Margins – their use as Metrics and Key Performance Indicators when Designing and Building Warships

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Synopsis

Warship acquisition projects are technically complex, high value, subject to intense public scrutiny, and typically take a long time to bring to fruition. The technical complexity and inevitable clash of priorities between hull form, platform systems and combat systems design may necessitate compromises between key platform characteristics. Due to both the interconnected aspects and the need to carefully balance platform and combat system requirements and performance, it is not practical to separate them completely.

When designing a warship to keep pace with the perceived threat environment, the long gestation period between project initiation and the First of Class vessel entering service can generate several problems for the delivery agency and the recipient Navy. These are caused by requirements creep due to evolving threat scenarios, technological advancement, obsolescence, and the impact of legislative changes. In addition, the delivered ship will often experience design trade-offs (i.e. combat systems equipment versus speed, range and weight growth) that have been required during the design, build and introduction-into-service phases.

The development and implementation stages for weapon, sensor and communication systems life cycles are often far shorter (system update cycles are planned on approximately 5-year periods) than the service life for a warship platform, which are typically >25 years but often end up being extended. This sets a difficult challenge for warship design and requires provision to be made in design for systems that are at a low Technology Readiness Level (for example, Directed Energy Weapons, or even conceptual systems, considering the increasing use of autonomous and off board systems). Thus, their interface requirements will be immature. Associated estimates for Space, Weight, Power and Cooling will inevitably need to be larger to cater for the increased uncertainty, making it more challenging to assess Margin requirements for future capability upgrades.

To deal with the problems identified above, metrics and key performance indicators are incredibly helpful in assessing a warship's potential to fulfil its design criteria through to end of life. These aid in determining whether the platform can meet its designated Mission System Requirements and if it is flexible enough to receive weapon and sensor upgrades through life to ensure it can deal with contemporary threat environments and deal with obsolescence. Using appropriate Margins ensures sufficient contingency is provided in the design and, their consumption or usage is monitored and controlled through the platform's life cycle, are excellent metrics and key performance indicators to assess the platform's fundamental capabilities.

Margin policies (traditionally stipulated for Space, Weight, Power and Cooling) have proved their worth many times during previous warship design and build projects. The specification and management of Margins that are intended to be consumed during design, build and in-service is therefore tantamount to ensuring a warship can maintain viability in a constantly changing threat environment. The purpose of this paper is to discuss the impacts Margins have on a vessel's capability and identify strategies to manage these proactively to ensure that the warship can meet its Mission System Requirements through to end of life.

Keywords: Warship Design; Shipbuilding; Space, Weight, Power and Cooling Margins; Frigate; Destroyer, Acquisition; Sustainment.

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1. Introduction

Margins are defined as the difference between a design parameter's minimum required value to ensure functionality and its actual capability. Margins allow Engineers to mitigate uncertainties of various kinds.

Warship acquisition projects are technically complex, high value, subject to intense public scrutiny, and typically take a long time to bring to fruition. The technical complexity and inevitable clash of priorities between hull form, platform systems and combat systems design may necessitate compromises between key platform characteristics. Platform impacts include stability, seakeeping, signatures, speed, range and endurance. Combat system capabilities affected include size of Vertical Launch System, Magazines, and Aviation facilities. Vessel range and sensor capability will also be affected by platform characteristics such as available structure to mount systems and the amount of electrical power and cooling available. Due to the need to carefully balance platform and combat system requirements and performance, it is not practical to separate them completely when developing a warship design.

Traditionally ship design can be performed by making use of the well-known Design Spiral[1], which was originally introduced in 1959[2] with an elaborated version published for Naval ship design in 1998.[3] The design spiral effectively illustrates the sequential course of ship design through the various design steps, the repeating, iterative procedure for the determination of ship dimensions and of other properties and, finally, the gradual approach to the final stage of detailed ship design.[4] This is illustrated below in Figure 1:

When designing a warship to keep pace with the perceived threat environment, the long gestation period between project initiation and the First of Class (FoC) vessel entering service can generate several problems for the delivery agency and the recipient Navy. These are caused by requirements creep due to evolving threat scenarios, technological advancement, obsolescence, and the impact of legislative changes. In addition, the delivered ship will have to cope with design trade-offs that have been required during the design, build and introduction-into-service phases.

The development and implementation stages for weapon, sensor and communication systems life cycles are often far shorter (system update cycles are planned on approximately 5-year periods) than the service life for a warship platform, which are typically >25 years but often end up being extended.[5] This sets a difficult challenge for warship design and requires provision to be made in design for systems that are at a low Technology Readiness Level (for example, Directed Energy Weapons, or even conceptual systems, considering the increasing use of autonomous and off board systems). Thus, their interface requirements will be immature. Associated estimates for Space, Weight, Power and Cooling will inevitably need to be larger to cater for the increased uncertainty, making it more challenging to assess Margin requirements for future capability upgrades.

To deal with the problems identified above, metrics and key performance indicators are incredibly helpful in assessing a warship's potential to fulfil its design criteria through to end of life. These aid in determining whether the platform can meet its designated Mission System Requirements and if it is flexible enough to receive weapon and sensor upgrades through life to ensure it can deal with contemporary threat environments and obsolescence. Using appropriate Margins ensures sufficient contingency is provided in hull and platform system design and, their consumption or usage is monitored and controlled through the platform's life cycle, are excellent metrics and key performance indicators to assess the platform's fundamental capabilities.

In Naval warship practice, a Margin is the owner's attempt to manage the risk associated with requirements setting, design, build and subsequent in-service changes.[6] Margin policies (traditionally stipulated for Space, Weight, Power and Cooling) have proved their worth many times during previous warship design and build projects. The specification and management of Margins that are intended to be consumed during design, build and in-service is therefore tantamount to ensuring a warship can maintain viability in a constantly changing threat environment.

The purpose of this paper is to discuss the impacts Margins have on a vessel's capability and identify strategies to manage these proactively to ensure that the warship can meet its Mission System Requirements through to end of life. This will be illustrated using Marine Engineering system, platform-centric examples based on a hypothetical warship design and build project (HMAS LANCLOVELY, a County Class Surface Combatant) developed by Gibbs and Cox Australia based upon the authors' combined shipbuilding experience.

