



# **Advisory Notes on Ballast Water Exchange Procedures**

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### **Cautionary Note**

It should be noted that the specific ballast sequence information contained in this document is based on detailed calculations and precise tank loading scenarios. Ballast management plans and ballasting procedures need to consider actual vessel operations and the level of complexity involved in implementation.

In addition, the procedures should consider the actual capabilities of the pumping and measuring devices to be employed, the parameters of the required weather window, and the ability of shipboard personnel to perform the intended operations under a range of operating conditions.

The specific ballast sequence information contained herein clearly demonstrates that ballast exchange procedures may require that the ship be at, or near, allowable operational limits during the procedure. Ship operators are urged to exercise the utmost caution when implementing any ballast exchange procedure.



# Advisory Notes on Ballast Water Exchange Procedures

## **Background**

Beginning in 1989 governments started to institute national and regional regulations intended to minimize the introduction of unwanted organisms from the discharge of ballast water in their local jurisdictions. IMO adopted voluntary standards in 1993, and adopted guidelines for management of ships' ballast water in 1997. Further, the United Nations *Convention on the Law of the Sea* requires signatory nations to "take all measures necessary to prevent, reduce and control the intentional or accidental introduction of species, alien or new, to any part of the marine environment, which may cause significant or harmful changes thereto." Future IMO Regulations may also be looming on the horizon.

Shipboard actions necessary to address (present and pending draft) ballast water exchange requirements involve a combination of design and/or operational measures. For newbuilds it would be desirable to consider the incorporation of vessel design features that simplify/improve a vessel's ability to perform ballast water exchange operations. However, in the case of existing vessels it is generally presumed that ballast water exchange will be addressed through operational measures, but a limited number of existing vessels may require changes to their ballast system.

This advisory describes the implications of ballast water management and ballast exchange using fourteen typical vessels. The findings focus on existing vessels, yet conclusions can also be drawn with respect to desirable features for newbuilds.

**It is noted that the details are vessel specific and the information contained herein should be viewed as typical, representative values, the results that might be obtained for any single vessel are highly dependent on vessel design and structure, which may vary greatly from one vessel to another. This Advisory is not intended as a substitute for vessel specific calculations and the independent professional judgement of the user.**

## **Means to Minimize Unwanted Organisms from Ballast Water**

There are several measures that can be taken to minimize the release of unwanted organisms from ships' ballast water. A summary of methods to mitigate the introduction of non-indigenous species through ballast water is as follows:

- a) Retention of ballast on board: Eliminating ballast water discharge is of course the most reliable means of preventing the introduction of aquatic organisms. Although complete elimination of ballast discharge is not always practical, in most cases proper ballast water management can minimize the quantity of ballast requiring exchange or treatment.

- b) Reducing organisms taken on board: Limiting the amount of ballast taken is the first step in an effective ballast management plan. Practices that minimize the intake of port and coastal sediment can also be effective in reducing aquatic introductions. Ballasting should be avoided in very shallow waters, in stagnant areas, in the vicinity of sewage outflows and dredging operations, in areas where target organisms or known pathogens are present, etc. Whenever practical, the loading of ballast should be delayed until the ship is in open ocean waters.
- c) Exchange of ballast at sea: Ballast water exchange is currently considered the single most practical method for ballast water management. Ballast water exchange can be accomplished by either the *sequential* empty-refill method or by *flow through* (also referred to as the *overflow* method). It has been reported that these methods are about 95% effective in eliminating aquatic organisms. Ballast water exchange operations should be performed in deep water away from coastal shelves and estuarine influences.

The *sequential* method entails completely emptying ballast tanks and refilling with open-ocean water. Emptying of certain tanks may lead to significantly reduced stability, higher stresses, high sloshing pressures, and/or reduced forward drafts. A secondary effect of reduced forward draft would be an increased probability of bow slamming.

The *flow through* method involves pumping open-ocean water into a full ballast tank. Ballast equal to approximately three times the tank capacity must be pumped through the tank to achieve 95% effectiveness in eliminating aquatic organisms. Applying the *flow through* method does not alter the stability, stress, and ship attitude.

- d) Shipboard ballast water treatment: Although ballast water treatments are currently being investigated, none has yet been shown to be practical or cost effective for general use by most ships.
- e) On-shore ballast water treatment: On-shore treatment in principle has several advantages to shipboard treatment. However, many ships do not currently have the capability in their piping system to discharge water ashore.

The information presented in this document focuses on the use of ballast water management practices and ballast water exchange (options a, b, and c), rather than treatment. The optimum solution typically involves a combination of these three methods. The information is based on the specific vessels described in the next section.

## **Description of Vessels Considered in the Study**

ABS studied ballast water exchange procedures using fourteen vessels covering four major vessel types. A general description of the vessels used in this study is as follows:

Table 1

| Vessel Type        | General Description     | LBP (m) | Beam (m) | Depth (m) |
|--------------------|-------------------------|---------|----------|-----------|
| Single Hull Tanker | 35,000 DWT              | 168.0   | 30.4     | 16.2      |
|                    | Suezmax                 | 261.0   | 50.0     | 25.1      |
|                    | VLCC                    | 313.0   | 56.6     | 28.6      |
| Double Hull Tanker | 40,900 DWT              | 174.3   | 32.2     | 19.2      |
|                    | Suezmax (A)             | 258.0   | 46.0     | 23.9      |
|                    | Suezmax (B)             | 289.8   | 46.2     | 25.3      |
|                    | Suezmax (C)             | 274.0   | 50.0     | 24.5      |
|                    | VLCC                    | 317.0   | 58.0     | 31.4      |
| Bulk Carrier       | Handysize               | 160.3   | 27.2     | 13.6      |
|                    | Panamax                 | 215.0   | 32.2     | 18.7      |
|                    | Capesize                | 270.0   | 45.0     | 23.8      |
| Containership      | Feeder (1200 TEU)       | 190.2   | 23.8     | 14.3      |
|                    | Panamax (2500 TEU)      | 205.2   | 32.2     | 20.3      |
|                    | Post-Panamax (4800 TEU) | 260.8   | 39.4     | 23.6      |

## **Comments on Ballast Exchange Sequences**

To gain insight on feasibility and trends, a few sequences were developed for each tanker and bulk carrier design. As will be explained later in this document, containerships were not evaluated for *sequential* and *flow through* exchange. The primary considerations in assessing *sequential exchange* scenarios focused on vessel stability, hull girder strength, propeller immersion, bridge visibility, and list angle. In addition, the effects of ballast water exchange on slamming, sloshing, and damage stability/survivability were considered. The time to execute a sequence, the number of steps, the number of tanks, the number of ballast movements, and the time to ballast to original (pre-exchange sequence) drafts were also considered as key elements in selection of viable ballast exchange options. For the *flow through* method, the time to overflow each tank individually and the time to overflow sets of tanks to reduce time are determined.

