, fresh or seawater supply dedicated for Mission Bay modules, consequently connections would need to be routed from extant pipework located elsewhere within the ship. It is expected that the ship has sufficient Chilled Water Margin to manage the peak Thermal Demands of a single LDEW.

Exhaust & Ventilation – The container module will require ventilation to remove wild heat generated by the electrical equipment and machinery and maintain a temperature rise above external ambient limited to 15°C [DEFSTAN 02-102 Part 1, 2005] equivalent to an auxiliary machinery space. Lloyd's Register Rules for Naval Ships details that where refrigerating machinery is located, outside the main machinery space, this compartment is to be equipped with mechanical ventilation to provide 30 air changes per hour.

It was confirmed that no interface to/from the Mission Bay HVAC system will be provided and that any module with HVAC requirements will draw from and exhaust to the Mission Bay. This drives the need for either forced ventilation or an air-cooled FCU to achieve the aforementioned requirements relying on ship spare cooling margin. Alternatively, the use of water cooled-FCU system would negate the issue of rejecting wild heat into the Mission Bay and instead make use of the ships chilled water system as the heat sink. This may prove prudent as it makes use of the CWP necessary for the LDEW cooling and air-conditioning respectively.

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7.2. Concepts

Calculations were completed to establish the operational characteristics of the components required to cool the LDEW system. An evaluation of suitable COTS components was used to determine the SWAP and material costs. Subsequently, 3D models of the concepts were produced to understand the spatial integration of the components within the container modules.

Concept 1 – Provision of Ancillary Equipment for LDEW and Ship's Interfaces;

This concept consists of purely the core equipment for a module required to provide cooling to the LDEW and consists of a 200kW worth of liquid cooling and a fan-coil unit of ~15kW capacity, positioned locally to the LDEW. Therefore requiring only modification to the chilled water system of the host platform; however, it is limited by the ships spare capacity and therefore unable to be scaled. Figure 7 illustrates the arrangement required, the chilled water either coming from a modular CWP or the ship's spare capacity depending upon the Concept.

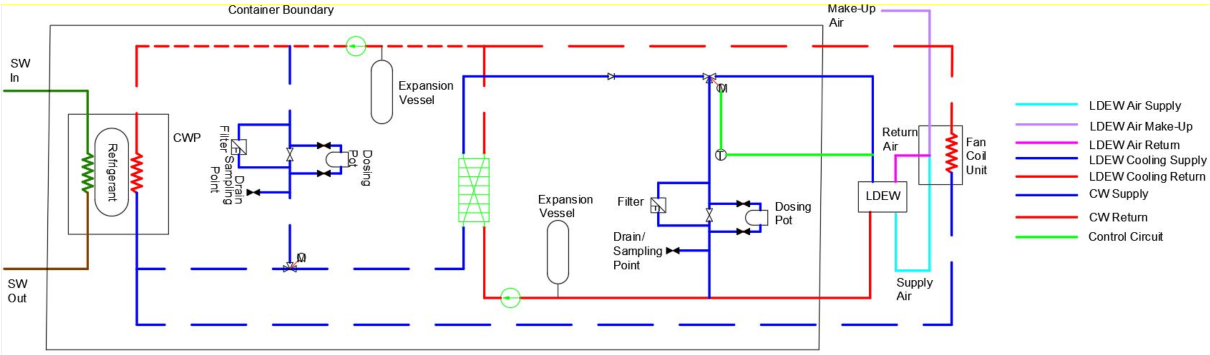

Figure 7 – Schematic Representation of a Containerised Modular LDEW Cooling System

Figure 8 shows how the arrangement of the Concept 1 may look within a 10ft DNV container (2.5Te tare), showing plenty of room for maintenance and operation. The SWAP cost of the module, including 10ft container, core equipment (detailed within

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Table 7) and assumed insulation, cladding, pipework and cabling equates to 3.73Te, 23.5kW consumed power and 3kW wild heat. The estimate material cost is £51,000 excluding integration and shock mounting.

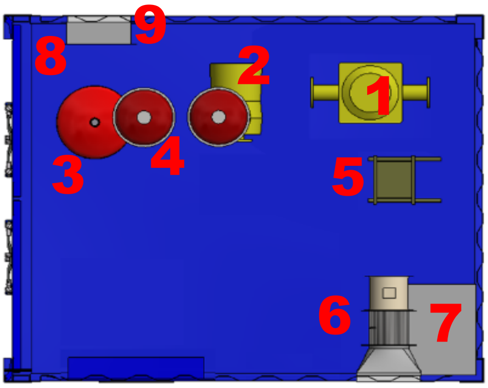

Figure 8 –Plan View of 10ft. ISO Container Incorporating Ancillary Equipment for LDEW Cooling

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Table 7: Core component SWAP and material cost

