Merits of Double Bottoms in Crude Oil Tankers as Applied to the "Exxon Valdez" Spill of March 24, 1989

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LIST OF FIGURES

NOTE: FIGURES ARE NOT DRAWN TO SCALE AND ARE FOR ILLUSTRATION PURPOSES ONLY.

INTRODUCTION:

At the request of Messrs. Hill Betts and Nash, Attorneys at Law, New York, NY, this firm has performed a study with the object of determining the effect the presence of a standard double bottom would have had on the amount of oil spilled during and after the grounding of the tanker "EXXON VALDEZ" on Bligh Reef, near Valdez, Alaska on March 24, 1989.

This study takes into account published and unpublished reports and opinions, independent studies performed by this office, and experience by this firm in analyzing and repairing bottom damages, and performing salvage on grounded vessels with both single and double bottoms.

This study provides the reader with guidance on evaluating the various opinions on the usefulness of double bottoms. This firm also provides the reader with its estimate of the amount of oil spilled if this incident would have occurred to a vessel the size of the "EXXON VALDEZ", but provided with a double bottom.

As far as the incident is concerned this report will solely deal with events occurring immediately after the vessel first impacted the reef, and as such does not render any opinion on the cause of the accident.

DESCRIPTION OF THE "EXXON VALDEZ" AND ITS CARGO AT THE TIME OF THE INCIDENT.

The subject vessel was designed and constructed by Messrs. National Steel & Shipbuilding Corporation (NASSCO) of San Diego, CA and completed in 1986 as builder's number 438. The vessel is identical to the "EXXON LONG BEACH", which was built in 1987 in the same yard.

The vessel was purposely designed for the Alaska service, and as far as can be determined by this firm, had always been operated in that trade up to the time of the incident.

The configuration of her tanks and equipment is shown in the general arrangement drawing attached to this report (Figure 1). The subject vessel is a crude oil carrier of relatively conventional design, with accommodations and engine room aft, a pump room immediately forward of the engine room, and the complete cargo and ballast tank section located forward of the pump room.

The cargo and ballast tanks are numbered from forward to aft (bow to stern), tank No.1 being the most forward tank, and tank No. 5 being the tank located furthest aft. In addition each tank number is subdivided into port (left), center, and starboard (right) tanks. Therefore tank No.3 Starboard would be the starboard tank in the third row counted from the bow.

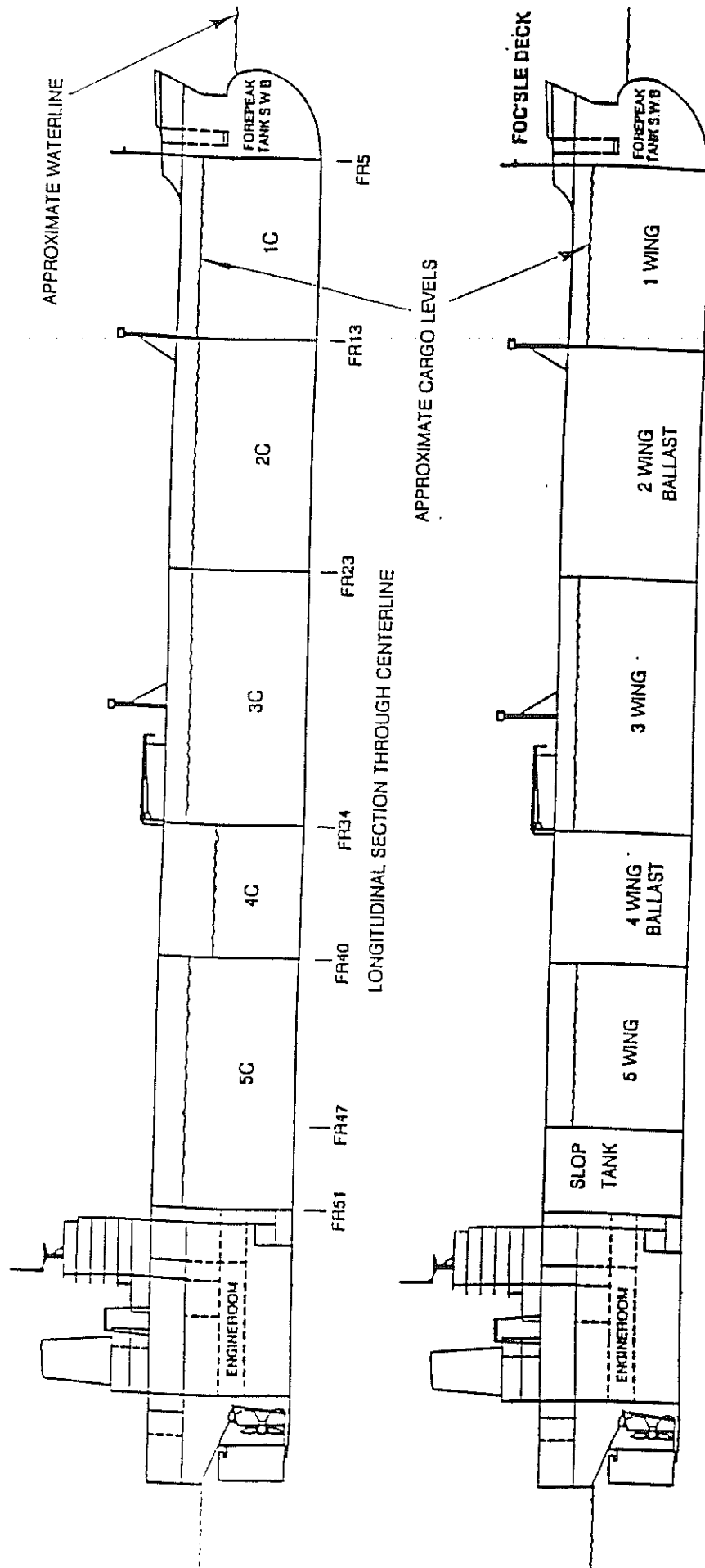The port and starboard tanks are commonly identified as wing tanks.

Forward of the No. 1 tank row is a forepeak tank, and aft of the engine room the vessel is fitted with an afterpeak tank. These two tanks together with tanks No. 2 port and starboard, and No. 4 port and starboard function as segregated ballast tanks.

Since crude oil carriers generally carry cargo in only one direction, from the oil well supply point to the refinery; they generally make the return trip empty, which is generally referred to as "in ballast". In order for the vessel to handle properly at sea when not loaded with cargo, she has to carry ballast, which for tankers is generally sea water. (The vessel needs a certain minimum draft in order to keep the propeller submerged, and to avoid damage to the vessel in heavy weather.)

Until recently this ballast would be carried in some of the cargo tanks. However, since these cargo tanks contain oil residue, discharge of the ballast prior to loading often resulted in pollution. Therefore, all tankers of the size of the "EXXON VALDEZ" are now built with segregated ballast systems where the cargo goes into designated tanks, and the ballast goes into other designated tanks and the two never mix, thereby preventing pollution during ballast water discharge.

The vessel is also fitted with four slop tanks, two each (one wing and one double bottom) located aft of tanks No. 5 port and starboard, which serve to collect any contaminated water which might result from the vessel's operations, such as tank cleaning and fuel oil purification. The slops in these tanks can only be discharged ashore in approved facilities, which frequently are provided by the receiving terminal or at the refinery of destination.

The vessel's structure is relatively conventional with longitudinal framing, two longitudinal bulkheads, transverse webframes, seven full transverse bulkheads, and a small number of partial transverse bulkheads.

APPROXIMATE WATERLINE

FOREPEAK TANK S W B

1C

FR13

2C

FR23

3C

FR34

4C

FR40

5C

FR47

FR51

FR5

ENGINEROOM

LONGITUDINAL SECTION THROUGH CENTERLINE

FOC'SLE DECK

FOREPEAK TANK S.W.B

1 WING

APPROXIMATE CARGO LEVELS

2 WING BALLAST

3 WING

4 WING BALLAST

5 WING

SLOP TANK

ENGINEROOM

LONGITUDINAL SECTION THROUGH WING TANKS

FOREPEAK TANK S.W.B

CARGO TANKS

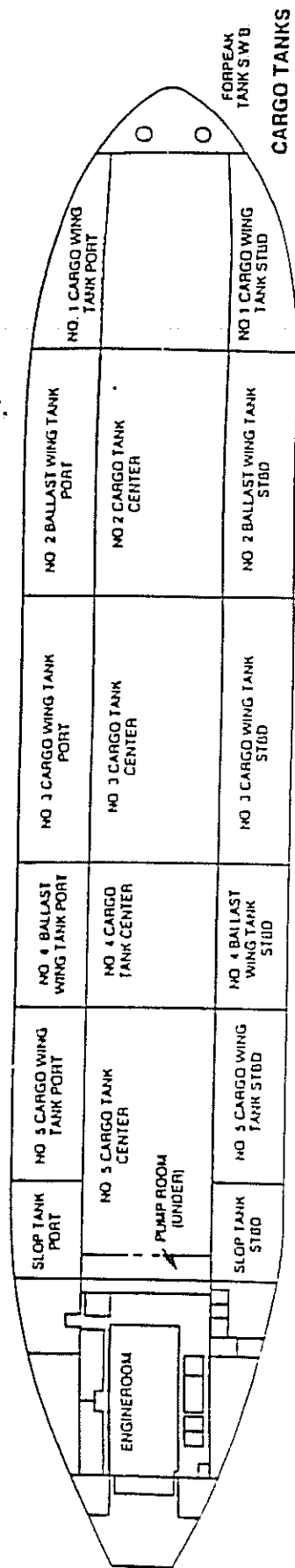| NO 1 CARGO WING TANK PORT | | |
NO 2 BALLAST WING TANK PORT	NO 3 CARGO WING TANK PORT	NO 4 BALLAST WING TANK PORT	NO 5 CARGO WING TANK PORT	SLOP TANK PORT
NO 2 CARGO TANK CENTER	NO 3 CARGO TANK CENTER	NO 4 CARGO TANK CENTER	NO 5 CARGO TANK CENTER	
NO 1 CARGO WING TANK STBD		
NO 2 BALLAST WING TANK STBD	NO 3 CARGO WING TANK STBD	NO 4 BALLAST WING TANK STBD	NO 5 CARGO WING TANK STBD	SLOP TANK STBD

PUMP ROOM (UNDER)

ENGINEROOM

FIGURE 1: GENERAL ARRANGEMENT OF MT "EXXON VALDEZ".

Bulkheads are watertight subdividers of the vessel; they divide the vessel into separate compartments. These subdivisions can be made for safety (flooding, oil spills or fire) purposes, for cargo carrying purposes, or for structural purposes. The transverse bulkheads are positioned from port side to starboard side, and the longitudinal bulkheads are positioned in the fore and aft direction.

Longitudinal framing refers to the way the vessel's shell is reinforced. In order to prevent the vessel's relatively thin shell from buckling during normal operational loading, the shell has to be reinforced on the inside by means of stiffeners. In a longitudinal structure the shell stiffeners run from the bow to the stern, and these stiffeners in turn are reinforced by regularly spaced larger transverse stiffeners, which are called web frames. Where a transverse bulkhead is required in the vessel, the web frame is omitted in favor of the bulkhead.

A perspective drawing of the vessel structural arrangement in way of her ballast and cargo tanks is attached to this report (Figure 2).

The vessel is constructed out of high tensile strength steel, which allowed the vessel to be constructed out of thinner plate than had she been constructed from regular mild steel. This reduced her structural weight and, since a lower proportion of the vessel's total carrying capacity is taken up by structural weight, increased her cargo carrying capacity.

For the purposes of this study the vessel's bottom plating weight will be averaged at 30.6 pounds per square foot, while the weight of the internals which support the bottom plating will be averaged at 45 pounds per square foot.

The weight of the internals includes all structural material which is located within the height of the internal floor stiffeners (approximately 13 feet).

Therefore, the weight of the bottom structure for the purposes of this study will be set at 75.6 pounds per square foot.

As is now generally known, the "EXXON VALDEZ" is not fitted with double bottom tanks in way of her cargo section.

The vessel was classed by the American Bureau of Shipping, and was reportedly designed in accordance with the standards of the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78), which amongst other design features, places her segregated ballast tanks such that they provide partial protection for her cargo tanks in case of collision and groundings, and limits the length of her cargo tanks, thereby limiting the amount of oil spilled when a single compartment is punctured.

Since the vessel was completed in 1986, and at the time of the incident only about three years old, it is safe to assume that wastage from corrosion in the vessel's structure can be ignored in any structural calculations performed in connection with this report.

