

Hydrocarbon Emission Containment in Tankers During Loading and Unloading

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ABSTRACT

This paper presents analysis and preliminary design of the containment scheme for hydrocarbon emission control of tankers during loading and unloading.

The economic and environmental impact due to hydrocarbon emission or simply VOC (Volatile Organic Compound) emission during loading, unloading and transport of crude oil in tankers (including shuttle tankers) is significant. In an earlier paper by the authors (Husain, et al. 2003) presented at the SNAME/WMTC 2003 describes a closed, negative pressure system to prevent or minimize VOC from tankers during transport. Negative pressure is not used in the VOC containment scheme during loading and unloading – the subject matter of this paper.

There are over 200 million barrels per year of oil being loaded at terminal facilities in the USA. Presently, the number of terminal vapor control facilities (nearly 172) is inadequate. This results in ozone formation/smog and financial loss from the evaporation of crude (0.2% loss by weight). Government regulations regarding crude oil emissions are rapidly evolving. Therefore an onboard vapor control system, free of dependency on crowded shore based (or non existent) facility is deemed necessary and appropriate.

NOMENCLATURE

C_p heat capacity
 D number of moles of uncondensed gas
 F number of moles fed
 F_g defined by the equation (3)
 K_i vapor-liquid equilibrium constant
 n_g moles in vapor phase
 n_l moles in liquid phase
 P_{ri} reduced pressure
 T_{ri} reduced temperature
 ΔT temperature differential
 \dot{W} weight flow rate
 x_i molar fraction in liquid phase
 y_D molar fraction left in vapor phase

y_i molar fraction in vapor phase
 z_i total molar fraction in both phases

Greek letters

ω_i acentric factor

INTRODUCTION

It is estimated that approximately four to seven millions tons of VOC are lost to the atmosphere, which is environmentally unacceptable and economically undesirable. There are government regulations regarding emissions from crude oil in the USA and European countries, and shore based terminal vapor control facilities are rapidly developing. However, Middle Eastern and other

developing countries are not as rigorous in controlling hydrocarbon emission; these countries generally lack modern terminal vapor control facilities.

The shore facilities process the vapor by utilizing one or more of these methods:

- Recovery-Refrigeration or Absorption
- Destruction – Combustion
- Balancing - Returning vapors to the storage tanks being emptied

In addition, the off-shore loading of shuttle tankers in the North Sea have pilot programs employing in-situ recovery plants, using refrigeration and oil absorption technologies. These pilot programs are limited to loading operations. The method described in this paper can be used to contain hydrocarbons during all three operational phases of the crude oil tanker i.e. loading, transport and unloading.

The use of underpressure in the ullage space of tankers has been investigated for the mitigation of cargo losses resulting from accidental hull rupture. This investigation led to detailed laboratory tests of various crudes over a range of temperatures and pressures. The findings were then applied to prevent or minimize VOC (Volatile Organic Compound) /hydrocarbon emissions occurring during transport of crude oil. The System, thus evolved and designed, was named American Underpressure System (AUPS).

This paper discusses the solution to contain hydrocarbon vapor or VOC during loading and unloading. AUPS will be referred to as an overall system, which may or may not use underpressure in all of its applications. Components of this overall system will be utilized at various times in different phases of tanker's operation: containment of VOC during loading, unloading, transport, and spill prevention or mitigation due to accidental rupture of tanker's hull.

BASIC UNDERPRESSURE SYSTEM FOR SPILL AVOIDANCE AND EMISSION CONTROL DURING TRANSPORT

The original underpressure system was developed and designed to prevent or reduce oil

spillage by maintaining a subatmospheric pressure in the ullage space of the crude oil tanker. The system was tested in full scale on a reserve fleet crude oil tanker USNS Shoshone. It is a closed-system designed for spill avoidance as well as control of emission from crude during transport and discussed in sufficient detail in the paper presented at the SNAME/WMTC 2003 Conference (Husain et al. 2003).

This closed-loop arrangement prevents VOC emissions from tankers in transit, with the added capability of containing spills in the event of accidental rupture of the hull. The schematic of the basic system is shown in Figure 1 in the Appendix. Dedicated piping recirculates the ullage gas using an in-line blower and a seawater heat exchanger. The control system regulates the transport of gases, effectively normalizing all perturbations, which may occur in-transit and could change underpressure or inertness of the ullage gases.

In the closed-loop underpressure system, negative pressure is maintained at a predetermined level to prevent cargo loss in the event of accident, while 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 the reduced-pressure ullage spaces, and the gases are returned to the tanks via a blower and seawater heat exchanger. The blower compensates for the pressure loss during transfer and the heat exchanger keeps the gas/vapor temperature perturbations within acceptable limits.

VAPOR RECOVERY LOOP

Compared to the basic AUPS system, described in the previous section, the new system includes a vapor recovery loop (VRL) as shown schematically in Figure 2 in the Appendix. 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, therefore, is reduced to the basic closed-loop underpressure system operation. The difference between the basic underpressure system and the system with the VRL operation arises during loading and unloading as described in the next section. Underpressure is not used during loading and unloading operations.

The following subsections give the quantitative analysis of the condenser and the power requirements for the compressor.

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 (GPM). 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

$$GPM_j = \left(y_j \frac{\text{lb - mole } j}{\text{lb - mole gas}} \right) \left(\frac{\text{lb - mole gas}}{1380.7 \text{ scf}} \right) \\ \times \left(\frac{1000 \text{ scf}}{1 \text{ Mscf}} \right) \left(\frac{MW_j}{\text{lb - mole } j} \right) \\ \times \left(\frac{\text{cu ft liq}}{\rho_{oj} \text{ lb } j} \right) \left(\frac{7.481 \text{ gal}}{\text{cu ft liq}} \right) \\ = 19.65 \left(\frac{y_i MW_j}{\rho_{oj}} \frac{\text{gal}}{\text{Mscf}} \right)$$

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 1: 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/m3
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
Pronanes 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/m3	Dry	1,589.8 Btu/scf	59.34 MJ/m3
Wet	1,692.9 Btu/scf	63.19 MJ/m3	Wet	1,562.2 Btu/scf	58.31 MJ/m3

