Alternative Double Hull Tanker Design
Double Side Hull + Sub-Atmospheric Ullage

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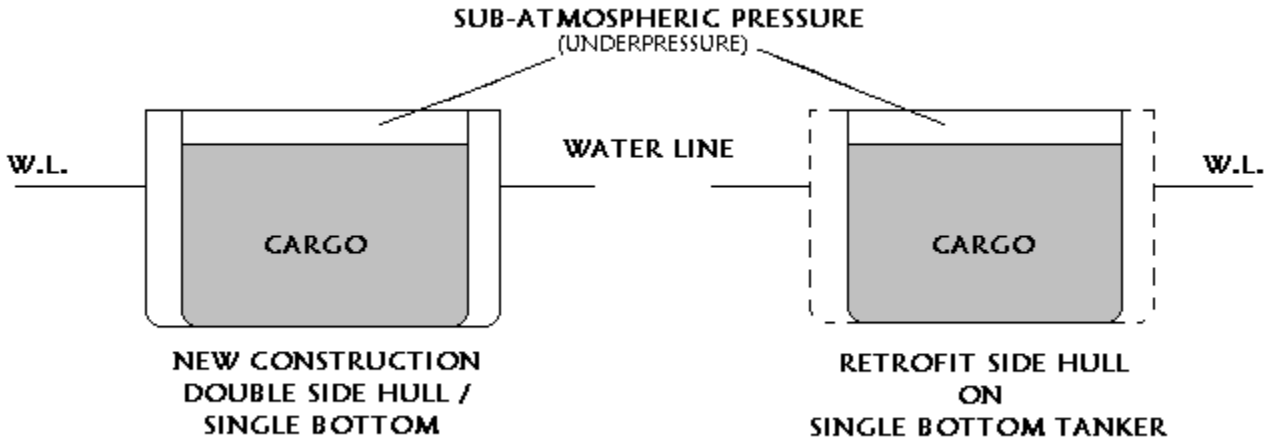

ABSTRACT

This paper presents an alternative to the double hull configuration now being constructed and used for crude oil transport service. As currently being built, these vessels meet their design objective of reducing oil spills resulting from collision or grounding. However, double hulls are structurally complex and expensive, and appear to be developing operational disadvantages as well. This paper proposes to have double side hulls on a single bottom hull (without an inner-bottom) for new construction or to simply retrofit a single hull tanker with double side hulls and add on the sub-atmospheric pressure in the ullage. The underpressure approach in this paper uses a closed loop vapor control system that prevents or drastically minimizes emission of crude oil vapor. This paper is presented in three parts:(1) Introduction to the underpressure system (2) Emission containment of crude oil vapor in the underpressure system and (3) Comparative probabilistic outflow analysis of double hull versus double side hull +underpressure system. Analysis to date indicates that this design concept can provide equivalent cargo loss protection at reduced cost without introducing risk elements or uncertainties.

KEY WORDS

Double Hull Tanker; Oil Spill Prevention; Collision & Grounding; Hydrocarbon Vapor Emission; Underpressure System; Probabilistic Methodology

INTRODUCTION

This paper presents an alternative to the double hull configuration now being constructed and used for crude oil transport service. These vessels meet their design objective of reducing oil spills resulting from collision or grounding, but are structurally complex and expensive, and appear to be developing operational disadvantages as well. The proposed alternative offers equivalent protection against oil spills, and is less costly, both in construction and in operation.

The double hull concept was developed in response to increased concern about oil spills from tanker vessels, and the current tanker fleet is gradually being replaced by double hull vessels. These are mandated by various international and national regulations such as, for example, IMO MARPOL regulation 19 of MARPOL Annex 1 and the United States Oil Pollution Act of 1990 (OPA 90). Ultimately, these regulations require the conversion of the legacy fleet to the double hull configuration, too.

Generally, the regulations require that all new tank vessels built after a certain date be fitted with double bottom and double sidewalls, thus providing a protective void between the cargo and the environment.

Apart from its cost and its inapplicability to the legacy fleet, the double hull has demonstrated some operational disadvantages. First of all, like every other option that has been proposed, it is not fully effective. It affords improved protection in minor incidents, but fails to do so in the case of more severe incidents.

In addition, experience with the current double hull fleet has shown a disconcerting tendency to corrode severely in the protective spaces, with resulting high maintenance costs and the possibility of premature localized failure.

Other problems may be developing. The required protective void spaces introduce new and awkward stability questions, especially after damage. Finally, the recovery at sea of cargo from a damaged vessel can be complicated by the presence of additional void spaces.

The design configuration proposed in this paper uses the double sidewall as the protective feature in collision incidents, and uses reduced ullage space pressure to mitigate cargo loss in grounding incidents. It also reduces the other adverse features of the current double hull concept.

The IMO guidelines set forth three distinct criteria by which to measure the effectiveness and equivalency of double hull tanker designs. These criteria are the probability of zero outflow, the average outflow and the extreme outflow resulting from various accident scenarios.

This paper proposes to have side hulls on a single bottom hull (without inner-bottom) for new construction or to simply retrofit a single hull tanker with side hulls and add on the underpressure system (i.e. reduced pressure in the ullage space). The underpressure system has been tested in a full-scale ship, a single hull US Navy tanker, to prove its efficacy to prevent spillage

The first section of the paper discusses the use of underpressure to prevent spillage of oil due to accidental rupture of a tanker hull. Dynamically controlled sub-atmospheric or negative pressure in the ullage is the key to mitigate or prevent spillage of oil in accidental grounding or collision. The combination of a double side hull, ullage underpressure, and a single bottom tanker has less outflow than a wrap around double hull.

The second section of the paper discusses a beneficial side effect of this approach. This benefit is VOC emission control. Inherent in the underpressure method utilized here is the ability of its closed-loop system to control emission of VOC venting of hydrocarbon vapor during transport, loading and unloading of crude oil from tankers, which amounts to a loss of four to seven million tons per year of expensive light crude fractions to the environment. The closed-loop feature of the underpressure system prevents or significantly minimizes VOC emissions. Finally, the conclusion and future prospects of side hull plus sub-atmospheric ullage in a tanker are discussed.

The third section of the paper discusses the outflow of a hypothetical single bottom tanker with a double side hull and using reduced pressure in the ullage spaces. The MARPOL methodology of probabilistic computation of outflow is discussed. Calculations indicate that single bottom tankers with double side hulls and sub-atmospheric ullage pressure are superior to the wrap-around double hull as judged by the average outflow criterion, and are comparable regarding probability of zero outflow and extreme outflow.

UNDERPRESSURE SYSTEM

The underpressure system discussed in this paper has been tested on a full-scale ship, a single hull US Navy reserve fleet tanker – USNS Shoshone.

The system described herein is known as the American Underpressure System (AUPS) and was developed by MH Systems, Inc. of the United States. The test and analysis of the AUPS was performed by MH Systems under the aegis of The Office of Naval Research (ONR). Discussion of the underpressure will necessarily be brief because of limitation of this paper and will highlight the principal features of the system as related to mitigation of outflow of oil.

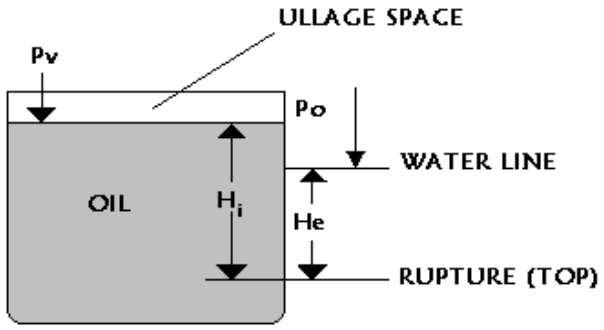

FIGURE 1

Theory of underpressure to prevent outflow at the rupture point from the above figure:

At the point of rupture (Figure 1), if the external pressure (Pe) is equal to the internal pressure (Pi), then there is a state of equilibrium, and there will be no outflow:

$P_e = P_i$
or
$P_a + D_w \times H_e = P_v + D_o \times H_i$
or
$P_v = P_a + D_w \times H_e - D_o \times H_i$

Therefore the required underpressure at the ullage = $P_a - P_v$

Where P_a = Atmospheric Pressure
Pv = Ullage Pressure
D_w = Density of water
D_o = Density of Oil

It is important to distinguish the term "closed loop" used to describe the underpressure system arrangement from the same term commonly used in control engineering. The former refers to the fact that the ullage gases are recirculated through the system as opposed to venting to the atmosphere or to the vapor recovery facility. The physical gas-vapor loop regulating the ullage and header pressure is always closed in the sense of control engineering.

In the closed-loop underpressure system, negative pressure must be maintained at a predetermined level to prevent cargo loss in the event of accident, while the oxygen content must be held within specified limits to eliminate fire danger. Inert ullage gases are circulated through the ullage spaces, primarily to dilute air that could leak into reduced ullage spaces, and the gases are returned to the tanks via blower and heat exchanger.

The following discussion of the underpressure system will include results of tests and analysis under the guidance of the Office of the Naval Research (Reference 5) and highlight the important consideration of the underpressure system.

Tankers Structural Capability to Withstand Negative Pressures:

A key requirement for underpressure system is the application of negative pressures in the ullage space of the tank(s). The negative pressure in the tank is required to attain hydrostatic equilibrium to prevent spillage due to a rupture of the hull.

There are of course many reports and anecdotal stories of tank implosion and resultant structural failure due to inadvertent closure of the vent during unloading of cargo. However, as our analysis and test results will show, measured and dynamic application of negative pressure is not only safe, but a creative method to prevent spillage of oil.

MH Systems commissioned the American Bureau of Shipping (ABS) to perform analysis to assess the impact of negative pressures on stresses and buckling loads at various levels of negative pressures (underpressure) – A tanker of 276,000 DWT was selected for the analysis.

In general -3 psi to -4 psi is used in the underpressure system. The ABS analysis shows that in those negative pressures, ample safety margin exists before the tank structure begins to yield. The data in Table 2 (load case #2) suggests that even at -8.5 psi, structural strength degradation would not occur for this particular tanker.

The ABS report states: " The analysis was performed for the purpose of obtaining the structural response for the center deck structure due to incremental results of underpressure. As such, there is no conclusion, just a presentation of results for the use of MH Systems. However, we can state that from a structural assessment point of view the underpressure procedure is a viable system"

Analysis:

The analysis includes a 3-D parallel mid-body model extended from port to starboard and bottom to deck, incorporated one tank length of 6 bays from the O.T. bulkhead to the O.T. bulkhead. The meshing of the entire model was coincident with the longitudinal stiffener spacing of the hull girder. In way of the center tank deck framing the meshing was further refined to 8 elements per longitudinal spacing.