The vessel's particulars are as follows:

Length Over All: 987.00 feet
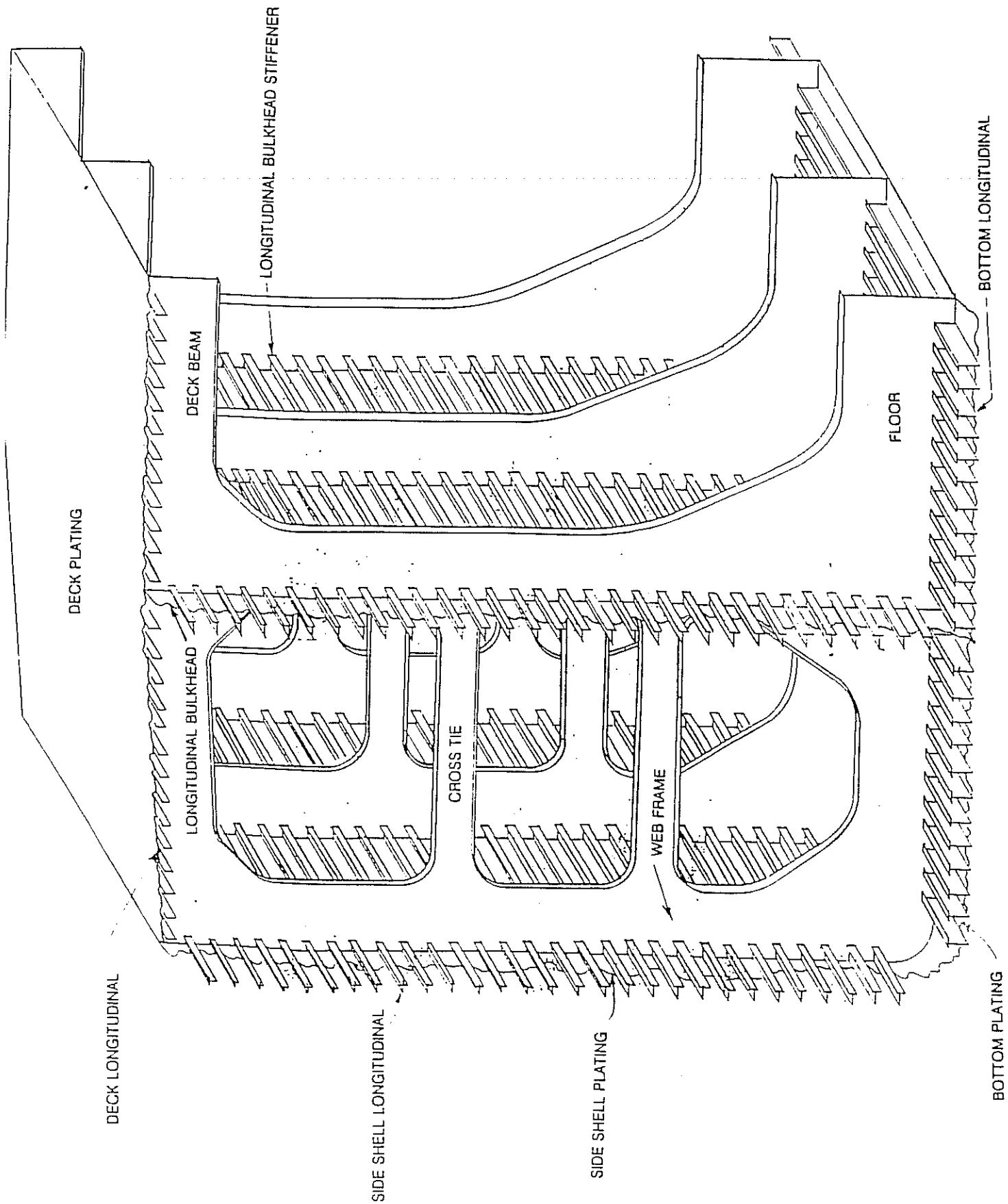
FIGURE 2: PERSPECTIVE VIEW OF STRUCTURE IN A CARGO/BALLAST TANK SECTION ON THE M/T "EXXON VALDEZ"

Labels in figure:
DECK PLATING
LONGITUDINAL BULKHEAD STIFFENER
DECK BEAM
BOTTOM LONGITUDINAL
FLOOR
DECK LONGITUDINAL
LONGITUDINAL BULKHEAD
CROSS TIE
WEB FRAME
SIDE SHELL LONGITUDINAL
SIDE SHELL PLATING
BOTTOM PLATING

Length Between Perpendiculars:	945.01 feet
Extreme Beam (Breadth):	166.14 feet
Depth (Molded Depth):	87.99 feet
Deadweight (cargo carrying capacity):	211,467.00 tons
Maximum draft:	64.56 feet
Tons per inch immersion:	334.9 tons

At the time of the incident the vessel had just left the port of Valdez, Alaska, loaded with a cargo of Alaskan crude oil bound for Long Beach, California.

Crude oil is oil which comes directly from the well, and which has not been processed. As such it is a mixture of a variety of light and heavy hydrocarbons rather than a more uniform product such as gasoline. Since it contains small proportions of very volatile hydrocarbons, it is quite flammable. The heavier, "tarrier", components of this mixture make it quite viscous (syrupy), which normally requires the oil to be heated if it has to be pumped. Once crude oil comes in contact with cold water and cools down it will become more viscous and will behave like a slurry. When compared to crude oils from other parts of the world, the Alaska crude is relatively light, and easy to pump.

Crude oil as a mixture of various hydrocarbons is generally lighter than sea water, and will therefore float on top of sea water.

The vessel was not loaded to her maximum capacity, on the trip which resulted in the grounding, reportedly due to draft restrictions at her discharge port. This resulted in cargo amounts in the various tanks as shown in the section headed "DISCUSSION OF DATA USED IN THIS STUDY". Further particulars on the "EXXON VALDEZ" can also be found under that heading.

DOUBLE BOTTOM TANKERS:

On ships a double bottom is a structural arrangement where the vessel is essentially built with two bottoms; the outer shell, and an inner shell, which is located a certain distance above the outer shell. These two shells are interconnected with internal stiffeners, also referred to as floors and girders.

A perspective drawing of a typical double bottom structure is attached to this report (Figure 3).

In general the space created between the two shells is subdivided into separate compartments which are called double bottom tanks. Often the double bottom tank subdivisions are similar to the tank subdivisions above the double bottom. In this regard the No. 3 double bottom (3DB) tank is located immediately underneath the No. 3 cargo tank. In this report such a numbering convention will be applied.

Double bottoms are not a new concept, and practically all ocean going vessels except tankers are fitted with double bottoms.

There are a variety of reasons why naval architects design ships with double bottoms, such as the need for smooth cargo hold bottoms (with a double bottom vessel few stiffeners have to protrude above the top of the double bottom), the need for ballast or fuel oil tank capacity which can be easily located in a double bottom, or the need to provide an extra margin of protection to the vessel and her cargo in the holds by means of a barrier between the sea and cargo.

Most tankers are not fitted with double bottoms since most designers and operators are of the opinion that a tanker without double bottom tanks is less expensive to construct and operate. Ballast needs were provided for by pumping ballast water into the cargo tanks, or in newer tankers and tankers modified to meet anti-pollution requirements, into the segregated ballast tanks or clean ballast tanks.

Construction costs for double bottom tankers are higher since they require additional material, welding and coating. While there are a wide variety of estimates on the cost difference between single skin and double bottom tankers, in our opinion, a double bottom tanker would cost approximately 5% more than a single skin tanker of the same capacity.

Many tanker operators have contended that double bottom tankers are more expensive to operate since the double bottom tanks would require additional maintenance, with poor access as compared to full height ballast tanks which have better access for maintenance. In addition, full height ballast tanks have less surface area requiring coating for the same amount of tank capacity.

This argument can be countered by the fact that double bottom tankers have smooth tank bottoms which reduce the amount of cleaning required in the cargo tanks, and simplify heating coil arrangements. In addition, the air space in the double bottom reduces the heat loss from the heated cargo to the sea.

This firm is aware of tanker operators who operate both types of tankers with negligible differences in operating costs.
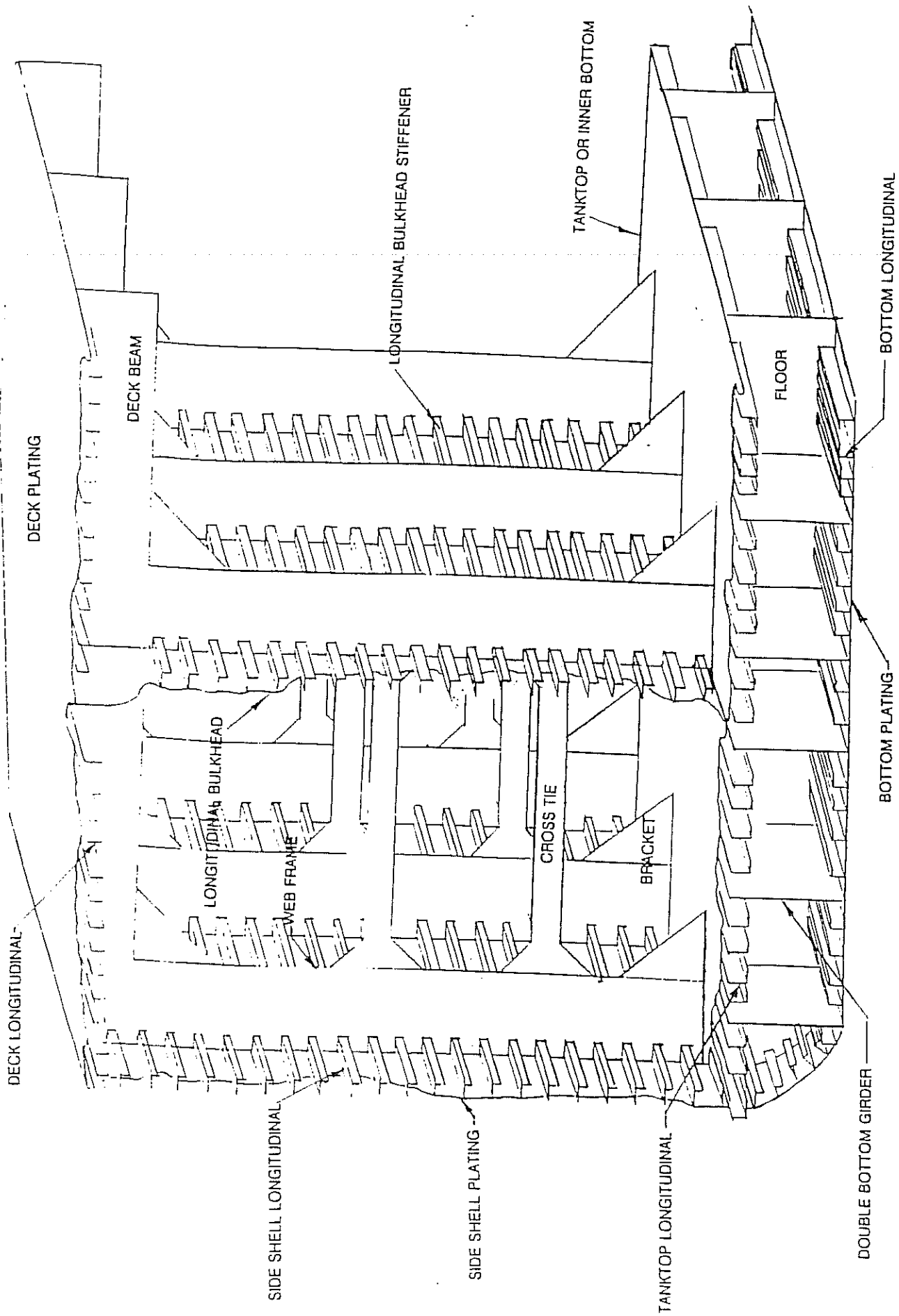
FIGURE 3: PERSPECTIVE VIEW OF STRUCTURE IN A CARGO/BALLAST TANK SECTION ON A TYPICAL DOUBLE BOTTOM TANKER.

Labels in figure:
DECK PLATING
DECK BEAM
LONGITUDINAL BULKHEAD STIFFENER
TANKTOP OR INNER BOTTOM
BOTTOM LONGITUDINAL
FLOOR
LONGITUDINAL BULKHEAD
WEB FRAME
CROSS TIE
BRACKET
BOTTOM PLATING
DECK LONGITUDINAL
SIDE SHELL LONGITUDINAL
SIDE SHELL PLATING
TANKTOP LONGITUDINAL
DOUBLE BOTTOM GIRDER

Recently other considerations such as the possibility of explosive conditions in double bottom tanks and salvage considerations, have also been presented as negative aspects of double bottom tankers. However, this firm and operators with double bottom tanker experience, do not believe these considerations are significant.

Therefore, the most important factor in determining whether a tanker is to be fitted with a double bottom or not is the initial purchase cost.

The obvious benefit of a double bottom in tankers is the additional protection from cargo outflow it provides in case of a grounding.

Double bottoms and various degrees of double hulls are presently commonly installed on chemical and product carriers, since some of the products carried by these vessels are sufficiently dangerous to the environment to warrant the extra protection of a double bottom or a double side shell.

In addition, a small number of double bottom crude oil tankers have been built for specific trades where legislation was pending or enacted requiring double bottoms. Ironically, one of these trades was the Alaska crude oil trade where at first it appeared that the vessels carrying "North Slope" crude would be required by law to be fitted with double bottoms.