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[1] (Bottero & Gualeni, 2024)
[2] (Evans, 1959)
[3] (Watson, 1998)
[4] (Papanikolaou, 2014)
[5] (Button, et al., 2015)
[6] (UK Ministry of Defence, 2009)

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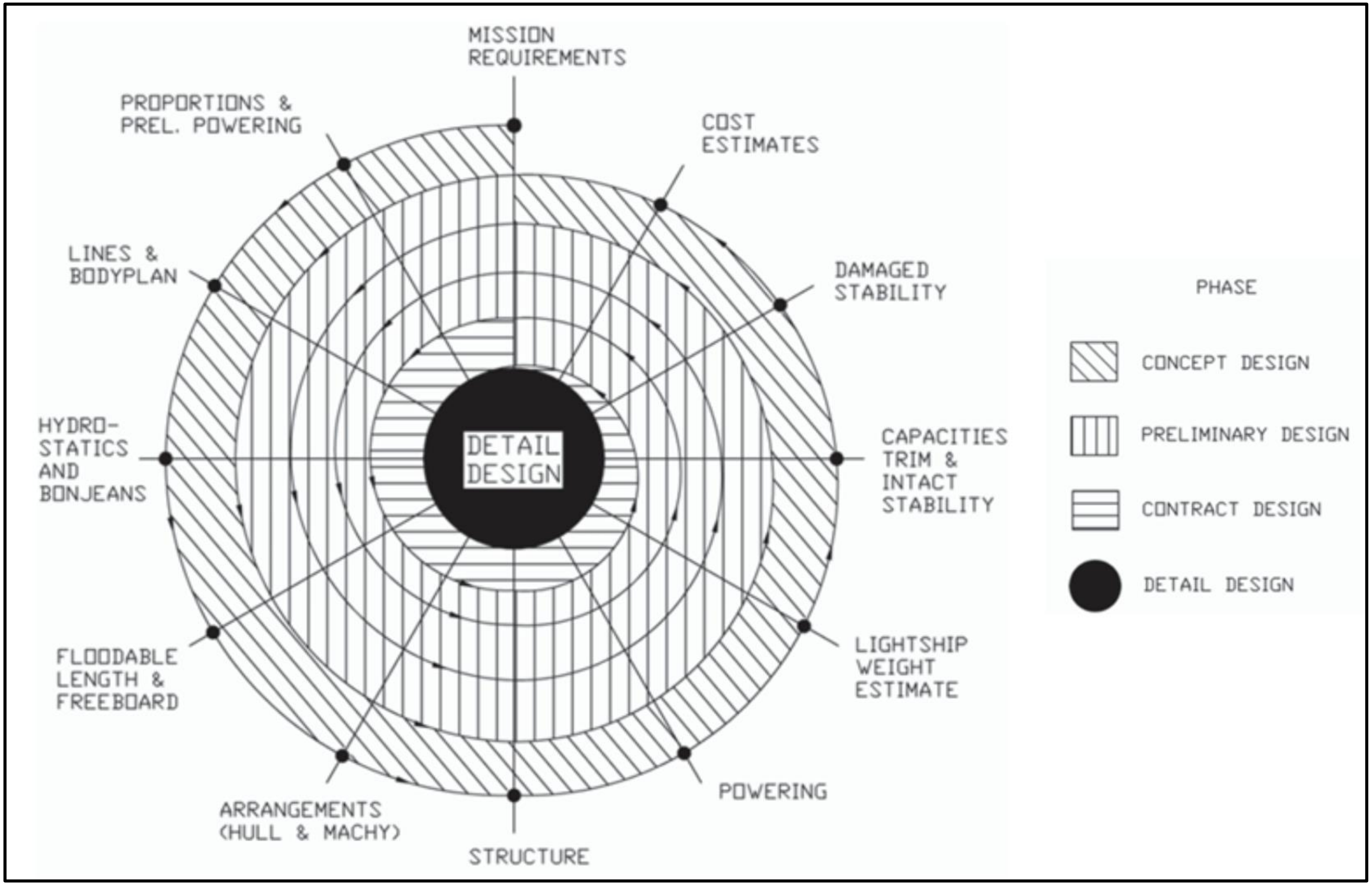

Figure 1: **Design Spiral**

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2. Margin Definitions

There are several different Margin types used commonly throughout warship Acquisition and In-Service phases. Policy and practice vary subtly between countries but, from an Australian perspective, the two standard references include ANP 4801 – Development and Maintenance of Materiel Margins for Naval Capabilities[7] and DEF(AUST) 5000 Volume 02 Part 29 - Margin Requirements,[8] in addition to the UK Maritime Acquisition Publication (MAP) 01-070 - Surface Ship and Submarine Margins Guidance.[9]

The three fundamental reasons for the various Margin types include:[10]

- Mitigating Uncertainty in Acquisition,
- Ensuring Safety Throughout the Service Life, and
- Providing Capacity for Technology Upgrades in an Evolving Threat Environment (utilising the philosophy of Upkeep, Update, and Upgrade).

Further detail on Margin types is outlined in Table 1, and these can be applied to any number of Margin categories. They are traditionally used for Space, Weight, Electrical Power and Cooling (Chilled Water and HVAC systems) as a minimum.

