TANKER TECHNOLOGY

LIMITATIONS OF DOUBLE HULLS

PHOTO: US Coast Guard

PHOTO: Natalia Bratslavsky

Living Oceans Society

Healthy Oceans. Healthy Communities.

A Report by
Living Oceans Society

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Executive Summary

There are aspects of a double-hull tanker's design, construction, operation, and maintenance that may actually increase the likelihood of a double-hulled tanker being involved in an accident and oil spill. The complex and relatively new designs of double-hull tankers—yet to be tested by industry service experience—can make them more susceptible to operational and maintenance issues. They may be prone to catastrophic structural failures, especially if they are not maintained and operated to the highest possible standards. Additionally, double-hull tanker designs do not address human factors which are responsible for up to 80 percent of total oil discharges. In fact, advances in tanker technology may actually *increase* the risk of spills due to human error. Although oil spill trends have been declining in recent years, oil spills continue to occur. They have been the consequence of double-hull tanker accidents in the past and will likely continue in the future. Double-hulled tankers cannot be viewed as a panacea for oil spill prevention.

Introduction

Following the *Exxon Valdez* oil spill in 1989, double-hull tanker technology was widely regarded as the solution to preventing future catastrophic oil spills. The United States and the International Maritime Organization subsequently enacted policies requiring all new tankers to be constructed with double hulls. The acts also set phase out schedules for all single-hull vessels by 2010.

In August 1989, the U.S. Coast Guard testified to Congress that even if the *Exxon Valdez* had been double hulled, the spill would have only been reduced by 60 percent at most, perhaps only 25 percent; even under the best case scenario, 4.4 million gallons of oil would have still leaked into Prince William Sound, still a catastrophic spill (5, 6).

Although it is recognized that double-hull tankers are less likely to spill oil than single-hulled tankers from minor groundings and low energy collisions, there are some incidents where a double-hull tanker may fair no better than its single-hulled predecessor (7). Because of double-hull tankers' complex design and structure, they are potentially more susceptible to problems of poor maintenance and operation.

Background

Double hull design

Double-hull (DH) tankers have an inner and outer hull separating cargo from the ocean (see Figure 1). Cargo is carried in one or more separated cargo tanks located within the inner hull. The space between the inner and outer hull is generally two meters wide and is also segregated into sections similar to the cargo tanks. These segregated spaces act as **ballast** tanks to carry water on unladen voyages (i.e. when the tanker is not transporting cargo). For an oil spill to occur from a DH tanker, both the outer and inner hull must be breached. The main purpose of the double hull is to reduce the probability of oil outflow following a collision or grounding (1).

Single-hull (SH) tankers have one hull and carry oil directly within the hull structure (see Figure 1). Some SH tankers carry oil and ballast water within the same tanks; whereas, some SH tankers have segregated ballast tanks within the hull (i.e. oil is carried directly within the hull, but the ballast tanks are separated from the cargo). The segregated ballast tanks are still only protected from the ocean by one hull. For an oil spill to occur from a SH tanker, only the single hull must be breached.[1]

1 If a segregated ballast tank on a single-hull tanker is breached, no oil will be spilled (unless the ballast water is contaminated).

Some ships have only double bottoms or double sides. Prior the mid-1990s most non-single-hull tankers were combination carriers—vessels which carried liquids and dry cargo in bulk. Following regulations enacted in the 1990s (see Regulations below), all vessels carrying oil in bulk must be double hulled by 2010.

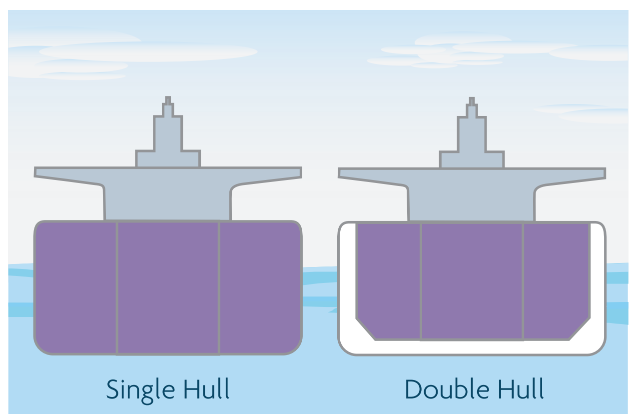

Figure 1
Hull configuration of single vs. double-hull vessel.

Regulation

In the wake of the *Exxon Valdez* oil spill in Alaska in 1989, the United States and International Maritime Organization enacted policies to eliminate the use of single-hull (SH) tankers as follows:

Oil Pollution Act of 1990

Largely due to public outcry following the *Exxon Valdez* disaster, the United States enacted the Oil Pollution Act of 1990 (OPA 90) to reduce the occurrence of oil spills and to reduce the impact of potential future spills through increased preparedness. The act includes tank vessel construction standards for vessels carrying oil in bulk. Section 4115 of the act excludes SH vessels 5000 gross tons (5,513 tonnes) or greater from entering U.S. waters after 2010 i.e. requires that tankers operating in U.S. waters must have double hulls (1)[2]. The act also established phase out of existing single-hull, double-bottom and double-sided tankers according to a schedule that began in 1995 and originally ran through 2015 depending on vessel age. Following the *Erika* oil spill off the coast of France in 1999 (see footnote 13), the final phase out date was revised to 2010.

International Convention for the Prevention of Pollution from Ships

In 1992 the International Maritime Organization (IMO) also adopted double-hull (DH) standards. The International Convention for the Prevention of Pollution by Ships (**MARPOL 73/78**) was amended to require all tankers of 5,000 **deadweight tons** (DWT) or more constructed after 1993 to be fitted with double hulls or an alternative design approved by the IMO (Regulation 13F) (2). The requirement for double hulls also applies to existing tankers under a program that began in 1995 to gradually convert or take out of service SH tankers (Regulation 13G).