Evaluating *sequential* and *flow through* exchanges require two different methodologies. The *sequential* method requires considerable planning to ensure that the ship will remain within the accepted criteria. The *flow through* method will not normally affect the ship's condition, but it is important to assess piping and overflow arrangements to ensure that the tank will not be over-pressurized.

The venting and overflow arrangements for each tank must be reviewed to insure that *flow through* is a practical alternative. For instance, in some cases the Forepeak and Aftpeak tanks overflow into enclosed spaces, which eliminates the *flow through* option for these tanks. Precautions should also be taken to avoid over-pressurization of tanks. It may be necessary to remove manhole covers or butterworth openings to assure sufficient venting. This raises a number of concerns: the removal and replacement of covers is labor intensive, potential safety risks to personnel accessing the upper deck will limit *flow through* exchange to favorable weather conditions only, and the overflow of ballast on deck is prone to icing in cold environments. For these reasons, ballast tanks in a number of recent newbuildings have been fitted with standpipes and valves, permitting overboard discharge of ballast through the shell just above the deep ballast waterline. (See figure 1.)

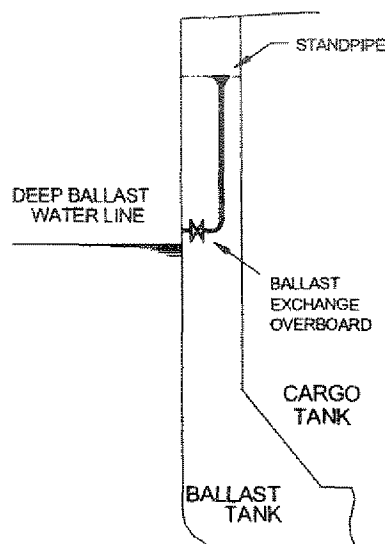


Figure 1  
Standpipe to facilitate flow through

## **Single Hull Tankers**

Three single hull tankers were evaluated using *sequential* and *flow through* exchange methods. These designs incorporate a standard MARPOL 73/78 segregated ballast tank arrangement, with ballast located in alternate wing tanks. Listed below are key findings arising from the ballast water management analysis of single hull tankers:

- Implementing the *sequential* method of exchange on single hull tankers is problematical. Due to the minimum number of ballast tanks and their distribution, it is difficult to maintain forward and aft drafts and satisfy the longitudinal strength criterion.
- Most of these exchange sequences are suitable for favorable weather conditions only. For single hull tankers, the *flow through* method is generally a more suitable alternative for exchange.
- The sequences tend to be complex, with approximately 50% more steps than there are ballast tanks. In contrast, the number of steps in the exchange generally does not exceed the number of ballast tanks for double hull tankers.

### **Sequential exchange**

While these tankers have a similar amount of ballast volume as double hull tankers of comparable size, the MARPOL 78 tankers lack flexibility in ballast exchange because the ballast is concentrated in a small number of relatively large wing tanks. The capability to control the ship's trim, drafts and strength during the exchange process is limited. For all of the sequences studied, fore/aft diagonally opposite side tanks were emptied in pairs (e.g., No.2S & No.4P were exchanged as a set). This is a standard method for single hull tanker sequences as it helps to maintain a reasonable forward draft, reduce the maximum list, trim and bending moment, and maximize bridge visibility.

The total time involved in the ballast exchange process is as follows:

Table 2

| Single Hull Tankers<br>Ship Type – Ballast condition | Time to perform exchange<br>Sequence (hours) | Additional time to ballast<br>to original drafts (hours) |
|--|--|--|
| 35,000 DWT – Normal Ballast                          | 15   | 3  |
| Suezmax – Normal Ballast                             | 29   | 9  |
| – Heavy Ballast                                      | 40   | 10   |
| VLCC – Normal Ballast                                | 41   | 9  |

General trends observed when developing exchange sequences for single hull tankers are listed below:

- The forward draft tends to become very light. Due to the few, large ballast tanks the forward draft is often reduced by more than 50% during the sequence.
- Trim can be quite high. However, the large trims are not a major concern as they occur when the vessel is deep in the water.
- Propeller immersion can be difficult to maintain.
- For many ships, the fore and aft wing ballast tanks do not have identical capacities. To prevent excessive heeling, the larger wing tanks must be initially pumped down together.
- Bending moments approach 100% allowable during the sequence.
- Bridge visibility is often not sufficient during these sequences, due to the high level of trim aft. However, it is noted that this occurs in the open sea where risk of collision is less significant.
- It is difficult to satisfy all of the criteria at all times using the *sequential* method for single hull tankers. The *flow through* method may be a more suitable alternative for exchange.

### Flow through exchange

For the single hull tankers, the overflow method is often a more attractive method than the *sequential* method. The *flow through* method eliminates concerns related to shallow forward and aft drafts and extreme trims. While it may take longer to carry out, there is less total “attention time” than with the *sequential* method, especially when sets of tanks are simultaneously overflowed.

The total time involved in the ballast exchange process, when performing operations in pairs of tanks, is as follows:

Table 3

| Single Hull Tankers<br>Ship Type | Volume capacity of<br>ballast tanks (m <sup>3</sup> ) | Time to perform flow<br>through exchange (hours) |
|----------------------------------|---|--|
| 35,000 DWT                       | 12,900  | 21   |
| Suezmax                          | 64,100  | 29   |
| VLCC Single Hull                 | 97,800  | 47   |

## Example of a sequential exchange procedure for a single hull Suezmax tanker

In order to illustrate the complexity of a sequential procedure the following is presented as an illustration of a procedure that was developed for a single hull Suezmax tanker. This is a 152,000 DWT single hull (MARPOL 78) tanker with 11 cargo tanks (5 center tanks and 3 pairs of wing tanks) and 6 ballast tanks (FP, 2 pairs of wing tanks, and AP) as shown below. Two initial ballast conditions, *Normal* and *Heavy*, have been reviewed for this vessel. The vessel has one ballast pump (rated for 3,500 m<sup>3</sup>/hr).

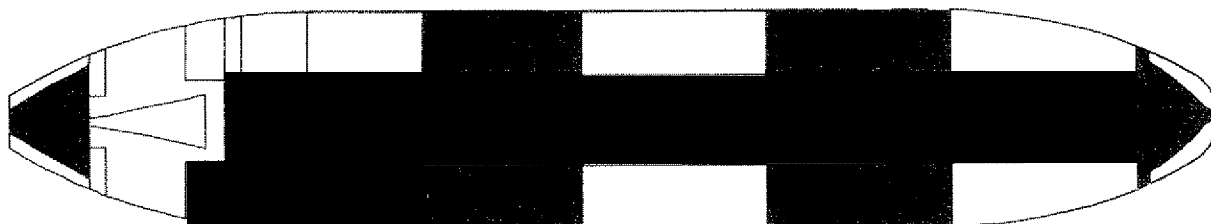


Figure 2

### General arrangement / tank layout

Two initial ballast conditions were investigated for this tanker. Further details on the *Normal* sequence are included here for illustration of a typical single hull tanker example. There are 8 steps and 12 ballast movements in the sequence. This appears to be typical for a MARPOL 78 Suezmax ship. The sequence takes 29.3 hours to complete. The forward draft was maintained as deep as possible, nevertheless, the sequence has a minimum forward draft of 2.46m, well below the target value. Since there are only six ballast tanks there is little flexibility in how the sequence is carried out.

