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BMD Support Ship (T-BMD)

T-AKE Mod-Repeat Approach

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Executive Summary

The U.S. Navy is currently in the concept design phase of the CG(X) class cruiser, which will replace the aging Ticonderoga class AEGIS cruisers. A primary mission of the new CG(X) cruisers will be track and engage ballistic missiles to provide an "umbrella" of protection for national assets. This mission will become more vital if the proliferation of nuclear arms to potentially unstable countries occurs. The presence of a Ballistic Missile Defense Support Vessel (T-BMD) could provide support to the CG(X) and other national assets by providing early detection and tracking of ballistic missiles in flight to allow for quicker prosecution times in the detect to engage kill chain without requiring land-based sensors.

The purpose of this project is to determine the feasibility of using the ongoing Dry Cargo/Ammunition Vessel (T-AKE 1) Class production line as the basis for a Modified Repeat or Minimum-Modification/Minimum Cost ship configured as a Ballistic Missile Defense Support Vessel (T-BMD). The T-BMD is a vessel that can accommodate X-Band and S-Band radars to search and track ballistic missile threats and pass track information to other assets for engagement and is similar in capability to the T-AGM(R), Cobra Judy (Replacement) that is entering construction. The study focused on using current T-AKE data, arrangements, weights, and drawings as a starting point. Several design variants were analyzed and the most capable and cost effective model was chosen. Modifications to the arrangements, structure, and weights were made as necessary to transform the original T-AKE into the chosen T-BMD variant. The variant was put through a series of structural and stability analyses and various seakeeping scenarios to determine the T-BMD's sea worthiness and mission effectiveness.

The results of this study verify that using the T-AKE as a basis for a new Ballistic Missile Support Vessel is a feasible solution from a capability perspective. The results demonstrate that the T-AKE can perform the mission of a Ballistic Missile Support Vessel with minimal modifications and design alterations and has significant margin for growth in mission capability. However, based on the assumptions, requirements, and analysis of the specified T-BMD variant, the T-AGM(R) may still be a more cost effective solution.

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1.0 Project Overview

1.1 Study Objectives

The U.S. Navy is currently studying ship options for sea-based Ballistic Missile Defense (BMD) whose primary mission will be track and engage ballistic missiles to provide an “umbrella” of protection for national assets. This mission will become more vital if the proliferation of nuclear arms to potentially unstable countries occurs. The presence of a Ballistic Missile Defense Support Ship (T-BMD) could provide support to other sea-based BMD assets and other national assets by providing early detection and tracking of ballistic missiles in flight to allow for quicker prosecution times in the detect to engage kill chain.

The purpose of this project is to determine the feasibility of using the ongoing Dry Cargo/Ammunition Ship (T-AKE 1) Class production line as the basis for a modified repeat, or minimum-modification/minimum cost ship configured as a Ballistic Missile Defense Support Ship (T-BMD). The T-BMD is a vessel that can accommodate X-Band and S-Band radars to monitor and collect data on ballistic missile threats. The deck area will be redesigned and utilized to accommodate the radar system, while the ship’s cargo holds will be converted to provide mission support. The design also includes the addition of limited self-defense weapons.

1.2 Customer Requirements

The primary mission of the T-BMD is the early detection and tracking of ballistic missiles to support a distributed missile defense system. This requires unique radar systems as well as the ability to effectively support assets that will actually engage the threats. There are always fiscal constraints involved with any new acquisition project, so the T-BMD must also be affordable now and in the future.

An Initial Capabilities Document (ICD) for the T-BMD does not exist. Actual requirements for the vessel were derived from conversations with project sponsors as well as requirements from the Cobra Judy Replacement (CJR) program. Table 1 lists the overarching customer requirements.

CR #	Description	Rationale
CR-1	BMD Mission Capability	Ability to support other assets in Theater Ballistic Missile Defense
CR-2	Affordability	Includes Initial Cost and Total Ownership Cost
CR-3	Service Life	Able to stay relevant to Fleet throughout life of ship, Upgradeability
CR-4	Suitability	Includes Reliability, Maintainability, Availability, Compatability with current shore facilities and fleet assets, Human/Systems Interface
CR-5	CLF Mission Capability	Support base T-AKE mission

Table 1 - Customer Requirements

Specific attributes to which the T-BMD is designed are listed in Table 2.

	Threshold	Objective
Speed	20 kts	20 kts
Range	12,000 nm	16,000 nm
Crew accommodations	88	60
Endurance	70 days	90 days
Seakeeping	Current T-AKE capabilities	Ability to maintain radar operations on all headings in seastate 6
C4I	Commercial off the shelf, FORCEnet compliant, with military GPS capabilities. Compatible with TBMD	Commercial off the shelf, FORCEnet compliant, with military GPS capabilities. Compatible with TBMD
Radar Types	X-Band	S-Band and X-Band
Radar Coverage	240 degrees	360 degrees
X-Band Radar	CJR Equivalent	FFOV X-Band
VERTREP Capability	None	50% T-AKE
CONREP Capability	None	50% T-AKE
Survivability	T-AKE standards	OPNAV 9070.1 Level II standards
Self Defense Capability	Current T-AKE	CIWS/RAM SH-60R capable

Table 2 – Design Attributes

1.3 Major Assumptions

The T-BMD will be operated by Military Sealift Command (MSC) with a Civilian Mariner (CIVMAR) crew and naval personnel detachment for operation of the communications and weapons systems. Independent and unreplenished ballistic missile monitoring patrols will be conducted in the open ocean for periods of 70-90 days, while maintaining 100% communications with supported sea-based BMD ships and naval shore commands.

The following assumptions were made for the T-BMD:

- 30 Year service life

- Two Ship Class (minimum)
- Ship will be Civilian Mariner (CIVMAR) operated, with a Military Detachment (MILDET) to operate mission systems
- Habitability standards will remain as those of the T-AKE class for civilians and OPNAVINST 9640.lA for military
- T-BMD will be built to ABS standards with the exception of the flight deck and communications systems
- X-Band and S-Band radar information will be notionalized based on Cobra Judy Replacement radars and other proprietary sources
- The hull form and propulsion system layout of the T-AKE will be retained
- Cargo holds will be adjusted as necessary for the support of BMD radars and systems
- The existing ship's fuel tanks will be converted to ballast tanks due to MARPOL 12A regulations
- The existing ship's cargo fuel tanks will be utilized for ship's fuel.
- Refrigeration Units/Space used for Cargo Hold 3 will be utilized for thermal management of radar systems

1.3.2 Design Margins

The ship margins are not altered for unchanged parts of the T-AKE baseline ship. Table 3 lists the design margins for portions of the ship that experienced additions or removals as part of the T-BMD conversion.

Margin	**Value**
Weight (Lightship)	10%
KG	8% of Current T-AKE
Ship Service Electrical	N/A
Air Conditioning Plants	20%
Speed / Power	N/A
Arrangeable Deck Area	2-5%
Tankage (Structural Allowance)	2% of Volume

Table 3 – Design Margins

Of special note, the Weight Margin of 10% relates to weight additions only. This is a more conservative approach for this project because the weight report provided by the sponsors was extremely accurate and the team felt their weight removal process was fairly precise. The margins for additions were for additional weight to be conservative for stability.

Table 4 lists the service life allowances used for changed portions of the T-BMD conversion

Allowance	Value
Weight (Lightship)	5%
KG, feet above full load	0.5 ft
Ship Service Electrical	20%
Air Conditioning Plants	20%
Speed / Power	N/A
Arrangeable Deck Area	N/A
Tankage	N/A

Table 4 – Service Life Allowances

1.4 Information Resources

1.4.1 Points of Contact

Name	Organization	Contact Information
James Harrison	NAVSEA T-AKE Ship Design Manager, NAVSEA 05	James.harrison2@navy.mil
Christopher Cable	NAVSEA Aux & Special Mission Director, 05D4, NAVSEA 05	Christopher.w.cable@navy.mil
Jeff Fink	NAVSEA T-AGM(R) Ship Design Manager, NAVSEA 05	Jeffrey.e.fink@navy.mil
James Ciba	NAVSEA IWS 2.0	James.ciba@navy.mil
Garry Holmstrom	Seapower Cabability Systems Center, RAYTHEON	Garry_holmstrom@raytheon.com
Edward Comstock	Integrated Defense Systems, RAYTHEON	Edward_n_comstock@raytheon.com
Joe Marra	NAVSEA O5D	Joseph.marra@navy.mil

1.4.2 References

- T-AKE Operational Requirements Document
- T-AGM(R) Ship Specification
- MIT 13A Cobra Judy 2 Conversion Project 2002
- Other proprietary information sources

1.5 Process Overview

1.5.1 Design Approach

1.5.1.a Develop Study Guide

A study guide was developed that documented the agreement between the project sponsors and design group. This listed the major inputs and assumptions for the design effort, including the customer requirements. The study guide is provided in Appendix A.

1.5.1.b Develop Design Approach and Project Plan

The project team developed a design philosophy and design parameters based on fulfilling customer requirements. The specific design philosophy and approach is explained in Section 2. This also included developing a project plan outlining the major tasks, schedule and tools to be used during the conversion design.

1.5.1.c Concept Exploration and Selection

A decision-making framework was developed based on cost-effectiveness of the project. This required the definition of the unmodified baseline T-AKE ship configuration around which the T-BMD study was based. Then, a technology survey and system-level evaluation/selection study was conducted to allow for the development of concept variants. These variants were then analyzed for cost-effectiveness to allow for the selection of the preferred conversion design concept that best satisfied performance, cost, and risk objectives. The detailed concept exploration and selection process is explained in Section 3.

1.5.1.d Concept Definition and Feasibility/Performance Analysis

The preferred concept was analyzed in detail to demonstrate its feasibility as well as assess its performance in satisfying customer requirements. Conceptual arrangements were developed, and the overall design assessed for multiple requirements including strength, stability, seakeeping, propulsion, and electrical power requirements. The detailed analysis of the preferred T-BMD concept is provided in Section 4.

1.5.1.e Documentation and Briefings

Upon completion of the technical performance analysis, this technical report was developed to provide the overall project details, conclusions and recommendations. Additionally, a briefing was developed for the project sponsor and for presentation at the Society of Naval Architecture and Marine Engineering (SNAME) Student Presentation.

1.5.2 Modeling Tools

1.5.2.a RHINO 3D

- For changes to general arrangements and placement of the radars and ancillary systems
- For final project diagrams and presentation

1.5.2.b EXCEL

- Concept exploration and selection process
- Weight additions and removals

1.5.2.c POSSE

- Structural Analysis
- Intact Stability
- Damaged Stability

1.5.2.d MAXSURF

- Seakeeping Analysis
  - Motions and Accelerations
- Powering and Resistance Analysis

1.5.3 Schedule

Date	Milestone/Event	Additional Info
20 Nov (F)	Pick project teams and topics (bring proposals to meeting)	Meetings 0900-1100
11 Dec (F)	Submit draft Study Guide	Electronically by COB
04 Jan (M)	IAP Kick-off meeting; Present draft Project Plan to faculty	Meetings 1100-1400; Bring hardcopies
08 Jan (F)	Review #1 (design approach/inputs); Submit draft report Ch's 1 & 2	Meetings 1100-1400; Bring hardcopies
15 Jan (F)	Review #2 (preferred concept selection); Submit draft report Ch's 3 and related Appendices	Meetings 1100-1400; Bring hardcopies
18-19 Jan (M)	Mid-point brief to sponsors	Teams arrange travel/telcon
22 Jan (F)	Review #3 (design/analysis results);	Meetings 1100-1400; Bring hardcopies
25 Jan (M)	Submit draft report Ch's 4 & 5 and related Appendices	Electronically by COB
28 Jan (Th)	Final Concept Review w/ faculty	Meetings 1100-1400; Bring hardcopies
29 Jan (F)	Submit Final Report and supporting files	Electronically by COB
TBD (Feb)	Final Concept Brief to sponsors	Teams arrange travel/telcon

2.0 Design Requirements and Plan

The process to be employed for this study is the development of a feasible ship concept using the T-AKE 1 as the parent or baseline vessel and modifying the design to meet the requirements of BMD-support vessel (T-BMD). The T-BMD will be developed to a Rough-Order-Of-Magnitude (ROM) level. Analysis and calculations will be developed to ensure that the weights, area/volume, intact stability and ships arrangement result in a balanced solution. In addition, the modified electric loads, ship's speed, and endurance will be analyzed and defined.

2.1 Design Philosophy

The philosophy for this project was to design a Mod-Repeat of a T-AKE to perform the duties and missions of a BMD Support Vessel with low Acquisition costs and Total Ownership Costs (TOC). Commonality and cost effectiveness are important attributes in today's ship design world and were kept in mind throughout the study.

Specifically, the goals were to only modify the materials and configurations necessary to produce a vessel that would perform the required duties of a BMD-Support Vessel. Existing T-AKE space configurations, power plant ratings and propulsion train were retained to efficiently attain T-BMD design requirements. Additionally, the vessel was upgraded to comply with MARPOL 12-A regulations.

To effectively achieve commonality, hull and superstructure materials and scantlings currently found onboard T-AKE were used and commercial off the shelf (COTS) components were utilized as much as possible. Notional data for existing X- and S-band radars (at an Unclassified level) were used in the design analysis

The ship hull form remained the same as the T-AKE as it has proven to be effective and offers a large amount of space to accommodate the radars and support equipment. Using this hull form alleviated the research and development costs of designing a clean sheet hull form. The ship superstructure and cargo rooms were modified as necessary to allow for the installation and operation of equipment required of a Ballistic Missile Support Ship.

CR #	Description	Rationale
CR-1	BMD Mission Capability	Ability to support other assets in Theater Ballistic Missile Defense
CR-2	Affordability	Includes Initial Cost and Total Ownership Cost
CR-3	Service Life	Able to stay relevant to Fleet throughout life of ship, Upgradeability
CR-4	Suitability	Includes Reliability, Maintainability, Availability, Compatability with current shore facilities and fleet assets, Human/Systems Interface
CR-5	CLF Mission Capability	Support base T-AKE mission

Table 5 shows the Customer Requirements (CR's) developed that supported the design philosophy, with the rationale behind the choice of each CR.

CR #	Description	Rationale
CR-1	BMD Mission Capability	Ability to support other assets in Theater Ballistic Missile Defense
CR-2	Affordability	Includes Initial Cost and Total Ownership Cost
CR-3	Service Life	Able to stay relevant to Fleet throughout life of ship, Upgradeability
CR-4	Suitability	Includes Reliability, Maintainability, Availability, Compatability with current shore facilities and fleet assets, Human/Systems Interface
CR-5	CLF Mission Capability	Support base T-AKE mission

Table 5: Customer Requirements

2.2 Design Parameters

The following design parameters (DP) shown in **Table** 6 represented the essential elements of the design and defined the trade space for the initial analysis of the design alternatives. These design parameters were directly related to the Customer Requirements and were in accordance with the overall design philosophy.

DP #	Description
DP-1	Radar Coverage
DP-2	S-Band Radar
DP-3	X-Band Upgrade
DP-4	Range
DP-5	Endurance
DP-6	Accommodations
DP-7	Exterior Communications
DP-8	Surface/Air Self Defense
DP-9	ASW Self Defense
DP-10	Survivability
DP-11	Seakeeping
DP-12	Draft
DP-13	VERTREP Capability
DP-14	CONREP Capability

Table 6: Design Parameters

By consulting with various subject matter experts (SME) and the project sponsors, the design space was more clearly defined and led to a focus on pertinent requirements for the T-AKE Conversion. Threshold and Objective values for the design parameters are found below in **Table** 7 and were determined from inputs by SMEs and sponsors, specifications of the current T-AKE model and Cobra Judy (Replacement) ship, and qualitatively from the design team's personal experience. Because this design was focused on supporting BMD, BMD Mission Capability was the primary consideration in the analysis. Affordability was also considered a significant driver, however cost was used as an independent variable for OMOE vs. Cost analysis.

Design Parameter	Threshold	Objective
Radar Coverage	240 Degrees	360 degrees
S-Band	X-Band Only	S and X Band Radars
X-Band Upgrade	CJR Equivalent	FFOV X-Band
Range	12,000 NM	16,000 NM
Endurance	70 Days	90 Days
Crew Accommodations	88 Personnel	60 Personnel
External Communications	Commercial off the shelf, FORCEnet compliant, with military GPS capabilities. Compatible with TBMD	Commercial off the shelf, FORCEnet compliant, with military GPS capabilities. Compatible with TBMD
Surface/Air Self Defense	T-AKE Baseline	CIWS/RAM + crew-served small arms
ASW Self Defense	Current T-AKE	1 SH-60R
Survivability	ABS (current T-AKE)	OPNAV 9070.1 Level II standards
Seakeeping	Current T-AKE	Ability to maintain radar operations on all headings in seastate 6
Draft	Current T-AKE	Within 2' Current T-AKE
VERTREP Capable	None (helo pad & hanger remain)	50% T-AKE capability
CONREP Capable	None	50% T-AKE Capability

Table 7: Design Parameter Thresholds

2.3 Evaluation and Decision Framework

At the top level of the design analysis, Quality Function Deployment (QFD) was utilized to map Design Parameters to Customer Requirements. By conducting the QFD analysis, the major design drivers were identified which assisted in developing the framework for conducting a full factorial design. The breakdown of the factorial design is discussed further in Section 3.

An analytical hierarchy process (AHP) using simplified pair-wise comparison was performed to determine what requirements and parameters were most important to the design's mission effectiveness and performance. Placing the parameters in an analytical hierarchy allowed each individual parameter to be weighted against the others with the subsequent results giving a good idea of which parameters were most important (i.e., highest weight) to the overall performance of the design. Excerpts of the QFD and AHP approaches are shown below in Figures 1 and 2. The complete AHP and QFD analysis is shown in Appendix C.

Functions (Hows)
Design Characteristics (Hows)

Customer Requirement (Whats)	*Weights*		Radar Coverage	S-BAND	X-BAND	Range	Endurance	Accomodation	Communications	Surface/Air Self Defense	ASW Self Defense	Survivability	Seakeeping	Draft	VERTREP Capability	CONREP Capability	
			Units	Units	Units	Units	Units	Units	Units	Units	Units	Units	Units	Units	Units	Units	
Mission Capability (BMD)	0.467	0.467	9	9	9				9		3		3				
Affordability	0.233	0.233	9	9	9				3	3	3	9			3	3	
Service Life	0.067	0.067	3	9	9			3	3			3		3	6	6	
Suitability	0.156	0.156		9				9	3	3	3		9			3	
Mission Capability (CLF)	0.078	0.078				5	5	3					9	9	9	9	
		0.000															
		0.000															
Check Sum		1.00															
Weighted Performance			6.5	8.3	6.9	0.4	0.4	1.8	5.6	1.2	2.6	2.3	3.5	0.9	1.8	2.3	44.4
Percent Performance			0.146	0.187	0.155	0.009	0.009	0.041	0.125	0.026	0.058	0.052	0.079	0.020	0.041	0.051	

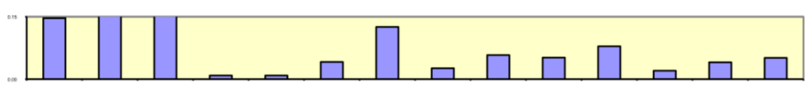

Figure 1: Quality Function Deployment

Mission Capability BMD

Criteria	Criteria	1 Radar Coverage	2 S-BAND	3 X-BAND	4 Communications	5 ASW Self Defense	6 Seakeeping	Weights
Radar Coverage	1	1	0.5	0.8	0.7	3	3	0.1559
S-BAND	2	2	1	1.6	1.3	6	6	0.3117
X-BAND	3	1.3	0.6	1	0.8	3.8	3.8	0.1948
Communications	4	1.5	0.7	1.2	1	4.5	4.5	0.2337
ASW Self Defense	5	0.3	0.2	0.3	0.2	1	1	0.0520
Seakeeping	6	0.3	0.2	0.3	0.2	1	1	0.0520
	7							
	8							
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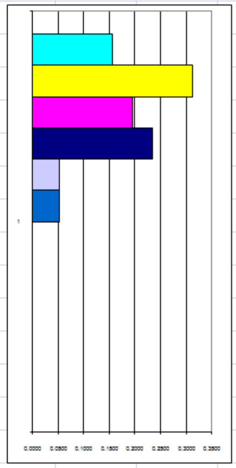


Criteria	Weight
Radar Coverage	0.156
S-BAND	0.312
X-BAND	0.195
Communications	0.234
ASW Self Defense	0.052
Seakeeping	0.052
Check Sum	1.000

Figure 2: Analytical Hierarchy Process Pair-wise Comparison (BMD Mission Capability)

Using the QFD and AHP results, an Overall Measure of Effectiveness (OMOE) table was generated to weight each design variant. The Measures of Effectiveness (MOE) and Measures of Performance (MOP) for the OMOE are shown in

Customer Requirement	Measure of Effectiveness	Design Parameter	Measure of Performance
BMD Capability	0.6087	Radar Coverage	.1644
		Radar Type	.3288
		Radar Power	.2055
		Communications	.2465
		ASW Self Defense	.0548
Service Life	.0870	Radar Type	.2857
		Radar Power	.1429
		VERTREP	.1429
		CONREP	.1429
		SUW Self Defense	.1429
		ASW Self Defense	.1429
Suitability	.2029	Radar Type	.250
		Accommodations	.250
		Seakeeping	.250
		SUW Self Defense	.125
		ASW Self Defense	.125
CLF	.1014	Range	.0869
		Endurance	.0869
		Accommodations	.0435
		VERTREP	.261
		CONREP	.261
		Seakeeping	.1738
		Draft	.0869

Table 8.