ID #	Component	Mass (kg)	ROM Material Cost (£)	Power (kW)	Wild Heat (kW)
1	HP Pump for LDEW	191	5850	11.5	1.75
2	LP Pump for CWP	59	4900	2.9	0.4
3	Buffer Tank (200l)	229	500	0	0
4	Expansion Vessels (26l)	43	100	0	0
5	Plate Heat Exchanger	172	2000	0	0
6	Axial Fan	7	1000	0.1	0.01
7	Recessed Interface Envelope and Control Panel	20	2000	0	0.5
8	Fire Dampers	12	750	0	0
9	Weather Louvre	5	100	0	0
10	Fan Coil Unit (not in module)	190	5000	5	0
Total for Core components		988kg	£23,150	19.5 kW	2.66 kW

Concept 2 – Provision of Ancillary Equipment and Chilled Water Plant for LDEW Cooling;

This concept is similar to Concept 1 but with the addition of CW, all contained within one 20ft container, as shown in Figure 9. After an options study, a single 200 kW Heinen & Hopman HHSCHSC1 was chosen as the candidate CWP. The SWAP cost of the module, including CWP, 20ft DNV container, core equipment and ancillaries equates to 7.33Te, 99kW consumed power and 10.7kW wild heat. The estimate material cost is £156,000.

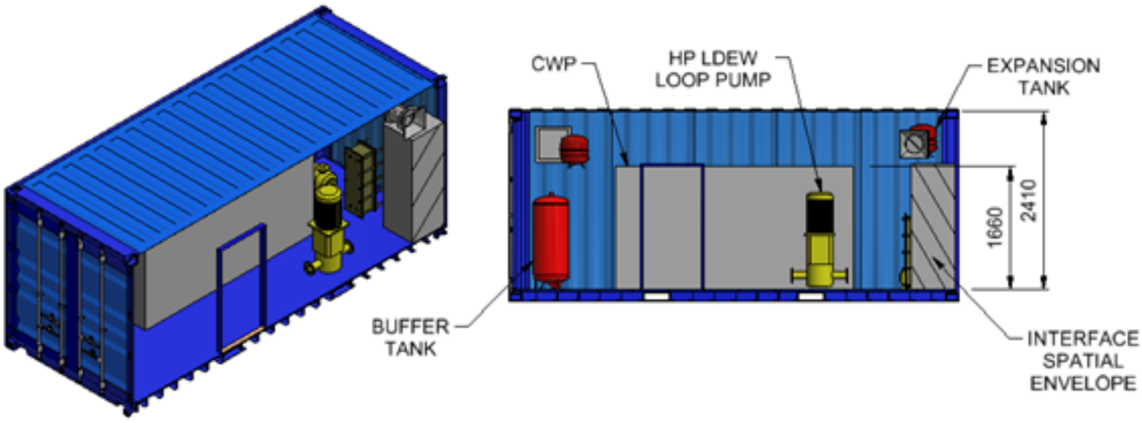

Figure 9 – 20ft. ISO LDEW Cooling Container Incorporating Chilled-Water Plant

This option provides more capacity than Concept 1 but cannot be scaled due to the ships spare electrical capacity, in the case of the chosen Frigate it is limited by the mission bay power distribution, so would require modifications to ships supply, as well as the pipework modifications required to the ships water system. It also places significant additional load on Mission Bay HVAC, unless cooled using the module CWP.

Concept 3 – Provision of Ancillary Equipment, Chilled Water Plant & Power Generation

This concept looks to negate the power limitations of the ship by installing a DG to power the ~100kW core equipment and CWP. The DG must be able to provide sufficient starting current for the CWP compressor (~250A) but it is also desirable to not exceed 375kW, as this creates a SOLAS Category A machinery space and all that entails. A 140kWe Kohler 200EOZDJ was selected as the candidate DG. It has a max motor starting current of 1030A and weighs 2.07Te.

The DG would be located in a 20ft container alongside the fuel tank and bund, see Figure 10, whilst the core equipment and CWP would be placed within the other 20ft container as per Concept 2, therefore taking up more space than the other Concepts. The DG would be able to use the extant Mission Bay F76 system for fuelling/defueling the DGs.

 https://doi.org/10.24868/issn.2515-818X.2020.064

The SWAP cost of the module, including DG, CWP, 2 x 20ft DNV containers, core equipment and ancillaries equates to 15250kg, 45 l/hr fuel, 13.5kW wild heat and a SW cooling requirement of 245kW. The estimate material cost is £236,000.

It is the routing of exhaust and air intakes from the DG container to the ambient that may prove impractical due to deckhead congestion, heat emission and also from infra-red and radar signature perspective. The DG also requires a large flow of coolant and places demand on Mission Bay HVAC to remove the significant wild heat.

