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THE ISOLATION OF OIL AND OTHER FLUIDS IN TANKERS FROM SEAWATER BALLAST USING IMPERMEABLE MEMBRANES.

Massachusetts Institute of Technology

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THE ISOLATION OF OIL AND OTHER FLUIDS IN TANKERS FROM SEAWATER BALLAST USING IMPERMEABLE MEMBRANES

BY

DEPARTMENT OF OCEAN ENGINEERING

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Cambridge, Mass. 02139

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13. ABSTRACT

This report investigates the feasibility of using impermeable membranes to permit the dual purpose use of cargo tanks in commercial vessels as clean water ballast tanks. Both engineering and economic assessments were made of the membrane method of isolating cargo and ballast in a common tank. The investigation included model tests, membrane material studies, ship structural analysis and a patent search of related membrane applications. Both new and converted existing tankers were considered in the study. Conversion costs and percentage increases in required freight rates are given. Additionally, the cost effectiveness in terms of dollars per cubic meter of operational and accidental pollution prevented are reported.

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Final Report, Vol. 1

Report No. 72-22

by

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1. SUMMARY

The study of the isolation of oil from seawater ballast in tankers using impermeable membranes is reported herein. This study is one of nine studies agreed upon at the 10th meeting of the subcommittee on Marine Pollution, as described in OP x/WP9.

The proposed use of membranes in large tanks required an engineering feasibility analysis to be conducted in addition to the design and economic investigation. The feasibility of utilizing membranes in dual-purpose, cargo and ballast water, tanks was investigated in the following areas:

1. Model tests using a 1/20 scale model tank.
2. Membrane material studies.
3. Ship structural analysis of special features of tanks fitted with membranes.
4. Patent search of related membrane applications.

The design and economic studies of the utilization of the membrane system were made for new and converted existing tankers of 250,000 and 50,000 DWT. The new tankers had double bottoms under all the cargo tanks to conform to the IMCO oil outflow and damage definitions, i.e., double bottom height equal to 1/15 of the beam. The dual purpose membrane tanks were also designed to have double deck arrangements.

The conversion designs of existing tankers included the provision of double decks and double bottoms in the dual

purpose tanks and the removal or covering of internal structure with plate.

The description of the preferred membrane arrangement for tankers is presented in Chapter 3 of this report and the principal design and economic features are tabulated at the end of the chapter.

The engineering study indicated that the use of membranes to isolate the oil cargo from the seawater ballast was feasible. Certain design and operational features, such as the use of inert gas, are necessary to provide a reliable system.

The study shows that there is a price that will have to be paid for the prevention of oil pollution. For a new 250,000 DWT tanker the introduction of membranes into the tanker will increase the shipbuilding cost by about 6-7%, and increase the required freight rate by about 5-6%. The predicted cost of reducing oil pollution due to operational discharges and outflows from accidents is 1,000-1,250 dollars per m^3.

The costs of conversion of existing tankers obviously depends on tanker being converted. In the cases examined the predicted prices for conversion were about 5-6% of the cost of new tankers. The increase in the required freight rate varied from 4% for the 50,000 DWT tanker to 10% for the 250,000 DWT tanker. In the latter case the capacity of the tanker was reduced by the conversion to accept membranes.

2. INTRODUCTION

The investigation described in this report was conducted in response to a request from the Sub-Committee on Marine Pollution of the Inter-Governmental Maritime Consultative Organization (ref. 2.1) for the "study of dual purpose tanks with means to isolate oil or noxious materials from water". This and other studies have been conducted to evaluate various methods of achieving the complete elimination of the intentional pollution of the sea by oil.

The dual purpose tanks of this study are the cargo ballast tanks in tankers, and the method of isolation examined is by means of flexible impermeable membranes. The cargo would be carried on one side of the impermeable membrane while ballast water would be carried, during the return passage to the loading port, on the other side of the membrane. Such an arrangement would prevent contact between the ballast water and the oil clingage. New tankers would be specially designed to accommodate membranes and existing tankers would be converted to accept membranes.

The idea of providing flexible containers is not new. The Dracone, a flexible rubber barge, was designed in 1957. Tank linings and membrane separators have been proposed for several modes of transportation and many patents have been granted. Some relevant patents are discussed in Chapter 4 of this report.

What is new in the proposed application of membranes is the size of the tank and its geometrical features compared with the other modes of transportation.

The number of tanks in any tanker that would be fitted with the impermeable membrane obviously depends on the tanker size and application but it is typically less than five per tanker. These special tanks can provide certain advantages to the operator because of their proposed materials of construction and other characteristics.

First, the membrane would be designed to prevent the contamination of the oceans with oily ballast water with minimum loss of cargo carrying capacity. This is the main purpose of the membrane and will not be discussed further. Secondly, the seawater corrosion effects could be reduced. The value of this advantage will depend upon the geometry selected, but it is expected to reduce the exposed steel in the cargo/ballast tanks by half. A third advantage of the membrane system is the improved tank integrity in the event of collision or grounding. This advantage also depends on the selected membrane geometry, but it would be expected to provide an additional barrier to cargo leakage in a proportion of collisions or groundings of tankers. The membrane material selected would be very tough and tear resistant and would undoubtedly survive the tank rupture in many instances.

Offsetting the above advantages of the membrane system are certain potential disadvantages. First, the possibility of the membrane preventing the complete filling or emptying of the cargo. For example, should the membrane foul the suction during cargo discharge there would undoubtedly be great difficulty freeing the membrane to complete the discharge. Secondly, the membrane system will incur an extra cost compared with conventional tankers. However, there will be a price to pay for all methods of preventing the contamination of the ballast water with oil. The membrane might also require repeated replacement because of the lack of compatibility with the oil cargo or because of rapid wear due to abrasion in a seaway.

The purpose of the study described in this report was to examine the engineering problems associated with the membrane, including the disadvantages discussed in the previous paragraph plus any further disadvantages that the study brought into prominence. The result was an economic assessment of the system in order to evaluate the probable economic impact of the introduction of membranes into tankers.

The investigation included an assessment of elastomer materials, testing of a representative but small scale model of the proposed system, preliminary design of tankers, structural analysis, weight estimation, and cost analysis.

REFERENCES

2.1 "Draft Report to the Maritime Safety Committee", IMCO Subcommittee on Marine Pollution, A Vll/Res. 246 November 1971.

3. THE PROPOSED MEMBRANE SYSTEM FOR TANKERS

The preferred arrangement of the membrane system for tankers is described in the following pages. The system was examined for the following tankers:

1. A new 250,000 DWT tanker designed to accept membranes, designated 250-Y.*
2. A representative existing 250,000 DWT tanker modified to accept membranes, 250-Z.
3. A new 50,000 DWT tanker designed to accept membranes, 50-Y.*
4. A representative existing 50,000 DWT tanker modified to accept membranes, 50-Z.

During normal operations of a tanker the membrane in a cargo-ballast tank would move from one side of the tank to the other at the times of refilling with cargo and with ballast. In existing conventional tankers the movement of the membrane would be obstructed by the internal strengthening members, ladders, pipes, and so forth. Moreover, considerable folding of the membrane would occur at the obstructions. Repeated deep folds, particularly at or near the bottom of the tank in the region of high hydrostatic pressure, would promote large local extensions of the membrane and lead to possible splitting. It was therefore concluded early in the study that membranes could only be expected to operate successfully in tanks having

*Two structural designs of web frame were considered, Y1 of conventional design and Y2 of optimized design (see section 3.2).

smooth walls.* The new tankers and modified tankers considered in this study therefore had dual-purpose tanks designed with smooth walls and no internal structure. In modified existing tankers the internal structure would be removed or covered with plate in the dual-purpose tanks.

3.1 TANKER DESIGNS

Preliminary designs were completed for new 250,000 DWT and 50,000 DWT tankers suitable for installation of the membrane system. In addition, analyses of the conversion of representive 250,000 DWT and 50,000 DWT tankers were undertaken to determine the extent and cost of the changes required to allow the membrane system to be installed in existing tankers. The main features of the preliminary designs were the provision of smooth dual-purpose tanks free of internal structure.

Special construction was called for with the dual-purpose membrane tanks. Double bottom and double decks were required in order to provide smooth tank walls. Small brackets were found to be necessary for structural reasons at the web frame corners, and these brackets would be covered by plate to maintain smooth walls.

Membranes would only be fitted in the center tanks because of the complexity of the structure in the wing tanks. Furthermore, the membranes would not be placed in adjacent tanks because the bulkhead structure could be neither removed nor efficiently covered with plate.

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*The extent to which the walls should be made smooth is being investigated in a further study.

3.1.1 The New Tanker Designs

The new tankers were designed to satisfy the IMCO recommendation (ref. 3.1) with regard to oil outflow. The sizes of the wing tanks were checked for compliance with the requirements. In addition, the double bottoms were designed for the full width and length of the tanker bottom (in the cargo area) at the recommended height. The double bottom was utilized in the designs for segregated water ballast.

The double deck was assumed over the dual-purpose membrane tanks only. The double deck space was arranged for segregated ballast.

The selection of the number, size, and position of the dual-purpose tanks was made with the aid of a ship design computer program. The various ship design features such as acceptable bending moments, reasonable tank sizes, and good trim in the full ballast condition were the criteria utilized to assess the preliminary designs of the new tankers. The maximum ballast was designed to be > 55% of the displacement which is consistent with the rules of the classification societies and the experience of tanker operators, ref. 3.2. The lines used in the study were based on the Esso Scotia 250,000 DWT and Mobil Valiant 50,000 DWT tankers. The 250,000 DWT tanker designed had 4 dual-purpose membrane tanks, and the 50,000 DWT tanker designed had 2 dual-purpose tanks.

The dimensions of the steel work in the midship section were determined using the ABS rules, ref. 3.3. The steel weight for the tanker was determined by factoring the weight of steel in the midships region of the tanker using the method described in ref. 3.4. The general characteristics of the 250,000 DWT and 50,000 DWT tankers are presented in table 3.1 and weight summaries are presented in table 3.2.

3.1.2 The Conversion of Existing Tankers

Representative 250,000 and 50,000 DWT tankers were selected for the conversion studies. The tankers selected were the Texaco Hamburg and the Mobil Valiant. The selection of the number and position of dual-purpose tanks were made on the basis of the minimum conversion cost consistent with good ship design practice. The ship design computer program was used to determine bending moment and trim in the full ballast condition. The full design ballast was taken as > 55% of the displacement as for the new tanker designs. Five ballast tanks were required.

The extent of conversion of the various center tanks necessary to provide the conditions for the membrane system depended on the design of the tanker. The deeper center deck girders would be cut back to minimize the loss in cargo space, and the reduction in strength would be compensated with the plating required to provide the smooth tank top. In some cases the swash bulkhead would be made watertight, and in other instances the bulkheads would be cut and reversed to remove the protruding structure from the dual-purpose tanks. These are all familiar operations in modern shipyards where conversion and modification are common tasks.

The sizes of the plates and stiffeners to provide smooth dual-purpose tanks were determined from the ABS rules for deep tanks, ref. 3.3.

The general characteristics of the representative 250,000 DWT and 50,000 DWT tankers are presented in table 3.1 and a summary of the modifications and resulting weight changes are given in table 3.3.

3.2 STRUCTURAL ANALYSIS

The operational requirement of smooth center tanks requires the removal of structure from the insides of the dual-purpose tanks. The dimensions of the adjacent brackets in the wing tanks were increased in order to maintain the same level of stresses as conventional tanker designs. Small web frame brackets of 2 ft. x 2 ft. were the only structural members remaining in the dual-purpose center tanks. These brackets would be covered with plates extending in the longitudinal direction in order to provide smooth walls.

3.2.1 Computer Analysis of the Structures

The removal of the internal structure in the membrane tanks poses structural problems to the designer. The new or modified structure must at least have the same strength and integrity as in a conventional tanker. ABS rules were used in the new and modified designs whenever possible. In addition a computer technique using the ICES-STRUDL program (Integrated Civil Engineering System-Structural Design Language) was followed to design and optimize the web frames.

The first step was to carry out a detailed analysis of the web frame for a conventional tanker using the computer frame analysis and finite element technique. The geometry of the web frame was then changed to have the double bottom, the double deck, and the small brackets. With this geometry the plate thickness and other details were adjusted to give the same or lower peak stress levels as in the conventional tanker.

Finally, the modified web frame was optimized for minimum weight. The plate thicknesses were adjusted such that at no point in the frame the stress level exceeds the yield stress (33,000 lbf/in^2) under any of the six critical loading conditions considered in the optimization procedure. In addition no plate thickness was less than 1/2 inch. The weight of the optimized web frame was approximately 26% lower than the original minimum bracket frame. The optimized frame was approximately 20% lower in weight than the conventional web frame. The new tankers designed with the optimized web frames were designated 250-Y2 and 50-Y2.

3.3 THE PREFERRED MEMBRANE SYSTEM

The best configuration of the membrane and the optimum operational procedure were developed from analyses of the possible systems and from model tests of a 1/20 scale model tank and membrane. Chapter 5 has a description of the tests.

The program for the test model included filling and emptying tests and experiments in a rocking mode to simulate operation in a seaway. It is believed that the model represented the important characteristics of a full size tank, and the experimental results can be used to predict the performances of membranes in tankers.

The preferred geometry has the membrane attached to the tank walls on the vertical center line of the tank with the membrane on the starboard side when filled with cargo as shown in figure 3.1. The membrane moves across to the port side when the dual-purpose tank is filled with ballast water.

Model tests demonstrated that the membrane would not always move smoothly from one side of the tank to the other, even when the tank had smooth walls. Wrinkles often formed at the bottom of the tank and on the sides as filling progressed. These wrinkles were sometimes of such a severe nature that the model membrane was in jeopardy due to high tension, and filling was stopped. This very serious problem was examined in detail, and a relatively simple remedy was developed to overcome it. The solution was to use gas pressure, not to blow the membrane across the tank as might be expected, but instead the pressure was used on the other side of the membrane to restrain it. With this restraint the membrane was able to roll over the tank bottom during the filling process without creating wrinkles. In addition only minor wrinkles were formed on the sides.

During the dynamic tests a combined electronic and high speed filming technique was used to observe the conditions at the top of the membrane during simulated rolling motion of the model tank. Movements of the membrane were noted as the liquid slapped against the membrane and the top of the tank. The membrane movements and slapping pressures in the model tank were very small, but scaled to the full-size tanker these could give rise to wear due to abrasion. The solution to this possible problem for the tanker in a seaway would be to use gas pressure to keep the membrane pressed against the tank top.

The inert gas systems used for reasons of safety in some modern tankers would also be utilized to provide the gas pressure to assist the membrane operation. Operation with the inert gas system in dual-purpose membrane tanks would be very similar to the inerting operations in conventional tankers.

3.4 MEMBRANE CONSTRUCTION

The materials and method of construction proposed for the impermeable membrane have been determined in conjunction with engineers and chemists from several of the rubber companies with experience in the fabrication of large rubber structures.

The requirements for the membrane are that it should provide a leakproof container for both oil and water, it should be capable of sustaining the loads imposed on it during filling and emptying operations, and it should function satisfactorily for the lifetime of the tanker in the tanker environment.

There are several possible rubbers and plastics with good properties in contact with oils and water. However, much of the experience has been based on an oil resistant rubber given the name Nitrile. This rubber has been widely used in situations where it is in contact with oil, and it has given good service. The rubber is also satisfactory in contact with water. There are other types of rubbers with superior abrasion properties in water but for fabrication reasons it is more satisfactory to use one type of rubber rather than different rubbers for the two sides of the membrane.

The loads on the membrane would be carried by a fabric reinforcement. Experience has shown that nylon provides a satisfactory reinforcement for rubbers, so that a tear resistant weave of nylon would be selected as the membrane reinforcement.

The membrane would be fabricated using Nitrile rubber calendered onto nylon fabric and joined by vulcanized overlapping seams to make the required geometry of the membrane.

3.5 REQUIRED FREIGHT RATE

3.5.1 Shipbuilding Costs

The costs chargeable to the membrane system have been established by similar methods to those used in the segregated ballast study (Study 1), ref. 3.4.

The cost of new construction is based on delivery in 1974 by Japanese shipyards. It was assumed that the new membrane tankers would have similar steelwork labor costs to tankers with double bottoms.

The costs of the conversion of existing tankers were determined from U.S. shipyard prices and were changed to Japanese costs by the same ratio of Japanese to U.S. costs as determined for new construction.

The prices for the fabricated rubber membrane were determined for U.S. manufacturers and not converted to Japanese prices.

An inert gas system is required for acceptable operation of the membranes. Large tankers are expected to have such a system for safety reasons and no cost was charged to 250,000 DWT tankers. Smaller tankers are not often fitted with inert gas systems so that the costs of the inerting system are charged to the 50,000 DWT tanker. The price for the inert gas system was based on Japanese prices.

The shipbuilding prices for the membrane tankers are summarized in table 3.4.

3.5.2 The Required Freight Rate

The required freight rate in $ per long ton is the total annual cost of ship operation, including amortization, divided by the total quantity of oil carried during the year.

The annual operating cost includes the cost of insurance, fuel, port charges, manning, repairs, provisions and stores, and miscellaneous costs. It is assumed that the fuel costs, port charges, provisions and stores, and miscellaneous charged for the tankers with membranes do not change from the conventional tankers of the same displacement. Insurance, using the method of cost estimation given in ref. 3.4, is influenced by the deadweight of the tanker and its first cost. Manning costs reflect the reduction in tank cleaning costs associated with double bottoms and segregated ballast. The repair costs take account of the increase in paint area in the membrane tankers.

The amortization of shipbuilding costs has been determined for 20 year life, 10% cost of capital, and 10% scrap value. The amortization with a 50% tax rate was also calculated. The amortization of the membrane assumed that the membrane would be replaced after ten years of operation as indicated in chapter 6.

The total quantity of oil carried during the year was based on the long voyage operations defined in table 3.5. The total quantity carried by the various tankers reflects the change in DWT and, in the case of the modified 250,000 DWT tanker, the reduction in cubic. The required freight rate data are presented in table 3.6.

3.5.3 Discussion of the Required Freight Rate Results

The increase in the required freight rate for new tankers designed for the membrane system is predicted to be about 4.5-5.5% at zero tax rate for the 250,000 DWT tanker and 3-4% for the 50,000 DWT tanker. The difference between the two tanker sizes reflects the difference in the number of membrane tanks required for the two sizes of tankers. The underlying reason, of course, is that the smaller tanker requires a smaller relative volume of segregated ballast because it has a higher proportion of light ship weight to its displacement.

The modified 250,000 DWT tanker (250-Z) has a 10-11% increase in predicted required freight rate. This increase is higher than the increase in cost of conversion because the capacity is also reduced by the conversion. The reduction in cubic results from the relatively large depth of the deck and keel girders, and from the large sizes of the brackets in the center tanks which must be covered with plate to provide smooth tank walls. The conversion design of a representative 50,000 DWT tanker indicated that increase in required freight rate was similar to that for a new tanker of the same size.

3.6 ASSESSMENT OF POLLUTION REDUCTION

It was expected that there would be a reduction in pollution both from operational discharges and from accidents with the use of the membrane system. The assessment of pollution uses similar prediction procedures to those presented in the segregated ballast study, ref. 3.4.

3.6.1 Operational Discharges

In the normal operations of conventional tankers utilizing load-on-top there are three main operational procedures which result in oil pollution:

1. The discharge of dirty ballast before tank cleaning.
2. The cleaning of dirty ballast tanks.
3. The routine cleaning of cargo tanks.

In all of these operations the seawater pumped overboard contains varying quantities of oil. In assessing the pollution from tanker operations it is necessary to define the quantities of oil discharged with the water. Following the method used in the segregated ballast study, ref. 3.4, the quantities of oil discharged were assumed to be:

1. Dirty ballast, 65 ppm of oil.
2. Sludge or slop tank effluent, 650 ppm of oil.
3. Ballast water from clean tanks, 10 ppm.
4. In discharging dirty ballast 10% goes to the sludge tank and the rest goes overboard.

In addition it was assumed that conventional tankers would have all their cargo tanks cleaned every four ballast voyages. For tankers with double bottoms it was assumed that tank cleaning would require smaller amounts of wash water and would be carried out only before dry docking. Two tank cleaning methods were assumed:

1. The cleaning is accomplished without recycling the wash water.
2. The cleaning is accomplished with recycling using high capacity machines.

For tankers utilizing membranes it was further assumed that there would be occasional leakage of oil through the membrane due to damage or wear. This was assessed assuming that the average life (MTBF) of the membrane was ten years and that after such a failure the ballast water would be treated as dirty ballast. There is therefore a slightly higher probability of pollution during operations with the membrane system compared to a tanker with segregated ballast.

The predicted volume of oil pollution due to operational procedures per (long) voyage is presented in table 3.7. The results indicate that a substantial reduction in pollution can be expected with the isolation of the ballast water from the cargo.

3.6.2 Accidental Discharge Due to Collision

The IMCO hypothetical outflow calculation was completed for each of the 250,000 DWT tankers. Since all the tankers have conventional wing tanks the hypothetical outflow method assumed that all the oil in damaged wing tanks would leak into the ocean. The damage was considered to occur in the most severe location. In addition, the "average" outflow was calculated assuming that the length of the damage region was 14.5 meters as in ref. 3.4. This calculation considers that the damage can occur at any point along the cargo wing tanks and provides a measure of the average outflow relative to the most severe outflow. The outflow predictions for collision damage are presented in table 3.8. The membrane tankers have smaller predicted outflow than the conventional tankers because of smaller sizes of the wing tanks.

3.6.3 Accidental Discharge Due to Stranding

The IMCO hypothetical outflow for stranding accidents assumes that tanks would be breached in the most severe location. The outflow is assumed to be 1/3 of the oil from the tanks in the most severe location. Credit is given for double bottoms if the height of the double bottom is greater than beam/15.

In addition, as in ref. 3.4, an estimate was made of the "statistical" outflow from stranding. A hydrostatic calculation was used to determine the expected outflow from tanks for the most severe location of the damage. It was assumed that the outflow would continue until the static head of oil remaining in the tank was equal to that of the sea outside. Account was taken of the rise and fall of the tide, waves and so forth, and in addition it was assumed that oil would partly fill the double bottom. The expected outflow predicted from hydrostatic considerations was factored first by a number that accounts for the probable outflow relative to the outflow at the most severe location. A second factor was introduced to allow for the protection afforded by the double bottom. It was assumed, as in ref. 3.4, that a double bottom of height equal to beam/15 would be breached in 39% of strandings*.

The IMCO hypothetical outflow and the "statistical" outflow are presented for the 250,000 DWT tankers in table 3.7. The predicted "statistical" outflows from the membrane tankers are smaller than the value from the conventional tanker due to:

1. The smaller tank sizes.
2. The double bottoms.
3. The freeboards are not increased.

3.7 COST OF POLLUTION PREVENTION FOR 250,000 DWT TANKERS

The annual costs of the various tankers have been established in the process of determining the required freight

*No account was taken of the possible protection provided by the membrane.

rate. The expected annual discharge of oil into the oceans from accidents and operational causes can be predicted as follows:

1. The "average" outflow of oil has been predicted for collisions and strandings. It is necessary to predict the probability of these events per annum. This estimate was made in ref. 3.4, yielding for a conventional 250,000 DWT tanker (250-Z):

   a. Strandings 103 m^3/yr.

   b. Collisons 52 m^3/yr.

   c. Rammings 2 m^3/yr.

2. The discharge of oil from tanker operations per trip has been predicted and is presented in table 3.7. With the assumption that a tanker makes 7 trips per year the annual discharge can be estimated.

The results of these calculations are presented in tables 3.10 and 3.11.

The results presented in these tables indicate that the use of the membrane system should reduce outflow due to accidents to about 26% of the value from current tankers and the pollution from operations to about 4% of the value from current tankers (using load on top)*.

The cost of reducing pollution has been predicted to be about 1,000 - 1,250 $/$m^3$ for new tankers. The cost of reducing pollution in existing converted tankers depends on

*These figures are for new tankers designed for the membrane system and having B/15 double bottoms.

the tanker design but would be somewhat higher. In the representative 250,000 DWT tanker (250-Z) the predicted cost was 4,340 $\$/m^3$.

REFERENCES

3.1 "Recommendation to put into Effect Requirements Relating to Tank Arrangements and to the Limitation of Tank Size from the Point of View of Minimizing Pollution of the Sea by Oil", IMCO Resolution A.247 (VIII), October 1971.

3.2 T. A. Gardner, "Investigation of High Depth Segregated Ballast Tankers", Report No. E11.15TMR. 71, Esso International Inc. Tanker Department, 1971.

3.3 Rules for Building and Classing Steel Vessels, American Bureau of Shipping, 1971.

3.4 "Study I - Segregated Ballast Tanker", Note by the United States, April 1972.