Customer Requirement	Measure of Effectiveness	Design Parameter	Measure of Performance
BMD Capability	0.6087	Radar Coverage	.1644
		Radar Type	.3288
		Radar Power	.2055
		Communications	.2465
		ASW Self Defense	.0548
Service Life	.0870	Radar Type	.2857
		Radar Power	.1429
		VERTREP	.1429
		CONREP	.1429
		SUW Self Defense	.1429
		ASW Self Defense	.1429
Suitability	.2029	Radar Type	.250
		Accommodations	.250
		Seakeeping	.250
		SUW Self Defense	.125
		ASW Self Defense	.125
CLF	.1014	Range	.0869
		Endurance	.0869
		Accommodations	.0435
		VERTREP	.261
		CONREP	.261
		Seakeeping	.1738
		Draft	.0869

Table 8: MOE and MOP Framework

3.0 Concept Exploration and Selection

3.1 Baseline Ship Description

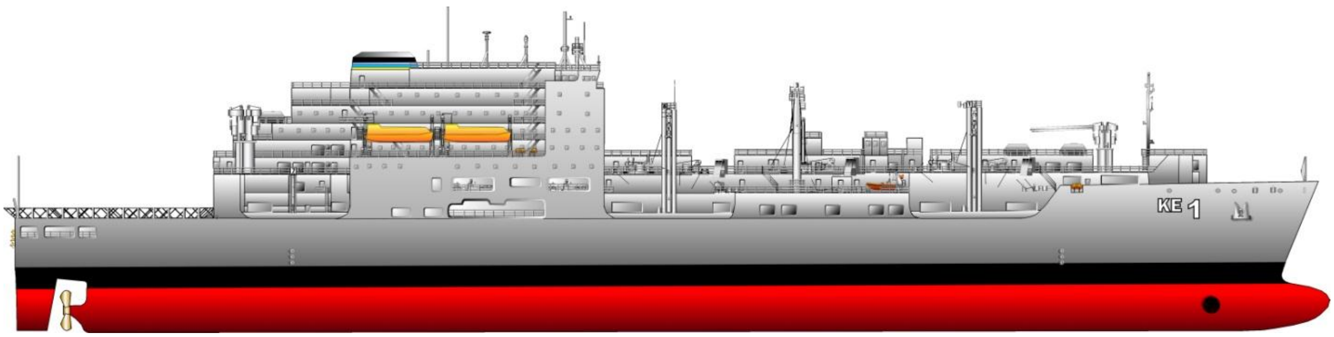


Figure **3**: Baseline T-AKE

The T-AKE baseline ship is Military Sealift Command's new Auxiliary Dry Cargo Carrier. T-AKE is intended for replenishment intended for replenishment at sea and fueling at sea (RAS/FAS) of surface combatants and support vessels and features a vessels and features a helicopter pad and dual hangar to support vertical replenishment (VERT REP). Powered with four Powered with four diesel engines (two 9 cylinder and two 8 cylinder), the T-AKE uses an Integrated Propulsion System (IPS) Propulsion System (IPS) to drive one propeller and generate power for all ship's electrical loads. A large continuous open continuous open transfer deck in the superstructure runs most of the length of the ship to facilitate stores staging and stores staging and handling. The T-AKE features two multi-purpose cargo holds (3 levels), one freeze-chill hold (3 levels) and chill hold (3 levels) and three specialty cargo holds (one level each), all serviced by two cargo elevators.

Length Over All	210m
Beam	32.2m
Draft (Full Load)	8.9m
Installed Power (IPS)	34.6 MW
Propulsive Power	22.8 MW
Ship Service Power	12 MW (IPS) + 2.3 MW (Emerg. Diesel)
Light Ship Displacement	18,130 MT
Full Load Displacement	35,000 MT
Sustained Speed	20 kts
Endurance	12000 nm (20 kts)
Dry Cargo Weight	5550 MT
Dry Cargo Stowage Capacity	33,400 m3
Cargo Staging Area	12,800 m3
Cargo Fuel Weight	4311 MT

Table 9 summarizes the key characteristics of the baseline T-AKE.

Table 9: Baseline T-AKE Key Characteristics

T-AKE's maintenance infrastructure, large deck area, large capacity IPS, and large cargo holds make it an attractive starting point for the Navy's Ballistic Missile Defense Support Ship (T-BMD).

3.2 Concept Exploration Approach

The design team used a Pair-wise Comparison chart to compare and rank the Customer Requirements created in Section 2.1 to each other. **Table 10** shows how important each CR was to each other. For example, BMD Mission Capability was twice as important as Affordability and three times as important as Suitability.

Item																		Item
Mission Capability	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Mission Capability
Mission Capability	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	Affordability
Mission Capability	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Service Life
Mission Capability	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Suitability
Mission Capability	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	Mission Capability (CLF)

Table 10, Customer Requirement Pair-wise Comparison

The results of the Pair-wise Comparison were placed into a Pair-wise Matrix (**Figure** 5) to calculate the weighting factors for each CR (right side of **Figure** 5).

Criteria	Criteria	Mission Capability (BMD) 1	Affordability 2	Service Life 3	Suitability 4	Mission Capability (CLF) 5	Weights
Mission Capability (BMD)	1	1	2	7	3	6	0.4667
Affordability	2	1	1	4	2	3	0.2333
Service Life	3	0	0	1	0	1	0.0667
Suitability	4	0	1	2	1	2	0.1556
Mission Capability (CLF)	5	0	0	1	1	1	0.0778

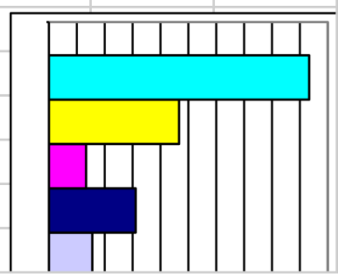


Figure 4, Customer Requirement Pair-wise Matrix

These weighting factors were discussed with the sponsors who viewed Affordability's weighting factor as being too low. This concern was addressed with cost being treated as an independent variable (CAIV), therefore the other weighting factors were not adjusted (the relative weights with each other remained the same).

The following Design Parameters (initially shown in Section 2.2) were decided based on team-member experience, looking at past projects, and sponsor feedback. More detailed discussion of the Design Parameters (and values used during analysis, where appropriate) follows.

3.2.1 Radar Coverage

Radar coverage refers to the unobstructed total coverage of any one radar. The ability to search or track over 360 degrees was seen as potentially invaluable to giving the ship the maximum maneuvering flexibility while accomplishing its mission. Therefore

In order to achieve 360 degree unobstructed coverage, the large deckhouse of the T-AKE (approximately 15m high) would have to be cut down to a much smaller size, necessitating the movement of accommodations into the hull. Additionally, the large radars, which ranged between 10m and 14m square, would require the creation of a forward pilothouse to allow forward visibility within ABS standards. While either are technically possible, this option was viewed to be very expensive for redesign and complex construction.

3.2.2 S-band Radar Presence

While researching radar information, the capability and functionality of the S-band radar was explored. It was found to add significantly to the BMD mission capability, due to its cueing capability, and was later weighted accordingly. PEO IWS provided information for an Advanced Missile Defense Radar System (AMDR-S) that was being developed for DDG-1000. This notional data was later used for weight, stability, and strength calculations.

3.2.3 X-band Radar Capability

Initially, radar power alone was a Design Parameter, but research showed the CJR radars to be of sufficient power. Increasing power would not achieve better results and there were no radars in development that required higher power. The only radar that currently requires higher power is that mounted on the SBX (Sea Based X-Band) but its capabilities were described as being more limiting than that desired for this ship.

Instead, Raytheon POCs provided information on a Full Field-Of-View (FFOV) X-band that was similar in size and weight to the X-band being designed for the CJR but with greater sensitivity and greater coverage due to beam steering. This choice was designated as the new Design Parameter.

3.2.4 Range

The published range for the T-AKE is approximately 11500NM. The exact range depends on a wide range of factors, including operating profile (speed) and draft. This value was rounded up to 12,000NM as a reasonable Threshold range. NAVSEA sponsors pointed out early in the project that new MARPOL 12 regulations would require ships to have double-hull protection around ship's fuel tanks, not just cargo tanks. Therefore, the conversion project would have to account for the reduction in ship's fuel tank volume due to additional hull plating. An alternative was to utilize the T-AKE's cargo fuel tanks, which were already double-hulled in the original design in accordance with previous MARPOL 12 regulations, and use the existing ship's fuel tanks for seawater ballast. This decision was also accounted for in classifying what constituted "CONREP Capability" later.

A quick assessment was performed and it was believed that utilizing the cargo fuel tanks, which can hold ~300MT more fuel than the ship's fuel tanks, would allow the design to achieve, and possible exceed, the Range Objective. Therefore, this DP was set to 'High'.

3.2.5 Endurance

Endurance here refers to the number of days the ship can remain at sea, with crew stores typically being the limiting factor. The T-AKE has stores to remain at sea for 70 days. This was set as the Threshold. A T-AKE typically deploys with 120+ personnel, most of whom are required to support the Combat Logistics Force (CLF) mission and would not be required if CLF capability was not retained. If the size of the crew could be reduced, standard T-AKE crew stores could easily support longer deployments. 90 days was chosen as a nominal Objective, with the potential for longer deployments with minimal modifications.

Based on the early assumption that crew size for the T-BMD would be less than the T-AKE, an Objective of 90 days was believed to be reasonably achievable. This DP was set to 'High'.

3.2.6 Accommodation

The Accommodation Objective was set to 88 personnel, in keeping with the CJR design's crew size. If CLF capability were retained, this accommodation would have to grow to support the crew dedicated to the CLF mission. After discussing with sponsors, a smaller crew size was set as an objective to lessen TOC.

No guidance was given for an Objective crew size, so the following rationale was used: With the minimal manning to run a ship of T-AKE's size being approximately 30 personnel, 30 additional personnel was deemed an aggressive Objective for operating the equipment related to its BMD mission, resulting in a total crew size of 60. The costs for this crew reduction could not be calculated with any confidence; instead, it was assumed that a smaller crew size would require greater automation, which would in turn require a higher up-front acquisition cost, but a lower TOC.

This DP was decided to be of secondary importance for BMD mission capability, but of high importance for TOC. Therefore, to limit the Full Factorial of the initial variant investigation, this DP was initially set to 'Low' with the intention of performing a second iteration full factorial with Accommodation as one of the variables.

3.2.7 Communications

To support the BMD mission, the T-AKE would require communications equipment similar to the CJR at a minimum. Additional communication equipment to link with warships and shore facilities would also be required. The T-AKE has a large deckhouse area that can support additional antennas and an under-utilized communications space. There was no data or opinions regarding a Communications Objective, so the Objective was set to the Threshold.

3.2.8 Surface/Air Self Defense

The T-AKE deploys with crew-served weapons for self-defense near shore and in-port. Space and structure has already been allocated to support the installation of a forward and aft CIWS. Other self-defense weapons were also evaluated, including larger caliber automatic weapons and RAM launchers.

Because the T-AKE already has the design weight and spaces for CIWS, installing the Block 1B variant, which includes an anti-surface capability, would provide excellent benefit at minimal up-front cost. Rolling Airframe Missile (RAM) systems, on the other hand, are not normally carried on USNS ships and would require structural and combat system modifications as well as additional maintenance costs. The team also qualitatively believed there would be a HERO (Hazardous Exposure to Radiation, Ordinance) concern between the powerful radars and the missile warheads and/or fuel. Therefore, this variable was set to 'Mid' to reflect the addition of CIWS to the standard crew-served weapons onboard T-AKE.

3.2.9 ASW Self Defense

Anti-Submarine Warfare (ASW) self-defense was not initially considered as a Design Parameter. However, there was interest in evaluating the cost versus benefit of adding a single SH-60R ASW helicopter for an organic ASW capability. The Threshold was set to no ASW capability with an Objective of one SH-60R helicopter with associated Command and Control infrastructure added to the ship.

A quick qualitative assessment was performed and it was determined the benefit for providing an organic ASW capability to a ship that would primarily operate independently in blue water was not worth the cost for modifying the hanger and modifying the ship's combat systems. Therefore, this DP was set as 'Low'.

3.2.10 Survivability

T-AKE is built to ABS standards, with the ability to handle flooding in two adjacent compartments. This was retained as the Threshold. A naval combatant is designed to more stringent standards, dictated by OPNAV 9070.1, Survivability Policy for Surface Ships of the U.S. Navy. The Objective Survivability level was set to Level II, Moderate, to allow for sustained operations with a battle group in a general war-at-sea area and allow for continued mission capability following weapons impact. Reaching this level would require additional subdivisions, additional structural integrity and additional redundancy in vital systems. Early sponsor feedback, based on previous research, indicated that ANY upgrades to survivability would require such extensive modifications that a new ship would likely be more economical.

Due to the high cost and questionable benefit, this DP was set to 'Low'.

3.2.11 Seakeeping

To support seakeeping, some research was completed on active and passive anti-roll systems. Utilizing guidance from Naval Architecture literature and the NAVSEA Design Data Sheet for passive anti-roll tanks (DDS 565-1), the basic sizing of the tanks was estimated. The exact details and control systems for the anti-roll tanks were beyond the scope of this design project. Instead, the team was focused on designing a rough-order-of-magnitude system that could achieve the Seakeeping Objective of minimizing roll to within the capability of the radars to continue operating up to seastate 6. The team decided to use a passive anti-roll system, essentially a tank across the beam of the ship at approximately mid-ship, that would greatly diminish roll near the ship's natural roll frequency. An active anti-roll system was ruled out due to time constraints, questionable benefit versus cost, and concerns over the effects of power spikes from the system on the radars.

Seakeeping was believed to be important not only for accomplishing the BMD mission during rough seas, but also for added crew comfort and reducing the stresses on the ship from excess motions. Seakeeping was set to 'Low' for the first full factorial exploration, and was later investigated in the second round of variant exploration.

3.2.12 Draft

It was recognized early that the T-BMD would have a similar Lightship weight as a T-AKE (removal of excess CLF mission equipment would be offset by the addition of radar equipment). However, the fully-loaded ship would most likely be much lighter. Even if 50% of CLF capability was retained, which means the ability to hold 50% of a T-AKE's stores, the fully-loaded T-BMD-variant would still be lighter than a fully-loaded T-AKE. Therefore, a Threshold draft of within 2' of the T-AKE was set, with an Objective of the same draft as a T-AKE. The sponsors believed having a shallower draft would not be an issue for stability, seakeeping, or range. This was verified during the analysis phase of this project.

While Draft was more valuable for Suitability and CLF Mission Capability, sponsor feedback highlighted that a shallower draft would not be detrimental and may even provide better range. Therefore, this DP was set as 'Low'.

3.2.13 VERTREP Capability

The T-AKE's large hangar and flight deck were intended to be untouched, so the ability to vertically replenish other ships could be retained. However, VERTREP capability also included the handling equipment belowdecks. The Threshold was set at zero, with an Objective of 50% meaning the ability to move 50% of the T-AKE's stores by helicopter.

3.2.14 CONREP Capability

CONREP Capability was easier to visualize during the design process. It was decided to look at retaining 50% CONREP capability, including at least one Replenishment At Sea (RAS) and Fueling at Sea (FAS) station. Retaining any more stations would most likely interfere with radar coverage, so only the aft stations would likely be retained.

Each DP was mapped to the appropriate CR using Quality Function Deployment (QFD) analysis. Each team member did this independently, using personal experience and qualitative judgment. The results were combined, discussed, and averaged where appropriate to arrive at the results seen in **Figure 6**. The weighting factors calculated in the QFD were used to calculate an Overall Measure of Effectiveness (OMOE) that is described in Section 3.4.

Functions (Hows)
Design Characteristics (Hows)

Customer Requirement (Whats)	*Weights*		Radar Coverage	S-BAND	X-BAND	Range	Endurance	Accomodation	Communications	Surface/Air Self Defense	ASW Self Defense	Survivability	Seakeeping	Draft	VERTREP Capability	CONREP Capability	
			Units	Units	Units	Units	Units	Units	Units	Units	Units	Units	Units	Units	Units	Units	
Mission Capability (BMD)	0.467	0.467	9	9	9				9		3		3				
Affordability	0.233	0.233	9	9	9				3	3	3	9			3	3	
Service Life	0.067	0.067	3	9	9			3	3			3		3	6	6	
Suitability	0.156	0.156		9				9	3	3	3		9			3	
Mission Capability (CLF)	0.078	0.078				5	5	3					9	9	9	9	
		0.000															
		0.000															
Check Sum		1.00															
Weighted Performance			6.5	8.3	6.9	0.4	0.4	1.8	5.6	1.2	2.6	2.3	3.5	0.9	1.8	2.3	44.4
Percent Performance			0.146	0.187	0.155	0.009	0.009	0.041	0.125	0.026	0.058	0.052	0.079	0.020	0.041	0.051	

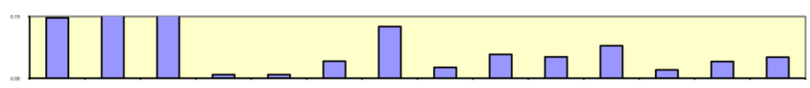


Figure 5, Quality Function Deployment Analysis Results

3.3 Technologies and System-Level Evaluation and Selection

A review of the current and near-term technology was conducted while researching background material for this Project. Subject Matter Experts (SMEs) from PEO IWS 2.0 (Program Executive Office, Information Warfare Systems) and Raytheon provided information on S-band and X-band radars that would be appropriate to install on the T-AKE. The Ship Design Manager for the T-AKE program at NAVSEA provided invaluable background information on the ship and feedback to the team's DP's. Due to the Unclassified nature of the project and its products, only notional data was used for radar power requirements and dimensions.

PEO IWS, Raytheon, and the CJR Program Office provided the S-band and X-band radar information.

Two variants of the X-band were looked at. One was the model scheduled to be installed on the CJR. The other was a Full Field of View (FFOV) variant, whose data was provided by Raytheon. The FFOV variant has slightly larger dimensions and similar power requirements to the model to be installed on the CJR but would provide the T-BMD greater tracking coverage and thus provide the Navy with more employment flexibility. The CJR X-band and FFOV X-band were selected as the Threshold and Objective X-band variants, respectively.