Again, there are many opinions published as to how effective double bottom tankers would be in preventing pollution due to groundings. This firm is of the opinion that double bottoms are quite effective in reducing the number of oil spills resulting from grounding. This firm and their engineers, serving among others, Owners and Marine Underwriters, have attended many grounding incidents, and have regularly encountered damages which would have resulted in significant cargo spills if the vessel had not been fitted with a double bottom. In addition, this office is not aware of any cargo spill due to grounding from tankers fitted with double bottoms.

This firm and their engineers have also attended grounding incidents which would not have resulted in cargo spills if the vessel had been fitted with a double bottom.

More specifically this firm attended at the groundings and oil spills of the tankers "PRESIDENTE RIVERA", "WORLD PRODIGY", and "BT NAUTILUS", which took place at about the same time as the "EXXON VALDEZ" grounding. It can be stated without reservation that neither the "PRESIDENTE RIVERA" nor the "BT NAUTILUS" spills would have taken place if these vessels had been fitted with double bottoms, and that the "WORLD PRODIGY" spill would have been greatly reduced.

All studies that this firm is aware of indicate that double bottoms reduce the incidence of cargo spills due to groundings. Since so many variables such as trading patterns, bottom conditions, improvements in navigational practices and equipment, vessel speed, damage depth and structural variations come into play, it is impossible to provide an exact number, but when taking the various studies into account we estimate that at least 50% of all oil spills due to grounding would be prevented, if all oil tankers were to be fitted with double bottoms.

In addition, these studies also indicate that during a high energy grounding causing rupturing of the inner bottom, the amount of cargo spilled from a double bottom tanker generally would be significantly less than from a single hull tanker. This reduction in the amount spilled is mostly due to the

lower number of cargo tanks which end up being ruptured on a double bottom vessel, and the containment of the cargo oil in the normally empty double bottom tanks.

DESCRIPTIONS OF TANKERS SIMILAR TO THE "EXXON VALDEZ", BUT FITTED WITH DOUBLE BOTTOMS:

In the seventies when the Alaska pipeline was being constructed, it appeared, due to environmental concerns, that the tankers loading oil at the "Valdez" terminal were going to be required by law to be constructed with double bottoms. Since the lead time for bringing a tanker into service for a particular trade is about two years, and since owners and operators (both independent shipowners and oil companies) did not want to be late in entering this trade, or construct vessels which might not conform to legal requirements, the earliest vessels constructed for this trade were built with double bottoms.

However, this legislation requiring double bottoms on tankers was never enacted, and by the time the oil started flowing from Alaska, tanker Owners and Operators were allowed to also enter single hull vessels in this trade. Since single skin tankers are less expensive to construct, no new contracts for construction of double hull tankers in this trade were placed.

In this regard the "Valdez" trade is presently serviced by older double bottom tankers, and newer single hull tankers.

The "OVERSEAS NEW YORK", "OVERSEAS WASHINGTON", "OVERSEAS OHIO", "OVERSEAS CHICAGO"(which comprise the "SAN CLEMENTE" class tankers), "KEYSTONE CANYON", "B.T. ALASKA", "B.T. SAN DIEGO", "ARCO ALASKA" and "ARCO CALIFORNIA" are examples of the earlier double bottom tankers, while the "EXXON VALDEZ", and her sister ship the "EXXON LONG BEACH" are examples of the newer single hull vessel.

These double bottom tankers are of a very conventional design, and are operated on an interchangeable basis with the single hull vessels.

All of the vessels noted above except the "KEYSTONE CANYON" were constructed at National Steel & Shipbuilding Corporation in San Diego.

Especially the "B.T. ALASKA", and the "B.T. SAN DIEGO" are interesting since these vessels are quite similar to the "EXXON VALDEZ", being only 34 feet shorter, 10 feet less deep, with exactly the same beam and 21,000 tons less in dead weight capacity.

The general arrangement of the "BT SAN DIEGO" is shown in Figure 4, and the general arrangement of the "SAN CLEMENTE" class vessels is shown in Figure 5.
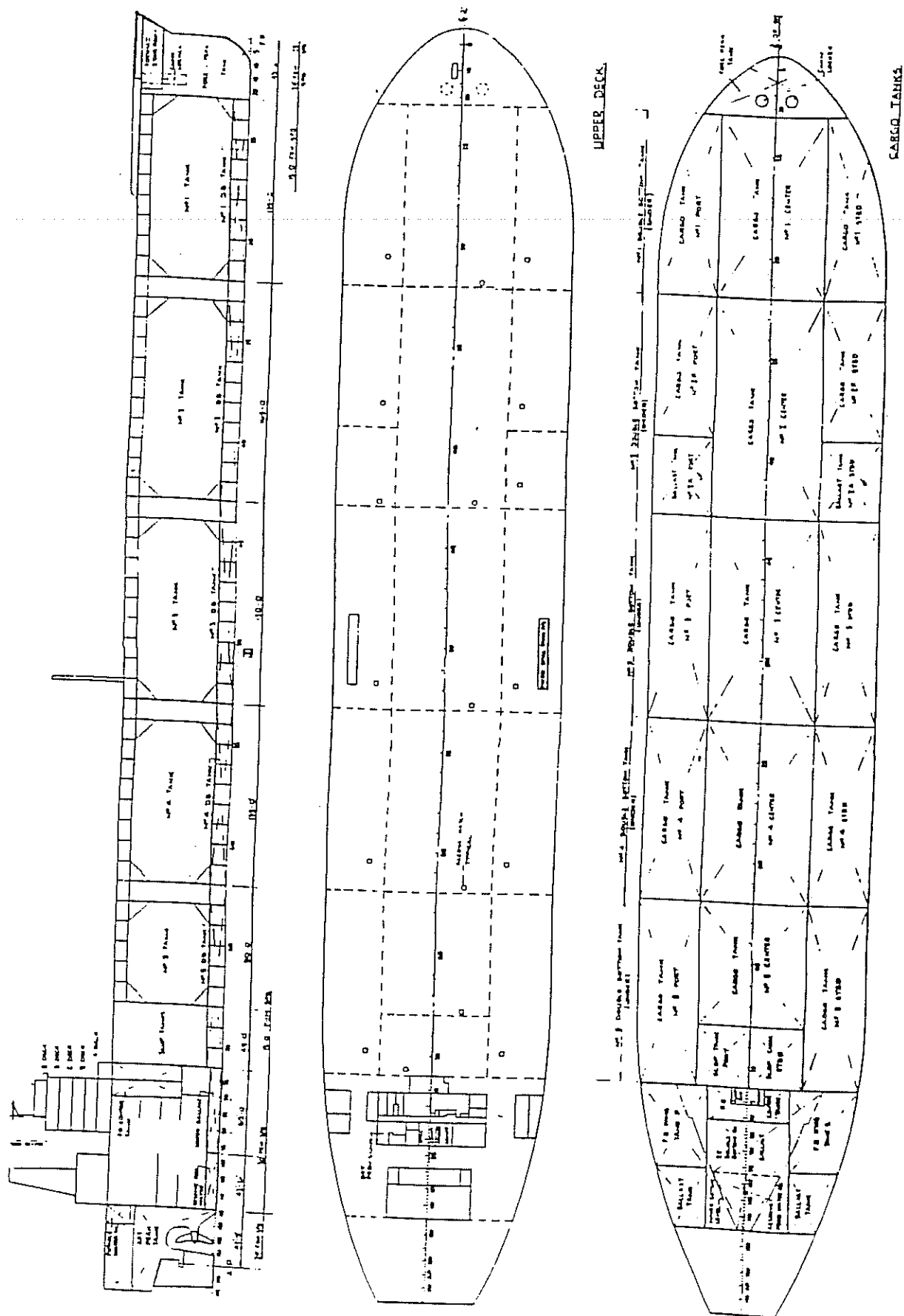
14

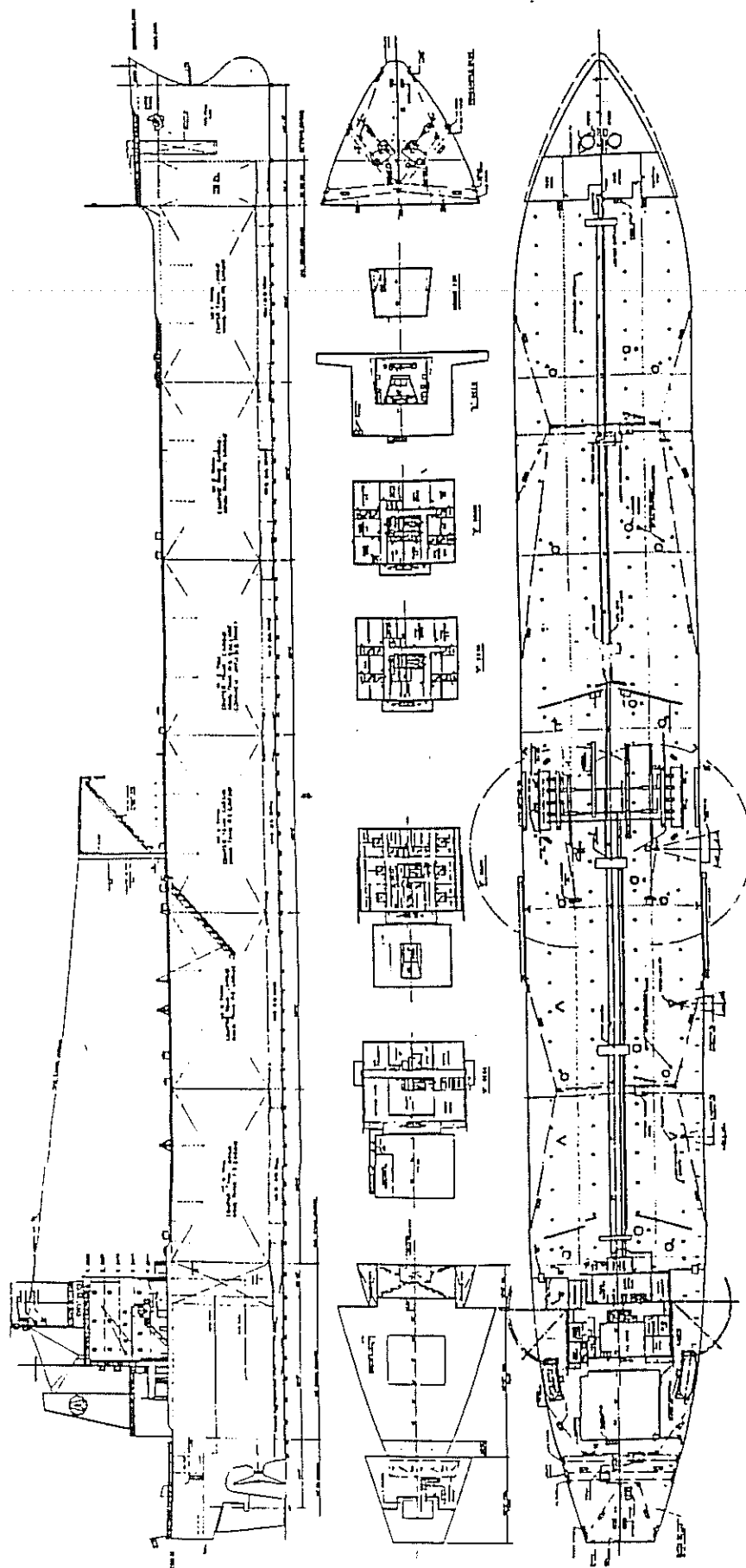FIGURE 4: GENERAL ARRANGEMENT 189,500 DWT, "SAN DIEGO" CLASS TANKERS

FIGURE 5: GENERAL ARRANGEMENT OF 89,700 DWT, "SAN CLEMENTE" CLASS TANKERS

DESCRIPTION OF AN IMAGINARY TANKER WITH THE SAME CARRYING CAPACITY OF THE "EXXON VALDEZ", BUT FITTED WITH A DOUBLE BOTTOM:

In order to be able to compare oil outflow after a grounding for a vessel of the same size as the "EXXON VALDEZ", but fitted with a double bottom, an imaginary double bottom tanker will have to be designed.

The design of ships is an art which involves many trade-offs, which all interrelate. For example, if a designer decides to increase the speed of a ship, he will have to fit a larger engine, or he will have to make the ship lighter, or he can combine the two. Any of these decisions will also affect other particulars of the vessel. For example, by fitting a larger engine, a larger engine room and larger fuel tanks might be required, which would increase the overall size of the vessel.

Based on the above, it is obvious that a certain approach will have to be chosen for designing an equivalent double bottom tanker. It also indicates that the particular design developed will not be the only possible alternative. As a matter of fact, it is very simple to design a double hull tanker which has the same cargo carrying capacity as the "EXXON VALDEZ", but which has such a shallow draft that the vessel would have never grounded on Bligh Reef. However, this vessel would not be a very representative double bottom tanker and probably not be very economical, and it is therefore that, for the purposes of this study, it was decided to make an effort to design a tanker which, in arrangement and construction, resembles existing double bottom tankers.

In order to maintain as many concrete and accepted constants as possible, it was also decided to design an equivalent double bottom tanker with the same depth, length and breadth (beam) as the "EXXON VALDEZ". It is not necessarily true that such a double bottom tanker will be the most efficient design, but it will enable a comparison of damages between the two types of vessels had they been involved in the same incident.