TABLE 3.1 PRINCIPAL CHARACTERISTICS

DESIGN	LBP meters	BEAM meters	DEPTH meters	DRAFT meters	SHP	SPEED knots
50-A	214.3	31.7	15.7	11.9	16,250	16
50-Y1	214.3	31.7	15.7	11.9	16,250	16
50-Y2	214.3	31.7	15.7	11.9	16,250	16
50-Z	214.3	31.7	15.7	11.9	16,250	16
250-A*	329.2	51.8	25.6	15.0	31,550	16
250-Y1	329.2	51.8	25.6	15.0	31,550	16
250-Y2	329.2	51.8	25.6	15.0	31,550	16
250-Z	329.2	51.8	25.6	15.0	31,550	16

TABLE 3.2 LIGHT SHIP WEIGHT (LONG TONS)

DESIGN	STEEL	OUTFIT	MACHINERY	MARGIN (3%)	LIGHT SHIP
50-A	9634	2855	850	400	13739
50-Y1	10103	2838	850	414	14205
50-Y2	9833	2838	850	406	13927
50-Z	9929	2900	850	410	14089
250-A*	30243	4246	1160	1069	36718
250-Y1	33449	4223	1160	1165	39997
250-Y2	32452	4223	1160	1135	38970
250-Z	32959	4352	1160	1154	39625

*Conventional tanker, similar to 250-A of Study 1, ref. 3.4.

TABLE 3.3 SUMMARY OF MODIFIED TANKER ADDITIONS

250-Z DESIGN	WEIGHT (L.T.)
Inner Bottom	747.05
Inner Deck	361.53
Long. Corner Plates	291.73
Additions to Web Frames	275.50
Transverse Corner Plates	220.32
Bulkhead Modifications and Additions	820.23
TOTAL WEIGHT ADDITION	2,716.36

50-Z DESIGN	
Inner Bottom	142.14
Inner Deck	71.27
Long. Corner Plates	21.24
Additions to Web Frames	39.13
Transverse Corner Plates	21.72
Bulkhead Modification and Additions	-
TOTAL WEIGHT ADDITION	295.50

TABLE 3.4 SUMMARY OF SHIPBUILDING PRICES FOR THE MEMBRANE TANKERS

(in dollars)

PRICE DIFFERENCE CATEGORIES	250-A	250-Y1	250-Y2	250-Z	50-A	50-Y1	50-Y2	50-Z
Steel		1,842,288	1,411,187	1,752,017		341,564	224,910	342,055
Coatings and Paint		481,683	481,683	137,095		172,393	172,393	46,284
Oil and Ballast Piping		-39,601	-39,601	168,577		-30,986	-30,986	77,940
Ballast Pump		84,000	84,000	-		38,000	38,000	-
Inert Gas System		-	-	-		188,000	188,000	188,000
Membrane		252,817	252,817	290,714		45,266	45,266	77,129
Membrane Attachment		15,050	15,050	21,415		4,862	4,862	8,967
Price Increment & % Increase Over Base		2,636,177 (7.06%)	2,191,591 (5.88%)	2,369,818 (6.35%)		759,099 (5.54%)	642,445 (4.69%)	740,375 (5.39%)
1974								
Delivered Price - Millions at 308 ¥/$	37.3M	39.9	39.5	39.7	13.7	14.5	14.3	14.4

250-A, 50-A Conventional Tankers, 250,000 DWT, 50,000 DWT

250-Y1, 50-Y1 Membrane Tankers

250-Y2, 50-Y2 Membrane Tankers Optimized Web Frames

250-Z, 50-Z Modified Conventional Tankers

TABLE 3.5 Principal Operating Bases (Long Voyage)

	50-A	250-A
Round Trip (n.m.)	22,000	22,000
Sea Speed (kt.)	16.24	15.95
Sea Days	56.4	57.3
Port Days	3.0	3.0
Days/Trip	59.4	60.3
Oper. Days/Yr.	350	350
Trips/Yr.	5.89	5.80
Cargo Deadweight (LT)	45,740	239,285
Cargo Delivered/Yr. (LT)	269,409	1,387,855
Dry Dock Cycle	18 months	18 months

TABLE 3.6 REQUIRED FREIGHT RATE - LONG VOYAGE (250 DWT CASE)

	250-A	250-Y1	250-Y2	250-Z
Construction Cost (MM$)	37.4	39.7	39.2	39.4
Membrane Cost	-	.25	.25	.29
Operating Cost (M$)				
Insurance	1,080.4	1,085.1	1,086.8	1,026.3
Fuel	1,099.0	1,099.0	1,099.0	1,099.0
Port Charges	295.4	295.4	295.4	295.4
Manning	350.0	347.7	347.7	349.0
Repairs	250.0	262.9	262.9	253.7
Prov./Stores	175.0	175.0	175.0	175.0
Miscellaneous	25.0	25.0	25.0	25.0
Total Operating Costs	3,274.8	3,290.1	3,291.8	3,223.4
Amortization 0-Tax				
Ship	4,125.0	4,379.0	4,323.8	4,345.8
Membrane	-	40.7	40.7	47.2
Total	4,125.0	4,419.7	4,364.5	4,393.0
Amortization 50% Tax				
Ship	6,309.4	6,698.2	6,613.8	6,647.5
Membrane	-	62.3	62.3	72.2
Total	6,309.4	6,760.5	6,676.1	6,719.7
Total Annual Cost				
0-Tax	7,399.8	7,709.8	7,656.3	7,642.7
50% Tax	9,584.2	10,050.6	9,967.9	9,969.4
Deadweight (LT)	249,952	246,673	247,700	234,919
Cargo Delivered/yr (LT)	1,391,722	1,372,703	1,378,660	1,304,530
RFR - 0-Tax ($/LT)	5.32	5.62	5.56	5.85
RFR - 50% Tax ($/LT)	6.89	7.32	7.23	7.64
% Increase in RFR - 0-Tax	-	5.65	4.41	10.10
% Increase in RFR - 50% Tax	-	6.27	4.94	10.92

TABLE 3.6L REQUIRED FREIGHT RATE - LONG VOYAGE (50 DWT CASE)

	50-A	50-Y1	50-Y2	50-Z
Construction Cost (MM$)	13.7	14.4	14.3	14.4
Membrane Cost	-	.045	.045	.077
Operating Cost (M$)				
Insurance	204.9	207.6	207.3	207.4
Fuel	603.7	603.7	603.7	603.7
Port Charges	58.9	58.9	58.9	58.9
Manning	350.0	347.7	347.7	349.0
Repairs	150.0	154.6	154.6	151.2
Prov./Stores	125.0	125.0	125.0	125.0
Miscellaneous	10.0	10.0	10.0	10.0
Total Operating Costs	1,502.5	1,507.5	1,507.2	1,505.2
Amortization 0-Tax				
Ship	1,511.1	1,588.3	1,577.3	1,588.3
Membrane	-	7.3	7.3	12.5
Total	1,511.1	1,595.6	1,584.6	1,600.8
Amortization 50% Tax				
Ship	2,311.4	2,429.6	2,412.7	2,429.6
Membrane	-	11.2	11.2	19.1
Total	2,311.4	2,440.8	2,423.9	2,448.7
Total Annual Cost				
0-Tax	3,013.6	3,103.1	3,091.8	3,106.0
50% Tax	3,813.9	3,940.3	3,931.1	3,953.9
Deadweight (LT)	50,340	49,874	50,152	49,990
Cargo Delivered/yr (LT)	269,409	266,664	268,301	267,347
RFR - 0-Tax ($/LT)	11.19	11.64	11.52	11.62
RFR - 50% Tax ($/LT)	14.16	14.81	14.65	14.79
% Increase in RFR - 0-Tax	-	4.0	3.00	3.82
% Increase in RFR - 50% Tax	-	4.56	3.47	4.44

TABLE 3.7 Operational Discharge Per Voyage, m^3

Ballast Loading Tank Cleaning Method		45% 1	45% 2	60% 1	60% 2
Ship Type	DWT/15,000				
50-A	3.8	.98	.33	2.86	1.73
50-Y1, Y2	3.8	.28	.05	.28	.05
50-Z	3.8	1.24	.41	1.50	.59
250-A	19.4	17.85	10.11	22.48	14.77
250-Y1, Y2	19.4	1.04	.27	1.04	.27
250-Z	19.4	5.99	2.00	7.99	2.67

TABLE 3.8 Collision Damage Analysis

SHIP	250-A	250-Y	250-Z
Cargo Tanks Damaged	4/5W	5/6W	5/6W
Volume of Tanks Damaged (m^3)	44,800	18,800	21,100
IMCO Hypothetical Outflow	44,800	18,800	21,100
"Average" Outflow	21,900	13,500	16,000

TABLE 3.9 Stranding Damage Analysis

SHIP	250-A	250-Y	250-Z
Cargo Tanks Damaged - Most Severe Location	4/5C;4/5W	5/6C;5/6W	5/6C;5/6W
Volume (m^3)	112,650	56,874	42,979
Volume Without Double Bottom (m^3)	112,650	0	35,331
IMCO Hypothetical Outflow (m^3)	37,550	0	11,800
Expected Outflow for most Severe Location (m^3)	20,600	12,900	8,900
Estimated Ratio, Average/ Severe	0.31	0.33	0.33
Likelehood Tanks will be Breached	100%	39%	89%
Statistical Outflow (m^3)	6,400	1,700	2,900

TABLE 3.10 Fleetwide Oil Outflow Estimates from Accidents Apportional on a Per 250 M DWT, Per Year Basis

SHIP	250-A	250-Y1	250-Y2	250-Z
Stranding Outflow (m^3)	103	27	27	47
Collision Outflow (m^3)	52	32	32	38
Ramming Outflow	2	2	2	2
Total Accidental Outflow	157	61	61	87
Oil Outflow Prevented Compared to 250-A	-	96	96	70
Amount Annual Costs Exceed 250-A $M	-	310	256	740*
Cost of Preventing Oil Outflow From Accidents, $/m^3$		3,229	2,666	10,571

*This value takes account of the reduction in cargo carried.

TABLE 3.11 Fleetwide Oil Outflow Estimates from Operational and Accidental Discharges Apportional on a Per 250 M DWT, Per Year Basis, 60% Ballast Condition

SHIP	250-A	250-Y1	250-Y2	250-Z
Total Accidental Outflow (m^3)	157	61	61	87
Total Operational Outflow (m^3)	157	7	7	56
Total Outflow (m^3)	314	68	68	143
Outflow Compared to 250-A (m^3)	-	-246	-246	-171
Annual Costs Compared to 250-A	-	310	256	740
Cost of Preventing Outflow from Operations Only $/$m^3$		2,070	1,710	7,330
Cost of Preventing Outflow from Accidents and Operations $/$m^3$		1,260	1,040	4,330

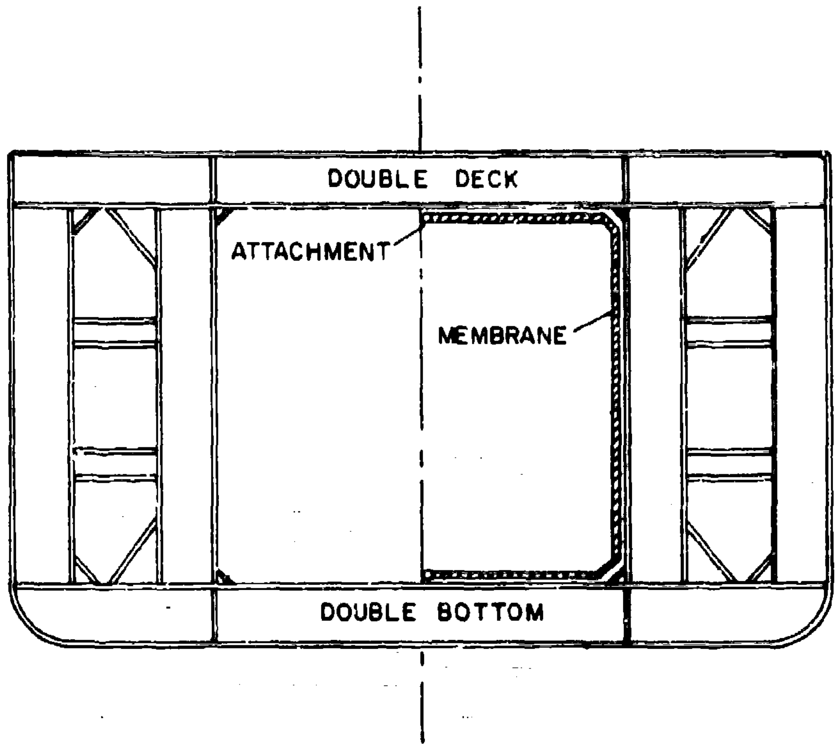


FIGURE 3.1 THE MEMBRANE ARRANGEMENT

4. MEMBRANE GEOMETRICAL CONFIGURATIONS

There are many possible ways of providing impermeable membranes in cargo/ballast tanks. All arrangements would require the removal of interior structure to provide smooth-walled tanks.

Each geometrical configuration considered is analyzed for the following features:

1. filling and emptying
2. venting requirements
3. comparative cost of the membrane
4. physical limitations

A patent search was conducted and all relevant patents were examined and are referred to in the following sections. In addition, the experience gained from the experiments with the tank model is factored into the assessments.

4.1 GEOMETRY 1 (Figure 4.1)

This configuration has the membrane attached to the tank walls on the horizontal center line and is similar to the geometries in U.S. Patent Numbers 2,696,185 (1954), 2,731,158 (1956) and 3,477,401 (1969). Oil is carried on top of the membrane, and ballast water is carried under the membrane.

The main disadvantage of this geometry is the problem of emptying the cargo. The cargo suction would have to be placed high in the tank, above the membrane, and it would be difficult to empty the lower half of the cargo. Water could be introduced under the membrane to raise the cargo, but this would not appear to be a satisfactory solution as complete emptying would be difficult. Venting on the water ballast side would not be practical, but it is not important to vent water as it has a low vapor pressure.

This geometry offers added protection from pollution in the event of grounding or stranding. A tough membrane would probably remain intact in a low-energy impact rupture of the vessel. The membrane has half the surface area of the tank and is therefore economical in the use of membrane material.

4.2 GEOMETRY 2 (Figure 4.2)

The membrane is fabricated as a large closed box or balloon with the inlet and attachment at the tank bottom. A similar configuration appears in U.S. Patent Number 2,991,906 (1961). In this geometry oil is loaded on top of the folded membrane, and ballast is loaded through the opening, thus expanding the membrane to conform to the tank.

This geometry requires nearly twice the minimum amount of membrane material. The ballast discharge is probably vulnerable to fouling. A further serious disadvantage is the fact that the weight of the cargo would be carried by the empty membrane in a crumpled and folded condition. Venting the ballast water would be difficult, but this is not expected to be serious because of the low vapor pressure of water.

The main advantage of this geometry is the simplicity of the attachment and sealing.

4.3 GEOMETRY 3 (Figure 4.3)

This geometry is similar to Geometry 2 except the top of the membrane has a rigid top or barrier. The purpose of this barrier is to protect the folded barrier when the cargo is pressing down on it. A membrane system of this geometry was described by Porricelli, et al. (ref. 4.1)

The main disadvantage of this configuration is the probable movement of the barrier in a seaway, since it could slam against the tank walls and damage the membrane, the barrier, and the tank structure. In addition, the membrane is likely to become crushed between the barrier and the tank walls during the ballast-water filling and emptying operations.

4.4 GEOMETRY 4 (Figure 4.4)

This configuration may be regarded as a further modification of Geometries 2 and 3. The membrane is constrained to move within a container having perforated sides and placed in a conventional tank containing structure. The membrane has a solid top or barrier which slides inside the perforated container. When the tank is filled with cargo the membrane is collapsed and folded at the bottom of the perforated container. In the ballasted condition the membrane is filled with water and the barrier is at the top of the container. A configuration of this type is described in U.S. Patent Application Serial Number 136,196 (1971). An additional feature of the patent application is a series of metal guide rings and contracting rings to fold the membrane neatly when it is being emptied.

A disadvantage of this configuration is the potential damage in a seaway due to the slamming of the barrier inside the perforated container. In addition the barrier is likely to become wedged in the container at some stage. The folding mechanism in the membrane is also unlikely to be reliable over the life of the tanker.

The configuration would require the minimum of structural change in existing tankers although an additional, rather complicated folding arrangement would be placed in each dual purpose tank.

4.5 GEOMETRY 5 (Figure 4.5)

In this configuration the membrane is attached along the vertical center line of the tank on the longitudinal axis of the tanker. This geometry has been described in U.S. Patent Number 3,421,663 (1969) for a railroad tank car application. In the loaded condition the cargo is on the port side of the membrane. After cargo discharge, the ballast water is loaded on the starboard side of the membrane.

Installation of the membrane may be difficult as there is a large sealing perimeter.

This geometry provides some protection in the event of collision if the membrane is between the point of impact and the oil in the tank. There are no venting problems, and tank cleaning is not difficult. A minimum area of membrane is required (as in Geometry 1).

4.6 GEOMETRY 6 (Figure 4.6)

This configuration is an asymmetric version of Geometry 5. However, except for a cubic tank, the membrane corners would not be correctly placed in both the cargo and ballast conditions. This disadvantage would eliminate Geometry 6 and all asymmetric configurations from serious consideration.

4.7 GEOMETRY 7 (Figure 4.7)

The configuration is similar to Geometry 2 with an additional attachment and opening at the top of the tank to allow venting. This arrangement has appeared in U.S. Patent Numbers 2,630,236 (1953), 2,758,747 (1956), 3,396,762 (1968) and Australia Patent Application Number PA 6265/71 (1971). In this geometry the oil is carried on the inside of the membrane.

The inside of the membrane would be difficult to clean and would probably be removed for cleaning purposes. As in Geometry 2, the surface area of the membrane is nearly twice the minimum value. The membrane in the ballast condition would be hanging limply from the top support and crushed by the pressure of the ballast water. It would also be subjected to large forces at the attachments in a seaway as it is supported from a relatively small attachment device.

The main advantages of this geometry are the enhanced protection of the cargo in the dual purpose tanks in the event of a grounding or collision and the relatively simple arrangements for attachment, not requiring perfect tailoring of the membrane to the tank dimensions.

4.8 SELECTION OF SUITABLE GEOMETRICAL CONFIGURATIONS

The attributes of the various membrane configurations were evaluated taking account of operational, engineering, and economic features. Geometry 5 was selected as the superior configuration and was utilized in the experimental test program and the tanker design studies. Some experiments were also conducted on Geometry 7 to examine the problems associated with box or balloon configurations.

Geometry 1, with the membrane attached at the horizontal center line, was eliminated from consideration largely because of the anticipated operational difficulties associated with emptying the cargo. However, this geometry may have application in water compensated fuel tanks where the fuel outlet is high in the tank.

REFERENCES

4.1 "Tankers and the Ecology", Joseph D. Porricelli, Virgil F. Keith, Richard L. Storch, S.N.A.M.E. paper presented November 11-12, 1971.