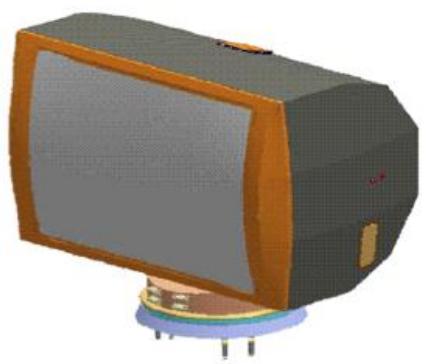


Figure 6, Notional X-band Radar (CJR-equiv & FFOV similar)

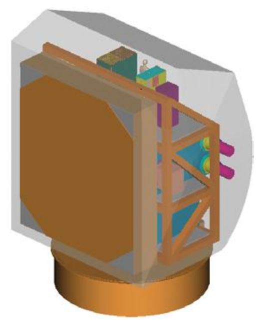


Figure 7, Notional S-band radar (CJR-equiv and AMDR-S similar)

<u>X-Band Notional Weights</u>

Equipment	**Maximum Weight**
Weather Enclosure & Contents	121,926 kg
Pedestal Assembly	142,247 kg
Total Above Deck Weight	**264,173 kg**

<u>X-Band Notional Dimensions</u>

Height	10 m
Width	14 m
Depth	10 m

<u>S-Band Notional Weights</u>

Equipment	**Maximum Weight**

Weather Enclosure & Contents	121,926 kg
Pedestal Assembly	149,359 kg
Total Above Deck Weight	**271,285 kg**

S-band Notional Dimensions	
Height	10 m
Width	10 m
Depth	10 m

For simplicity, the AMDR-S (Advanced Missile Defense Radar, S-band) was selected as the S-band variant. It is scheduled to be installed on the DDG-1000. Its dimensions, capabilities, and power requirements are similar to the S-band that is scheduled to be installed on the CJR.

All other systems and modifications planned for the T-BMD were to be Commercial Off-the-Shelf (COTS) or currently installed on US Naval combatants (e.g., CIWS).

3.4 Concept Variants Description, Evaluation, and Selection

With fourteen DPs to choose from, a Full-Factorial design of experiments (DOE) would require 2^{14} variants to evaluate: 16,384. The number of DP's was limited to four in order to conduct a more appropriate Full-Factorial DOE on sixteen variants.

Because BMD Mission Capability was the non-cost-related CR with the highest weight, focus was placed on the most important DPs that supported BMD Mission Capability, with Radar Coverage, S-Band capability and X-band capability as the most important of these DPs. The fourth variable was summarized as CLF Capability, which combined the DPs of VERTREP Capability and CONREP Capability. Taken together, their summed impact on CR's was fifth behind the above three and Communications. As previously discussed, Communications was already determined to have the same Threshold and Objective values (based on lack of data for a higher Objective) so it was not varied.

The other DPs were set High or Low as discussed under Section 3.2.

3.4.1 Summary of Design Parameters for Full Factorial DOE

Table 11 summarizes which DPs would be varied for the first DOE.

Design Parameters	Impact on CRs	Select for Study	L	H
Radar Coverage	0.146	X	240	360
S-BAND	0.187	X	X	X&S
X-BAND	0.155	X	CJR-equiv	FFOV
Range	0.009		12000	16000
Endurance	0.009		70	90
Accomodation	0.041		88	100
Communications	0.125		TBMD	TBMD
Surface/Air Self Defense	0.026		None	CIWS
VERTREP Capabilty	0.041	X	None	50% T-AKE
Survivability	0.052		ABS std	OPNAV 9070.1 Lvl II
Seakeeping	0.079		T-AKE	Conduct TBMD msn in SS 6
Draft	0.020		T-AKE+2'	T-AKE
ASW Self Defense	0.058		T-AKE	1 SH-60R
CONREP Capability	0.051	X	None	50% T-AKE
Check	1.000			

Table 11, Summary of Design Parameters Selected for Study

Table 12 shows the Full-Factorial results that were used in the OMOE calculations.

	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15	V16
Radar Coverage	L	L	L	L	L	L	L	L	H	H	H	H	H	H	H	H
S-BAND	L	H	L	H	L	H	L	H	L	H	L	H	L	H	L	H
X-BAND	L	L	H	H	L	L	H	H	L	L	H	H	L	L	H	H
Range	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
Endurance	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H
Accomodation	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Communications	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Surface/Air Self Defense	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
VERTREP Capabilty	L	L	L	L	H	H	H	H	L	L	L	L	H	H	H	H
Survivability	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Seakeeping	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
Draft	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
ASW Self Defense	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L
CONREP Capability	L	L	L	L	H	H	H	H	L	L	L	L	H	H	H	H

Table 12, Full Factorial First-Round Variant Selection

For DPs marked as 'High', a value of '1' was assigned. DP's marked as 'Low' were assigned a value of '0'. The DP marked as 'Mid' was assigned a value of '0.5'. In an OMOE calculator, each DP was multiplied by its weighting factor. These products were summed to arrive at an OMOE score. Because some DPs were already set to '0' for all variants, the absolute number wasn't as important as the difference between numbers.

3.4.2 Estimating Costs

Cost estimates were of very rough order of magnitude and were normalized on a scale of 1 to 10. Some rough estimates for the cost of a standard T-AKE, different radar systems, and retention of 50% and 0% CLF capability were used to come up with total costs for each variant. Normalized values were used because these values were often very rough estimates or educated guesses. It was more important for the team to qualitatively assess which variant would be more expensive than to develop more accurate and more precise cost estimates.

After the initial OMOE vs Cost results were calculated, some cost sensitivity was performed. The costs of variables in **Table 13** were varied by 20% and the results were compared to the initial results. The team found that within a 20% cost variation, the OMOE vs. Cost results were generally consistent.

Variant	Coverage	S-band Type	X-band	CLF capability	Est Cost ($M)	**NORMALIZED**
16	1	1	1	1	1204	**10.00**
15	1	0	1	1	854	**5.18**
14	1	1	0	1	1154	**9.31**
13	1	0	0	1	804	**4.50**
12	1	1	1	0	1100	**8.57**
11	1	0	1	0	750	**3.75**
10	1	1	0	0	1050	**7.88**
9	1	0	0	0	700	**3.06**
8	0	1	1	1	1054	**7.94**
7	0	0	1	1	704	**3.12**
6	0	1	0	1	1004	**7.25**
5	0	0	0	1	654	**2.43**
4	0	1	1	0	950	**6.50**
3	0	0	1	0	600	**1.69**
2	0	1	0	0	900	**5.82**
1	0	0	0	0	550	**1.00**

Table 13, First Round Full Factorial Normalized Cost Summary

3.4.3 OMOE vs. Cost Results, 1st Round

The intent of plotting OMOE vs Cost is to evaluate the 'knee in the curve', where one obtains the best variant at the minimal cost. As the results are plotted in **Figure 8**, the knee is towards the upper-left. Variant 4 was found to provide the greatest capability at best price. Other variants, namely Variant 3 and 12, were also competitive and would be worthy of further study. Due to time constraints for the project, only Variant 4 was explored further.

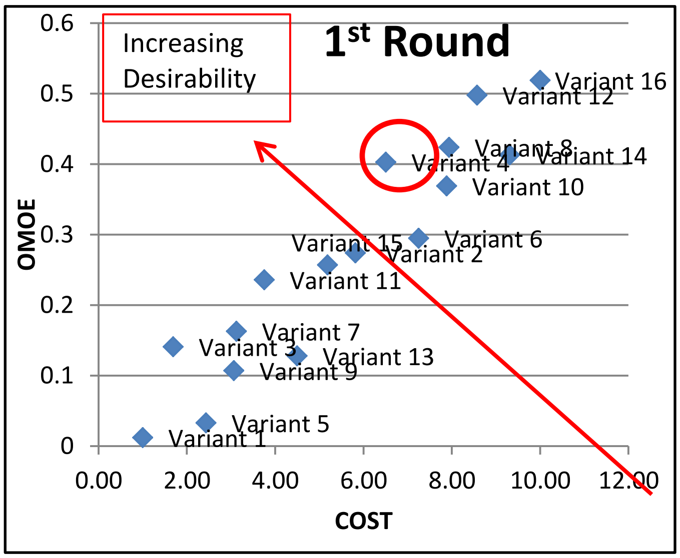


Figure 8, First Round Full Factorial Results

Variant 4 was the used for the next round of experiments, where Accommodations and Seakeeping were varied.

3.4.4 OMOE vs Costs, 2nd Round

The team decided, based on feedback from sponsors, that varying seakeeping would provide additional mission capability, while reducing crew size would greatly benefit TOC. A second round of analysis was performed on Variant 4, conducting a Full Factorial DOE with Accommodations and Seakeeping varied.

	V4-1	V4-2	V4-3	V4-4
Radar Coverage	L	L	L	L
S-BAND	H	H	H	H
X-BAND	H	H	H	H
Range	H	H	H	H
Endurance	H	H	H	H
Accomodation	L	L	H	H
Communications	L	L	L	L
Surface/Air Self Defense	M	M	M	M
VERTREP Capabilty	L	L	L	L
Survivability	L	L	L	L
Seakeeping	L	H	L	H
Draft	L	L	L	L
ASW Self Defense	L	L	L	L
CONREP Capability	L	L	L	L

Table 14, Second Round Full Factorial Summary

Costs were estimated on a very rough order of magnitude and again normalized between 1 and 10. Because no TOC models were available for this type of ship, the team could only evaluate up-front costs for modifying Accommodations.

Variant	Crew Size	Seakeeping	Cost	Normalized
4-1	0	0	0	**1.00**
4-2	0	1	20	**2.57**
4-3	1	0	50	**6.43**
4-4	1	1	70	**10.00**

Table 15, Second Round Full Factorial Cost Summary

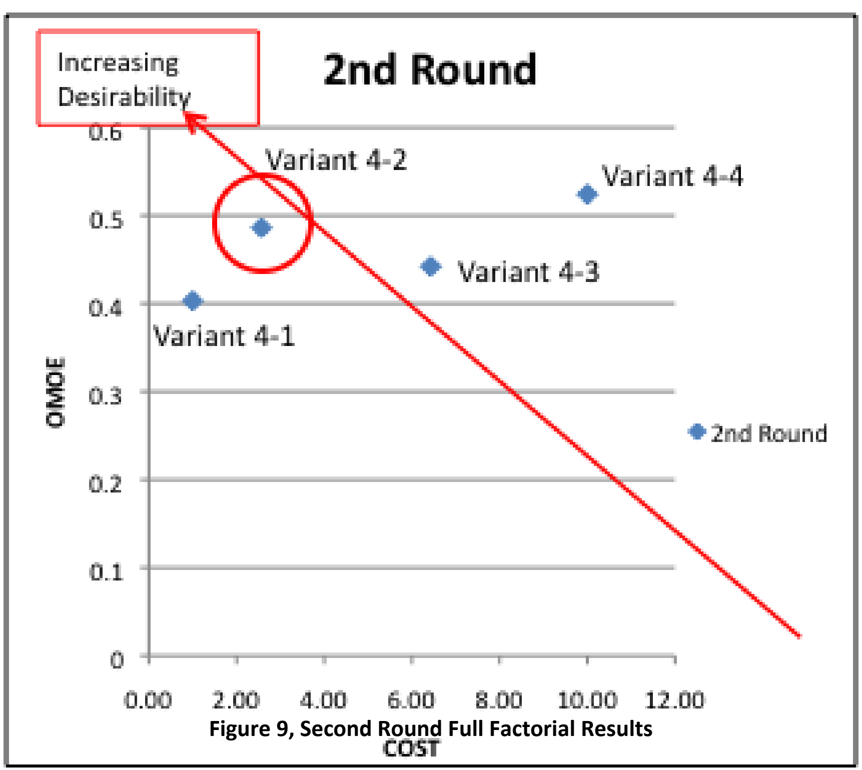


Figure 9, Second Round Full Factorial Results

The ‘knee in the curve’ in Figure 9 was closest to Variant 4-2. This Variant will be discussed in more detail in Section 3.5, Final Variant.

Reducing accommodations is acknowledged to have a significant effect on reducing TOC. However, due to the limited information available, the focus was placed on estimating initial, up-front costs for OMOE vs Cost comparisons. Additionally, from a rough order of magnitude design perspective, tackling a more stringent seakeeping requirement was deemed to be more technically challenging and would still provide good information to the sponsors if similar goals were desired.

In contrast, reducing accommodations would likely result in greater weight for automated equipment, but the details and integration of such equipment would be beyond the scope of this project.

3.5 Final Variant

The final variant that resulted from the above analysis is summarized below:

DP	Variant 4-2
Radar Coverage	Minimum 240 deg coverage for each radar
S-Band Radar	CJR-capability or AMDRS installed
X-Band Upgrade	Higher capability (FFOV) installed
Range	16000NM, achievable while still meeting MARPOL 12 regulations on double-hulled protection of ship's fuel
Endurance	90 days
Accommodations	Standard Crew size of 88, combination of CIVMAR and MILDET
Exterior Communications	Commercial off the shelf, FORCEnet compliant, with military GPS capabilities. Compatible with TBMD
Surface/Air Self Defense	2 x CIWS (fwd/aft) + crew-served weapons
VERTREP Capability	None (hangar and flight deck remain)
Survivability	ABS levels (unchanged from T-AKE)
Seakeeping	Able to conduct mission up to SS 6 utilizing passive anti-roll tanks
Draft	Within 2' of current T-AKE
ASW Self Defense	None
CONREP Capability	None

Table 16, Final Variant Characteristic

Raytheon and PEO IWS sponsors provided the statistics for the S-band and X-band radars. While some capabilities are common between the radars, the S-band radar is primarily for searching for ballistic missile threats and provides cueing information and the X-band is primarily for tracking the ballistic missiles. The pictures below are for illustrative purposes only. Actual radars installed would likely look different and have slightly different dimensions, but these dimensions were reasonably close to prove the ability of the ship to conduct its mission.

	X-band FFOV	AMDR-S/S-band
Height	10m (incl pedestal)	13m (incl pedestal)
Width	14m	10m
Depth	10m	8m (est)
Weight	275MT	170MT

Table 17, Notional T-BMD Radar Specifications

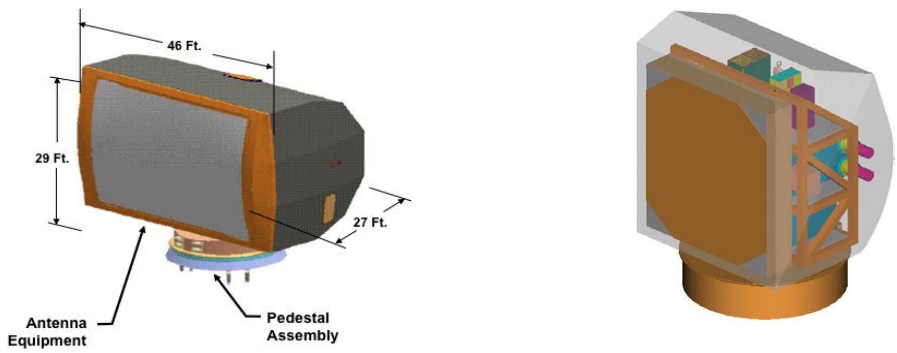


Figure 11, Notional X-band and S-band Radars, Courtesy Raytheon Corp and PEO Ships

Power requirements for the radars were taken from unclassified CJR data. The T-AKE's IPS can provide 33.6MW, with 12MW available to non-propulsion loads. The radars require a maximum of 6MW, including margin for equipment growth. The details of redesigning the IPS were not investigated, and the weight of cabling to the radar spaces was assumed to be offset by the removal of CLF mission-related electrical equipment. Space requirements for the operating equipment to support the radar systems were assumed to be similar to CJR but the T-AKE's larger size allowed for bigger spaces. The differences between CJR's required space size and what the T-AKE can provide is discussed further in Section 4.

The team developed cartoon drawings to place the radars on the deck and decide which equipment was reasonable to remove from the T-AKE. Some notes on radar placement

- By placing the X-band higher and aft of the S-band, greater coverage was achievable (~280 deg); only the deckhouse blocked the X-band aft.

- The S-band was blocked aft by the larger X-band radar and blocked forward by the forward weatherdeck.

- The weatherdeck was shortened to give the S-band 240 degree coverage. The team felt that any further shortening of the weatherdeck would increase the risk of green water onto the S-band turret pedestal and only provide a few more degrees of coverage before the CIWS equipment space became the limiting obstacle.

- The team decided to place the X-band higher to give the T-AKE more maneuvering flexibility while tracking. There was no requirement for either radar to be higher.

- The team qualitatively decided to give the S-band more limited coverage because it was primarily a search tool, the ship could conceivably conduct racetrack maneuvers while searching down a threat axis.

- Either radar's maximum height was limited by ABS Line-of-Sight requirements, which require unobstructed views forward of the pilothouse beyond two times the ship's waterline or 500m, whichever is less. (This requirement is shown below as a diagonal line starting at the pilothouse.)

- The dashed lines on the port-side show the FOV down to the horizon for each radar (the starboard side's FOV is identical to the port for each radar).

Section 4 will discuss further the stability and seakeeping ramifications of placing these large radars at their respective heights.

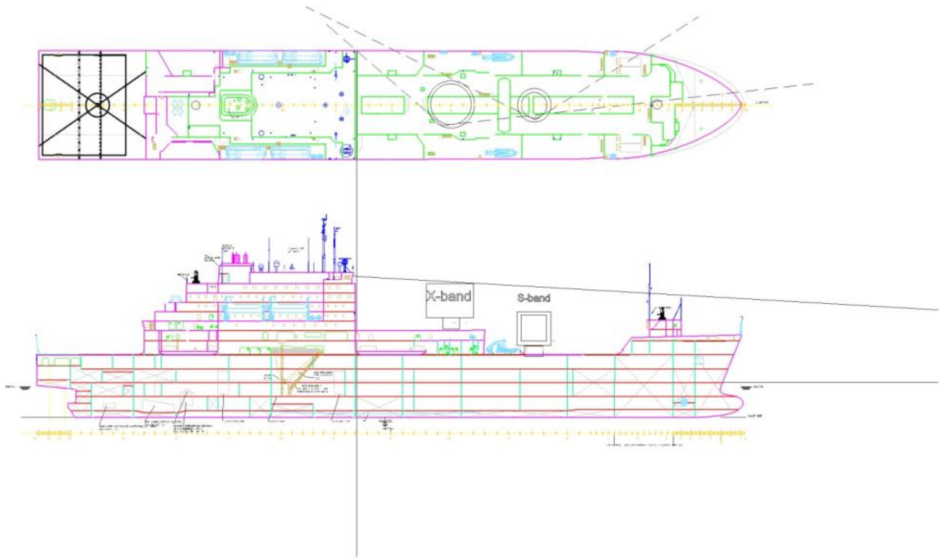


Figure 11, T-BMD Top- and Side-View

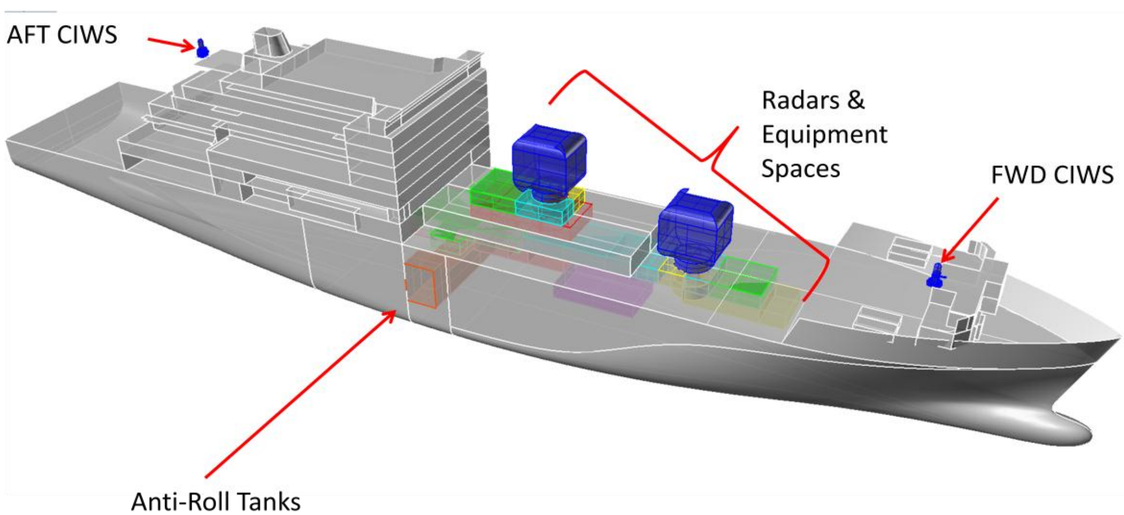


Figure 12, T-BMD Isometric View

4.0 Concept Definition and Feasibility/Performance Analyses

4.1 Design Definition

4.1.1 System-level Characterizations

The primary additions to the existing T-AKE hull are the S and X Band radars and their support systems. Additional equipment included two CIWS, forward and aft, for AAW and ASUW self-defense, and additional communications equipment atop the deckhouse.