Margin Type	Notes
Design and Build Margin (DBM)	During the design and build phases, the designer faces uncertainty around design characteristics. This uncertainty is gradually reduced and then retired as the design evolves and matures towards a production baseline. The amount of Design and Build Margin should address the development risk and design uncertainty in the program. Following expiry of warranties, unused Design and Build Margin is rolled into the Capability Upgrade Margin (CUM) or the In-Service Growth Margin (ISGM). DBM may need to be split into two separate Margins if the design and build are performed by different organisations.
Contract Modification Margin (CMM)	Due to the complexity of naval ships, and the typically long development time from initial requirements establishment to delivery, there are often changes to requirements or Government Furnished Material (GFM) allocations during the acquisition phase. The customer may include Margins to account for these uncertainties during design and build. Unused Contract Modification Margin at delivery is rolled into CUM or ISGM.
In-Service Growth Margin (ISGM) or Through-Life Growth Margin (TLGM)	Margins are included at the design stage to allow for unplanned, unattributable or uncontrolled changes that typically occur during the service life. These changes can be forecast based on historical data, and various standards offer recommendations on the Margins to apply in early design for different ship types, based on analysis of technical records from current and previous classes. This Margin is also referred to as IGM in ANP 4801, and separately as the Through-Life Growth Margin (TLGM) for mechanical and electrical systems.
Capability Upgrade Margin (CUM)	Margins should be included to address future uncertainty around technology development, and the changing threat environment over the life of the vessel. There is also the inevitable need to add equipment or change configuration to avoid obsolescence and remain effective in an evolving threat environment. Margins applied for capability upgrade depend on the type of missions the ship performs, the expected pace of technology development associated with the threat environment, and the types of systems needed to address the future threat environment (for example, Directed Energy Weapons).

Table 1 – Margin Types

[7] (Directorate of Naval Engineering, 2023)
[8] (Directorate of Naval Engineering, 2008)
[9] (UK Ministry of Defence, 2009)
[10] (Catton, 2022)

The Margin types described in Table 1 should be applied to Platform systems (eg, Chilled Water and Electrical Distribution systems) and attributes (eg, Weight, Centre of Gravity) as required to ensure that operability, safety, environmental, service life and legislative requirements are not compromised. Achieving the correct Margin size is a compromise between allowing sufficient contingency to deal with uncertainty, requirements creep, growth in-service and design change, and the increased cost that arises from this provision.[11] Margin categories that are typically tracked and analysed throughout the vessel life are described in Table 2 below. These are based upon Platform design, but the concept applies equally well to Combat systems.

Margin Category	**Notes**
Weight	Weight distribution and aggregation has a significant influence on stability, loading, speed, range, and seakeeping. These are all critical to the vessel's ability to meet its Mission System Requirements. Tracking, control and assessment of weight growth throughout the life of the ship is critical to assuring adequate Service Life Margin.[12]
Centre of Gravity (CoG)	The position and magnitude of the Vertical and Longitudinal Centres of Gravity (VCG and LCG) fundamentally influence the ship's stability and seakeeping characteristics. Accurate and effective control over these throughout the entire ship life cycle is critical in meeting many of the ship's core performance requirements.
Structural Strength	Allowances for Corrosion Margins are stipulated as part of broader global structural strength considerations to ensure that hull strength has not been eroded below an acceptable level, and thickness measurements should be routinely undertaken in service to support this. Guidelines issued by Classification Societies focus upon allowable diminution, noting that any nominal thicknesses should always be considered as the minimum as these form the basis for global strength calculations.[13]
Space	Bidding for space allocation is always undertaken early in the design cycle, and once it is exhausted, retrospective changes to the General Arrangement are time consuming, difficult and expensive. The most common types of Space tracked via the Margins process include compartment volume or deck area for capability upgrades, stores volumes and accommodation. Care is to be taken that if volumes are aggregated, the space is usable and not compromised by compartment geometry or protruding fittings.
Chilled Water	The Chilled Water system cooling capacity and associated Margins is critical to the platform's ability to support cooling for combat systems and habitability via the Heating, Ventilation and Air Conditioning (HVAC) system) throughout the life of the vessel. Monitoring of the overall magnitude and distribution of cooling load is key, along with the ability to meet required coolant flow rates through to end-of-life.
HVAC	Similar to the Chilled Water system, monitoring of cooling load (including wild heat[14] and heat transmission through ship structure[15]) by sub-system (typically broken down into Damage Control zones) and maximum air flow rates is key. Use of Margins to monitor required cooling air flow rates versus maximum capacity is also important.
Electrical Power	Electrical distribution system generation capacity, redundancy and functionality in normal and reversionary operating modes is critical to the platform's ability to fulfil its Mission System Requirements and support in-service growth and capability upgrades.
Environmental Management Systems	Environmental System capacity is vitally important to patrol endurance, particularly when operating in Special Areas as defined in MARPOL 73/78.[16] Attributes to be tracked include Black Water, Grey Water and Sullage storage capacities.

Table 2 – Platform Margin Categories

[11] (Catton, 2022)
[12] (Pedatzur, 2016)
[13] (Lloyd's Register, January 2001)
[14] (UK Ministry of Defence, 2007)
[15] (International Standards Organisation, 2002)
[16] (International Maritime Organisation, 2019)

Warship designers and Navies are under increasing pressure to provide enhanced levels of automation and control that brings with it the associated benefits of enhanced remote and/or automatic modes of operation plus the potential to reduce personnel numbers. Hence, consideration should also be given to assigning Margins to systems such as the Platform Management System, including numbers of spare channels and server capacity.

From a Combat System perspective, the challenge is more acute, as weapon, sensor and communication systems life cycles are often shorter, and the corresponding rate of growth in infrastructure requirements can be significant. Assigning Margins to key systems (including attributes such as Combat System hardware and data handling capacity, or Communications system bandwidth) is also recommended.

3. Specific Considerations for Cooling and Power Margins

The main ethos behind Margins management during Acquisition and In-Service phases is to ensure that the platform remains fit-for-purpose, safe to operate, and can meet its Mission System Requirements. This needs to apply across the whole ship life cycle. Figure 2 illustrates many of the parameters to be considered.

Technology upgrade cycles for weapons, sensors, and communications are often shorter in duration than the equivalent for platform systems, so it is important that sufficient provision is made to cater for this, which can be challenging as it can be hard to quantify requirements for systems that haven't yet been invented.