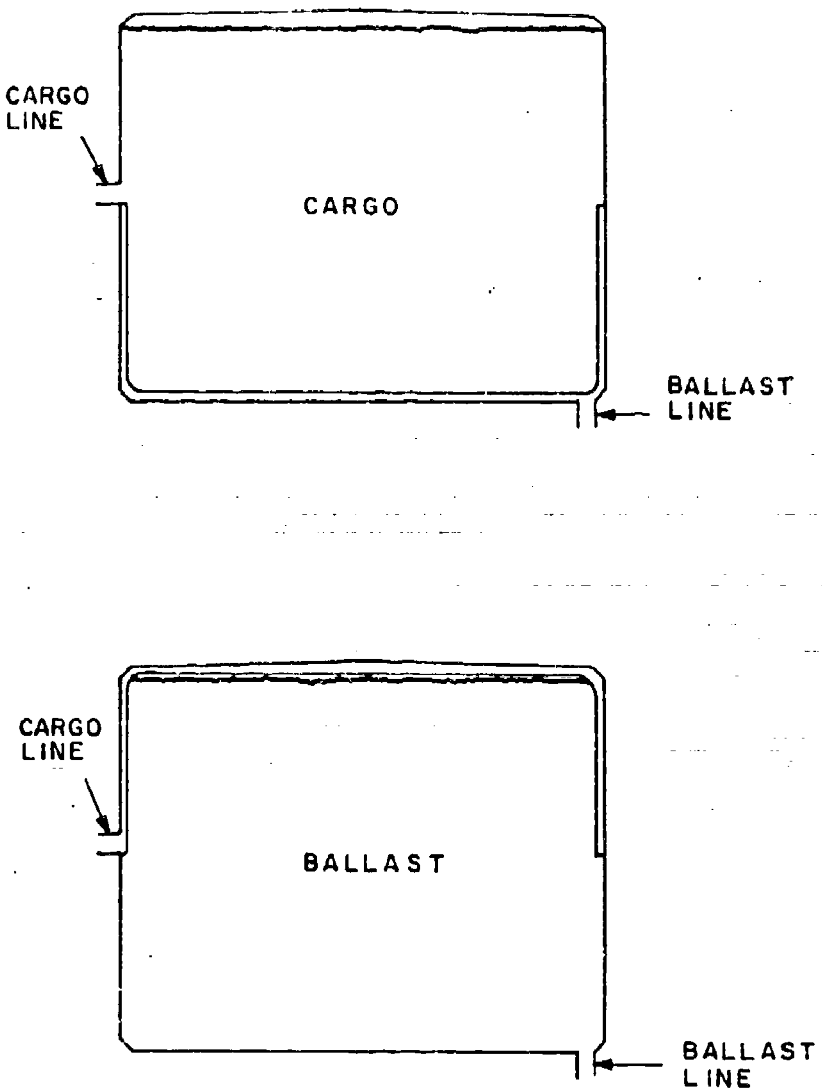


FIGURE 4.1 GEOMETRY NUMBER I

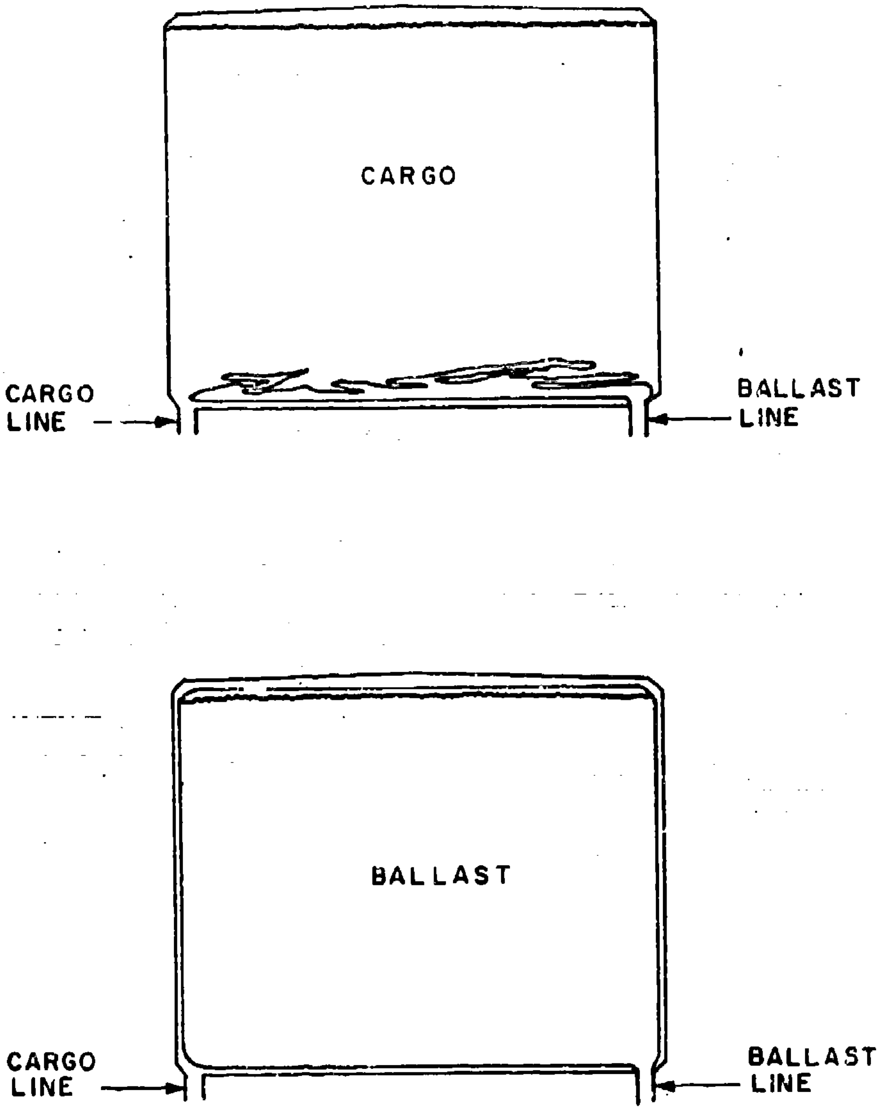


FIGURE 4.2 GEOMETRY NUMBER 2

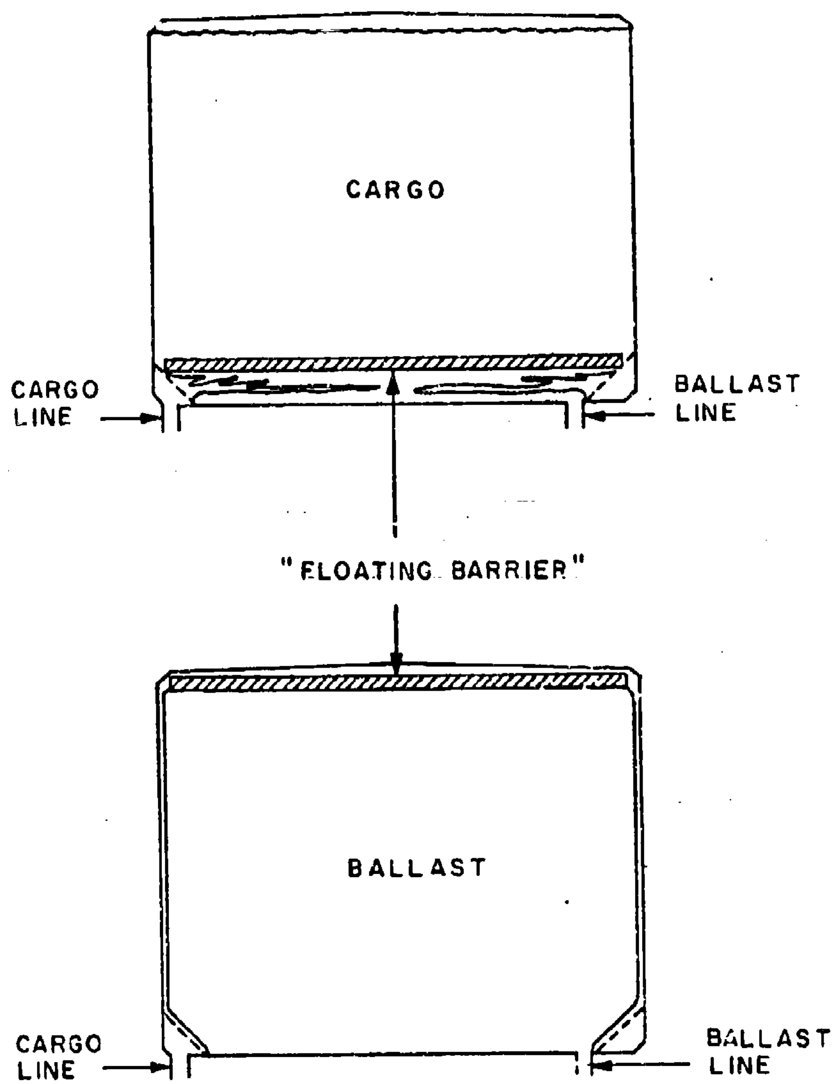


FIGURE 4.3 GEOMETRY NUMBER 3

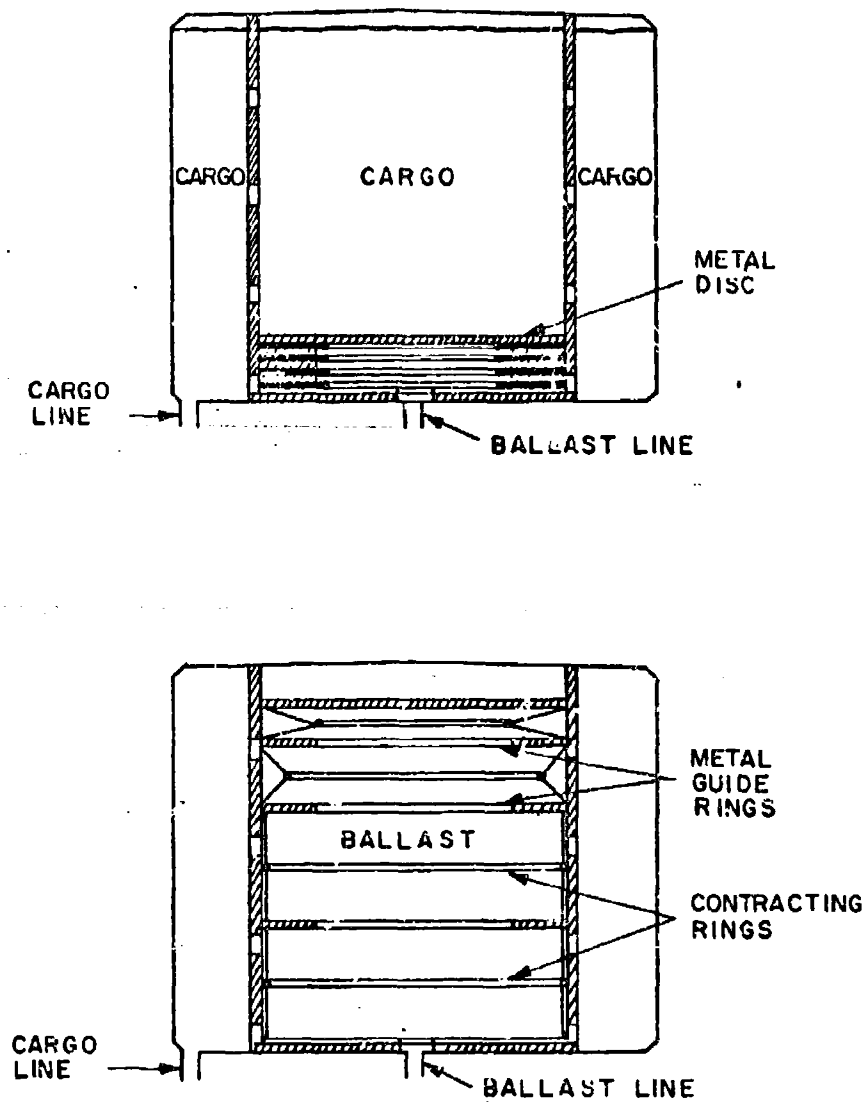


FIGURE 4.4 GEOMETRY NUMBER 4

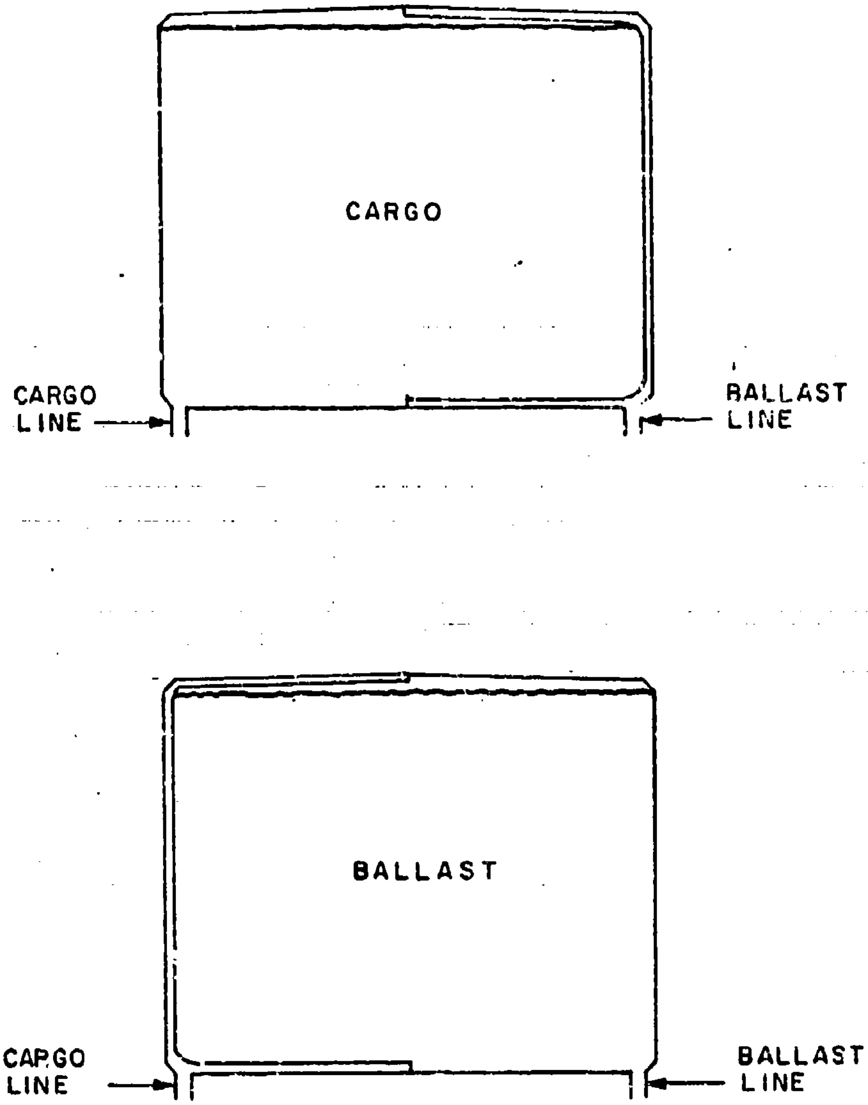


FIGURE 4.5 GEOMETRY NUMBER 5

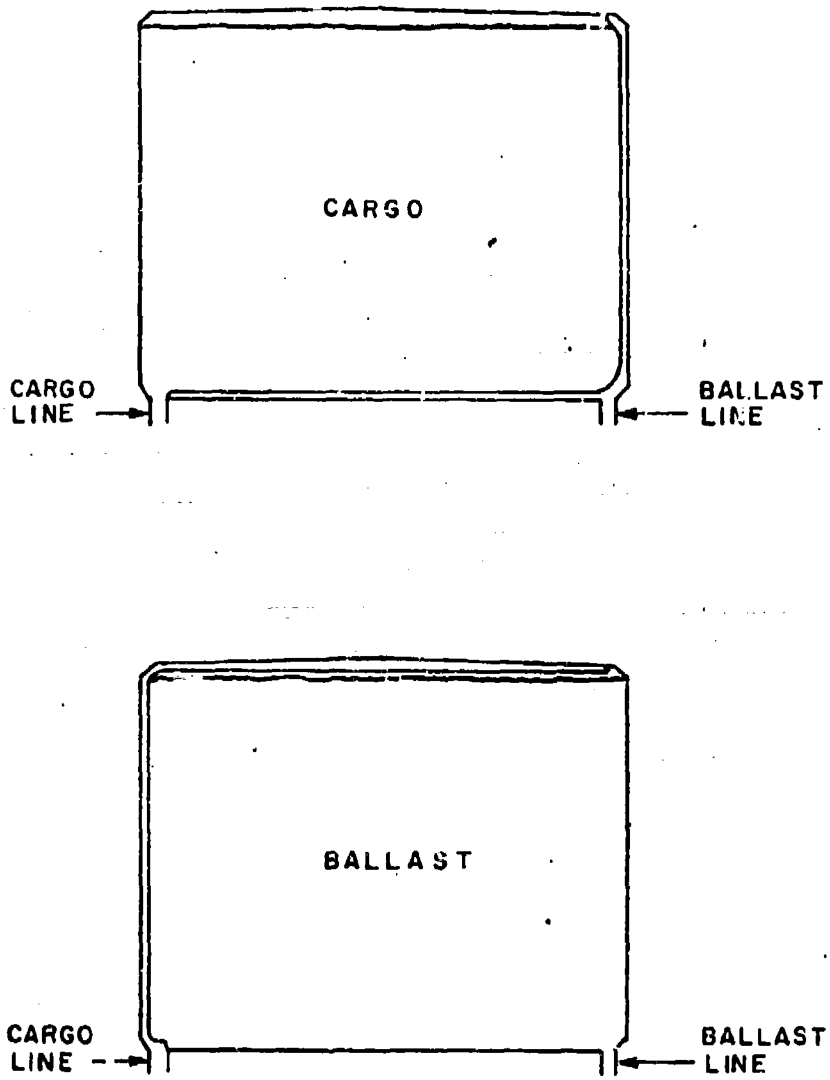


FIGURE 4.6 GEOMETRY NUMBER 6

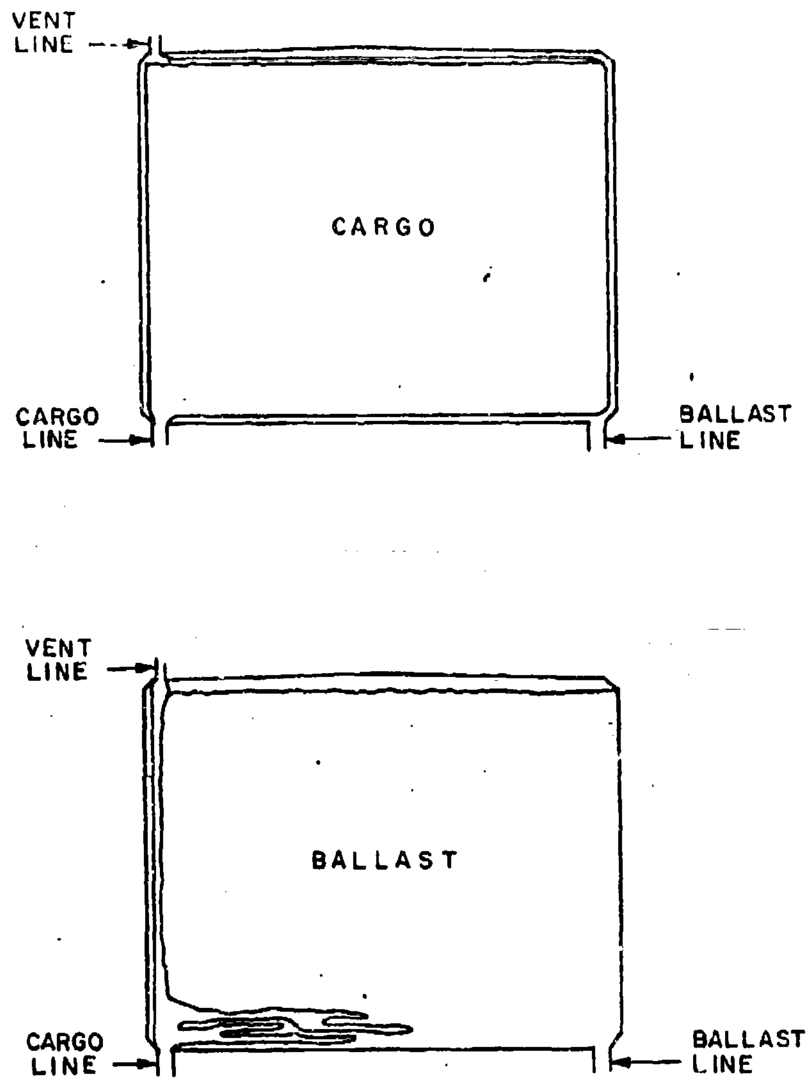


FIGURE 4.7 GEOMETRY NUMBER 7

5. MODEL TESTS

The preliminary engineering feasibility of the membrane concept was established from experiments using the geometrical configurations selected in Chapter 4. Obviously, it would be very difficult to test the membrane in a full size cargo tank which typically measures 100 ft. by 80 ft. by 70 ft. Insteaa the tests were performed on a smaller model of the tank constructed to an appropriate scale.

5.1 SCALE EFFECTS IN MODEL TESTING

Scale model testing is an established method of experimentation and is employed in the analysis of many fields including ships, pipe flow, airfoils, and pumps. The intention is to identify all the independent non-dimensional groups which can be formed from the parameters that are considered to be important in describing the physical situation. The formal procedure for this, known as the PI Theorem, is not used here because all the expected non-dimensional groups are well established in the field of hydrodynamics and need only be interpreted for the membrane problem.

The pertinent variables in the membrane problem are:

L	length
g	acceleration due to gravity
ρ_{L1}, ρ_{L2}, ρ_m	density of the liquids (oil and water) and of the membrane
Q	volume flow rate
EI	membrane stiffness per unit length

ω	frequency of oscillation
ν_1, ν_2	kinematic viscosity of the liquids
σ_1, σ_2	surface tension of the liquids
μ	coefficient of friction

In this case surface tension effects can be ignored as they are not important. Also the viscous effects of water and oil are neglected because liquid shear forces are expected to be small compared to other forces.

The next step is to arrange the remaining 9 variables into 6 independent non-dimensional groups by relating them to the hydrodynamic groups of dimensionless parameters. These groups are tabulated below:

MEMBRANE PARAMETER		CORRESPONDING HYDRODYNAMIC PARAMETER	
$Q/L^{2.5}g^{\frac{1}{2}}$	Flow Number	$V/\sqrt{gL}$	Froude Number
$EI/\rho_L gL^5$	Membrane Stiffness Number	$P/\rho V^2$	Pressure Coefficient
$\omega(\frac{L}{g})^{\frac{1}{2}}$	Reduced Frequency Parameter	$\omega L/V$	Reduced Frequency Parameter
$(\rho_m - \rho_L)/\rho_L$, $(\rho_{L2} - \rho_{L1})/\rho_{L1}$	Density Functions		Same
μ	Friction Coefficient		Same

These parameters are independent but may be combined to form new, dependent, non-dimensional parameters such as $EI/\rho_L Q^2$ which is the Membrane Stiffness Number divided by the Flow Number squared. From consideration of the above relationships, proper tests can be performed on a scale model and then related to the full size tank.

5.1.1 The Scaled Tank and Membrane

The length scale for the model tank was determined from consideration of the relative stiffness of available thin plastic membranes and the full size rubber membrane. The model tank was designed to be approximately 1/20 scale of the tanks for a 250,000 DWT tanker.

The scale size fixes the model tank dimensions as 5 ft. long, 4 ft. deep, and 3 1/2 ft. wide. A discharge rate of about 11 GPM scales a full size flow rate of 20,000 GPM, and a loading rate of about 7.5 GPM is comparable to 20,000 barrels per hour in the full size tank. The frequency of oscillation for a 10 second roll period of the tanker scales to 2.2 seconds for the model.

A model tank was constructed of clear plexiglas reinforced with aluminum to provide good viewing of the membrane. Filling and discharge ports in the tank bottom and venting ports at the tank top were provided. A supporting frame and bearings were assembled to allow simulated seaway movement in roll. Photographs of the tank are presented in figure 5.1. The membrane of Geometry 5 configuration was clamped between aluminum bars attached to the tank walls.

5.2 FILLING TESTS ON GEOMETRY 5

A series of tests were conducted to investigate the problems of filling the model tank with the membrane in place.

Tests were conducted varying the filling rate, the fabric stiffness, and the effective friction between the membrane and the tank. At the outset, it was found that the model membrane did not move neatly into place but rather it formed a series of folds and wrinkles. On many occasions the wrinkling was so serious that complete filling of the tank was impossible because of the high loads imposed on the membrane.

The most serious wrinkles were created on the bottom of the tank at the beginning of the filling operation when the membrane moved across the tank. Additional wrinkles of less serious consequence occurred at the sides of the tank as filling progressed.

The magnitude of the wrinkling problem in terms of number and size of wrinkles was estimated for each test. The results are plotted in figure 5.2 for the bottom wrinkles and in figure 5.3 for the side wrinkles. The anticipated conditions for the full size tanker are illustrated on the figures. The non-dimensional parameters used as the abscissa in the figures were selected to provide the best correlation of the data. From these figures it was demonstrated that wrinkles at the bottom of the tank increase with filling flow rate and friction, and decrease with membrane stiffness. The wrinkles at the side of the tank increase with flow rate, friction, and membrane stiffness. The full size tanks were expected to operate in the regions where relatively serious wrinkles could be anticipated.

5.2.1 Prevention of Wrinkles

It is obvious that the membrane method of separating the ballast water from the cargo would be a failure unless practical methods could be developed for reducing the formation of serious wrinkles. Since the wrinkles occur as a result of the movement of the membrane from one side of the tank to the other during filling, it was assumed that artificial methods of moving the membrane might be successful. Methods using gas pressure and mechanical methods of moving the membrane were examined.

5.2.1.1 Pressurization Methods

Gas pressure may be utilized to position the membrane. Air pressure could be used although for safety reasons inert gas would be preferred and is generally available in modern tankers. Inert gas systems typically operate at 1 to 2 lbf/in^2 above atmospheric pressure; this pressure would be satisfactory to position the membrane. Tanks are designed to withstand an overpressure of about 4 lbf/in^2. Excess pressure is prevented by pressure-vacuum relief valves which are set to open between 1/2 and 3 lbf/in^2.

The first pressurization method investigated in the model tank used the gas pressure to blow the membrane across the tank prior to filling, figure 5.4. The results of this test were disappointing since serious wrinkles were formed during the movement of the membrane. The pressure necessary to move the membrane was low and corresponded to about 5 in H_2O in the full size tank.

The second pressurization method utilized the gas pressure to restrain the membrane during the initial stages of filling, figure 5.5. The gas pressure was applied on the opposite side of the membrane from the filling side, and the pressure was released as the filling commenced. The gas force opposed the liquid force until sufficient depth of liquid was provided to overcome the gas pressure. At this point the membrane moved across the tank in a smooth rolling action without the formation of bottom wrinkles. The pressure necessary to restrain the liquid and the membrane tension developed during this process were calculated analytically and found to be acceptable and in agreement with the model tests, (see Chapter 6). The tank could then be completely filled with only minor wrinkles on the sides of the tank.

A third pressurization method, which combined the other two methods, utilized the gas pressure to restrain the membrane initially, but when the tank was about half filled, the filling process was stopped for a short while, in order to blow the upper portion of the membrane into place from the filling side. Filling was then continued and only small wrinkling occurred, figure 5.6.

5.2.1.2 Mechanical Methods

The membrane can be moved from one side of the tank to the other and constrained to conform to the tank by mechanical methods. Two methods were tested on the model tank:

1. Using a pair of hinged frames or gates at the ends of the tank to support the membrane.

2. Utilizing cables in the top corners to pull the upper part of the membrane across the tank.

The first mechanical method used a pair of hinged frames or gates to carry the membrane across the tank, figure 5.7. Each frame was approximately half the tank width, and the hinges were formed by the membrane material at the vertical attachments. The membrane material was attached to the frame so that the membrane and frame move together at the ends of the tank. The intention was to move the membrane across the tank between emptying and refilling. However, the membrane invariably became fouled at the top corners of the frames and the membrane could not be put into place, figure 5.8. Several modifications to the shape of the frame were not successful and this method was concluded to be unacceptable.

The second mechanical method utilized cords attached to the model membrane near the top corners. Before refilling the tank, the corners of the membrane were pulled across the tank and fixed to the top corners of the tank. The tension in the cord to move the membrane was high because of the displacement of the air in the tank. The initial filling operations were very similar to the second pressurization method. The pressure difference created by pulling the top corner into place restrained the movement of the membrane until sufficient depth of liquid accumulated to make the membrane move across smoothly. This method of filling was not entirely successful because the membrane formed wrinkles towards the top of the tank. The problem occurred because the membrane, which was only supported at the corners, sagged towards the middle of the tank under its own weight. The resulting folds were trapped by the liquid. Several methods can be devised to overcome this problem, including additional cables on the top edge of the membrane, and the application of gas pressure on the filling sides to move the membrane up to the top of the tank.

5.2.1.3 The Preferred Solution

The most satisfactory method of preventing wrinkles that was developed during the model tests on Geometry 5 was the second pressurization method. It will be recalled that with this method the membrane does not form bottom wrinkles because of the restraint imposed by gas pressure. The operational aspects of this proposed filling and emptying method are discussed in Chapter 7.

5.3 EMPTYING TESTS ON GEOMETRY 5

Emptying tests were performed after each filling test to determine whether fouling of the suction could occur. It was observed in every case that the bottom of the membrane remained stationary during the emptying operations with no tendency to move across to the suction outlet. The weight and friction force on the membrane was obviously much greater than the hydrodynamic forces trying to move the membrane across the tank bottom. It is therefore concluded that there would be no problems during emptying operations for Geometry 5.

5.4 DYNAMIC TESTS ON GEOMETRY 5

The dynamic tests were carried out to observe the action of the membrane during simulated roll motions and to attempt to determine whether serious wear due to abrasion could be expected as a result of movement between the membrane and the tank walls.

Observations during the simulated roll movements demonstrated that the motion of the membrane was restricted to the top of the tank where the ullage space allowed the liquid surface to move the membrane. During rolling motion the liquid slapped the membrane to the tank top.

Wear due to abrasion is associated with a normal force and a relative movement of the rubbing surfaces. A combined electronic and high speed filming technique was used to examine these two features on the model tank, figure 5.9. The pressure exerted by the membrane on a small area of the tank top was measured using a transducer. The transducer signal was also used to trigger a light as the pressure wave arrived. The light and the membrane top were filmed with a high speed camera to provide measurements of the movement of the membrane against the top of the tank together with synchronizing marks for the pressure records. With this technique an average pressure and movement diagram for one cycle of roll was constructed and is presented in figures 5.10 and 5.11 for the model tank.

For the full size tank both the movement and the pressure would be scaled linearly for tank size. It might be expected, therefore, that abrasion could be a serious problem in the full size tank. This topic is discussed in Chapter 6. However, there is some doubt about the accuracy of the modeling technique because of the lower friction coefficient for the model compared to the full scale tank and membrane. It is believed that in the tanker, abrasion will be a matter for concern but it should not be as serious as predicted in the model tests. Further mitigating features are the possibility of providing lubrication to reduce abrasion and also the provision of an operational procedure to pressurize the tank with inert gas. The gas pressure would push the membrane against the top of the tank thereby reducing the membrane movement, and the wear. to negligible proportions. This operational procedure is discussed in Chapter 7.

5.5 MODEL TESTS ON GEOMETRY 7

A series of tests were conducted with the scale model tank using the membrane configuration described in Chapter 4 as Geometry 7. Although this geometry has certain disadvantages, as described in section 4.7, it was tested as a representative of the box or balloon type of configuration. Testing was not as detailed as the study of Geometry 5 and was restricted to filling and emptying tests of the membrane system.

The membrane was fabricated as a closed box having the inside dimensions of the tank using 0.002 in polyethelene. This is the same material as used in the majority of the tests for Geometry 5. The oil inlet was located at the after corner of the tank bottom, and the vent opening was directly above it. These locations were considered to be the optimum positions for the openings from operational considerations.