The next dimension to be determined is the height of the double bottom to be fitted in the vessel. The height of the double bottom in vessels such as these is not fixed according to strict rules, but is influenced by a number of factors, such as the height of stiffeners required in the vessel bottom, the amount of ballast space required, and the optimum height for accessibility during inspection.

For structural considerations the American Bureau of Shipping 1986 rules state that the height of the double bottom should be 96.98", or 8'-1". (Rule 7.3.2). (American Bureau of Shipping rules are used since the "EXXON VALDEZ" is also classed by the American Bureau of Shipping)

Coincidentally, this height is considered to be practical from a maintenance and inspection point of view.

In order to accommodate all necessary ballast normally located in the mid-body ballast tanks in the double bottom, higher double bottom tanks would be required, but this would also require special consideration by the American Bureau of Shipping, and might not comply with MARPOL. In addition, higher double bottom tanks might not be all that efficient from a structural point of view, would make double bottom tank inspection and maintenance more difficult, and could cause stability problems.

Nevertheless it should be noted that the "BT ALASKA", and the "BT SAN DIEGO" are fitted with 12 foot high double bottom tanks, and therefore, based on the need to develop an equivalent double bottom which resembles existing double bottom tankers, a 12 foot double bottom height could also be considered to be a viable choice.

At this stage only the 8 foot double bottom tanker will be used in the comparison, but as an example the 12 foot double bottom case is also shown.

The total amount of ballast that can be accommodated in the 8 foot 1 inch double bottom tanks is 23,971 tons.

This is 32,973 tons short of the mid-body ballast tank capacity on the "EXXON VALDEZ". In order to design an equivalent vessel to the "EXXON VALDEZ", this difference will have to be carried in ballast tanks fitted above the double bottom. Since the 8 foot double bottom vessel, when ballasted with seawater, is to have approximately the same draft and trim as the "EXXON VALDEZ", this ballast tank will have to be fitted in way of wing tanks No. 2B and 3A, as is shown in Figure 6.

Another decision to be made is the subdivision of the double bottom tanks. Based on the subdivision used in existing double bottom tankers, the double bottom tanks will follow the same outlines as the tanks located above the double bottom, except in way of the segregated wing ballast tanks where the fore and aft division will coincide with the centerline tank bulkheads.

The total amount of ballast that can be accommodated in the 12 foot double bottom tanks is 36,280 tons. A possible general arrangement of the 12-foot double bottom equivalent tanker is shown in Figure 7.

The reason that a double bottom tanker costs about 5% more to construct than a single bottom tanker is that the structural weight of a double bottom tanker is higher, and to a large extent the cost of a vessel is related to the weight of her structure.

For the vessels in question, the increase in structural weight of the double bottom tanker is almost exclusively concentrated in the inner (double) bottom plating.

This office made approximate calculations of the plating thicknesses required for an equivalent double bottom tanker, and it was found that the bottom plating thickness of the double bottom tanker would be the same as the bottom plating of the single skin vessel.

In addition, the weight of the internals per square foot could also be conservatively estimated to be the same as the weight per square foot for internals of a single skin tanker.

The inner bottom plating weight was estimated to be 27.74 pounds per square foot.

Consequently the bottom structure of the double bottom vessel is estimated at an average of 103.34 pounds per square foot, while the bottom structure of the single bottom vessel was earlier estimated at an average of 75.6 pounds per square foot.

The additional weight of the inner bottom amounts to about 1500 tons of steel. Since the

18

APPROXIMATE WATERLINE

FOREPEAK TANK S W B

FR5

1C

FR13

2C

FR18

FR23

3C

FR28

FR34

4C

FR40

5C

FR47

FR51

ENGINEROOM

LONGITUDINAL SECTION THROUGH CENTERLINE

FOC'SLE DECK

FOREPEAK TANK S W B

APPROXIMATE CARGO LEVELS

1 WING

2A WING

2B WING BALLAST

3A WING BALLAST

3B WING

4 WING

5 WING

SLOP TANK

ENGINEROOM

LONGITUDINAL SECTION THROUGH WING TANKS

FOREPEAK TANK S W B

CARGO TANKS

NO. 1 CARGO WING TANK PORT

NO 1 CARGO TANK CENTER

NO 1 CARGO WING TANK STBD

NO 2A CARGO WING TANK PORT

NO 2B BALLAST WING TANK PORT

NO 2 CARGO TANK CENTER

NO 2B BALLAST WING TANK STBD

NO 2A CARGO WING TANK STBD

NO 3A BALLAST WING TANK PORT

NO 3B CARGO WING TANK PORT

NO 3 CARGO TANK CENTER

NO 3B CARGO WING TANK STBD

NO 3A BALLAST WING TANK STBD

NO 4 CARGO WING TANK PORT

NO 4 CARGO TANK CENTER

NO 4 CARGO WING TANK STBD

SLOP TANK PORT

NO 5 CARGO WING TANK PORT

NO 5 CARGO TANK CENTER

PUMP ROOM (UNDER)

NO 5 CARGO WING TANK STBD

SLOP TANK STBD

ENGINEROOM

FIGURE 6: GENERAL ARRANGEMENT OF EQUIVALENT 8 FOOT DOUBLE BOTTOM TANKER.

LONGITUDINAL SECTION THROUGH CENTERLINE

LONGITUDINAL SECTION THROUGH WING TANKS
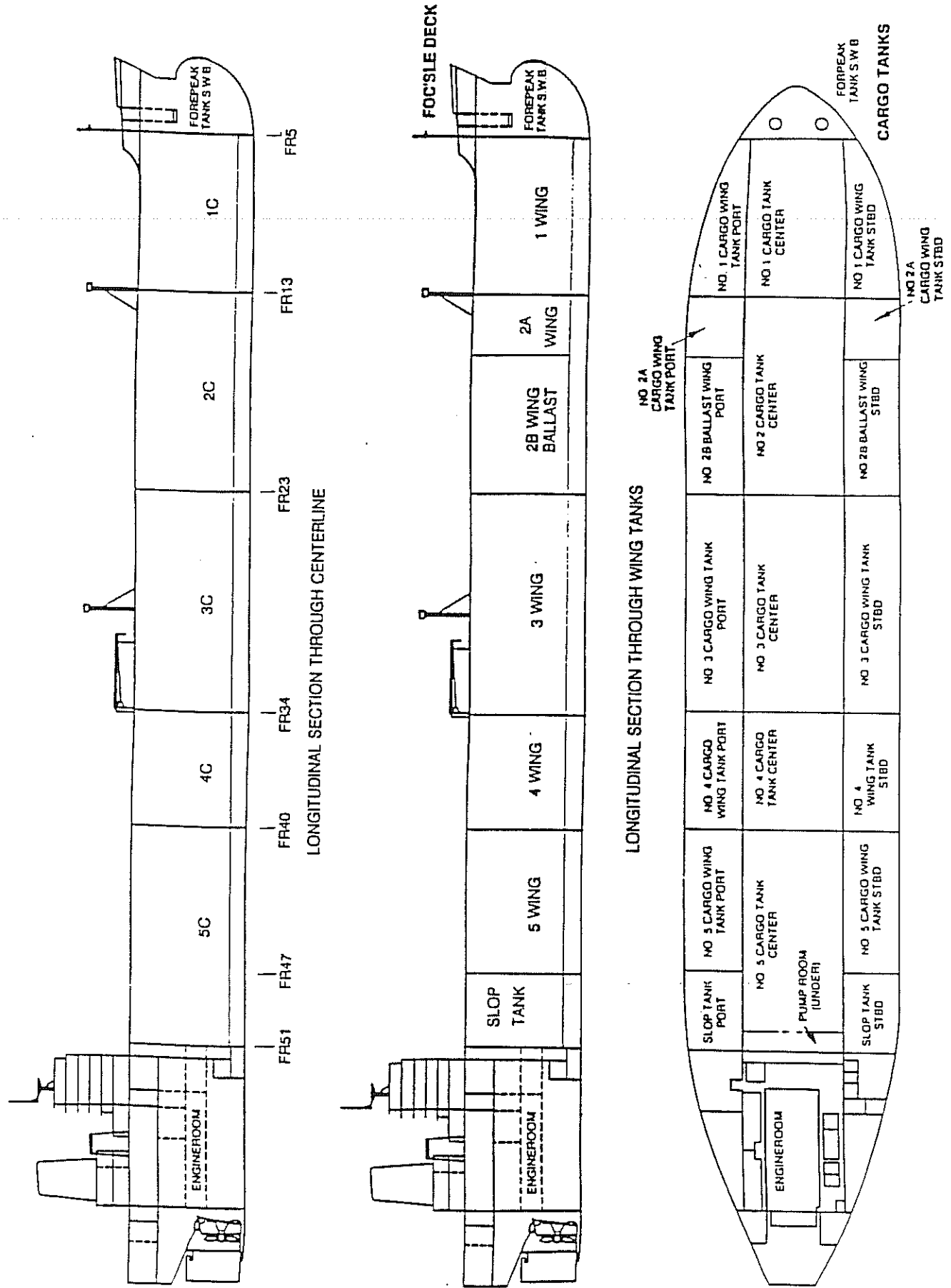
CARGO TANKS

FIGURE 7: GENERAL ARRANGEMENT OF EQUIVALENT 12 FOOT DOUBLE BOTTOM TANKER.

vessel's structure is heavier, in actuality the double bottom equivalent vessel will have slightly less cargo carrying capacity. However, since 1500 tons represents only a very small proportion of the vessel's total cargo carrying capacity, this weight differential between the two cases will not be considered.

It should be emphasized that a truly equivalent double bottom vessel cannot be designed. The two equivalents above are considered to be reasonable initial designs (within the constraints of this study; equivalent length, beam and depth), such as would be used in comparison studies for establishing optimum ship sizes and configurations to serve particular trades. While an effort was made to design equivalents which are realistic, it is possible that these designs might not fully conform to the numerous regulations which apply to commercial vessels. If a double bottom vessel were to be designed with the same cargo carrying capacity as the "EXXON VALDEZ", our studies indicate that the vessel would probably have less depth, and greater length, which would immediately reduce the amount of oil outflow from the vessel.

The two equivalent designs represent various ends of the design spectrum, and as such the results which are derived from these designs will also show a range rather than an exact number. However, it will become apparent in this study that in this particular grounding the height of the double bottom does not greatly affect cargo outflow.

DISCUSSION OF DATA USED IN THIS STUDY:

The following were used as sources of information in preparing this study:

National Research council report: "TANKER SPILLS: PREVENTION BY DESIGN", pre-publication copy February 12, 1991

National Transportation Safety Board: "MARINE ACCIDENT REPORT, GROUNDING OF THE U.S. TANKSHIP EXXON VALDEZ ON BLIGH REEF, PRINCE WILLIAM SOUND NEAR VALDEZ, ALASKA, MARCH 24, 1989.", No. PB90-916405, dated July 31, 1990.

Ross-McNatt, Inc., proposal for THE FORUM ON ALTERNATIVE TANK VESSEL DESIGN, sponsored by the American Petroleum institute on June 5, 1990.

"EFFECTIVENESS OF DOUBLE BOTTOMS IN PREVENTING OIL OUTFLOW FROM TANKER BOTTOM DAMAGE INCIDENTS" by James C. Card, Lt.Commander USCG, Marine Technology, January, 1975.

National Transportation Safety Board: Exhibit No. 4M Docket No. DCA 89 MM 040, "LOAD SUMMARY/LOADING DETAIL", and Exhibit No. 4S, "SOUNDINGS @ GROUNDING SITE".

American Bureau of Shipping Report No. PO8963 dated April 19, 1989.

"RULES FOR BUILDING AND CLASSING STEEL VESSELS, 1986", published by the American Bureau of Shipping.

Russel Brierly & Associates, Inc. Survey report No. 257289, dated January 15, 1990.

United States Coast Guard memorandum on double bottom designs dated 25 May, 1989.

"EXXON VALDEZ HULL DAMAGE ASSESSMENT", prepared by J.H. Leitz & Associates, Inc.

Many other papers, books and publications were reviewed in preparing this study, but no data from them was used in this study.

The following data were found in the EXXON VALDEZ loading computer printout (National Transportation Safety Board, "Load Summary/Loading detail", Exhibit 4M, Docket No. DCA 89 MM 040), and are considered to be applicable at the time of the incident.

Cargo Specific Gravity: .873

Drafts:	Forward:	56.02 feet
	Midship:	56.32 feet
	Aft:	56.58 feet

Displacement: 207,256.20 long tons

Cargo tank capacities:

Tank No.	Capacity 98% in barrels
1C	152,987
1P	67,671
1S	67,671
2C	196,740
3C	216,414
3P	119,772
3S	119,772
4C	118,044
5C	210,519
5P	74,102
5S	74,102

Ship light weight: 28,822 long tons

The following data was taken from the NTSB report, Appendix F:

High water on the night of the grounding at Rocky Point, 6.3 miles from the accident site: 0155 hours at 12.5 feet above mean low water. Tide at 0004 hours, 10.1 feet above mean low water. Low tide at 0811 hours at 0.0 feet above mean low water.