This meshing was consistent for the middle three frames of the tank and for the finer meshing also performed for the deck longitudinals in way of these frames. All plating was idealized using bending plate elements. The faceplates and panel stiffening of the web frames were also idealized using bending plates. Rod elements were used to idealize the faceplates of longitudinals and tripping brackets. The one liberty taken in the modeling was the exclusion of the O.T. bulkhead horizontal stringers.

The end bulkheads are the boundaries of the model and only the plating and stiffeners were modeled. Springs idealizing the hull girder plating shear area vertically and horizontally were introduced for vertical and athwart ship restraints at these bulkheads. The applicable nodes of the side shells and longitudinal bulkheads were restrained at the neutral axis against movement of the longitudinal direction.

Sagging bending moments were introduced at these boundaries as linear line forces along the hull girder shell and longitudinal bulkheads such that an initial allowable compressive stress of 2480 kg/cm^2 (35,270 psi) was introduced at the deck side, mid-hold of the model. Since the O.T. bulkhead horizontal girders are to one side of the bulkhead, the added extent and effort to include these structures was considered too extensive for the minimal impact it would have on the results for the center tank main deck. Appendix C shows selected sections of the 3-D finite element model. Following are the basic conditions:

- Base Load Condition was still water condition; Draft 70.50 ft (21.5 m); wing tanks and the center tanks "pressured" to ullage level; pressure against the deck is zero in the still water condition.

- A vertical hull girder bending moment was applied at the ends of the model such that the deck stress is equal to the ABS allowable of 25,374 psi or 1784 kg/cm^2 for mild steel or 2480 kg/cm^2 or 35, 273 psi for the actual AH36 deck plate.

- The load cases investigated include the center tank until the elastic failures are reached for portions of center deck and supporting web structure.

The following pressure load cases were investigated

TABLE 1 Base Load Conditions

Load Case #	***Condition***	***Underpressure* (- kg/cm^2)**	***Underpressure* (- psi)**
1	Stillwater	0.0	0.0
2	Stillwater	0.1	1.42
3	Stillwater	0.2	2.84
4	Stillwater	0.3	4.26
5	Stillwater	0.4	5.69
6	Stillwater	0.5	7.11
7	Stillwater	0.6	8.53
8	Stillwater	0.7	9.95
9	Stillwater	0.8	11.38
10	Stillwater	0.9	12.80
11	Stillwater	1.0	14.22

Acceptance Criteria:

The allowable Hencky-von Mises stress is taken

a) The allowable Hencky-von Mises stress is taken as 85% of the yield stress of the material. For mild steel, this is 2040 kg/cm^2 (28,900 psi) and for AH36 steel, 3060 kg/cm^2 (43,342 psi).

b) For"highly localized" stress concentrations, the stress concentration may be 1.25 times the yield stress for mild steel and marginal to the yield stress for high tensile steel. We could even go to 1.1 times the yield stress for the HTS, if highly localized.

c) The criteria for panel buckling must be met, i.e. unity check for elastic panel buckling

TABLE 2 Summary of H-v-M Stresses for Center Tank Web Frames

Load Case	**Web kg/cm^2**	**Face plate kg/cm^2**	*Web Psi*	**Faceplate Psi**
1	1170	1160	16,594	16,566
2	1250	1150	17,741	16,315
3	1350	1360	19,260	19,342
4	1610	1430	22,880	20,333
5	1880	1500	26,781	21,307
6	2170	1740	30,856	24,729
7	2460	1810	35,045	25,807
8	2790	1890	39,678	29,572
9	3130	2160	44,553	30,759
10	3480	2240	49,492	31,930
11	3830	2330	54,468	33,116

Table 2 summarizes the H-v-M stresses for the center tank deck webframes. Web and face plates are of mild steel which has an allowable allowance 2040 kg/cm^2 (28,900 psi)..

TABLE 3 Summary of H-v-M Stresses for Center Tank Slab Longitudinals and in Way of the Tripping Brackets

Load Case	**Long. Kg/cm^2**	**iwo Brkt kg/cm^2**	*Long. Psi*	**iwo Brkt Psi**
1	2040	2040	28,979	28,979
2	2010	2150	28,545	30,584
3	1960	2260	27,908	32,191
4	2060	2380	29,311	33,799
5	2160	2490	28,358	35,410
6	2260	2600	29,646	37,021
7	1990	2720	28,373	38,634
8	2080	2830	29,572	40,248
9	1970	2490	27,983	41,863
10	2040	3060	29,043	43,479
11	2120	3170	30,121	45,096

Table 3 summarizes the H-v-M stress for the center tank slab longitudinals and the stresses in way of the panel stiffeners and tripping brackets.. These structures are of mild steel.

The ABS report states: " The analysis was performed for the purpose of obtaining the structural response for the center deck structure due to incremental results of underpressure. As such, there is no conclusion, just a presentation of results for the use of MH Systems. However, we can state that from a structural assessment point of view the underpressure procedure is a viable system"

Control System:

(Discussion of the control system is necessarily brief because of the nature and scope of this paper-detail discussion is included in Reference 5)

The control system provides for fully automated operation of the underpressure system in both routine and casualty modes. Personnel in the control room will be provided with consoles that display the critical parameters needed for monitoring and start/stop plant operations. There is minimal interface with ship services since the underpressure system contains its own electric power and inert gas supply. The closed-loop control architecture is shown schematically in Figure 2.

The principal hardware items are blowers to circulate gas and meet the pressure demands, modulating inlet valves to each tank to maintain ullage pressure, and the instruments that measure the pressure, oil and O_2 level in the ullage spaces and blower performance. The software architecture will control the functions under dynamic conditions in response to sensor data with minimal human intervention.

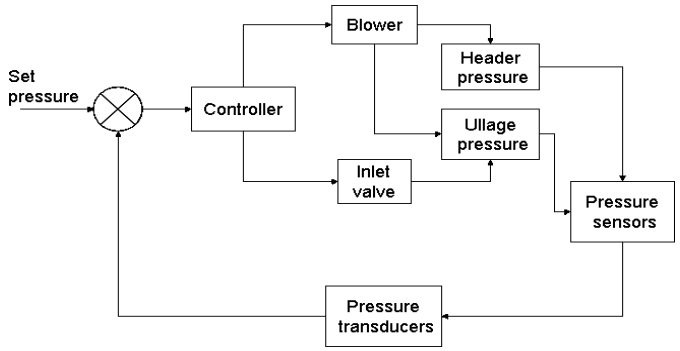

FIGURE 2 Closed Loop Control System Architecture

Risk Assessment

Risk management is a process of weighing alternatives for controlling risks and selecting the most appropriate course of action. Modern risk-based analysis is required for development and implementation of technology like the underpressure system. Accordingly, a preliminary risk assessment was performed for the underpressure system in all of its operational phases. This analysis identified potential adverse events, their frequency of occurrence, and the consequences of failure and possible mitigating measures. Finally, numerical reliability of the underpressure system is computed.

As a result, the related design features include:

- An autonomous control system that ensures functional units and shipboard supporting services are operable, especially during a collision when the man/machine interface may not be fully available.
- Functional units are independent and separate from ship's systems, and are located where they are least susceptible to damage from a collision. The key units are the standby inert gas supply module, the electric/pneumatic power supply system, the gas distribution system and the controls and data transmission system.
- Design features redundancies and degraded modes of operation built into the hardware and software systems, including a dedicated inert gas generator.

Reliability of the underpressure system

As part of the risk-based design of the underpressure systems, a thorough risk assessment was made including a reliability analysis and a failure modes and effects (FMEA) analysis. The first cut reliability analysis, comprised of 336 hours of operation, resulted in a total failure rate of 3.89 x $10^{-4,}$ for a reliability of 0.8775. This was deemed unacceptable. Therefore, adding a standby blower, a level sensor and a control communication unit, system reliability of 0. 9969 was achieved and is regarded as an acceptable number, nearly approaching the aerospace industry's reliability.

The system is composed of proven marine components and there is no operator in the loop in the event of a casualty. The risk management design considerations were safety of personnel and the reliability of the system to function effectively in a collision or grounding. The methodology of the risk is shown in Figure 3.

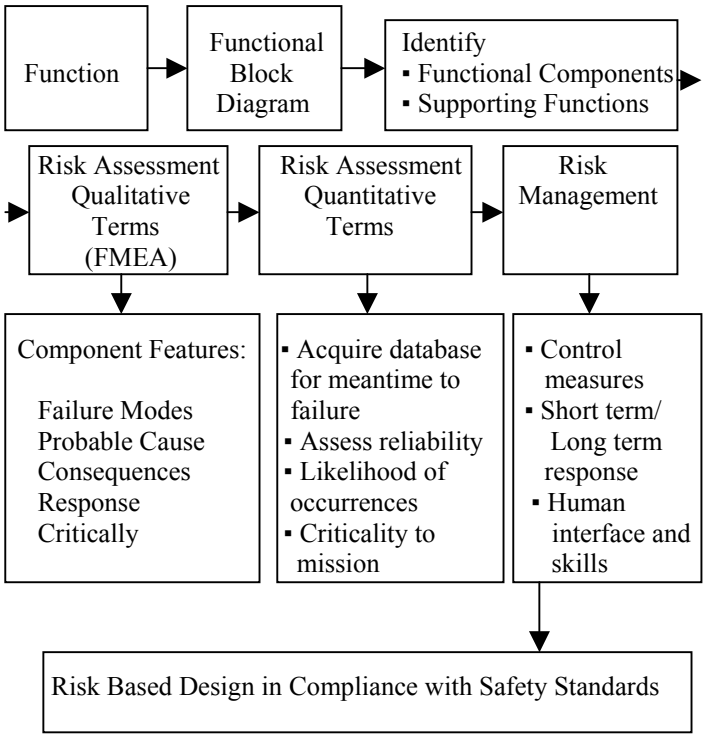

FIGURE 3 Risk Assessment Methodology

FMEA's were prepared for the various modes of operation. When the failure of a component was critical and the failure rate was marginal, redundancy was provided. This resulted in a design philosophy of local control at each tank networking to the main controller. Table 6 shows the final reliability calculations resulting from the risk analysis.

