Probabilistic Damage Stability vs. Two-Compartment Deterministic Damage Stability: Mission impact on Military Sealift Command

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ABSTRACT

The purpose of this paper is to provide an overview of how the US Navy's Military Sealift Command (MSC) applies commercial stability criteria to quasi-military vessels and to illustrate the findings of how applying probabilistic criteria vice two-compartment deterministic criteria impacts T-AE and T-AOE Class MSC vessels and their mission.

The matters discussed in this paper reflect the views of the authors and not those of the U.S. Department of Defense or its components.

Keywords: *probabilistic, damage, stability*

1. INTRODUCTION

U.S. Navy's Military Sealift Command (MSC) is the largest employer of merchant mariners in the United States, with a fleet of over 100 non-combatant, civilian-crewed ships worldwide, and access to 64 Ready Reserve Force ships that are kept in reduced operating status.

In many respects MSC operates much like a commercial operator, albeit with two principal differences. First, MSC operations are not driven or limited by a profit margin. Instead, MSC operations are guided by the most practical and effective means to accomplish its various missions. Secondly, as part of the U.S. Navy, MSC is not legally bound to comply with most accepted commercial standards. Nonetheless MSC does so voluntarily as a matter of policy.

The first part of this paper will provide a brief overview of the MSC fleet, its missions, and operating practices.

MSC's stability requirements for most ships are a combination of U.S. Coast Guards Wind Heeling criterion and U.S. Maritime Administration (MARAD) Design Letter No. 3, a deterministic one-compartment damage criterion. In addition, MSC holds certain vessels to a more stringent two-compartment damage criterion. In many cases the application of that criterion results in operating restrictions with considerable impact on the ships ability to perform the mission in the most effective way.

It is widely accepted that aspects of the deterministic approach to damage stability may not represent "real world" damage scenarios. Deterministic standards focus on the single worst event and do not adequately reflect the overall safety level of the ship, and consequently may impose unrealistically conservative operating restrictions.

The second part of this paper will look at two MSC vessel classes that have various operational restrictions imposed from the deterministic damage stability analyses. A probabilistic damage stability analyses has been performed for these ships and the results evaluated with reference to the ships mission performance, and the practicality of the subject operational restrictions.

2. MILITARY SEALIFT COMMAND OVERVIEW

2.1 MSC Mission

The U.S. Secretary of Defense in 1949 established Military Sealift Command as the operating agency for providing strategic sealift in support of national security objectives. The mission of MSC is to provide ocean transportation of equipment, fuel, supplies and ammunition to sustain U.S. forces worldwide during peacetime and in war for as long as operational requirements dictate.

During wartime, more than 95 percent of all equipment and supplies needed to sustain the U.S. military is carried by sea. MSC operates ships that provide combat logistics support to U.S. Navy ships at sea; special mission support to U.S. government agencies; pre-positioning of U.S. military supplies and equipment at sea; and ocean transportation of Department of Defense cargo in both peacetime and war.

2.2 MSC Fleet

Military Sealift Command performs its mission through the employment of

Sealift Forces from two principal sources: U.S. Government-owned ships and chartered U.S.Merchant Marine ships.

The MSC fleet is divided into four component forces: Naval Fleet Auxiliary, Special Missions Support, Pre-positioning and Strategic Sealift.

Naval Fleet Auxiliary Force. The NFAF is composed of fleet ocean tugs, fast combat support ships, fleet replenishment oilers, combat stores ships, ammunition ships, rescue-salvage ships, and two hospital ships.

Through underway replenishment NFAF ships provide fuel, food, ammunition, spare parts and other supplies to U.S. and Allied naval ships at sea, enabling the fleet to operate at the highest operational tempo possible.

In addition, NFAF ships conduct towing and salvage operations and serve as floating medical facilities.

Special Missions Program. This program is responsible for ships that provide operating platforms and services for unique U.S. military and federal government missions including oceanographic and hydrographic surveys, underwater surveillance, missile flight data collection and tracking, acoustic surveys and submarine support.