5.5.1 Filling Tests

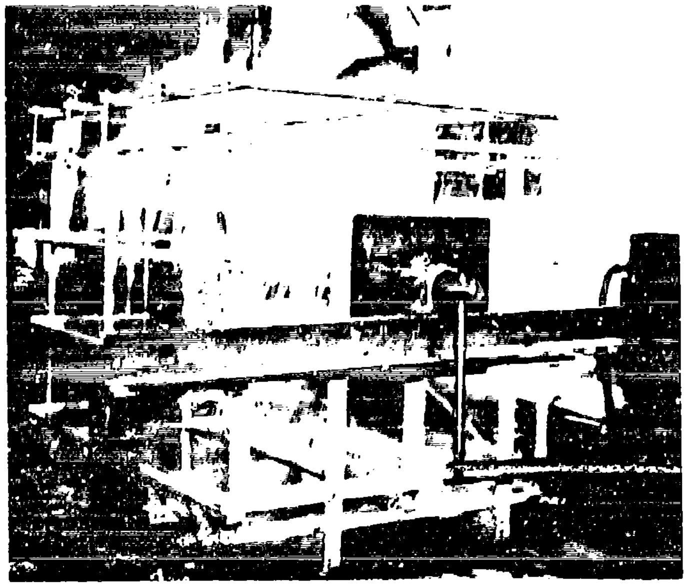
The tank was first filled on the ballast side of the membrane, i.e. outside the membrane. During this operation the air trapped in the membrane caused the membrane to float, creating high tension at the inlet attachment. The tank was then emptied, and the membrane was left in a crumpled state at the bottom of the tank. Attempts to fill the membrane to represent filling with cargo were singularly unsuccessful. Large wrinkles were formed which prevented the membrane from covering even the bottom of the tank. Filling had to be halted to prevent damage to the membrane.

Pressurization was tried in an attempt to duplicate the success of the method with Geometry 5. The tests were conducted with a small depth of water on the tank bottom to assist the movement of the membrane. Pressurization also proved to be unsuccessful. Very large wrinkles again formed, and in one instance the membrane became twisted in the tank, figure 5.12.

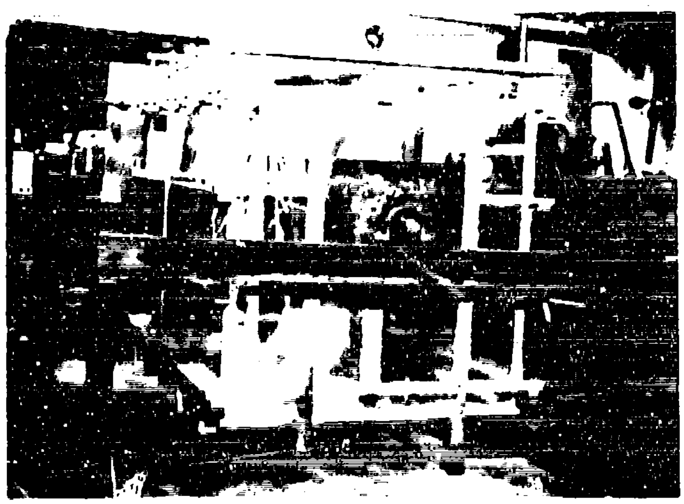
It was concluded that there is no satisfactory method for filling Geometry 7 or similar types of membrane configurations.

5.6 CONCLUSIONS FROM THE MODEL TESTS

Tests with the model tank have shown that Geometry 5 can be used to provide a practical means of isolating oil cargo from ballast water. Initial indications were that wrinkling of the membrane would prove to be troublesome but a gas pressurization method was developed which can overcome the difficulties. In addition, the possibility of abrasion at the top of the membrane was identified as a potential problem for the system. Again, gas pressurization can be used to reduce the magnitude of wear due to abrasion. The operation of a tanker with dual purpose tanks utilizing an inert gas system is described in Chapter 7.