TABLE 4 Unit Failure Rates

UNIT	UNIT FAILURE RATES	FAILURE RATES FOR NON-REDUNDANT UNITS	FAILURE RATES FOR REDUNDANT UNITS
Blower	1.22×10^{-6}		1.22×10^{-6}
Pipe Assembly	0	0	
Electrical actuator	0	0	
Valves (3 per tank)	2.19×10^{-6}	2.19×10^{-6}	
Electrical cable	0	0	
Computer peripherals	0	0	
Connectors	0	0	
Control Communication Unit	3.06×10^{-4}		3.06×10^{-4}
Control Panel	4.50×10^{-7}	4.50×10^{-7}	
Diesel Generator	0	0	
Display	0	0	
Pressure sensor	2.22×10^{-6}	2.22×10^{-6}	
Temperature Sensor	0	0	
Level sensor	7.78×10^{-5}		7.78×10^{-5}
Flow gauge	0	0	
Pressure transducer	0	0	
Heat exchanger	0	0	
Total Failure Rate	3.89×10^{-4}	9.2×10^{-6}	

For 336 hours of operation per year without redundant units this gives the reliability of $e^{-0.000389 \times 336} = 0.8775$. This is unacceptable, and standby units are necessary. The combined reliability of the non-redundant units is $e^{-0.0000092 \times 336} = 0.9969$. The combined reliability of the units with redundancy is

$$1 - (1 - e^{-0.00000122 \times 336})(1 - e^{-0.000306 \times 336})(1 - e^{-0.0000778 \times 336}) = 0.9999$$

Vapor Generation and Vapor Safety

The underpressure system AUPS is configured to re-circulate inert gas at below atmospheric pressure through the tanks' ullage spaces. This closed system satisfies the requirement for VOC emission and spill containment on crude oil tankers. AUPS requires a revision to the present regulations that mandates a positive ullage pressure in all operating modes.

The key issues raised because of the use of underpressure in a closed-loop arrangement are:

- Safety hazards due to air leakage and local concentrations of potentially flammable leaked air.
- Continuous evaporation with underpressure.
- Maintenance of the inert gas composition and underpressure subject to mass and heat transfer effects during the voyage.

All these issues have been addressed by analysis and tests, by full-scale on board test, and by laboratory tests (Reference 4).

Crude Oil Vaporization and Composition

(HYCAL Energy Research Laboratory of Canada conducted the experimental and theoretical evaluation of representative crude oils.)

Experimental Work

Experiments were conducted to measure gas evolution from the crude oil at reduced pressures and at various temperatures.

The cargo properties for both vapor and liquid were determined at pressures below atmospheric [0 to –5 psig], crude oil temperatures ranging from 67°F to 110°F, crude oil types [API 12 to 37] and ullage gas/oil volumes ranging from .02 to 0.8. Predictions of liquid-vapor transformation were modeled from the Peng-Robinson Equation of State. The amount of material vaporized in reaching equilibrium and the composition of the gas mixture and source liquid were determined for use in the evaluation of AUPS Underpressure System.

Three crude oils were selected to cover the range from 12 API to 37 API. The compositional analyses of crude oils were performed. For each of them a series of gas evolution tests was performed at pressures of 0 psig, -2 psig and –5 psig at temperatures 75 F, 80 F, and 110 F and the liberated gas compositions were measured.

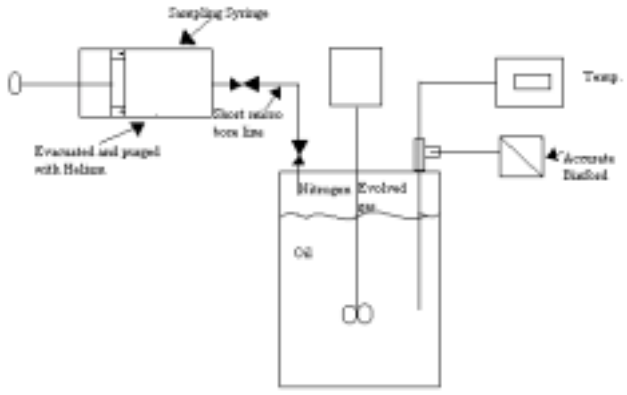

FIGURE 4 – Vaporization Experimental Setup

The gas evolution study indicated that the vaporization of light components from crude oil depends on:

- The API gravity of the crude oil – For heavy oils, the vaporization can be considered insignificant.

- Temperature – A temperature increase favors the vaporization of intermediate components.
- Pressure – As pressure decreases below atmospheric pressure, the gas composition becomes richer with intermediate components.

Table 5 (below) summarizes the mole fractions of crude oil vaporized at a given pressure and temperature.

TABLE 5 Mole Fraction of Vaporized Crude Oil

CRUDE OIL	**Temperature** (F)	**Pressure**			
		0 psig	**-2 psig**	**-3 psig**	**-5 psig**
		Mole Fraction			
12 API	67	0.0013	0.0500	0.0744	0.1234
	80	0.0092	0.0568	0.0807	0.1288
	110	0.0245	0.0703	0.0933	0.1398
30 API	67	0.0009	0.0327	0.0507	0.0956
	80	0.0167	0.0535	0.0756	0.1371
	110	0.0868	0.1626	0.2240	0.5298
37 API	67	0.0007	0.0300	0.0470	0.0906
	80	0.0139	0.0479	0.0687	0.1284
	110	0.0683	0.1329	0.1837	0.4093

The vaporization described above is in accordance with expectations. In terms of quantity, even the worst-case scenario of highest temperature and lowest pressure, the amount of vaporized components was within 0.55% in mole, as shown in Table 5. That means that the change in the crude oil composition is practically insignificant (References 6 and 7).

The differences in the composition before and after the process of vaporization are practically within the error of chromatography measurements. This is a good indicator that the properties of crude oil are not affected by this degree of vaporization. On the other hand, because the gas vaporized remains in equilibrium with the crude oil, depending on conditions the evaporants may again go into solution either partially or fully.

In addition to laboratory tests, the compositions of liberated gases were calculated using Peng-Robinson equation of State (PREOS). The PREOS was chosen because of its superiority in fluid phase behavior predictions as compared to equations developed for the prediction of ideal gas behavior. The EOS parameters were tuned to match the data such as the density of the crude oil, the bubble point pressure and gas composition associated measured at 0 psig and 67 F. The tuned parameters were then used to predict the gas compositions at reduced pressures and at given temperatures. This procedure was followed for each crude oil.

Comparisons of measured and calculated results are shown in Appendix D.

Vapor Recovery Process/VOC Containment

Hydrocarbon emission from crude oil tankers is a significant on-going environmental and economic problem. EU countries have already sponsoring laws to limit such emission for environmental reasons. It is estimated that approximately four to seven million tons per year worldwide of hydrocarbon vapor or are lost to atmosphere. That is environmentally unaccepTable 6nd economically undesirable. The use of the underpressure system aids in the mitigation or containment of VOC.

Vapor Recovery Loop

The underpressure system in its closed-loop arrangement essentially re-circulates ullage gases via a blower, seawater heat exchanger, and modulating valves, with controls to maintain the underpressure at a selected value.

For vapory recovery function the closed loop arrangement includes a vapor recovery loop (VRL) as shown schematically in Appendix B. The VRL includes dryer, compressor, heat exchanger and pressurized storage tank. During the normal in-transit operation, all valves in the VRL are closed. The system is therefore reduced to the basic closed-loop underpressure operation. The difference between the basic or 'Open' underpressure system and the system with the VRL operation arises during loading and unloading operation. Underpressure is not used during loading and unloading operations.

Appendix A gives the quantitative analysis of the condenser and VOC emission prevention during loading and unloading operation.

Calculations based on a 127,000 dwt tanker show that approximately 200 tons to 300 tons of oil from each loading event is saved from releasing to the atmosphere. (Preliminary calculations are shown in Appendix A.) An average of 0.2% of crude oil can be saved during loading operation. This is a considerable saving in terms of environment and economy as well. Added to this, the emission during transport and unloading, the problem becomes environmentally unacceptable, but quite solvable in a manner that is economically sensible.

MH SYSTEMS MARPOL-BASED PROBABILISTIC OUTFLOW METHODOLOGY

The MARPOL 73/78 Guidelines

Annex I, Regulation 13F and Appendix 7 of MARPOL 73/78 detail Guidelines for the approval of alternative methods of design and construction of oil tankers under 13F(5). The Guidelines outline two sets of computational procedures under which the acceptability of a given tanker design is to be established. These procedures postulate an incident environment of collision and grounding events, and provide a means of estimating the oil spill consequences of a given ship design operating in that environment. They specify a "conceptual" mode in which trim and draft remain constant after a damage incident, and a "survivability" mode in which the effects of the damage incident are reflected in the trim and draft of the vessel. There are other differences as well. The first is simpler, and is adapted to comparative or preliminary design work, while the second is more difficult, and is intended to provide the basis for a formal approval process for a specific design intended for construction. This second version would normally be integrated into the formal ship detail design process.

The present study is exploratory in nature, and no specific, detailed design configuration is being proposed for actual construction. Thus we use the "conceptual" mode to compare different approaches for spill control.

The Guidelines define a computational process with the following elements.

- A set of statistical distributions that define collision and grounding damage events that are expected to occur. Each damage event results in a rectangular damage region that may penetrate cargo tanks.
- A specified proportion of collision and grounding events.
- A set of criteria under which the amount of cargo lost can be calculated for the given ship designs after it suffers a given rectangular region of damage.
- A set of rules under which the calculated cargo loss is translated into statistical measures of oil spill severity.

Principal Features and Characteristics:

The Guidelines did not allow for the effects of possible manipulation of ullage pressure as a means of mitigating oil spills. In addition, the tank volume calculation requires offsets and thus requires that considerable initial design effort must be made. Overall, the current version of the calculation reflects the following objectives and assumptions.

- Damage is defined by the statistical distributions provided in the Guidelines, comprising five graphical plots for collision and five for grounding incidents. These define longitudinal location and area, vertical or transverse location and area, and depth. Thus each damage incident produces a rectangular region of total damage extending to a specific depth.
- Ruptures occur over a finite area defined by the overlap between the damage area and the projected tank area. The vertical extent of the damage must be taken into account in the hydrostatic calculation of cargo loss.
- Control issues and related dynamic effects are not considered. This assumption is common to the Guidelines.
- Underpressure systems can have either of two operative principles, either that the pressure is held constant or that the pressure is controlled to hold the upper level of cargo constant. The Guidelines do not make provision for underpressure as a spill control measure.
- Tanks are rectangular volumes. This replaces the MARPOL format, in which offsets are used.
- Regardless of damage, the trim and draft of the ship are unaffected and remain constant. This assumption corresponds to the "conceptual" approach defined by the Guidelines.
- The cargo fluid is of lower density than the surrounding fluid (seawater or freshwater).
- Collision damage is assumed to reach, or fail to reach, centerline tanks according to the depth of the tank boundary as compared to the depth of damage.
- The computational algorithm need not, at least initially, be capable of addressing unusual configurations such as the mid deck.
- The Guidelines provide for corrections for tidal range and for dynamic effects. Tidal range can be represented in the calculation by a reduction in draft. The dynamic correction follows the Guidelines in simply allowing a specified fraction (one percent in the Guidelines) of the cargo in a ruptured tank as a loss. The underpressure system is designed to adjust pressure to account for tidal range by keeping the upper cargo level constant, so to a first order these effects are compensated for.
- The computational algorithm allows for the imposition of a structural limit on underpressure, so that the control policy can be overridden.
- Grounding and collision are treated as occurring in a user-selected ratio. The same is true for the Guidelines, which use 60:40 grounding:collision.
- Double hull features are modeled directly by comparing tank location with damage depth.