Special mission ships work for several different U.S. Navy customers, including the Naval Sea Systems Command and the Oceanographer of the Navy.

In addition to its government-owned ships, the Special Mission Program is responsible for chartered vessels, which handle several unique U.S. government operations, such as deep-water search and rescue missions, Navy submarine test support escorts, and Navy and Marine Corps warfare development.

Pre-positioning Program. This program is responsible for forward deployment of vital military equipment, fuel, and supplies in key ocean areas around the world. Pre-positioning ships remain at sea, ready to deploy on short-notice to support US military forces in the event of a contingency.

Pre-positioning Program ships include long-term chartered commercial vessels, activated Ready Reserve Force ships, as well as U.S. government-owned ships.

The Pre-positioning Program is divided into three separate elements:

- The Combat Pre-positioning Force, which supports the US Army;
- The Maritime Pre-positioning Force, which consists of ships especially configured to transport supplies for the U.S. Marine Corps;
- The Logistics Pre-positioning ships, which support the US Navy, the Defense Logistics Agency, and the US Air Force.

Sealift Program. This program provides the required ocean transportation to the US Department of Defense (DoD) in peace, contingency, and war.

The Sealift Program is made up of three Project Offices:

- The Tanker Project Office, which works closely with the Defense Energy Support Center to transport petroleum products to DoD storage and distribution facilities around the world;
- The Dry Cargo Project Office, which handles all DoD cargo requirements that cannot be accommodated by regularly scheduled ocean liner service;
- The Surge Project Office, which manages strategic sealift ships that can be activated from reduced operating status to support the U.S. military in exercises, contingencies and war.

2.3 MSC Regulatory Compliance

MSC's U.S. Government-owned ships (vice privately-owned vessels under charter to MSC) are considered "public vessels", as defined in Title 46, United States Code, Section 2101, and as such are exempt from mandatory United States Coast Guard (USCG) inspections. Additionally, to maintain a necessary level of diplomatic immunity from Port State Control, these ships are not subject to the provisions of international treaties, such as the International Convention for the Safety of Life at Sea (SOLAS), the International Ship and Port Facility Security (ISPS) Code, or the International Convention for the Prevention of Pollution from Ships (MARPOL). Accordingly, MSC vessels are not issued formal SOLAS, ISS, or MARPOL certificates.

Instead, MSC has voluntarily established a policy of USCG inspections to ensure the safety of each MSC vessel, and to that end signed a Memorandum of Agreement with USCG.

Also, MSC follows a policy of voluntary compliance with international standards, and each MSC vessel that complies with these standards is issued a Statement of Voluntary Compliance.

Nonetheless, as an operator of "public vessels" MSC is authorized to request waivers from U.S. navigation and vessel inspection laws when it is in the interest of national security. This authorization applies to vessels operated by or chartered to MSC. The waiver authority, however, does not extend to provisions of international treaties that apply to ships chartered from commercial operators.

2.4 MSC Stability Standards

MSC requires all vessels owned, operated, or chartered by MSC be capable of surviving flooding in any one compartment as defined in MARAD Design Letter No.3, the MARAD damage stability standard required for designs seeking federal shipbuilding subsidies.

However, in the event that USCG regulations impose more stringent requirements, e.g., a two-compartment standard for a tanker of 150 m (492') or more, then the

MARAD Design Letter No.3 is superseded by those regulations. Exceptions are:

- T-AE (Ammunition Ships), T-AOE (Ammunition/Oilers), T-AKE (Ammunition/Dry Cargo Ships) Classes – Given the high value of the cargoes carried, these classes are subject to the more stringent two-compartment damage criterion (essentially the SOLAS Chapter II-1, Part B, Passenger Ship requirements).
- T-ATF (Fleet Ocean Tugs) Class – These ships are only subject to Righting Energy intact stability criterion as defined in USCG CFR 46 Subchapter S.
- For any vessel, when a particular condition results in a greater required GM under the USCG weather criterion, then that criterion takes precedent.