Following the *Erika* oil spill, the IMO adopted a revised, stricter phase out schedule for SH tankers which came into force in the spring of 2003 (the 2001 amendments to MARPOL 73/78). In December of 2003, regulation 13G (regulation 20 in the revised Annex I which entered into force on January 1, 2007) was again revised to accelerate the phase out schedule. The revisions came into force in April of 2005 along with a new regulation banning the carriage of **heavy grade oil** (HGO) in SH tankers of 5,000 DWT or greater by 2005 and between 600 and 5,000 DWT by 2008. The revised regulation set the final phase out date for **pre-MARPOL** tankers[3] for 2005. For **MARPOL**[4] and smaller[5] tankers the final phase out date was brought forward to 2010 from 2015.

Oil Pollution Prevention Regulations

In Canada the **Oil Pollution Prevention Regulations** combine the requirements of OPA 90 and Annex 1 of MARPOL 73/78 (3). The revised MARPOL 73/78 requirements govern tankers on international voyages in waters under Canadian jurisdiction, and the OPA 90 provisions govern Canadian tankers on domestic voyages or trading to the U.S. and for U.S. tankers trading in waters under Canadian jurisdiction (4).

The OPA 90 and Annex 1 of MARPOL regimes are not identical, but they are close enough that overall neither offers a significant difference in protection of the environment (4).

2 Vessels without double hulls are allowed to operate in designated lightering areas or deepwater offshore oil ports until 2015 (1).

3 Oil tankers of 20,000 DWT and above carrying crude oil, fuel oil, heavy diesel oil or lubricating oil as cargo, and of 30,000 DWT and above carrying other oils, which do not comply with the requirements for protectively located segregated ballast tanks (27).

4 Oil tankers of 20,000 DWT and above carrying crude oil, fuel oil, heavy diesel oil or lubricating oil as cargo, and of 30,000 DWT and above carrying other oils, which do comply with the protectively located segregated ballast tank requirements (27).

5 Oil tankers of 5,000 DWT and above but less than the tonnage specified for Pre-MARPOL or MARPOL tankers (27).

Limitations of Double Hulls

Design and construction issues

Lack of experience

The shift from single-hull (SH) to double-hull (DH) designs represents a departure from established, successful designs. Many shipyards designed and built their first DH tankers based on their own calculations and guidance from a Classification Society (whose experience was also limited) (8). This type of design and construction has been coined 'revolutionary' rather than 'evolutionary' due to the lack of operational service experience and unknown safety factors. The most likely consequence will be fatigue cracks in early years of service, especially in larger DH tankers (8).

"Some of the first generation double-hull tankers suffer from defects in poor design details, such as poor alignment of the cruciform joints, poor support of the lower knuckle between cargo tank and ballast tank and lack of understanding of the need for good weld profiling in areas of high stress. None of these issues was relevant on single-hull tankers (8 p. 7)."

Factory techniques

Shipyards are constantly driven to optimize tanker designs in order to remain competitive in the world market. They have adopted 'factory' techniques in order to improve productivity and reduce ship construction times (8). In the early 1970s a Very Large Crude Carrier (VLCC) may have taken two years to build; today, a new VLCC can be built in eight to nine months (8).

There are guidelines for good practice in design and construction. However, they are not enforceable. It is up to the owner of the tanker under construction to insist on adherence to the guidelines (if the shipyard even allows the enhancements which may not be compatible with the shipyard's production practices) (8). It is also up to the owner to insist on enhancing previous standards and designs and ensuring properly conducted maintenance.

The result is often ***design for producibility***—the philosophy of designing a hull structure to minimize construction man-hours with little concern for the internal stress flow and its effect on structural performance (9). This can lead to fatigue cracks and even structural failure in early years of service life (discussed further in subsequent sections).

Limited warranty

Shipyards offer little in terms of vessel warranties which allows them to build weaker ships more quickly. A typical (abbreviated) ship building guarantee looks similar to the following from Devanney (2006, p.273):

> The Builder for the period of Twelve (12) months after delivery guarantees the Vessel and all her parts against all defects discovered within this Guarantee period which are due to defective material, construction miscalculation or negligent or other improper acts of the Builder.
>
> The Builder shall have no responsibility or liability for any other defect whatsoever in the Vessel other than the Defects specified in Paragraph 1.
>
> Nor shall the Builder under any circumstance be responsible for any consequential losses or expenses directly or indirectly occasioned by the reason of the defect specified in Paragraph 1.
>
> The guarantee contained above replaces and excludes any other liability, guarantee, warranty and/or condition imposed or implied by the law, customary, statutory or otherwise by reason of the construction and Sale of the Vessel to the Buyer.

Essentially this means that the shipyard is only liable to fix things that fall apart in the first year. With such a guarantee, the builder is absolved from any consequential liability and the design objective becomes: "build the cheapest possible ship that won't completely fall apart in the first 12 months (9 p. 274)"—something that shipyards have become very good at.

Weakened class rules

Since the 1960s, **Class Rules**—a Classification Society's vessel construction requirements—have weakened significantly. Generally, this is done to reduce steel requirements in order to remain competitive. Early tankers were viewed to be overdesigned, and as such, the Rules were weakened to construct more conservative vessels (e.g. with less materials), often to the detriment of the vessel (e.g. more prone to fatigue cracking, higher stress levels, etc.).

As new design techniques were introduced, the **safety factors**—design allowances for unknown factors—were reduced in order to minimize construction cost and to obtain a maximum deadweight for minimum **draft** (10)—i.e. carry as much oil as possible while still maintaining the same draft as an older, heavier vessel (an older, heavier vessel will sit lower in the water than a newer vessel with a lower **lightweight**, when carrying the same amount of cargo). A good example is the *Manhatten*, a 105,000 DWT tanker built in 1962. She had a lightweight of 30,000 tons (33,076 tonnes). By 1967, **190,000** DWT tankers were being built with lightweights of 30,000 tons (33,076 tonnes) (i.e. were built with the same volume of steel but could carry much more cargo).[1]

1 Additionally, the Manhatten had 45 tanks and two 16,000KW main engines. A modern tanker of this size will have as few as nine cargo tanks and a single 14,000KW engine (9, pg. 174). Engine redundancy is an important safety feature absent in the majority modern tankers. In 2006, 99.5 percent of all tankers with a DWT of 10,000 tons or more had only one engine, one propeller and one rudder, and are therefore only one power failure away from being adrift (12).