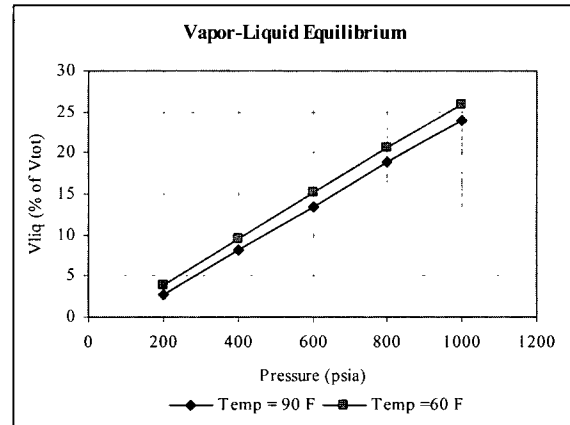
Necessary background from thermodynamics used in these calculations is given in the Appendix. These calculations provide theoretical liquid yield. In the actual design and implementation of the condenser it is necessary to perform more detailed calculations, involving vapor-liquid equilibrium. The following equation should be used in the design (Treybal 1980, p.369):

$$\ln \frac{F}{D} = \int_{y_i}^{y_D} \frac{dy}{1-x^*(y)},$$

where F is the total number of moles of gas fed into the condenser containing the molar fraction of y_i of recoverable HC compound; $x^*(y)$ be the equilibrium molar fraction of this HC compound in the liquid; D is the number of moles of uncondensed gas containing the molar fraction y_D of unrecovered HC compound. The equilibrium curve $x^*(y)$ depends on the composition of oil as well as on temperature and pressure in the condenser. This equation can be applied to each HC compound.

For the crude oil with vaporized gas composition from Table 1, the liquid volume from total hydrocarbon volume with pressure at temperatures of 60 F (15.56 C) and 90 F (32 C) is shown in the figure below. The vapor-liquid equilibrium was calculated

using Peng-Robinson equation of state. The volume in vapor phase is mostly composed of inert gas and some light hydrocarbon components, while the intermediates are mostly in liquid phase at these conditions. Necessary background from thermodynamics used in these calculations is given in the Appendix.



Compressor Power Requirements

The following calculations show the estimated power required to operate the compressor.

Pressure (10 Bars)	=	162 psia
Pressure Ratio (R)	=	162/14.7 = 11.0
Temp Ratio	=	(R) ^{1/3.5} = 1.98
ΔT	=	0.98 x Inlet Temp
	=	0.98 x 550 = 539

$$\Delta T_{ACT} = \Delta T / \text{Efficiency} = 539 / 0.75 = 719$$

(\dot{Q}) Flow Rate = Cargo Pump Flow Rate at High Head

	=	8x10 ³ m ³ /hr (282x10 ³ ft ³ /hr)
Weight Flow Rate	=	\dot{Q} x Density of Gas
	=	282x10 ³ x 0.1 lb/hr
	=	282x10 ² /3.6x10 ³ = 7.8 lb/sec

HP Compressor	=	$\frac{\dot{W} J C_p \Delta T_{ACT}}{550}$ where $\dot{W} = \text{lb/sec}$
	=	7.8 x $\frac{778 \times .24}{550}$ x 719 = 1904 hp (1427 kW)

VOC EMISSION PREVENTION DURING LOADING AND UNLOADING OPERATION

Prior to loading of crude oil in the tanker, tanks are inerted and continue to be inerted as the crude oil cargo is being loaded in the tanks. Three or more tanks are loaded by routinely venting the displaced ullage gases to the atmosphere. The vent area is sized to match the cargo pumps rate. This venting configuration continues as long as the Hydrocarbon (HC) vapor/inert gas ratio remains below 5% by volume.

Figure 3 (Appendix) shows a typical change in HC/ullage gas at each vent pipe as the loading proceeds. This phenomenon is due to the stratification by density of the HC vapors and inert gas. The heavier HC form a blanket layer across the cargo surface and are the last to be vented.

Figure 4 (Appendix) shows the loading operation with low HC vapor concentration and the VRL not active. The HC vapor concentration in the ullage gas is continuously monitored by a sensor. When it reaches 5% by volume, a programmable logic controller (PLC) turns on the VRL. This mode of operation is shown in Figure 5 (Appendix). Ullage gases are circulated through the VRL. After condensing in the *pressurized storage tank*, the liquid HC compounds are returned to the cargo tank. This eliminates emission of the HC vapors to the atmosphere.

Unloading operations are shown in Figures 6 and 7 are shown in the Appendix. While the unload operation is in progress as shown in Figure 6, the VRL is closed. Tank is being filled with inert gas as cargo is unloaded. At completion of the unload operation (Figure 7) there are still HC vapors remaining in the cargo tank. They are recovered by circulating the gas mixture through the VRL, but liquid is not returned to the cargo tank.

CONCLUSIONS

Calculations based on a 127,000 dwt tanker show that approximately 200 tons to 300 tons of oil from each event of loading (and unloading) is saved from releasing to the atmosphere. (Preliminary calculations are shown in appendix.) 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.

This paper studies the feasibility of having a simple pressurized storage tank to retain vapor during loading and unloading. Crude oil tankers will be able to store vapor during loading and unloading, where there are no vapor recovery vessels exist. Shuttle tankers can use this simple system as well. Once the vapor is collected, it can be deposited in a convenient land based facility. The system uses a pressure vessel of 200-300 psi and the power requirement is a modest 1900 HP. At this juncture, the authors find it prudent to postpone the economic analysis until more detail design is completed.

APPENDIX

Thermodynamic Background

Thermodynamic studies or experiments are generally focused on a chosen system, while the rest is called surroundings. The system surface, real or imaginary, is called a boundary. A system is called a closed system if it does not exchange matter with the surroundings, and an open system if it exchange matter with the surroundings. Both systems may exchange energy with the surroundings. If a system does not exchange matter or energy with the surroundings, it is called isolated. The closed system is called homogeneous closed system if it contains a single phase and a heterogeneous closed system if it contains more than one phase. A phase is a term used in physics for the homogeneous portion of matter.

In case of the heterogeneous closed system, each phase may be viewed as a homogeneous open system, as long as any components may move across the phase boundaries from one phase to another. For all practical purposes, each phase in a heterogeneous closed system may be considered as a homogeneous closed system when the entire system is at *equilibrium state*. At this state, there are no potential differences to cause any net flux of matter or energy across the phase boundaries. Therefore, for a heterogeneous system, the property calculations should be preceded by the determination of the equilibrium state of the system.