Margin monitoring can provide excellent metrics and key performance indicators to assess the platform's overall ability to support warship capability through life. Accordingly, in addition to the guidance notes provided in Table 2 for Margin categories, the following considerations are offered for the engineering management of Cooling and Power Margins. Space and Weight will be covered in a later technical paper

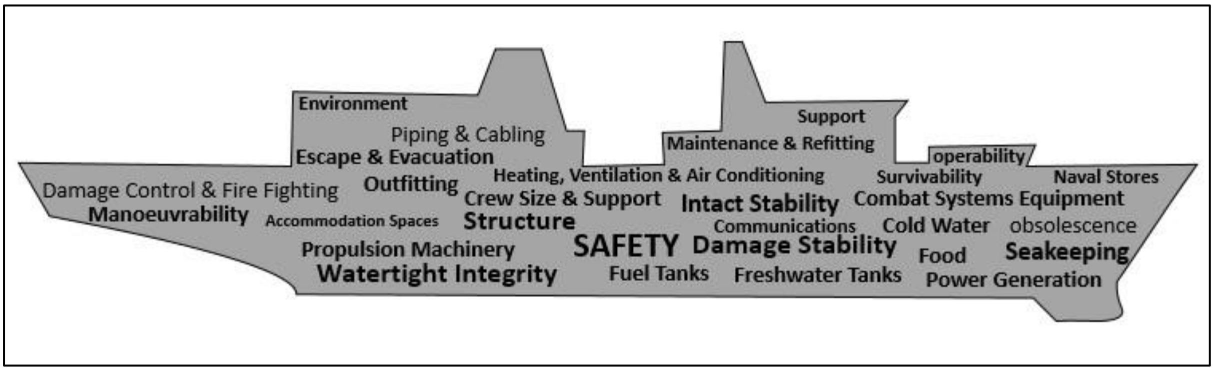

Figure 2: Gibbs and Cox Australia Warship Design Parameters and Requirements[17]

3.1 Cooling Margins

Cooling Margins are typically specified for the Chilled Water and HVAC systems, but can also be used for other key cooling systems as required. Examples include a Low-Pressure Sea Water (LPSW) system used to cool propulsion and/or auxiliary systems, or dedicated fresh water cooling systems utilised for the Phased Array Radar or Combat System consoles. For the purposes of this paper, Chilled Water system Margins will be used to illustrate the generic engineering management principles for Cooling systems.

3.1.1 What Key Design Parameters should be Applied – Chilled Water System

Chilled Water system cooling supports equipment serviceability (directly and indirectly) and personnel habitability (via the HVAC system). In a typical Surface Combatant, it would be commonplace to have a Chilled Water system design supplying reticulated coolant around the ship via a ring main, that can be reconfigured into smaller sub-systems for survivability and redundancy purposes in high threat states. The system would feature multiple Chilled Water Plants (CWP) and it is a generally accepted operating principal that the Chilled Water system must be capable of supplying the required maximum cooling load[18] with (N-1) CWPs with the Chilled Water system configured in a ring main whilst in cruising watches (N = No. of CWPs). A generic example of a typical Surface Combatant Chilled Water system schematic is illustrated in Figure 3:[19]

[17] (Blackwood, 2021)
[18] (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2019)
[19] (UK Ministry of Defence, 2007)

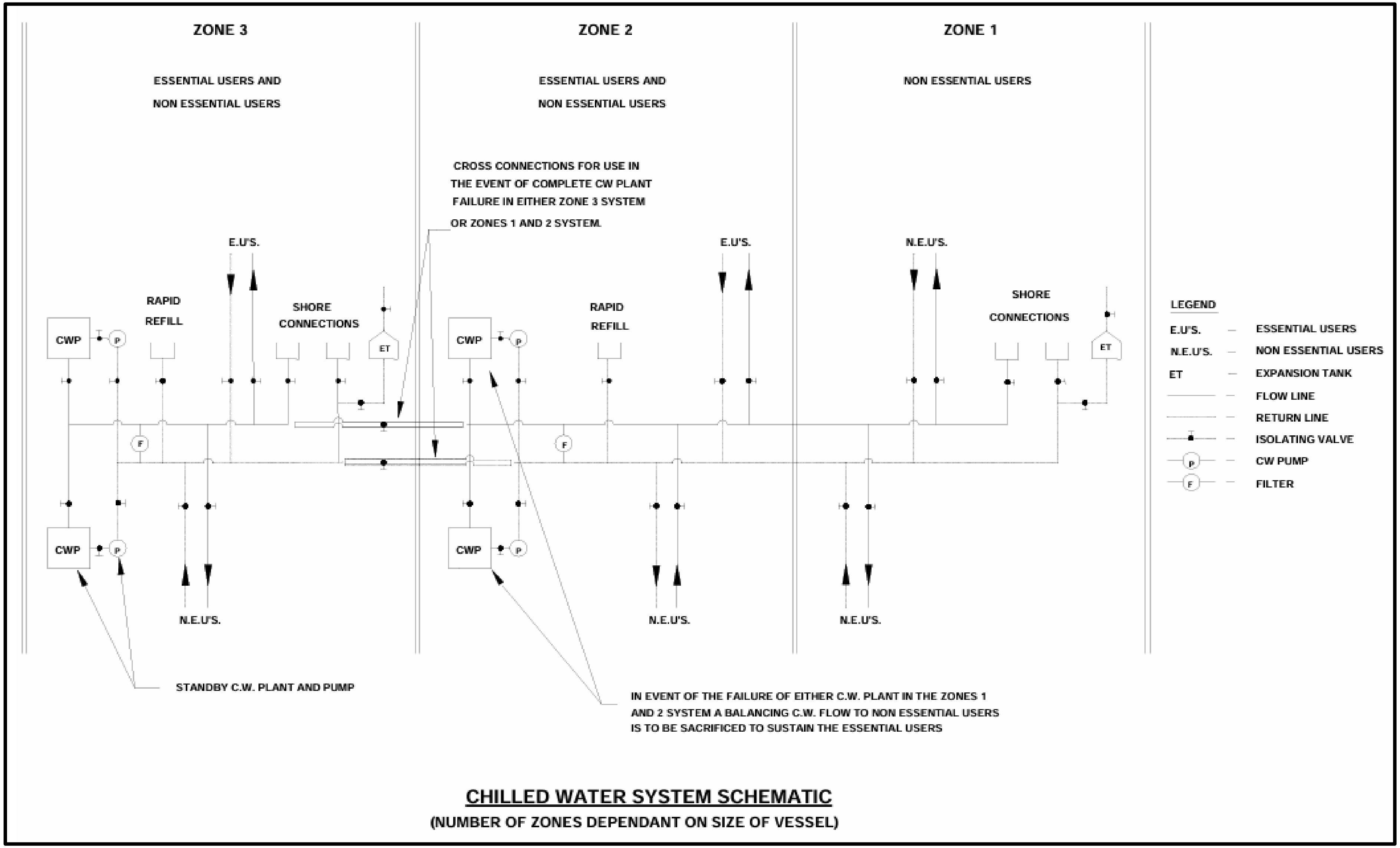

Figure 3: HMAS LANCLOVELY Chilled Water System Schematic

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Example 1 – Chilled Water System (N-1) Cooling Capacity

HMAS LANCLOVELY is the FoC vessel for the new County Class of Surface Combatants that have just been ordered for the Royal Australian Navy.