The Forepeak is partially filled while the No.2s and No.4s are exchanged. This is to maintain the deepest possible forward draft but remain below the 100% allowable bending moment. In order to minimize heeling, the No.2 ballast tanks were pumped down to the same weight as the No.4 ballast tanks. The sequence was run and then the No.2 tanks were refilled to 100% capacity.

The following table shows the limiting values and the peak values from the sequence. The limiting values are exceeded for the forward draft, trim and bridge visibility deadzone limits. The minimum forward draft of 2.46m falls well below the target value, increasing the likelihood of slamming in heavy weather. Additionally, the aft draft target value is not satisfied during a significant portion of the exchange sequence. The maximum trim of 5.08m is a concern, as it leads to problems with the bridge visibility deadzone.

Table 4

|                                  | Peak Value | Limiting Value | Limiting Value Reason         |
|----------------------------------|------------|----------------|-------------------------------|
| Draft AP (m) [min]               | 7.54       | 8.164          | 100% propeller immersion      |
| Draft FP (m) [min]               | 2.46       | 5.263          | MARPOL Reg. 13 for tankers    |
| Trim at Perpendiculars (m) [max] | 5.08       | 3.915A         | MARPOL Reg. 13 for tankers    |
| GMt (m) [min]                    | 16.2       | 0.15           | IMO A167                      |
| Static Heel (deg) [max]          | 0.1P       | 1.0            | Assumed                       |
| Bridge Visibility Deadzone (m)   | 808        | 500 m          | IMO MSC/Circ. 403             |
| B.Moment (% Allowable) [max]     | 99%        | 100%           | Permissible Still-Water Value |
| Shear (% Allowable) [max]        | 67%        | 100%           | Permissible Still-Water Value |



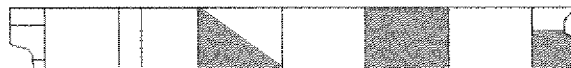

Details of the step-by-step ballast exchange sequence are presented on pages 7 and 8.



## Sample Suezmax tanker ballast exchange sequence

| Operating Criteria (limiting value during sequence step)            |               |               |           |                |                    |                         |                   |          |                        | Status of Ballast Tanks at Start of Sequence Step (% Full) |         |         |         |          |    |
|---|---------------|---------------|-----------|----------------|--------------------|-------------------------|-------------------|----------|------------------------|--|---------|---------|---------|----------|----|
|   | Draft AP<br>m | Draft FP<br>m | Trim<br>m | Prop Imm.<br>% | Static Heel<br>deg | Bending Mom<br>% Allow. | Shear<br>% Allow. | GMt<br>m | Bridge Visibility<br>m | NO. 4 P  | NO. 4 S | NO. 2 P | NO. 2 S | Forepeak |    |
| Start   | 8.86          | 6.46          | 2.4A      | 1.09           | 0                  | 73                      | 67                | 16.9     | 530                    |  | 60      | 60      | 100     | 100      | 0  |
| 1. Pump Forepeak to 52% capacity                                    | 7.98          | 6.46          | 2.4A      | 97             | 0                  | 73                      | 67                | 16.4     | 530                    |  | 60      | 60      | 100     | 100      | 52 |
| 2. Pump SWB No.2 P to 52% capacity & SWB No. 2 S empty              | 8.02          | 4.17          | 4.8A      | 98             | 0                  | 71                      | 64                | 16.4     | 737                    |  | 60      | 60      | 100     | 100      | 52 |
| 3. Pump SWB No. 4 P to empty & continue pumping SWB No.2 S to empty | 7.54          | 2.46          | 5.1A      | 91             | 0.1P               | 99                      | 51                | 23.0     | 808                    |  | 60      | 60      | 52      | 52       | 52 |
| 4. Pump SWB No. 2 S to 52% capacity & SWB No. 4 P to 60% capacity   | 7.82          | 7.48          | 0.3A      | 93             | 0                  | 97                      | 51                | 17.4     | 801                    |  | 0       | 60      | 52      | 0        | 52 |
| 5. Pump SWB No. 2 P and SWB No. 4 S to empty                        | 7.54          | 2.46          | 5.1A      | 91             | 0                  | 99                      | 51                | 22.9     | 808                    |  | 60      | 60      | 52      | 52       | 52 |

## Sample Suezmax tanker ballast exchange sequence (continued)

| Operating Criteria (limiting value during sequence step)                             |          |      |           |             |             |          |      |                   |     | Status of Ballast Tanks at Start of Sequence Step (% Full)                           |         |         |         |          |   |
|--|----------|------|-----------|-------------|-------------|----------|------|-------------------|-----|--|---------|---------|---------|----------|---|
| Draft AP   | Draft FP | Trim | Prop Imm. | Static Heel | Bending Mom | Shear    | GMI  | Bridge Visibility |     | NO. 4 P  | NO. 4 S | NO. 2 P | NO. 2 S | Forepeak |   |
| m  | m        | m    | %         | deg         | % Allow.    | % Allow. | m    | m                 |     |  |         |         |         |          |   |
| 6. Pump SWB No. 2 P to 100% capacity & SWB No. 4 S to 60% capacity                   |          |      |           |             |             |          |      |                   |     |    |         |         |         |          |   |
| 7.67   | 2.62     | 5.1A | 93        | 0           | 97          | 51       | 22.4 | 802               |     | 60   | 0       | 0       | 52      | 52       |   |
| 7. Pump SWB No. 2 S to 100% capacity & continue pumping SWB No. 2 P to 100% capacity |          |      |           |             |             |          |      |                   |     |    |         |         |         |          |   |
| 7.98   | 4.44     | 4.5A | 97        | 0           | 69          | 65       | 16.2 | 703               |     | 60   | 60      | 52      | 52      | 52       |   |
| 8. Pump Forepeak to empty  |          |      |           |             |             |          |      |                   |     |  |         |         |         |          |   |
| 8.51   | 6.46     | 2.4A | 104       | 0           | 73          | 67       | 16.7 | 530               |     | 60   | 60      | 100     | 100     | 52       |   |
| Finished   |          |      |           |             |             |          |      |                   |     |  |         |         |         |          |   |
|  | 8.86     | 6.46 | 2.4A      | 109         | 0           | 73       | 67   | 16.9              | 530 |  | 60      | 60      | 100     | 100      | 0 |

## **Double Hull Tankers**

Five double hull tankers were evaluated using *sequential* and *flow through* exchange methods. These designs incorporate typical tankage arrangements for modern double hull tankers, with two-across cargo tanks for the Panamax and Suezmax sizes, and three-across cargo tanks for the VLCC. Most of the ballast tanks are the L-type, although one Suezmax and the VLCC each have one U tank. Listed below are key findings arising from the ballast water management analysis of double hull tankers:

- Vessels with relatively smaller and greater numbers of ballast tanks, higher aggregate ballast capacity, and/or hull girder strength margins in excess of the minimum required have more options and generally better options when developing *sequential* exchange scenarios.
- Bridge visibility is often not sufficient during these sequences, due to the high level of trim aft.
- “U” tanks can present problems when developing *sequential* exchange scenarios
- The ballast arrangements for the double hull tankers provide more flexibility for *sequential* exchange than the single hull tankers. Two or three sequences were developed for each of the double hull tankers in the study.