4.1.2 Ship Geometry

The T-BMD class ship is based on the existing T-AKE hull form as shown in Figure 13. The T-AKE has a displacement hull form with a bulbous bow, and a long mid-body to maximize the amount of usable area and volume onboard. The superstructure is predominantly located on the aft portion of the hull. The hull is broken up into four decks and the superstructure consists of seven levels. A helicopter hangar and flight deck are located on the aft most portion of the hull on the main deck.

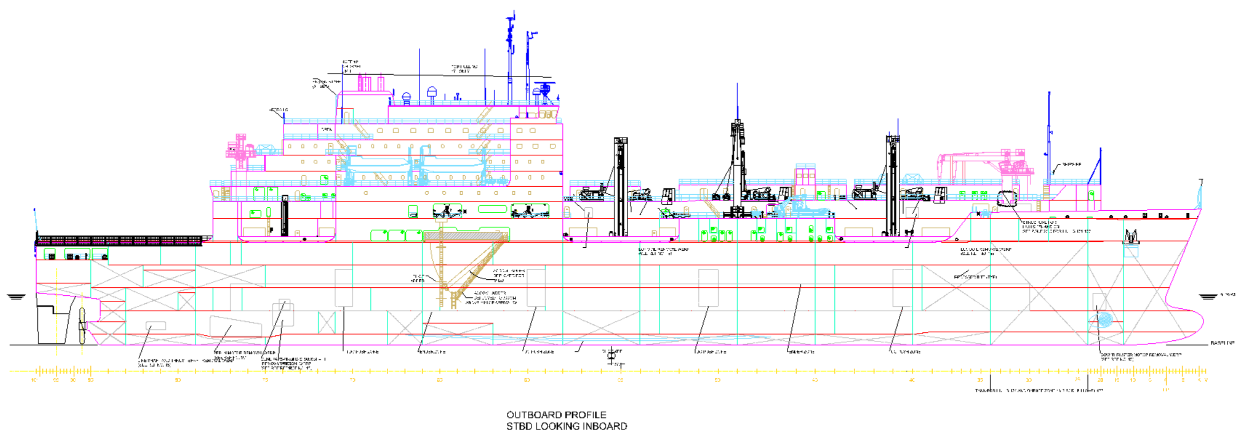


Figure 13: Baseline T-AKE

4.1.3 Arrangement Modifications

The majority of modifications made to the T-AKE were in the removal of CLF capability and installation of the two radars and their support systems. A comparison of the baseline hull and the hull with CLF systems and portions of the FWD O-1 and O-2 Levels removed is shown below in Figure 14.

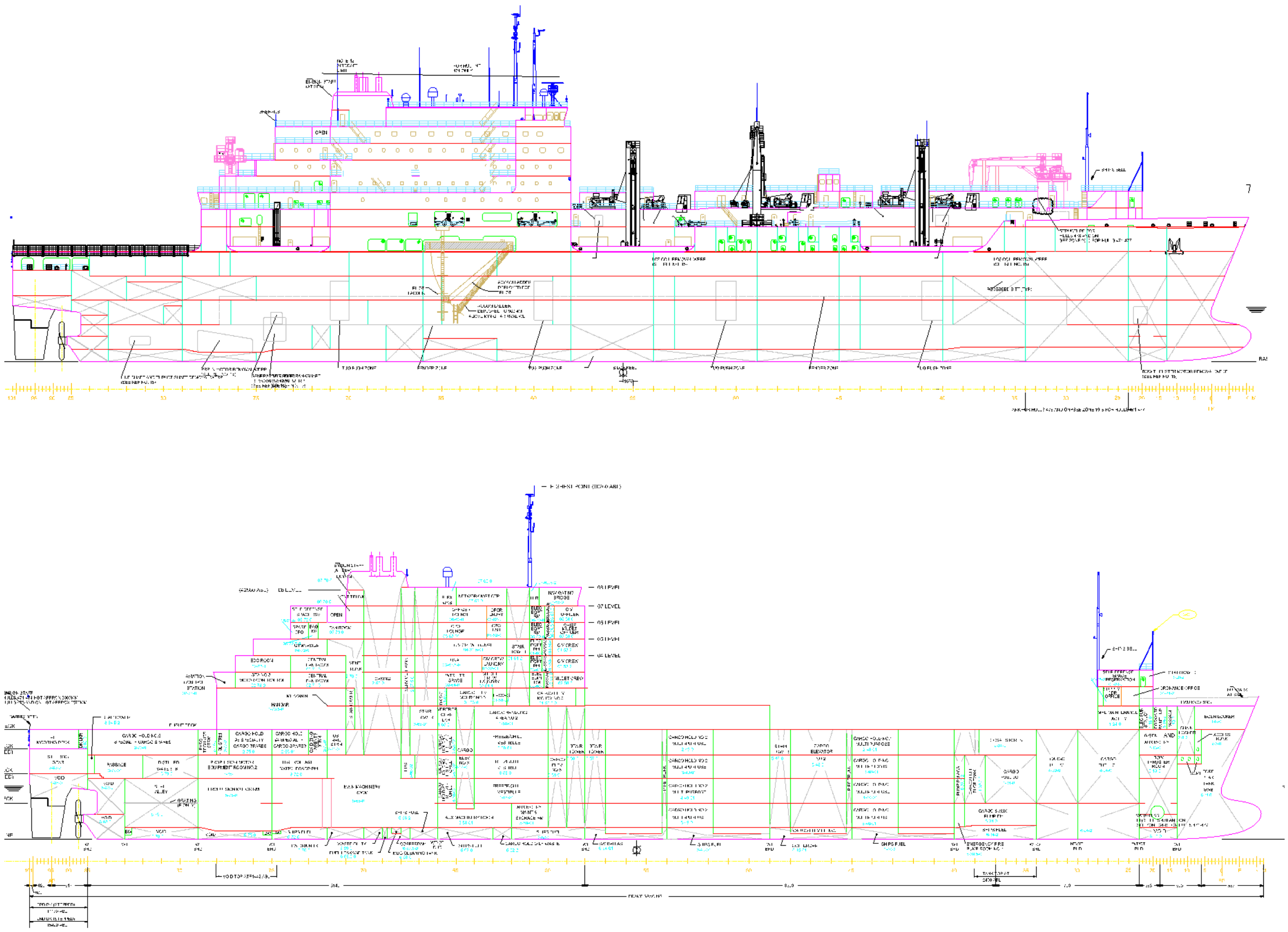


Figure 14: Baseline Hull Comparison

As mentioned in Section 3, the radar heights were staggered to maintain ABS LOS requirements and maximize X-band radar coverage. This necessitated the removal of 01/02 levels forward of frame 49 (~40m forward of the deckhouse). These levels were retained underneath the X-band radar to raise it above the S-band radar and the result is shown below in Figure 3. Removing these levels will also produce a small cost savings due to reduction in materials and construction time.

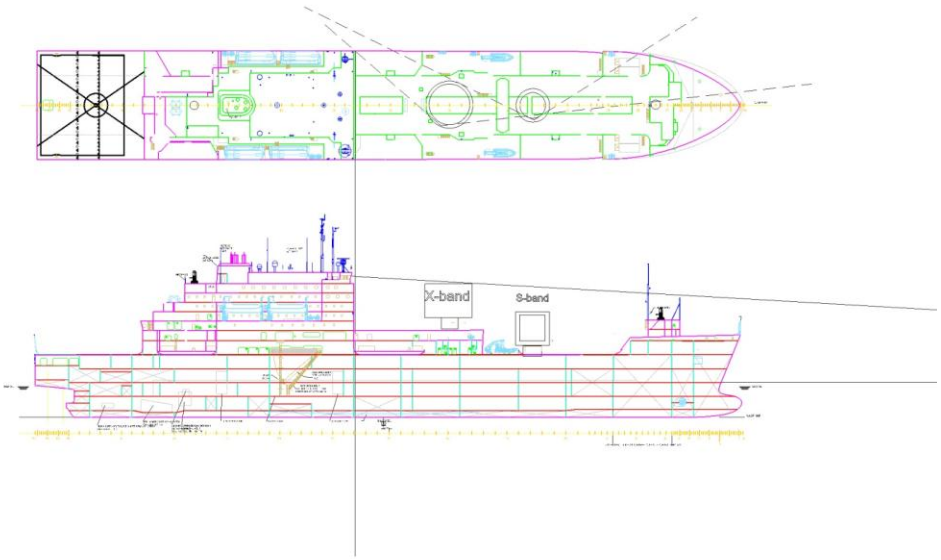


Figure 15: Radar LOS

The revised T-BMD with S and X band Radars, CIWS, and additional communications equipment is shown below in Figure 16.

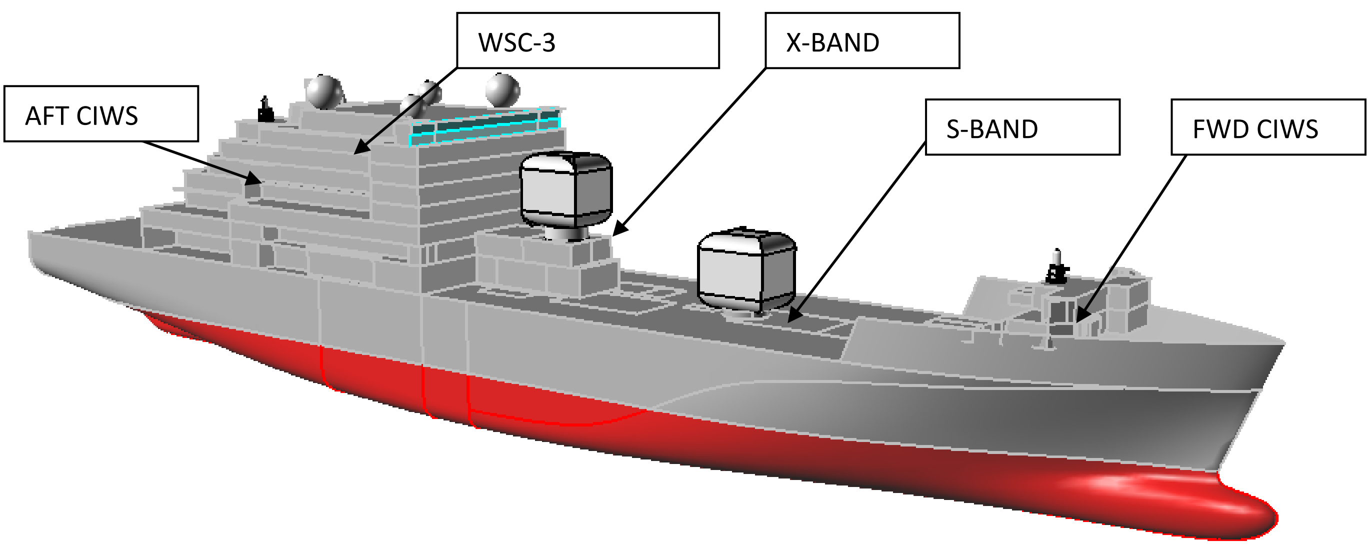


Figure 16, T-BMD Final Variant

On the deckhouse, communications equipment was added to increase connectivity with other BMD assets. At a minimum, additional WSC-3 and WSC-6 suites would be required for more robust, secure satellite communications. A more robust communications system than that on CJR would be required, but additional and more precise details on the communications equipment required was not available. However, the large deckhouse area (approximately 350 m^2 between the pilothouse and stack) should be sufficient to add additional equipment without major modifications to the underlying structure. Detailed drawings showing the changes to the communication suite are found in Appendix C.

Two CIWS mounts were added forward and aft in spaces already allocated for self-defense equipment on the T-AKE. Detailed drawings outlining these changes are found in Appendix C. A SQL-32 Electronic Warfare suite was also added in the aft section of the deckhouse to reduce interference with the BMD radars. No additional modifications were made for self-defense systems.

The required spaces to support both S and X band Radars are categorized as primary and secondary spaces. Primary spaces include the radars, control rooms and all support equipment and require modifications to existing bulkheads and passageways to meet the specified proximity requirements for essential radar equipment. The secondary spaces include workshops, destruction rooms, and weather balloon launch and support facilities. These spaces utilize existing spaces and require little or no modification. The primary spaces are shown below in Figure 17 as a functional block diagram. Each block is described by subsequent dimensioned spaces. Required areas of spaces were derived from the T-AGM(R) ship specifications. Detailed drawings of each affected deck are found in Appendix C. All added spaces are summarized below in Table 18.

Space #	Space Name	Required Area	Allocated Area	Location
B-1	X-Band Radar Front-End Equipment Service Room & Airlock	10	12.25	O-1
B-2	X-Band Radar Cable/Hose Wrap Room (Upper Level)	32	32	O-1
B-3	X-Band Radar Pedestal Control Room	76	81	O-1
C-1	X-Band Radar Parts Storeroom	38	38	Main Deck
C-2	X-Band Radar Cable/Hose Wrap Room (Lover Level_	32	32	Main Deck
C-3	X-Band Radar Power Room	38	69.5	Main Deck
C-4	X-Band Radar UPS Room	31	36	Main Deck
D-1	Mission Radar Cooling Equipment Room	130	135	2nd Deck
D-2	Mission Radar HAZMAT Stowage Room	35	42	2nd Deck
D-3	Mission Equipment Service Locker	15	24	2nd Deck
F-1	S-Band Radar Front-End Equipment Service Room & Airlock	76	81	2nd Deck
F-2	S-Band Radar Cable/Hose Wrap Room (Upper Level)	32	32	2nd Deck
F-3	S-Band Radar Pedestal Control Room	10	12.25	2nd Deck
G-1	S-Band Radar Cable/Hose Wrap Room (Lower Level)	32	32	3rd Deck
G-2	S-Band Radar Power Room	106	106	3rd

				Deck
G-3	S-Band Radar Parts Storeroom	37	40.5	3rd Deck
H-1	Electronic Test Room	62	63	4th Deck
H-2	Test Equipment and Tool Crib	36	36	4th Deck
H-3	Precision Measurement Equipment Laboratory (PMEL)	55	63	4th Deck
J-1	Data Packaging & Storage Room	73	73	4th Deck
J-2	Sponsor Staff Office & Data Terminal Room	26	26	4th Deck
K-1	Post Processing Equipment Room	28	36	3rd Deck
K-2	Radar Common Back-End Equipment Room	46	52.2	3rd Deck
K-3	Operations Control Center	98	99	3rd Deck
L-1	Destruction Room No. 2	AN	30	2nd Deck
L-2	Transmitter Room	51	54	2nd Deck
L-3	Communication Control Center	77	78	2nd Deck
L-4	Communication Stowage Room	22	22	2nd Deck
L-5	Crypto Vault	8	8	2nd Deck
L-6	Mission Communication Center	29	30	2nd Deck
L-7	Message Processing Center	41	50	2nd Deck
L-8	Destruction Room No. 1	AN	30	2nd Deck
MISC	Mission Communication Power Room	AN	30	2nd Deck
MISC	Working Deck Area	136	Flight Deck	O-1
MISC	Balloon Preparation and Launch Room	47	Hangar	O-1
MISC	Helium Tank Storeroom	AN	AN	O-1
MISC	Spheres and Balloon Ready Stowage	18	18	O-1
MISC	Balloon and Sphere Storeroom	21	21	O-1
MISC	Weather Station	19	19	O-1
MISC	Conference Room No. 1	AN	AN	O-2
MISC	Conference Room No. 2	AN	AN	O-2

MISC	Technical Library	24	24	O-1
MISC	Sponsor Training Room	45	45	O-1
MISC	Computer Maintenance Office	45	45	O-1
MISC	Mission Filter Cleaning Room	13	13	O-1
MISC	Sponsor Machine Shop	49	50	2nd Deck
MISC	Mission Supply Office	20	20	2nd Deck
MISC	Mission Breakout Area	35	40	2nd Deck
MISC	Mission Storerooms	170	200	Various
	Total Area (m^2)	2014	2068.45	

Table 18, T-BMD Added Space Summary

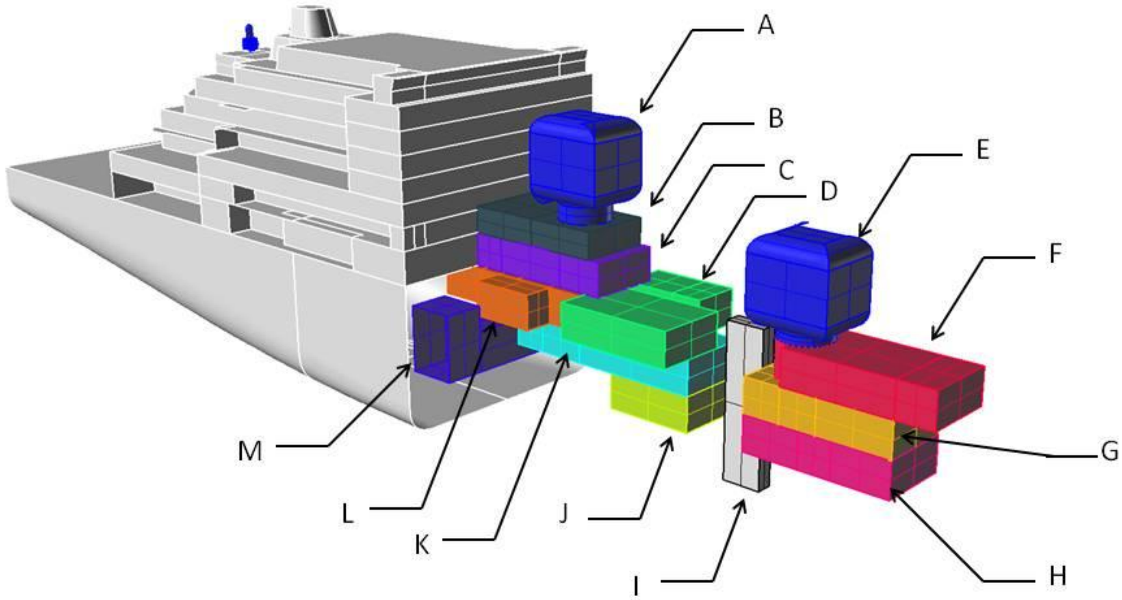


Figure 17, T-BMD Functional Block Diagram

Block A: X-Band Radar

The X-Band Radar is positioned immediately forward of the pilothouse with the base of the pedestal assembly on the O-1 Level. The X-Band Radar utilized by the T-BMD is shown below in Figure 6.

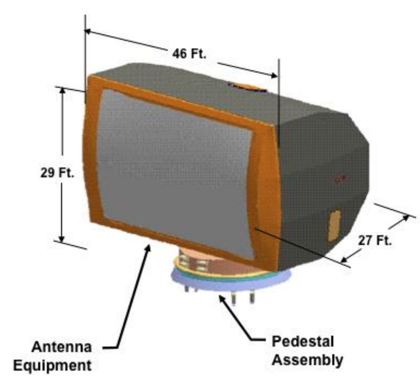


Figure 18, Notional X-band FFOV Radar, Courtesy Raytheon

Block B: X-Band Radar Front-End Equipment Spaces, Upper Deck (O-1 Level)

The X-Band Radar Front-End Equipment Spaces are located directly below the X-Band Radar to minimize cable and waveguide lengths. A detailed breakdown is shown below in **Figure 19** and

Table 19.