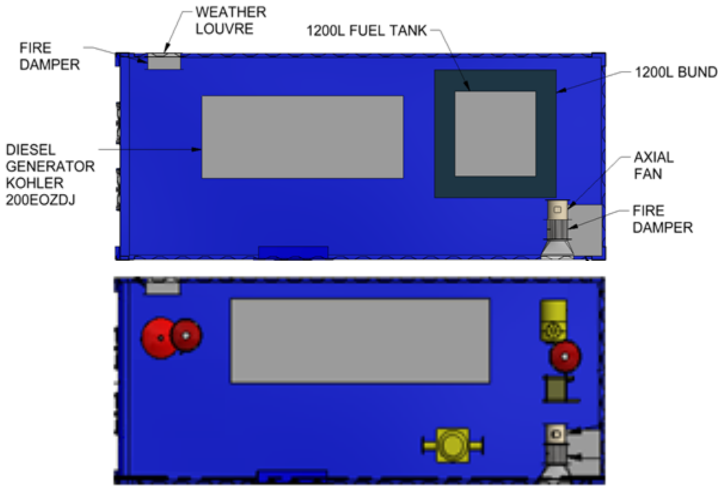

Figure 10 – Plan View of 2 x 20ft. ISO Containers Incorporating Power Generation and Chilled Water Plant

Concept 4 – Hybrid Cooling Approach utilising a Thermal Energy Storage Container;

Another potential opportunity identified is a hybrid option, which is a combination of the two Task cooling concepts, both modular and with TES. A hybrid solution could utilise the ships existing spare CW capacity (particularly when increased margin is available at night due to lower environmental temperatures) to cool down a 20ft container fitted with a wax-based TES system. Then a 10ft container, fitted with the core equipment only, could be used to exchange heat between the TES and the coolant. This solution could therefore provide the coolant at the correct temperature and flow rate to the LDEW. Thereby only placing a small power demand on the vessel and making use of the spare CW margin. This also has the potential for scalability as it could also be used in conjunction with a CWP module variant.

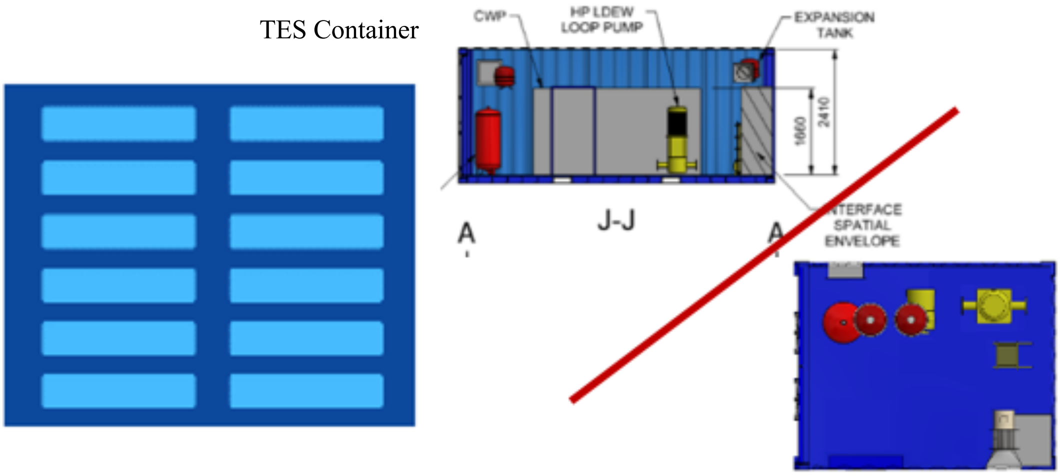

Figure 11 - Hybrid Cooling Approach Utilising a Wax PCM Thermal Energy Storage Container

https://doi.org/10.24868/issn.2515-818X.2020.064

8. Conclusions

Our work has shown that the high and stochastic thermal demands posed by LDEW systems, together with future scale-ability requirements poses a significant challenge for both In-Service Naval Ships and for the design of future platforms. This challenge can be met by applying today's cooling technologies effectively, and by investing in the development of new cooling technologies to enable future efficiency improvements.

Our work has shown that both water and wax can feasibly provide integrated TES cooling solutions. A PCM wax based solution has a much larger specific cooling capacity than water and therefore offers greater benefits for the thermal management of LDEWs. Thanks to the diurnal cycle of a ships CW loading, a Wax TES solution could be used to sustain multiple LDEWs over a long period of time and be efficiently re-charged overnight.

Similarly, a modular cooling solution would be feasible. However, modification of the ship's infrastructure is necessary in order to supply the required mechanical and electrical services to the Mission Bay. The number of modifications can be minimised by using the ships spare CW margin; however, this will eliminate most of the ships spare CW margin and limit it to the use of one LDEW system. Depending upon the finalised duty times, the use of a modular wax-based TES in combination with another wax based heat exchanger module, would allow for greater cooling capacity whilst not requiring significant modifications to the ships services.

 https://doi.org/10.24868/issn.2515-818X.2020.064

Acknowledgements;

The Authors would like to thank Andrew Tate of the UK Defence Science and Technology Laboratory (DSTL) for sponsoring the above study, and providing expert guidance throughout the project.

The Authors would also like to thank Jon Daw of MBDA for providing insight into the baseline thermal demand characteristics of near-term and future Naval LDEWs, together with system interfaces and potential operational requirements.

The views expressed in this paper are that of the Authors and do not necessarily represent the views and opinions of either Babcock or DSTL.

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