3. CASE STUDIES

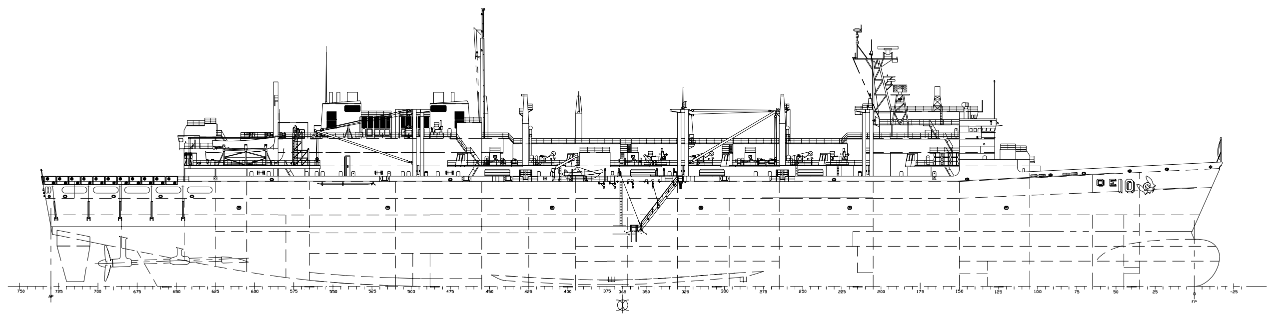

Figure 1 – Profile of T-AOE Class

Two MSC vessel classes were selected for probabilistic damage stability analysis due to their operational restrictions, which have a significant impact on their mission flexibility, T-AOE 6 Class Fast Combat Support Ships and T-AE 32 Class Ammunition Ships.

3.1 T-AOE 6 Class

Mission Description. The fast combat support ships of the T-AOE 6 Class are one of the world's largest active combat logistics ships. The T-AOE 6 Class have the speed to keep up with the carrier strike groups. They rapidly replenish Navy task forces and each ship can carry more than 1964 m3 (177,000 barrels) of oil; 2,150 tons of ammunition; 500 tons of dry stores; and 250 tons of refrigerated stores. The T-AOE's receive petroleum products, ammunition and stores from shuttle ships and redistribute these items simultaneously to carrier strike group ships.

Principal characteristics.

▪ Length:	227 m (754 ft)
▪ Beam:	32.6 m (107 ft)
▪ Draft:	11.58 m (38 ft)
▪ Displacement:	49,300 tons
▪ Speed:	25 knots
▪ Civilian Mariners:	160
▪ Military Detachment:	28

Stability criteria. The required GM curve is based on the two-compartment damage standard. When operating in a light condition (i.e. no cargo), case-by-case permission has been granted to operate under a required GM curve based on the USCG weather criterion.

Operating restrictions.

- No centerline cargo oil tank shall be emptied below 98% until all cargo oil wing tanks are emptied to 24% capacity.
- No cargo oil wing tank shall be filled above 24% capacity until all cargo oil centreline tanks are filled to 98% capacity.

- No cargo oil wing tank is to be emptied below 24% capacity.

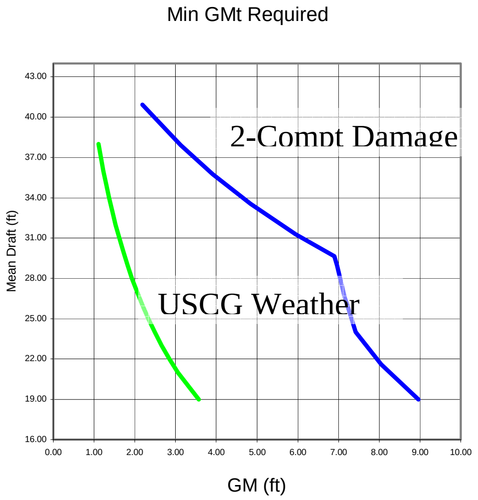

Fig. 2 – T-AOE 6 Required GM Curve.