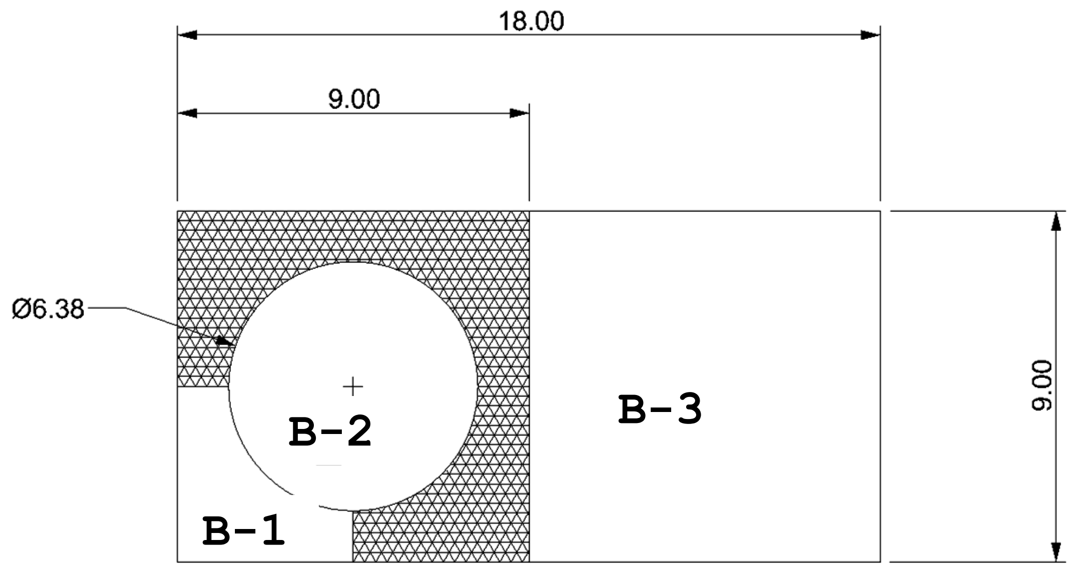


Figure 19, X-Band Front-End Equipment Space, Upper Deck

Space #	Description	Area Required (m^2)	Area Allocated (m^2)
B-1	X-Band Radar Front-End Equipment Service Room & Airlock	10	12.25
B-2	X-Band Radar Cable Hose Wrap Room	32	32
B-3	X-Band Radar Pedestal Control Room	76	81

Table 19, X-Band Front-End Equipment Space Allocation, Upper Deck

Block C: X-Band Radar Front-End Equipment Spaces, Lower Deck (Main Deck)

The X-Band Radar Front-End Equipment Spaces, Lower Deck is positioned directly below the Upper Deck. A detailed breakdown is shown below in Figure 20 and Table 20.

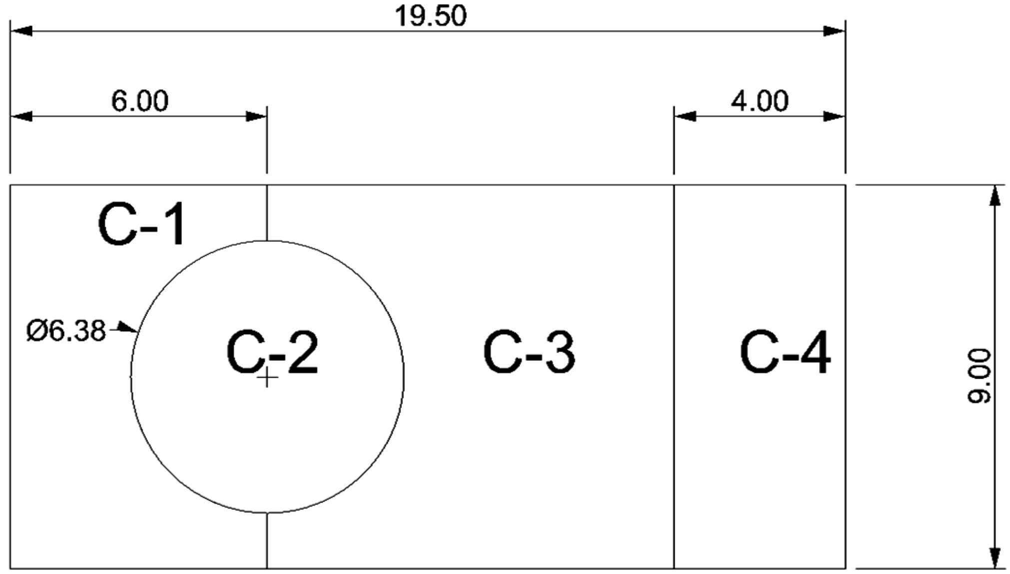


Figure 20, X-Band Radar Front-End Equipment Space, Lower Deck

Space #	Description	Area Required (m^2)	Area Allocated (m^2)
C-1	X-Band Radar Parts Storeroom	38	38
C-2	X-Band Radar Cable Hose Wrap Room	32	32
C-3	X-Band Radar Power Room	38	69.5
C-4	X-Band Radar UPS Room	31	36

Table 20, X-Band Radar Front-End Equipment Space Allocation, Lower Deck

Block D: Other Mission Radar Equipment Spaces (2nd Deck)

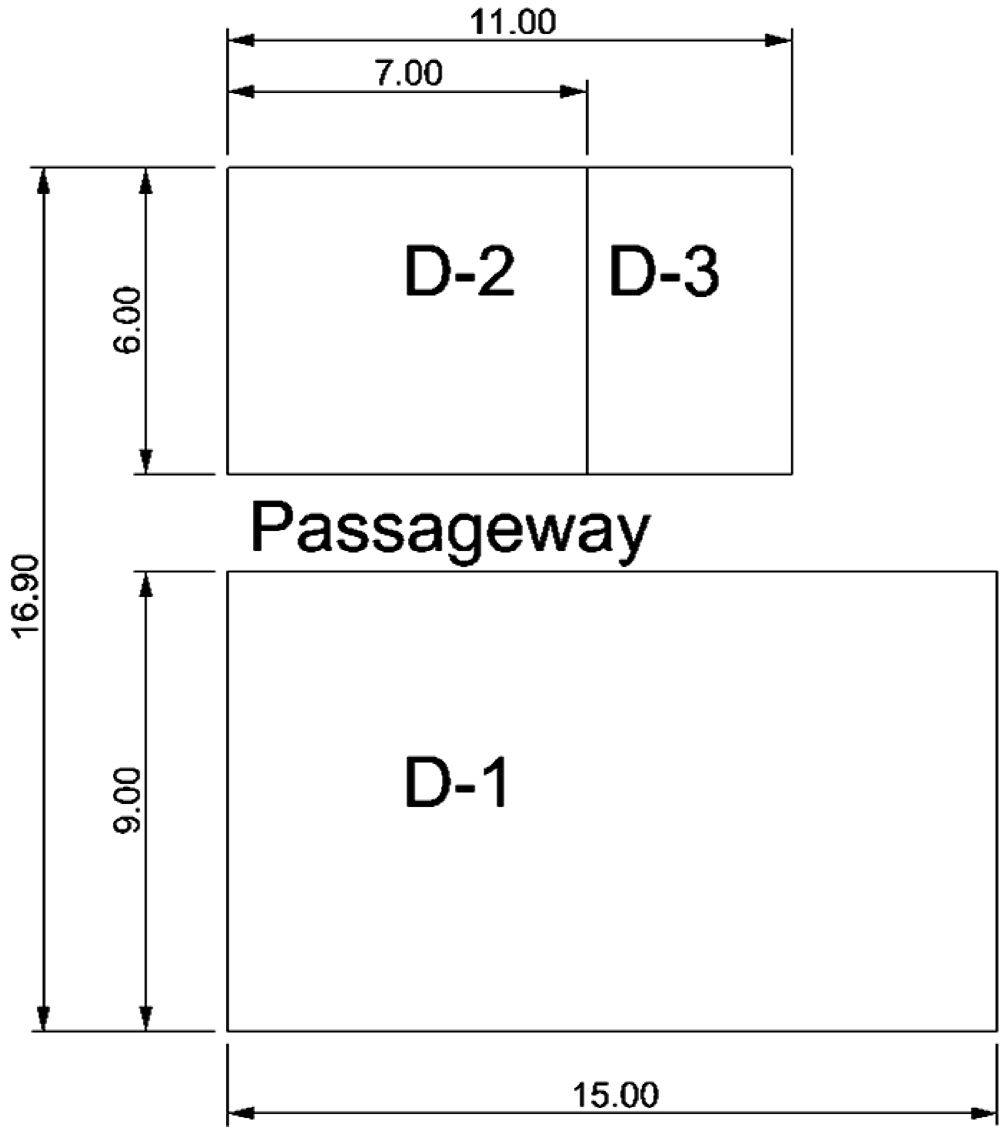


Figure 21, Other Radar Equipment Spaces, 2nd Deck

Space #	Description	Area Required (m^2)	Area Allocated (m^2)
D-1	Mission Radar Cooling Equip Room	130	135
D-2	Mission Radar HAZMAT Storage Room	35	42
D-2	Mission Equipment Service Locker	15	24

Table 21, Other Radar Equipment Space Allocation, 2nd Deck

Block E: S-Band Radar

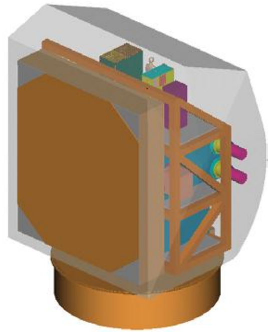


Figure 22, Notional S-band Radar, Courtesy PEO Ships

Block F: S-Band Radar Front-End Equipment Spaces, Upper Deck (2^{nd} Deck)

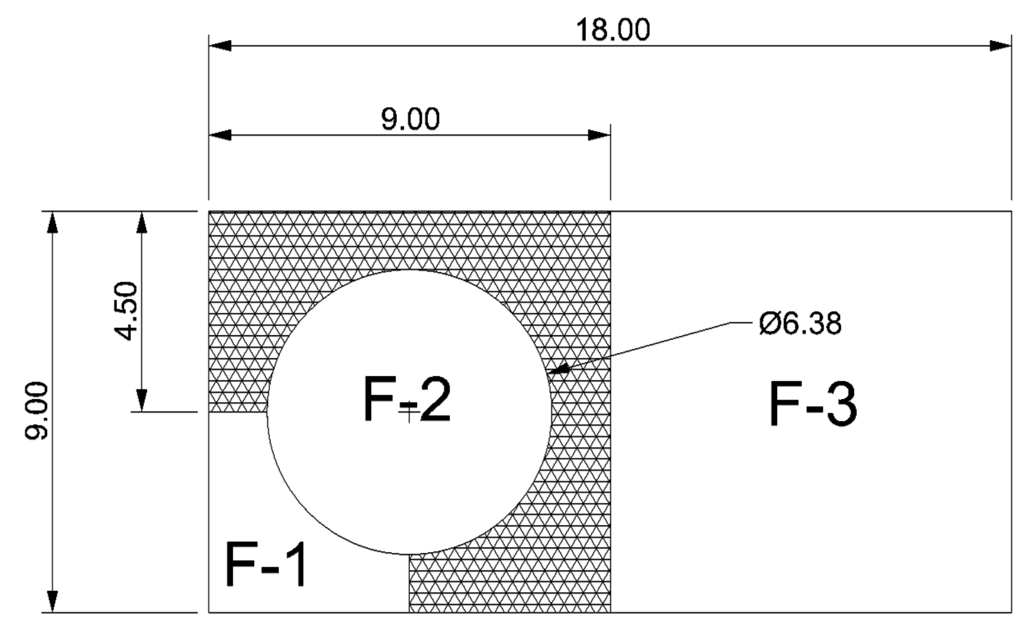


Figure 23, S-Band Radar Front-End Equipment Spaces, Upper Deck

Space #	Description	Area Required (m^2)	Area Allocated (m^2)
F-1	S-Band Radar Front End Equipment Service Room and Airlock	10	12.25
F-2	S-Band Radar Cable Hose Wrap Room	32	32
F-3	S-Band Radar Pedestal Control Room	78	81

Table 22, S-Band Radar Front-End Equipment Space Allocation, Upper Deck

Block G: S-Band Radar Front-End Equipment Spaces, Lower Deck (3rd Deck)

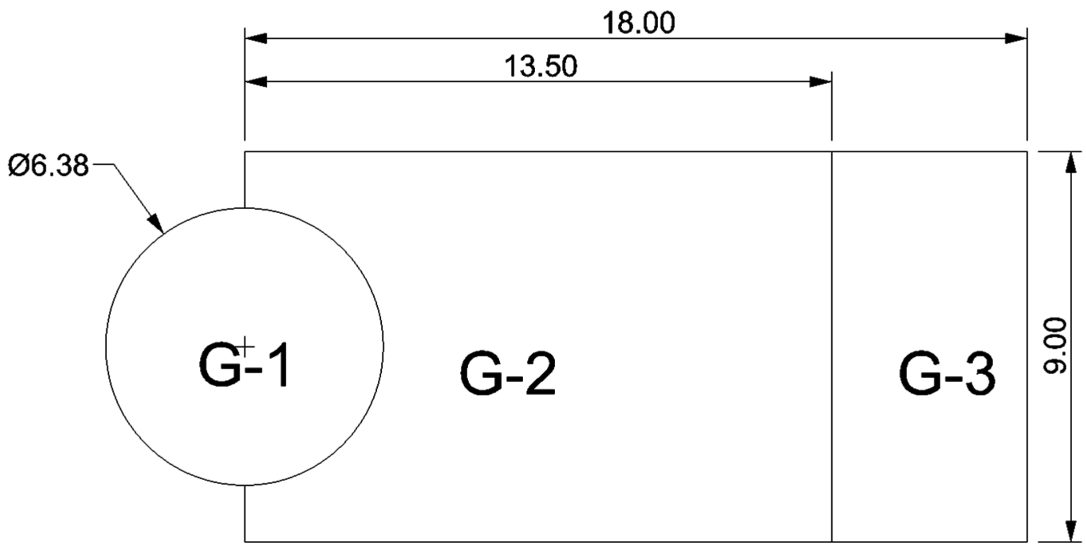


Figure 24, S-Band Radar Front-End Equipment Spaces, Lower Deck

Space #	Description	Area Required (m^2)	Area Allocated (m^2)
G-1	S-Band Radar Cable Hose Wrap Room	32	32
G-2	S-Band Radar Power Room	106	106
G-3	S-Band Radar Parts Storeroom	37	40.5

Table 23, S-Band Radar Front-End Equipment Space Allocation, Lower Deck

Block H: Mission Radar Common Back-End Equipment Spaces (4th Deck)

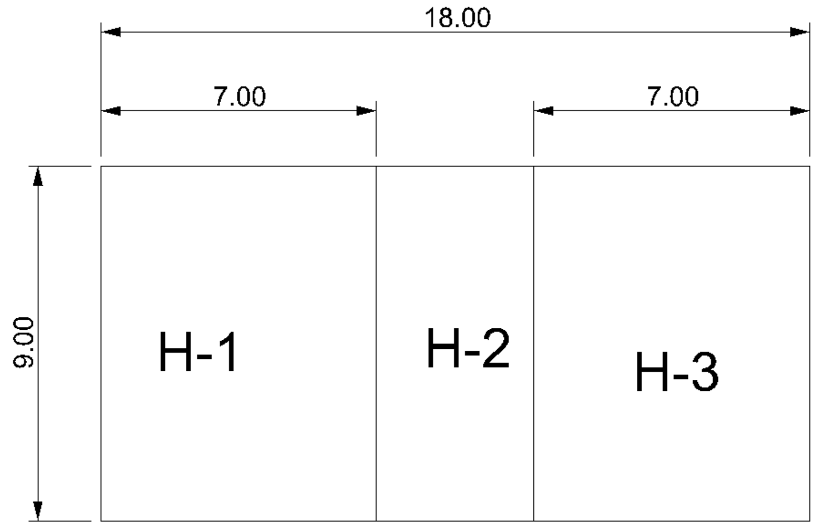


Figure 25, Mission Radar Common Back-End Equipment Space

Space #	Description	Area Required (m^2)	Area Allocated (m^2)
H-1	Electronic Test Room	62	63
H-2	Test Equipment Tool Laboratory	36	36
H-2	Precision Measurement Equipment Laboratory	55	63

Table 24, Mission Radar Common Back-End Equipment Space Allocation

Block I: Radar Cargo Elevator

The Radar Cargo Elevator utilizes the existing Elevator # 2 found in the T-AKE baseline and requires little modification to meet the requirements for the S and X Band Radars. The elevator shaft will be shortened to account for the removal of the O-1 and O-2 levels.

Block J: Mission Radar Common Back End Equipment Spaces, Lower Deck (4th Deck)

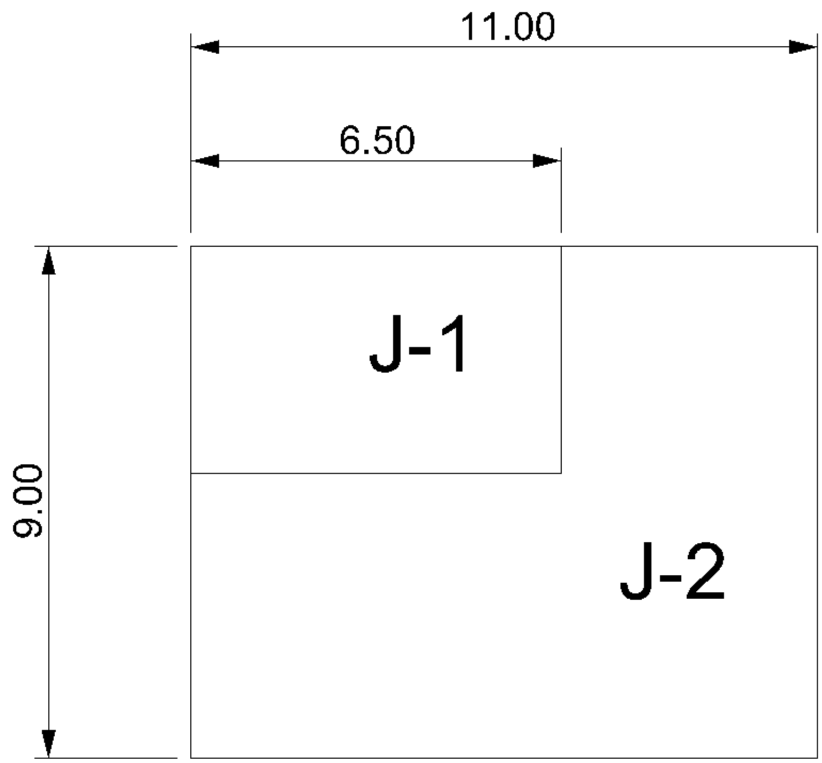


Figure 26, Mission Radar Common Back-End Equipment Spaces, Lower Deck

Space #	Description	Area Required (m^2)	Area Allocated (m^2)
J-1	Data Packaging and Storage Room	26	26
J-2	Sponsor Staff Office and Data Terminal Room	73	73

Table 25, Mission Radar Common Back-End Equipment Space Allocation, Lower Deck

Block K: Mission Radar Common Back End Equipment Spaces (3rd Deck)

The Mission Radar Common Back End Equipment Spaces include Precision Measurement Laboratories and various test rooms and is positioned centerline amidships to minimize the effects of pitch and roll. Details of Mission Radar Common Back End Equipment Spaces are shown below in Figure 27.