Table 1
Reduction in tanker lightweight to deadweight over time

Years	Deadweight (DW)	Approx. lightweight (LW)	LW/DW
1940s	16,500	6,000	0.36
1950s	50,000	12,000	0.24
1960s	100,000	27,000	0.27
1960s	200,000 (VLCC)	30,000	0.15
1970s	300,000	40,000	0.13
1970s	500,000	65,000	0.13

Adapted from National Research Council (1991)

The reduced ratio of lightweight to deadweight seen in Table 1 directly reduces the cost of a vessel per tonne of cargo. This generally means that a vessel can carry more cargo for a given draft but also implies less of a margin to deal with construction and maintenance errors or unusual operational events (10).

A National Research Council (1991) report concluded that "advancements in design techniques and analyses unquestionably have made modern tankers more vulnerable to failure under conditions of unusual stress, or less-than-diligent maintenance (10 p. 33)."

Use of high tensile steel

In addition to weakened Class Rules, shipyards use more high tensile steel (HTS) in order to further minimize steel weight and reduce overall cost. The increased use of HTS on a hull makes the hull more flexible and increases the potential for deflection. It also requires more precise fabrication techniques which are less forgiving of fabrication errors (10).

If used extensively in construction, the resulting increase in deflections and stress levels impacts negatively on structures' fatigue lives and effective lifetime of the protective coating systems (8). Additionally, higher operation stresses associated with HTS increase the risk of fatigue cracks developing, ranging from nuisance cracks to cracks severe enough to cause leaks or structural failure (discussed in subsequent sections) (1). It is expected that the use of HTS will have more of a detrimental impact on the operational performance of DH tankers than their single-hull predecessors (8). Again, it is up to the owner to identify and limit the use of HTS in new tankers, at a cost to themselves.

Operational issues

Higher stress levels

Double-hull (DH) tankers operate with overall stress levels 30 percent higher than single-hull (SH) tankers—close to the maximum level accepted by Classification Societies (8). This is due in part to higher **girder bending moments** caused by uniform distribution of cargo and ballast over the length of a DH vessel (i.e. the aligned arrangement of cargo and ballast tanks makes the structural support beams more prone to bending). In SH tankers, the ballast tanks can be located to minimize shear stresses and **longitudinal bending** (e.g. **sagging** or **hogging**) which reduces overall stress levels. The higher stress levels in DH tankers increase the risk of buckling failure (especially if corrosion has reduced plate thickness after a few years in service) and the likelihood of small fatigue cracks.

In order to account for these higher stress levels in DH tankers, owners must insist that they be built with extra steel thicknesses or additional ballast tanks to reduce bending moments. Due to commercial pressure, most tanker owners would unlikely be willing to take on the financial penalty of these improvements.

The number of **cruciform joints** is also significantly increased in a DH tanker compared to a SH. Many of the joints are located in critical areas (i.e. areas where high stress levels combined with potential stress concentration features may lead to failure of the primary structure) (8 p. 5). Design, construction and inspection of these areas are crucial but may be another area at odds with shipyard production practices.

Cargo leaks

All owners of DH tankers need to guard against, and be prepared to deal with, cargo leakage into ballast tanks. Leakages generally occur due to fractures in the bulkhead plating between cargo and ballast tanks. These fractures may be caused by local stress concentration, fatigue, construction defect, or corrosion. The structural design of DH tankers makes them more prone to minor failures of these types than SH designs (8).

If a cargo leak develops in a SH tanker, it leaks directly into the ocean where it can be spotted and dealt with relatively quickly with a patch or **hydrostatic balancing** before a significant amount of oil is lost. In a DH tanker, the leak will be into the ballast tanks or bottom hull structure.

The only way to stop the leak would be to completely empty the damaged tank. This is usually not possible because there is rarely enough room in the other cargo tanks, and even if there was, the transfer would likely over-stress the tanker's structure (9). Even worse, there is a chance the leak will go undetected for some time. In theory, a leak should be detected by a gas detection system (if the tanker is equipped) or an inspection (see subsequent sections); however, detection systems are notoriously unreliable and difficult to maintain, and some crews do not regularly inspect the double bottom spaces (9).

Gas detection

According to the Center for Tankship Excellence, the most important cause of SH tanker spillage and tankermen deaths is leakage into segregated ballast tanks followed by a fire or explosion. With the advent of double hulls, the interface area between cargo tanks and segregated ballast tanks is more than five times what it was for single-hull, pre-MARPOL tankers (9).

Crude oil vapours are highly flammable. If a cargo leak develops in a DH tanker, over time an explosive concentration of hydrocarbon vapour can build up in the ballast spaces, increasing the risk of a major explosion. What could have been a minor, easily handled spill in a SH vessels could be major explosion leading to a spill or even a sinking of a DH tanker.

All new oil tankers constructed on or after January 1, 2012 will be required to have fixed hydrocarbon gas detection systems for measuring gases in ballast tanks and void spaces adjacent to cargo tanks (11). This will help identify the presence of gases and could assist in the detection of structural defects of the cargo tanks, but there is always the possibility of equipment malfunction, and there is no such requirement for existing tankers.

Machinery failure

Machinery failure is a problem in all tankers regardless of hull configuration. These failures are obscured in most tanker casualty databases because almost all casualties are documented as groundings, collisions, fires, etc. It is often a grounding or collision that results in an oil spill, but the grounding or collision would not have occurred without a failure in the first place.[2] Initial machinery failures have led to some of the worst spills in history. For example, in most spill databases the *Warfa*[3], one of the top 20 tanker spills of all time, is listed as a structural failure when the actual initial cause was a loss of propulsion due to power failure when the engine room flooded (12). Additional examples include:

- the *Amoco Cadiz* and the *Braer*: listed as groundings opposed to steering gear failure and loss of power, the true causes (respectively);
- the *General Colocotronis* and *Olympic Bravery*: listed as sinkings opposed to losses of power
- the *British Ambassador*, the *Andron* and the *Genzina Brovig*: all listed as sinking opposed to loss of propulsion (all similar to the *Warfa* incident); and
- the *Nassia* and the *Baltic Carrier*: listed as collisions opposed to losses of steering (12).