At a given temperature and pressure, a system is in a state of phase equilibrium, if the chemical potential of every component in the system is identical in all phases. Therefore, the calculation of the phase equilibrium at respective system conditions requires the evaluation of the chemical potential for each component in all phases.

The thermodynamic behavior of a crude oil depends strongly on composition, pressure and temperature. At different temperature and pressures, the crude oil may split in two phases, oil and gas in equilibrium with oil, i.e. the components may be distributed between phases.

The ratio between the mole fraction in the gas phase and mole fraction in the liquid phase

$$K_i = \frac{y_i}{x_i} \quad (1)$$

is called the *K-Value* or the *Equilibrium Constant*. The *K-Value* is a key quantity in the analysis of gas-liquid equilibrium and in the calculation of saturation points.

The phase equilibrium calculations consist of defining the amounts and compositions of equilibrium phases, usually liquid and gas, at the given pressure, temperature and overall composition. An inherent obstacle in solving this problem is the fact that we don't necessarily know if two equilibrium phases will form at the specified pressure and temperature. The mixture may exist as a single phase, or it may split into two (or more) phases.

The component and phase material balance constraints can be written in equation form

$$z_i = F_g y_i + (1 - F_g) x_i \quad (2)$$

where x_i , y_i and z_i are respectively the liquid-, gas-, and overall mole fractions of the component i in the system, and

$$F_g = \frac{n_g}{n_g + n_l} \quad (3)$$

where n_g and n_l are the number of moles, respectively, in gas phase and in liquid phase. Additionally, the mole fractions of the equilibrium phases and of the overall mixture must sum to unity,

$$\sum_i y_i = \sum_i x_i = \sum_i z_i = 1 \quad (4)$$

This constraint can also be expressed through

$$\sum_i y_i - \sum_i x_i = 0 \quad (5)$$

Introducing the equilibrium ratio K_i into Equation 1.2, and taking into the consideration the above constraint, we obtain

$$h(F_g) = \sum_i \frac{z_i (K_i - 1)}{1 + F_g (K_i - 1)} = 0. \quad (6)$$

This equation is usually referred to as the Rachford-Rice equation, and in most cases it can be readily solved through a Newton-Raphson procedure.

Expressing the incipient-phase mole fraction in terms of K -Values as

$$y_i = z_i K_i \quad (7)$$

the bubble-point pressure can be calculated by

$$1 - \sum_{i=1}^N z_i K_i = 0. \quad (8)$$

The two-phase equilibrium criterion is that the function below must be greater than one.

$$\sum_{i=1}^N z_i K_i > 1. \quad (9)$$

In order to evaluate initial gas and liquid compositions, a composition independent equation for calculating initial *K*-Value K_i can be used (Wilson's equation):

$$K_i = \frac{\exp\left[5.3727(1 + \omega_i)(1 - T_{ri}^{-1})\right]}{P_{ri}} \quad (10)$$

where T_{ri} is the reduced temperature of component *i*, P_{ri} is the reduced pressure of component *i*, and ω_i is the acentric factor of component *i*

The equilibrium gas compositions are evaluated as

$$y_i = \frac{z_i K_i}{1 + F_g (K_i - 1)} \quad (11)$$

As it can be derived from the thermodynamic equilibrium criteria, for a closed system at a given pressure and temperature, gas-oil equilibrium can only be changed if either pressure or temperature changes.

Knowing the composition and the physical properties of equilibrium gas (either by GC measurement or using the abovementioned calculation procedure), the theoretical liquid yield can be easily calculated based on conversion of mole fraction of recoverable components in liquid volume fraction.

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	= 0.139x10 ⁶ m ³ (4.9x10 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 °F
Weight of Cargo Oil	= 4.9x10 ⁶ x55
	= 269x10 ⁶ lbs
Weight of Condensate	= 10,590 x 35
	= 3.68x10 ⁵ lbs

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

Potential cargo loss without VOC Containment:

$$\text{Cargo Loss} = 0.4 \times 10^6 \text{ lbs}$$

Assume HC Vapor in Tank is Butane

(M) Molecular Weight = 58.08

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

Volume of HC Gas =

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

$$= \frac{3.68 \times 10^5}{0.15}$$

$$= 2.45 \times 10^6 \text{ ft}^3$$

Volume of HC Gas/Tank Volume =

$$\frac{2.45 \times 10^6}{4.9 \times 10^6} = 0.5$$

This ratio is typical of VOC fraction

Required (worst case) Storage Volume:

Pressure	= 200 psia
Min. volume of condensate	= 300 m ³ (10.6 x 10 ³ ft ³)
Assume volume of lighter HC	= 30 % of 300 m ³
Total volume of tank	= (10.6 x 10 ³ + 3.18 x 10 ³) ft ³
	= 13.78 x 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.

Gas Liquid Recovery

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. 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 volume fraction.

Three crude oils with different API gravities were tested in the laboratory and the vaporized gas compositions were measured. The volume fractions of liquid yields were calculated. The minimum and a maximum range of liquid yields are given in Tables 1 and 2. For lighter crude oils the theoretical liquid yield can be as high as 2.2 liters/lm³ or 390 bbl/MMscf of vaporized gas.

Theoretical Recovery Equations

Assume that the total number of moles outgassed is equal to F and let y_{iF} be the mole fraction of each compound in the gas phase. The recovery process may be viewed as a condensation, and the following equation applies¹:

$$\ln \frac{F}{D} = \int_{y_{iF}}^{y_{iD}} \frac{dy_i}{y_i - x_i^*},$$

where D is the total number of moles recovered, y_{iD} is mole fraction of each component in recovered condensate, and x_i^* is the mole fraction of the component in the condensate in equilibrium with y_i .

Assuming that $y_i = K_i x_i^*$, we can integrate the above equation to obtain:

$$\left(\frac{F}{D}\right)^{\kappa_i} = \frac{y_{Di}}{y_{Fi}},$$

where $\kappa_i = (K_i - 1)/K_i$. This equation is written for each component. Thus for N components we have N equations for the unknown quantities y_{iD} .