A) AFTER END OF THE MODEL TANK



B) FORWARD END OF THE MODEL TANK

FIGURE 5.1 THE MODEL TANK

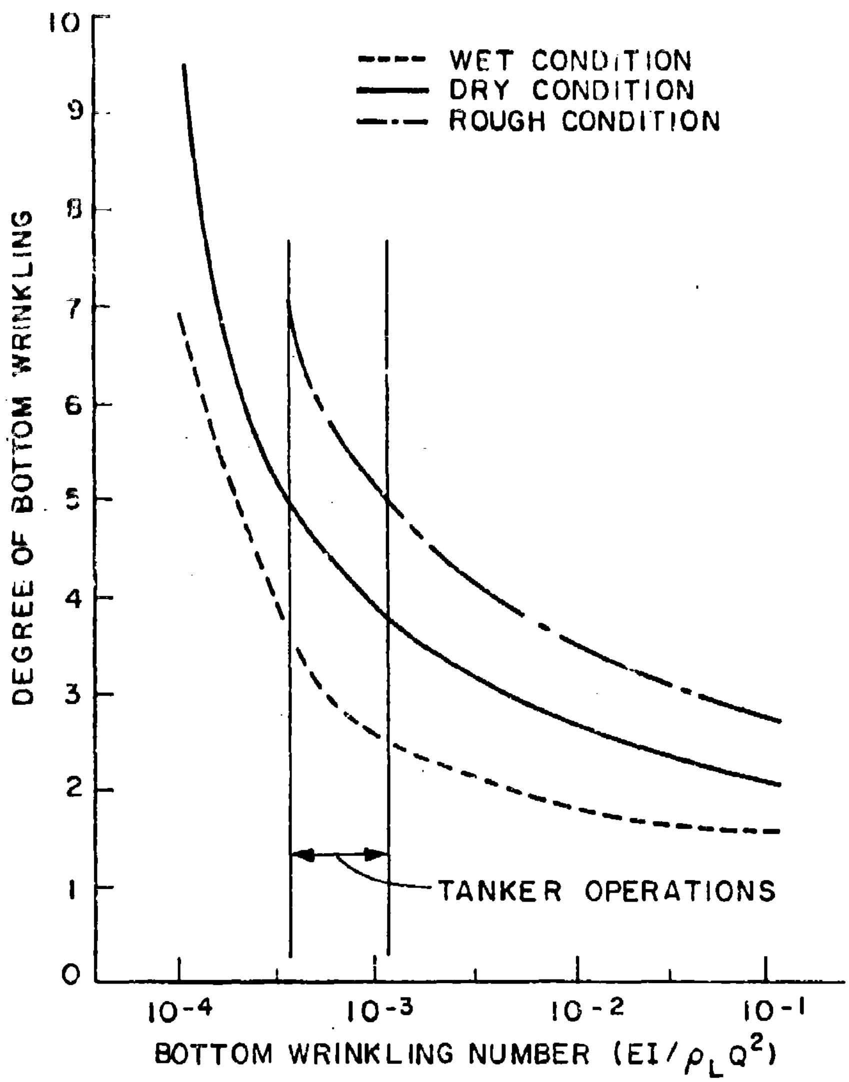


FIGURE 5.2 SEVERITY OF BOTTOM WRINKLES FROM MODEL TANK TESTS

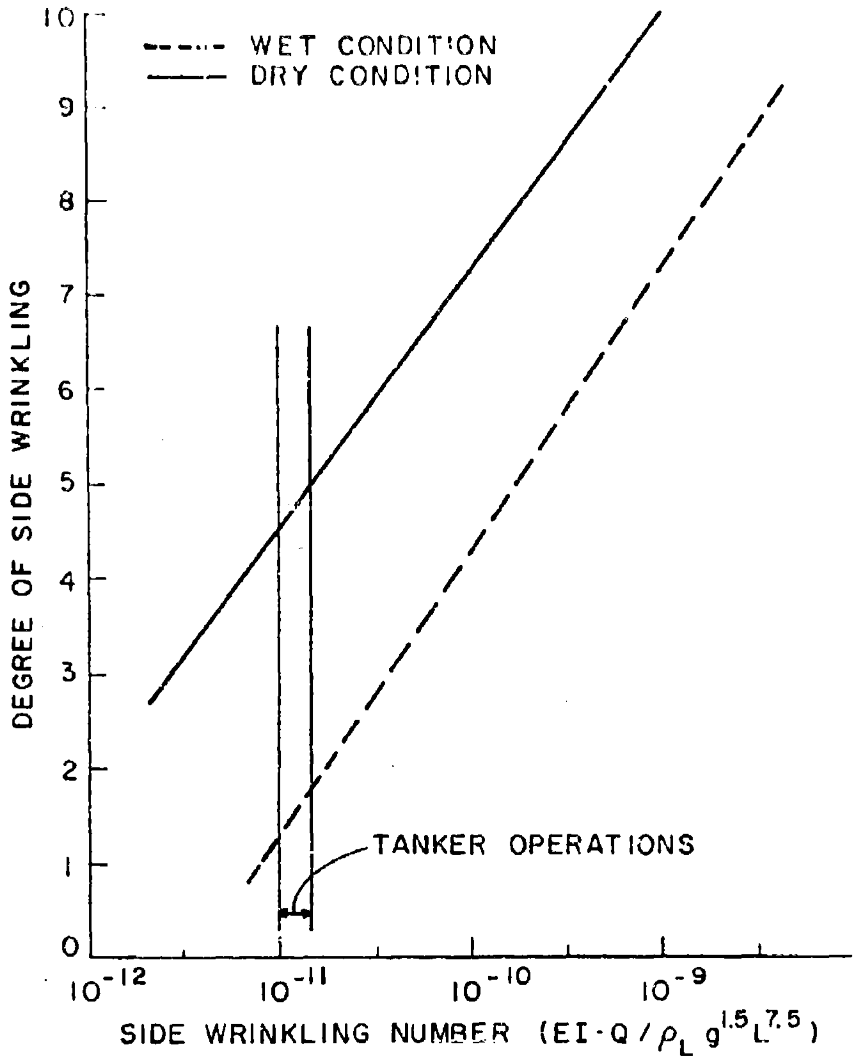


FIGURE 5.3 SEVERITY OF SIDE WRINKLES FROM MODEL TANK TESTS

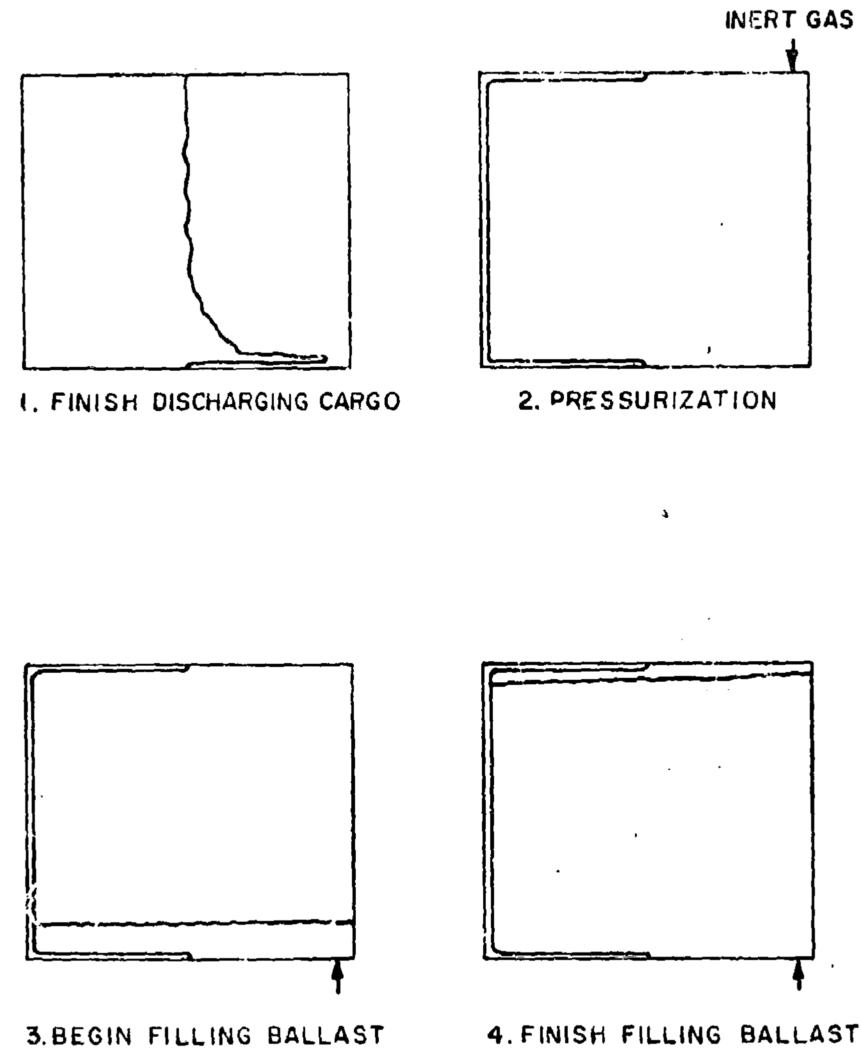


FIGURE 5.4 PRESSURIZATION METHOD NO. 1

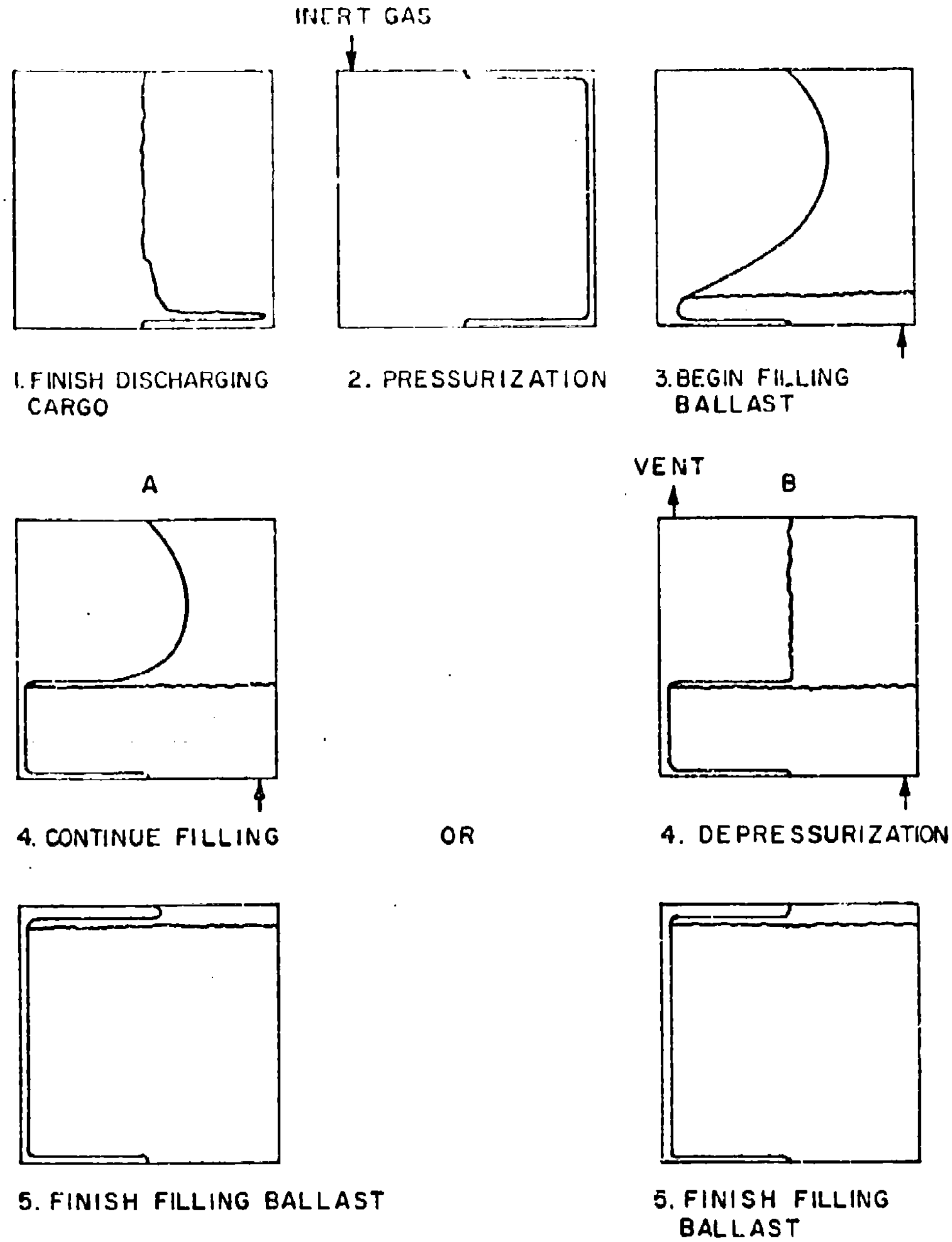


FIGURE 5.5 PRESSURIZATION METHOD NO. 2

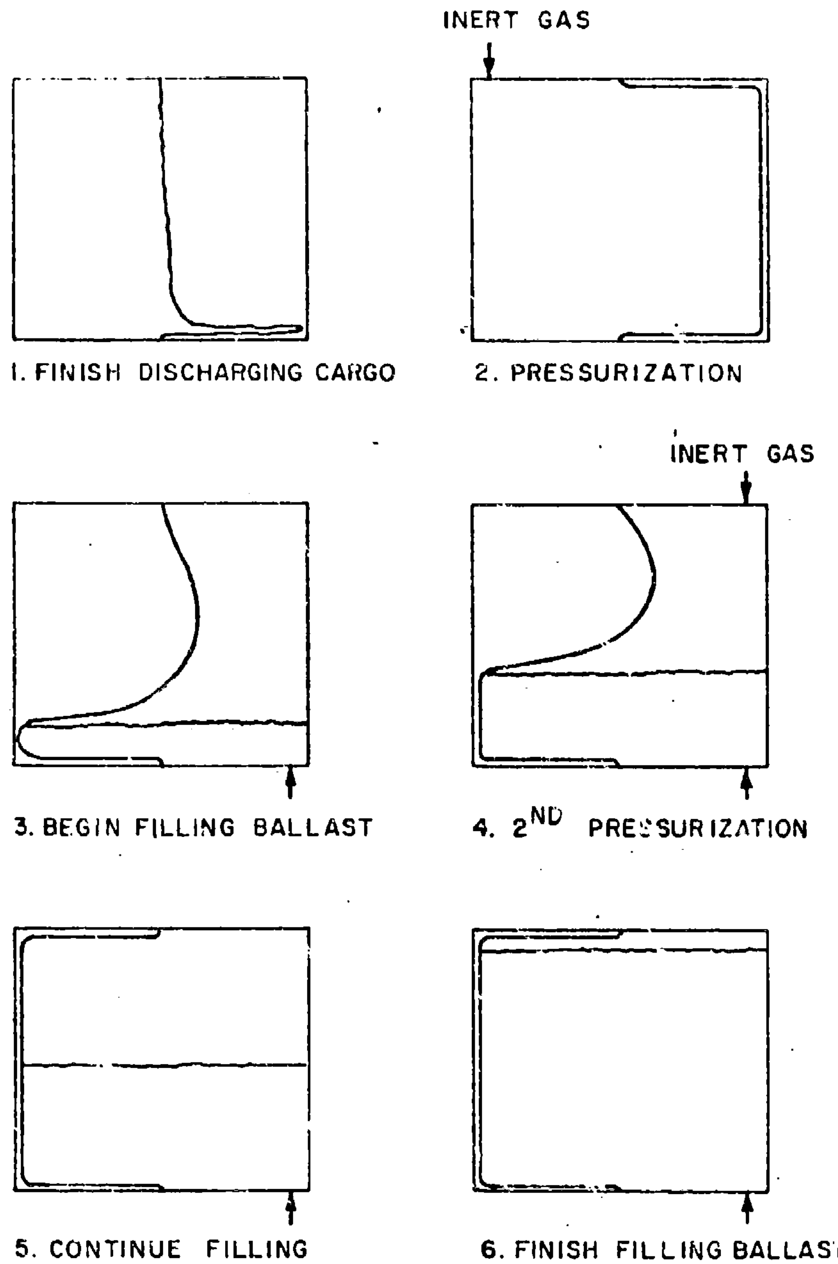


FIGURE 5.6 PRESSURIZATION METHOD NO. 3

FIGURE 5.7 MODEL TANK FITTED WITH THE HINGED FRAMES

FIGURE 5.8 DETAIL OF MEMBRANE FOULING AT CORNER OF THE HINGED FRAME

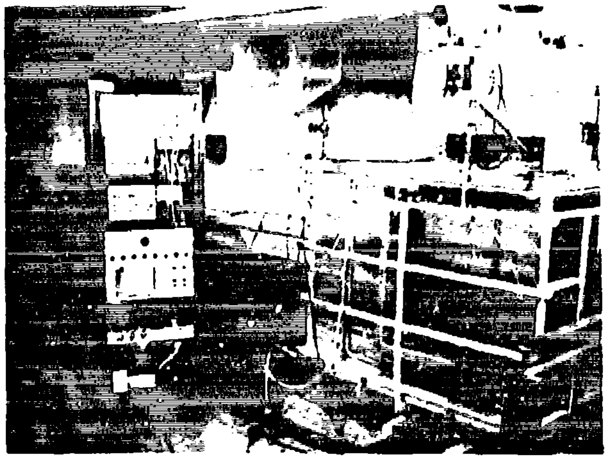


FIGURE 5.9 HIGH SPEED FILMING APPARATUS FOR DYNAMIC TESTING INCLUDING CAMERA, CHART RECORDER, AND ELECTRONIC EQUIPMENT

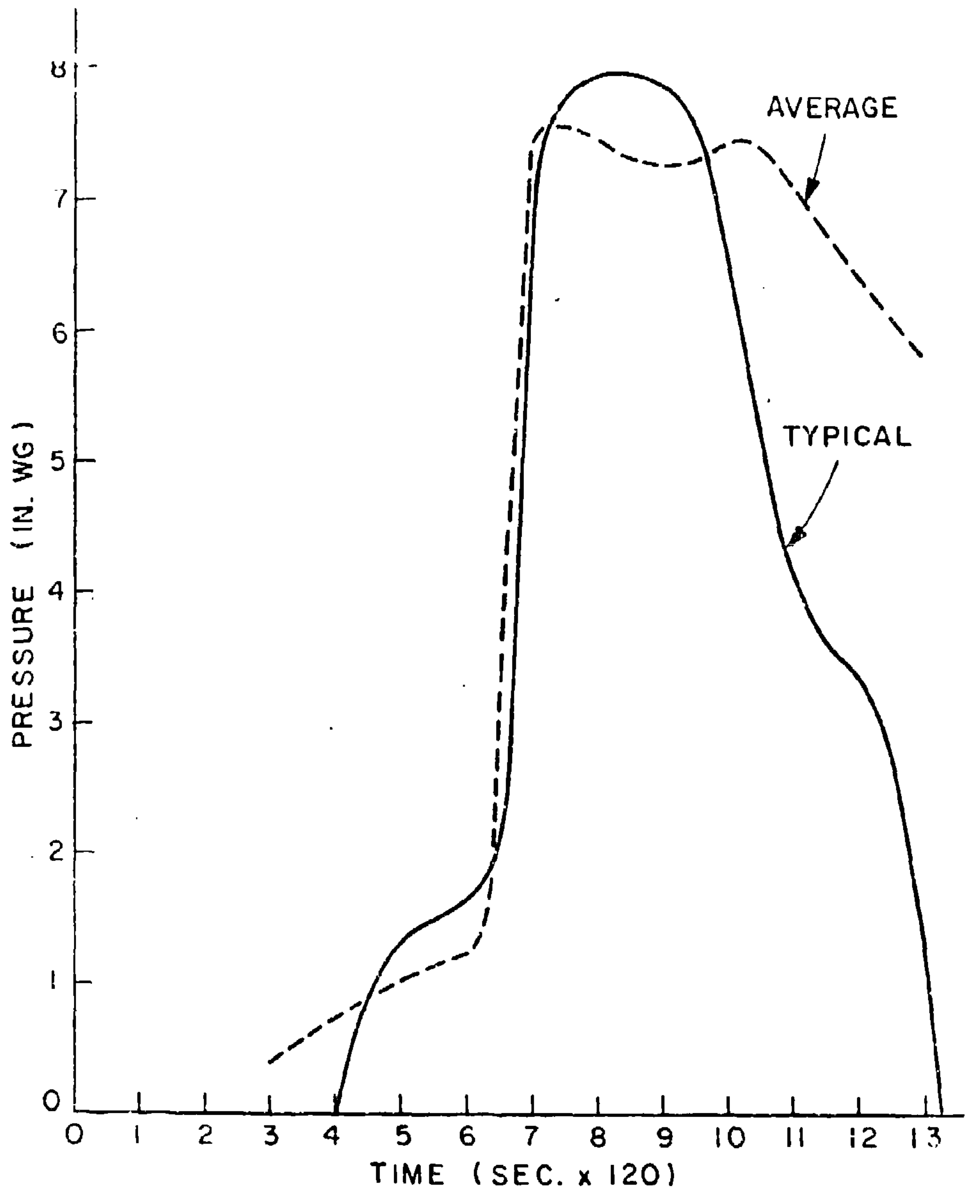


FIGURE 5.10 PRESSURE BETWEEN THE MEMBRANE AND THE MODEL TANK TOP DURING THE DYNAMIC TESTING

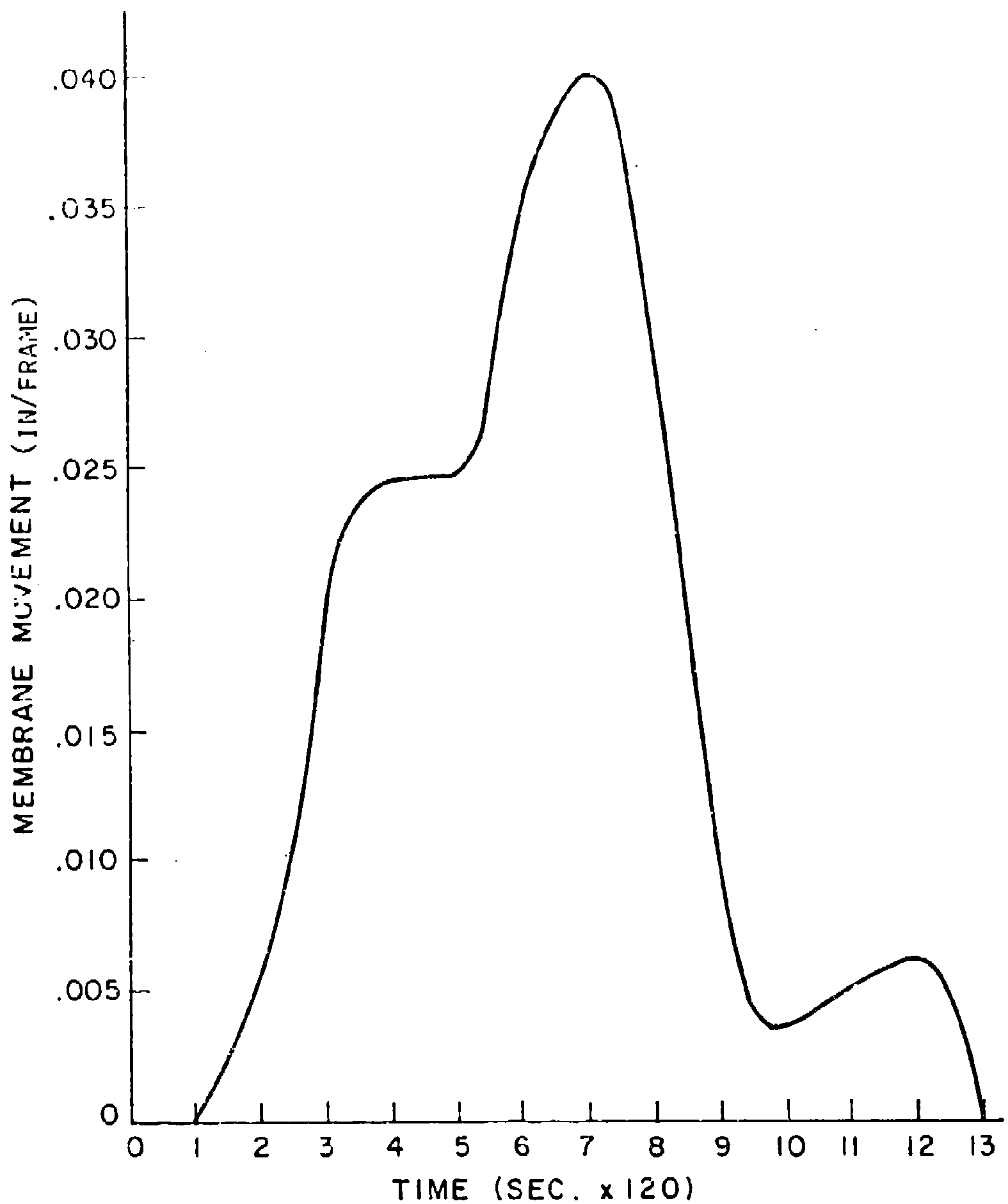


FIGURE 5.11 MEMBRANE MOVEMENT IN THE MODEL TANK DURING THE DYNAMIC TESTING

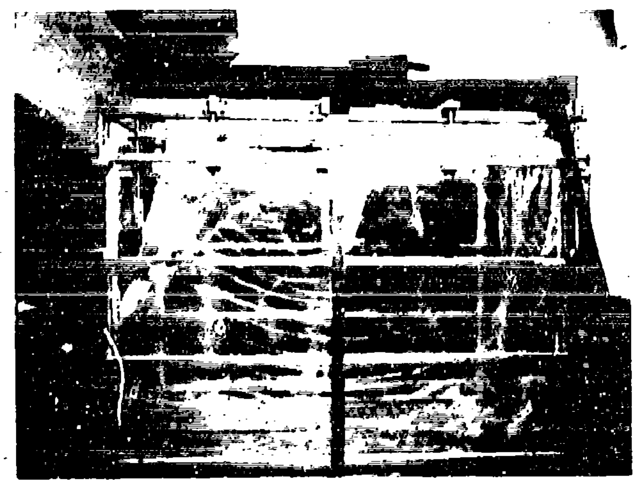


FIGURE 5.12 AIR PRESSURIZATION OF GEOMETRY NUMBER 7 INDICATING MASSIVE WRINKLING OF THE MEMBRANE PRIOR TO FILLING

6. MEMBRANE MATERIALS

Rubbers reinforced with nylon fabric have been used with great success for many years to provide containers for oils and other liquids. The membrane system proposed for tankers is a new application of rubber membranes but sufficiently similar to utilize the developed technology.

6.1 EXPERIENCE WITH FLEXIBLE OIL CONTAINERS AND MEMBRANES

Flexible oil storage containers for gasolines and other oil fuels have been used by the military with success in extremes of climatic conditions for more than a decade.

The Dracone oil barge, first designed in 1956 has been a successful oil container and transporter. It is subject to different loads and operating conditions from the proposed tanker membrane but it has oil on one side of the rubber and seawater on the other.

Fuel for jet engines in airplanes is contained in rubber wing tanks. These tanks are much smaller than the proposed tanker application, but they are subject to incessant movement and accelerations.

A close similarity exists between the proposed tanker system and the fuel conserving membranes in some large gasoline tanks. These membranes have been used for more than two decades to contain and conserve the vapor from volatile liquids in tank farms. The vapor collected forces the membrane to rise and form a hemisphere inside a special steel roof above the liquid. As the liquid cools the vapor condenses and falls into the liquid, the membrane then drops, often to rest on the surface of the liquid until more vapor forms. The sizes of the proposed membranes for tankers are commensurate with the membranes in these stationary gasoline tanks.

It is concluded that the technology exists to provide the membrane materials for the proposed membrane system for tankers.

6.2 OPERATING ENVIRONMENT

Membranes in tankers are expected to operate successfully with all types of hydrocarbon cargoes ranging from heavy fuel oils to high octane gasolines. The majority of tankers, however, are expected to carry crude oils.

In the presence of the cargo or the ballast water the temperature, due to climatic effects, is unlikely to fall outside the range 32°F (0°C) to 120°F (49°C). When the tank is empty of liquid the temperature range would be increased to -10°F (-23°C) to 150°F (66°C). However, cargo heating of heavy fuels and tank washing operations are sometimes carried out at higher temperatures, up to 180°F (82°C).

The membrane, once it has been installed in the tanker, will operate in a darkened atmosphere, free of the detrimental effects of ultraviolet radiation and ozone. The inert gas system which uses stack gases may contain impurities such as certain sulphur products which may prove to be harmful.

6.3 MATERIAL SELECTION

The main rubber used in Dracones, pillow tanks, and the membranes for gasoline tanks is Nitrile. This is a synthetic rubber which has excellent properties in contact with oil, and there has been fabrication experience using nylon reinforced Nitrile for more than two decades. Another synthetic rubber, Neoprene, has excellent properties in the presence of water and very good abrasion properties, and this is sometimes used as the material on the outside of flexible containers. The abrasion properties of Nitrile are not as good as Neoprene; nevertheless they are very good.

New materials both plastics and elastomers have been developed in recent years which have attractive properties. However, many of these new materials have been eliminated from consideration because of the possible high temperature, the presence of vapors, and acidity of some of the cargoes. A recently developed elastomer, Hydrin, has excellent properties, it is compatible with oil and water, and the standard tests suggest that it has the combined good characteristics of Nitrile and Neoprene, see table 6.1. However, this is a new material without the background of experience, and it would be unwise to select it as the membrane rubber at the present time.

The recent developments of materials for membrane reinforcement have provided alternatives to the nylon fabric.

However, much of the experience in the fabrication of high strength membrane materials has been with nylon fabrics; there appears to be no justification for change.

There is no problem with the world supply of the membrane materials. The raw materials are readily available and the size of the potential tanker market would not embarrass the fabricators.

6.4 MEMBRANE FABRICATION

Large reinforced rubber structures are normally fabricated by joining together lengths of rubber coated fabric with overlapping seams. Another technique used with some materials is to spray the rubber onto the fabric which has been sewn into the required shape and then to cure the rubber.

The method currently favored with the fabricators is to join the lengths of cured nylon reinforced rubber by means of vulcanized overlapping seams. The most satisfactory procedure for the seam construction is to use a single rubber, Nitrile, for the two sides of the membrane rather than using Nitrile on one side and Neoprene on the other.

Nitrile is not considered as a suitable rubber for the spraying technique. The properties of the final product are not satisfactory.

6.5 FABRIC STRENGTH

The maximum fabric tension during the normal operation of the membrane system, would occur as the tank is being filled. The procedure is to hold back the liquid with inert gas pressure. This action, as demonstrated by model tests facilitates the smooth operation of the membrane. The tension in the membrane during the filling procedure can be calculated using a simple numerical procedure, ref. 6.1. The geometry assumed for the calculation is shown in figure 6.1. The results for a large tank 100 ft. x 80 ft. x 70 ft. are presented in figures 6.2, 6.3 and 6.4. The calculated pressure difference across the membrane, fabric tension, and liquid depths are plotted against the distance of the membrane from the wall. The results were used to predict the membrane tension and the pressure difference across the membrane which allow it to move to the tank wall. The calculations were extended to determine the effect of having a pressure difference in excess of this value. The results show that the membrane would remain away from the tank wall and there would be an increase in membrane tension but not to dangerous levels. In all the gas pressurization experiments with the model tank, the displacement of the membrane created the pressure difference necessary to support the liquid as the membrane reached the tank wall, i.e. zero distance from the wall. The depth of liquid in the model at this point was exactly as predicted from the analysis. The predicted fabric tension at this point is about 100 lbf/in and the pressure difference is approximately 0.25 lbf/in^2 in the full size tank. The strength of nylon fabric necessary to support this tension with an adequate safety factor is about 600 - 800 lbf/in breaking strength for the 250,000 DWT tanker.

6.6 RUBBER THICKNESS

The required rubber thickness on both sides of the nylon reinforcement depends on the conflicting requirements of wear of the rubber as a result of abrasion and the rubber stresses in folds.

The region where abrasion is likely to occur was shown from the model tests to be at the tank top. This abrasion would arise from the movement of the membrane as the liquid slaps against the membrane which is pressed against the tank top. The uncertainities with regard to the nature of surface roughness of the tank top, the movement and pressure of the membrane as predicted from the model tests, and the abrasion properties of the rubber, all combine to reduce the confidence level of the prediction of membrane life. Nevertheless, an attempt has been made to predict the time to abrade 0.1 inch of rubber in the full size tanker using the results from the model test and the available wear data for rubbers, ref. 6.1. The predicted life is less than 500 hours in moderate waves; this is obviously unacceptable. Lubrication of rubbers has been shown to reduce the wear of rubbers. On the oil side of the membrane, lubrication can be anticipated with crude oils and heavy fuels because of the oil that would cling to the membrane and the tank top. On the ballast side of the membrane lubrication would be uncertain and could not be relied upon, although provisions could be made to provide water as a lubricant. It is believed that the abrasion problem could be reduced to negligible proportions by providing a slight inert gas pressure, 6 in H_2O, over the liquid. The membrane would press against the tank top and would have little tendency to move in a seaway. This operational feature is discussed in Chapter 7.

The folds that would occur in the tanker membrane applications are at the attachment corners and in wrinkles formed on the tank surfaces. In all cases the folds are likely to be very tight leading to high local extensions and stresses in the rubber. The nylon reinforcement would not extend in the folds and would constrain the rubber. Experience shows that thin rubber has lower extensions in folds.

The rubber thickness need not be uniform over the whole membrane, it could be thicker at the regions where abrasion is anticipated and thinner elsewhere where folding or wrinkles could occur. For the purposes of determining the cost of the membrane it was assumed that the thickness of the rubber would be 1/4 inch for the 250,000 DWT tanker. This value is comparable to the rubber thickness on large Dracones but thicker than that used in gasoline tank membranes and pillow tanks.

6.7 MEMBRANE ATTACHMENT

The preferred membrane configuration, Geometry 5, is attached around the periphery of the dual purpose tank on a vertical center line. The attachment must provide a perfect seal and allow the membrane to move without damage from one side of the tank to the other during the filling processes. Furthermore, the attachment must be strong enough to withstand the forces imposed by the membrane for the life of the tanker.

The most serious problems with regard to damage of the rubber at the attachment occur at the corners of the tank where deep folds are formed. The small brackets at the corners, required for structural reasons, reduce the seriousness of the folding action because one large fold at each corner becomes two smaller folds at each bracket. A further possible source of damage would occur when the membrane is pressed against the attachment with high hydrostatic pressure. Sharp edges of any sort are obviously unacceptable in this situation.

A suitable attachment method was designed and tested with the aid of a full size model of a tank corner, as shown in figures 6.5 and 6.6, and the maximum extensions in the folds were measured. The maximum extension was approximately 75% at the folds. This is not a high extension for rubber and would be expected to provide an almost infinite fatigue life. The attachment provides generous radii for the membrane to bend over, there are no sharp edges to damage the membrane, and the nuts are sunk beneath the top of the attachment. All these features would enhance the life of the rubber.

6.8 MEMBRANE LIFE

In new applications of rubber materials it is difficult to predict with adequate precision what the operating life will be. Experience from similar applications are the only guides. The average life of membranes in the gasoline tanks is about 10-12 years, and flexible fuel tanks have an operational life of 5 or 6 years because of aging due to ultraviolet radiation. It is therefore expected that the life of tank membranes will be such that each membrane would, on average, be replaced once during the operational life of the tanker.

6.9 MEMBRANE COSTS

The costs of the membrane, including materials and fabrication costs have been estimated by U.S. manufacturers for multiple orders assuming 1/4 inch Nitrile rubber reinforced with 13 oz/yd nylon

250,000 DWT tankers	\$10-15	per sq. yd. for material
	\$17.50-32	per sq. yd. for fabrication, including material
50,000 DWT tankers	\$10-15	per sq. yd. for material
	\$18-32	per sq. yd. for fabrication, including material

\$25 per sq. yd. was used in the economic analysis.

REFERENCES

6.1 Volume III of this report, also Rubin, Leslie, "A Study of Impermeable Membranes for the Isolation of Oil from Seawater Ballast in Tankers", M.S. Thesis, Department of Ocean Engineering, MIT, January 1973.

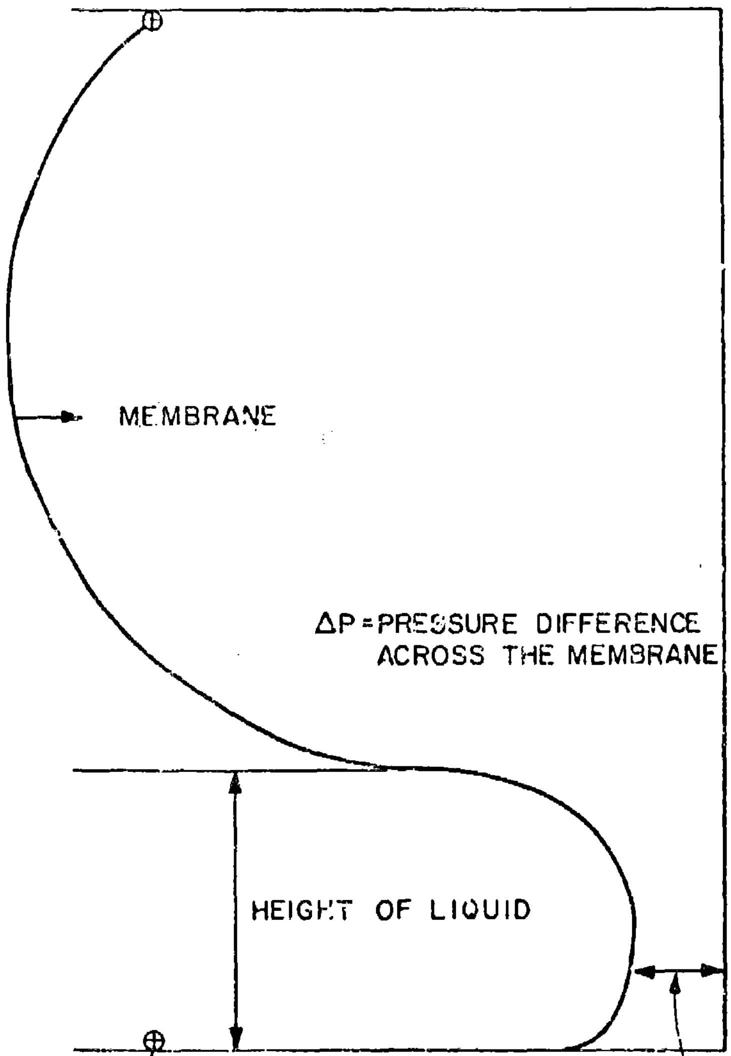


FIGURE 6.1 DIAGRAM SHOWING THE GEOMETRY USED FOR THE ANALYSIS OF THE FILLING PROCEDURE

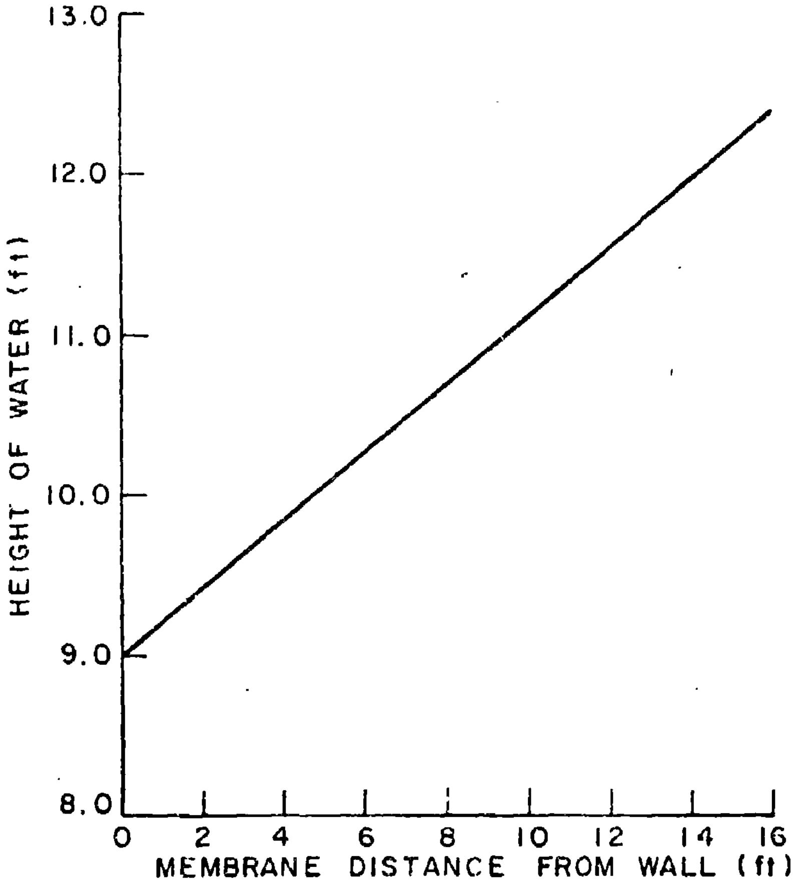


FIGURE 6.2 HEIGHT OF WATER AS A FUNCTION OF MEMBRANE DISTANCE FROM WALL

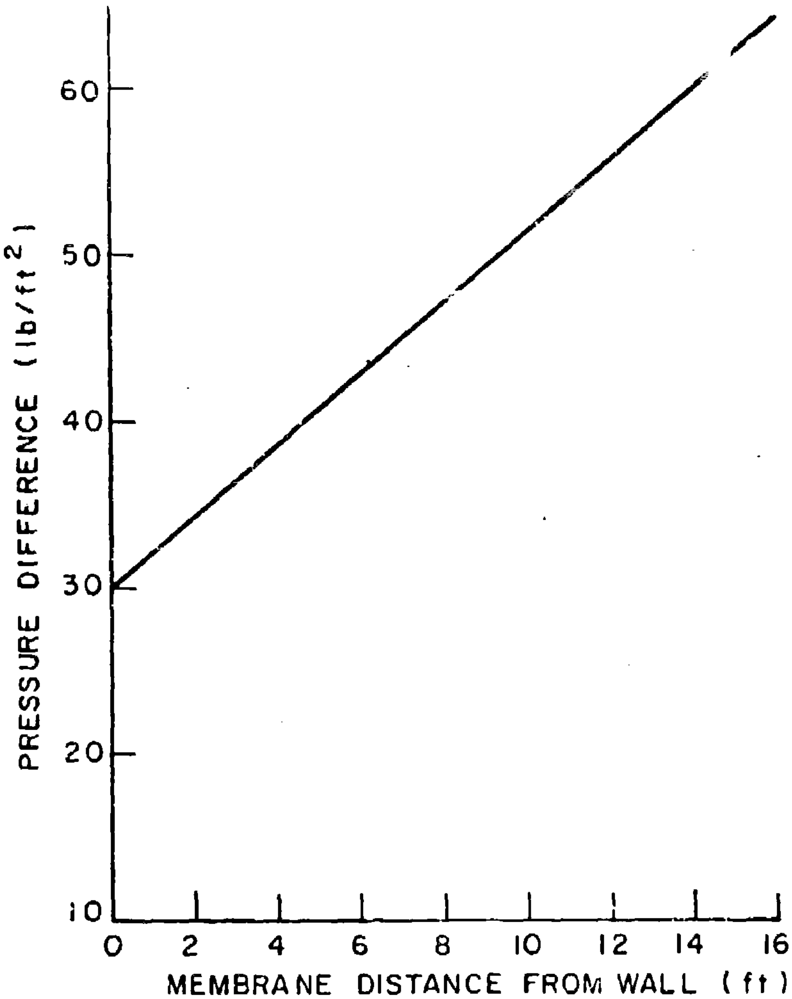


FIGURE 6.3 PRESSURE DIFFERENCE AS A FUNCTION OF MEMBRANE DISTANCE FROM WALL

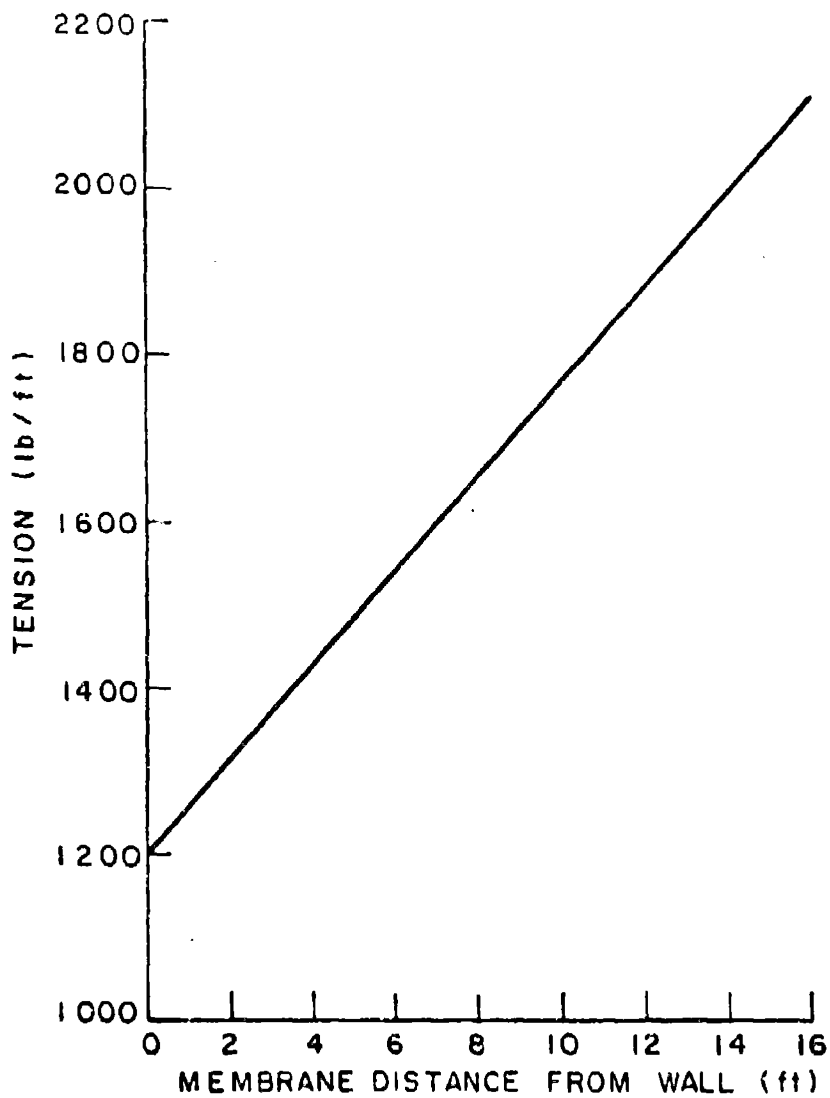


FIGURE 6.4 MEMBRANE TENSION AS A FUNCTION OF MEMBRANE DISTANCE FROM WALL

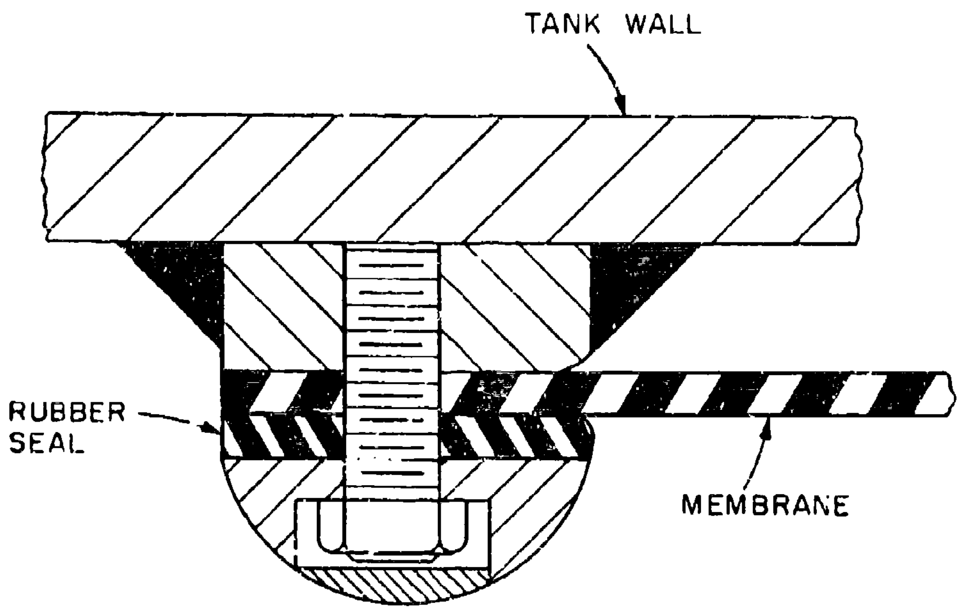
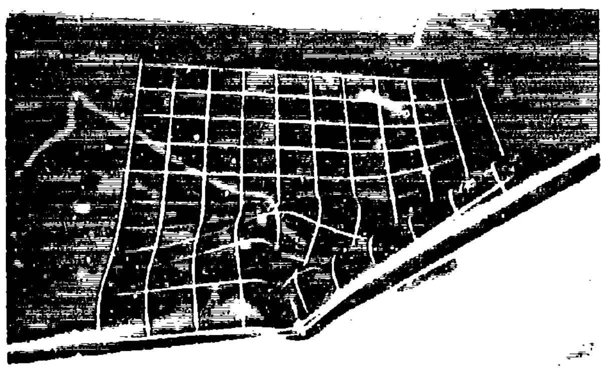


FIGURE 6.5 PROPOSED ATTACHING MECHANISM

A) SIMULATED CARGO FILLED CONDITION



B) SIMULATED BALLAST WATER FILLED CONDITION SHOWING A DEEP FOLD

FIGURE 6.6 FULL SIZE MODEL OF THE TANK CORNER AND ATTACHMENT MECHANISM

7. TANKER OPERATIONS WITH MEMBRANE TANKS

Model tests have established that Geometry 5 is probably the optimum configuration for membrane systems in tankers. The test program has also indicated that the main problem areas associated with the operation of membranes in tankers are likely to be the formation of wrinkles during filling and the possibility of abrasion in a seaway. Methods were developed during the study to overcome these problems. The experience gained from the model tests has been utilized to provide a practical mode of operation for the dual purpose tanks.