### **Sequential exchange**

The ballast arrangements for the double hull tankers provide more flexibility for *sequential* exchange than the single hull tankers. Two or three sequences were developed for each of the double hull tankers in the study.

The total time involved in the ballast exchange process is as follows:

**Table 5**

| <b>Double Hull Tankers<br/>Ship Type – Ballast condition</b> | <b>Time to perform exchange<br/>sequence (hours)</b> | <b>Additional time to ballast<br/>to original drafts (hours)</b> |
|--|--|--|
| 40,900 DWT – Light Ballast                                   | 18   | 2  |
| – Normal Ballast   | 18   | 5  |
| – Heavy Ballast  | 19   | 2  |
| Suezmax (A) – Normal Ballast                                 | 9  | 4  |
| – Heavy Ballast  | 9  | 1  |
| Suezmax (B) – Light Ballast                                  | 9  | 1  |
| – Normal Ballast   | 9  | 4  |
| Suezmax (C) – Light Ballast                                  | 15   | N/A  |
| – Heavy Ballast  | 26   | 4  |
| VLCC – Light Ballast   | 29   | N/A  |
| – Heavy Ballast  | 30   | N/A  |

Listed below are key findings arising from the ballast water *sequential* exchange analysis of double hull tankers:

- Bridge visibility is often not sufficient during these sequences, due to the high level of trim aft. However, it is noted that this occurs in the open sea where risk of collision is less significant.

- The degree to which a vessel is suited to *sequential* ballast exchange is highly dependent on the vessel design. Two of the vessels that were studied had very efficient sequences, while the other three vessels required more complex sequences. Some of the design features impacting sequences are as follows:

Ships with large aggregate ballast volumes (beyond the minimum IMO requirement) and a relatively larger number of ballast tanks (i.e. 6x2 rather than 5x2 arrangements) provide greater flexibility for *sequential* exchange. (Efficiently does not necessarily imply the least amount of time. Other factors, such as maintaining the vessel within list, trim, strength, and stability limits may determine whether or not a sequence is desirable.)

In certain vessel designs, use of the Forepeak and Aftpeak tanks may lead to large bending moments making them unusable in the planning of ballast sequences.

Ballast exchange is facilitated in designs where there is excess hull girder strength margins beyond class requirements.

“U” tanks present problems, particularly in the 5 tank long ballast tank arrangement typical of double hull VLCC’s. The “U” tank precludes the option of diagonally exchanging ballast to control bending moment and trim.

In designs where there are significant variations in tank ballast capacities fore and aft, when performing diagonal exchange of ballast, the static heel becomes excessive.

Smaller ballast tanks located at the ends of the cargo block can assist in the development of efficient ballast exchange sequences.

- Bending moments typically approach allowable values when large midships tanks are emptied.
- “Relatively speaking;” in smaller vessels, small differences in the consumables could have a significant effect on the loading conditions and exchange sequence suitability.

### **Flow through exchange**

In some specific cases *flow through* exchange may be more attractive than *sequential* exchange for double hull tankers. Using the *flow through* method eliminates the concerns of shallow forward and aft drafts, and extreme trims. While it may take somewhat longer to carry out, there is less total “attention time” than with the *sequential* method, especially when sets of tanks are simultaneously overflowed.

The total time involved in the ballast exchange process, when performing operations in pairs of tanks, is as follows:

Table 6

| Double Hull Tankers<br>Ship Type | Volume capacity of<br>ballast tanks (m <sup>3</sup> ) | Time to perform flow<br>through exchange (hours) |
|----------------------------------|---|--|
| 40,900 DWT                       | 12,900  | 32   |
| Suezmax (A)                      | 55,000  | 27   |
| Suezmax (B)                      | 60,900  | 32   |
| Suezmax (C)                      | 74,400  | 46   |
| VLCC Single Hull                 | 105,000   | 44   |

Listed below are key findings arising from the ballast water *flow through* exchange analysis of double hull tankers:

- Applying the *flow through* method does not alter the stability, stress, and ship attitude. While it typically takes longer to carry out than *sequential* exchange, the process requires less “attention time” from the ship’s personnel.
- Double hull VLCC’s, with cargo and ballast tanks arranged five long within the cargo block, have difficulty with *sequential* exchange. For these vessels, *flow through* is an attractive alternative.

## **Bulk Carriers**

Three typical bulk carriers were investigated for *sequential* and *flow through* ballast exchange. These included a Handysize, Panamax, and Capesize. These ships are arranged with upper and lower hopper ballast tanks, and each design has one midships cargo hold fitted to carry ballast.

Listed below are key findings arising from the ballast water management analysis of bulk carriers.

- Sequences for the bulk carriers are quite complex, requiring many steps to maintain drafts and longitudinal strength within acceptable limits. Safe application of these sequences will require careful monitoring by the ship’s crew.
- Bending moments approach the 100% allowable value for each of the bulk carrier exchange sequences. These ships were not designed to have ballast tanks emptied during the course of the voyage and, therefore, careful planning is necessary to ensure that bending moments are maintained within acceptable levels.
- For all designs, it is difficult to exchange ballast in the cargo hold while maintaining compliance with forward draft, shear force and bending moment criteria.
- The cargo holds are generally not designed to withstand loads induced by resonant sloshing experienced during partial filling conditions. This precludes exchanging ballast in the holds during severe weather conditions.

## Sequential exchange

Bulk carriers are similar to tankers in that they are frequently in “ballast only” conditions. *Normal* and *Heavy* sequences were evaluated for each bulk carrier. Partial load conditions were not investigated.

The total time involved in the ballast exchange process is as follows:

Table 7

| Bulk Carriers<br>Ship Type – Ballast condition | Time to perform exchange<br>sequence (hours) | Additional time to ballast<br>to original drafts (hours) |
|--|--|--|
| Handysize – Light Ballast                      | 27   | 2  |
| – Heavy Ballast                                | 40   | 9  |
| Panamax – Normal Ballast                       | 17   | 29   |
| – Heavy Ballast                                | 6  | 11   |
| Capesize – Light Ballast                       | 36   | 4  |
| – Normal Ballast                               | 44   | 8  |

Observations related to the development of exchange sequences for the bulk carriers are as follows:

- Sequences are relatively complex as draft forward, draft aft, and bending moments frequently approach the limiting values. For the vessels investigated the sequences require between 12 and 19 independent steps, and up to 65 ballast movements.
- It is difficult to concurrently maintain adequate propeller immersion and forward draft.
- Capesize vessels generally have large double bottom ballast tanks extending two holds in length. It may not be possible to exchange some ballast tanks when the cargo hold is filled with ballast water, as excessive shear forces are encountered. In situations where the hold is emptied, the drafts are greatly reduced to near those in the light ballast condition.
- Shear force values for all of the *Heavy* ballast condition sequences that were studied are close to allowables.
- The Panamax vessel is fitted with overboard valves in the upper hopper ballast tanks. This allows quick gravity discharge of the ballast, significantly reducing the sequence time and providing more flexibility in how the pumps are used.