In general, the requirements of the Guidelines can be met straightforwardly by incorporating them into the standard calculations of detail ship design. The respective probabilities are incorporated into the calculations in a direct, causal way using a stratified structure. We have found it easier and more flexible, however, to use a Monte Carlo approach in which a large number of accident scenarios are generated and randomly played against the hydrostatic models of the cargo tank system.

Testing a Damage Incident to Determine if a Given Tank is Involved

After each set of damage data is randomly created, it is then tested against each tank to determine if it overlaps the tank. We define, for a collision incident, (1) the longitudinal location and length of the tank, (2) the vertical location and depth of the tank, and (3) the transverse location of the tank. For a grounding incident, the parameters are (1) the longitudinal location and length of the tank, (2) the transverse location and depth of the tank, and (3) the vertical location of the tank. These data are compared with the corresponding damage parameters to determine if the tank has been ruptured.

As the calculation of each incident is very fast, the necessary number of simulated incidents can be handled easily. Typically, for example, a million incidents, 400,000 collision and 600,000 grounding, can be run in a few seconds to yield a repeatability of two places or better in the results. Ten times that number can easily be accommodated in a routine study.

A general calculation algorithm has been developed for a single tank. Having given the overall depth of the tank, the cargo depth, the cargo density relative to seawater, the location of the waterline above the bottom of the tank, and the vertical extent of the rupture, the calculation determines the direct and displacement outflows resulting from the specified damage.

The outflow calculation is driven by a damage incident simulation process in which either a side (collision) damage or a bottom (grounding) incident is assumed. For either, five random numbers are chosen on the unit interval and are used with the MARPOL-specified damage distributions defined by the guidelines charts to find specific random values of the location, extent and depth of a possible incident. The outflow resulting from each such random incident is computed and the resulting outflows are accumulated over a very large number of iterations. The result is the complete statistical distribution of collision and grounding outflow quantities. This distribution can then be processed to yield the expected loss, the probability of zero loss and the average of the tenth highest losses. These conform to the measures derived in the guidelines. Other appropriate measures could also be developed.

The following sections describe the individual components of the computing process.

Cargo Loss Analysis for a Single Event

The loss parameters are represented by two variables, T, the top of the rupture area and B, the bottom of the rupture area, both relative to the bottom of the tank. For a point rupture, a direct loss is that due to hydrostatic pressure difference across the rupture, while a displacement loss is attributable to the pressure gradient across the rupture after the pressure itself has equalized.

There are five possible locations for each of the rupture boundaries, T and B. These are as follows.

- Above the tank
- In the ullage space
- In the cargo, above the waterline
- In the cargo, below the waterline
- Below the tank

Thus there are 5 x 6 / 2 = 15 possible damage configurations. Each must be considered based on hydrostatics, coupled with some level of practical logic. For instance, a pressure difference cannot keep a fluid from escaping to the air.

For bottom damage in grounding, the breach is defined by a rectangular volume removed from the outermost surface of the ship

It is important to note, in considering the results of the analysis process, that the damage dimensions defined by Marpol are scaled to ship size, so that to a considerable degree the proportionate results of analysis, like average loss fraction, tend to be independent of ship size. There is some variability, however, because the sidewall and bottom protective spaces do not scale with size.

Random Number Generation

A function is needed that will return a random number on the unit interval. The standard Microsoft Dot-Net random number function is used, and probably cannot be improved upon.

Testing a Damage Incident to Determine if a Given Tank is Involved

After each set of damage data is randomly created, it is then tested against each tank to determine if it overlaps the tank. Adopting the notation of the previous section, we define, for a collision incident,

X_{loc} and Length are the longitudinal location and length of the tank,

Z_{loc} and Depth are the vertical location and depth of the tank, and

Y_{loc} is the transverse location of the tank

these locations being taken to the aft, lower, starboard corner of the rectangular tank. Now for a tank to escape damage, we must have one or more of the following conditions.

- Lower boundary of the damage area above the upper boundary of the tank.
- Upper boundary of the damage area below the lower boundary of the tank.
- Forward boundary of the damage area aft of the aft boundary of the tank.
- Aft boundary of the damage area forward of the forward boundary of the tank.
- The depth of the damage region is insufficient to reach the outermost boundary of the tank.

Measures of Loss Prevention Effectiveness

The criteria developed by the calculation procedure are as follows:

- The probability that a specific tank will be hit.
- The probability that a specific tank will be ruptured if it is hit.
- The amount of cargo initially in the tank, in cubic feet or cubic meters.

- The expected cargo loss as a fraction of the cargo initially present.
- The probability of zero loss for the tank if it is ruptured.
- The probability of *any* loss.
- The net probability of zero loss considering all factors.

SUPPORTING COMPUTER PROGRAM

Input Data:

The program accepts a standard input data format. The complete input format is summarized below.

Host Vessel

Ship length between perpendiculars
Ship beam
Ship depth

Ullage policy and settings

The ullage policy,
The default ullage pressure
The limiting minimum (most negative) ullage pressure

Individual tank parameters

Total depth of the tank
Cargo fill depth
Waterline measured from the bottom of the tank
Cargo density divided by seawater density
Relative to the tank bottom (if required)
Length of the tank as an equivalent rectangle
Width of the tank as an equivalent rectangle
Hit probability of the tank in collision and grounding
Tank Location, Longitudinal, from the after perpendicular
Tank Location, Transverse, from the starboard side
Tank Location, Vertical, from the baseline

Tank locations are taken to the aft, starboard, bottom corner of the tank.

Program Operation

A user-specified number of collision and grounding incidents are generated, each defined by a randomly selected type, location and extent of damage. For each damage configuration, the hydrostatic and displacement cargo loss components are found and damage statistics are accumulated, loss parameters are summarized. These calculations reflect the ullage pressure selected for the run or determined for the specific damage configuration.

The following are accumulated for each tank for both collision and grounding

Number of hits, total, on the tank
Number of hits resulting in zero loss
Number of misses
Total cargo loss, cubic feet (or meters)

In addition, each loss is assigned to one of, say, 100 cells, corresponding to equal steps over the range from zero to the total capacity of the ship. The number of occurrences and total loss are then accumulated by cell for all incidents, for both collision and grounding.

Output Data:

Once a set of input data has been entered, the normal calculation mode is entered. The following summarizes the primary output.

- A summary of hit and loss statistics by tank.
- For each tank, and for all tanks collectively, the expected (average) loss per incident and the probability of zero loss.
- For collision, grounding and for all incidents, the probability distribution loss magnitude.

Notes on Specific Marpol 73/78 Requirements

Collision Damage. The guidelines require the assumption that *any* damage to *any* tank in collision will result in a complete loss of the cargo contained in that tank. A part of the benefit conferred by the use of reduced ullage pressure is that tanks ruptured in collision will retain part of their contents. To represent this effect, the hydrostatic calculation of cargo loss in collision had to be added to the MHS methodology.

Tidal Change Effects. The guidelines specify three levels of tidal change for which separate outflow calculations are to be made. These three are then to be combined to yield a weighted cargo loss component. The underpressure system is sufficiently rapid in response to accommodate these tidal changes, and thus, although the program is *capable* of evaluating them, the MARPOL tidal change penalty is not invoked.

Positive Ullage Pressure. The Guidelines require a positive pressure of 0.05 bar, about 0.75 psi or 1.63 ft of seawater, to represent the positive inert gas pressure provided in current ship designs. Plainly this is at variance with the underpressure concept, and is provided in these calculations only as the "baseline" against which to compare underpressure performance.

Dynamic Outflow. The Guidelines require a flat one percent loss of cargo for any ruptured tank adjacent to the bottom surface of the ship. This feature is intended to represent flow and inertial effects.

Likelihood of Collision and Grounding Incidents. The Guidelines specify a proportion of 40 percent collision and 60 percent grounding. In the MHS program, these proportions are represented simply by using random incidents assigned in the desired ratio.

Void Spaces Adjacent to Cargo Tanks. The Guidelines provide that when a tank is ruptured coincidentally with an adjoining void space, then the void space is credited with saving cargo equal to 50 percent of its volume. This benefit is not included in the calculation, so the results are somewhat pessimistic in relation to the Guidelines.

Analysis Using Standardized Operating Conditions

Comparisons and evaluations were made with a standard set of conditions for all ships and for all ullage conditions. Cargo specific gravity was 0.833 relative to seawater, ullage space was two percent, dimensions and draft were taken at the design values and the one percent dynamic loss allowance was omitted. This loss allowance as well as the allowance for tidal range, was not applied, on the argument that dynamic effects can be avoided by a minor increase in underpressure to create a water barrier to losses. Equally, the very slow changes in draft could easily be accommodated by corresponding changes in the ullage pressure.

Some incidents may rupture the ullage space itself; in these cases the calculation assumes that the ullage pressure immediately changes to and remains at atmospheric.

Reduced ullage pressure alters hydrostatic balance, and thus can reduce outflow of cargo to the sea. However, it is assumed that a hydrostatic pressure difference cannot prevent cargo from flowing outward to the atmosphere.

An ullage pressure set to counter a grounding should result in zero loss when grounding occurs; an ullage pressure set to counter a rupture below the waterline should result in zero loss when a rupture occurs at the point for which pressure was set. Calculations support these assumptions, except for the one percent dynamic allowance invoked by the Guidelines, which occurs independently of the ullage pressure. It is arguable, however, that dynamic underpressure control, based on observation of fluid level and other factors, could, and probably would, prevent dynamic loss to some degree. Similarly, a somewhat higher initial underpressure than required could be used, creating an initial inflow of seawater at the time of rupture.

RESULTS OF THE CARGO LOSS CALCULATION

Ship Configuration

The approach in this calculation is to establish a number of baseline ships that represent double hull configurations typical of current practice. Three different vessel sizes were selected, nominally of 60,000, 150,000, and 283,000 deadweight. The three ships were taken from the MARPOL document, Reference 4, where they are designated ships 2, 3 and 4. For each of the three baseline vessels, two comparison vessels were created having the design feature being considered, namely a double sidewall and no double bottom and having protective ullage underpressure levels to defend against cargo loss from grounding.