The list goes on.

A marine vessel casualty analysis conducted in 1994/1995 in the Los Angeles/Long Beach port area revealed that an average of one in 100 commercial vessels (one per week) sustained some type of steering or propulsion failure during the inbound or outbound transit (13).

The Center for Tankship Excellence makes a conservative estimate that the worldwide fleet of approximately 3,600 tankers with a deadweight of 10,000 tons (11,025 tonnes) or more (2006 values) are averaging at least one major[4] tanker loss of power incident every day (9) with as many

2 Often machinery failure, but can also include: errors in navigation or conning, structural failure, etc.

3 The *Warfa* was stranded off the Cape of Agulhas, South Africa in 1971. Upon grounding all six port cargo tanks and two of the six centre tanks were breached, spilling 40 million litres of oil (12).

4 The Center for Tankship Excellence defines a 'major' loss of power as one lasting a day or more; a 'minor' failure lasting approximately one hour or less (9).

as two to four minor losses of power/steering failure per day (12).

Det Norske Veritas, a Classification Society, estimated a "loss of control" number equivalent to one loss of power/steering every 1.7 ship years (14).[5] If this number is correct, overall the large tanker fleet is suffering approximately six losses of power/steering per day.

Most machinery failures and minor losses of power likely go unreported to regulatory authorities. A vessel could have a loss of power and restore it before grounding, likewise with other failures. More importantly, no vessel owner or Class will voluntarily report a machinery failure unless forced to—it would be bad for business (12); therefore, we can expect losses of power on a more frequent level than those mentioned above.

Intact stability

The ability of a vessel to stay upright and resist listing or capsizing is known as its **transverse stability**. In SH tankers transverse stability was never really an issue because longitudinal bulkheads were used in cargo tanks to provide longitudinal strength which influenced stability (8).

Because the inner hull of DH tankers provides sufficient strength for structural purposes[6], many tankers up to 150,000 DWT were built without longitudinal bulkheads in the cargo tanks. Without the subdivision of longitudinal bulkheads, the result is single cargo tanks spanning the ship from side to side. These wide cargo tanks substantially increase the free surface effect in the tanks. Free surface effect is the "degradation in transverse stability which occurs when there are slack surfaces (8 p. 8)" (i.e. when a cargo tank is not fully loaded, the liquid surface of the cargo, the slack surface, is not restricted by the deck structure and the cargo is relatively free to slosh around).

The combination of increased free surface effect and the double bottom space, which raises the vessel's center of gravity, results in a significant reduction of **intact stability** in DH tankers. This has already led to instances of vessels taking on a sudden list during cargo operations and can occur instantaneously during cargo and ballast loading and unloading (8).[7]

Mud build-up

Mud build up is a more significant problem in DH than SH tankers. When a tanker takes on ballast water it often contains sediment i.e. mud. The configuration of ballast tanks in DH tankers causes a higher retention of the sediment compared to the ballast tanks of SH tankers (they are more cellular than the wide tanks in SH tankers). Some owners fit ballast washing systems to combat this effect, but again, at an additional cost (8). Mud build-up is an issue because it can contain anaerobic bacteria which can enhance corrosion in the ballast tanks (see Corrosion in next section).

Maintenance issues

Sole owner responsibility

Modern tanker designs, although approved by Classification Societies, are based on the assumption that all necessary repairs will be identified and undertaken by the owner for the lifetime of the vessel. The **Flag State**, **Classification Society**, **underwriter** or **charterer** can have an influence on the owner/manager (through detention, loss of business, certification withdrawal, etc.), but they are not in a position to be privy to the condition of the tanker as the manager or owner (8). Unless enforced, strict-maintenance regimes, which are costly, may be substituted for less than diligent practices.

5 Statistic taken from page 248. Original source unavailable.

6 Including longitudinal bulkheads in DH tankers also increases the amount of steel used during construction, making the design more expensive, less marketable and less attractive to prospective owners (8).

7 This can often be remedied by having well trained crewmen and the assistance of on-board computer programs which can plan and monitor loading and unloading operations. See Human Factors section.

Corrosion

Corrosion is a fact of life when it comes to tankers. The internal structure of cargo tanks is constantly exposed to corrosive gases, seawater, crude oil, and oil products.

Crude oil is often loaded at temperatures higher than the ambient air and seawater temperatures. The cargo and tank structure maintains a higher temperature than normal due to the insulating effect of the double hull, known as the 'thermos bottle effect.' This promotes a more corrosive environment: warm, salty air in ballast tanks, humid, acidic conditions in vapour spaces of cargo tanks (from crude oil residues and/or gases from the inert gas system[8]) and anaerobic bacteria thriving in the sludge along tank bottoms create ideal conditions for corrosion (8). As such, ballast tanks and the underdeck and bottom of cargo tanks are areas in a DH most prone to corrosion.

All tankers are subject to **pitting corrosion**. Crude oil generally contains a certain amount of water and a significant amount of sulphur which makes the water acidic. During voyage, some of the acidic water will settle out in a layer just above the bottom of the tank. This low pH (high acidity) solution will combine with oxygen-rich sludge to initiate corrosion that starts out as a dimple but can develop into a hole or pit that can penetrate steel quite quickly.

A study conducted by the Oil Companies International Marine Forum (1997) determined:

> The normal corrosion rate of uncoated cargo deck plating is 0.10mm or less per year. However, annual wastage rates as high as 0.16mm to 0.24mm have been reported on ships less than 3 years old. This accelerated corrosion rate, which is approximately 2 to 3 times that which would normally be anticipated, is sometimes accompanied by accelerated general corrosion of the vapour space steelwork.... There has also been an increase in the incidence and severity of pitting corrosion in cargo tank plating. In one specific instance, a 150,000DWT tanker is reported as having an average pit depth of 4.0mm. This is only after 2 years in service (15 p. 2).