Assessment of Mission Impact. Central to the T- AOE's mission is the ability to transfer a fixed quantity of petroleum products to combatants at sea. The current operating restrictions clearly limit this quantity to 11.5% of the total cargo oil capacity. This is effectively a loss of 20,355 barrels per deployment. A significant amount of cargo oil is being transported at cost, but for zero benefit to the fleet at sea; in many instances requiring an additional deployment to make up for the shortfall.

The operating restrictions, when viewed in terms of the larger Navy mission, can put individual Masters in particularly difficult situations. Scenarios have occurred where Masters have had to deny a combatant vessel's request for fuel oil for fear of violating the operating restrictions. To date the vessel's safety at sea has remained paramount, however it is easy to envision a situation where the military need for fuel oil at sea overrides the safety of a single vessel.

3.2 T-AE 32 Class

Mission Description. MSC's ammunition ships provide underway replenishment of all types of ammunition via connected replenishment and vertical replenishment. Additionally, the T-AEs frequently assist with the transfer of ammunition between weapons storage and maintenance facilities worldwide.

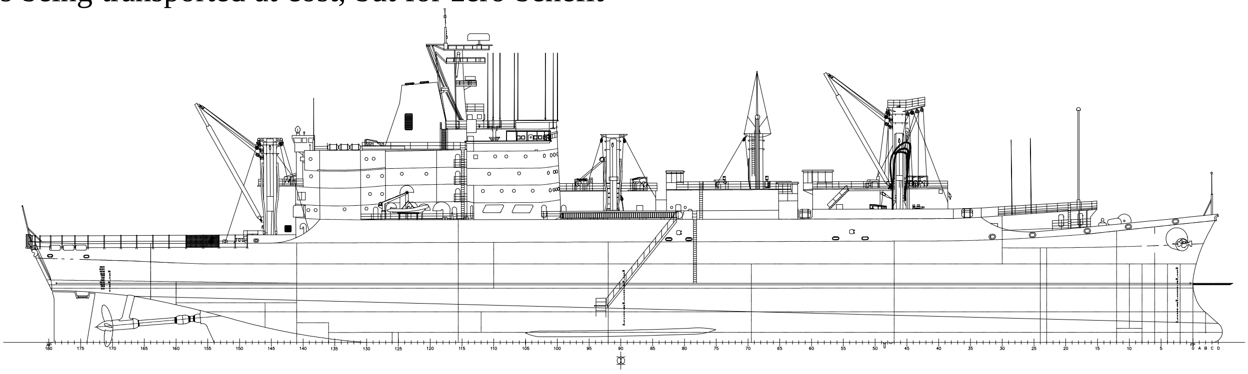

Figure 3 – Arrangement of T-AE Class

Principal Characteristics.

- Length: 172 m (564 ft)
- Beam: 24.7 m (81 ft)
- Draft: 8.53 m (28 ft)
- Displacement: 20,300 tons
- Speed: 20 knots
- Civilian Mariners: 125
- Military Detachment: 55

Stability criterion. When carrying ammunition, the required GM curve is based on a two-compartment damage criterion. When operating without ammunition, the required GM curve based on the USCG weather criterion is used.