The Chilled Water system is configured in a ring main that supplies essential and non-essential users utilising a design methodology similar to that illustrated in Figure 3. It is supplied by 4 CWPs, each rated at 1,250 kW Cooling capacity at the maximum specified sea water temperature of 40˚C.

Whilst the ship is operating at Action Stations, for survivability purposes, the ring main is reconfigured into 4 quadrants, with each CWP supplying a quadrant each.

Total Cooling capacity = 4 x 1,250 = 5,000 kW

(N-1) Cooling capacity = 3 x 1,250 = 3,750 kW

3.1.2 Cooling Margin Determination – Chilled Water System

To assess and monitor the Chilled Water system Margins, the Gibbs and Cox Australia (GCA) Mechanical Auxiliaries team collated all the estimated direct-cooled equipment and HVAC cooling loads (these correspond to variables a1 and a2 in Example 2). A 15% Through-Life Growth Margin was then added to account for the physical inequities of in-service growth plus degradation in mechanical performance over time (this figure has been validated empirically over a number of warship design and build programs).[20]

For each of the individual equipment cooling loads, which is generally based upon data supplied from the original equipment manufacturer (OEM), a Design and Build Margin is applied. This is specified as a percentage of the equipment estimated cooling load (typically 15-20% initially) and this figure is gradually reduced over time to 0% as design maturity improves. The methodology for gradually reducing DBM over time is documented succinctly in the UK MAP 01-070.[21] Margin reductions can occur upon receipt of accurate equipment wild heat and/or load data from suppliers, and derivation of utilisation and diversification factors. A worked example of DBM percentages based upon design maturity used by GCA is presented below in Table 3:

DBM Code	DBM Percentage	Notes
00	20%	Equipment specification is preliminary, Wild Heat or Electrical load figures are rough estimates based upon similar installations.
01	16%	Equipment specification is immature, preliminary Wild Heat or Electrical load figures have been discussed with potential suppliers.
02	12%	Equipment specification is partially mature and broad equipment parameters have been agreed with suppliers. This should permit a greater degree of confidence in Wild Heat or Electrical load figures.*
03	8%	Equipment specification is mainly mature, Wild Heat or Electrical load figures are based upon OEM figures and procurement contracts have been placed, allowing these figures to be verified.
04	4%	Equipment specification is mature, Wild Heat or Electrical load figures are based upon OEM figures and the equipment has been integrated fully into the design.
05	0%	Equipment specification is fully mature, Wild Heat or Electrical load figures have been verified and documented within the Load Chart.

Table 3 – DBM Codes and Categories for Chilled Water and Electrical Systems

* DBM Code 02 (Margin = 12%, in Green) has been used in Example 2 (CW) and Example 4 (Electrical).

[20] (DE&S SE Sea - Surface Ship Division, December 2007)
[21] (UK Ministry of Defence, 2009)

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For future Capability upgrades throughout the nominal 25-year service life of the County Class, a nominal Capability Upgrade Margin of 150 kW is also applied as a contingency figure for potential future equipment installations of Directed Energy Weapons (based upon a nominal 500 kW Optical power rating).[22]

Deductions from the overall cooling load can also be made for direct solar gains (applicable to the upper deck and superstructure exposed to solar radiation that cover the entire width of the ship) whilst the sun is not directly overhead.[23] Research indicates that there is a degree of variance in the way these are applied and, consequently, these are not included in the example below.

Chilled Water flow rates are also important, and provision of sufficient spare capacity (typically 15-20%) is important to (a) ensure continued cooling performance through life and (b) accommodate future capability upgrades without having to remove other equipment to ensure sufficient coolant flow.[24]

It is also instructive to assess the Chilled Water system load on each of the 4 CWPs with the system configured into quadrants whilst the ship is in a high threat state, noting that the forward CW load is often greater due to the cumulative effect of direct-supplied cooling loads for the Operations Room complex.

An example of the overall Chilled Water system Margin calculated relatively early in the design phase is presented below, illustrating the practical quantification of the various Margin types.

Example 2 – Chilled Water System Margin

1)	Estimated Chilled Water system HVAC Cooling Load =	2,000 kW	(a1)
	Estimated Chilled Water system Direct-Cooled Load =	600 kW	(a2)
	Through-Life Growth Margin = 0.15 x (a1 + a2) =	390 kW	(b)
2)	Design and Build Margin (DBM Code 02) = 0.12 x (a1 + a2) =	310 kW	(c)
3)	Capability Upgrade Margin =	150 kW	(d)
4)	Total Cooling Load (inc. Margins) = (a1) + (a2) +(b) + (c) + (d) =	3,450 kW	(e)
5)	(N-1) cooling capacity = 3 x 1,250 =	3,750 kW	(f)
6)	Available Cooling Margin = (f) – (e) = 3,750 – 3,450 =	**+ 300 kW**	

3.1.3 Cooling Margin Assessment – Chilled Water System

In the example above, the GCA Mechanical Auxiliaries team have done a good job and have managed to maintain a small, positive Chilled Water system cooling Margin of +300 kW (+8.0% of the (N-1) Cooling capacity). This also includes a 12% Design and Build Margin of 310 kW (based upon DBM Code 02, Table 3), which will reduce further over time as design and equipment maturity improves, with the aim that the Cooling Margin remains in positive territory. This means that the Marine Engineers of HMAS LANCLOVELY are able to use the Chilled Water system whilst operating no more than 3 of the 4 CWPs in cruising watches. This helps to promote long-term equipment serviceability and enhance habitability.