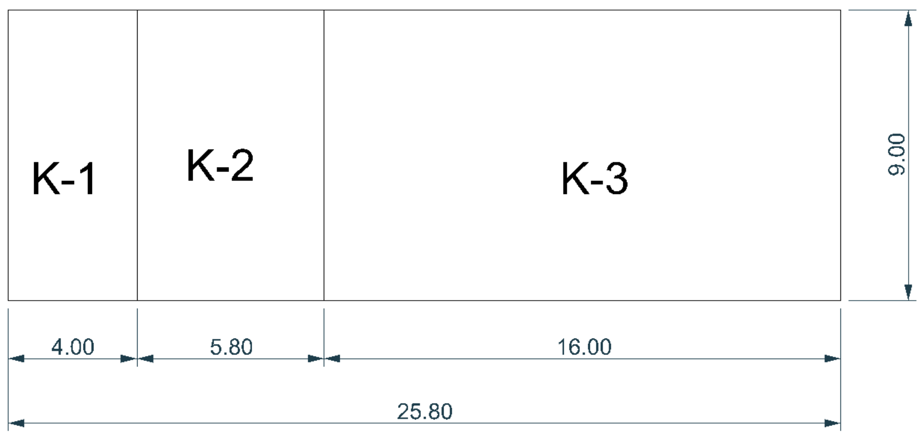


Figure 27, Mission Radar Common Back-End Equipment Space, 3rd Deck

Space #	Description	Area Required (m^2)	Area Allocated (m^2)
K-1	Post Processing Equipment Area	28	36
K-2	Radar Common Back-End Equip Room	46	52
K-3	Operations Control Room	98	99

Table 26, Mission Radar Common Back-End Equipment Space Allocation, 3rd Deck

Block K: Mission Control Spaces (2nd Deck)

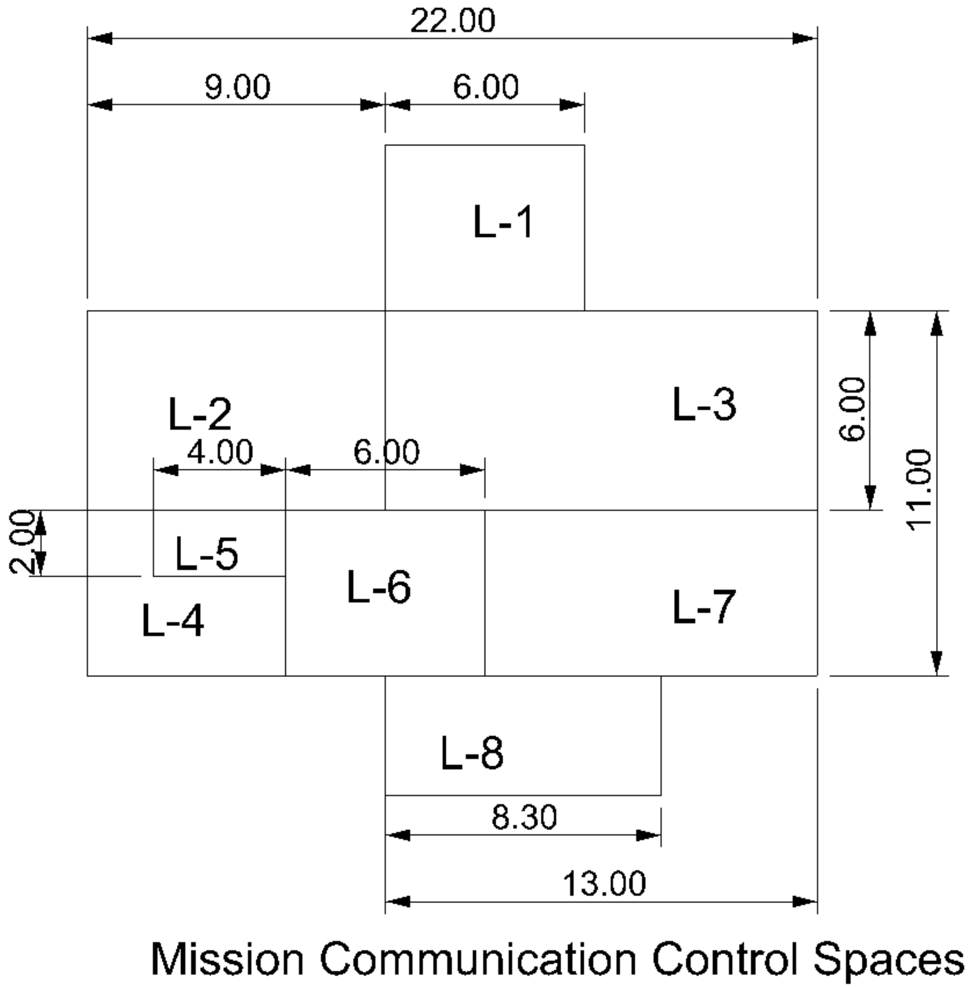


Figure 28, Mission Control Spaces, 2nd Deck

Space #	Description	Area Required	Area Allocated
L-1	Destruction Room #2	As Required	30
L-2	Transmitter Room	51	54
L-3	Communication Control Center	77	78
L-4	Communication Stowage Room	22	22
L-5	Crypto Vault	8	8
L-6	Mission Communication Center	29	30
L-7	Message Processing Center	41	50
L-8	Destruction Room #1	As Required	30

Table 27, Mission Control Space Allocation, 2nd Deck

Block L: Anti-Roll Tank

The anti-roll tank is a controlled-passive U-tube design. An active anti-roll tank was considered, but not decided on due to concerns that the instantaneous pump power requirements might have on the quality of electrical power to the radars. A passive free-surface tank was also considered, but this would have required a discontinuity in an entire deck of the structure. Based on concerns over the effect that this would have on the longitudinal strength of the hull, this was not selected either.

The general size and location of the tank was based on guidance from NAVSEA DDS 565-1. The Anti-Roll Tank is positioned amidships above the waterline running through decks 2 and 3. This provided a balance between a high location, which is good location for effectiveness of the tank, and a lower location, which is better for KG of the ship. Anti-Roll Tank Dimensions (m) are shown below in Figure 29.

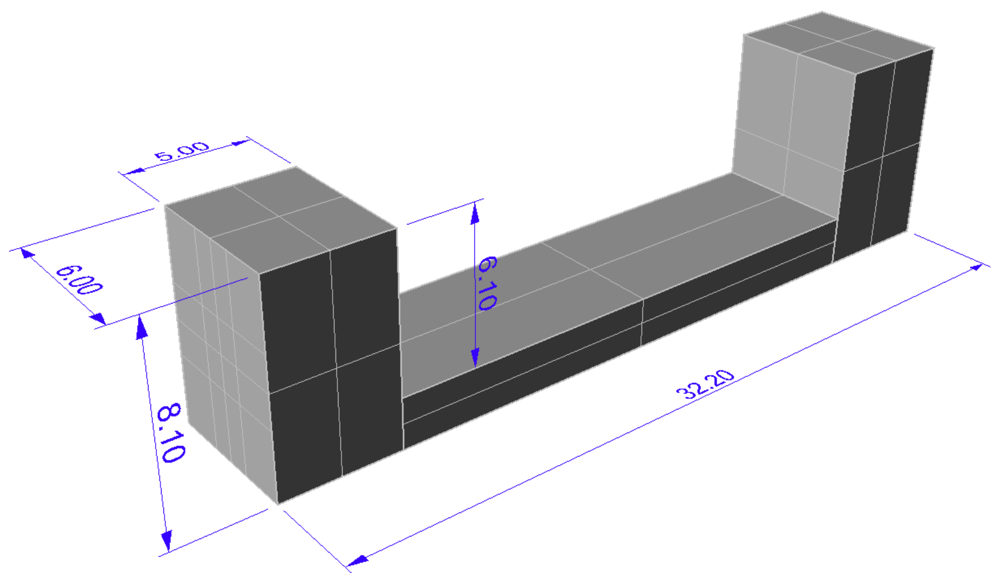
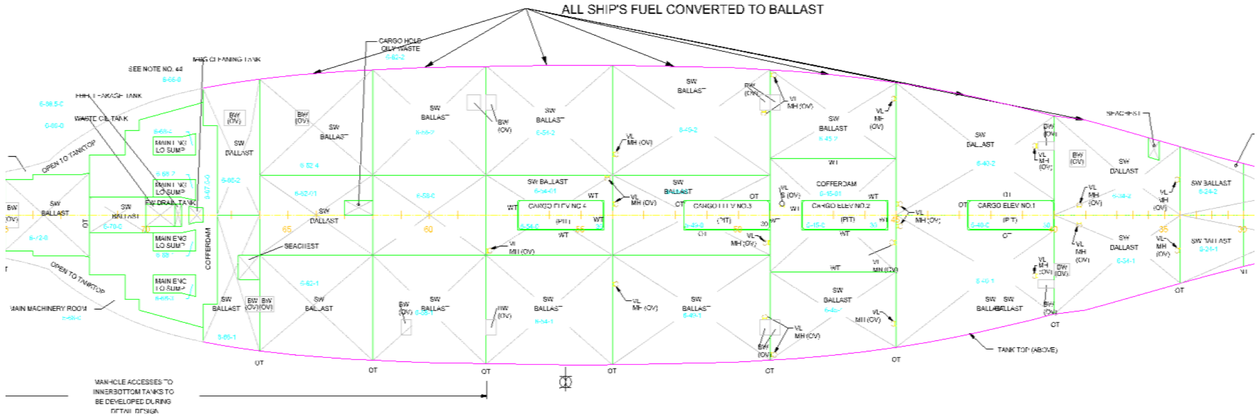


Figure 29: Anti-Roll Tank Dimensions

4.1.4 Hull Subdivision

The watertight bulkheads of the original T-AKE design were not altered giving the T-BMD the same watertight integrity as the original design. Because the T-BMD is a modified repeat design, it is subject to MARPOL 12 A regulations which fuel tanks to be surrounded with double hull protection. To meet these regulations, the original fuel fanks located within the inner bottom of the hull were replaced with fresh water ballast. The revised inner bottom tanks are shown below in Figure 30.



INNER BOTTOM

Figure 30, T-BMD Inner Bottom Plan

The cargo fuel tanks of the original T-AKE were double hull protected and have been re-designated as ships fuel tanks. These modifications are shown below in Figure 31 and Figure 32.

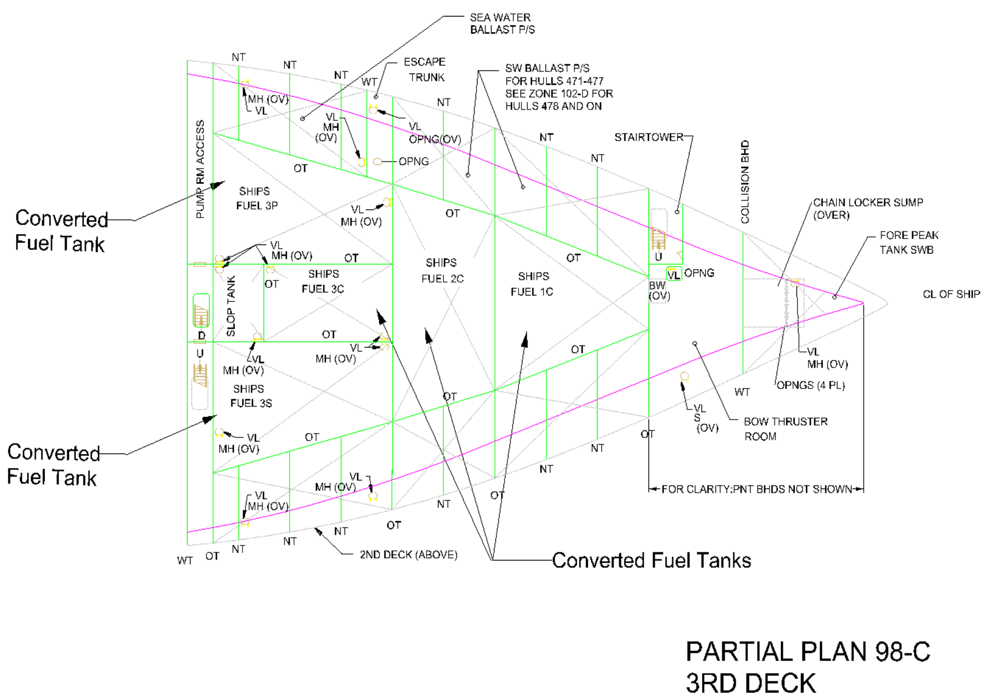


Figure 31, T-BMD Cargo Fuel Re-design 3rd Deck

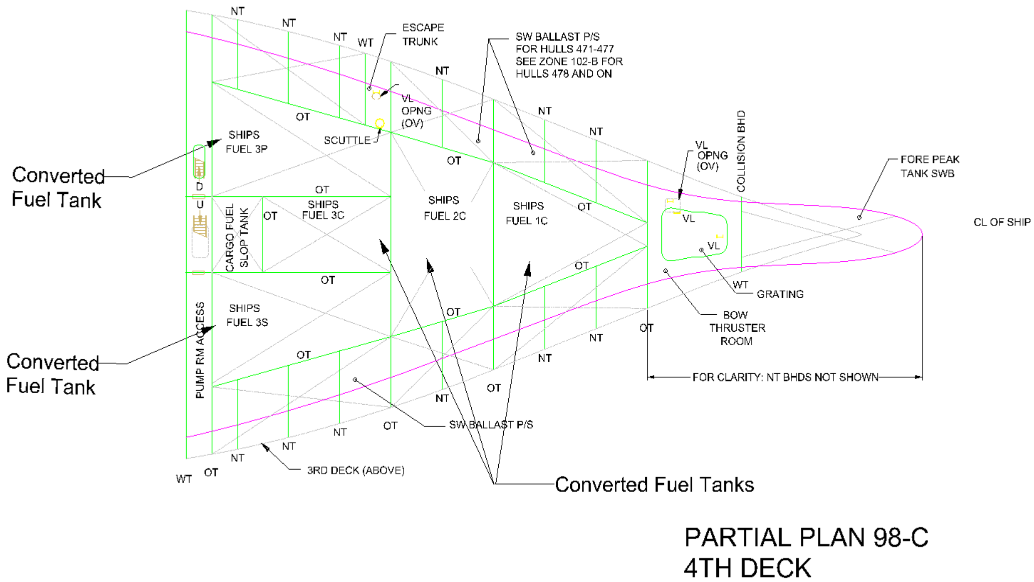


Figure 32, T-BMD Cargo Fuel re-design, 4th Deck

4.1.5 Structural Arrangement/Design

The majority of the existing structural design of the T-AKE was kept for the T-BMD design. No significant structural changes were made to the design aft of frame 58. Forward of frame 58 required modifications to the structural arrangements to satisfy mission requirements.

- The O1 and O2 levels forward of frame 49 were removed
- The foundation for the X-Band Radar Pedestal was added to the O1 and O2 level at frames 49 to 52
- The foundation for the S-Band Radar Pedestal was added to the main deck at frames 40 to 43
- The Anti-Roll tank installed at frames 56-58.

The removal of the O1 and O2 levels had a direct effect on the longitudinal strength of the design. The original T-AKE design considered the O1 and O2 fully effective in carrying primary loads and removing these levels forward of frame 49 made the O1 and O2 levels discontinuous. The analysis outlined in section 4.2.3 showed that this was not a problem for the strength of the design. The Anti-Roll Tank also inserted a discontinuity in the midship section by removing the outboard 3 meters of the 3rd deck. This location was selected for the tank since the 3rd deck is located approximately at the neutral axis of the structural section so the removal of part of the deck would not have an appreciable change in the longitudinal strength of the hull.

Due to the limited scope of the project, detailed design of the radar pedestals and foundations were not conducted. The weights of the foundations and pedestals were estimated using CJR data and accounted for in the SWBS 100 group for lightship distribution. The removal of the O1 and O2 levels was also taken into account by SWBS 100 group weight removal.

No midship section model existed for POSSE, so one was created based on the T-AKE design with the modifications described above.

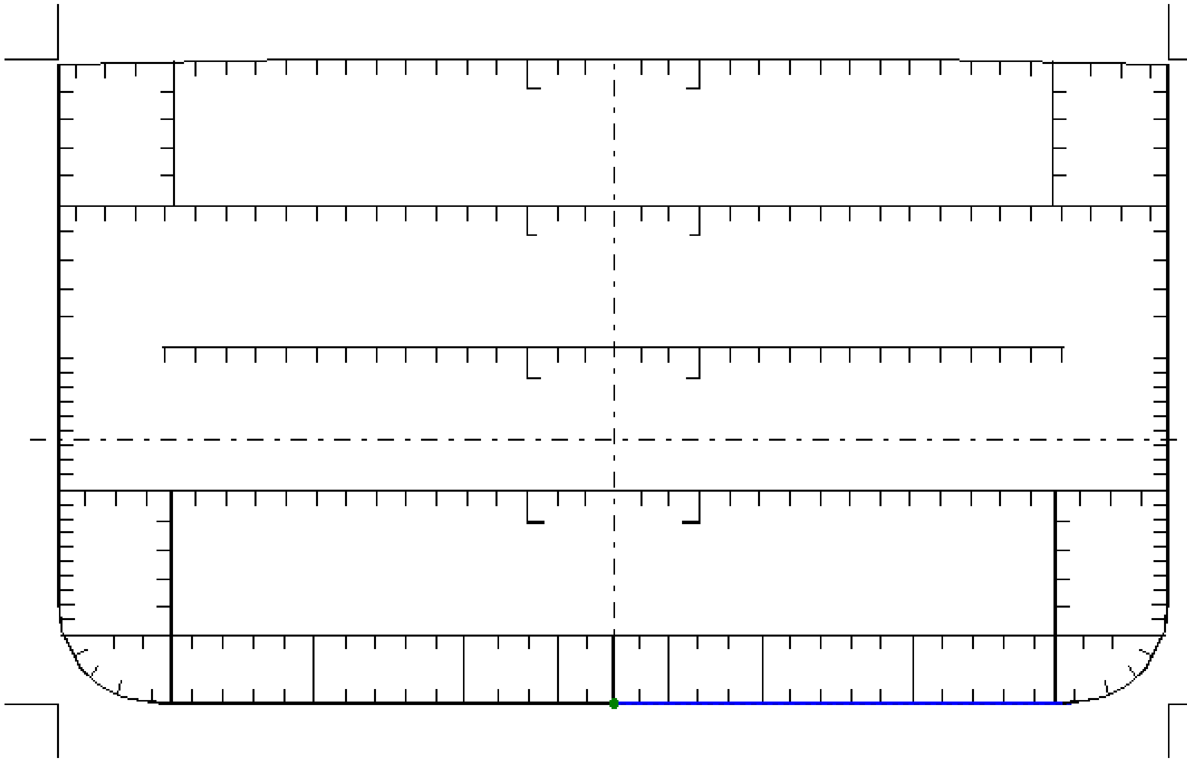


Figure 33, T-BMD Midship Section

4.1.6 Power and Propulsion Plant

The existing Power and Propulsion plant consists of an Integrated Power System (IPS) with a 33.6 MW capacity (plus 2.4 MW of emergency diesel generation capacity), 12 MW of which is available to support hotel and mission loads on the T-AKE. Hotel loads for the T-BMD are slightly reduced with the removal of the CLF capability and much of the IPS is under-utilized in all T-AKE operating conditions, therefore the majority of the 12 MW is available for powering the radars and their support equipment at all speeds.

The table below compares the greatest demand case for the T-AKE with the T-BMD. There is enough electrical capability remaining at 20kts to power both radars at full rated power. While this condition is not optimal from an engine-wear perspective (keeping the diesel generators loaded at 80% or less is considered optimal for maintenance and service life), it is still possible and highlights the flexibility that the T-AKE's IPS offers.

Description	TRANSIT		T-BMD
of Equipment	**20 KT**		**20kts**
season:	**WINTER**		**Winter**
Propulsion and Steering	19207		**18300**
Auxiliary Machinery	1319		**1320**
Heating, Ventilation and Air Conditioning Eq	4501		**4500**
Command & Surveillance	144		**350**
Hotel	426		**430**
Deck Machinery	49		**0**
Replenishment Systems	37	**Radar:**	**4600**
Electric Plant and Power Conversion	465		**464**
ELECTRIC PLANT TOTALS	26148		**29964**
PROPULSION MOTOR (SEE NOTE G)	18330		**17400**
SHIP SERVICE LOAD ONLY (No. 9 MINUS No. 1	7818		**12564**
Ship Service Load minus 4200KW of Radar			**8364**
NON GROWTH LOADS (No.1 PLUS No.7)	19244		**18300**
GROWTH LOADS (No. 9 MINUS No. 12)	6904		**11664**
20% GROWTH MARGIN (No. 13 (WORST CAS	1381		**2812.8**
E-PLANT TOTALS PLUS GROWTH MARGIN	27528		**32776.8**
Total MDG capacity			**34680**
Excess capacity			**1903.2**
% MDG rating (ave)			**0.95**
% MDG rating w/o 20% growth margin			**0.86**
Pwr avail @ 80% MDG rating:			**27744**
Transit Loads (radar support sys only)			**25764**

Table 28, Electric Plant Load Comparison between T-AKE and T-BMD

4.1.7 Auxiliary Systems

Many of the T-AKE auxiliary systems will be retained for the T-BMD mission such as:

- CHT
- Fresh Water
- Ballast
- Ventilation (aft of frame 58)
- Mooring/Anchoring Equipment
- Steering Gear
- Propulsion Plant ancillary equipment
- Bow Thruster

Most of the hydraulic equipment required for the T-AKE CLF mission will be removed and replaced with equipment specifically designed for the radar assemblies. This equipment will be installed locally in the equipment spaces allocated for the radars.