## Flow through exchange

The *flow through* method eliminates concerns of exceeding shear force and bending moment limits. *Flow through* exchange is an attractive alternative to the *sequential* exchange for the Capesize heavy ballast condition; it eliminates the light draft problem associated with *sequential* exchange.

The total time involved in the ballast exchange process, when performing operations in pairs of tanks, is as follows:

Table 8

| Bulk Carriers<br>Ship Type | Volume capacity of<br>ballast tanks (m <sup>3</sup> ) | Time to perform flow<br>through exchange (hours) |
|----------------------------|---|--|
| Handysize                  | 17,200  | 46   |
| Panamax                    | 32,300  | 50   |
| Capesize                   | 69,700  | 45   |

#### Example of a sequential exchange procedure for a Handymax bulk carrier

To illustrate the complexity of a sequential procedure the following is presented as an illustration of a procedure that was developed for a Handymax bulk carrier. This is a 28,000 DWT bulk carrier with 5 cargo holds and 5 P&S sets (a set consists of upper and lower tanks) of hopper ballast tanks. Ballast is also allocated to the Forepeak, Hold No.3, and Aftpeak as shown below. Two ballast exchange sequences, *Normal* and *Heavy*, have been reviewed for this vessel. The vessel has two ballast pumps (each rated for 500 m<sup>3</sup>/hr).



Figure 3

#### General arrangement / tank layout

Two initial ballast conditions were investigated for this bulk carrier. Further details on the *Normal* sequence are included here for illustration of a typical bulk carrier example. For the *Normal* sequence, there are 19 steps and 28 ballast movements and it takes 27.1 hours to complete. The initial condition for the *Normal* ballast condition has all ballast tanks full and the Hold No.3 (Ballast Hold) empty. The sequence starts and ends with the same tank levels, which is all ballast tanks at 100% capacity. This exchange sequence is quite complex. For instance, during the sequence the Forepeak Tank is emptied (step 1), filled to 10% capacity (step 2), filled to 30% capacity (step 6), filled to 35% capacity (step 14), and then filled to 100% capacity (step 18). This approach is necessary in order to satisfy the bending moment and propeller immersion requirements while maximizing forward draft.

Table 9 shows the limiting value and the peak values from the sequences. Target values are met for bending moment, shear strength, and aft draft during the sequence. The target values for forward draft, trim, heel, and bridge visibility are not met during several steps of the sequence.

**Table 9**

|                                  | Peak Value | Limiting Value | Limiting Value Reason                         |
|----------------------------------|------------|----------------|---|
| Draft AP (m) [min]               | 5.92       | 5.92           | 100% propeller immersion                      |
| Draft FP (m) [min]               | 3.02       | 4.00           | Assumed $2\text{m} + 0.0125 \cdot \text{LBP}$ |
| Trim at Perpendiculars (m) [max] | 3.30       | 2.39           | Assumed $0.015 \cdot \text{LBP}$              |
| GMt (m) [min]                    | 6.2        | 0.15           | IMO A167                                      |
| Static Heel (deg) [max]          | 1.4        | 1.0            | Assumed                                       |
| Bridge Visibility Deadzone (m)   | 341        | 321m           | IMO MSC/Circ. 403                             |
| B.Moment (% Allowable) [max]     | 97%        | 100%           | Permissible Still-Water Value                 |
| Shear (% Allow) [max]            | 67%        | 100%           | Permissible Still-Water Value                 |

Details of the step-by-step ballast exchange sequence are presented on pages 15 to 17.



Sample Handymax bulk carrier ballast exchange sequence

| Operating Criteria (limiting value during sequence step)   |                  |                  |           |                   |                       |                            |                   |          |                           | Status of Ballast Tanks at Start of Sequence Step (% Full) |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |          |    |
|--|------------------|------------------|-----------|-------------------|-----------------------|----------------------------|-------------------|----------|---------------------------|--|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|----------|----|
| Sequence<br>step   | Draft<br>AP<br>m | Draft<br>FP<br>m | Trim<br>m | Prop<br>Imm.<br>% | Static<br>Heel<br>deg | Bending<br>Mom<br>% Allow. | Shear<br>% Allow. | GMt<br>m | Bridge<br>Visibility<br>m | Afterpeak  | NO. 5 UW P | NO. 5 UW S | NO. 5 DB P | NO. 5 DB S | NO. 4 UW P | NO. 4 UW S | NO. 4 DB P | NO. 4 DB S | NO. 3 UW P | NO. 3 UW S | NO. 3 DB P | NO. 3 DB S | NO. 2 UW P | NO. 2 UW S | NO. 2 DB P | NO. 2 DB S | NO. 1 UW P | NO. 1 UW S | NO. 1 DB P | NO. 1 DB S | Forepeak |    |
| Start  | 6.00             | 4.17             | 1.8A      | 101               | 0.1S                  | 83                         | 66                | 6.2      | 264                       |  |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |          |    |
| 1. Pump Forepeak to empty  | 6.00             | 3.28             | 3.3A      | 101               | 0.1S                  | 83                         | 66                | 6.2      | 341                       | 100  | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100      |    |
| 2. Pump Forepeak to 10% capacity<br>3. Pump SWB No. 4 DB P&S to empty<br>4. Pump SWB No. 2 DB P&S to empty<br>(Item 4 commencing when tanks in Item 3, SWB No. 4 P&S, are at 46% capacity) | 5.93             | 3.04             | 3.3A      | 100               | 0.1S                  | 83                         | 67                | 6.4      | 341                       | 100  | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 0        |    |
| 5. PumpSWB No. 2 DB P&S and No. 4 DB P&S to 100% capacity<br>6. Pump Forepeak to 30% capacity  | 5.94             | 3.06             | 3.1A      | 100               | 0.1S                  | 81                         | 67                | 6.4      | 332                       | 100  | 100        | 100        | 100        | 100        | 100        | 100        | 0          | 0          | 100        | 100        | 100        | 100        | 100        | 100        | 0          | 0          | 100        | 100        | 100        | 100        | 100      | 10 |
| 7. Pump SWB No. 2 UW P&S and No. 4 UW P&S to empty   | 6.10             | 3.04             | 3.1A      | 103               | 0.1S                  | 80                         | 66                | 6.6      | 336                       | 100  | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100      | 30 |
| 8. Pump SWB No. 2 UW P&S and No. 4 UW P&S 100% capacity  | 6.16             | 3.10             | 3.1A      | 104               | 0.1S                  | 78                         | 65                | 6.6      | 334                       | 100  | 100        | 100        | 100        | 100        | 0          | 0          | 100        | 100        | 100        | 100        | 100        | 100        | 0          | 0          | 100        | 100        | 100        | 100        | 100        | 100        | 100      | 20 |