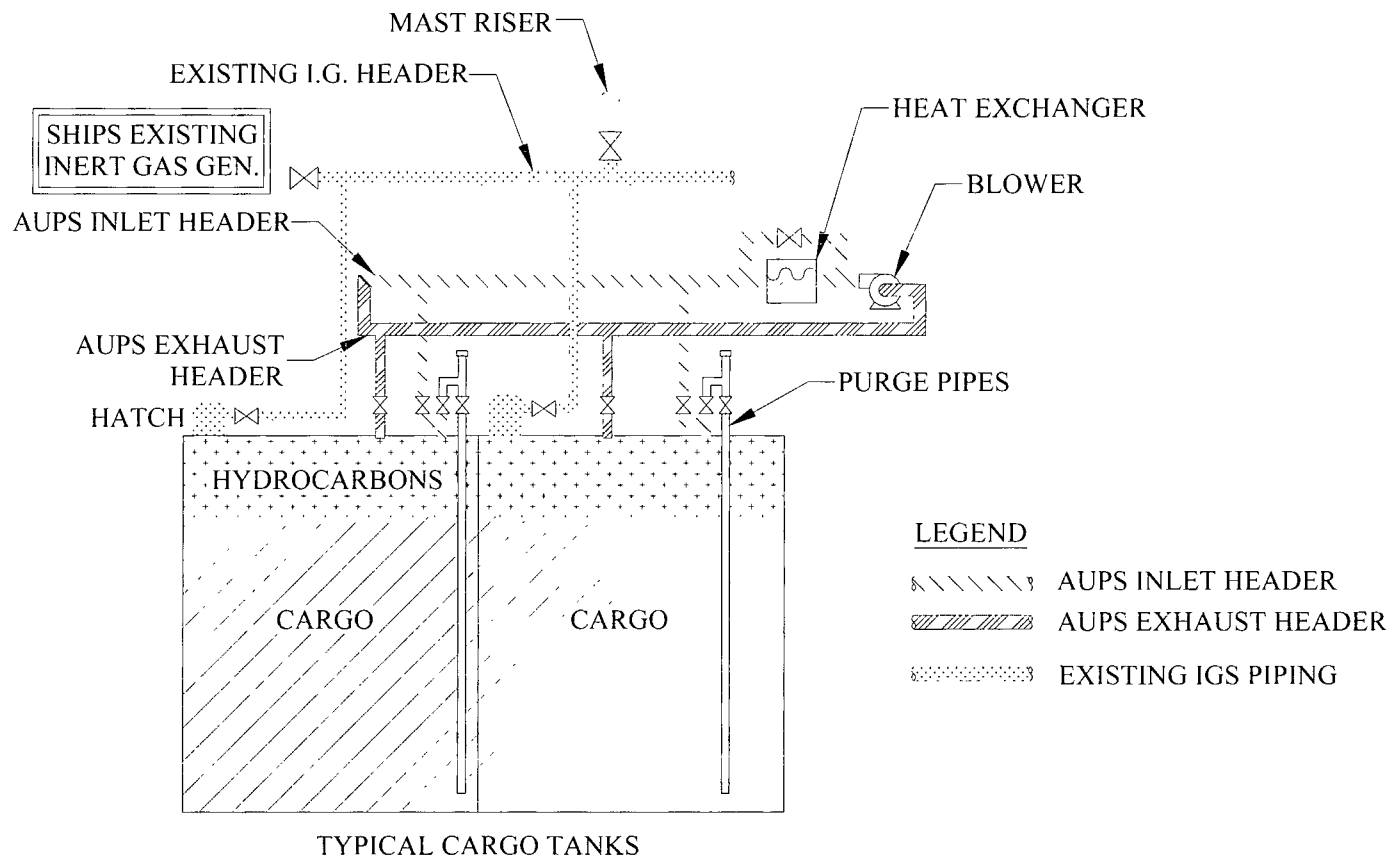
An additional equation for the unknown quantity F/D is obtained by summing over all the components:

$$\sum_i \left(\frac{F}{D}\right)^{\kappa_i} y_{Fi} = 1.$$

This combined set of equations can be solved numerically to obtain the total fraction of gas that can be recovered as well as the fraction for each component that can be recovered.