In each case, the first of the two comparison designs was created by simply removing the inner bottom, the sidewall spaces being retained at their original transverse width. This approach results in a decrease in ballast capacity and a corresponding increase in cargo capacity. Although this is a somewhat awkward design for actual use, it is easy to understand and allows simple hand calculations to check results. At least, it preserves the external dimensions of the ship, and thus may be presumed to have comparable performance and seakeeping capabilities, as well as approximately equal structural weight.

The second of the two comparison designs is a somewhat more realistic model in which the inner bottom is removed to increase cargo capacity and at the same time the cargo space width is narrowed to decrease cargo capacity by a corresponding amount. The resulting configuration continues to preserve the outer dimensions while also preserving cargo and ballast volumes. It is not suggested that this is an entirely suitable design, but it represents a class of alternatives that can be compared directly to the parent double hull. We note in this connection that the increase in ballast width has two benefits, the first of which is that there is added protection against collision damage. This benefit is reflected in the calculations presented. A second is that the design with wider ballast spaces may provide improved structural simplicity and economy by allowing more continuity in the longitudinal bulkheads.

For both comparison alternatives the compartment arrangement concept of the baseline ship is preserved. In comparing the modified designs against the baseline double hull, the ullage pressure is an important factor. For the double hull, the MARPOL document, Reference 4, mandates a positive ullage pressure of 0.05 bar, or about 0.75 psig. This pressure is typical of the positive pressure used in contemporary tankers. On the other hand, the underpressure designs use a sub-atmospheric ullage pressure to protect against bottom rupture. In this case there are two options under which the pressure can be chosen. In one case, the pressure is set to defend against a grounding incident, while in the other case a somewhat greater underpressure may be used to afford additional protection against collision incidents.

Evaluation Data Format

Calculations were performed for three ships, each loaded to 98% capacity (i.e. having a two percent ullage space). The analysis assumes a crude oil cargo having a specific gravity of 0.833 relative to seawater. For each of the three ships there are three alternative configurations: (1) the baseline double hull vessel as originally designed, (2) the same vessel with the innerbottom removed, and (3) the same vessel with the innerbottom removed and the ballast space formerly occupied by the double bottom moved to augment the sidewall ballast spaces. In this third arrangement the total cargo and ballast volumes are unchanged from those of the baseline double hull.

The primary output was the average cargo loss per incident, expressed as a fraction of the total cargo loading and the probability of zero outflow in the threat environment defined by MARPOL 73/78. Other outputs included the cargo volumes, required underpressure settings and other supporting data.

Reviewing first the smallest of the three baseline designs, Table 6 shows five lines of data in three groups. The first group represents the baseline double hull design operating with the

positive ullage pressure of 0.05 bar as required by MARPOL 73/78. The data row shows, in order, the ship designation, the gross cargo tankage in cubic meters, the sidewall protective and ballast spacing in meters, the ullage pressure in meters of seawater, the expected (or average) cargo loss per incident as a fraction of total cargo, the expected loss quantity in metric tons, and finally the probability of zero outflow and its complement, the probability of *any* outflow. These quantities will be discussed further later on.

Returning to Table 6, the second group, two lines of data, is for the same vessel with the innerbottom removed. As noted previously, this simple step gives us a means of evaluating the effect of the double hull, but has something of a disadvantage in that it has an increased cargo capacity and a decreased ballast capacity compared with the baseline configuration. The two lines of data in this group are for two different levels of ullage pressure, the first a level that is able to protect against a rupture whose upper bound is at the bottom of the ship, and the second for a small rupture occurring just at the waterline. This second case represents the limit of effectiveness of the underpressure system, since ruptures above this point prevent the underpressure system from operating.

The last group of two lines of data is for the same vessel, except that the innerbottom has been removed *and* the ballast space formerly enclosed by the double bottom is transferred to the ballast wing tanks. As our interest is focused on measuring the effectiveness of the double sidewall with underpressure, this configuration together with the baseline, allows an unbiased comparison between two identical vessels, having the same cargo and ballast capacities and the same outer dimensions and proportions. They differ only in the means used to minimize cargo loss due to collision or grounding.

The 60,000 dwt Baseline Ship

This vessel, corresponding to the MARPOL "Ship 2", has a gross tankage volume of 77,000 cubic meters in a conventional double hull arrangement with two rows of tanks. Note that this number is the actual calculated volume of the tanks *using the rectangular approximation* needed by the cargo loss calculation. The sidewall space, two meters, is a series of ballast tanks that also serve to protect the cargo from collision incidents. The space below the innerbottom, also a separation of two meters, can contain ballast and also protects the cargo in grounding incidents. The ullage pressure is plus 0.05 bar, conforming to current practice and to MARPOL 73/78. The ullage pressure is given in meters of seawater, about +0.5 meters.

This ship design, fully loaded to 98 percent, was evaluated using the MHS program based on the MARPOL requirements. It was subjected to 400,000 random collision events and 600,000 random grounding events, using the statistical database provided by MARPOL to generate event parameters. For each event, each tank was evaluated to determine if it had been penetrated, and if so, what cargo loss had occurred. Data were collected and processed for all events. Although a number of interesting statistical parameters can be derived, the two of primary interest are the expected cargo loss per event and the probability that an event will occur without causing any cargo loss at all. Consulting the table, the expected loss is about one percent of the total cargo per incident, or about 750 m3. The probability of zero loss is about 82 percent, that is, only about 180,000 out of 1,000,000 simulated incidents actually resulted in any loss.

Caveat

This is a good point at which to remind the reader that these numbers are very approximate, and that they are not very useful in absolute terms. Collisions and groundings are rather untidy events, and are not easily reduced to the simple hydrostatic format that must be used to implement the IMO model. Too, the statistical damage distributions may not represent reality very well. Fortunately for the world, there aren't very many major cargo loss incidents from which to build a precise statistical database. The process we are following, however, is very useful in *comparing alternatives* at the preliminary design stage, and that is what it was created for.

The 60,000 dwt Ship with the Innerbottom Removed

In this configuration, the innerbottom is simply removed from the design without implementing any other changes. Obviously there would be some structural changes, but these would probably not affect ship vulnerability very much. As mentioned previously, this arrangement has a larger cargo volume than the double hull configuration, about 87,000 m3 of available tankage volume. Putting that aside, however, it clear that the revised arrangement offers some notable improvement in loss characteristics. The expected loss is 0.46 percent of the total cargo. This loss is around one-half the average cargo loss found for the double hull baseline. The probability of zero loss is 0.94. The reason for this improvement is that the underpressure containment is more effective against grounding loss as compared with the double bottom.

It must be noted, however, that the one percent loss assignable to secondary effects in the Guidelines has not been included in the calculation. For the double bottom, it is because the tanks are not at the bottom interface and are not vulnerable under the MARPOL requirement. For the underpressure arrangement, it is because the ullage pressure required to protect against bottom rupture can be slightly increased either in advance of trouble or dynamically, to create a loss prevention barrier of seawater at the bottom of a cargo tank. In addition, any loss that does occur as a result of secondary effects raises the *bottom* surface of the cargo, so these effects diminish after any loss occurs.

It may be relevant also that the arbitrarily chosen one percent for dynamic and secondary losses is quite comparable or even higher than that calculated by the elaborate and detailed statistical analysis of direct damage.

The 60,000 dwt Ship with Innerbottom Removed and Ballast Rearranged

This is the best case to consider in comparison with the baseline double hull, since the two ships being compared are essentially identical except for the containment. In this case we see that

the sidewall spacing increases from two meters to about four in order to accommodate the ballast displaced from the double bottom. This increase has a significant effect on the sidewall vulnerability-- it is simply a matter of the depth of penetration as defined by the threat environment. Thus the collision loss is materially reduced. Effectively, the average cargo loss per incident, as compared with the baseline, is reduced from 750 m3 to about 200 m3, while the probability of zero outflow is increased from 82 to 96 percent. The frequency of loss is reduced by about five to one.

The treatment of ullage pressure is a little complicated. First of all, it is envisioned that the system will have means for adjusting the ullage underpressure as circumstances require. Among other factors, it could be adjusted to a higher level of protection when in restricted waters or limited visibility, and reduced in open water. For grounding, a moderate underpressure is sufficient to prevent loss, and there is no benefit, so far as grounding is concerned, to making it more extreme. This value is identified with the word "grounding" in the table. An underpressure set at this level would prevent grounding loss and materially reduce collision loss. In collision, a greater underpressure is perhaps preferable, but in this case there are at least two choices. Normally, the ullage pressure would be set to hold the upper cargo surface at its original position, the pressure being calculated assuming a rupture at the waterline. A rupture above the waterline renders underpressure ineffective. The value that holds the cargo fixed is shown with the words "As required". It is possible, though, to employ higher underpressure than this, thus causing the cargo to rise, perhaps as high as the top of the tank. This option has the disadvantage that it may lead to ingesting cargo into the ullage gas system as the cargo surface approaches the top of the tank. On the other hand, a rise of this kind has the advantage that it creates a buffer layer of seawater at the bottom of the tank.

A broader question is one of timing. Preferably, the ullage pressure will be set and held at a selected level. Then, when a collision or grounding occurs, the pressure would be readjusted, if possible, to correspond with the damage condition-- ultimately, a good compromise is to set the pressure to hold the level of the cargo constant. For any given installation, there will be a design tradeoff between the rate at which ullage pressure can be changed, as against the potential improvement in cargo loss.

For both of the underpressure designs, we have shown two options: the effect of an ullage pressure that is set for a grounding incident as against a more extreme ullage pressure set for the worst possible condition, a collision rupture at the waterline. It can be seen from these data that the increased underpressure (that is, the more negative) is from about -2 m to -4 m, a fairly significant increase, while the result in terms of reduced cargo loss is quite small. Thus, at least theoretically, a very moderate level of underpressure is probably best. Underpressures are given in meters of seawater, admittedly a rather unusual measure of pressure. However, this unit is easy to interpret in the context of cargo level control. The more familiar unit of pressure in English measure, pounds per square inch, is about 1.5 times the value in meters s/w given in the tables.

The 150,000 dwt Baseline Ship

This ship corresponds to the MARPOL "Ship 3" provided as an example of the analysis methodology in the IMO reference. It is similar in general layout to the 60,000 dwt ship previously discussed previously and is geometrically similar as well. The sidewall spacing, however, is the same among all three ships, while the threat environment, as represented by the specified damage parameters, is scaled to ship overall dimensions.

In general, the analysis of the 150,000 dwt ship, summarized in Table 7, demonstrates approximately the same advantage of the double sidewall configuration over the conventional double hull.

The simple elimination of the innerbottom increases the approximated cargo tankage from 188,000 to 209,000 m3, reduces expected cargo loss by about half and increases the probability of zero loss from 83 to 94 percent.