| Operating Criteria (limiting value during sequence step)  |               |               |           |                |                    |                         |                   |          |                        | Status of Ballast Tanks at Start of Sequence Step (% Full) |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |          |
|---|---------------|---------------|-----------|----------------|--------------------|-------------------------|-------------------|----------|------------------------|--|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|----------|
| Sequence step   | Draft AP<br>m | Draft FP<br>m | Trim<br>m | Prop Imm.<br>% | Static Heel<br>deg | Bending Mom<br>% Allow. | Shear<br>% Allow. | GMt<br>m | Bridge Visibility<br>m | Atpeak   | NO. 5 UW P | NO. 5 UW S | NO. 5 DB P | NO. 5 DB S | NO. 4 UW P | NO. 4 UW S | NO. 4 DB P | NO. 4 DB S | NO. 3 UW P | NO. 3 UW S | NO. 3 DB P | NO. 3 DB S | NO. 2 UW P | NO. 2 UW S | NO. 2 DB P | NO. 2 DB S | NO. 1 UW P | NO. 1 UW S | NO. 1 DB P | NO. 1 DB S | Forepeak |
| 9. Pump SWB No. 1 DB P and No. 5 DB S to empty  |               |               |           |                |                    |                         |                   |          |                        |  |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |          |
| 10. Pump SWB No. 1 UW P and No. 5 UW S to empty<br>(Item 10 commencing when tanks in item 9, SWB No. 1 DB P and No. 5 DB S are at 55% capacity) | 5.94          | 3.08          | 3.0A      | 100            | 1.2P               | 71                      | 67                | 6.6      | 331                    | 100  | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 30       |
|   |               |               |           |                |                    |                         |                   |          |                        |  |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |          |
| 11. Pump SWB No. 1 DB P, No. 1 UW P, No. 5 DB S, and No. 5 UW S to 100% capacity  | 5.95          | 3.10          | 2.9A      | 100            | 1.2P               | 72                      | 67                | 6.6      | 324                    | 100  | 100        | 0          | 100        | 0          | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 30       |
|   |               |               |           |                |                    |                         |                   |          |                        |  |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |          |
| 12. Pump SWB No. 1 DB S, No. 1 UW S, No. 5 DB P, and No. 5 UW P to empty  | 5.94          | 3.08          | 3.0A      | 100            | 1.4S               | 70                      | 67                | 6.7      | 328                    | 100  | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 30       |
|   |               |               |           |                |                    |                         |                   |          |                        |  |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |          |
| 13. Pump SWB No. 1 DB S, No. 1 UW S, No. 5 DB P, and No. 5 UW P to 100% capacity  |               |               |           |                |                    |                         |                   |          |                        |  |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |          |
| 14. Pump Forepeak to 35% capacity   | 5.95          | 3.10          | 2.9A      | 100            | 1.4S               | 73                      | 67                | 6.6      | 324                    | 100  | 0          | 100        | 0          | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 35       |
|   |               |               |           |                |                    |                         |                   |          |                        |  |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |          |
| 15. Pump SWB No. 3 UW P&S and No. 3 DB P&S to empty   | 5.99          | 3.02          | 3.0A      | 101            | 0.1S               | 97                      | 66                | 6.6      | 331                    | 100  | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 25       |
|   |               |               |           |                |                    |                         |                   |          |                        |  |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |          |

Sample Handymax bulk carrier ballast exchange sequence (continued)

| Operating Criteria (limiting value during sequence step)    |                  |                  |           |                   |                       |                           |                  |          |                           | Status of Ballast Tanks at Start of Sequence Step (% Full) |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |          |     |    |
|---|------------------|------------------|-----------|-------------------|-----------------------|---------------------------|------------------|----------|---------------------------|--|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|----------|-----|----|
| Sequence<br>step  | Draft<br>AP<br>m | Draft<br>FP<br>m | Trim<br>m | Prop<br>Imm.<br>% | Static<br>Heel<br>deg | Bending<br>Mom<br>% Allow | Shear<br>% Allow | GMt<br>m | Bridge<br>Visibility<br>m | Aftpeak  | NO. 5 UW P | NO. 5 UW S | NO. 5 DB P | NO. 5 DB S | NO. 4 UW P | NO. 4 UW S | NO. 4 DB P | NO. 4 DB S | NO. 3 UW P | NO. 3 UW S | NO. 3 DB P | NO. 3 DB S | NO. 2 UW P | NO. 2 UW S | NO. 2 DB P | NO. 2 DB S | NO. 1 UW P | NO. 1 UW S | NO. 1 DB P | NO. 1 DB S | Forepeak |     |    |
| 16. Pump SWB No. 3 UW P&S and No. 3 DB P&S to 100% capacity | 6.07             | 3.10             | 3.0A      | 102               | 0.1S                  | 93                        | 66               | 6.5      | 320                       |  | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 0          | 0          | 0          | 0          | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100      | 35  |    |
| 17. Pump Aftpeak to empty                                   | 6.20             | 3.66             | 2.6A      | 105               | 0.1S                  | 70                        | 60               | 6.6      | 300                       |  | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100      | 35  |    |
| 18. Pump Forepeak to 100% capacity                          |                  |                  |           |                   |                       |                           |                  |          |                           |  |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |          |     |    |
| 19. Pump Aftpeak to 100% capacity                           | 5.92             | 3.83             | 2.2A      | 100               | 0.1S                  | 83                        | 66               | 6.2      | 284                       | 0  | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 35       |     |    |
| Finished  | 6.00             | 4.17             | 1.8A      | 101               | 0.1S                  | 83                        | 66               | 6.2      | 264                       |  | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100        | 100      | 100 | 35 |

## **Containerships**

Containerships rarely operate in “ballast only” conditions. A typical voyage may consist of ten or more port calls, with containers generally loaded and off-loaded at each port. Ballast is allocated during the course of the voyage to accommodate changes in the distribution of cargo and consumables, and in response to operational requirements such as draft limitations. For containerships the procedure is more of a “management plan” than a ballast exchange process.

There are a number of sometimes-conflicting objectives facing the containership planner as containers are assigned to specific slots on the vessel. There is strong economic incentive to avoid re-handling of containers (i.e. moving containers to allow the cargo below to be off-loaded or shifting containers to adjust for trim or strength limitations). Stowage preferences limit the planner’s ability to optimize with regard to trim, bending moments, and stability, and it is unlikely that container stowage could be significantly modified to facilitate ballast exchange.