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BASIC AUPS SYSTEM

FIGURE 1

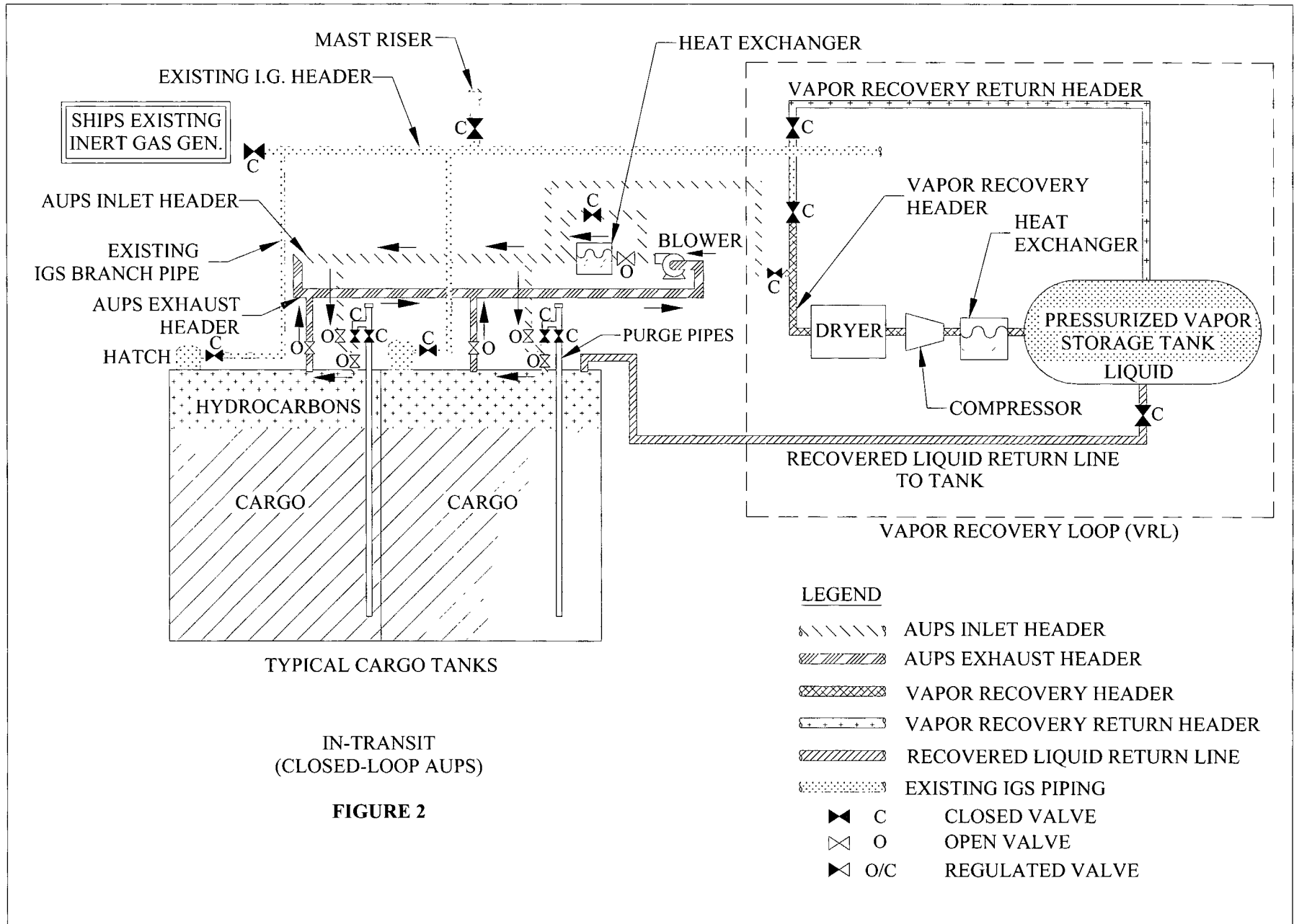