The T-AKE has a significant chilled water plant capacity installed with five-2100 kW AC plants. Specific thermal loads from the radar and associated equipment to be installed in the T-BMD are unknown, but should be easily met with the existing HVAC equipment from the original T-AKE design. A large portion of the T-AKE chilled water load is required for the refrigerated cargo hold 3 (~2621 kW). The T-BMD will be able to use the chilled water capacity to provide thermal management to the radar equipment and spaces. A breakdown of the total chilled water cooling capacity available for the T-BMD radar mission is summarized in Table 29.

Total Chilled Water Plant Capacity (5 Plants)	10500	kW
4 Plants + 1 Standby	8400	kW
4 Plants with 20% Margin	6720	kW
Accommodations Space Load (same as T-AKE)	1728	kW
Machinery Space Load (same as T-AKE)	2064	kW
Capacity for Radar Equipment and Spaces	**2928**	**kW**

Table 29, Available Radar Cooling Capacity

4.1.8 Weight Estimation

To account for changes in weight to the design, the most recent quarterly weight report for T-AKE 7 was used as a basis to track weight additions and removals to the vessel. To be conservative in the design, the following margins were applied to the design:

- 10% margin was added to all weight additions
- 10% margin was applied to all weight removals (Accounts for scenario where only 90% of the estimated weight is actually removed)
- 8% margin was applied to the estimate KG for removals and additions

An Excel spreadsheet provided by the NAVSEA O5D T-AKE program office was used to keep track of the weight additions and subtractions. This allowed for the removal of unnecessary weight down to the 3 digit SWBS level. This resulted in thousands of items being removed from the design. The following table highlights the modifications to the lightship of the T-AKE.

REMOVALS	ADDITIONS
O1/O2 Decks (forward of frame 49)	S Band Radar Array
Forward RAS Stations	X Band Radar Array
Forward FAS Station	S Band Pedestal and Foundation
Cargo Elevators (1,2,4,6)	X Band Pedestal and Foundation
Cargo Munition Equipment	CIWS (FWD)
Kingposts/Supports	CIWS (AFT)
Cargo Hold Equipment	AN/WSC-6 SHF Gear
Material Handling Equipment	AN/USC-38 EHF SATCOM
	AN/SLQ-32 EW System (X2)
	S Band Ancillary Equipment
	X Band Ancillary Equipment

Table 30, T-BMD Major Ship Modifications Summary

The sum of all the additions and subtractions of weight were tabulated and grouped into 1-digit SWBS level groups. The detailed breakdown of the weight modifications is provided in Appendix D. The net result of the design is the T-BMD having reduction in lightship weight of 2818 MT. It should be noted that the majority of the weight added and removed was between frame 49 and frame 30. The resulting Lightship weight breakdown for the T-BMD is shown along with the current T-AKE in the table below:

SWBS	GROUP NAME	Current T-AKE 7	VCG	LCG	T-BMD	VCG	LCG	DIFFERENCE
100	HULL STRUCTURE	15709.4	13.537	103.645	13795.1	13.747	107.823	-1914.3
200	PROPULSION PLANT	1398.4	6.524	152.755	1392.6	6.625	152.817	-5.8
300	ELECTRIC PLANT	1019.6	14.010	136.335	1012.8	14.146	136.511	-6.7
400	COMMAND AND SURVEILLANCE	248.0	16.695	109.622	718.7	22.816	80.914	470.7
500	AUXILIARY SYSTEMS	3686.5	15.598	106.883	2871.0	15.710	116.711	-815.5
600	OUTFIT AND FURNISHINGS	2217.0	19.079	117.400	2070.0	19.783	120.804	-147.0
700	ARMAMENT	1280.8	12.666	73.469	296.4	20.748	73.658	-984.3
	LIGHTSHIP	25559.5	13.937	107.842	22156.7	14.523	112.997	-3402.9
	INCLINING CORRECTION	-91.8						
	LIGHTSHIP W/INCLINING	25467.8			22156.7		112.997	-3311.1
	MARGINS	0.0			492.3		70.044	492.3
	TOTAL LIGHTSHIP	25467.8	14.073	107.674	22649.0	14.815	112.063	-2818.8

Table 31, T-AKE/T-BMD Lightship Weights Comparison

4.1.9 Synthesis and Convergence

The following table outlines the required convergence criteria for the design and compares these criteria to the T-BMD characteristics.

Essential Requirements		
Requirement	**Threshold/Objective**	**T-BMD**
Speed	20 knots	20+ knots
Range	16000 nm	16880 nm
Crew Accommodations	88	88+
Endurance	90 days	90 days +
Seakeeping	CJR Requirements	Meets all CJR Stability Requirements
Radar Coverage	240 Degrees	240 Degrees
Volume	CJR Volume	Exceeds by more than 10%
Area	CJR Area	Exceeds by more than 10%
Intact Strength	ABS Regulations	Meets ABS Strength Criteria
Stability	100kt Beam Wind High Speed Turn	Meets both requirements
Trim	0.5 m by the stern	~0.5 m by the stern

Table 32, Synthesis and Convergence Criteria

4.2 Feasibility and Performance Analyses

4.2.1 Weight Distribution and Load Conditions

With the lightship weight estimated in the procedure outlined in section 4.1.8, the lightship distribution was then developed based on the T-AKE POSSE ship project file from NAVSEA OOC. The 1 digit level SWBS removals and weight additions were then adjusted as weight blocks in POSSE ship project editor. This is shown in the figure below.

		Magnitude	Center	Extents	
No.	Name	Weight	LCG	Aft	Fwd
		MT	m-FP	m-FP	m-FP
27	SWBS 100 Removal	-2,177	70.19	108.60	24.60
28	SWBS 200 Removal	-1	27.31	32.31	22.31
29	SWBS 300 Removal	-3	56.60	61.60	51.60
30	SWBS 400 Removal	-1	92.85	97.85	87.85
31	SWBS 500 Removal	-802	70.93	108.60	30.00
32	SWBS 600 Removal	-139	64.62	102.00	30.00
33	SWBS 700 Removal	-993	73.16	108.60	45.60
34	S Band Radar	294	53.08	58.08	48.08
35	X Band Radar	294	77.58	82.58	72.58
36	S Band Equipment	99	50.00	70.00	40.00
37	X Band Equipment	99	80.00	102.00	70.00
38	FWD CIWS	7	10.00	15.00	5.00
39	AFT CIWS	7	155.00	160.00	150.00
40	SATCOM	6	127.50	132.50	122.50
41	SLQ-32	2	161.00	166.00	156.00

Figure 34, Weight Block Adjustments

These adjustments allowed for the combined Lightship weight distribution shown in Figure 35 below.

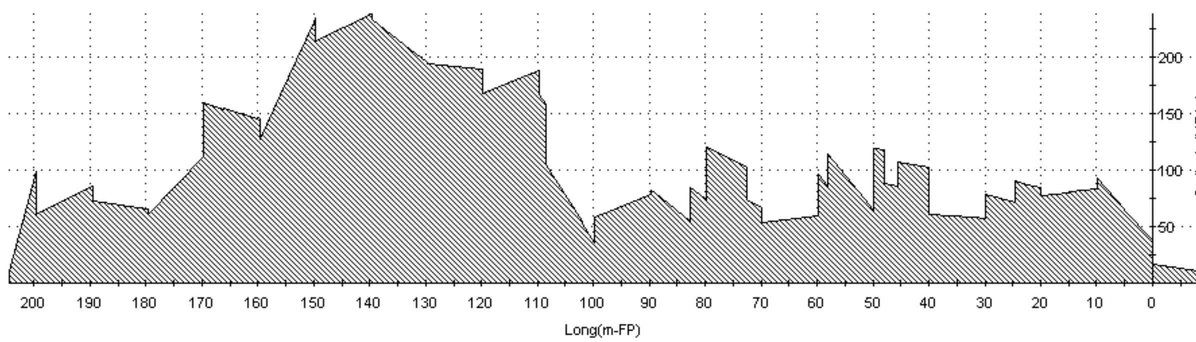


Figure 35, T-BMD Lightship Weight Distribution

It is clear that the T-BMD design is very light forward of the deckhouse (~108m FP). This distribution results in a natural hogging condition that is mitigated by the T-AKE through a combination of ship's fuel oil, SW ballast, and cargo. Since the T-BMD does not have any cargo, this leaves only the ballast tanks (and ship's fuel oil tanks that were converted to ballast tanks) in the inner bottom to alleviate this natural hog. For this reason, the inner bottom ballast tanks are filled in both Full Load and Minimum Operating (MIN OP) conditions. Since this means the inner bottom ballast tanks are essentially permanent ballast, freshwater was selected as a medium to reduce the corrosive effects of seawater. The remaining ballast tanks in the bow and stern remained as variable SW ballast tanks.

The T-BMD was loaded in POSSE (exclusive of the SW ballast tanks) in accordance with DDS 079-1 for both Full Load and MIN OP conditions. A 5% service life margin for weight and a 0.5 foot margin for KG was applied for end of life conditions. The variable SW ballast tanks were then loaded to achieve a desired trim of ~0.5 m by stern for both conditions based on recommendations by the project sponsors. The load conditions are summarized in Table 33 below.

	Full Load Condition	MINOP Condition	Full Load End of Life
Lightship (MT)	22649	22649	-
Fuel Oil (MT)	3893	1621	-
Fresh Water (MT)	347	347	-
Lube Oil (MT)	260	98	-
Ballast (MT)	8080	9643	-
Misc (MT)	117	31	-
Stores (MT)	169	78	-
Displacment (MT)	35515	34467	37290.75
VCG (m)	11.885	11.703	12.035
LCG (m-MS)	0.441F	0.638 F	.441F

Table 33, T-BMD Loading Conditions

4.2.2 Reserve Buoyancy, Stability and Trim

With the T-BMD loading conditions found, the initial trim and stability analyzed in POSSE. As explained in section 4.2.1, a 0.5 meter trim by stern was desired based on sponsor recommendations for the T-AKE hull form. A summary of the trim and initial stabilities under the various load conditions is shown in the table below:

	Full Load Condition	MINOP Condition	Full Load End of Life
Trim (m + by Stern)	0.487	0.502	0.487
GMt (Solid)	4.016	4.326	3.664
GMt (FS Corrected)	3.38	3.739	3.059
GMt/B	0.105	0.116	0.095

Table 34, Intact Trim and Initial Stability

These loading conditions were then analyzed against DDS 079-1 stability requirements for two appropriate scenarios:

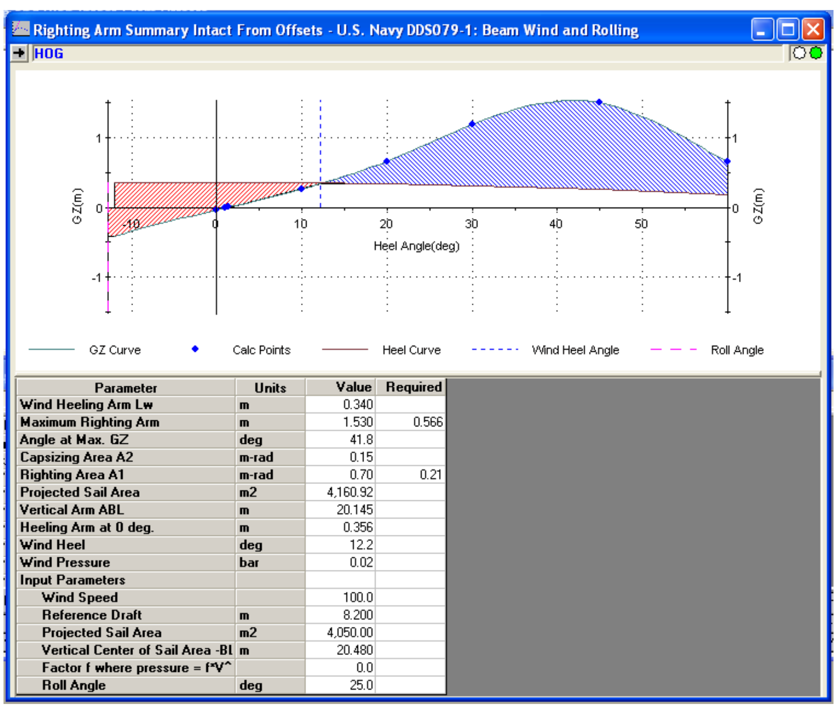
- Beam winds combined with rolling for 100 knot winds
- High Speed Turning

The 100 knot wind requirement was selected since operationally the T-BMD may be required to remain on station as long as possible and not have the ability to avoid centers of tropical disturbances. The specific requirements for the scenarios are listed below in Table 35.

Wind Heeling Requirements			
Load	100 kts	Sail Vertical Center	20.5 m Above BL
Sail Area	4050 m^2	Initial Roll Angle	25° (Into the Wind Heel)
A1 (Righting Area)	≥ 1.4 A2 (Capsizing Area)	Righting Arm at Wind Heel	≤ 0.6 Maximum Righting Arm
High Speed Turn Requirements			
Speed	20 knots	Turning Circle Radius	250m
Angle of Steady Heel		< 15 degrees	
Reserve Dynamic Stabilty		≥ 0.4 Total Area Under GZ Curve	
Righting Arm at Turn Heel		≤ 0.6 Maximum Righting Arm	

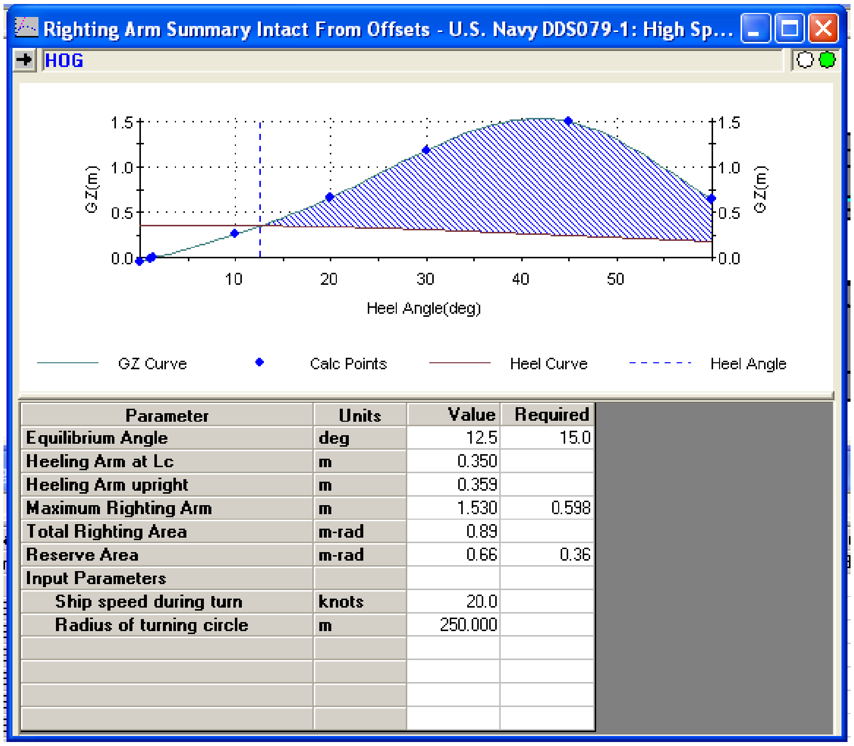
Table 35, Stability Requirements

The T-BMD passed all intact stability requirements in all of the analyzed loading conditions. For both the beam winds combined with rolling for 100 knot winds and the high speed turn requirements, the Full Load at end of life in a hogging condition presented the most limiting case, but the T-BMD still passed with plenty of margin. These stability case analyses are shown below in Figure 36 and Figure 37. The full intact stability analysis for all loading conditions is provided in Appendix E.



Parameter	Units	Value	Required
Wind Heeling Arm Lw	m	0.340	
Maximum Righting Arm	m	1.530	0.566
Angle at Max. GZ	deg	41.8	
Capsizing Area A2	m-rad	0.15	
Righting Area A1	m-rad	0.70	0.21
Projected Sail Area	m2	4,160.92	
Vertical Arm ABL	m	20.145	
Heeling Arm at 0 deg.	m	0.356	
Wind Heel	deg	12.2	
Wind Pressure	bar	0.02	
Input Parameters			
Wind Speed		100.0	
Reference Draft	m	8.200	
Projected Sail Area	m2	4,050.00	
Vertical Center of Sail Area -Bl	m	20.480	
Factor f where pressure = f*V^		0.0	
Roll Angle	deg	25.0	

Figure 36, Full Load EOL (HOGGING condition) Beam Winds with Rolling Stability



Parameter	Units	Value	Required
Equilibrium Angle	deg	12.5	15.0
Heeling Arm at Lc	m	0.350	
Heeling Arm upright	m	0.359	
Maximum Righting Arm	m	1.530	0.598
Total Righting Area	m-rad	0.89	
Reserve Area	m-rad	0.66	0.36
Input Parameters			
Ship speed during turn	knots	20.0	
Radius of turning circle	m	250.000	

Figure 37, Full Load EOL (HOGGING condition) High Speed Turning Stability

A detailed damaged stability analysis of the T-BMD was not conducted for the following reasons:

- The watertight bulkheads of the T-AKE were not altered
- The T-BMD has a smaller displacement than the T-AKE
- The T-BMD has a lower KG than the T-AKE at Full Load

For the feasibility of the design, it is reasonable for the damaged stability analysis conducted on the T-AKE to be used to reasonably assume the modified T-BMD would pass damaged stability requirements without major modifications.

4.2.3 Strength

The T-AKE was built to ABS regulations and not Navy SDS 100-1 standards or OPNAV 9070.1 survivability requirements. During the design process, as discussed in Section 3, it was decided that the T-BMD would keep the same survivability and strength requirements of the T-AKE built to ABS standards. Specific scantling conformance to ABS regulations was not checked, however global longitudinal strength was.

As described in section 4.1.5, a significant alteration was done for the T-BMD design in removing the O1 and O2 decks. Since these were considered global strength decks, their removal would have a significant impact on the overall longitudinal strength of the vessel. A model of the T-BMD midship section (with portion of the 2nd deck neglected for the addition of the anti-roll tank) was developed in

POSSE to allow for calculation of the section modulus of the ship. It was determined that the removal of the O1/O2 decks, while reducing the moment of inertia of the section, resulted in an increase in deck section modulus due to the fact the distance from the neutral axis to the extreme fiber was much lower for the T-BMD (main deck) compared to T-AKE (O2 deck). The keel section modulus was also increased due to the neutral axis moving closer to the keel. The net result was a 'stronger' ship even though structure was removed.

The section modulus of the T-BMD exceeded the ABS requirements for hull girder section modulus in accordance with section 3-2-1 of the ABS rules for building and classing steel vessels. The table below shows the summary of the T-BMD midship section properties compared to the ABS requirements.

	T-AKE	T-BMD	Units
Section Modulus Required	202,002	202,002	cm^2-m
Section Modulus (top)	207,558	239,500	cm^2-m
SM_{top} Margin	2.75%	18.56%	
Section Modulus (bottom)	322,194	345,500	cm^2-m
SM_{bottom} Margin	59.50%	71.04%	

Table 36, Midship Section Modulus Comparison

A quasi-static analysis of the T-BMD was conducted in POSSE for all loading conditions to determine stresses at various stations along the hull. This included both hogging and sagging conditions with a trochoidal wave of 8.61 meters based on the following equation:

$$H(ft) = 1.1\sqrt{LBP\ (ft)}$$

This required the section modulus at every section to be analyzed to be entered as an input into the POSSE ship project file. Instead of creating separate section models in POSSE, the relative change in midship section properties between the T-AKE and T-BMD was applied to the other T-AKE section properties. This allowed for a 1st order estimate of the structural properties of different sections for the T-BMD, which are shown below.