However, the fact that containerships retain cargo onboard throughout the voyage presents some benefits with regard to ballast management. Some tanks may remain permanently empty; some tanks can be maintained permanently full with locked in ballast; and it may be possible to discharge other tanks at sea rather than in port. For a given trade, the quantities and weights of containers loaded and off-loaded in each port generally follow repetitive and/ or cyclic trends. These historical data are used by planners to pre-plan stowage, and by ship Masters to aid in their decisions regarding allocation of ballast and consumables. By pre-planning an entire voyage cycle, it is expected that the amount of ballast moved and particularly the need to discharge ballast in port can be minimized.

This study investigated the practicality of a ballast management approach that considers entire voyages for three containerships. The ships selected for this analysis include a 1200 TEU feedership operating between Northern Europe and the Mediterranean Sea; a 2500 TEU Panamax containership operating between the U.S. West Coast, Hawaii, and Japan; and a 4800 TEU Post-Panamax containership operating in the U.S.-Far East trade. For each ship, the following investigations were carried out.

Development of voyage specific ballast water management approaches: A complete voyage cycle was developed using historical data from actual voyages for container weights and distributions, and other consumables. As far as practical, the actual ballast allocation scheme was also retained, although adjustments were made to eliminate the discharge of contaminated ballast in port or during inter-port legs through shallow waters. When allocating ballast, priority was given to maintaining compliance with the stability and strength regulations. An effort was also made to maintain the draft, trim, list, propeller immersion, and visibility within the acceptable limits. Within these constraints, ballast was allocated in order to minimize the amount of ballast to be discharged in port or coastal waters. When deballasting in port was unavoidable, the ballast was either originally loaded in deep ocean waters or an exchange was carried out in deep water.

Ballast movements for each vessel (voyage) are summarized in table 10.

Table 10

| Containerships<br>Ship Type | Total ballast movement<br>during voyage (MT) | Ballast discharged while in<br>port (MT) |
|-----------------------------|--|--|
| 1200 TEU – Feeder           | 930  | 440 (Coastal Water)                      |
| 2500 TEU – Panamax          | 10,600                                       | 3,700 (Deep Ocean)                       |
| 4800 TEU – Post-Panamax     | 11,100                                       | 0  |

The 1200 TEU Feedership was the only vessel where required in-port discharge of coastal ballast water. For this Feedership, tanks are maintained empty or pressed up throughout the voyage with the exception of the No. 2 Wing Tanks P/S, which are used to control heel during cargo operations. As the ballast system does not allow for internal transfers, it is necessary to discharge a total of 440 MT of coastal ballast water while in port. If it were possible to transfer ballast between this pair of wing tanks, zero discharge of ballast could be achieved for the voyage.

For the three voyages that were evaluated, effective ballast water management procedures can be implemented with little impact on vessel operations. Nevertheless, it should be recognized that a containership loaded to its marks and approaching GM or bending moment limits will be unable to exchange ballast without exceeding allowables. Generally this will only impact Panamax and smaller vessels. The post-Panamax containerships have ample excess ballast, deadweight capacity, and stability margin to bring additional ballast onboard before initiating the exchange process.

Impact of ballast water exchange on ship properties: To assess the “worst case” scenario, each vessel was fully loaded to her summer loadline draft in such a way that both the  $GM_t$  (actual GM equal to the required GM) and still-water bending moment (actual still-water bending moment equal to the permissible still-water bending moment) were at their limiting values. Each tank was run through an exchange sequence to determine the effect of the exchange on the drafts, trim, propeller immersion, static heel, still-water bending moments and shear forces,  $GM_t$ , and bridge visibility. Containers were then removed from the upper-most tiers on deck until compliance with the stability and strength criteria could be maintained throughout the exchange process.

To assess the impact of emptying and re-filling tanks, each ship was loaded to its loadline such that the GM equals the minimum permissible, and the still-water hogging moment is at maximum permissible value. Then each tank or pair of tanks was run through an exchange cycle. The maximum changes to the stability and bending strength characteristics encountered during the exchange of any one tank or pair of tanks is displayed in table 11:

Table 11

| Containerships<br>Ship Type | Maximum change to<br>hogging bending moment | Maximum change<br>to $GM_t$ (m) |
|-----------------------------|---|---------------------------------|
| 1200 TEU – Feeder           | 17%   | 0.52                            |
| 2500 TEU – Panamax          | 10%   | 0.36                            |
| 4800 TEU – Post-Panamax     | 8%  | 0.54                            |

Containerships are frequently stability and strength limited. Ballast exchange has a detrimental effect on stability due to the introduction of free surface effects as the tanks are made slack, as well as the rise in the ship’s center of gravity as double bottom tanks are emptied. As shown above, the maximum

reduction in  $GM_t$  during the exchange of a tank or pair of tanks on the three vessels ranged from 0.36 to 0.54 meters, and the increase in hogging moment ranged from 8% to 17% of the allowable. The table below provides values for the reductions in payload required to allow exchange of these tanks; if the initial load condition has the vessel fully loaded to her marks with stability and bending moments at their limiting values. As illustrated in the analysis of the three containerships, such payload losses can generally be avoided as ballast can be “locked in” when a vessel is heavily loaded.

**Table 12**

| <b>Containerships<br/>Ship Type</b> | <b>Reduced payload to account<br/>for change in bending<br/>moment</b> | <b>Reduced payload to<br/>account for change in <math>GM_t</math></b> |
|-------------------------------------|--|---|
| 1200 TEU – Feeder                   | 1474 MT / 17% B.M. change  | 759 MT / 0.52m $GM_t$ change  |
| 2500 TEU – Panamax                  | 345 MT / 10% B.M. change   | 950 MT / 0.36m $GM_t$ change  |
| 4800 TEU – Post-Panamax             | 1965 MT / 8% B.M. change   | 930 MT / 0.54m $GM_t$ change  |

Listed below are key findings arising from the ballast water management analysis of containerships:

- The 1200 TEU feedership does not have heeling tanks or other means for internally transferring ballast from side to side. Since ballast adjustments are required to control list during cargo operations, there is no alternative but to discharge ballast in port. A substantial portion of the voyage for the 1200 TEU vessel studied involved inter-port transits through shallow waters. It was not possible to exchange ballast water in the deep ocean, resulting in unavoidable in-port discharge of coastal waters.
- With the exception of the above mentioned problem of controlling heel on the feedership, it was found that for the three voyages and ships analyzed, effective ballast water management procedures can be implemented with little impact on vessel operations and with no loss of container payload.
- Through planning, the amount of ballast exchange can be minimized, as many tanks can be maintained either full or empty during the course of the voyage. In preparation of a port call, tanks can often be initially ballasted in the deep ocean, which further reduces the need for exchange.