The elimination of the innerbottom, combined with the shift of innerbottom ballast space from the ship's bottom to the sidewall creates a more exact basis for comparative evaluation of the double sidewall concept as against the double hull. In this case, the modification reduces the expected cargo loss from one percent per incident to about half a percent, and increases the probability of zero loss from 83 percent to 97 percent.

The 283,000 dwt Baseline Ship

This ship corresponds to the MARPOL "Ship 4" provided by the IMO reference. It is similar to the smaller designs except that it has three rows of cargo tanks instead of two. The results for this design are shown in Table 8. For this size, too, the advantage of the double sidewall is reasonably clear.

For this design, as for the two smaller designs already discussed, the expected cargo loss for the double hull baseline is about one percent of the total cargo per incident. The probability of zero cargo loss is around 80 percent, a little lower than the results for the two smaller ship designs. At least part of the reason for this difference is that the sidehull spacing is uniformly two meters for all three designs, while the damage dimensions are scaled to the ship dimensions in the MARPOL formulation.

The removal of the innerbottom, coupled with the use of underpressure, increases cargo capacity at the expense of ballast capacity from 337,000 m3 to 390,000 m3. Cargo loss per incident is reduced by about half and the probability of zero outflow is increased from about 80 to about 90 percent.
The removal of the innerbottom, coupled with redistribution of cargo and the use of underpressure, provides a reduction in expected loss from one percent to one-fifth percent. The probability of zero loss is increased from about 80 percent to about 95 percent.

Summary

The primary objective of analysis is to determine how the double sidewall with underpressure concept compares with the familiar double hull concept. The tables 6, 7 and 8 draw this comparison for each of the three ships chosen for analysis. The evaluation of each ship compares a baseline, or "parent", double hull ship with two alternative designs of comparable capacity and proportions that use only a double sidewall and provide grounding damage protection by the use of reduced ullage pressure.

The method of analysis follows the MARPOL 73/78 Guidelines, with minor modifications to facilitate calculation. Some further modifications must be noted. The use of negative ullage pressure ("underpressure") violates the explicit requirement of Appendix 7, Par 5.1.5.4 for 0.05 bar positive pressure. The use of negative ullage pressure also allows some control of exchange and dynamic losses, and therefore the one percent penalty for these losses is not taken. In addition, credit is not taken for cargo saved by flow into non-cargo spaces as allowed in Par 5.1.5.7. Finally, the *total* loss from tanks ruptured in collision, as defined in 5.1.5.2, does not apply when ullage pressure can control some or all of this loss. Instead, hydrostatic analysis is used to calculate loss.

The calculation of cargo loss, using the methods specified in MARPOL 73/78, can be carried out to any desired number of decimal places. The intrinsic accuracy, however, is low because the modeling of cargo loss is very simple and because the statistical representations of damage are based on very limited data. The methodology provides an invaluable tool for comparing alternative design concepts and, to some degree, for comparing alternative design details.

If the three ships were exactly scaled versions of the same basic design, then the fact that the threat environment is also scaled to ship size would mean that any dimensionless criteria derived from the analysis would be essentially the same. The ships are, in fact, closely similar, so the criteria such as expected loss and probability of loss are similar, too. An exception is that the protective two-meter side spacing common to all three designs is not scaled, so losses increase somewhat with size.

TABLE 6 60,000 dwt

	Tankage Capacity	Sidewall Spacing	Ullage Pressure	Expected Loss Probability %			
				%	Mtons	0 loss	Any loss
Conventional Double hull	77,000	2.00	0.05 bar 0.49 m	0.98	750	81.79	18.21
Double Sidewall with Innerbottom removed	87,000	2.00	Grounding -1.19	0.53	460	93.23	6.77
			As req'd -3.45	0.50	430	93.26	6.74
Double Sidewall with Ballast rearranged	77,000	3.73	Grounding -1.19	0.27	210	96.50	3.51
			As req'd -3.45	0.25	190	96.54	3.46

TABLE 7 150,000 dwt

	Tankage Capacity	Sidewall Spacing	Ullage Pressure	Expected Loss Probability %			
				%	Mtons	0 loss	Any loss
Conventional Double hull	188,000	2.00	0.05 bar 0.49 m	1.04	2000	83.30	16.70
Double Sidewall with Innerbottom removed	209,000	2.00	Grounding -2.79	0.48	1010	93.56	6.44
			As req'd -5.60	0.43	898	93.56	6.44
Double Sidewall with Ballast rearranged	188,000	4.09	Grounding -2.79	0.23	433	96.93	3.07
			As req'd -5.60	0.20	384	96.92	3.08

TABLE 8 283,000 dwt

	Tankage Capacity	Sidewall Spacing	Ullage Pressure	Expected Loss Probability %			
				%	Mtons	0 loss	Any loss
Conventional Double hull	338,000	2.00	0.05 bar 0.49 m	1.01	3430	78.88	21.12
Double Sidewall with Innerbottom removed	390,000	2.00	Grounding -3.31	0.55	2140	88.96	11.04
			As req'd -6.98	0.52	2020	89.00	11.00
Double Sidewall with Ballast rearranged	337,000	7.30	Grounding -3.31	0.18	610	96.36	3.64
			As req'd -6.98	0.17	580	96.33	3.67

Description of Table Items:

- *Tankage Capacity*: The gross capacity of all tanks, including fuel, in cubic meters.
- *Sidewall Spacing*: The sidewall ballast tank spacing (at midship), in meters.
- *Ullage Pressure*: The nominal ullage pressure setting, in meters of sea water.
- *Expected Loss*: The expected (average) cargo loss per incident, as a fraction of total cargo and in cubic meters.
- *Loss Probability*: The probability, for any incident, of zero loss and of any loss, percent

We summarize that the double sidewall ship with underpressure is at least as favorable as the conventional double hull in its ability to control tanker cargo loss in collision and grounding incidents. The best ullage pressure setting is probably the pressure required to completely offset grounding damage. This same pressure also provides considerable reduction in collision losses. Higher values of underpressure (that is, more negative pressures) are probably not justified.

Conclusions

As an alternative to the double hull, the double-sidewall-plus-underpressure ship design offers equivalent or superior protection against accident-induced cargo loss, reduces hydrocarbon vapor emissions and is less expensive to construct or to retrofit, without introducing risk elements or uncertainties.

Cargo loss in collision and grounding incidents was determined for a set of typical single-sidewall vessels using the MARPOL methodology. Cargo loss was equivalent to or less than that of the double hull

A study by the American Bureau of Shipping confirmed that a design utilizing ullage space underpressure presents no structural difficulties.

All tankers must use inert gas, derived from a combustion process, to prevent fire risk in the ullage space. Ordinarily this gas is discharged to the atmosphere. An underpressure system uses the same inert gas, but tends to retain the gas within the closed-circuit system. This feature reduces hydrocarbon and CO_2 loss to the atmosphere.

Reliability has been estimated to be better than 0.996.

Implementation

The implementation of this improved loss-prevention technology must begin with concerted effort by flag states, ship owners, shipyards and naval architects, with support from classification societies and the International Maritime Organizations, (IMO).

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APPENDIX A – Quantitative Analysis of VOC Emission Prevention During Loading and Unloading

Recovery of HC Vapors in the Condenser

The natural gas liquids are recovered from natural gas by condensation or absorption in field separators, scrubbers, gasoline plants or cycling plants. Natural gas liquids are in a sense an intermediate product lighter than what is usually considered crude oil and heavier than what is usually considered natural gas. The liquid yield of a natural gas depends on the composition, pressure and temperature. The quantities of recoverable liquid products usually are determined in barrels of liquid per million standard cubic feet or in gallons of liquid per thousand standard cubic feet. The composition of gas must be known in order to make these calculations.

Complete recovery of this product is not feasible. A general rule of thumb is 5-10 % of ethane, 80-90% of propane, 95 % or more of butane and 100% of the heavier components can be recovered in a relatively simple "plant".

The liquid yield of vaporized gas, which occurs during loading, and/or unloading of crude oil, is different for different crude oils. For lighter oils the vaporized gas contains more intermediate components and is expected to have more recoverable liquid fractions. The theoretical liquid yield calculation is based on conversion of mole fraction of recoverable components in liquid volume fraction, knowing the composition and the physical properties of each component of the equilibrium gas. The mole fraction can be converted in e.g. gal/Mscf as follows:

$$GPM_j = \left(y_j \frac{\text{lb - mole j}}{\text{lb – mole gas}}\right)\left(\frac{\text{lb – mole gas}}{\text{l380.7 scf}}\right) \times \left(\frac{1000\text{scf}}{\text{lMscf}}\right)\left(MW_j \frac{\text{lb j}}{\text{lb - mole j}}\right) \times \left(\frac{\text{cu ft liq}}{\rho_{oj}\ \text{lb j}}\right)\left(\frac{7.481\,\text{gal}}{\text{cu ft liq}}\right) = 19.65\left(\frac{y_i MW_j}{\rho_{oj}} \frac{gal}{Mscf}\right)$$

where y_j is the mole fraction of component j in the total gas mixture, MW_j is the molecular weight of component j and ρ_{oj} is the density of component j , lb/cu ft, as a liquid at standard conditions.

Three crude oils with different API gravities were tested in the laboratory. At different temperatures, the system was allowed to equilibrate and the vaporized gas compositions in equilibrium with crude oil were measured. The volume fractions of liquid yields were calculated. The results for the total liquid yields and for each intermediate component in case of liberated gas from a 37 API crude oil @ 14.7 psia AND 110 F are given in Table 1. For lighter crude oils the total liquid yield was around 390 bbl per million standard feet or 2.2 liters per one cubic meter of vaporized gas at standard conditions

TABLE 8 GAS PROPERTIES FROM 37 API CRUDE OIL @14.7 PSIA AND 110 F

Component Name	Chemical Symbol	Mole Fraction As Analyzed	Mole Fraction Acid Gas Free	Liquid Volume STB/MMscf	Liquid Volume mL/m^3
Nitrogen	N2	0.9875	0.9879		
Carbon Dioxide	CO2	0.0004	0		
Hydrogen Sulphide	H2S	0	0		
Methane	C1	0.0027	0.0027		
Ethane	C2	0.0029	0.0029		
Propane	C3	0.0034	0.0034	2.229	12.513
i-Butane	i-C4	0.0007	0.0007	0.537	3.013
n-Butane	n-C4	0.001	0.001	0.777	4.36
i-Pentane	i-C5	0.0004	0.0004	0.354	1.989
n-Pentane	n-C5	0.0002	0.0002	0.136	0.763
Hexanes	C6	0.0001	0.0001	0.124	0.699
Heptanes Plus	C7	0.0007	0.0007	0.756	4.244
Total		**1**	**1**	**4.913**	**27.581**
Propanes Plus	C3+	0.0065	0.0065	4.913	27.581
Butanes Plus	C4+	0.0031	0.0031	2.684	15.068
Pentanes Plus	C5+	0.0014	0.0014	1.371	7.696