The National Safety Transportation Board report No. PB90-916495 (Page 27) lists the following amounts for cargo lost (for completeness cargo amounts for undamaged tanks are also included):

BARRELS OF CARGO LOST FROM DAMAGED TANKS

Tank No.	Cargo dep. Valdez	Cargo after grounding	Cargo loss
1C	136,061	82,870	53,191
1P	60,159	60,159	0
1S	60,257	36,552	23,705
2C	172,095	111,092	61,003
3C	189,441	124,200	65,241
3P	107,085	107,085	0
3S	107,107	62,397	44,710
4C	79,051	70,910	8,141
5C	173,132	124,490	48,642
5P	61,942	61,942	0
5S	61,978	44,790	17,188

Total barrels lost from damaged tanks: 321,821

BARRELS OF CARGO GAINED IN DAMAGED BALLAST TANKS

Tanks	Cargo gained
Forepeak	30,428
No. 2 Starboard tank	65,645
No. 4 Starboard tank	935
Total barrels gained:	97,008

Net Loss   224,813 Barrels (by March 25, 1989)

These amounts are used for the purposes of this study, as far as the losses in cargo tanks are concerned. However, EXXON calculated that the total amount lost was 258,000 barrels. As far as the total amount is concerned, the EXXON number appears to be realistic, since the amounts of cargo gained in the ballast tanks as listed in the NTSB report appears to be high.

The amount of cargo lost will be further discussed in the "RECONSTRUCTION OF THE "EXXON VALDEZ" GROUNDING PROCESS" section.

Maximum height of bottom upsets (distortions) in the various tanks are listed in Messrs. Russell Brierly & Associates, Inc.'s report No. 257289, dated January 15, 1990. These measurements were taken in drydock on August 15, 1989 and subsequent dates at National Steel and Shipbuilding Company in San Diego, CA, and are as follows, with the maximum vertical damage heights as reported in the NTSB report listed next to them:

	MAX BOTTOM UPSET	MAX. DAM. HEIGHT
Forepeak tank	24"	
No. 1 Starboard	54"	131"
No. 1 Center	30"	
No. 1 Port	0"	0"
No. 2 Starboard	72"	180"
No. 2 Center	12"	132"
No. 2 Port	0"	0"
No. 3 Starboard	78"	119"
No. 3 Center	54"	108"
No. 4 Starboard	6"	
No. 4 Center	18"	
No. 5 Center	18"	
No. 5 Starboard	18"	

For the tanks where no specific maximum damage height was noted the damage ranged from less than 1 foot to 8 feet in height according to the NSTB report.

Figure 8 is copied from the NTSB study and indicates which cargo tanks were damaged, and shows a rough outline of the damages superimposed on the vessel's plan view. The damage heights noted in the diagram by NTSB apparently do not exactly agree with the damage heights noted in the NTSB written report. We have no explanation for this apparent discrepancy.

In addition to the foregoing, the height from the ship's bottom to the top of the large rock embedded in the hull at frame 10 was measured by Mr. Harrison of Messrs. Russell Brierly & Associates, Inc.and found to be 80".
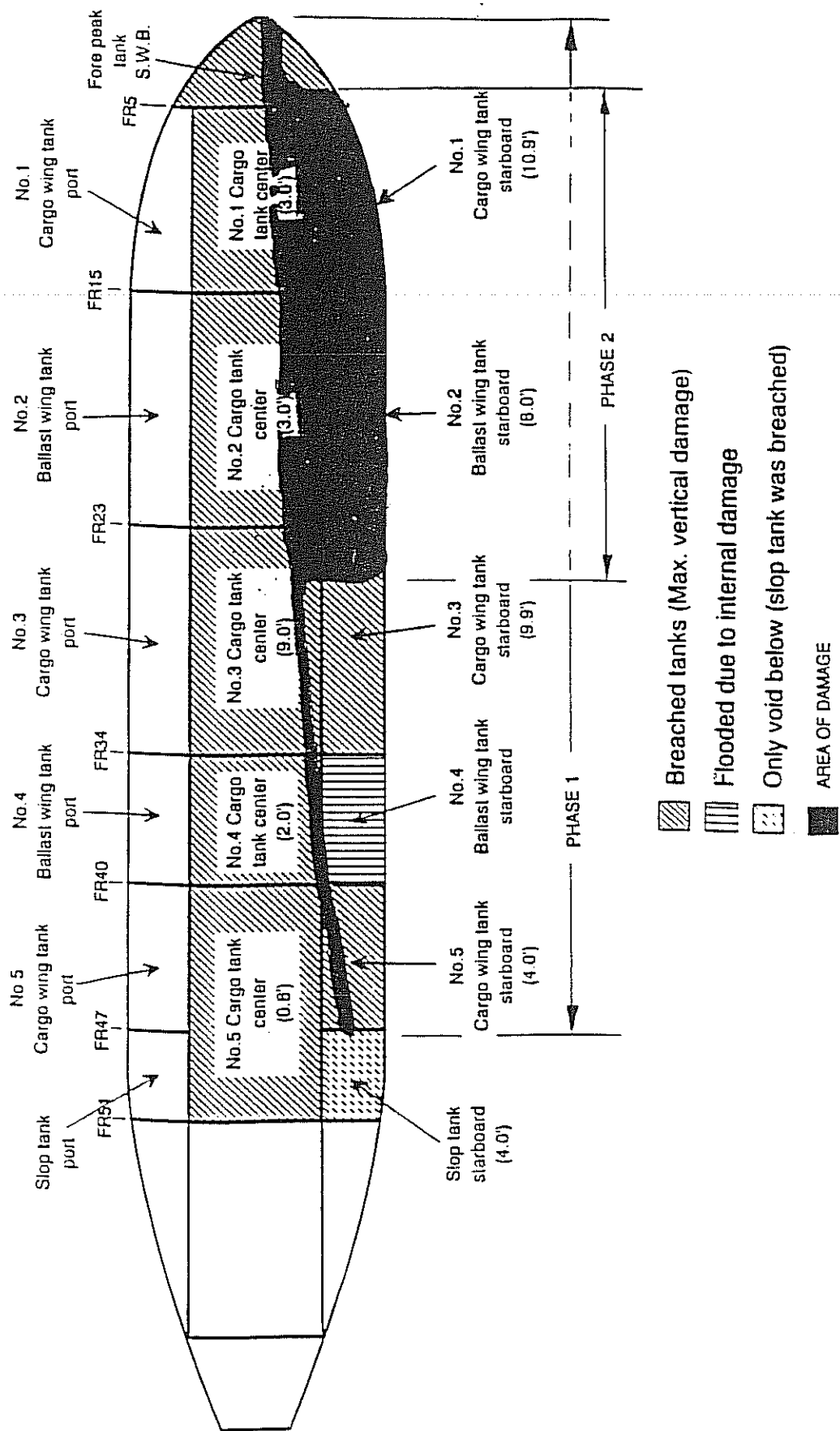
FIGURE 8: PLAN VIEW SHOWING DAMAGED TANKS ON THE MT "EXXON VALDEZ".

Legend:
- Breached tanks (Max. vertical damage)
- Flooded due to internal damage
- Only void below (slop tank was breached)
- AREA OF DAMAGE

Labels:
- Fore peak tank S.W.B.
- FR5
- No.1 Cargo wing tank port
- No.1 Cargo tank center (3.0')
- No.1 Cargo wing tank starboard (10.9')
- FR15
- No.2 Ballast wing tank port
- No.2 Cargo tank center (3.0')
- No.2 Ballast wing tank starboard (8.0')
- PHASE 2
- FR23
- No.3 Cargo wing tank port
- No.3 Cargo tank center (9.0')
- No.3 Cargo wing tank starboard (9.9')
- FR34
- No.4 Ballast wing tank port
- No.4 Cargo tank center (2.0')
- No.4 Ballast wing tank starboard
- PHASE 1
- FR40
- No.5 Cargo wing tank port
- No.5 Cargo tank center (0.8')
- No.5 Cargo wing tank starboard (4.0')
- FR47
- Slop tank port
- FR51
- Slop tank starboard (4.0')

GENERAL DISCUSSION OF VESSEL BEHAVIOR DURING GROUNDING:

It is exceedingly difficult to exactly predict the behavior of a vessel running aground. This difficulty stems from the fact that very small variations in calculation techniques and assumptions can result in vastly different conclusions.

One, and at this time probably the only practical, method for predicting the behavior of a vessel running aground is a time step method. The vessel's entire structure is modeled in a computer. Then a simulation is run whereby the vessel encounters an obstacle at a certain speed. The speed of the vessel determines the force exerted, at which time a structural and a dynamic/hydrostatic calculation is performed. This calculation determines the damage to the vessel's structure, and the energy dissipated through deformation and failure of structure and general movement of the vessel. The model is then updated to a new damaged shape and moved a very small amount through the obstacle, at which time a new structural and dynamic/hydrostatic calculation is performed.

The process continues until all the energy has been dissipated, and a steady state has been achieved, at which time an accounting can be made of the damage to the vessel.

After the grounding, further damage and pollution can be incurred due to tidal and wave movements of the vessel on the underwater obstruction. Calculation of such damage is very similar to the process outlined above.

The technique described above has been applied in the aerospace industry and to a lesser extent in the automotive industry. It has been applied only sporadically in the maritime industry, but is commercially available.

This technique is very useful and sufficiently accurate for straightforward collision scenarios, such as an automobile hitting a concrete wall. However, in vessel grounding scenarios this technique is only reliable if the number of unknowns can be kept to a minimum, which is not possible in the subject grounding incident due to a general lack of relevant details. An example of a damage incident which can be relatively accurately modeled is shown in the attached photograph of an old ship with a classically buckled bow damage. (Figure 9)

The following are factors which can make a time step analysis of a real life vessel grounding unreliable:

A.   Lack of knowledge of the shape of the obstruction.

B.   Lack of knowledge of the structural characteristics of the obstruction, i.e., will the obstruction break off under a certain impact, and how does this broken piece interact with the structure.

C.   Lack of knowledge of the way the vessel is responding to contact with the obstruction, i.e., will the vessel rise when it starts to impact the obstruction, or does the vessel settle due to its loss of watertight integrity and/or buoyancy.

D.   The chaotic behavior of failure in real life rather than under predetermined conditions. i.e., a
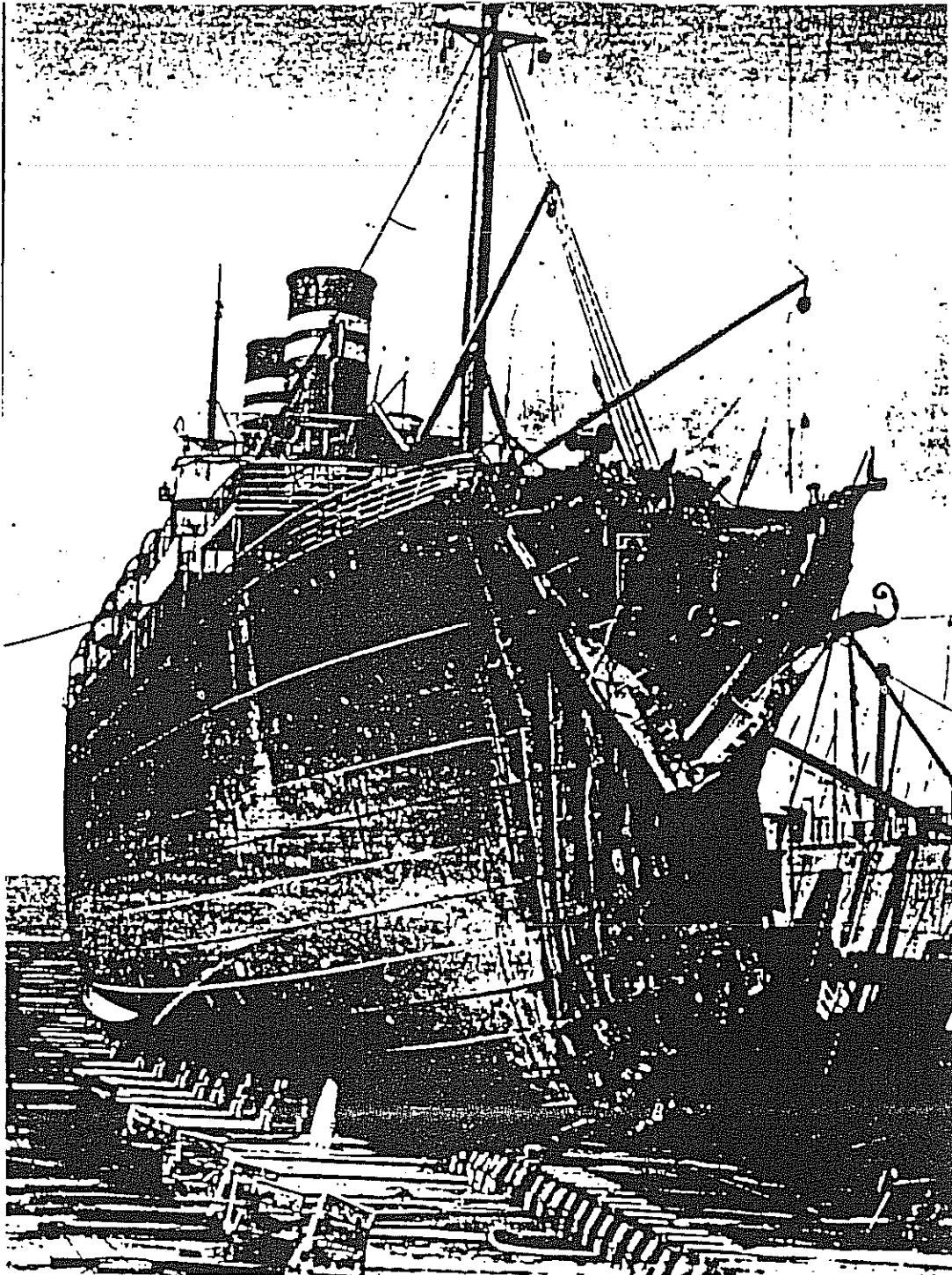
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FIGURE 9: BUCKLED BOW ON A VESSEL IN DRYDOCK.

small event can make a significant difference, such as a stiffener breaking loose and failing, but then subsequently rotating and blocking passage of the obstacle.