## **Slamming**

For the ballast exchange operations studied, it was common to have a decrease in forward draft during ballast exchange sequence operations. This was particularly evident in the case of tankers and bulk carriers. In order to consider the implications of the reductions in forward draft, a seakeeping analysis was performed. The goal of this analysis was to determine limits on sea conditions to reduce the incidence of slamming to an acceptable value. The acceptance criteria for slamming used in the study was a 3% (3 slams in 100 pitch oscillations) slam probability for tankers and bulk carriers, and a 5% slam probability for containerships. Each vessel was investigated using actual ballast conditions as presented in its loading manual. In addition, each tanker was investigated using the minimum forward draft permitted by MARPOL 78. (Load cases identified in table 13 by the notation “IMO” are load cases that considered the minimum MARPOL 78 forward draft). To briefly summarize the analysis: Acceptable slam probabilities are achieved for all vessels at significant wave heights below 8 meters (approximately Beaufort Force 7, Moderate Gale).

The resulting limits of significant wave heights, where slamming acceptance criteria are not satisfied, are as follows:

**Table 13**

| Vessel type        | General description     | Load case | Maximum $H_{1/3}$ wave height (m) |
|--------------------|-------------------------|-----------|-----------------------------------|
| Single hull tanker | 35,000 DWT              | Normal    | 8                                 |
|                    |                         | IMO       | 8                                 |
|                    | Suezmax                 | Normal    | 12                                |
|                    |                         | IMO       | 12                                |
|                    | VLCC                    | Normal    | 12                                |
|                    |                         | IMO       | 12                                |
| Double hull tanker | 40,900 DWT              | Normal    | 9                                 |
|                    |                         | IMO       | 8                                 |
|                    | Suezmax (A)             | Normal    | 12                                |
|                    |                         | IMO       | 12                                |
|                    | Suezmax (B)             | Normal    | 12                                |
|                    |                         | IMO       | 12                                |
|                    | Suezmax (C)             | Normal    | 12                                |
|                    |                         | IMO       | 12                                |
| Bulk carrier       | VLCC                    | Normal    | 12                                |
|                    |                         | IMO       | 12                                |
|                    | Handysize               | Normal    | 9                                 |
|                    | Panamax                 | Normal    | 12                                |
|                    | Capesize                | Normal    | 12                                |
|                    | Feeder (1200 TEU)       | Normal    | 12                                |
| Containership      | Feeder (1200 TEU)       | Full      | 12                                |
|                    |                         | Full*     | 10                                |
|                    | Panamax (2500 TEU)      | Full      | 12                                |
|                    |                         | Full*     | 10                                |
|                    | Post-Panamax (4800 TEU) | Full      | 12                                |
|                    |                         | Full*     | 11                                |

\* Limiting modified full load "actual voyage condition"

## **Sloshing**

Despite the violent nature of the sloshing phenomenon, little damage has been seen to date, in the three types of vessels considered in this document. The damage that has been reported has mainly been limited to long cargo tanks in large tankers, and to cargo holds in dry cargo ships that have been partially filled for ballasting purposes, especially in bulk carriers. Sloshing loads are not much of a concern in double-bottom or double-hull tanks, as the dense internal structure of these tanks usually restricts the fluid motion to such a large extent that resonant sloshing can not occur. Therefore, sloshing analysis is confined to large tanks on tankers and cargo holds on the bulk carriers.

Sloshing analysis was performed on the three single hull tankers (35,000 DWT, Suezmax and VLCC) and on the Panamax and Capesize bulk carriers. Sloshing resonance was a problem in the single hull Suezmax tanker and in both of the bulk carriers. However, one should not draw any conclusions regarding the acceptability of the smaller tankers and VLCC's. Sloshing is highly dependent on tank geometry and structure, which can vary greatly from one vessel to another. Sloshing in tankers is generally limited to pitch resonance, and can usually be rectified with only modest mitigation design measures, such as changes to tank geometry, or the addition of swash bulkheads. Sloshing in partially

filled holds on bulk carriers may be due to pitch and/or roll motion resonance, and is a major concern that is not easily dealt with.

In the case of single hull tankers it is possible to reduce sloshing motion amplitudes and to bring the loads on the structure within acceptable limits. For the Suezmax tanker considered in this study, by limiting the vessel's pitch amplitude to that encountered in seastates of Beaufort Force 7 or less, sloshing loads would be brought down to acceptable limits, making the study vessel satisfactory with respect to sloshing in a majority of sea conditions. Similar operational limits would not be practical for ballasting of bulk carrier cargo holds.

Listed below are key findings arising from sloshing analysis:

- Single hull tankers and bulk carriers typically have tanks of sufficient size and proportions to pose sloshing concerns.
- Sloshing loads in single hull tankers need to be carefully considered in the development of ballast exchange sequence scenarios.
- At sea ballasting of bulk carriers cargo holds using procedures that involve partially filled hold spaces is considered impractical for most conventional bulk carrier designs.

### **Comments on Damage Stability and Survivability**

Survivability was assessed based on a probabilistic damage stability analysis for a limited number of vessels. The conclusion of our assessment was that because the conditions involved were ballast conditions, the survivability was quite high, both for the normal ballast condition and for the “worst case” Ballast Water Exchange condition.

### **Comments on the Probability of Completion of Ballast Water Exchange**

Assuming no interruptions, the duration of exchange sequences evaluated in this study ranged from ½ day to 2 days. In general, a ballast sequence can be interrupted and continued with some additional time requirements to return from the ballast condition required to operate in the higher sea conditions. However, this is not the desired behavior. Ideally, once the ballast exchange sequence has begun it should proceed until completion. From published data it is concluded that even with a series of conservative assumptions, the probability of completing a 44 hour exchange sequence in any given 44 hour period is over 95%.

For some relatively short routes, e.g. the TAPS trade on the U.S. West Coast, there may be concerns over completion of the sequence once interrupted. Fortunately, the duration of sea states above 7.5 m significant wave height are relatively short. Published data indicates that storms with significant wave heights over 7.5 m (i.e. Beaufort 7 and above) have an expected duration of 7 hours. Thus interruptions to ballast exchange should be short and only exceptionally short voyages with long sequences should be compromised.



## Concluding Remarks

These advisory notes summarize the findings of a study that focuses on the use of ballast management practices. The intent of ballast management is to minimize the discharge of ballast in port and coastal waters, and when such discharges cannot be avoided, restrict them to ballast that has been loaded or exchanged in the open-ocean. This is done in order to limit the discharge of ballast water that may contain unwanted aquatic organisms. Shipowners and designers have only recently become aware of the importance of ballast management—therefore, when the existing fleet of cargo vessels was designed, little or no consideration was given to the ability to exchange ballast. As a consequence, exchange sequences can be quite complex, and a wide range of issues including stability, hull girder strength, resonant sloshing, slamming, and propeller immersion must be considered.

Two general conclusions emanating from this study are:

1. The complexity of exchange sequences on certain vessels present safety concerns, as human error and equipment failures could potentially endanger the vessel. Personnel training will be an essential part of a ballast water management program. System reliability may also be a concern, particularly on older ships.
2. Ballast exchange should be given due consideration during the design process. The ballast system layout, ballast capacity, tankage configuration, and hull girder strength are a few of the design decisions which influence the ability to sequentially exchange ballast. When *sequential* exchange is impractical, the overflow system should be arranged so that *flow through* can be carried out without risk of over-pressurizing tanks.