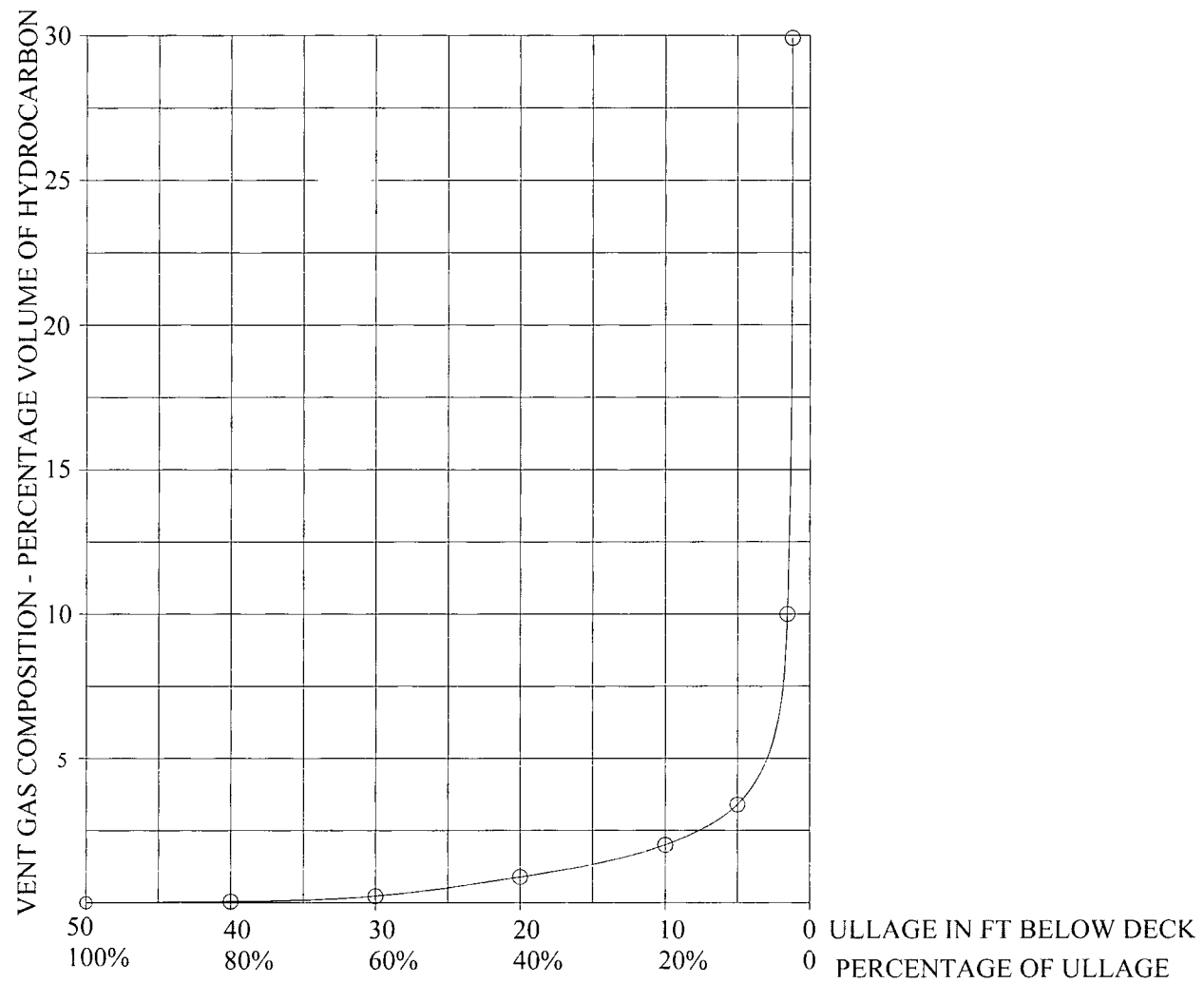
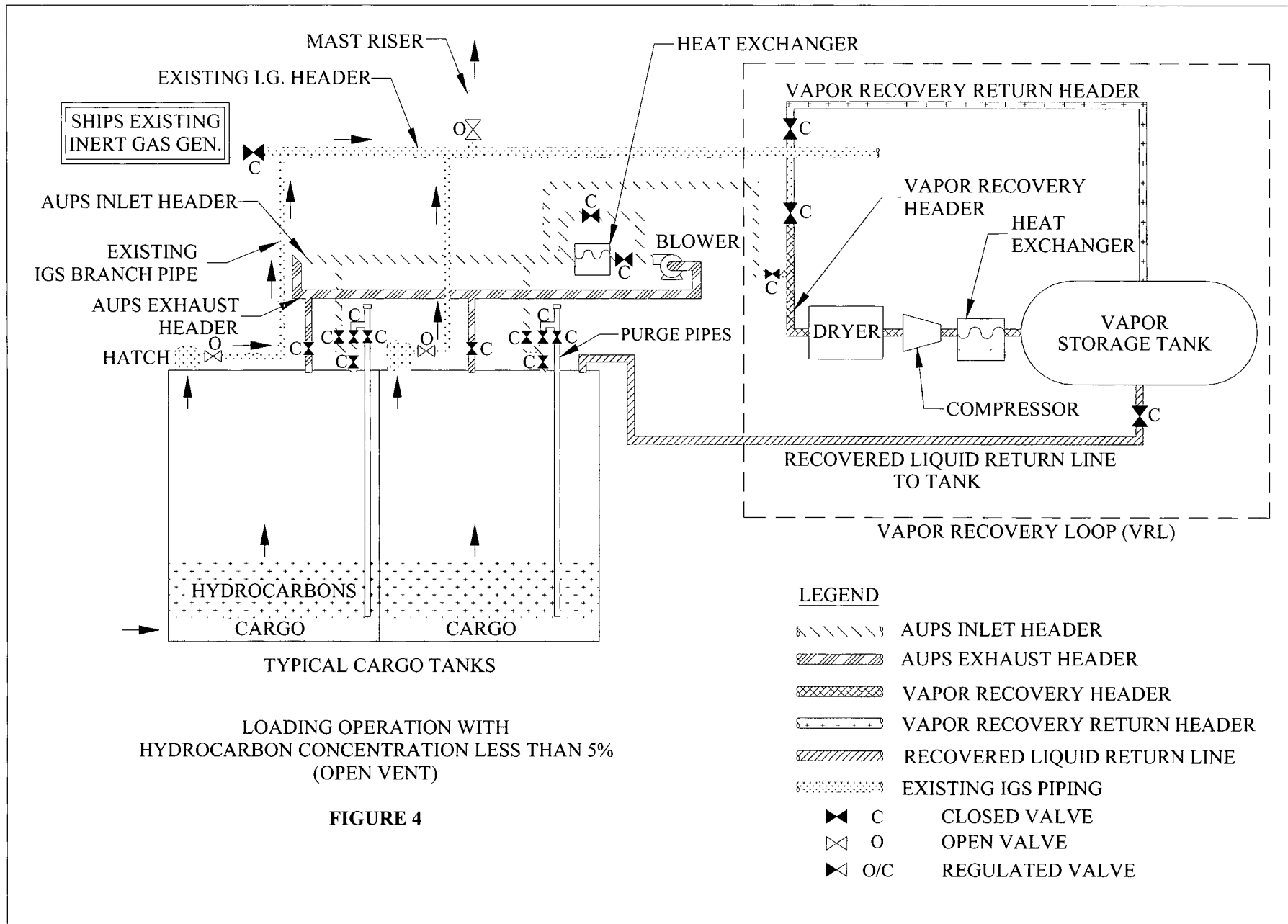