This rate of corrosion is cause for serious concern. Typical VLCC steel thicknesses mid-ship are around 19.5-20mm for main deck and inner tank plating (16).[9]

If corrosion goes unnoticed during inspections, the reduced material thickness will lead to reduced structural integrity. If corrosion proceeds at a rate greater than allowed for in the design, oil leakage into ballast spaces may occur, increasing the risk of explosion. In a worst case scenario, corrosion can lead to a major structural failure (8). In terms of spill volume, hull structural failure is by far the most important cause of tanker casualties (9), and undetected corrosion is the main cause of some of the more spectacular structural failures in history—e.g. the *Kirki*[10], *Nakbodka*[11], *Erika*[12], and *Prestige*.[13]

8 Inert gas systems pump inert gases (i.e. with oxygen content less than five percent), usually from the boiler exhaust, into tank spaces to reduce the risk of explosion. Boiler gas contains sulphur dioxide which is highly acidic and corrosive.

9 Thirty years ago, VLCCs were designed with 24-25mm main deck plating and 26-28mm bottom shell plating; the combined effect of double-hull designs, weakened Class Rules and increased use of HTS has therefore led to a reduction of around 20 percent in plating thickness in certain areas.

10 In 1991 the *Kirki* ran into bad weather off the coast of western Australia while loaded with volatile crude oil. The forepeak ballast tank was significantly corroded, and the hull structure failed on deck at the bulkhead between the forepeak tank and the forward-most cargo tanks. Eventually, after a series of fires, the entire forepeak tank fell off and 17,700 tonnes of light crude were spilt (30). The *Kirki* was fully approved by her Classification Society (9).

11 In 1997 the fully loaded *Nakhodka* broke in two in the Sea of Japan in heavy weather spilling 6,200 tonnes of medium fuel oil (31). Inspections of the vessel's bow afterward found average corrosion in the deck steel close to 40 percent. The corrosion was so significant that the supporting members of the underdeck had detached from the deck. The Japanese inspectors concluded that if the ship had not been corroded, she would have easily weathered the storm (9).

12 In 1999 the *Erika*, loaded with 31,000 tons (34,179 tonnes) of heavy fuel oil, was traveling south of Brittany, France when she ran into bad weather and developed a hull crack on her starboard side. Over 24 hours the fracture extended upward to, and then across, the main deck. Shortly thereafter, the ship broke in half. The bow sank on December 12th and the stern the following day. The *Erika* was fully approved by her Classification Society and had even undergone a Special Survey only 18 months previous (9). The *Erika* spilled 19,800 tonnes of oil; 400 kilometres of polluted coastline had to be cleaned, and over 250,000 tonnes of oily wastes were removed from the shoreline (29).

13 In 2002 the *Prestige*, loaded with 77,000 tonnes of heavy fuel oil, suffered hull damage in heavy seas off the northern coast of Spain. The tanker took on a severe list but was denied a port of refuge by both Spain and Portugal. The *Prestige* was towed fur-

Corrosion is an issue in all tankers, but it will be more significant in DH tankers because of their increased surface area. Owners of DH tankers will now have to maintain 225,000 square meters of segregated ballast tank space compared to only 25,000 square meters in a SH tanker (which itself was very difficult to maintain) (9).

The most effective way to prevent corrosion is to protect and maintain the hull with a coating system and by inerting the cargo and ballast tanks.

Protective coatings

The effectiveness of the coating system, and its ability to reach its target life, depends on the type of coating,[14] steel preparation, operational environment, application, inspection and maintenance (17). Coating needs to be applied in both ballast and cargo tanks.

Ballast tanks

The International Maritime Organization (IMO) under SOLAS '74 (Regulation II-1, 3-2.1) requires that all ballast tanks in tankers built after 2008 be provided with corrosion prevention systems, which is currently best achieved by protective coatings (18); however, this requirement does not apply to tankers built before 2008, and premature failure of the protective coating in ballast tanks of ships already in service is often noted (7).

If tank coatings fail before the tanker's projected operation lifetime, reapplying an effective coating is very difficult and expensive due to the cellular nature of DH ballast spaces. Once coating failure has started, corrosion propagates at an accelerated rate on exposed areas, and extensive steelwork replacement is often then required. The failure to maintain the protective coating and **cathodic protection** in ballast tanks has led to leakage, and even explosions.

Cargo tanks

Pitting corrosion on the inner bottom plating of cargo tanks can lead to leakage into the ballast spaces (i.e. the double bottom area) which increases the risk of pollution during **deballasting** operations and explosions due to hydrocarbon vapour build up (7). Corrosion to the upper deck of the cargo tank can lead to a reduction in longitudinal strength which increases the risk of a more serious structural failure occurring (7).

Accelerated corrosion has been found in the cargo tanks of a number of DH tankers carrying crude oil or residual fuels (8). This led the IMO to further amend SOLAS '74 to require all ships with new building contracts on or after January 1, 2013[15] to have protective coatings applied to the inner walls of their cargo tanks during construction (17). However, this requirement is only for new vessels. No such regulation exists for ships already in service.

The new requirement for cargo tanks dictates a useful coating life of only 15 years. This is considered to be the time period, after initial application, that the coating system should remain in "good" condition (good condition still allows minor spot rusting); however, tankers are generally expected to be in service longer than 15 years, and as mentioned previously, once a coating fails, it is very difficult to reapply. Even a small rust spot—currently allowed under the good rating—can propagate quickly and cause coating failure. Therefore, the actual useful life of protective coatings will vary depending on actual conditions encountered in service (17), and coating life will likely be a determining factor in the economic trading life of DH tankers (8).

Fatigue cracks

Fatigue cracks can occur on all types of steel vessels including double-hull tankers. If steel is highly stressed in one direction and then the other, and the process is repeated, the steel will eventually develop a crack.

ther ashore where she eventually broke in two, spilling 63,000 tonnes of oil (33).