E. Failure behavior related to structural deterioration, i.e., the effect of a small fracture in a weld which initiates the failure of a full plate segment; something that would not have ordinarily occurred.

F. Lack of knowledge of what rudder or engine power was being used at what time during the grounding.

These limitations are not new. On numerous occasions this firm has performed grounding and collision analysis for underwriters where damages due to efforts to refloat have to be identified, or angle of blow and speed investigations have to be performed. The above limitations always make such analyses problematic.

For angle of blow and speed analysis there have been various efforts at formalizing the calculation technique, starting with Hellesoe's work in the early sixties. While these attempts were helpful in providing insight in the motions and forces involved in collisions, they are severely limited in providing exact answers. Therefore, the approach taken by most experienced surveyors is to first gather as much supporting information (log abstracts, charts, statements from witnesses) as possible, and then to carefully home in on a solution by process of elimination, estimation, intuition and experience with analogue or somewhat analogue cases.

This firm considered using a computerized time step analysis for the subject grounding, but in-depth study revealed that such an analysis is not required in this particular case. It was determined that a side-by-side comparison using the known damages to the single hull vessel was a more direct technical approach for obtaining reliable estimated cargo outflow amounts.

As far as groundings are concerned, there are quite a number of generalizations which can be reliably made.

1. The amount of time it takes for a vessel to stop on an obstacle is directly (but not necessarily proportionally) related to the amount of structural steel the obstacle encounters.

2. If sufficient structure encounters an obstacle, the obstacle could fail.

3. Once the vessel's bottom is being broached and torn rather than deformed, from a pollution point of view, it is better to have the vessel stop quickly, so the fewest number of compartments are ruptured.

4. Of all failure modes of steel, such as bending, brittle fracture, buckling, stretching or tearing, stretching and tearing are the most efficient mechanisms of dissipating energy.

5. The further away the cargo is kept from the obstacle, the less likely is the chance of the cargo being spilled.

6. The hydrostatic behavior of the vessel during and after the grounding determines to a large

extent how the vessel is affected by the obstacle. (Hydrostatics being defined as the way the vessel floats; a heavier vessel floating deeper, and a lighter vessel floating higher, and a vessel with holes having a tendency to float deeper in the water.)

7.   Flexible uniform structures are best at preventing ruptures, but in a scenario where rupturing will take place, a stiff non-uniform structure is more effective at quickly dissipating energy.

8.   Strong longitudinal bottom structures can function as skids, and make the vessel ride over damage, but are not as effective in slowing down the vessel as transverse bottom structures are.

9.   Once the damage to the cargo tanks has been determined it is reasonably possible to make an estimate of the amount of cargo spilled.

RECONSTRUCTION OF THE "EXXON VALDEZ" GROUNDING PROCESS:

Based on the information available it is possible to determine with a fair degree of certainty what took place during the short period of time between the instant that the "EXXON VALDEZ" first impacted Bligh Reef and when she came to a full stop.

The estimate of the vessel speed at the time of the first impact is based on the NTSB report statement that the vessel was placed in the "load up program" at 2352, which is about 17 minutes prior to the grounding. The "load up program" takes the vessel from her "maneuvering full ahead speed" of 11 knots at 55 rpm to her "full-ahead sea speed" at 78.9 rpm. This program takes about 43 minutes according to the report.

"Full ahead sea speed" corresponds to about 16 knots in loaded condition. (Incidentally, a photograph of the vessel maneuvering characteristics posted on the bridge shows the full ahead sea speed RPM to be 82.6 rather than 78.9.)

Consequently, the vessel was moving at a speed between about 11 and 16 knots at the time of the grounding. For the purposes of this study, the speed is estimated at 13 knots, this speed representing a constant acceleration over about 17 minutes of the 43 minute interval.

The damage to the vessel's bottom has two distinct phases, as shown in figure No. 8.

Examination of the records of the damage reveals that there is a long and relatively narrow and shallow gash which runs almost over the entire length of the vessel from the bow to frame 49 where it leaves the vessel at the starboard turn of the bilge. This gash will be called the "first damage phase".

In all likelihood this gash was caused by a single pinnacle, which quite possibly was located a fair distance from where the vessel came to rest. This pinnacle was solely responsible for the rupture of tanks No. 4C, No. 4S (ballast), No. 5C, No. 5S, and the starboard side slop tank.

The "second damage phase" is the massive damage which extends from the bow to frame 24 in the No. 3 tanks and has the shape of a tunnel, with gradual lessening of the tunnel towards frame 27. It appears that the latter phase is caused by the pinnacle on which the vessel came to rest.

Naturally the "first phase" damage is obliterated by the "second phase" damage up to frame 27, although from the transverse location of the "first phase" damage at frame 27 it would appear that the "first phase" pinnacle alone would have also holed the Nos. 1, 2, and 3 center cargo tanks.

It is not known how far in distance the "first phase" pinnacle and the "second phase" pinnacle were separated, and consequently it is hard to estimate how long it took the vessel to come to a halt from the first impact. The shortest time estimate would be by assuming that the "first phase" pinnacle was only a few feet behind the vessel once it came to rest. This means that the vessel came to rest in approximately 1000 feet (her own length). Using this assumption we arrive at an estimate of 91 seconds between the first impact and the vessel coming to a full stop, using constant deceleration.

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This time represents the minimum time between the first breech of cargo tanks and a full stop.

Another approach would be to assume that the vessel ran over the "first phase" pinnacle without losing significant speed and then to lose the majority of her momentum on the "second phase" pinnacle, which would result in a stopping time of about 36 seconds. This is a way of calculating the maximum constant deceleration that the vessel would have encountered. This deceleration is determined to be - 0.6056 ft/sec^2, or approximately 0.0188 g.

It should be noted that this deceleration is quite low , and is much less than would be experienced in a very smoothly braking automobile, and would not be sufficient to knock anybody off their feet or to cause any damage from surging liquids in the tanks.

While the "first phase" grounding caused considerable damage, in total amount of steel disturbed, it is smaller than the "second phase" damage.

It is estimated that the "first phase" disturbed about 0.49 tons of steel per foot for a total length of 740 feet, while the "second phase" disturbed about 2.53 tons of steel per foot for a total length of 396 feet.

This works out to 350 tons of deformed steel for the "first phase" and 1,000 tons for the "second phase", for a total amount of 1,350 tons.

As noted in the various reports, a tunnel about 75 feet wide, with a maximum height of about 8 feet was cut into the bottom of the vessel in way of the "second phase" damage, and a gash approximately 4 feet high and 20 feet wide was cut in way of the "first phase" damage. The frontal areas for these damages are estimated at 300 square feet and 40 feet respectively.

NASSCO in their paper on the damage repairs on the subject vessel, published in "Marine Technology" states that a total of 2635 tons of steel was renewed during the damage repairs. This amount is considerably more than the actual damaged steel since some of this steel was renewed for access, and some of the steel damages were caused while the vessel was resting on the reef, with tidal changes and wave action.

While the damage heights stated above are listed as constant over the length of the vessel, in actuality the damage heights vary for a number of reasons.

When first making contact with the reef the vessel's bow was most certainly lifted which enabled the vessel to ride over the obstacle with little puncture damage.

When the vessel moves further over the obstacle, the ground reaction increases because a greater part of the vessel is now being lifted, and at a certain moment the vessel's bottom is punctured by the obstacle and the vessel sinks back to her original draft since the ground reaction is drastically reduced.

Once the bottom is punctured the vessel's flotation starts to change, which changes the penetration depth of the obstruction into the vessel. Depending on whether a cargo tank or a ballast tank is punctured the vessel can either rise slowly, or sink quickly.

The vessel will rise slowly if a full cargo tank is punctured, and the viscous oil runs out slowly from a relatively small pressure differential, limited by the amount of air that can flow through the vent pipe.

The vessel will sink quickly if an empty ballast tank is punctured, and water floods the space from a relatively large pressure differential, limited by the amount of air that can flow through the vent pipe.

In addition, since the damage is positioned away from the centerline, the vessel will start to heel.

While all of this is taking place, in the case of the EXXON VALDEZ, the obstruction is also changing since pieces of rock are breaking off which changes the height and size of the obstruction while the vessel is passing over it.

Due to a general lack of information on the geometry of the reef, and the sequence at which the various tanks were punctured it is hard to arrive at any exact calculation of the vessel's behavior during the grounding.

Fortunately for the purposes of this study, these changes in attitude are of a minor nature as far as their effect on the final amount of damage is concerned, and can be considered from a random point of view, which will average out over the entire length of the vessel and will be comparable in both single and double bottom grounding scenarios.

Finally, once the vessel comes to rest, the action of waves and tide and possible progressive loss of flotation will force the obstruction deeper into the vessel. It is at the point where the vessel rests on the reef that one expects to see the deepest penetration into the hull if one ignores deformation of the obstruction while the vessel is moving.

With a hole in the bottom, not all the cargo in a ruptured tank flows out into the sea. From a physical point of view cargo will flow out of the tank until the hydrostatic pressure between the column of oil inside the tank, and the column of water outside the tank has been equalized. Figure 10 illustrates that principle.

In addition, some of the cargo in the ruptured tanks adjacent to a ruptured ballast tank might flow through the holed common bulkhead into the ballast tank and stay there until salvaged.

In the case of the "EXXON VALDEZ", the National Safety Transportation Board report states that 224,813 barrels of oil spilled out of the vessel as measured on March 25, 1989. This amounts to 42 * 224,813 = 9,442,146 gallons, or 9,442,146 / 7.4805 = 1,262,234 cubic feet of oil.

At a later time EXXON calculated that the total of lost cargo was about 258,000 barrels.

Figure 11 illustrates the oil outflow calculations performed by this office. The vessel went aground at a draft of 56.29 feet, near high tide. The tidal range in the Prince William sound is approximately 10 feet. Any tank which is ruptured will empty to a level of about 54.35 feet based on hydrostatic equivalency at low tide as shown in Figure 10. In this calculation it is assumed that the vessel is on an even keel.
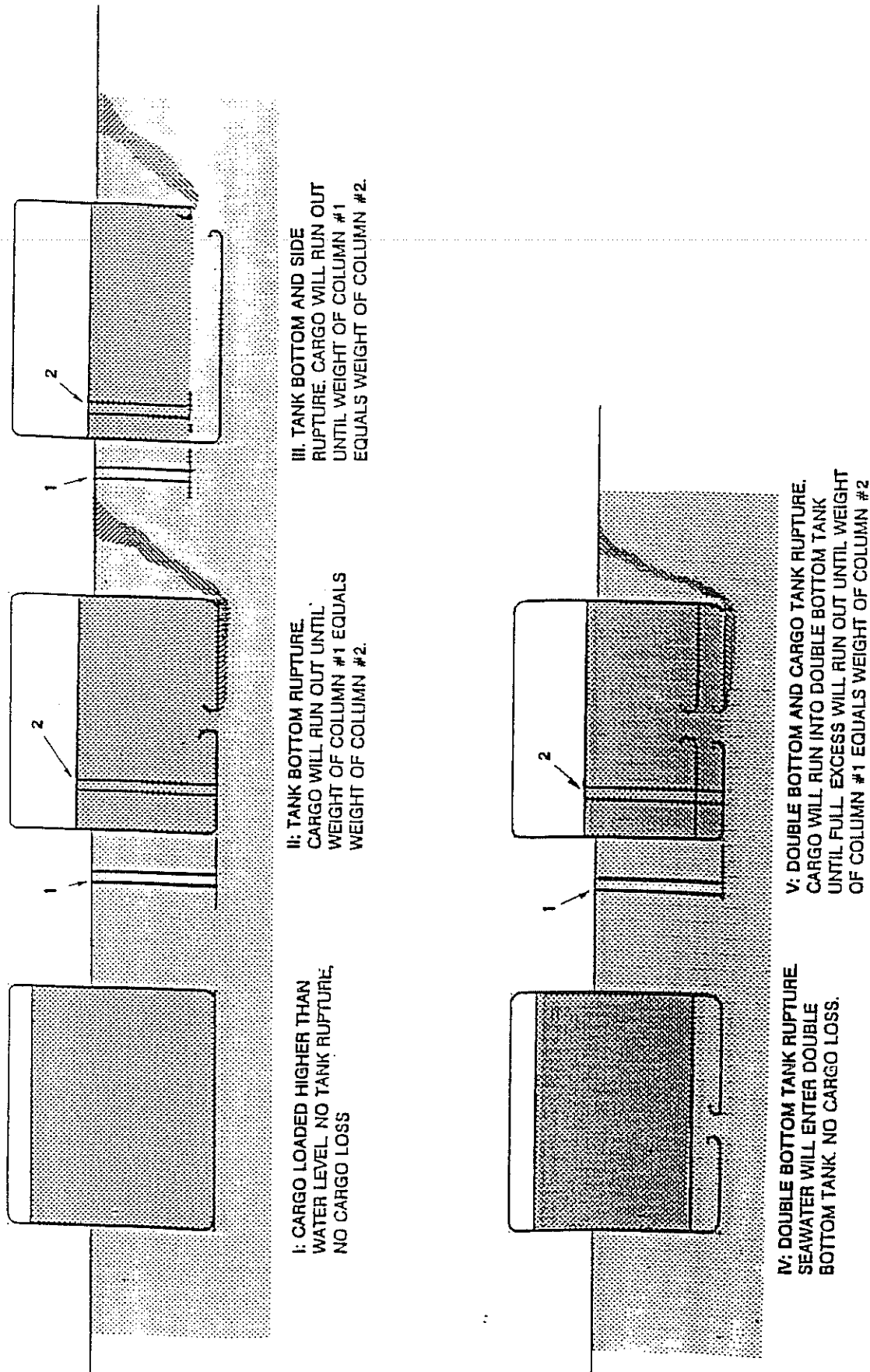
I: CARGO LOADED HIGHER THAN
WATER LEVEL. NO TANK RUPTURE,
NO CARGO LOSS