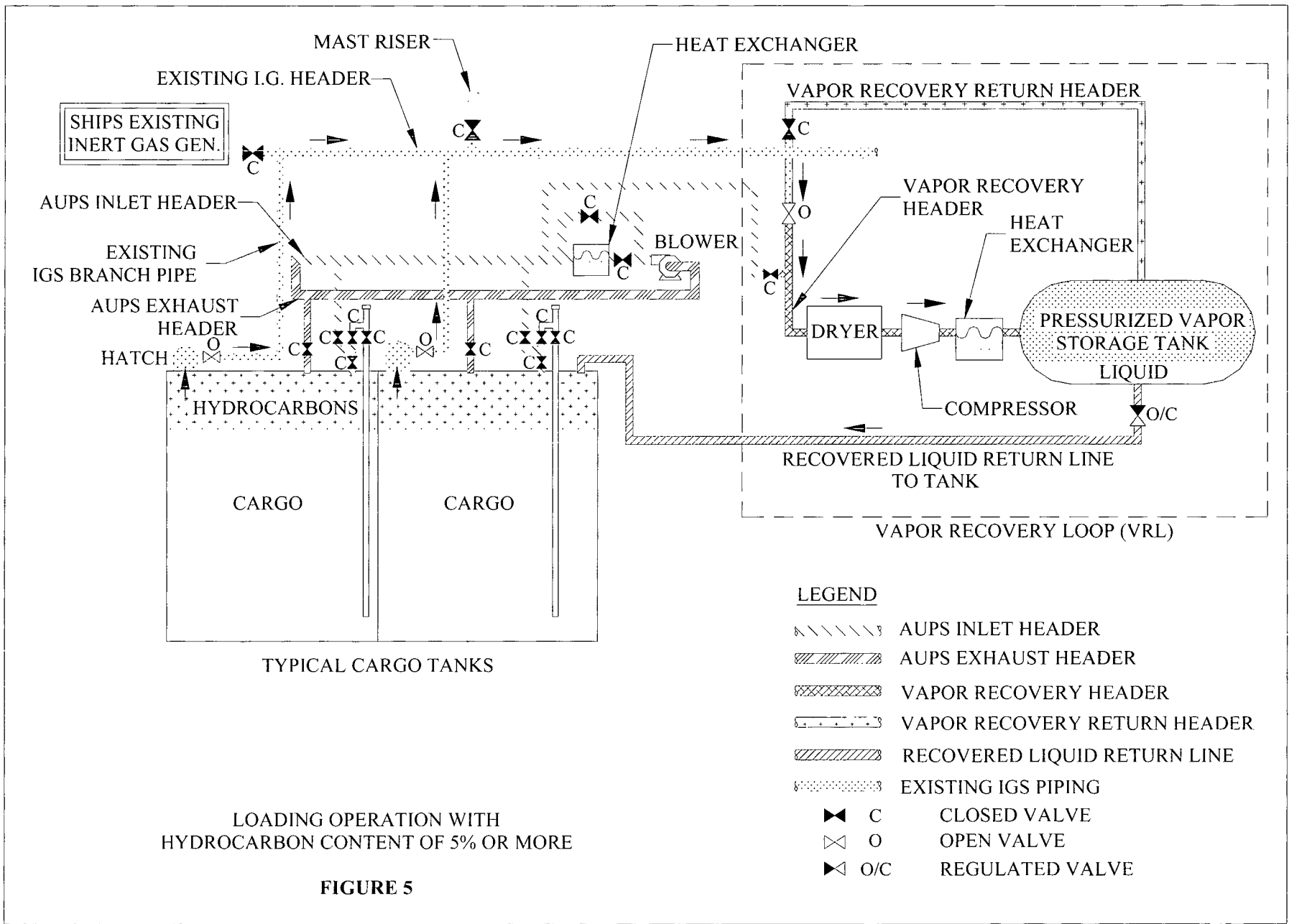
FIGURE 2

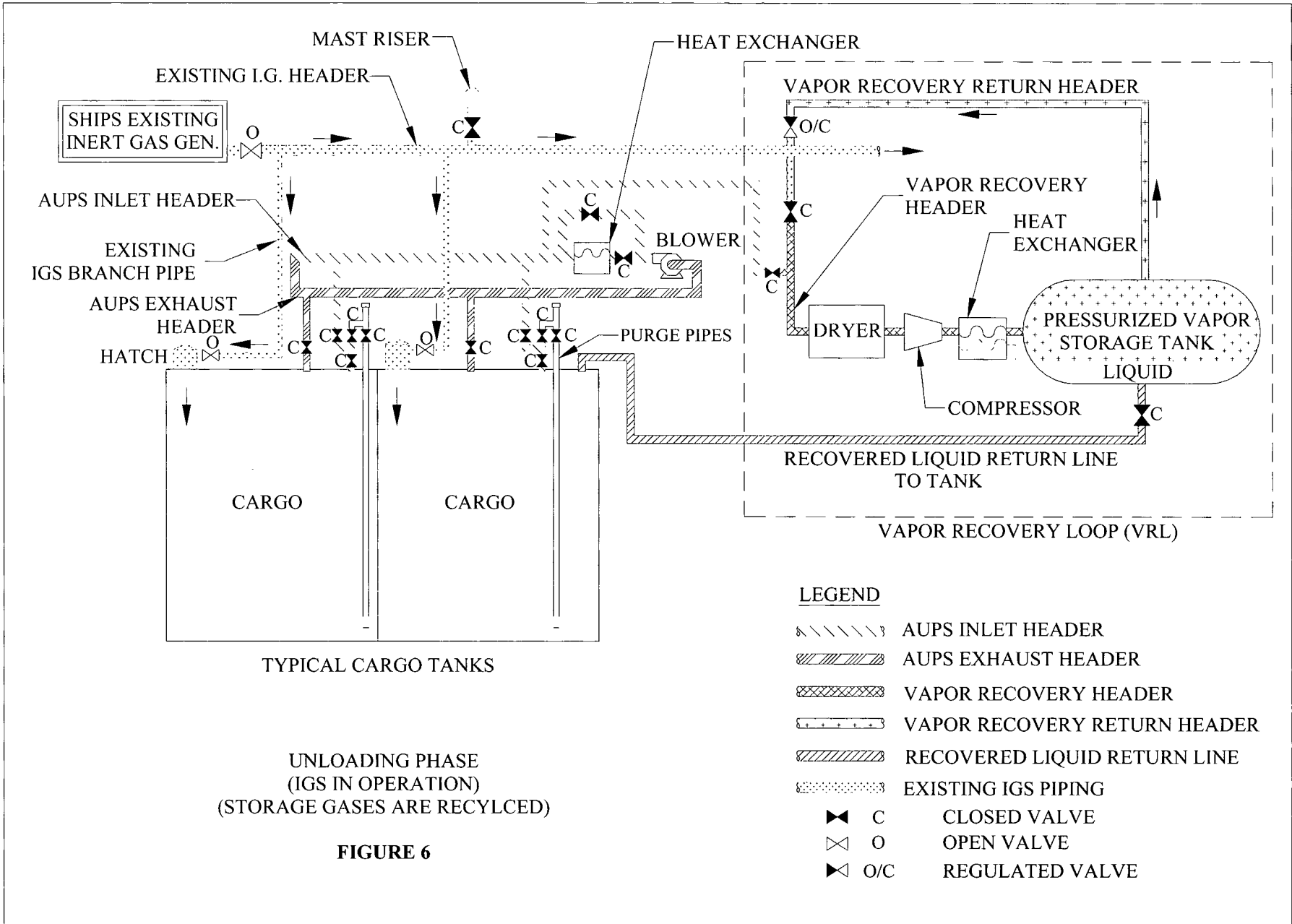


VENT GAS COMPOSITION DURING LOADING
(INITIALLY INERTED TANKS)