7.1 CARGO AND BALLAST WATER OPERATIONS

Model tests have shown that gas pressure can be utilized to reduce the formation of wrinkles and also to minimize the wear due to abrasion at the top of the membrane. Gas pressure is available from inert gas systems which are normally installed in large modern tankers.

7.1.1 The Proposed Inert Gas System

Typical inert gas systems in use at the present time take flue gas from the boiler uptakes, pass it through a scrubber, and deliver the gas under pressure to the tanks.

In the dual purpose tanks the system should be arranged to deliver inert gas to both sides of the membrane at a pressure sufficient to support the membrane, at least 6 in H_2O. The satisfactory operation of the membrane system requires the inert gas to be provided on the liquid side during transit in order to minimize the wear due to abrasion at the top of the membrane, and also during the emptying operation in order to restrain the membrane when filling commences. At the beginning of the filling operation inert gas should be switched to the filling side. What happens to the inert gas on the other side of the membrane at this time is not critical. The following situations are considered satisfactory:

1. The gas may be vented to atmosphere.
2. The tank may be allowed to vent to atmosphere through a relief valve set at a pressure of about 0.5 lbf/in^2.
3. The gas valve may be left open so that gas can be transferred to the other side of the membrane by the displacement of the membrane.

When the tank is filled, the inert gas valve on the liquid side remains open while the valve on the other side is closed. The operations are illustrated on figure 7.1.

The main requirement of the inert gas system is that it should be capable of providing inert gas when the pressure in the gas main drops below a set value. The dual purpose tanks would be fitted with two venting systems having pressure-vacuum relief valves and two inert gas systems fitted with manual or remote controlled valves.

The filling and emptying operations described above are essentially simple procedures and consistent with the current method of using inert gas systems in tankers.

7.2 CLEANING OPERATIONS

Tank and membrane cleaning is required for various reasons, such as to upgrade the cargo. The method of doing this for dual purpose tanks is basically no different from conventional tanks. The tank is first filled with inert gas to reduce the explosion risk and to push the membrane against the tank walls, and a conventional washing method is used. After pumping the wash residue to a slop tank, the tank is then clean and ready to accommodate an upgraded cargo.

Occasionally it is necessary to send men into the tanks to remove solidified matter from the tank bottom. The smooth bottom design of the dual purpose tanks would require less frequent "mucking" than conventional tanks. A portable ladder could be used to provide access after gas freeing. The men would only have to clean the tank bottom and not the membrane bottom because there would be very little residue on the membrane. This operation would not be encumbered by the membrane as it would hang clear of the work area and not move to threaten the men except in very rough weather when mucking would not be contemplated.

7.3 SAFETY CONSIDERATIONS

The main concern is the possibility of fire and explosion arising from the use of a membrane in the dual purpose tanks.

The membrane itself has no effect on fire and explosion. There is no possibility of producing static electricity by rubbing the elastomer against the tank surfaces, and the membrane should not support combustion.

There is one feature of the membrane operation that is different from conventional tank operations. This is due to the displacement of the membrane during the initial stages of filling, which causes gas to be sucked into the filling side. If the vents were open at this time, then air would enter as well as the inert gas and an explosive mixture could result. However, the risk is probably lower than that associated with filling an air-filled conventional tank with the same cargo. Reliable pressure vacuum valves on the vent system should be provided to allow only inert gas into the membrane tanks, thus assuring safety.*

Tank cleaning operations for membrane tanks, as discussed earlier, would be carried out in an inert atmosphere and would therefore have the same safety qualities as in conventional tanks.

It is concluded that the safety of tankers with membranes would probably be as good if not better than equivalent conventional tankers.

7.4 MISCELLANEOUS OPERATIONS

Certain additional tanker operations require modification due to the inclusion of a membrane. Cargo heating is necessary for some cargoes, but there can be no protuberances into the tank. Thus, the heating device would be either flush with the tank wall on the cargo side of the membrane near the cargo suction or it could project into the tank provided it is covered over by plating.

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*Tanks pressurized with inert gas provide a safety hazard because of possible "blowing" of hatch covers. All tankers with inerting systems have this hazard and safe hatch designs are required.

The measurement of the ullage would be made more complicated by the presence of the membrane. It is thought that the usual pressure measuring devices would provide this measurement, but they would have to be flush or nearly flush with the tank walls. More sophisticated methods can be conceived, but all methods requiring mechanical transit of the tank depth would be eliminated.

As mentioned previously, access to the tank would be provided by portable ladders or other extractable devices.

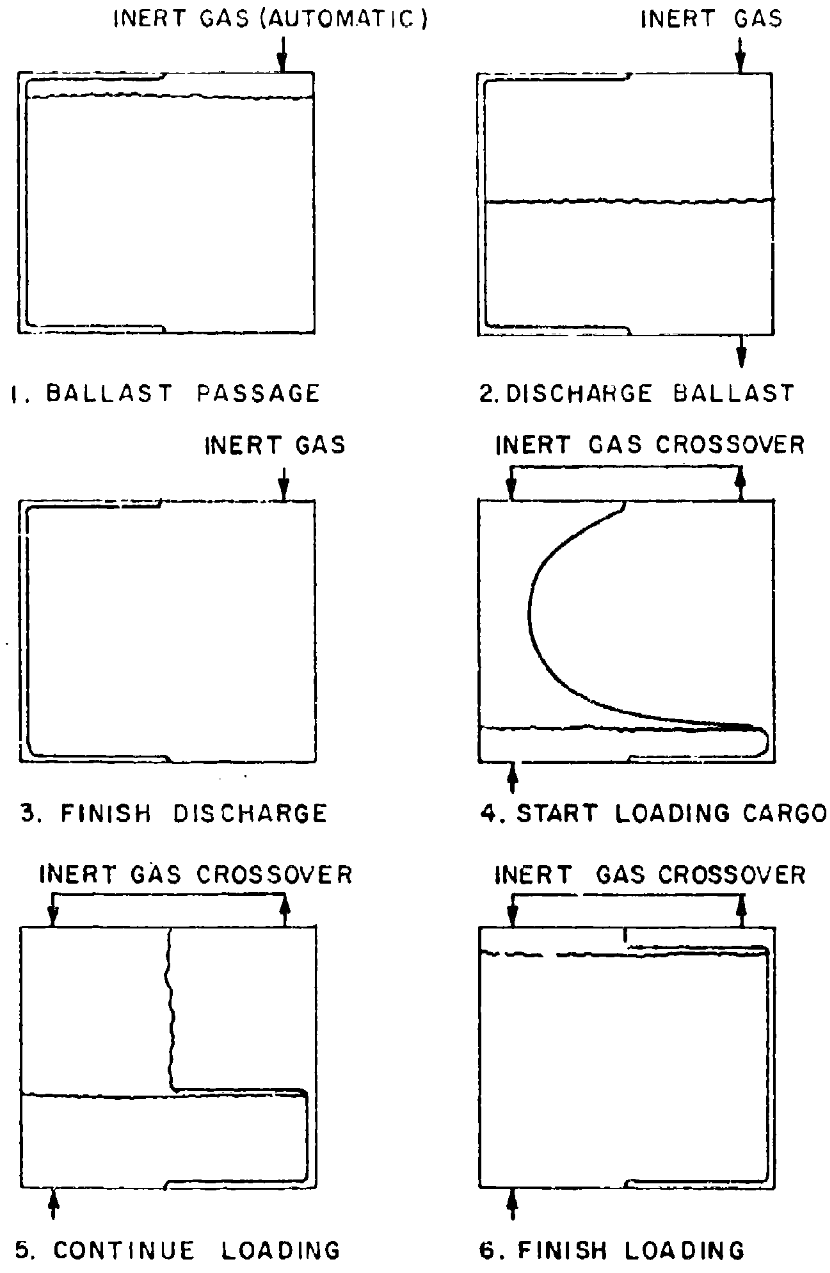

FIGURE 7.1 PROPOSED OPERATION OF PREFERRED INERT GAS SYSTEM

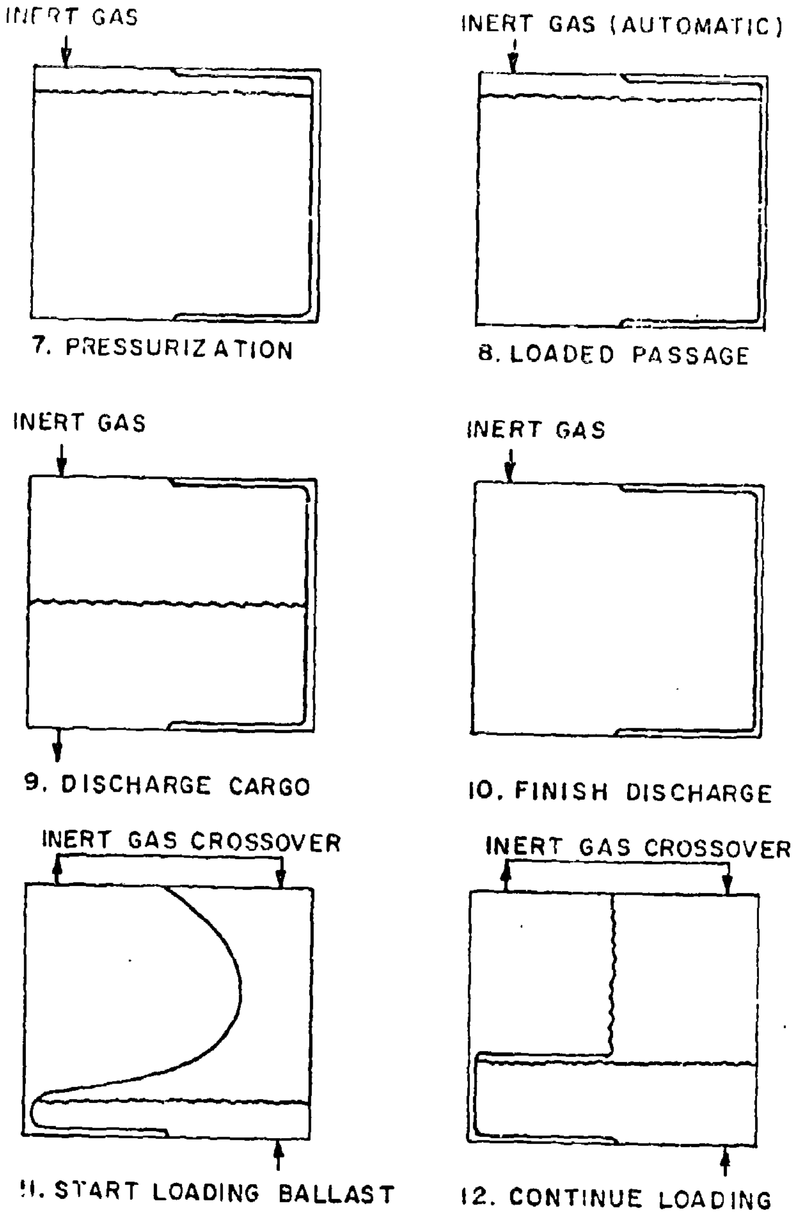

FIGURE 7.1 PROPOSED OPERATION OF PREFERRED INERT GAS SYSTEM (CONTINUED)

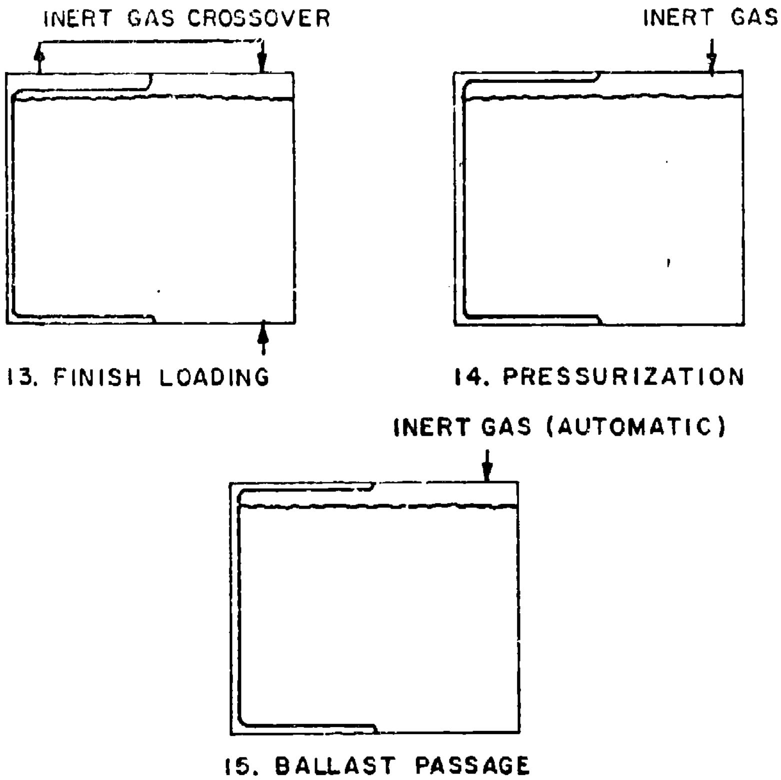

FIGURE 7.1 PROPOSED OPERATION OF PREFERRED INERT GAS SYSTEM (CONTINUED)

8. TANKER DESIGN

8.1 REQUIREMENTS FOR MEMBRANE EQUIPPED TANKERS

Tankers to be equipped with impermeable membranes have special design requirements compared to conventional tankers. The most important difference is that the cargo/ballast tanks must have smooth walls on all six faces and be free of all internal structure. This basic requirement leads to concern for the placement of the structure in tanker designs and provides the following constraints:

1. The membrane tanks will be center tanks.
2. Consecutive tanks will not have membranes.
3. The membrane tanks will have double bottoms and double decks.

8.1.1 Double Bottom Arrangement

The double bottoms in the designs of the new tankers have been arranged to conform to the IMCO recommendations, ref. 8.1, which require that the double bottoms extend over the full width and length of the tanker bottom under the cargo and have a minimum height corresponding to the beam divided by 15. The double bottom provides volume for segregated ballast water and space for a pipe tunnel. In the modified tankers the double bottom is restricted to the membrane tanks and the space would be utilized for segregated ballast water.

8.1.2 Double Deck Arrangement

The double deck encloses the deck girders and would be used for clean ballast water only in both the new and modified tankers. The space is too small and inconvenient for the carriage of cargo.

8.2 BALLAST REQUIREMENTS

The ballast requirement for tankers is partially covered by classification society rules but is more a matter of experience. The rules require a minimum draft forward for good sea-keeping performance. Experience from a fleet of tankers shows that a somewhat larger ballast is utilized than is required by the rules, ref. 8.2. The typical ballast requirement was about 55% displacement. In the design studies described here the ballast requirement was taken as > 55% of displacement for the new and the modified tankers.

8.3 NEW 250,000 DWT TANKER

The inner bottom height of 11 ft. 4 inches was calculated using IMCO recommendations, ref. 8.1. Minimum deck, inner bottom, and bottom scantlings were determined from ABS Rules, ref. 8.3, and were used to calculate the ship scantlings. The section modulus of the existing 250,000 DWT tanker was calculated and used as the required section modulus for the new 250,000 DWT tanker. Minimum bottom scantlings were used along with the inner bottom to find the scantling of the deck necessary to retain the section modulus of the existing tanker on the new tanker. The resulting deck scantlings were greater than minimum ABS rules.

In order to maximize the effectiveness of the membrane tanks the width of the center tank was increased from 69 ft. on the parent ship to 87 ft. on the new 250,000 DWT tanker. A survey of literature indicated that this center tank width was large but it was within the conventional building practice. The length of the center tanks was limited by ABS rules to .1L of the tanker (108.5 ft.) for tanks without swash bulkheads. In membrane tanks (2, 4, 6, 8 center) the inner deck height was set at 6.562 ft. below the deck plating. The deck girder height is 7.562 ft. in all tanks except membrane tanks. In the membrane tanks the deck girder is cut down to 6.562 ft. and the inner deck acts as a large flange on the deck girders.

The tank arrangement is shown in figure 8.1. This arrangement provides 61% of full load displacement in the ballast condition and a cargo capacity of 236,673 L.T. at 34°API, a loss of 1.4% of the parent ship's cargo capacity. The maximum still water bending moment was in the full load condition and was 1,634,336 ft. tons. Trim was 5.269 ft. by the bow. Tables 8.1, 8.2, 8.3 and 8.4 provide additional design data.

8.4 MODIFIED 250,000 DWT TANKER

The swash bulkheads on the parent ship were replaced by oil-tight bulkheads; this gives the modified 250,000 DWT tanker 9 center tanks. All stiffening structure on the existing tanker was aft of the oil-tight bulkhead. This means that for membranes in 1, 3, 5, 7, 9 center three of the existing bulkheads would be turned. The five new bulkheads added in place of the swash bulkheads will be placed such that the stiffening structure is outside the membrane tanks.

The ABS Rules were used to determine the scantlings of the inner bottom and inner deck to be added to the existing 250,000 DWT tanker. The inner bottom was set at the keel height, and additions to the web frame were made so that the inner bottom was supported by this structure. The deck girders in the membrane tanks were cut away by 1 foot, and additions to the web frame were made so that the inner deck was supported by this structure. Corner plates were added to cover the brackets between the longitudinal bulkheads and the inner bottom, between the oil-tight bulkhead and the inner bottom, between the inner deck and the longitudinal bulkhead, and between the oil-tight bulkheads and the inner deck.

The arrangement of the modified 250,000 DWT tanker is shown in figure 8.2. This arrangement results in a 56.6% of full load displacement ballast condition and a cargo capacity of 224,919 L.T., a loss of 6.3% of the cargo capacity of the parent ship.

8.5 NEW 50,000 DWT TANKER

The inner bottom height of 7 feet was calculated using IMCO Recommendations, ref. 8.1. The scantlings for the new 50,000 DWT Tanker were determined by the same method as the new 250,000 DWT tanker's scantlings.

The center tank width was not changed from that of the parent tanker. The length of the tanks were set to the maximum allowable length according to ABS Rules (.1L = 73.33 ft.) Two membrane tanks provide the necessary ballast for 62.8% of the full load displacement. The inner deck height in the two membrane tanks was set at 4.92 ft. below the deck plating. The deck girder height was set at 5.92 ft. everywhere except in the membrane tanks. Again, as in the new 250,000 DWT tanker the deck girder height was cut down to 4.92 ft. in the membrane tanks.

The tank arrangement is shown in figure 8.3. This arrangement allows a cargo capacity of 45,274 L.T. at 34° API, a loss of 1.02% of the parent ship's cargo capacity. The maximum still water bending moment was in the full load condition and was 713,793 ft. tons. Trim was 2.554 ft. by the bow.

8.6 MODIFIED 50,000 DWT TANKER

Five of the ten center tanks were used as dual purpose tanks which provide the modified 50,000 DWT tanker with 57.8% of full load displacement in the ballasted condition. All stiffening structure on the oil-tight bulkheads is aft of the bulkheads. For membranes in 2, 4, 6, 8, 10 center, five of the center bulkheads would be turned.

The ABS Rules were used to determine the scantlings of the inner bottom and inner deck to be added to the existing 50,000 DWT tanker. As in the modified 250,000 DWT tanker the inner bottom was set at the keel height and additions to the web frame were made. The deck girders were cut away by one foot and additions to the web frame were made to support the inner deck. Corner plates were added as in the modified 250,000 DWT tanker.

The arrangement of the modified 50,000 DWT tanker is shown in figure 8.4. This arrangement results in a cargo capacity of 45,390 L.T. at 34°API, or a loss of 0.8% of the cargo capacity of the parent ship. The maximum still water bending moment was in the full load condition and was 889,870 ft. tons. Trim was 5.328 ft. by the bow.

REFERENCES

8.1 "Recommendation to put into Effect Requirements Relating to Tank Arrangements and to the Limitation of Tank Size from the Point of View of Minimizing Pollution of the Sea by Oil",IMCO Resolution A.247(VII), October 1971.

8.2 T. A. Gardner, "Investigation of High Depth Segregated Ballast Tankers," Report No. E11.15TMR. 71, Esso International Inc. Tanker Department, 1971.