Operating Restrictions. (when carrying ammunition only)

- May not exceed 93% of the loadline displacement.
- May not exceed 88% of the loadline displacement when operating with trim by the stern.
- With increasing trim by the stern, the allowable operating displacement is reduced. For example, 9 feet trim by the stern limits displacement to no more than 78% of the loadline displacement.
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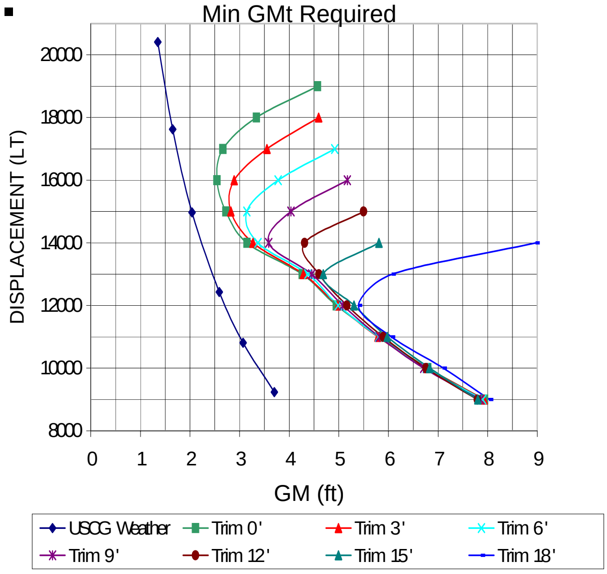

Note: All trims are by the stern.

Fig. 4 – T-AE 34 Required GM Curve.

Note: Operating restrictions are due solely from partial submersion, in the upright equilibrium condition, of the aft mooring deck (12.34m ABL & 2.21m below the Main Deck) in two specific damage cases.

Assessment of Mission Impact. The T-AE Class' sole mission is the ability to carry and transfer munitions. The restrictions on the maximum operating displacement obviously impact the capabi]lities of the T-AE, either by reducing the amount of munitions carried or limiting the range of the vessel.

The reduction in allowable operating displacement as trim by the stern increases affects two issues. First, to control the amount of trim (hence increase allowable displacement) significant weight must be kept far forward of the longitudinal center of flotation in the forward cargo holds. Mission execution intensifies the vessel's hog; the resultant increase in bending moment therefore demands closer consideration of the longitudinal strength.

Secondly, the need to control the trim constrains flexibility with regards to placement of munitions within the T-AE's cargo holds. The lack of loadout flexibility requires the T-AE to follow a pre-determined at-sea transfer plan. This places a practical limit on the type and quantity of munitions available to recipient naval vessels, severely constraining the ability to meet emergent munitions requirements.

4. PROBABILISTIC DAMAGE STABILITY ANALYSIS OVERVIEW

Probabilistic criteria are used to set appropriate standards in many engineering disciplines. These probabilistic methods are based on risk concepts where the likely loads on a system are compared to the likely level of the system to resist the loads. In the case of ship damage stability, probabilistic methods consider the full range of potential damage scenarios that the ship might be subjected to and compare these to the ability of the ship to survive these types of damage. The resulting Attained Subdivision Index measures the capability of a ship to remain afloat after a loss of watertight integrity.

4.1 Background

Probabilistic criteria have been used for the evaluation of damage stability since the late 1950's. This methodology was developed to address the inconsistencies in the classical one- and two-compartment deterministic damage standards, which have been in place internationally since 1929. Results from deterministic damage stability calculations have been found to be overly conservative when compared to the true ability of a vessel to survive following damage and flooding.

Probabilistic standards more closely represent the true ability of a vessel to survive damage and flooding. These standards were first adopted as an equivalent alternate method for passenger ships in 1974, (IMO, 1974) and became mandatory for dry cargo ships in 1992 (IMO, 1990).

The International Maritime Organization (IMO) has recently adopted harmonized probabilistic regulations applicable to both passenger and cargo ships (IMO, 2004). These regulations are set to become mandatory with the next set of SOLAS amendments, likely in 2007 or 2008.

4.2 Approach

A representative vessel from the T-AOE 6 Class, USNS SUPPLY, and T-AE 32 Class, USNS MOUNT BAKER, were selected for the Case Studies discussed in Section 3 of this paper. These two vessels have been evaluated using the two IMO-adopted probabilistic criteria: 1) the current SOLAS rules for dry cargo ships, 2) the upcoming SOLAS rules for both passenger and cargo ships.