		T-BMD			T-AKE		
Structural Section	Location m-FP	Shear Area m^2	SM(deck) m^3	SM(keel) m^3	Shear Area m^2	SM(deck) m^3	SM(keel) m^3
F32	28.1	2.8	24.6	15.6	3.4	15	20
F39	42.1	3.2	27.9	19.4	3.8	17	25
F45	63.1	3.8	34.5	24.1	4.6	21	31
F49	77.1	4.1	34.5	24.9	4.9	21	32
F57	105.1	4.0	34.5	24.1	4.8	21	31
F66	133.72	3.0	32.8	18.7	3.6	20	24
F69	143.14	2.8	27.9	16.3	3.3	17	21
F73	155.7	2.4	26.2	10.1	2.9	16	13
F77	168.26	2.2	19.7	7.0	2.6	12	9

Table 37, Sectional Strength Properties

The resulting analysis showed that the T-BMD did not experience any bending stresses above the ABS nominal permissible bending stress of 17.5 kN/cm^2 (from ABS 3-2-1/3.7.1) or the nominal permissible shear stress of 11.0kN/cm^2 ordinary (mild) steel. The worst-case scenario was Full Load at End of Life (EOL) – the results are shown in Figure 38.

Strength Summary

HOG

Name	Location m-MS	Weight MT	Buoyancy MT	Shear MT	Shear Stress kN/cm2	Wt. Moment m-MT	Buoy. Moment m-MT	Bending Moment m-MT	Deck Stress kN/cm2	Keel Stress kN/cm2
F77	68.485A	3,992	507	3,485	1.3	61,749	5,255	56,494H	4.6	-5.9
F73	55.925A	6,068	1,540	4,528	1.5	124,896	16,884	108,012H	6.7	-8.3
F69	43.365A	8,808	3,735	5,073	1.5	217,915	48,858	169,057H	9.9	-7.7
F66	33.945A	11,301	6,075	5,227	1.4	312,255	94,538	217,717H	10.7	-9.1
F57	5.325A	18,362	15,713	2,649	0.5	739,225	399,414	339,811H	15.9	-10.7
Mx	6.797F	20,256	20,300	-44	0.0	974,116	617,689	356,426H	16.7	-11.1
F49	22.675F	22,418	25,918	-3,500	-0.7	1,312,355	985,726	326,629H	15.2	-10.1
F45	36.675F	23,882	30,013	-6,131	-1.3	1,637,727	1,378,389	259,338H	12.2	-8.2
F39	57.675F	26,884	33,837	-6,953	-1.8	2,167,402	2,054,061	113,341H	6.4	-4.5
F32	71.675F	31,141	34,907	-3,765	-1.1	2,571,877	2,536,343	35,534H	2.3	-1.7

Values | Shear & Moment | % of Allowables | Stresses

Figure 38, Longitudinal Strength Assessment (Full Load EOL)

The longitudinal strength assessments for all load conditions are provided in Appendix F.

4.2.4 Seakeeping

The T-BMD was loaded onto MaxSurf's Seakeeper program to compare its seakeeping performance to the T-AKE. Since the hullform is identical, the major differences were the draft and vertical center of gravity. Seakeeper does not simulate the effects of anti-roll tanks, so their effects to T-BMD's seakeeping performance could only be estimated from other references such as Principles of Naval Architecture.

The T-BMD seakeeping performance was evaluated at Full Load condition at SS 6 at three speeds (5, 12, and 20 knots) and five headings with respect to seas (000, 045, 090, 135, and 180 degrees relative). Actual seakeeping performance was provided for T-AKE by NAVSEA 05D for comparison. Heave, pitch, and roll were evaluated as well as an index in Seakeeper called Man Seasickness Index (MSI), which is a measure of how long crewmembers can stand watch before becoming too sick to continue.

In all cases, heave and pitch were comparable to the T-AKE and better than CJR's requirements. Roll was worse at high speeds than the T-AKE with seas off the beam or stern quarter. However, since Seakeeper did not account for anti-roll tanks, its believed that roll would be greatly diminished in these cases where ship's roll approaches its natural frequency and would actually be better than a T-AKE.

The natural roll period for the T-BMD was calculated by the following formula from Principles of Naval Architecture:

$$T = \frac{2\pi \bullet k_4}{\sqrt{g \bullet GM}}$$

where k_4 is the roll radius of gyration, measured as 11.914m by Seakeeper, and GM is the metacentric height, measured at 3.38m by Seakeeper.

The natural roll period for the T-BMD calculates out to 13.1 sec. The T-AKE natural roll period was calculated to be 15.9 sec. The lower roll period became apparent in the Seakeeper analysis as greater roll angles and higher lateral accelerations than the T-AKE were observed. Again, the effects of the anti-roll tanks were not accounted for in Seakeeper.

Seakeeper also does not evaluate greenwater on deck, which was a major concern for the performance and reliability of the AMDR-S (the forward and lower S-Band radar). However, greenwater was evaluated for the T-AKE and in no cases was greenwater observed on deck, even during SS9 simulations. The AMDR-S, therefore, could conceivably operate in SS6 without experiencing greenwater on the radar face or turret.

The main restriction for operating the ship in SS6 was found to be the MSI, which showed discomfort after two hours on the bridge and forward radar station when traveling at 20 kts into head seas. Other headings (045R, 135R) showed similar results. However, MSI for 5 kts and 10 kts were within limits at all headings. Further evaluation by more defined software such as SMP would be required to fully evaluate the T-BMD's performance in all cases. The CR Objective of being able to fully operate in SS6 is considered to be met, as lowering speed to less than 10 kts brings the MSI within 8+ hour limits at all headings.

Figure 39 summarizes the differences between the T-BMD, T-AKE, and requirements for the CJR. The model testing for the CJR was unavailable for this report. The T-BMD meets or exceeds all of the requirements for the CJR with the exception of pitch angle, which was measured at a higher sea-state. Because of the assumptions required to be input into Seakeeper, the small differences between T-BMD, T-AKE, and CJR's requirements are within reason. Further detailed analysis in SMP would be worthwhile. to confirm T-BMD's performance meets the requirements.

Condition	Ship Speed (knots)	Ship Heading	Wave Height (feet) (g)	Roll (deg) (f)	Pitch (deg)	Deck Wetness (No./hr) (a)	Lateral Acceleration (in g's) Bridge (c)	Vertical Acceleration (in g's)	
								Pilot House (c)	Transom(CJR), Fwd Radar (T-BMD)
Transiting (CJR)	20	All	8-13	8	3	30	0.2	0.4	0.4
Transiting (T-AKE)	20	All	14-20	5.5	2.1	0	0.1	0.1	n/a
Transiting (T-BMD)	**20**	**All**	**14-20**	**<4 deg (est)**	**4.3**	**0**	**0.26**	**0.16**	**0.26**
Loitering (CJR)	5	All	8-13	8	3	30	0.2	0.4	0.4
Loitering (T-AKE)	5	All	14-20	3.1	2.0	0	0.05	0.1	n/a
Loitering (T-BMD)	**5**	**All**	**14-20**	**<4 deg (est)**	**3.1**	**0**	**0.26**	**0.15**	**0.2**

Natural Roll Period (T-AKE) (FL) 15.9 sec

Natural Roll Period (T-BMD) (FL) 13. 1 sec

NOTES:

a) Station 0 at deck edge of principal weather deck
b) Slams at station 3 at keel
c) On centerline at helmsman's station. Effect of T-BMDs anti-roll tanks could not be determined on Seakeeper. Believe actual lateral accel will be <0.2g
d) Main Deck, on centerline, for CJR. Main Deck at S-Band Radar, on centerline, for T-BMD
e) Roll, pitch and acceleration values are significant single amplitude
f) Roll for T-BMD based on estimated effects of anti-roll tanks. Actual worst-case values were 10.8 deg at Loiter, 8.6 deg at Transit
g) T-BMD values were calculated at SS 6, the Design Requirement Objective for Seakeeping.

Figure 39, CJR, T-AKE and T-BMD Seakeeping Comparison

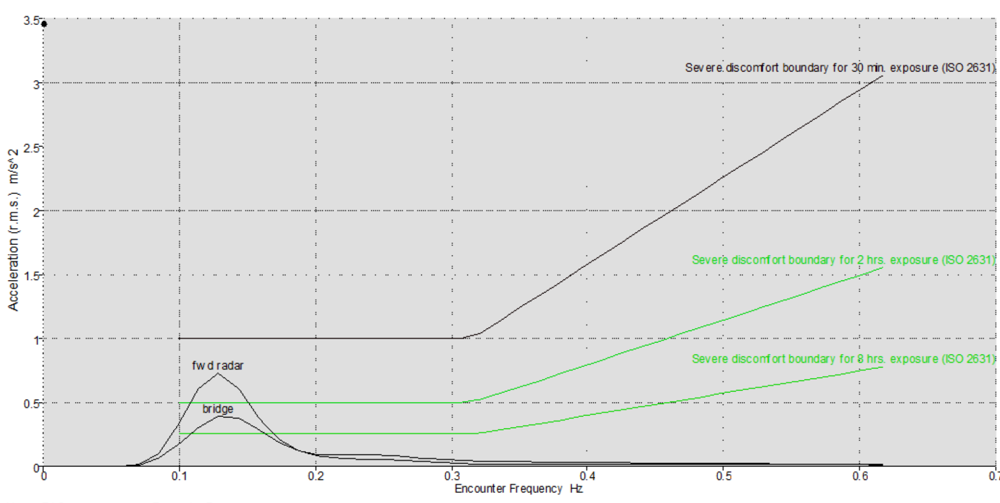


Figure 40, Worst-Case Seasickness Case: Seastate 6, 20 kts, Ahead Seas

4.2.5 Powering/Resistance

Maxsurf's HullSpeed program was used to evaluate T-BMDs powering requirements and range. The hull form was not changed from the T-AKE, therefore only the draft and trim were adjusted for Hullspeed. Holthrop analysis was used, as it best met the characteristics of the T-BMD and also accounted for bulbous bows (which the T-AKE hullform has). The results were compared to model testing and sea-trial results of the T-AKE to ensure they were reasonable. Range calculations were based on Hullspeed's powering results and the usage of the forward cargo tanks for ship's fuel (4311MT). Transiting at 20 kts (with radars powered down), the T-BMD has an estimated range of 16,880NM. If a slower transit speed is used (14-16 kts), a further range is expected.

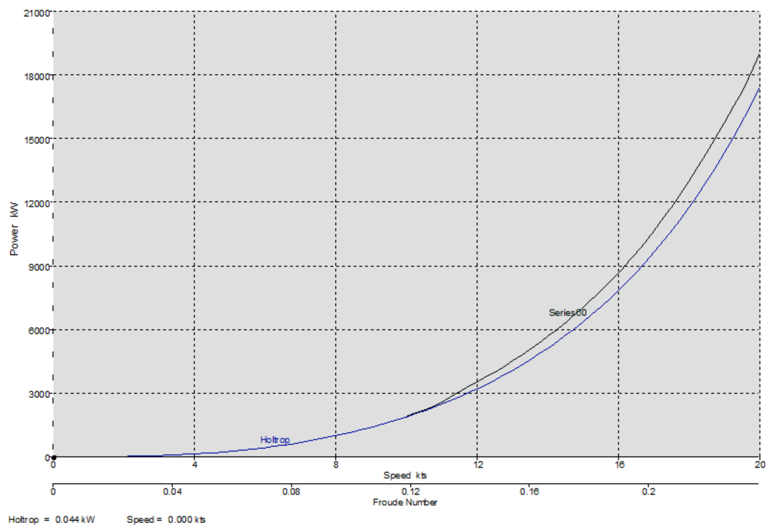


Figure 41, T-BMD Powering Results

4.2.6 Comparative Analysis

A comparison of the T-BMD to the T-AKE and T-AGM(R) is provided below in Table 38.

DIMENSIONS	T-BMD	T-AKE	T-AGM 25 (CJR)
LOA, m	210	210	162.8
LBP, m	199.5	199.5	156
Beam, m	32.2	32.2	27
Draft, m	6.55	8.34	9.12
PERFORMANCE			
Installed Power, MW	33.3	36	22
Sustained Speed, knots	20	20	20
Range	16888	14000	12000
Endurance on Station	90	90	60
WEIGHTS (MT)			
SWBS 100	13795.1	15709.4	5900.0
SWBS 200	1392.6	1398.4	822.6
SWBS 300	1012.8	1019.6	565.0
SWBS 400	718.7	248.0	788.5
SWBS 500	2871.0	3686.5	774.1
SWBS 600	2070.0	2217.0	923.1
SWBS 700	296.4	1280.8	0.5
Lightship with Margins	22649.0	25467.8	9773.8
Loads	12866.0	16439.2	2761.8
Design Full Load	35515.0	41906.9	12679.0
MISC			
Crew	88	137	88

Table 38, T-BMD/T-AKE/CJR General Comparison

4.3 Design Refinements

General assumptions were made on the T-BMD design regarding electrical power requirements. It was assumed that the quality of electrical power to the radar would be able to be addressed with the power conversion equipment installed with the radars. An in-depth electrical engineering analysis would need to be done to analyze if there are modifications required to the T-AKE IPS plant to support the electrical power to the radars.

4.4 Cost

As discussed in Section 2, actual cost estimates were not determined other than in a broad, quantitative sense. Some very rough estimates were derived for the base hull and various conversions in order to compare options, but little time was spent validating these estimates. Therefore, the costs discussed below are very rough-order-of-magntitude comparisons to the base T-AKE and CJR. Quantitative comparisons, mostly based on the experience of the team members, was used.

4.4.1 Producibility and Acquisition Cost

The T-BMD hull remained mostly untouched from the base T-AKE hull. As discussed earlier, much of the 01/02 levels forward of frame 49 were removed, spaces were built into Cargo Holds 1 and 2 to hold various radar systems, and an anti-roll tank was added in the aft section of Cargo Hold 2, decks 2 and 3. Most of these changes were structurally simple and would offset the cost and material savings from removing the CLF equipment and 01/02 levels. Therefore, minus the radar systems, a very rough estimate is the cost for the T-BMD hull would be comparable to a complete T-AKE.

Since the radars are similar to those on the CJR, the costs for the radars would be expected to be similar. The size of the T-BMD would conceivably make it easier to install and test the radars. However, it is believed the total cost of the CJR would likely be less than a T-BMD, due to less material and less building costs for the ship.

4.4.2 Operations and Support Cost

The Operations and Support Cost for the ship itself will likely be less than either the baseline T-AKE and the CJR. The reasoning for this is that the T-BMD has less equipment than the T-AKE to maintain. Compared to the CJR, the T-AKE hull being used has a more established maintenance and parts program which should keep maintenance costs less than the (currently) one-off CJR design. If additional CJR's are produced, this advantage will likely disappear.

4.4.3 Total Life Cycle Cost

Total Life Cycle Cost (LCC) was not explicitly determined beyond the rough estimates discussed in section 4.4.1 for Procurement and Acquisition costs. Rather, many of the decisions qualitatively made during the design process were made to minimize LCC. Historically, the largest components of LCC are fuel and personnel costs. Fuel costs will largely be determined by the operating profile of the ship. If an operating profile is chosen to maximize the time spent loitering at low speeds, with higher speeds only utilized for transits to/from operating areas, then the T-BMD should have a much lower fuel LCC than the T-AKE. Personnel costs should also be much lower than the T-AKE (due to lower number of personnel required to operate the radar versus conducting the CLF mission) and should be a little lower than the CJR (if a military detachment is used to operate the radar systems instead of contractors or civilian mariners).

The large amount of ballast required by the T-BMD could also lead to additional costs. Maintenance costs could be reduced by using freshwater ballast (as was assumed in all calculations above) but some inspection requirements would still remain and lead to maintenance costs throughout the ship's life. If lead were used for ballast, a greater upfront cost would be incurred.

Compared to the CJR, the LCC would likely be greater, primarily due to the preservation of the larger hull and the fuel costs for driving a larger hull. The utilization of the T-AKE maintenance programs would greatly aid in keeping LCC for maintenance down, but the fuel costs and preservation would likely outweigh lower maintenance costs.

4.5 Technical Feasibility and Risk Assessment

The modifications performed on the hull are not believed to be excessive or risky. In fact, the T-AKE was picked due to the early belief that the radars could be installed with minimal modifications required to the structure and electric plant. The radar equipment is also either in-use or under development for other programs. The greatest risk from using the T-AKE comes from the uncertainty that the IPS plant can provide the quality of electrical power needed for the radars power conversion equipment. Overall, however, the risk in building this design is believed to be low.

5.0 Conclusions and Recommendations

5.1 Summary of Final Concept Design

The Final Concept Design is summarized below:

Radar Coverage	240 deg S-Band coverage, 280 deg X-Band coverage
S-Band Radar	AMDR-S installed
X-Band Upgrade	Higher capability (FFOV) installed
Range	16,880NM
Endurance	>90 days
Accommodations	Standard Crew size of 88, combination of CIVMAR and MILDET. 172 Total Berthing
Exterior Communications	Commercial off the shelf, FORCEnet compliant, with military GPS capabilities. Compatible with TBMD
Surface/Air Self Defense	2 x CIWS (fwd/aft) + crew-served weapons
VERTREP Capability	None (hangar and flight deck remain)
Survivability	ABS levels (unchanged from T-AKE)
Seakeeping	Able to conduct mission up to SS 6 utilizing passive anti-roll tanks
Draft	8.1m at Full-Load
ASW Self Defense	None
CONREP Capability	None

Table 39, Final Concept Design Summary

5.2 Study Conclusions (Key Insights) and Areas for Further Study

Developing a Mod-Repeat design of the T-AKE to fulfill a BMD mission proved a greater challenge than initially envisioned. The coordination of radar capability, radar placement, power requirements, and minimization of hull structural modifications was a challenging endeavor even for this large ship.

The use of the T-AKE hull to conduct a T-BMD mission is not believed to be very cost-effective when compared to building additional CJR's to support the BMD mission. The CJR is currently being built, so exact cost data will be available to NAVSEA, but it is reasonable to assume the CJR will be cheaper to produce than building a modified T-AKE hull and adding the radar and other equipment necessary to conduct a T-BMD mission. The T-BMD will require modifications to the hull and its largely unused volume will require ballasting. This ballast, whether in the form of freshwater in the ballast tanks or lead, is significant and could lead to greater LCC than would be experienced by a ship that doesn't require significant ballast.

The T-BMD does provide greater capability than the CJR, however. The IPS allows it to fully power the radar systems, even accounting for additional growth in power demand, at all speeds. The size of the hull precludes greenwater from reaching either radar turret and the addition of an anti-roll tank promises to further increase the ability of the T-BMD to operate in a greater range of seas than the CJR would be expected to perform in. The lower height of the radars on the CJR and their position in the stern would require the CJR to operate with seas aft of the forward quarter when conducting searches, which would lead to large rolls and be detrimental to crew performance.

In contrast, the forward position of the radars on the T-BMD allows it to search into the seas, and the anti-roll tanks promise to greatly dampen the rolls when seas are on the beam or abaft the beam, extending the comfort level of the crew and increasing the mission effectiveness.

The T-BMD as designed had a large amount of excess deck space even despite the removal of portions of the O-1 and O-2 Levels. With such large amount of excess area it is certainly feasible that the T-BMD could have additional missions if required. If desired, the T-BMD has enough excess area to retain a large portion of the CLF capability or any similar mission.

5.3 Recommendations

While the variant designed and discussed in this paper would likely cost greater than a CJR, the additional capability of the T-AKE IPS and large hull size allow for greater flexibility and greater growth potential for a BMD mission. Therefore, a more detailed analysis on the modifications required to support the installation of the radars is warranted to gain better fidelity on potential costs and provide the Fleet with a better performance-versus-cost metric if further BMD-support vessels are desired.