8.3 Rules for Building and Classing Steel Vessels, American Bureau of Shipping, 1971.

TABLE 8.1 CAPACITIES

DESIGN	DWT	NO. DUAL-PURPOSE TANKS	CARGO m^3	SEGREGATED BALLAST (L.T.)	DUAL TANK BALLAST (L.T.)	TOTAL CLEAN BALLAST (L.T.)	DISPLACEMENT (L.T.)	BALLAST DISPLACEMENT ÷ FULL LOAD DISPLACEMENT %
50-A	50,340	---	59,514	10,825	---	10,825	64,079	45.5
50-Y1	49,874	2	56,499	13,854	7,717	21,571	64,079	63.0
50-Y2	50,152	2	56,499	13,854	7,717	21,571	64,079	62.6
50-Z	49,990	5	61,984	7,390	10,936	18,326	64,079	57.8
250-A	249,952	---	302,700	35,555	---	35,555	286,670	28.7
250-Y1	246,673	4	303,011	52,534	73,297	125,831	286,670	61.3
250-Y2	247,700	4	303,011	52,534	73,297	125,831	286,670	61.0
250-Z	234,919	5	267,334	78,904	33,588	112,492	274,544	56.6

TABLE 8.2 CARGO CARRYING CAPACITY

DESIGN	AVAILABLE CARGO CAPACITY (L.T.)	MAXIMUM CARGO CARRIED (L.T.)	% LOSS IN CARGO CARRIED
50-A	50,072	45,740	----
50-Y1	47,535	45,274	1.01
50-Y2	47,535	45,552	.41
50-Z	52,150	45,390	.76
250-A	254,674	239,952	----
250-Y1	254,936	236,673	1.36
250-Y2	254,936	237,700	.93
250-Z	224,919	224,919	6.26

TABLE 8.3 LONGITUDINAL STRENGTH SUMMARY

DESIGN	CONDITION OF MAX. BENDING MOMENT	BENDING MOMENT (ft-tons)	SHEAR FORCE (tons)
50-A	----	----	----
50-Y1	FULL LOAD	713,793	5,789
50-Y2	FULL LOAD	713,793	5,789
50-Z	FULL LOAD	889,870	5,891
250-A	----	----	----
250-Y1	FULL LOAD	1,634,336	9,455
250-Y2	FULL LOAD	1,634,336	9,455
250-Z	----	----	----

TABLE 8.4 TOTAL INTERNAL TANKAGE AREA REQUIRING SPECIAL COATING

DESIGN	AREA (m^2)	AREA (ft^2)
50-A	72,000	775,000
50-Y1	85,800	922,500
50-Y2	85,800	922,500
50-Z	75,700	814,600
250-A	95,700	1,030,000
250-Y1	134,000	1,442,100
250-Y2	134,000	1,442,100
250-Z	106,500	1,147,300

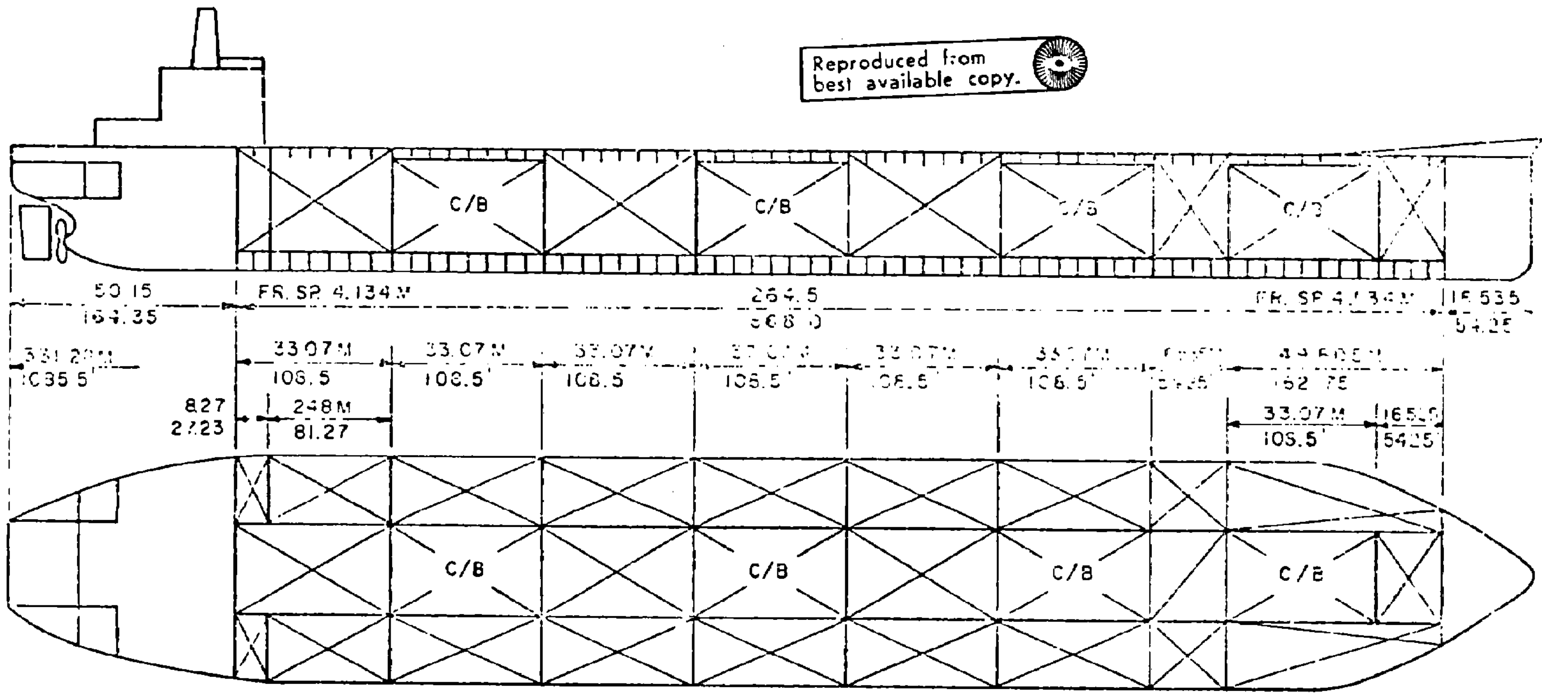

FIGURE 8.1 ARRANGEMENT OF NEW 250,000 DWT TANKER (250-Y1, 250-Y2)

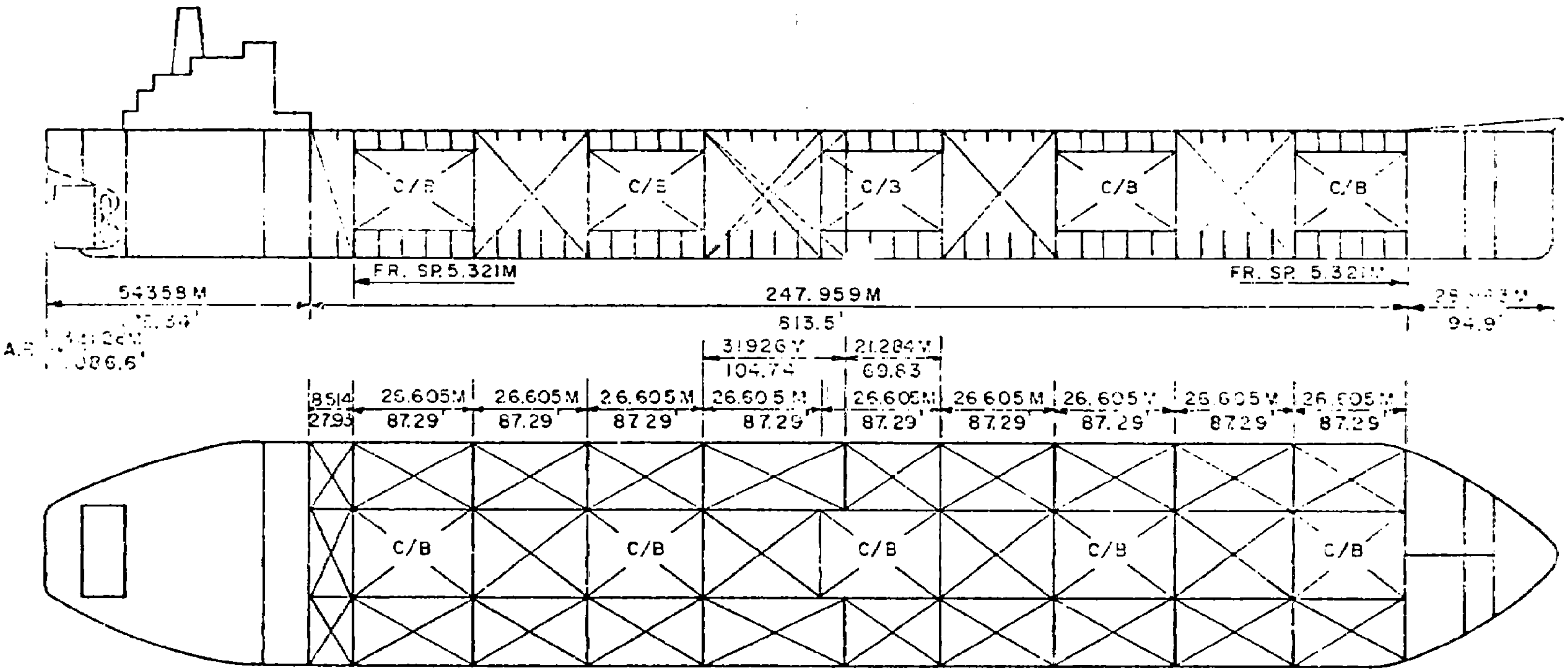

FIGURE 8.2 ARRANGEMENT OF MODIFIED 250,000 DWT TANKER (250-Z)

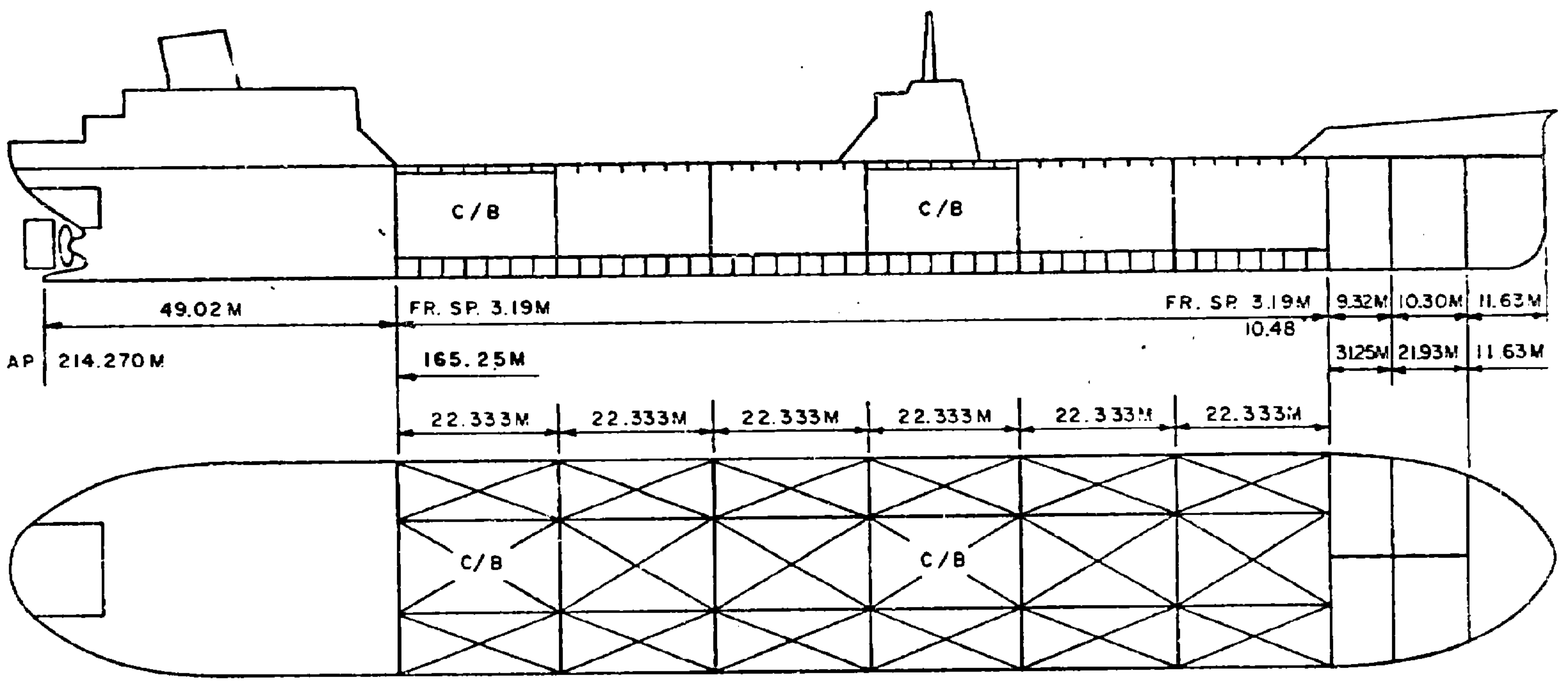

FIGURE 8.3 ARRANGEMENT OF NEW 50,000 DWT TANKER (50-Y1, 50-Y2)

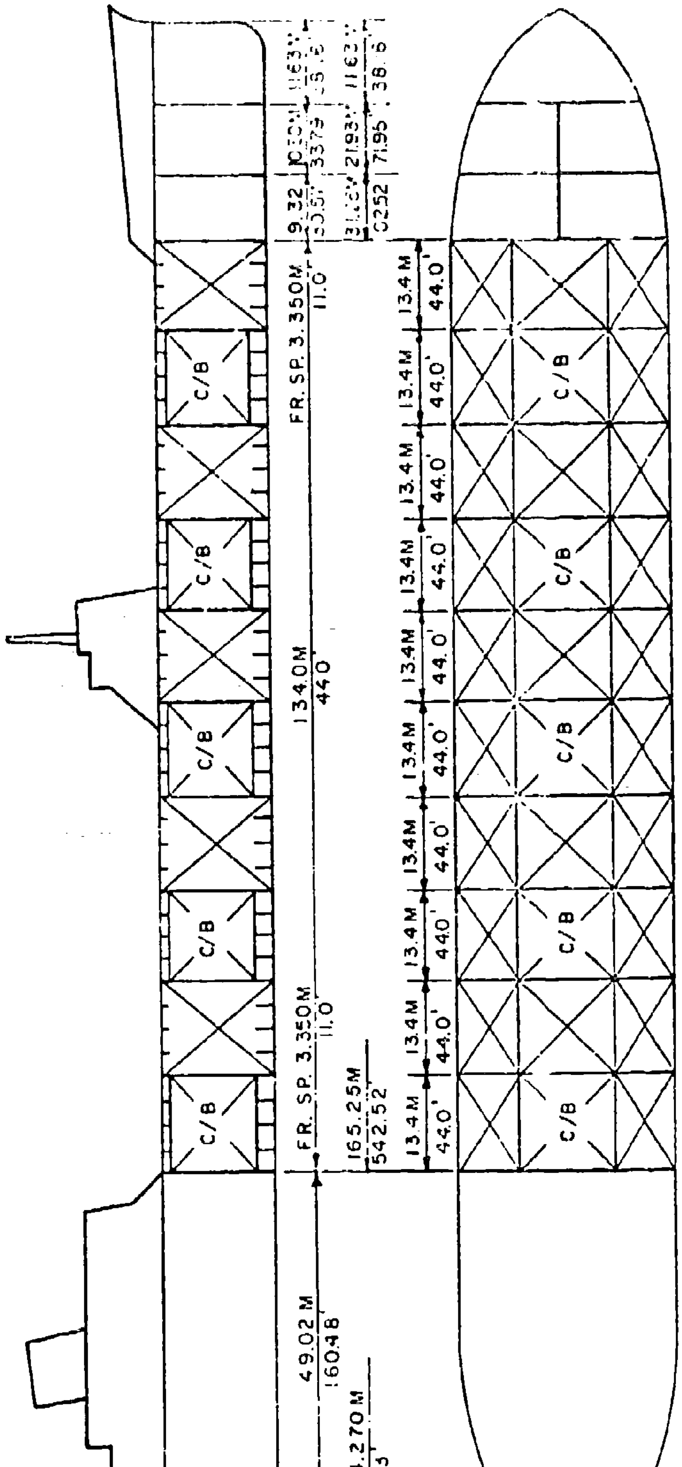

FIGURE 8.4 ARRANGEMENT OF MODIFIED 50,000 DWT TANKER
(50-Z)

9. STRUCTURAL DESIGN

It was pointed out earlier in this report that the tanks fitted with membranes should have smooth walls. This in turn calls for web frames of unconventional design in the proposed new tankers. Figure 9.1 shows a sketch of a typical web frame for tanks to be fitted with membranes. The favored configuration is that of double bottom, double deck center tanks with minimum brackets (b) of the web frames on the center tank side, covered with plating along the entire tank length. In order to recover the loss in strength at the bottom joints, oversized brackets (B) in the wing tanks may be necessary, figure 9.1. The double bottom and double deck allow for stiffening the center tanks on the outside, therefore, satisfying the smoothness requirements inside the tanks.

The critical issue that has to be investigated is the strength of the web frame, particularly at the center tank bottom bracket. In addition to the reduction of the size of these brackets, it is well known that high stress concentration occurs at this location which may ultimately lead to plastic collapse, ref. 9.1.

Two aspects of the structural part of the project will be presented in this chapter. The first objective is to analyze and design a web frame of adequate strength that satisfies the minimum bracket requirement in the center tank. This may lead to an addition of steel and an increase in the light ship weight particularly with the presence of the double bottom and double deck. The second objective is to minimize the weight of the designed web frame under a given maximum allowable stress level keeping the geometry unchanged.

For these purposes a representative 225,000 DWT tanker of the following characteristics was considered.

L.B.P.	=	1030' - 0"
Breadth molded	=	143' - 6"
Depth molded	=	91' - 0"
Draft (summer)	=	70' - 0"
Displacement	=	258,000 tons

Detailed information on the web frame for such a conventional tanker was available and used as the base for a comparative study. The minimum bracket web frame for the membrane tanker was designed using ABS rules, then analyzed using the problem oriented computer program ICES - STRUDL II, ref. 9.2, developed at M.I.T. After establishing the required bracket dimensions and plate thicknesses, ref. 9.3, the entire web frame was optimized using the fully stressed optimality criteria and a double iteration procedure developed at M.I.T., ref. 9.4.

9.1 FINITE ELEMENT ANALYSIS AND DESIGN OF A MINIMUM BRACKET WEB FRAME

A design procedure was adopted based on comparisons with a web frame of the existing tanker. The analyses and design procedure is described in the following paragraphs.

9.1.1 Analysis of an Existing Web Frame

A sketch of the web frame of the existing tanker is shown in figure 9.2. Because of symmetry of the frame and the applied loads about the center line, it was necessary to analyze only one half of the frame. For framework analysis, the web frame was modeled as shown in figure 9.3 with symmetry conditions applied at the center line. The deck and bottom longitudinal girders are represented by springs of stiffness constant "k" calculated as discussed in ref. 9.3. Because of the high stiffness of the longitudinal bulkheads in comparison with the longitudinal girders, roller supports restraining the vertical deflection were introduced at these locations.

Sizing of the frame members was completed using methods discussed in ref. 9.3 and utilizing the effective breadth of plating in accordance with the charts presented in refs. 9.5 and 9.6. Each member was divided into several segments in order to account for variation in the moment of inertia and other section properties.

Six loading conditions were assumed to act on the web frame as shown in figure 9.4a, b, and c. These loads were considered to be critical at the bottom brackets area.

The results of the framework analysis which was performed using ICES - STRUDL showed that the most critical loads on the bottom brackets area were loading conditions 2, 5 and 6. These loads caused the largest end moments near the bottom bracket area. The bending moment diagrams for these loading conditions are shown in figure 9.5a, b, and c. The stresses resulting from the end moments were used as boundary conditions for the finite element model of the bottom bracket area.

The bottom bracket area was modeled by discretizing the continuum and representing it as a collection of elements. In order to allow for more accurate results a fine mesh was used at the points where it was felt stress concentration may occur. Face plates and effective breadth of plating were modeled as beam members connected at the nodes of the elements.

The von Mises yield criterion was used to determine the location of the elements that had yielded.

9.1.2 Analysis of the Minimum Brackets Web Frame

As a first trial, the dimensions and scantlings of the modified web frame with double bottom, double deck and minimum brackets in the center tank were estimated using ABS rules whenever possible. The 2' x 2' brackets in the bottom of the center tank were used as a first trial to examine if they satisfy the structural requirements. The bottom brackets in the wing tanks were enlarged to account for the loss in the section modulus. Most of the attention was given to the bottom brackets since these were much more critical than the top brackets. This can be seen from the magnitudes of the moments acting at these joints which are shown in figure 9.5.

The model used for the framework analysis was the same as the one used for the existing web frame except for the changes of the section moduli of the different members. The three critical loading conditions used in 9.1.1 were again applied to the frame. Most of the end moments of the frame members remained close to their original values in the existing web frame except in members (7b) and (8b). Due to the changes in the moments of inertia the end moment in member (8b) was reduced while that in member (7b) was increased.

The framework results were used to estimate the boundary conditions for the bottom bracket area in the same manner as in 9.1.1. The von Mises yield criterion was again used to determine the elements that had yielded. For comparative purposes, the material was assumed to be 33,000 lbf/in^2 mild steel throughout the analysis.

9.1.3 Design of the Minimum Bracket Web Frame

The results of the analysis of the existing web frame and the minimum brackets web frame described above were compared. The first trial configuration of the latter gave a high stress concentration of about 37,000 lbf/in^2. This occurred in the elements adjacent to the top and the bottom of the 2' x 2' bracket. A second trial configuration was then made in which the wing tank bracket was slightly increased in size, and the plate thickness in the high stressed area was also increased. The result of these changes was a lower stress level in general. The second (and final) configuration of the bracket is shown in figure 9.6. According to the von Mises yield criterion, some elements had yielded in both the existing and the final minimum bracket configuration.

Figures 9.7 and 9.8 show the location of the yielded elements under loading condition number 6 for the existing and minimum bracket web frames respectively. This was the only loading condition that caused a yield in the minimum bracket design, and it occurred in one element only. It was therefore clear that the yielded area in the minimum bracket design is smaller than the existing one, and the design was considered adequate.

It should be noted that if initial yielding occurs under a constant load in small localized areas, this will not lead to complete failure of the structure because of redistribution of the strains. It should also be noted that the loading condition number 6 is an extreme one and that the probability of encountering such a load during the operational life time of the ship is very small, ref. 9.7.

The deck section for the minimum bracket web frame is shown in figure 9.9.

9.2 STRUCTURAL OPTIMIZATION OF THE WEB FRAME

The objective of this part of the study was to minimize the weight of the minimum bracket web frame keeping the geometry unchanged. The only free variable in the optimization was therefore the web plate thickness. For this purpose, the fully stressed optimality criterion was used. This optimality criterion states that the only constraint on the weight is that the elasticity of the material must be preserved under all loading cases considered. Since these considerations may lead to unacceptably thin plates in certain areas of the web frame (particularly near the deck) a minimum thickness was stipulated in the program as will be discussed later. The mechanism by which the fully stressed design was reached is as follows:

1. An initial design was assigned.* The minimum bracket web frame shown in figure 9.6 was used for that purpose. This design was based on ABS rules and checked using the finite element analysis as discussed in section 9.1.2.
2. The web frame was then analyzed for each of the six loading conditions shown in figure 9.4. Finite element analysis was again used in this step. The maximum effective stress in each element of the web frame was found using the von Mises yield criterion.
3. The web frame was then redesigned and the plate thicknesses of the web in each zone were changed by the ratio of the maximum effective stress to the yield stress. If the new plate thickness in any zone was found to be less than the minimum given thickness, this minimum thickness was assigned to the zone.
4. With the new design, the process was iterated from step 2. Termination occurred after a test had established that satisfactory convergence had been reached.

*In general, the initial design is rather arbitrary. However, it is advantageous to start from as good a design as possible since that accelerates the convergence.

The details of this procedure and the computer program are given in ref. 9.4.

The plate thicknesses of the initial web frame are shown in figure 9.10. As discussed earlier, a minimum acceptable thickness had to be assigned for all zones. The reason for the minimum thickness is that a very small thickness would be unrealistic and would induce buckling and vibration problems in the web frame. Figure 9.11 shows the influence of the minimum thickness on the results of the optimization. The minimum thickness was set to be 1/2", 3/8", and no limitation on thickness. The latter case was, of course, unacceptable and was used only for comparison. In the other two cases the convergence was smooth and the process was stopped by the convergence criteria after fifteen iterations. The final designs weigh 27.88 tons for 1/2" minimum thickness and 22.83 tons for 3/8" minimum thickness and are shown in figures 9.12 and 9.13 respectively. The stated weights represent reductions of 26.1% and 37.3% over the weight of the original minimum bracket structure, which was 36.39 tons (not including stiffeners). Since the minimum thickness in the original existing web frame was 1/2", this thickness was conservatively selected for the final design, figure 9.12. Therefore, a weight reduction for the web frame of about 26% is to be expected from such an optimization procedure.

The web frame in the original conventional tanker had a weight of 35 tons. Thus, the optimized web frame for the membrane tanker was 20% lower than the original tanker. However, this weight reduction is for the web frame alone; there are additional weights associated with the double deck and double bottom.