Current SOLAS probabilistic rules for dry cargo ships are generally considered appropriate for vessels meeting a classic one-compartment deterministic standard (i.e. MARAD Design Letter No. 3). The impending SOLAS passenger ship rules are more appropriate for ships carrying large numbers of individuals, bulk oils and fuels, and ammunition which would traditionally be required to meet a two-compartment standard.

4.3 Software and Methodology

The Damage Stability module of the HECSALV suite of naval architectural programs was used for the probabilistic evaluation of the case studies. This software is able to generate and organize hundreds of damage stability runs, representing the potential damages that the ship might encounter, along with the probability of occurrence for each damage case.

Survival criteria (permissible static heel angle, GZ, range of positive stability, and immersion of down-flooding points) are then applied to each damage case.

The resulting Attained Subdivision Index is the sum of the probabilities of occurrence for each survival case, weighted for two or three drafts over the operating draft range. For example, in the case of the New Cargo and New Passenger probabilistic regulations (see below), the resulting index is weighted based on the following: 40% from the deepest subdivision loadline, 40% from the partial loadline, and 20% from the lightest service draft.

4.4 Criteria Used for Evaluation

Three probabilistic standards are used for the evaluation of the case studies, namely:

Existing Cargo. These are SOLAS Part B-1 regulations for cargo ships that have been in force in 1992 for all dry cargo ships on international voyages. These regulations use two drafts for developing the average Attained Subdivision Index. The survival criteria is based on a GZ lever of 0.10m with a positive range of 20 degrees and a static heel angle of 25 degrees or less for 100% survival and 30 degrees or more for 0% survival. The Existing Cargo regulations use a fixed permeability of 0.70 for all dry cargo spaces.

New Cargo. These are the cargo ship part of the new "harmonized" probabilistic regulations that were approved in 2005 and will replace the part B-1 cargo ship regulations when they are adopted in the next round of SOLAS conference amendments. The survival criteria is based on a GZ lever of 0.12m with a positive range of 16 degrees and a static heel angle of 25 degrees or less for 100% survival and 30 degrees or more for 0% survival. The New Cargo regulations use a permeability for dry cargo spaces that varies from 0.70 at deep drafts to 0.95 at the light service draft.

New Passenger. These are the passenger ship part of the new "harmonized" probabilistic regulations. The survival criteria is based on a GZ lever of 0.12m with a positive range of 16 degrees and a static heel angle of 7 degrees or less for 100% survival and 15 degrees or more for 0% survival.

Note: None of the three probabilistic criteria consider the classic Margin Line immersion. Immersion limits for the static condition are based on weather-tight down-flooding points, escape hatches, or evacuation routes only.

5. PROBABILISTIC DAMAGE STABILITY ANALYSIS

5.1 T-AOE Class Results

The results of the three probabilistic analyses for the T-AOE 6 are indicated in the following table. Each analysis was run at the same required GMs for the existing 2-compartment standard requirements.

	Exist Cargo	New Cargo	New Passenger
Ds	0.942	0.942	0.628
Dp	0.997	0.993	0.747
Dl		0.755	0.775
Total A	0.969	0.952	0.705
Required R	0.611	0.593	0.710

Without any tank operating restrictions, the results from the Existing and New Cargo analyses are fairly similar and indicate that the ship significantly exceeds these requirements. However, the Attained Index is just slightly under the Required Index for the New Passenger regulations (also without any tank operating restrictions). As mentioned before, the New Passenger regulations are the closest comparable probabilistic criteria to the existing two-compartment damage stability standard.

5.2 T-AOE Class Operating Restrictions

For the T-AOE Class, the most onerous damage condition is with fuel and cargo tanks empty. The table above represent unrestricted tank loading results (i.e. no operating restrictions). Any operating restrictions requiring minimum fill levels will improve the Attained Index. For example, requiring the cargo oil wing tanks to be 16% full only at the deepest load-line draft will raise the Ds index to 0.644 and the overall A index to 0.711, meeting the New Passenger criteria while imposing only minimal operating restrictions (current operating restrictions limit the cargo oil wing tanks to no less than 24% capacity).