This is important as it is often difficult and challenging from a technical and logistical perspective to keep all the CWPs serviceable whilst deployed away from base port for extended periods. If significant maintenance on the CWP refrigeration circuit or compressor is required, this often involves vacuum dehydration which is time consuming and protracted due to the large amount of refrigerant gas contained within CWPs.[25]

3.1.4 Cooling Margin Management Strategy – Chilled Water System

In this instance, the Chilled Water Margin appears relatively healthy, noting that the available Margin is positive and that further reductions in the Design and Build Margin (DBM) can be expected as the design matures. As a result, no significant increases in CWP capacity or Chilled Water flow rates are required.

Recommended strategy for Chilled Water loads and flow rates – Monitor noting that the overall Margin should improve incrementally as the DBM decreases over time (no active intervention required at this stage)

[22] (Sayler, et al., 22 August 2023)
[23] (UK Ministry of Defence, 2007) and (Naval Sea Systems Command, n.d.)
[24] (UK Ministry of Defence, 2009)
[25] (Thomas, 2010), (TRANE, February 2021) and (NSC Ships Support Agency, July 1998)

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3.2 Power Margins

For the purposes of this technical paper, coverage of Power Margins is applicable to the Electrical Generation and Distribution system. This article does not cover the determination of Propulsion Power Margins that would be undertaken early in the ship design process to determine Prime Mover installed power ratings.[26]

During the design phase, the initial focus is to select the balance of generating plant that produces and distributes the main generation voltage (if this is higher than 440V) plus the 440V AC Ship Services system. The analysis can also be extended to other sub-systems, including specialist supplies such as 440V, 400 Hz that may be required for weapon and/or sensor systems. Use of Margins to monitor and validate design assumptions is extremely useful and instructive to ensure there is adequate supply provision.

3.2.1 What Key Design Parameters should be Applied – Electrical Generation and Distribution System

In a typical Surface Combatant, the Electrical Distribution system would comprise four Diesel Generators (DG) located in a number of different compartments to enhance Combat Survivability. The system would be configured to supply two main switchboards, directly connected consumers (for example, Chilled Water Plants and the main Phased Array Radar), and Normal and Alternative supplies to the Electrical Distribution Centres located around the ship.

It is considered good practice that the Electrical Distribution system must be capable of supplying the maximum required electrical load with (N-1) DGs operational (N = No. of DGs), thereby enabling one DG to be under maintenance.[27] Whilst this may appear somewhat conservative, the continued growth in demand for installed electrical power attributable to the increased use of high power weapons and sensors shows no sign of abating, and justifies this approach.[28]

If the Propulsion design includes Electric Drive, which requires the DGs to supply electricity for Propulsion purposes as well (as per the indicative example illustrated in Figure 4), the (N-1) requirement is still valid but needs to factor in the maximum Propulsion and Ship Services electrical load. In addition, these loads may vary significantly between Tropical, Temperate and Cold environmental conditions.

As well as comparing the generating capacity and the load, it is also important to assess the distribution system's ability to cope with the sudden loss of one of the Switchboards (Partial Electrical Failure scenario), causing all of the load to be carried by one switchboard.[29] In the example system illustrated in Figure 4, a key metric in this scenario would be the capacity and available Margin for the Ship Services Transformer.[30]

Example 3 – Electrical Generation and Distribution System (N-1) Generation Capacity

HMAS LANCLOVELY's Electrical Distribution system is illustrated in Figure 4, and features 4 x DGs, used to supply Propulsion and Ship Services, each rated at 2.5 MW generating capacity.

Total Generating capacity = 4 x 2.5 MW =	10.0 MW
(N-1) Generating capacity = 3 x 2.5 MW =	7.5 MW
Rating of AC Electric Drive Propulsion Motors (x 2) =	2.2 MW
Maximum estimated 440V Ship Services load =	1.8 MW
Rating of Ship Services Transformers (x 2) =	1.5 MVA

[26] (Lui, et al., 2022)
[27] (Directorate of Naval Engineering, 2015)
[28] (Defence Science and Technology Laboratory, October 2020) and (Hart, 12 Jan 2022).
[29] (Lloyd's Register, January 2024)
[30] (MOD(PE) Sea Systems, 1995)