14 Additionally, the colour of the coating can affect timely detection of corrosion. Dark coloured coatings, like coal-tar epoxies, conceal rust; whereas, light coloured coatings, like light blue epoxies, make flaws more visible.

15 In the absence of a contract: to be built on or after July 1, 2013 or delivered on or after January 1, 2016.

High stress, which causes deflection of the structure, and cyclic loading (i.e. back and forth deflection) are required to generate fatigue cracks. Relaxed vessel design and construction requirements since the 1960s[16] and cutting corners in structural detailing has led to higher stress levels, while wave action provides constant cyclic loading to ships at sea. Fatigue cracks have been linked to "'optimized' design structures, poor design details, corrosion, stress concentration, incorrect use of high tensile steel and a vessel's trading patterns/area of operation. Fatigue cracks are generally found in older vessels although they have been found on vessels within five years of delivery (7 p.13)."

On tankers, the cracks generally develop in the side shell of the outer hull, just above the waterline, usually in the forward end of the vessel.[17] If corrective action is not taken when the fatigue crack is discovered (e.g. repair, modify design, etc.), the crack will propagate over time and could lead to major structural failure.

Inspection

Inspection of cargo tanks is difficult because it requires a lengthy process of washing, gas freeing and ventilation before the tanks are safe to enter. The internal spaces are dark, wet, slippery, and dirty with no means of access to much of the tank structure (7). Additionally, the surface area of DH can be three times larger than a SH, making inspection even more difficult and time consuming (5). "Within one tanker there are literally tens of thousands of intersections of crossing structural members, each of which has several points of attachments, and all of these joints are susceptible to cracks (10 p. 81)."

Outer walls of cargo tanks can be made more inspection-friendly by installing permanent fore and aft **stringers** and/or walkways for access to areas that need close inspection; however, the inside of cargo tanks are virtually free of internal structures (8), making inspection very difficult. The use of floating rafts is often the only way to thoroughly inspect the inner cargo hull.

Even though stringers or walkways may be installed on the outside of tanks, access may still be hazardous. Full-scale shipyard trials on completed double hulls have found that it can be impossible to blow air from the deck down the side of a U-shaped DH ballast tank and vent out the other side, despite apparent ample openings (8). Entry into these areas, which is necessary to detect corrosion, leaks and mud build up, can be extremely hazardous. Sufficient openings for ventilation need to be considered during design but "is a feature which is usually not fully appreciated by shipyard designers who have no operational experience (8 p.9)."

The result is that non-Class inspectors (e.g. port-state inspectors) do not always go in the cargo tanks, and corrosion can continue unchecked. For example, the *Erika* had undergone eight port-state inspections in the three years before she sank (9). She was fully approved by her Classification Society.

Even Special Surveys—which a vessel is supposed to undergo every five years and a Class surveyor does go in all of the tanks—can miss corrosion.[18] Thousands of steel thickness measurements are taken with an ultrasonic gauge. Thousands of measurements sound like a significant amount, but it is less than one pencil-sized reading per square meter (9). Steel corrodes unevenly, so an area highly corroded can be surrounded by steel that is barely discoloured. The gauge works adequately on unrusted steel because it is easy to get a good coupling between the transducer and the steel. The more corroded the steel, the harder it is to get a reading, so inspectors end up taking readings from less corroded areas unintentionally, and the readings are automatically biased to the good side (9).

16 Fatigue cracking was not observed in tankers until the late 1970s after Class Rules were weakened (9).

17 If a single- hull tanker is loaded when a crack develops, it will start leaking oil which is usually how the crack is identified. Because cracks generally form above the waterline, hydrostatic balance is of no use.

18 Classification Societies require ships to undergo a Special Survey every five years regardless if the ship owner is operating under the International Maritime Organization Regulation 13G or the Oil Pollution Act of 1990 (1 p. 187).

Human Factors

Despite "improvements" in tanker design and construction, systems operation, regulatory oversight, and a general decline in the number of marine oil spills in recent years, oil spills continue to occur. **Human factors**, whether individual or organizational, have been estimated to cause as much as 80 percent of all oil discharges (18, 19).

Human behaviours and actions are intrinsically linked to the technology people design, build, maintain, and operate. Humans impact the functioning of technology, but technology can also influence how decisions and actions are made. As tankers, single- or double-hulled, become increasing reliant on engineered systems and automated technologies, the operators of these technologies are also increasingly subject to new challenges that may actually increase accident risk.

A 2006 synthesized report commissioned by the Prince William Sound Regional Citizens' Advisory Council found:

> Technological improvements may increase accident risks due to increased complexity of the system, skills- or knowledge-based lapses in operator abilities, or risk compensation behavior at the individual or organizational level. Increased automation often results in reduced manning levels, which can increase the number and complexity of job tasks assigned to each operator while simultaneously removing or reducing the operator's ability to bypass or override automated systems in an emergency (19 p. 3).

Oil spill prevention measures, such as the introduction of the double hull, are disproportionately focused on engineering and technological "fixes" because they are most easily remedied (19); however, although technology-based systems may reduce the severity of an oil spill once a human error is made, they cannot interrupt the chain of events that may have caused the accident in the first place.

The maritime system is a people system, and will thus always be influenced by human error (19 p. 7).

Double-Hull Tanker Spills

Double-hull tankers do not reduce the risk of an accident. They may reduce the amount of oil outflow after a casualty, but even this is not guaranteed. Since the advent of mandatory double-hull requirements, there have been numerous oil spills from double-hulled vessels including the following in the past two years alone:

Bunga Kelana 3

On May 25, 2010 the Malaysian-registered *Bunga Kelana 3* collided with the St. Vincent and the Grenadines registered bulk carrier *MV Wally* in the Strait of Singapore. The collision resulted in a ten meter gash on the port side of the *Bunga Kelana 3*, which then spilled an estimated 2,500 tonnes of crude oil into the sea (20). The spill resulted in a four by one kilometer wide oil slick in the surrounding area.