II: TANK BOTTOM RUPTURE.
CARGO WILL RUN OUT UNTIL
WEIGHT OF COLUMN #1 EQUALS
WEIGHT OF COLUMN #2.

III. TANK BOTTOM AND SIDE
RUPTURE. CARGO WILL RUN OUT
UNTIL WEIGHT OF COLUMN #1
EQUALS WEIGHT OF COLUMN #2.

IV: DOUBLE BOTTOM TANK RUPTURE.
SEAWATER WILL ENTER DOUBLE
BOTTOM TANK. NO CARGO LOSS.

V: DOUBLE BOTTOM AND CARGO TANK RUPTURE.
CARGO WILL RUN INTO DOUBLE BOTTOM TANK
UNTIL FULL EXCESS WILL RUN OUT UNTIL WEIGHT
OF COLUMN #1 EQUALS WEIGHT OF COLUMN #2

FIGURE 10: EXPLANATION OF CARGO OIL LEVEL IN A GROUNDED TANKER WITH RUPTURED
TANKS.

LEVEL AND VOLUME COMPARISON OF EXXON VALDEZ CARGO LOSSES

. . . .

SEAWATER SPECIFIC GRAVITY	1.03	
CARGO SPECIFIC DENSITY	.87	
VESSEL DRAFT	56.29	FEET
DROP OF TIDE AFTER GROUNDING	10	FEET
CARGO HEIGHT AFTER GROUNDING	54.35	

	CAPACITY 98%	CAP/FT	CARGO @ GROUNDING	CARGO HGT ABV. KEEL	CARGO LOSS AFT. GND	REPORTED CAR LOSS	CAR HGT NSTB
FORE PEAK	41259	478.42	0			-30428	63.60
1C	152987	1773.97	135923	76.62	39508.45	53191	46.64
1P	67671	784.68	60160	76.67	0	0	76.67
1S	67671	784.68	60246	76.78	17598.79	23705	46.57
2C	196740	2281.31	171510	75.18	47521.70	61003	48.44
2P BALLAST	108624	1259.55	0	0		0	0
2S BALLAST	108624	1259.55	0	0		-65645	52.12
3C	216414	2509.44	189420	75.48	53032.86	65241	49.48
3P	119772	1388.82	107085	77.10		0	77.10
3S	119772	1388.82	106958	77.01	31476.01	44710	44.82
4C	118044	1368.78	78973	57.70	4580.02	8141	51.75
4P BALLAST	65314	757.35	0	0		0	0
4S BALLAST	65314	757.35	0	0		-935	1.23
5C	210519	2441.08	172769	70.78	40096.98	48642	50.85
5P	74102	859.25	61942	72.09		0	72.09
5S	74102	859.25	62007	72.16	15306.88	17188	52.16
			1206993		249121.68	224813	

EXXON REPORTED LOSS: 258000 BARRELS

FIGURE 11: CARGO OUTFLOW CALCULATIONS ON THE MT "EXXON VALDEZ"

In actuality the tanks will empty to a somewhat lower level due to wave action which has a mixing and pumping effect on the tanks. In addition, the change of heel and trim of the vessel due to changes in tide will also variously influence the level of cargo in each tank.

In Figure 11 when comparing "CARGO HEIGHT AFTER GROUNDING", which shows the calculated cargo height after the vessel grounded, and the column marked "CARGO HEIGHT NTSB", which shows the cargo height as derived from the NTSB report there are significant differences.

The cargo heights in the forward tanks are significantly lower (meaning the cargo loss is higher) than the calculated value, while cargo heights in the aft tanks are only marginally lower than the calculated value.

This trend can be explained for two reasons. First the vessel probably rotates about the end of the No. 2 tanks (frame 23, where she is hung up on the reef), which with lowering tides causes the stern to settle, thereby keeping the hydrostatic pressure in the aft tanks higher. Secondly, the openings in the forward tanks generally were larger than the openings in the aft tanks, allowing easier mixing and pumping action due to waves.

Also, when trimming by the stern when the tide goes down, additional amounts of oil will escape from under the bow due to uneven levels of fluid in each tank. (See figure 12)

In general, the amounts lost from each cargo tank are considered to be reasonable and realistic, and the differences found between the calculated level, and the actual levels will be similarly applied to the oil outflow calculations in the double bottom grounding simulation.

While the levels of oil in the cargo tanks appear to be realistic, the amounts of oil which ended up in the ballast tanks as noted in the NTSB report are much higher than would be expected.

Especially the amount of oil in the forepeak is unrealistically high since the amount of oil reportedly contained in this tank would result in a cargo height of 63.60 feet, which is significantly higher than the calculated level of 54.35 feet. (this calculated level is quite approximate due to the irregular shape of the tank). Since this tank is similarly holed as the No. 1C tank, the cargo height should be approximately the same as this tank (46.64 feet), and actually will be somewhat less due to the fact that this tank collects a mixture of oil and water.

The same argument applies for the No. 2S ballast tank which also has a cargo height which is higher than the comparable tanks.
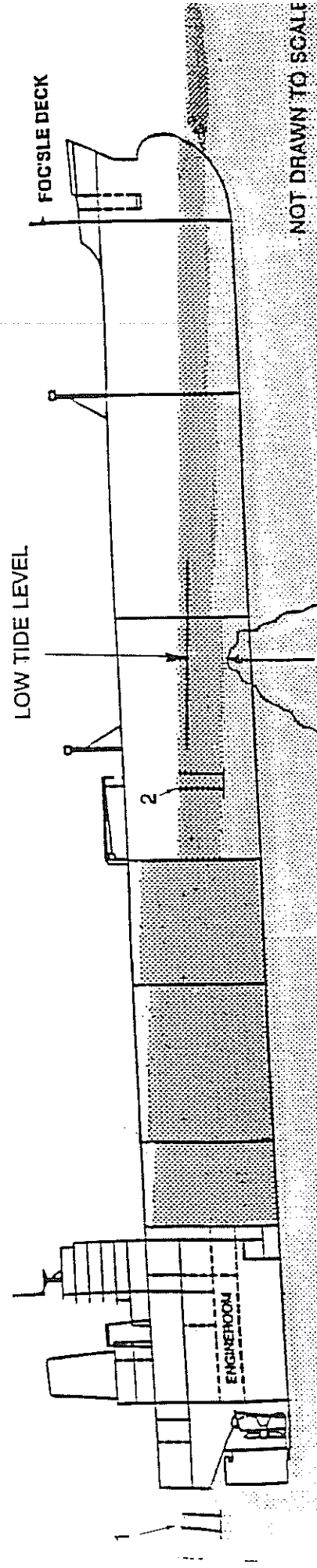
It is not entirely clear where the amount of cargo recovered in the ballast tanks as listed in the NTSB report came from, but these amounts should be lower.

In the same report, it is noted that EXXON states a total amount of 250,000 barrels lost.

It appears that this EXXON amount of 258,000 barrels is quite realistic when assuming that the amount of oil recovered in the ballast tanks is lower than reported by about 34,000 barrels while the actual amounts of cargo left in the cargo tanks is close to what is listed in the NTSB report.

TIDE LEVEL AT TIME OF GROUNDING

FOC'SLE DECK
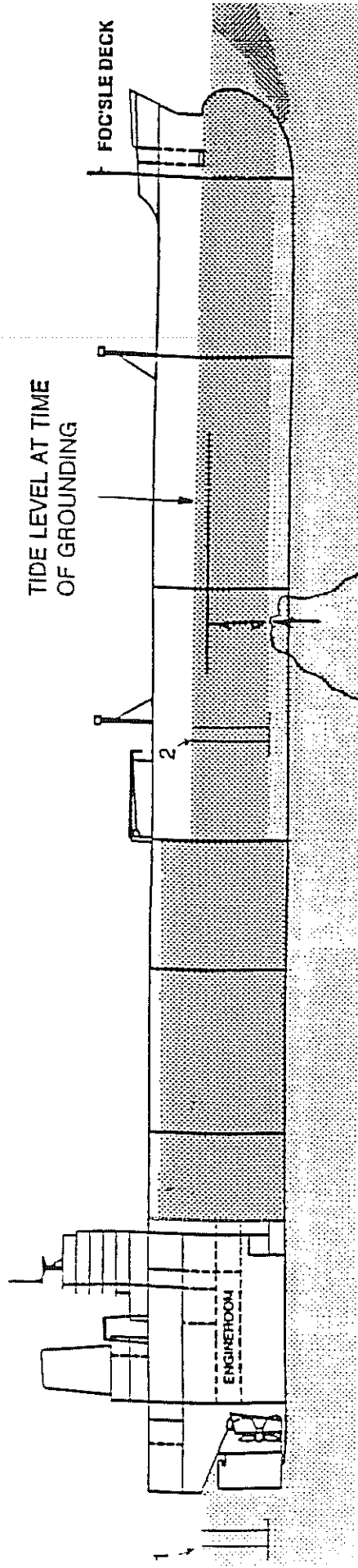
VESSEL GROUNDS AT EVEN KEEL AND OIL FLOWS OUT UNTIL WEIGHT OF COLUMN #1 EQUALS WEIGHT OF COLUMN #2

LOW TIDE LEVEL

FOC'SLE DECK

NOT DRAWN TO SCALE

TIDE GOES DOWN AND VESSEL TRIMS BY STERN THEREBY RAISING BOW CAUSING ADDITIONAL CARGO TO FLOW OUT UNTIL WEIGHTS OF CARGO COLUMNS EQUALS WEIGHTS OF SEAWATER COLUMNS

FIGURE 12: EXPLANATION OF CARGO OUTFLOW ON A GROUNDED VESSEL WITH RUPTURED TANKS, AND TRIM BY THE STERN.

DEVELOPMENT OF THE EQUIVALENT DOUBLE BOTTOM TANKER GROUNDING PROCESS:

Since the double bottom equivalent vessel has been purposely kept identical in size and draft, the initial conditions of the grounding are the same in that the amount of energy present in the system is the same as the "EXXON VALDEZ".

For the sake of clarity it is noted that the double bottom tanker is the equivalent tanker with the 8 foot 1 inch double bottom as developed earlier in this report.

Just like the single skin tanker, the double bottom equivalent will encounter the "first phase" pinnacle. This pinnacle will tear through the bottom in the same fashion as the single skin tanker, resulting in ruptured double bottom tanks underneath the same cargo tanks as the single skin vessel.

Since the damages inflicted by the "first phase" pinnacle are no higher than 4 feet from the bottom, based on this firm's experience with numerous double bottom damages, it can be stated with certainty that none of the cargo tanks will be ruptured by the "first phase" damage.

The double bottom ballast tanks and the forepeak tank, on the other hand, will be ruptured over the entire length and width of the vessel, and seawater will rapidly fill these tanks.

The forepeak tank will fill at exactly the same speed as the ruptured forepeak tank of the "EXXON VALDEZ", causing the same incremental change in flotation when impacting the "first phase" pinnacle.