Calculated Gross Heating Value @ Standard Cond.			Calculated Net Heating Value @ Standard Cond.		
Dry	1,722.9 Btu/scf	64.31 MJ/ m^3	Dry	1,589.8 Btu/scf	59.34 MJ/ m^3
Wet	1,692.9 Btu/scf	63.19 MJ/ m^3	Wet	1,562.2 Btu/scf	58.31 MJ/ m^3

Preliminary Estimates of the VRL Add-on Capability During Loading of Cargo (Based on a 127,000 dwt tanker)

Cargo Volume (98%) = 138,947 m^3

Recovered VOC Condensate = 250-350 m^3

Density of Condensate = 0.57 kg/dm^3

Composition of Condensate (by vol):

Methane	0.01 %
Ethane	0.04 %
Propane	7.40 %
Butane	45.90 %
C_5	27.35 %
C_6	13.60 %
C_{7+}	5.70 %

VOC Recovered = 300 m^3 (10,590 ft^3)

Cargo Volume = 0.139×10^6 m^3 (4.9×10^6 ft^3)

Density of Condensate = 0.57 kg/dm^3 (35 lb/ft^3)

Assume Density of Cargo Oil = 55 lb/ft^3

Temperature of Loaded Oil = 90 ºF

Weight of Cargo Oil = $4.9 \times 10^6 \times 55$

= 269×10^6 lbs

Weight of Condensate = 10,590 x 35

= 3.68×10^5 lbs

$$\frac{\%\ Weight\ of\ Condensate}{Weight\ of\ oil} = \frac{3.68 x 10^5}{269 x 10^6} 10^2 = 0.14\%$$

Potential cargo loss without VOC Containment:

Cargo Loss = 0.4×10^6 lbs

Assume HC Vapor in Tank is Butane

(M) Molecular Weight = 58.08

Density of HC Gas @ STP= $\frac{M}{986}$ = 0.15 lb/ft^3

Volume of HC Gas $= \frac{Weight\ of\ HC\ (Condensate)}{Density\ of\ HC\ Gas}$

= $3.68 \times 10^5 / 0.15$

= 2.45×10^6 ft^3

Volume of HC /Tank Volume = $\frac{2.45 x 10^6}{4.9 x 10^6}$ = 0.5

This ratio is typical of VOC fraction

Required (worst case) Storage Volume:

Pressure = 200 psia

Min. volume of condensate = 300 m^3 (10.6×10^3 ft^3)

Assume volume of lighter HC = 30 % of 300 m^3

Total volume of tank = ($10.6 \times 10^3 + 3.18 \times 10^3$) ft^3

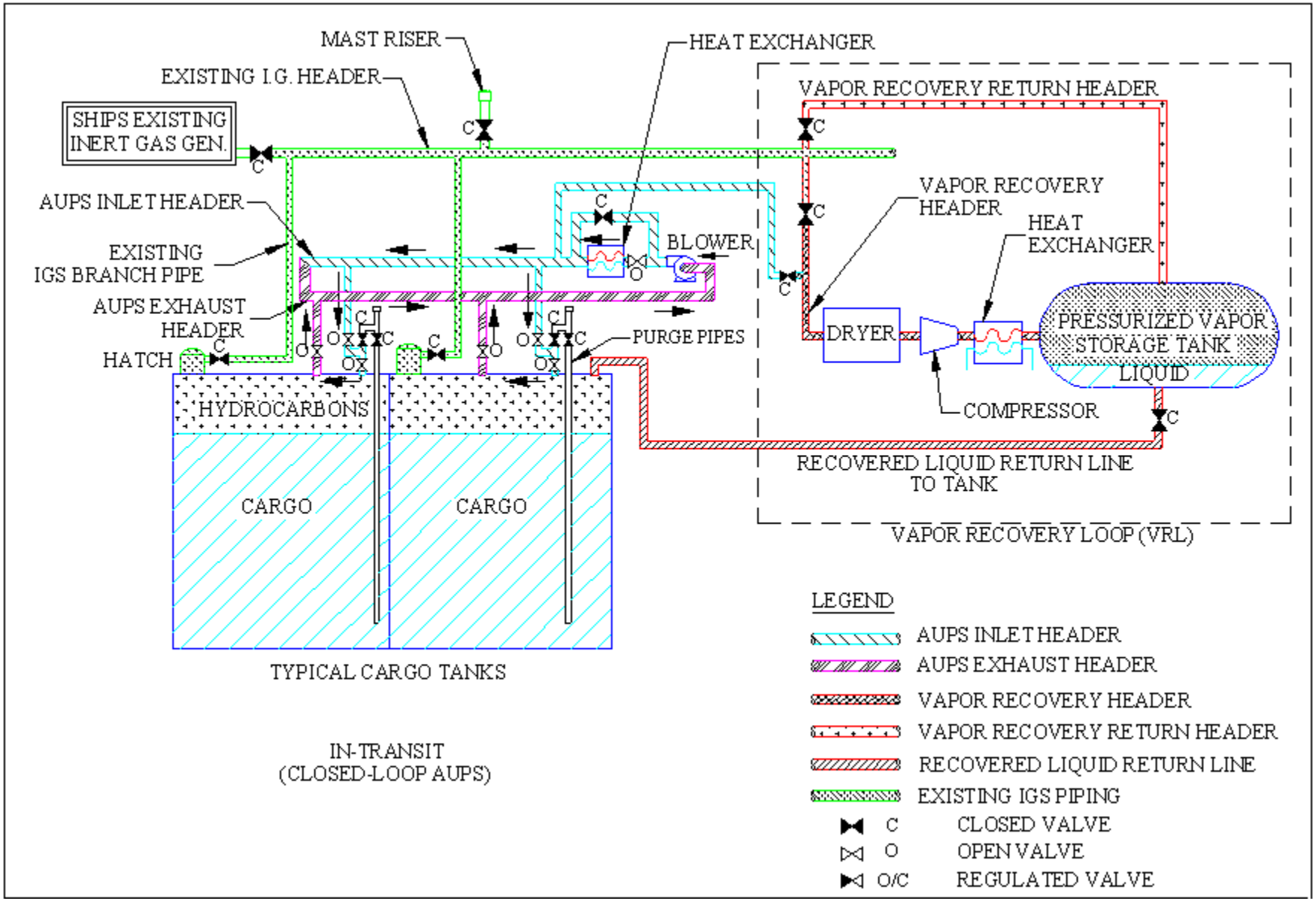
= 13.78×10^3 ft^3

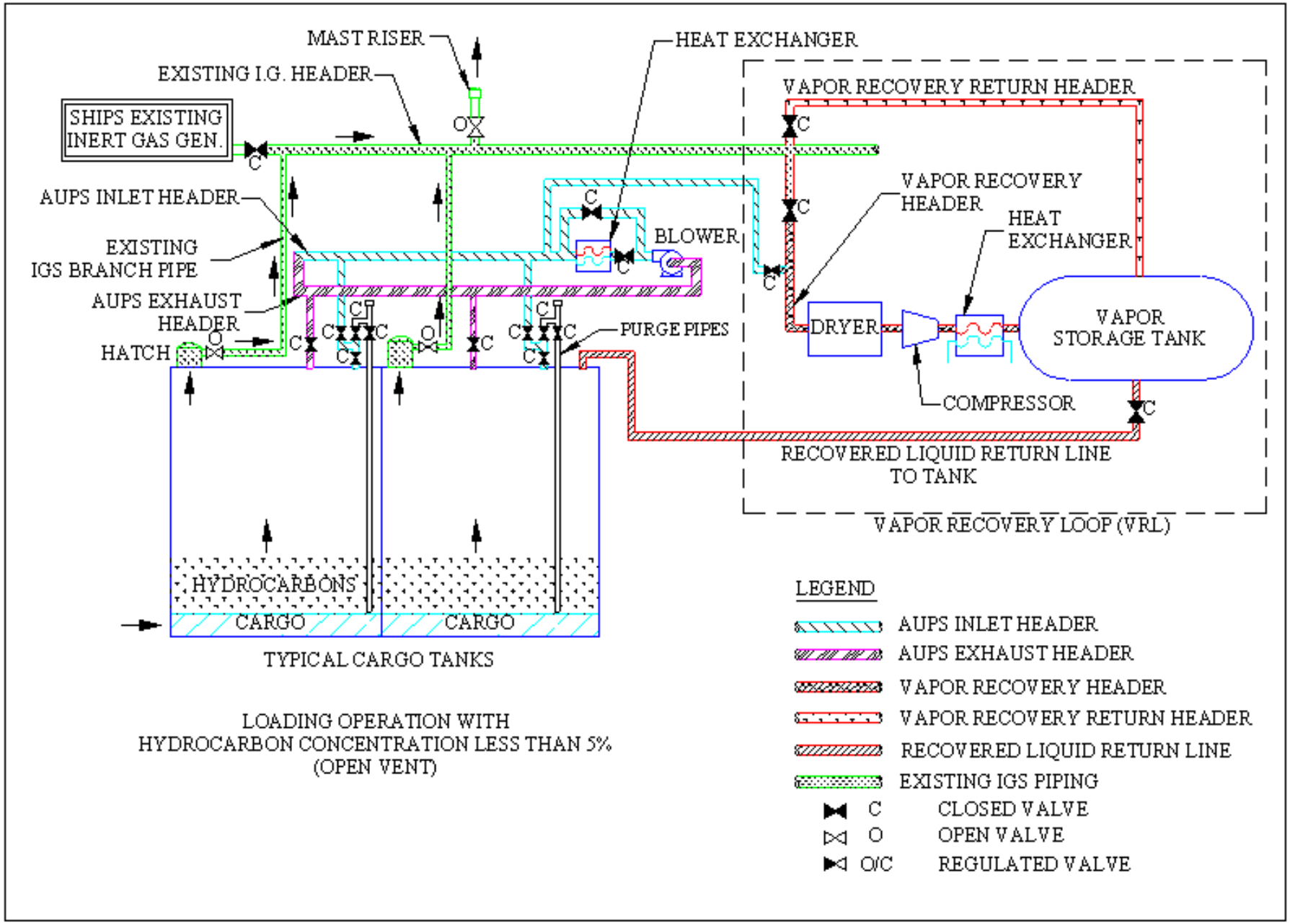
If diameter of cylinder = 5 m (16 ft)

Length of cylinder = 68 ft

Similar to refrigeration stored dimensions. However, by periodically returning the condensate to the cargo tanks, the dimensions of the container can be significantly reduced