Eagle Otome

On January 23, 2010 the *Eagle Otome*, bound for Exxon Mobil Corporation's refinery in Beaumont, Texas, collided with an outbound vessel towing two barges. The towing vessel tore open the side of the tanker, and an estimated 450,000 gallons (approximately 11,000 barrels or 1.7 million litres) of crude oil was spilled in the port of Port Arthur, Texas (21). The ruptured compartment was carrying 80,000 barrels of oil, but luckily the crew was able to transport 69,000 barrels elsewhere.

Krymsk

On October 20, 2009 the Liberian-flagged *Krymsk* collided with the **lightering** service vessel *AET Endeavor* southeast of Galveston, Texas in the Gulf of Mexico. The *Krymsk* had just finished taking crude oil from a larger tanker, the *Vega Star*, which was too large to enter port. The service vessel pierced one of the *Krymsk*'s fuel tanks, and 18,000 gallons (68,140 litres) of No. 6 bunker fuel spilled (22). None of the cargo tanks were damaged[1].

For a more extensive list of double-hull tanker casualties see **Appendix A: Double-Hull, Double-Bottom and Double-Sided Spills**.

1 The *Krymsk* is a double-hulled tanker but the fuel tank that was breached was single skinned (32). This substantiates the claim that double-hulled tankers do not reduce the risk of an accident.

Conclusion

Double-hull (DH) tankers are not a panacea for oil spill prevention. They may reduce the severity of an oil spill from a grounding or low energy collision, but they are susceptible to a range of design, construction, operation, and maintenance issues, some which may actually *increase* the risk of an oil spill. Furthermore, double hulls do not address the role of human factors in tanker casualties which have been attributed to as much as 80 percent of oil discharges.

Poorly designed, constructed, operated and maintained DH tankers have as much, if not more, potential for disaster compared to single-hull designs. All parties responsible for monitoring these standards, as well as those parties and individuals involved in the tanker industry, must be aware of the limitations of DH tankers and implement effective assessment and inspection procedures to address them (8).

Glossary

Ballast: seawater carried in the ballast tank when the cargo tanks are empty in order to sink the vessel deep enough to provide proper propeller and rudder immersion and to avoid structural damage from bow slamming (6).

Bending moments: when a moment (i.e. a force that tends to distort an object) is applied to a structural element causing it to bend; measured as force multiplied by distance (23).

Cathodic protection: "prevents corrosion by converting all of the anodic (active) sites on the metal surface to cathodic (passive) sites by supplying electrical current (or free electrons) from an alternate source. Usually this takes the form of galvanic anodes which are more active than steel. This practice is also referred to as a sacrificial system, since the galvanic anodes sacrifice themselves to protect the structural steel or pipeline from corrosion (24)."

Class Rules: a Classification Society's vessel construction requirements (9).

Classification Society: entity which inspects ships for a fee and certifies that the ship meets its requirements (9).

Charterer: buyer of tanker transportation services; the tanker owner's customer (9).

Cruciform joints: "a specific joint in which 4 spaces are created by the welding of 3 plates of metal at right angles. In the American Bureau of Shipping Rules for Steel Vessels, cruciform joints may be considered a double barrier if the two substances requiring a double barrier are in opposite corners diagonally. Double barriers are often required to separate oil and seawater, chemicals and potable water, etc. (25)."

Deballasting: the process of pumping ballast water out of the ship, almost always into the sea (9).

Design for Producibility: the philosophy of designing a hull structure to minimize construction man-hours with little concern for the internal stress flow and its effect on structural performance (9).

Draft: depth of water a vessel draws i.e. how low the vessel sits in the water.

Deadweight tons (DWT): carrying capacity of the tanker in tons, including the tanker's fuel.

Flag State: the country where the ship is registered.

Girder: steel support beam.

Heavy grade oil: under IMO regulations refers to any of the following: a) crude oils having a density at 15ºC higher than 900 kg/m^3; b) fuel oils having either a density at 15ºC higher than 900 kg/m^3 or a kinematic viscosity at 50ºC higher than 180 mm^2/s; or c) bitumen, tar and their emulsions (26).

Hogging: form of longitudinal bending when a stress causes the hull to bend upward; caused when a wave equal in length to the ship crests mid-ship causing the middle of the ship to bend upward.

Human Factors: the characteristics or behaviour of an individual or organization that causes an accident casualty, rather than a structural or mechanical failure or some environmental or other contextual factor that is outside of human control (19).

Hydrostatic balance: situation in which the external seawater pressure at the top of the tank damage is equal to the internal tank pressure at this point thereby preventing oil leaking from the tank. Damage higher than this point will cause oil to leak out of the vessel because the seawater pressure is too low to restrain it.

Intact stability: tanker stability during operation when no damage has occurred.

Lightering: ship-to-ship transfer of cargo - usually conducted offshore from a larger vessel to a smaller vessel whose draft is small enough to allow it to enter a destined port.

Lightweight: weight of the ship when emptied of fuel and cargo, in tons.

Longitudinal bending: bending along the vessel's length, from end to end e.g. sagging or hogging.

MARPOL tanker: single hull tanker of 20,000 DWT and above carrying crude oil, fuel oil, heavy diesel oil or lubricating oil as cargo, or of 30,000 DWT and above carrying other oils, which do comply with the protectively located segregated ballast tank requirements (27).

Pitting corrosion: rapid localized corrosion of cargo and ballast tank bottoms (9).

Port-state: the country where the ship loads or discharges.

Pre-MARPOL tanker: single hull tanker of 20,000 DWT and above carrying crude oil, fuel oil, heavy diesel oil or lubricating oil as cargo, or of 30,000 DWT and above carrying other oils, which do not comply with the requirements for protectively located segregated ballast tanks (27).

Safety Factors: design allowances for unknown factors.

Sagging: a form of longitudinal bending when a stress causes the hull to bend downward; caused when a wave is equal in length to the ship and crests at the bow and stern with the trough mid-ship, causing the middle of the ship to bend downward.

Stringers: horizontal structural members running the length of the tank.

Transverse stability: ability of a vessel to stay upright and resist listing or capsizing completely.