5.3 T-AE Class Results

Results of the three probabilistic analyses are indicated in the following table. Each analysis was run at the required GM for the existing 2-compartment standard requirements with level trim.

	Exist Cargo	New Cargo	New Passenger
Ds	0.915	0.922	0.889
Dp	0.965	0.962	0.768
Dl		0.992	0.829
Total A	0.940	0.952	0.828
Required R	0.537	0.567	0.700

As with the T-AOE Class, the results from both the Existing and New Cargo analyses are fairly similar and indicate that this ship significantly exceeds these requirements. This ship also easily meets the New Passenger regulations, which should be comparable to the 2-compartment standard used in the deterministic analysis.

5.4 T-AE Class Operating Restrictions

With the deterministic criteria this ship requires progressively greater deadweight restrictions with increasing aft trim, primarily driven by the immersion of the main deck Margin Line at the transom. Since the probabilistic criterion considers only down flooding and not the Margin Line immersion, the probabilistic results are far less sensitive to trim aft. For example, running the New Passenger probabilistic calculations at the maximum 18 foot trim by the stern results in a total Attained Index of 0.729. While this is a substantial reduction from the 0.828 index for the level trim case, it still meets the criteria without any tank or deadweight operating restrictions.

6. COMPARISON OF RESULTS

6.1 T-AOE Class

The results of the probabilistic analysis indicate that these ships can easily meet the Existing Cargo ship and the New "harmonized" Cargo ship requirements. However, without any tank operating restrictions, the ships fall slightly short of the New "harmonized" Passenger ship requirements, which are the closest comparable probabilistic criteria to the existing two-compartment damage stability standard. Nonetheless, the results also show that with only minor operating restrictions, requiring minimal fill levels at the deepest drafts, the New Passenger criteria can be met. These operating restrictions are much less stringent than the existing restrictions derived from the deterministic criteria. Subsequently, with the application of the probabilistic criteria, these ships can have much greater flexibility in accomplishing their mission than is presently possible, due to restrictions imposed by the deterministic criteria.

6.2 T-AE Class

The results of the probabilistic analysis indicate that these ships can easily meet the Existing Cargo ship, New "harmonized" Cargo, and New Passenger requirements. The probabilistic analysis has shown that the operating restrictions imposed by the deterministic criteria, which are driven by the immersion of the Margin Line, are excessively conservative. By considering the down-flooding points rather than Margin Line immersion, the results reflect a much more realistic survival capability of these ships. Subsequently, with the application of the probabilistic criteria, these ships can have much greater flexibility in accomplishing their mission than is presently possible, due to the restrictions imposed by the deterministic criteria.

7. CONCLUSIONS

Both deterministic and probabilistic analyses are accepted methods to specify a high standard for surviving flooding of a ship’s watertight spaces.

However, deterministic analysis is based on finding the single worst damage case at each of the ships operational drafts. Subsequently, operating restrictions are often required at deep drafts or large trims to keep the required GM within reasonable operational limits for these governing damage cases. For ships like the T-AE and the T-AOE Class, which have only moderate freeboard to the Margin Line and high levels of deck tightness (no low exposed down-flooding points), the Margin Line immersion drives the deterministic design, but has little impact on the actual survivability of the ship.

Probabilistic analysis gives an overall average rating to the survivability of the ship and is less driven by specific damage cases. The survival criteria of modern probabilistic regulations are based on conditions that directly impact the survivability and operability of a damaged ship (heel angle, righting arm and range, and immersion of down-flooding points and escape routes) and ignore immersion of the Margin Line.

The case studies presented in this paper have demonstrated that the application of the deterministic standard can impose excessively conservative restrictions on the ships operation, which subsequently can have significant impact on the ships ability to perform its mission.

8. REFERENCES

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