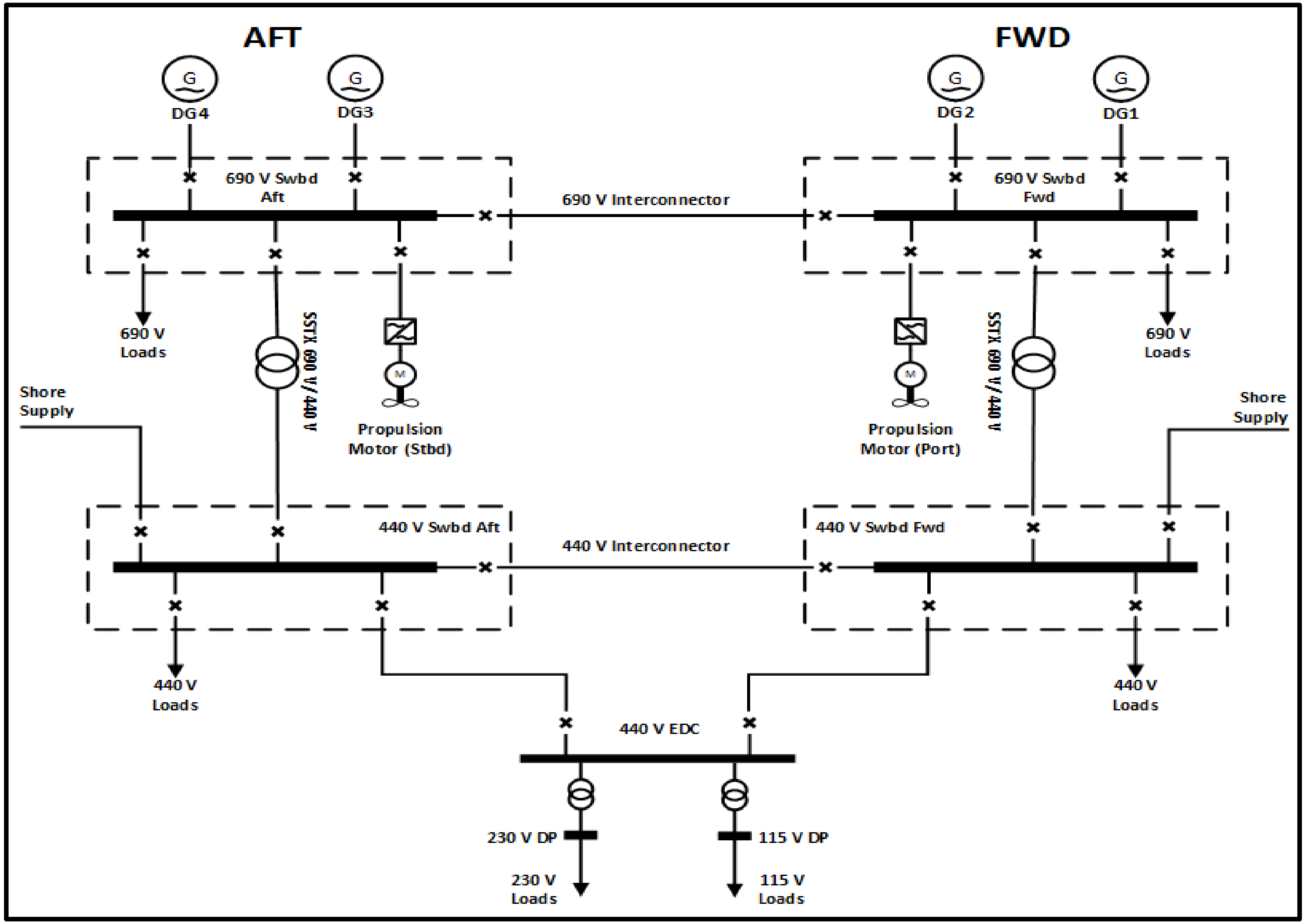

Figure 4: **HMAS LANCLOVELY Electrical Generation and Distribution System**[31]

[31] (Fleisher, et al., 2022)

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3.2.2 Electrical Power Margin Determination

Following similar principals utilised for the Cooling Margins, the GCA Electrical team collated all the estimated Propulsion system and Ship Services loads (a1 and a2 in Example 4), and 15% Through-Life Growth Margin was then added to this total (this 15% figure is, again, based upon guidance in MAP 01-070.

For each of the individual system or equipment electrical loads (based upon OEM-supplied data), a Design and Build Margin is then applied. This is specified as a percentage of the estimated load (typically 15-20% initially) and this figure is gradually reduced over time to 0% as design maturity improves, updated equipment load data is obtained from suppliers, and accurate utilisation factors are derived. For Example 4 documented below, a DBM Margin of 12% has been used (Table 3 refers).

For future Capability upgrades throughout the estimated 25-year service life of the County Class, a nominal Capability Upgrade Margin of 0.4 MW is also applied as a contingency figure for potential future equipment installations, including systems such as Directed Energy Weapons (based upon a nominal 500 kW Optical power rating) and Combat System upgrades.[32]

As mentioned previously, the ability of a single SSTX to handle the maximum Ship Services load in the event of a Partial Electrical Failure scenario is key. For ships that have provision of electrical ride-through for seamless transition from Normal to Alternative supplies, and/or the capability to provide maintained supplies (to key systems such as the Combat system), allocating TLGM to the SSTX is advantageous.

In addition, monitoring the number of spare breakers in the Electrical Distribution Centres (EDCs), broken down into Essential, Non-Essential and Sheddable[33] sections is highly recommended. If required, this philosophy can also be applied to the capacity of cable glands and cable trays in key compartments such as Switchboards and EDCs.

Example 4 – Electrical Generation and Distribution System Margin

1)	Estimated Propulsion Electrical Load =	4.4 MW	(a1)
	Estimated Ship Services Electrical Load =	1.8 MW	(a2)
	Through-Life Growth Margin = 0.15 x (a1 + a2) =	0.9 MW	(b)
2)	Design and Build Margin (DBM Code 02) = 0.12 x (a1 + a2) =	0.7 MW	(c)
3)	Capability Upgrade Margin =	0.4 MW	(d)
4)	Total Electrical Load (inc. Margins) = (a1) + (a2) +(b) + (c) + (d) =	8.2 MW	(e)
5)	(N-1) Generating capacity = 3 x 2.5 MW =	7.5 MW	(f)
6)	Available Electrical Margin = (f) – (e) = 7.5 – 8.2 =	**- 0.7 MW**	

3.2.3 Electrical Power Margin Assessment

This scenario is more complex than the previous Cooling Margin example due to the inclusion of Propulsion load as well as Ship Services load. The installed Generating capacity is 10.0 MW, the maximum estimated load is 8.2 MW, and this includes a DBM of 0.7 MW (which should reduce over time as design maturity improves). Historical precedent indicates that consideration should be given to the inherent maintenance burden of Diesel engines which puts a strong onus on adhering to (N-1) Generating capacity.

Warships featuring hybrid Electric Drive propulsion configurations are commonly designed such that the Electrical Distribution system default setting is to bias load priority to Ship Services in preference to Propulsion. The corollary of this is that for a constant Generating capacity, if the Ship Services load increases, the available power for Propulsion (and hence maximum ship speed in Electric Drive) decreases. This does not generally apply to warships with Integrated Full Electric Propulsion (IFEP) due to the typical mix of Generation plant including large Main Turbine Generators (MTG) combined with much smaller Auxiliary Turbine Generators (ATG).[34]

[32] (Sayler, et al., 22 August 2023)
[33] (Butterfield & Szymanski, 2018)
[34] (Partridge, 2022)

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The other Propulsion design factors that influence the tension between Electrical supply and demand are the maximum cruise speed and corresponding range. The cruise speed needs to be sufficient such that the ship can economically perform its roles in this Propulsion mode, but also ensure that the prime movers and fuel tanks required to achieve this can be spatially accommodated within the platform. When designing sprint Propulsion configurations, because speed is directly proportional to the cube of the power installed, there is a significant increase in fuel consumption for each extra knot of top speed (and a corresponding drop in range).[35]

The other major concern in this illustrative example is the capacity of each SSTX (rated at 1.5 MVA) compared to the maximum estimated Ship Services load of 1.8 MW. Irrespective of how much Margin may have been included in system design, in a fault situation where one Switchboard is lost, the SSTX fed from the unaffected Switchboard cannot handle the full load required by the 440V system as affected EDCs switch over to their alternative supplies. This could cause anything from unanticipated load shedding through to a Total Electrical Failure, and this is not a great outcome for a warship featuring Electric Drive. The obvious solution would be to increase the size of the SSTX, and this should have been picked up during the initial Design phase.