Each ruptured double bottom tank will fill with about 5.2 feet of water within seconds after the tank is punctured. This type of flooding is only restricted by the area of the punctures, which in this case are quite large, and results in compression of the air in the double bottom tanks. Further flooding of the double bottom tanks takes considerably longer since such flooding is restricted by the amount of air which can escape from the vent pipes.

Consequently, by the time the vessel encounters the "phase two" pinnacle she will have settled approximately 5 feet by the bow and stern, regardless of the distance between the "first phase" pinnacle and the "second phase" pinnacle (unless the "first phase" pinnacle was, say, more than 15 minutes away, in which case the double bottom tanks could flood completely, but this is unlikely).

Once the vessel encounters the "second phase" pinnacle she will make contact with this pinnacle a few feet further forward along the hull than the single skin tanker, since she is deeper in the water and, therefore, will strike first higher on the hull, which at that point of the hull is also further forward.

At this stage of the grounding, the vessel will drive itself onto the pinnacle until all her energy is dissipated. Since the vessel is deeper in the water than the single hull vessel, the damage pattern will change.

While the actual damage pattern cannot be determined due to the fact that the shape of the pinnacle is not known, the damage pattern which was found on the single skin vessel due to resting on

the bottom, would indicate that damage over a considerably greater width would take place, particularly on the starboard side.

Close examination of the damage pattern on the "EXXON VALDEZ" indicates that the damage would extend over about 30% greater width. The vessel will keep moving over the reef until the kinetic energy has been dissipated. Assuming that each pound of deformed steel absorbs as much energy in the single skin grounding as the double skin collision (a very conservative estimate since the double skin is structurally more stable and therefore absorbs more energy per pound of steel structure), the vessel will come to rest once 1000 tons of steel have been deformed (1350 tons - 350 tons which were deformed in phase 1).

It is calculated that 1000 tons of steel will have been deformed once a 222 feet long swath has been cut in the vessel over a width of 97.5 feet. This places the damage around frame 19 or 20, which in the 8 foot double bottom configuration, will be in way of the No. 2 tanks, where the after part of the No. 2S tank is a ballast tank.

Figure 13 shows the arrangement of the 8 foot double bottom equivalent design with the damage superimposed.

It can be seen from this figure that the damaged tanks will be tanks Nos. 1C, 1S, 2C, 2SA and 2SB.

The vessel will be resting on the reef with her fulcrum at about frame 18, and when the tide goes down will take on a significant stern down attitude. As compared with the "EXXON VALDEZ", the double bottom equivalent vessel will be resting on the reef with a greater draft due to the fact that she impacted the "phase two" pinnacle with flooded double bottom tanks.

Figure 14 shows the cargo arrangement in the 8 foot double bottom equivalent vessel, where the cargo is arranged to get the same longitudinal center of gravity as the "EXXON VALDEZ", while keeping the free surface effect to a minimum.

Figure 15 shows the cargo outflow calculation for the 8 foot double bottom equivalent vessel using the same assumptions as those used in the "EXXON VALDEZ" cargo outflow calculations (Figure 11).

In this calculation hydrostatic equivalency at low tide is applied and the margins between the calculated cargo level (ignoring waves and trim) and the actual cargo level in each "EXXON VALDEZ" tank is superimposed.

It is assumed that amounts of cargo similar to those amounts encountered in the "EXXON VALDEZ" were retained in each ruptured ballast tank.

No allowance was made for containment of cargo in the double bottom structure. While it is possible that a significant amount of cargo was retained in the double bottom structure, no meaningful calculations can be easily performed to quantify that amount, and therefore none is considered in the amount stated below.
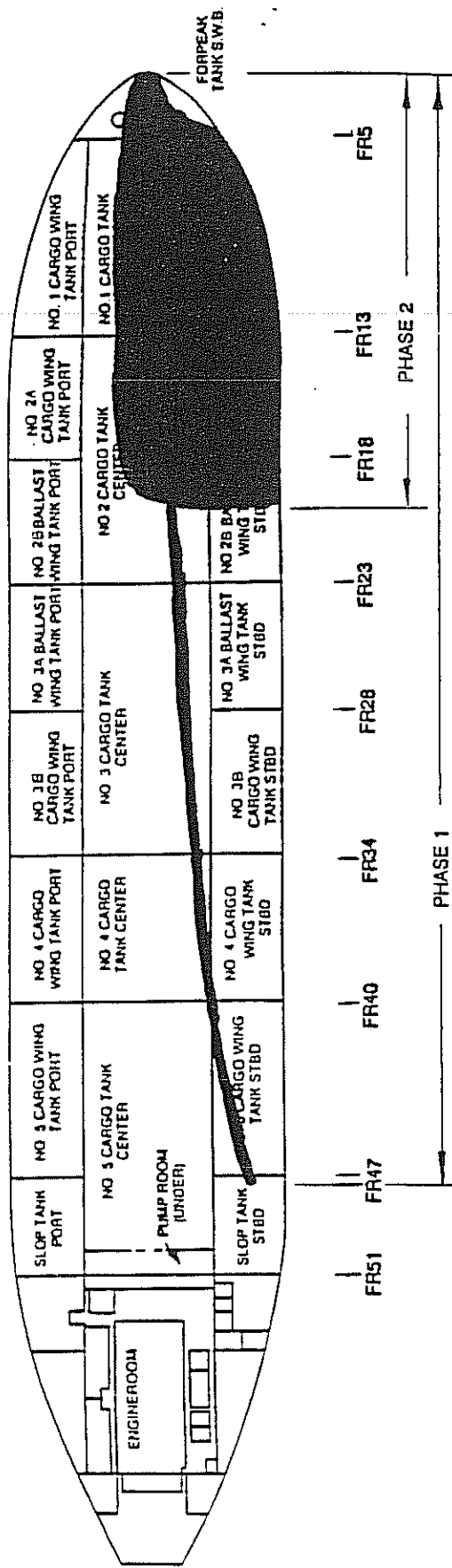
FIGURE 13: PLAN VIEW SHOWING DAMAGED TANKS ON THE 8 FOOT EQUIVALENT DOUBLE BOTTOM TANKER.

TANK	BETWEEN FRAMES	WEIGHT L. TONS 100% CAP 41.464 CUFT/TON	CARGO ON BOARD WEIGHT L. TONS 41.464 CUFT/TON	PERCENT FULL	DISTANCE FROM BASE LINE TO TOP OF CARGO
1 CNTR	5-13	19192.34	18808.5	98.00%	86.40
2 CNTR	13-23	24751.25	24256.2	98.00%	86.40
3 CNTR	23-24	27226.39	26681.9	98.00%	86.40
4 CNTR	34-40	14850.76	14553.7	98.00%	86.40
5 CNTR	40-51	26411.71	25883.5	98.00%	86.40
1 WING P	5-13	9005.72	8825.6	98.00%	86.40
1 WING S	5-13	9005.72	8825.6	98.00%	86.40
2A WING P	13-18	6919.18	4372.5	63.19%	58.58
2A WING S	13-18	6919.18	4372.5	63.19%	58.58
3B WING P	28-34	7978.73	5436.0	68.13%	62.53
3B WING S	28-34	7978.73	5436.0	68.13%	62.53
4 WING P	34-40	8263.34	0	.00%	0
4 WING S	34-40	8263.34	0	.00%	0
5 WING P	40-47	9541.07	9350.3	98.00%	86.40
5 WING S	40-47	9541.07	9350.3	98.00%	86.40
SLOP P	47-51	4631.25	4538.6	98.00%	86.40
SLOP S	47-51	4631.25	4538.6	98.00%	86.40
		205111.01	175229.74		

FIGURE 14: CARGO ARRANGEMENT ON THE 8 FOOT EQUIVALENT DOUBLE BOTTOM TANKER.

LEVEL AND VOLUME COMPARISON OF 8 FEET EQUIVALENT DB TANKER LOSSES

SEAWATER SPECIFIC GRAVITY	1.03
CARGO SPECIFIC DENSITY	.87
VESSEL DRAFT, PLUS 5.27 FT	61.56 FEET
DROP OF TIDE AFTER GROUNDING	10 FEET
CARGO HEIGHT AFTER GROUNDING	60.54 FEET

	CAPACITY 98%	CAP/FT	CARGO 8 GROUNDING	CARGO HGT ABV. KEEL	TRIM/WAVE LOSS	CARGO LOSS AFT. GND
FORE PEAK	41259	478.42	0			-20000
1C	138901	1776.14	138901	86.40	8	60144.91
1P	65177	833.42	65177	86.40		0
1S	65177	833.42	65177	86.40	8	28222.01
2C	179132	2290.57	179132	86.40	6	72984.02
2AP	50076	640.33	32291	58.58		0
2AS	50076	640.33	32291	58.58	5	1948.36
2BP BALLAST	50076	640.33				0
2BS BALLAST	50076	640.33				-10000
3C	197046	2519.64	197046	86.40		0
3AP BALLAST	50076	640.33				0
3AS BALLAST	50076	640.33				0
3BP	57744	738.38	40145	62.53		0
3BS	57744	738.38	40145	62.53		0
4C	107479	1374.34	107479	86.40		0
4P	59804	764.72	0	0		0
4S	59804	764.72	0	0		0
5C	191149	2444.24	191149	86.40		0
5P	69052	882.97	69052	86.40		0
5S	69052	882.97	69052	86.40		0

CARGO ON BOARD: 1227037 BARRELS

TOTAL CARGO LOST: 133299.30 BARRELS
EXXON REPORTED LOSS: 258000 BARRELS
REDUCTION IN OUTFLOW WITH A DOUBLE BOTTOM: 124700.70 BARRELS
OUTFLOW IS   48.33 % LESS WITH A DOUBLE BOTTOM

FIGURE 15: CARGO OUTFLOW CALCULATIONS ON THE 8 FOOT EQUIVALENT DOUBLE BOTTOM TANKER.

Figure 15 shows that approximately 48% less cargo would have spilled if the "EXXON VALDEZ" had been fitted with double bottoms as used in this report.

In summarizing, the double bottom grounding differs from the single skin grounding in that the first phase pinnacle did not rupture any cargo tanks, but caused the double bottom vessel to increase her draft.

When impacting the second phase pinnacle, the double bottom vessel struck at greater draft, which together with her more massive bottom structure caused her to come to a rest before the No. 3 cargo section was punctured, thereby reducing the number of ruptured cargo tanks from 8 to 4.

CONCLUSION:

This study was performed incorporating published information, discussions with colleagues familiar with the aspects dealt with in this study, and multiple parametric and analytical approaches, in order to embrace the widest realistic scope.

The results developed from this work are considered to be an opinion based on rigorous evaluation, and in this regard it can be stated with certainty that a vessel equivalent to the "EXXON VALDEZ", but fitted with a traditional double bottom would have released significantly less oil than the "EXXON VALDEZ".

Furthermore, it can be stated safely, based on the work performed by this office, that the amount of oil spilled from a tanker equivalent to the "EXXON VALDEZ", but fitted with a double bottom would have been less than 133,299 barrels as compared to 258,000 barrels which spilled into the environment from the EXXON VALDEZ on March 24, 1989.

In arriving at this conclusion, the following conservative assumptions were made:
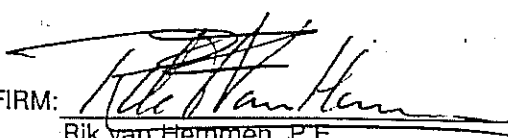
1. The equivalent vessel had the same beam and depth as the "EXXON VALDEZ", while it appears that a somewhat shallower vessel would have been a more suitable double bottom alternative to the "EXXON VALDEZ".

2. The same amount of energy per ton of bottom structure gets dissipated by a single skin tanker as by a double skin tanker, while it is expected that a double skin structure can absorb greater amounts of energy.

3. The same amount of cargo is assumed to have been lost by wind and wave action and tidal changes, while the containment characteristics of the breached double bottom structure would make it likely that less cargo would spill out due to wind and wave action.

4. It is assumed that no cargo was contained in the double bottom structure.

5. The same amount of cargo loss due to vessel trim was assumed, while preliminary estimates would indicate that the double hull vessel developed less bow up trim due to the more forward location of the fulcrum point.

6. Under all circumstances, an effort was made to locate tanks and cargo in the 8 foot equivalent double bottom tanker in a manner which does not specifically favor the reduction in cargo outflow. In other words, at many times it would have been possible to choose a configuration which would reduce cargo outflow, but these were discarded in order to avoid criticism on skewing this investigation.

7. Various calculations were performed based on assumptions. These assumptions were purposely made in such a way that they would be more likely to underestimate the effectiveness of double bottoms than overestimate the effectiveness of double bottoms.

Based on the above argument and the amount shown above, it is expected that in actuality the amount spilled would be less.

Based purely on the firm's prior experience, and qualitative knowledge developed during this study, it is possible that the amount spilled would have been as low as 90,000 barrels.

At the same time, it can also be stated with certainty that as long as a double hull vessel equivalent to and with the same draft as the "EXXON VALDEZ", would have grounded on Bligh Reef the same way as the "EXXON VALDEZ", some rupturing of cargo tanks would have taken place.

FOR THE FIRM: _____
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