Underwriter: ship's insurer.

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Appendix A

Double-Hull, Double-Bottom and Double-Sided Spills

Table 2 lists double-hull, double-bottom and double-sided tanker casualties that have resulted in spills over 1,000m^3 as reported in the Center for Tankship Excellence (CTX) database. It is likely incomplete. The double hull issue is a misleading safeguard regarding transport of goods by sea. The majority of the tankers in Table 2 did not get into trouble because they were double-hulled, double-bottomed or double-sided; more important than hull configuration is the true cause of the accident e.g. non-inerted tank, navigational error, limited low speed maneuverability, etc. This table is provided merely to dispel claims that there have been no major spills from double-hulled tankers.

Table 2
Major Double-Hull (DH), Double-Bottom (DB) and Double-Sided (DS) spills

Date	Vessel Name	Vessel Type	Hull Type	Litres spilled	Dead	Description
23/01/2010	*Eagle Otome*	Crude oil tanker	DH	1700000	0	Collision with tug barge. 50 metre gash.
18/08/2009	*Formosaproduct Brick*	Product tanker	DH	5000000	9	Collision with *Ostende Max* led to fire/explosion and severe list.
04/02/2005	*Genmar Kestrel*	Crude oil tanker	DS	1557000	0	Collision with crude oil tanker *Trijata*. Cause unknown.
18/11/2004	*Good Hope*	Crude oil tanker	DH	1600000	0	Spilled during loading. Potential cause equipment failure.
15/11/2004	*Vicuna*	Chemical tanker	DB	5000000	6	Explosion during methanol loading. Sank.

Date	Vessel Name	Vessel Type	Hull Type	Litres spilled	Dead	Description
26/05/2004	*Morning Express*	Product tanker	DH	1500000	0	Collision bulk carrier *Pos Bravery* near pilot boarding station.
28/02/2004	*Bow Mariner*	Chemical tanker	DB	12600000	21	Non-inert tank cleaning caused explosion. Sank.
29/03/2001	*Baltic Carrier*	Chemical tanker	DH	2900000	0	Steering failure caused collision with bulk carrier *Tern* causing extensive damage.
08/06/1998	*Maritza Sayalero*	Product tanker	DH	1110000	0	Broken hose during discharge.
08/02/1997	*San Jorge*	Product tanker	DB	5880000	0	Grounded on "uncharted" rock.
18/01/1997	*Bona Fulmar*	Ore/Bulk/Oil (OBO) Carrier	DB	9450000	0	Collision with chemical tanker *Teotal*. 4m x 3m hole leaked 7,000t of gasoline.
01/10/1993	*Frontier Express*	Product tanker	DS	8260000	0	Grounded. Cause unknown. Volume suspect.
16/06/1993	*Korea Venus*	Product tanker	DS	4280000	0	Grounded. Cause unknown.
03/12/1992	*Aegean Sea*	OBO Carrier	DH†	87000000	0	Grounded in bad weather, broke in two, caught fire and sank.
19/09/1990	*Algarrobo*	Ore, Oiler	DH	2000000	32	Sank off Chile loaded with ore. No message sent. Probably DB leak and explosion.
06/08/1990	*Sea Spirit*	OBO Carrier	DH	7770000	0	Collision with LPG carrier *Hesperus*.
15/03/1990	*Alexandre P*	OBO Carrier	DH	1600000	24	Sank in good weather. No distress signal. Cause unknown.
13/07/1988	*Nord Pacific*	Crude oil tanker	DB	2440000	0	Hit berth while mooring.
08/10/1987	*Cabo Pilar*	Ore, Oiler	DB	7000000	0	Grounded. Unknown cause.
18/11/1986	*Kowloon Bridge*	OBO Carrier	DH	2000000	0	Hull failure then steering loss. Grounded. Sank.
17/05/1986	*Valparaiso*	OBO Carrier	DH	2300000	0	Grounded. Cause unknown.

† At the time of casualty, the Aegean Sea was reported as a double-hull tanker by the Tanker Advisory Center; this has not been confirmed. She was definitely double-bottomed and since the cause of the spill was a grounding then fire, having double sides as well would have made very little difference.

Date	Vessel Name	Vessel Type	Hull Type	Litres spilled	Dead	Description
09/12/1983	*Pericles GC*	OBO Carrier	DH	54100000	0	Engine room fire. Sank.
18/10/1983	*Monemvasia*	OBO Carrier	DH	4000000	0	Unknown.
09/09/1980	*Derbyshire*	OBO Carrier	DH	2400000	44	Hatch cover collapsed in storm. Sank. Loaded with iron ore.
20/10/1979	*Berge Vanga*	Ore, Oiler	DH	5000000	40	Disappeared. Probably repeat of *Berge Istra*.
01/09/1979	*Chevron Hawaii*	Crude oil tanker	DB	32000000	3	Lightening strike caused explosion (no/poor inerting). Broke in two. Salvaged.
26/06/1979	*Vera Berlingieri*	Product tanker	DH	6000000	29	Collision with bulk carrier *Emmanuel Delmas*. Fire and explosions. Sank.
23/06/1977	*Siljestad*	OBO Carrier	DH	1000000	0	Fire. Scrapped. Cause unknown.
31/01/1977	*Exotic*	OBO Carrier	DH	3500000	9	Cargo tank explosion then grounding.
29/12/1975	*Berge Istra*	Ore, Oiler	DH	5000000	30	Series of explosion in DB space. Sank. 30 of 32 killed.
13/05/1975	*Epic Colocotronis*	Ore, Oiler	DH	6700000	0	Cause unknown. Potentially engine room fire or hull crack.
22/02/1974	*Nai Giovanna*	OBO Carrier	DH	3490000	8	Fire and explosions in empty tanks. Sank. Cause unknown.
06/12/1960	*Sinclair Petrolore*	OBO Carrier	DH	60000000	n/a	Explosion. Sank. Cause unknown.

For more information on all of these spills, visit the CTX tanker casualty database: http://www.c4tx.org/ctx/job/cdb/do_flex.html