3.2.4 Electrical Power Margin Management Strategy

The Electrical system Margin is under duress (the Margin is - 0.7 MW which is -9% of the (N-1) Generating capacity). The size of the negative Margin compared to (N-1) Generating capacity is a key performance indicator and illustrates the scale of the issue. There are also issues with SSTX capacity, noting that they cannot handle the whole Ship Services load in the event of the loss of one of the Switchboards.

This is an artificial scenario but one that illustrates the potential severity of the issues if not dealt with early on during the design phase when fundamental choices are made regarding allocation of space, size of Main Machinery Spaces, and type and size of prime movers.

Recommended strategy for the Electrical Generation and Distribution System – fundamental redesign is required (including potentially increasing the capacity of the DGs and SSTXs, or reducing system load).

Figure 5: HMAS LANCLOVELY in Build

[35] (Steele, 18-19 June 2024)

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4. Summary

The paper describes the role of Margins within warship Acquisition and In-Service phases and documents an approach that can be taken to manage the risks associated with warship requirements setting, design, build and subsequent in-service changes. Margins assist in mitigating uncertainty in Acquisition, ensuring safety throughout the Service Life, and providing capacity for technology upgrades in an evolving threat environment.

Margin types (including DBM, CMM, ISGM/TLGM and CUM) are described, along with practical engineering management guidance as to how to interpret and apply these to technical categories (including Space, Weight, Power , Cooling, Environmental Management Systems and other attributes as required).

Specific worked examples based upon a hypothetical design for a County Class Surface Combatant (HMAS LANCLOVELY) were presented, to assist in demonstrating the utility of Margins as Metrics and Key Performance Indicators. For Cooling and Power, these were developed further based upon indicative system designs for Chilled Water, and Electrical Generation and Distribution.

The paper notes the type of Margins that are typically utilised during warship Acquisition and In-Service phases, as well as the Margin categories used. All of these can provide numerically based metrics that can be used to assess the enduring ability of the warships to meet its Mission System Requirements during the whole warship life cycle, including Design, transition to Production, and through to end-of-life.

5. Conclusions

It is concluded that continuous monitoring of key Margins provides a powerful management tool for enduring quality assurance of a warship's capabilities as it transitions from Design and Production into service.

For specific platform characteristics (including Cooling, Power, Weight and Space), some of the metrics lend themselves readily for use as Key Performance Indicators. Examples of these include adherence to (N-1) operating philosophy for Cooling and Power Margins.

The following specific observations and conclusions are presented for Cooling and Power Margins:

Cooling	Chilled Water Margins were analysed using a representative Chilled Water system design. HMAS LANCLOVELY's metrics highlighted the importance of adhering to an (N-1) operating philosophy, as well as ensuring sufficient provision is made for coolant flow rates for future weapon, sensor, and platform capability upgrades. Chilled Water Margins are critical to ensuring adequate Cooling for (a) weapons, sensors and communications, and (b) habitability. In the example presented, the design offered a positive Margin indicating that the design was fit for purpose and suitable to cope with the challenges of the warship's in-service phase.
Power	Electrical Power Margins were illustrated based upon the Electrical Generation and Distribution system for a CODLOG system design. For warships that keep Propulsion power separate from Ship Services, the importance of achieving (N-1) Generation capacity is evident. This also applies to hybrid systems such as the HMAS LANCLOVELY design that supplies Propulsion and Ship Services, noting this can be more challenging to achieve. This philosophy does not apply to IFEP warships due to the significant difference in installed power between large MTGs and smaller ATGs. The worked example and the negative Margin evident indicated the issues caused by a lack of adherence to the (N-1) philosophy, as well as the inadequate size of the SSTX which is challenging when dealing with system operation in reversionary modes. This example illustrates the benefits of using Margins to assist with analysing system capacity and any consequential operational shortfalls that may arise, particularly under fault conditions.

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Glossary

Term	**Description**
AC	Alternating Current
ATG	Auxiliary Turbine Generator
CMM	Contract Modification Margin
CoA	Commonwealth of Australia
CODLOG	Combined Diesel Electric or Gas Turbine
CoG	Centre of Gravity
CUM	Capability Upgrade Margin
CW	Chilled Water
CWP	Chilled Water Plant
DBM	Design and Build Margin
DC&FF	Damage Control and Fire-Fighting
DEF(AUST)	Royal Australian Navy Defence Standard
Def Stan	UK Defence Standard
DEW	Directed Energy Weapon
DG	Diesel Generator
EDC	Electrical Distribution Centre
EM	Propulsion Electric Motor
EU	Chilled Water Essential Users
FoC	First of Class
HVAC	Heating Ventilation and Air Conditioning
IFEP	Integrated Full Electric Propulsion
IMO	International Maritime Organisation
IPMD	Initial Provision Made in Design
ISGM	In Service Growth Margin
Hz	Hertz
kW	Kilo Watt
LCG	Longitudinal Centre of Gravity
LPSW	Low Pressure Sea Water
MAP	UK MOD Maritime Acquisition Publication
MARPOL	Maritime Pollution Convention
MTG	Main Turbine Generator
MVA	Mega Volt Amps
MW	Mega Watt
NEU	Chilled Water Non-Essential Users
NSSG	Australian Department of Defence - Naval Shipbuilding and Sustainment Group
OEM	Original Equipment Manufacturer
PAR	Phased Array Radar
PMS	Platform Management System
RAN	Royal Australian Navy
SSTX	Ship Services Transformer
TLGM	Through Life Growth Margin
VCG	Vertical Centre of Gravity

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