FIGURE 3







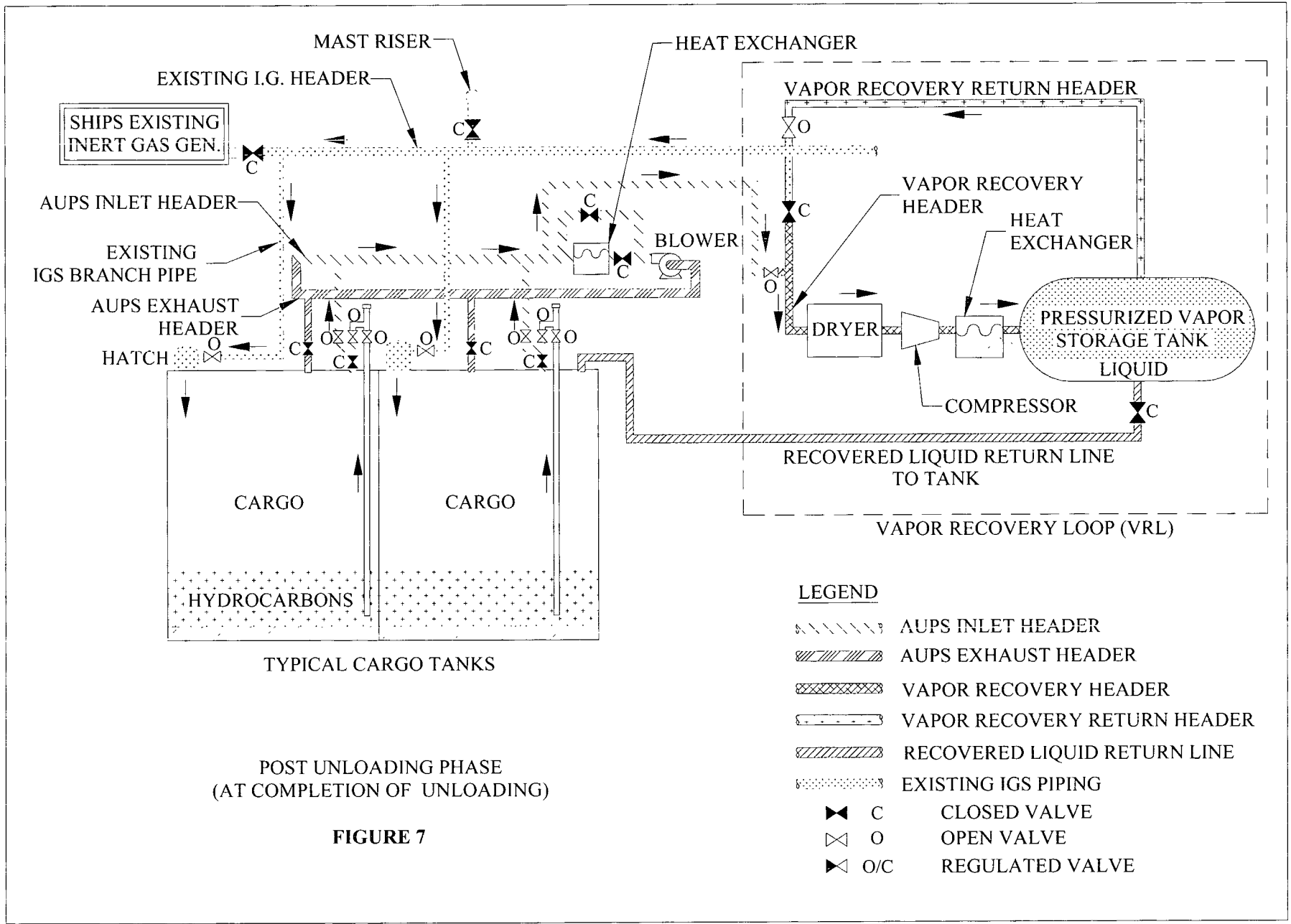


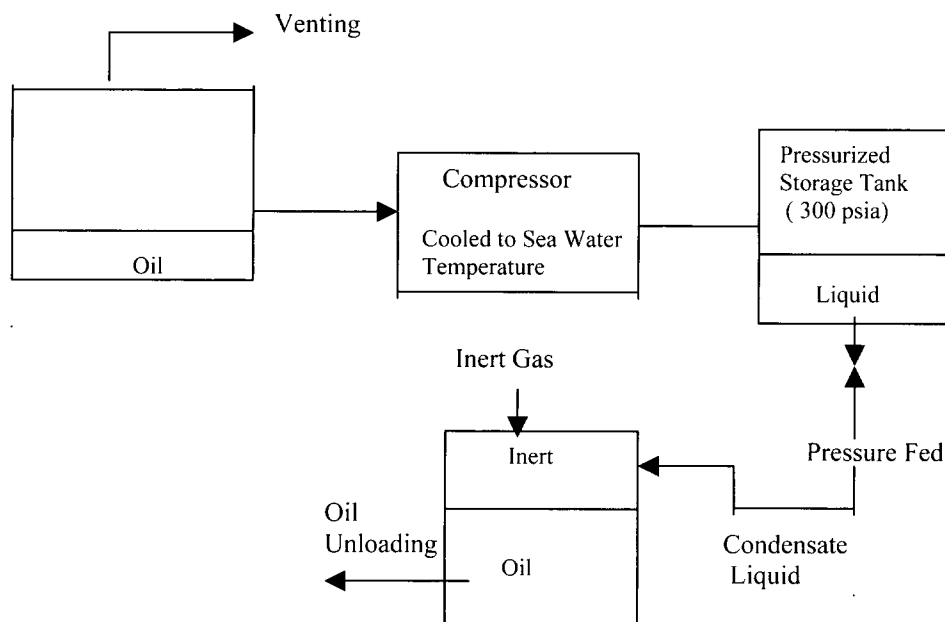
FIGURE 7

DISCUSSION

There were no written discussions submitted for this paper. However the author noted several important verbal discussions. The discussers include Prof. Ed Wiggins, Prof. Jose Femia, Mr. John Malone and others. Primarily two basic questions were asked:

Q.1 The vapor is condensed or collected at a pressure within 200 psi and 300 psi; how does the vapor or the liquid discharged at an ambient pressure without flashing?

Q.2. Any economics and cost analysis performed for the system?



Answers to Question #1.

Cargo Loading: The above diagram depicts the processing and discharge of the liquid condensate.

This processed gas is compressed and cooled to 300 psia and 90° F (the liquid content is approximately 6% of the processed gas. This small quantity of liquid can be pressure fed back to the tank without flash. It should be noted that at this stage vapor pressure of the liquid in the pressurized storage tank is approximately 8 psi and the liquid in the cargo tank is about 15 psia.

The advantage of pressure controlled container is that the size of container can be relatively small. The volume in vapor phase is mostly composed of inert gas and some light hydrocarbon

components, while the intermediates are mostly in liquid phase at these conditions.

Cargo Unloading:

The condensate is returned to the cargo tanks when inert gas @ 15 psia, is being introduced to maintain the pressure during cargo unloading.

The condensate is introduced to the cargo tank and the pressure is reduced to 15 psia. At these conditions the liquid condensate will not boil/flash since its vapor pressure is well below total imposed pressure of 15 psia. However, some vaporization will occur at a slow rate to equalize specific partial pressures across the

liquid/vapor boundary to reach equilibrium pressures.

Answer to Question #2.

Extensive economics analysis has not been performed for this concept of VOC Loading and Unloading. However a preliminary cost analysis indicates that a total of 400 tons of crude oil can be saved on each trip for the 127,000 DWT shuttle tanker referenced in this paper. Assuming 50 trips per year, 20,000 tons could be saved. At \$50 a barrel that is approximately \$6.2 million saving. A stand-alone VOC loading and unloading system cost is estimated to be approximately \$6 million in an US shipyard.