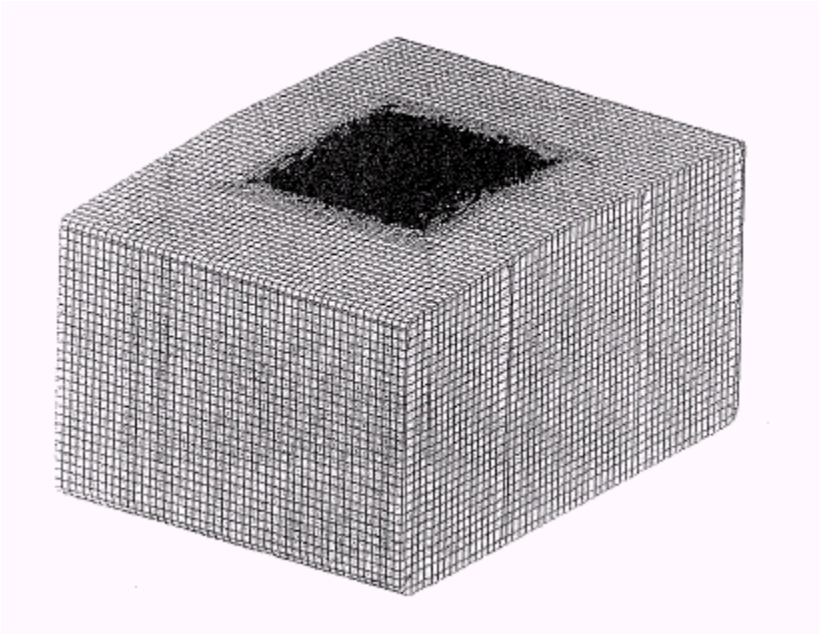
APPENDIX B


MAST RISER
HEAT EXCHANGER
EXISTING I.G. HEADER
VAPOR RECOVERY RETURN HEADER
SHIPS EXISTING INERT GAS GEN.
AUPS INLET HEADER
VAPOR RECOVERY HEADER
HEAT EXCHANGER
EXISTING IGS BRANCH PIPE
BLOWER
AUPS EXHAUST HEADER
PURGE PIPES
DRYER
PRESSURIZED VAPOR STORAGE TANK
HATCH
LIQUID
HYDROCARBONS
COMPRESSOR
RECOVERED LIQUID RETURN LINE TO TANK
CARGO
CARGO
VAPOR RECOVERY LOOP (VRL)
TYPICAL CARGO TANKS
IN-TRANSIT (CLOSED-LOOP AUPS)
LEGEND
AUPS INLET HEADER
AUPS EXHAUST HEADER
VAPOR RECOVERY HEADER
VAPOR RECOVERY RETURN HEADER
RECOVERED LIQUID RETURN LINE
EXISTING IGS PIPING
C CLOSED VALVE
O OPEN VALVE
O/C REGULATED VALVE

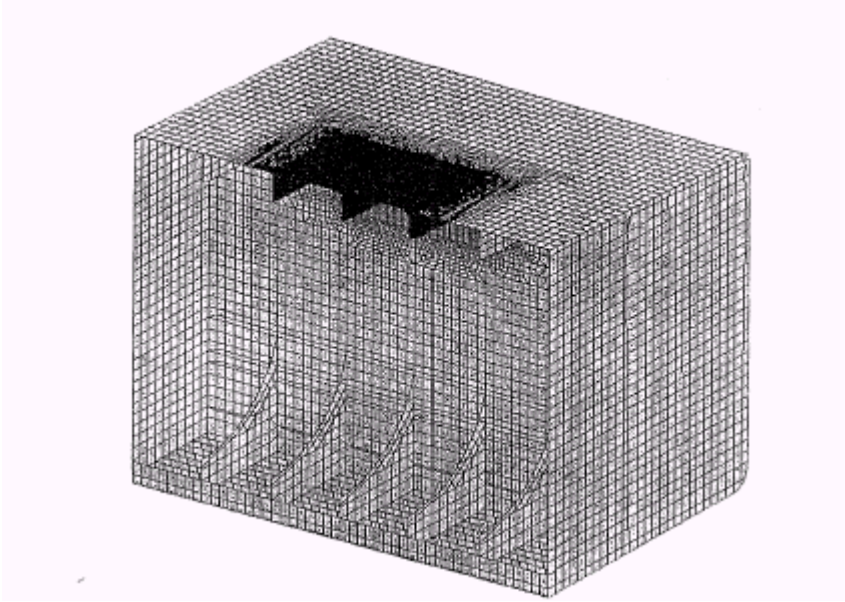


LOADING OPERATION WITH
HYDROCARBON CONCENTRATION LESS THAN 5%
(OPEN VENT)

APPENDIX C

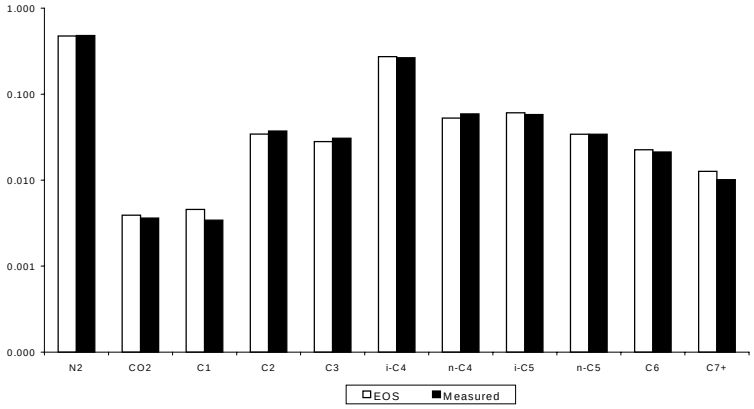


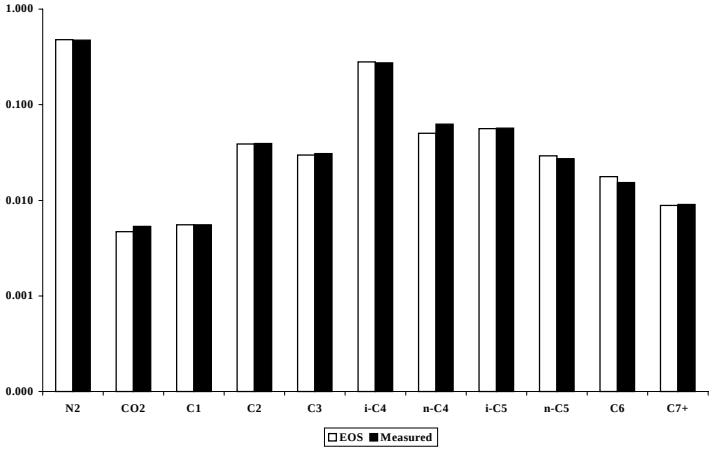
TOTAL 3-D FINITE ELEMENT MODEL

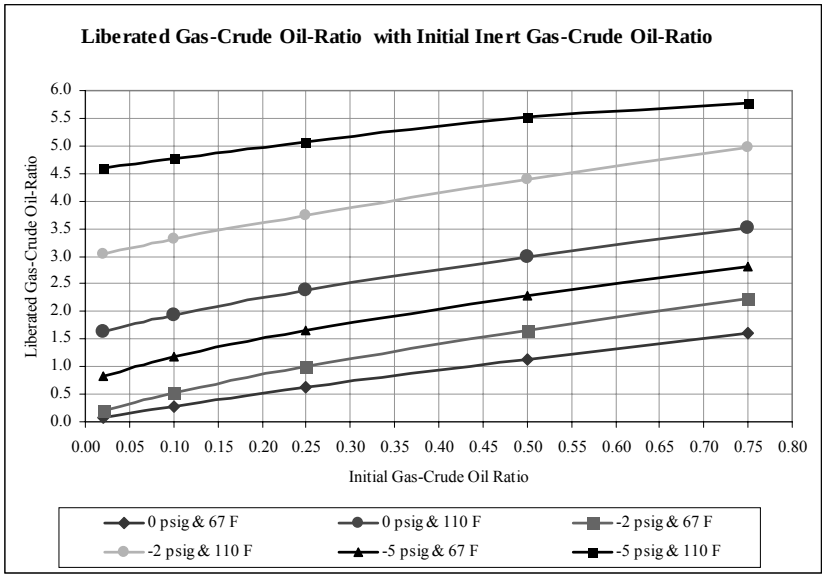


FINITE ELEMENT MODEL LOOKING OUTBOARD AT CENTER TANK

APPENDIX D


1.000
0.100
0.010
0.001
0.000
N2
CO2
C1
C2
C3
i-C4
n-C4
i-C5
n-C5
C6
C7+
EOS
Measured


1.000
0.100
0.010
0.001
0.000
N2
CO2
C1
C2
C3
i-C4
n-C4
i-C5
n-C5
C6
C7+
EOS
Measured


Liberated Gas-Crude Oil-Ratio with Initial Inert Gas-Crude Oil-Ratio
Liberated Gas-Crude Oil-Ratio
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80
Initial Gas-Crude Oil Ratio
0 psig & 67 F
0 psig & 110 F
-2 psig & 67 F
-2 psig & 110 F
-5 psig & 67 F
-5 psig & 110 F

REFERENCES:

1. AMERICAN BUREAU OF SHIPPING – Advanced Analysis Department – Finite Element Analysis, Underpressure System, Technical Report – AA-04005
2. HUSAIN, M., APPLE, R., THOMPSON, G. and SHARPE, R., "Full-Scale Test of the American Underpressure System (AUPS) on Board the USNS *Shoshone*." SNAME Northern California Section Meeting. (Sept. 2001).
3. HUSAIN, M., HUNTER, H., ALTSHULLER, D., SHTEPANI, E., and LUCKHARDT, S., "Crude Oil Under Negative Pressures and Hydrocarbons Emission Containment." World Maritime Technology Conference, SNAME 2003 (Oct. 2003).
4. MARPOL 73/78 (2002) – International Maritime Organization (IMO)
5. OFFICE OF NAVAL RESEARCH, U.S. Department of Defense – "Complete the Test Program of the American Underpressure System" – Contract No. 000-14-02-C-0515
6. SHTEPANI, E., WEINHARDT, B.E., and POTSCH, K.T.: "A New Modification of Cubic EOS Improves Prediction of Gas-Condensate Phase Behaviour"; 1996, SPE 36924, Europec '96, Milan, Italy, Vol. 2, p. 459 – 464.
7. THOMAS, F.B., SHTEPANI, E., IMER, D., and BENNION, D.B.: "How Many Pseudo-Components Are Needed to Model Phase Behavior", *Journal of Canadian Petroleum Technology*, (Jan. 2002), Vol. 41, No. 1, pp. 48-54.