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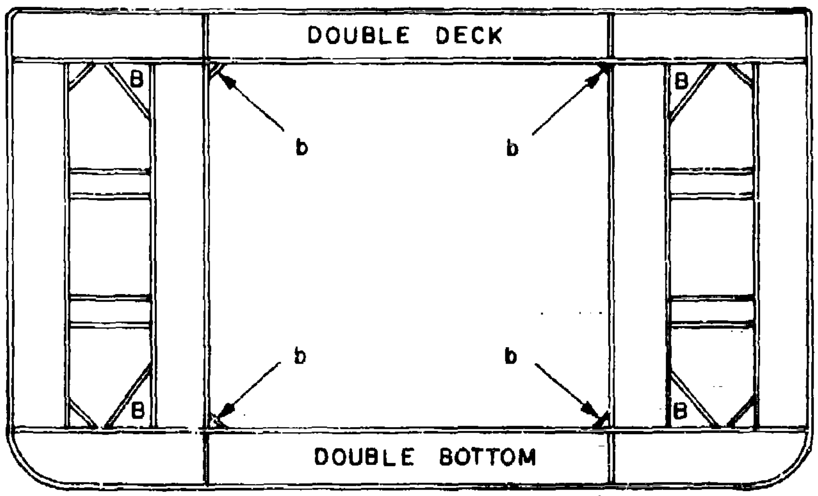

FIGURE 9.1 MINIMUM BRACKETS WEB FRAME

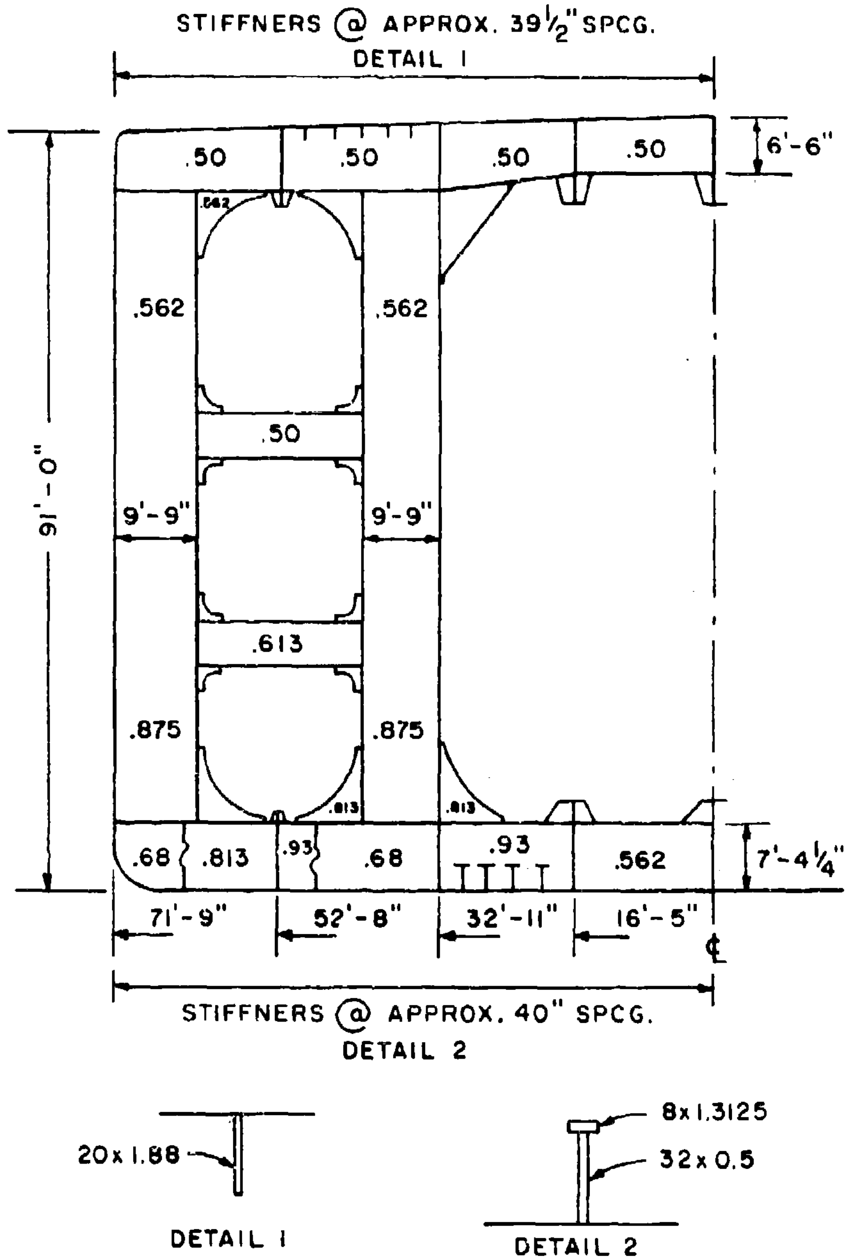

FIGURE 9.2 WEB FRAME OF AN EXISTING TANKER

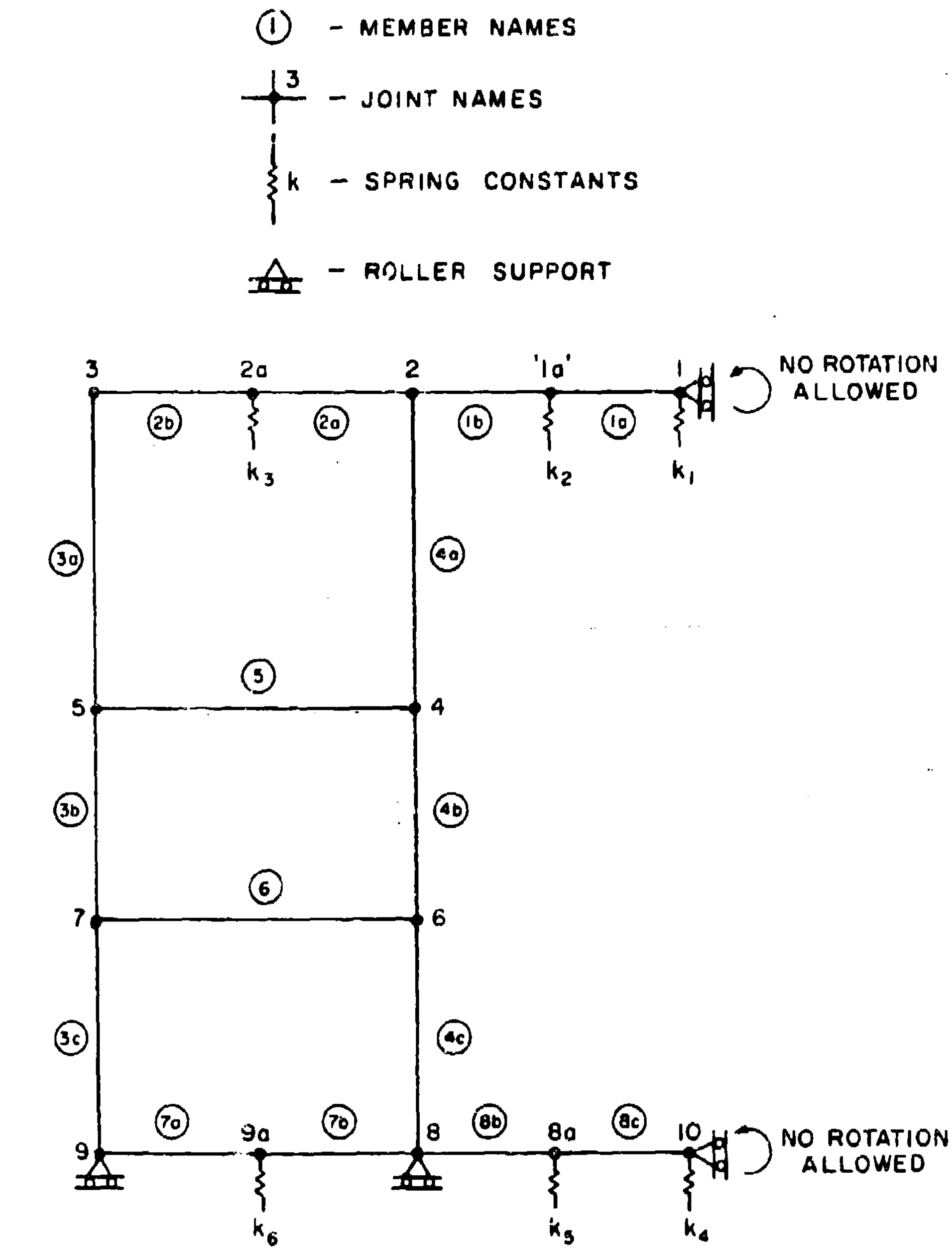

FIGURE 9.3 FRAME ANALYSIS MODEL-EXISTING TANKER

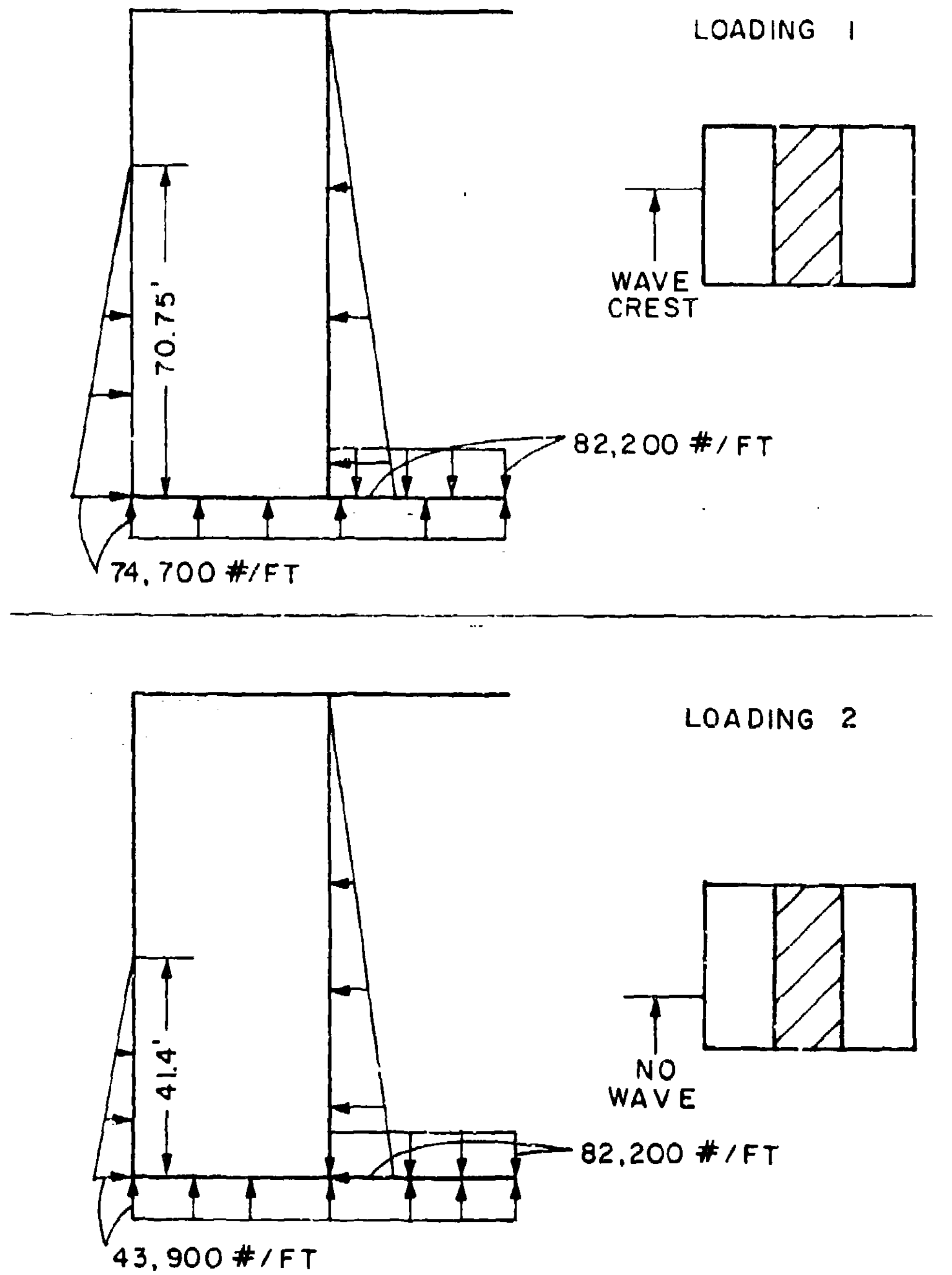

FIGURE 9.4a LOADING CONDITIONS

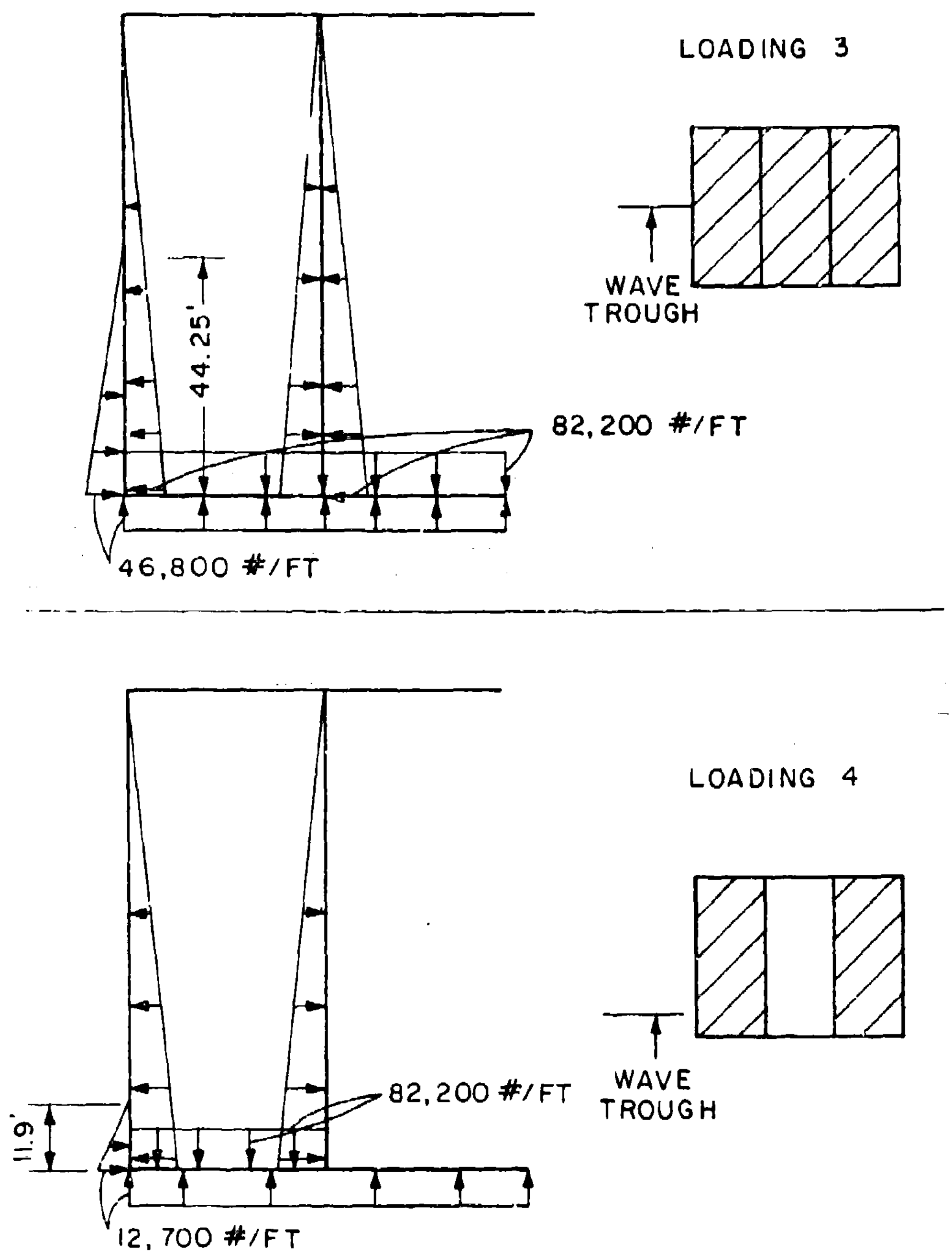

FIGURE 9.4b LOADING CONDITIONS

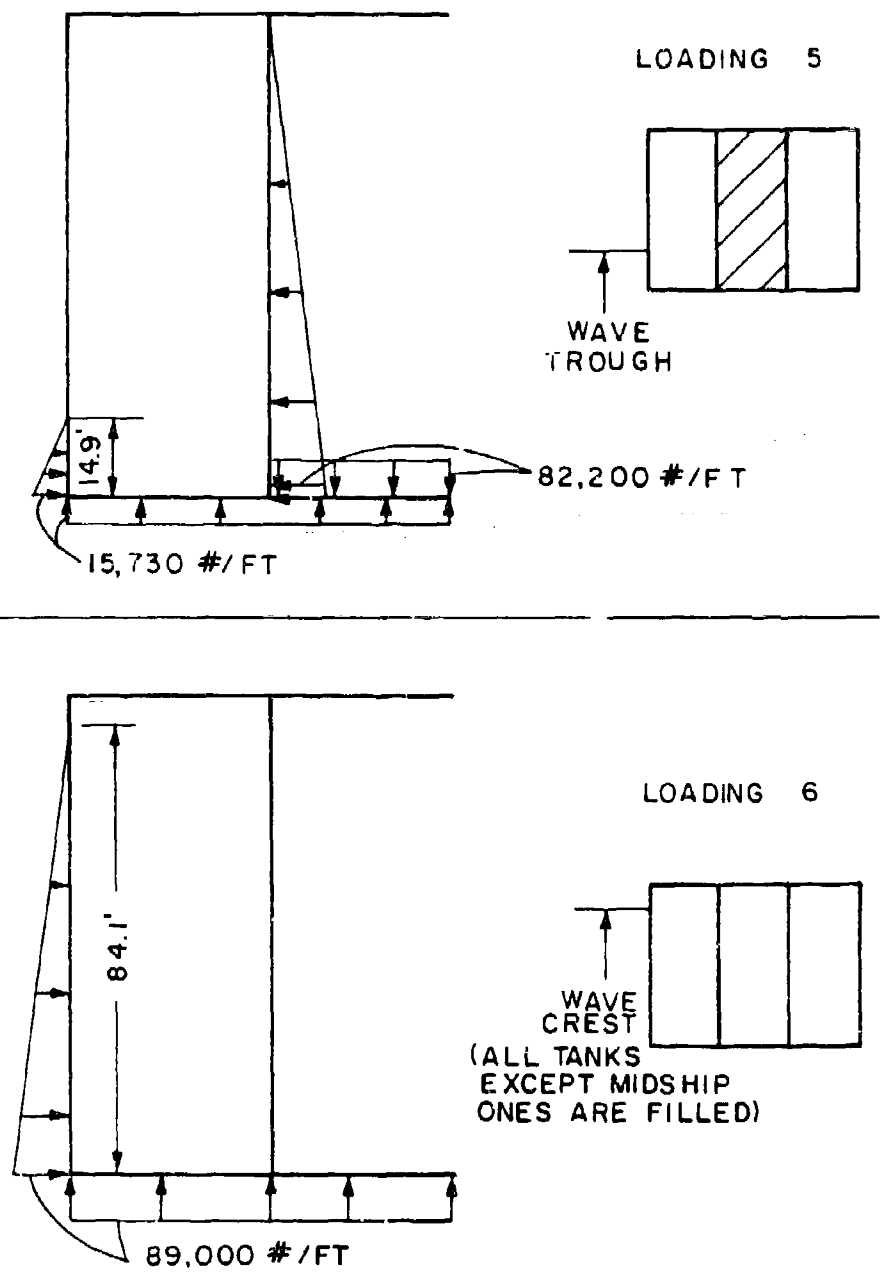

FIGURE 9.4c LOADING CONDITIONS

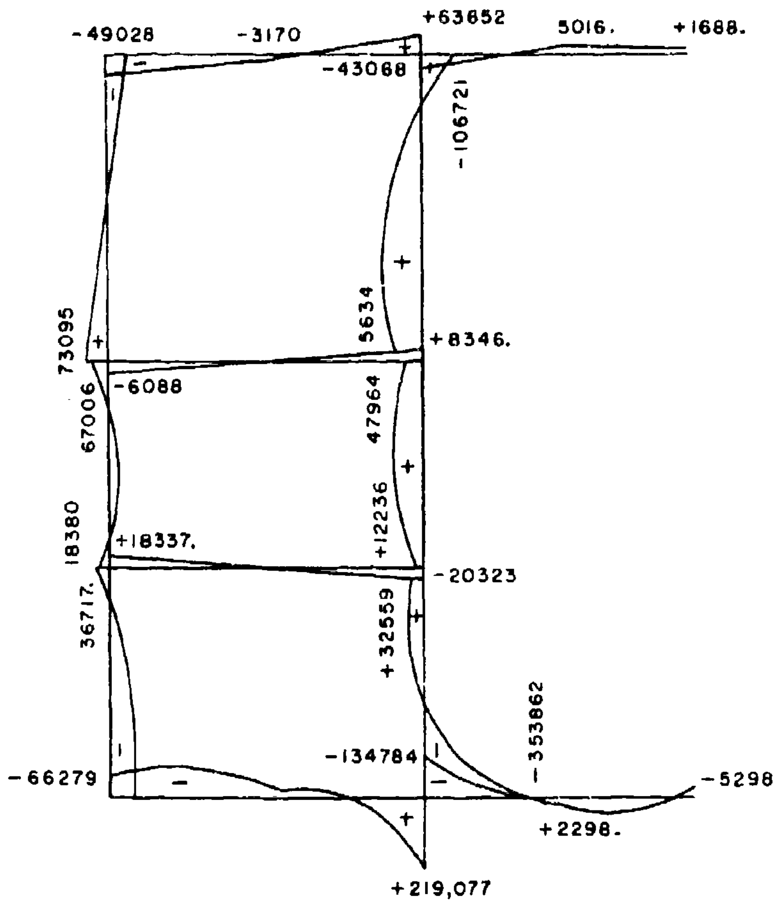

FIGURE 9.5a BENDING MOMENTS (KIP-INCH)-LOAD 2
EXISTING WEB FRAME

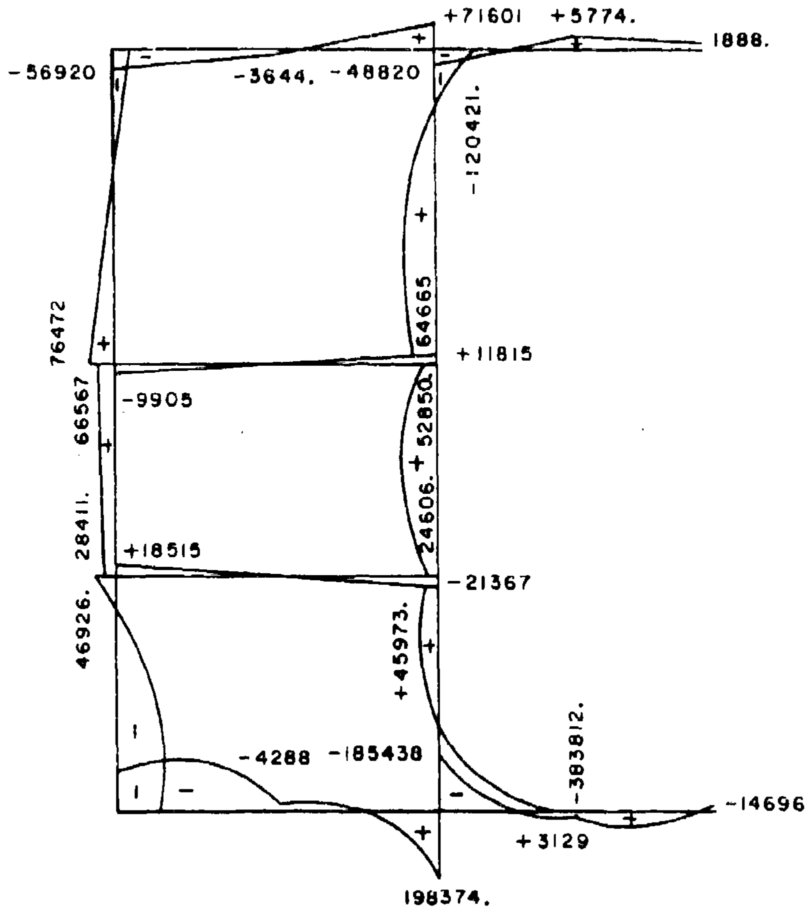

FIGURE 9.5b BENDING MOMENTS (KIP-INCH)-LOAD 5
EXISTING WEB FRAME

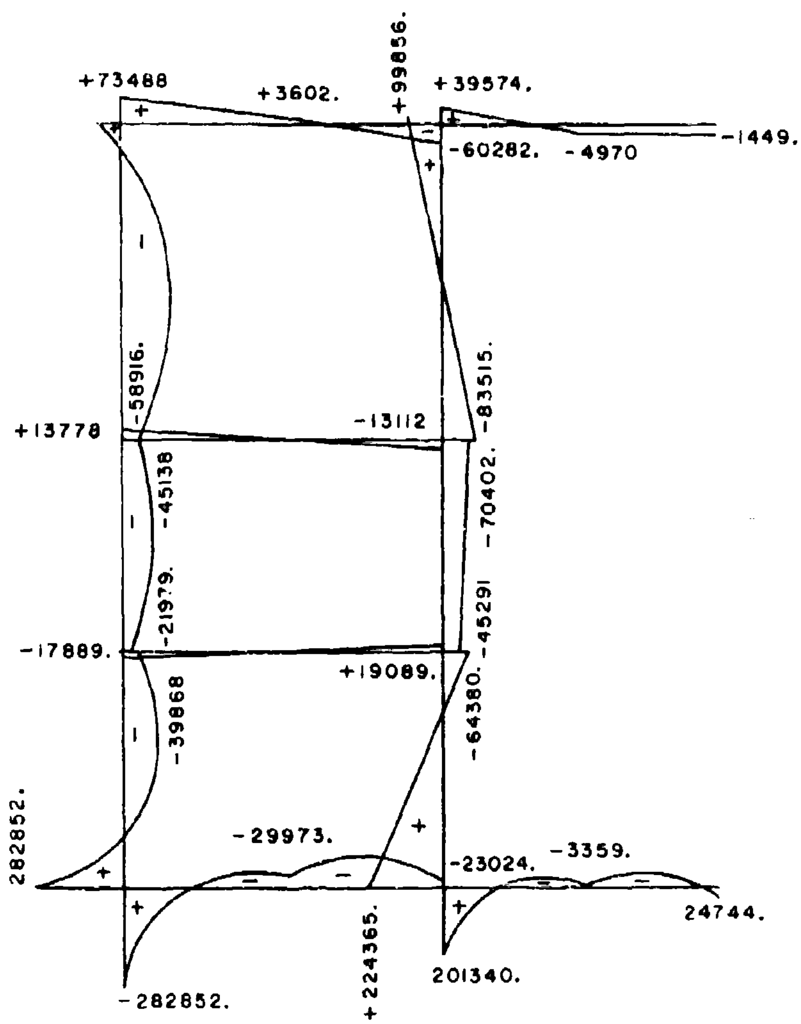

FIGURE 9.5c BENDING MOMENTS (KIP-INCH) - LOAD 6
EXISTING WEB FRAME

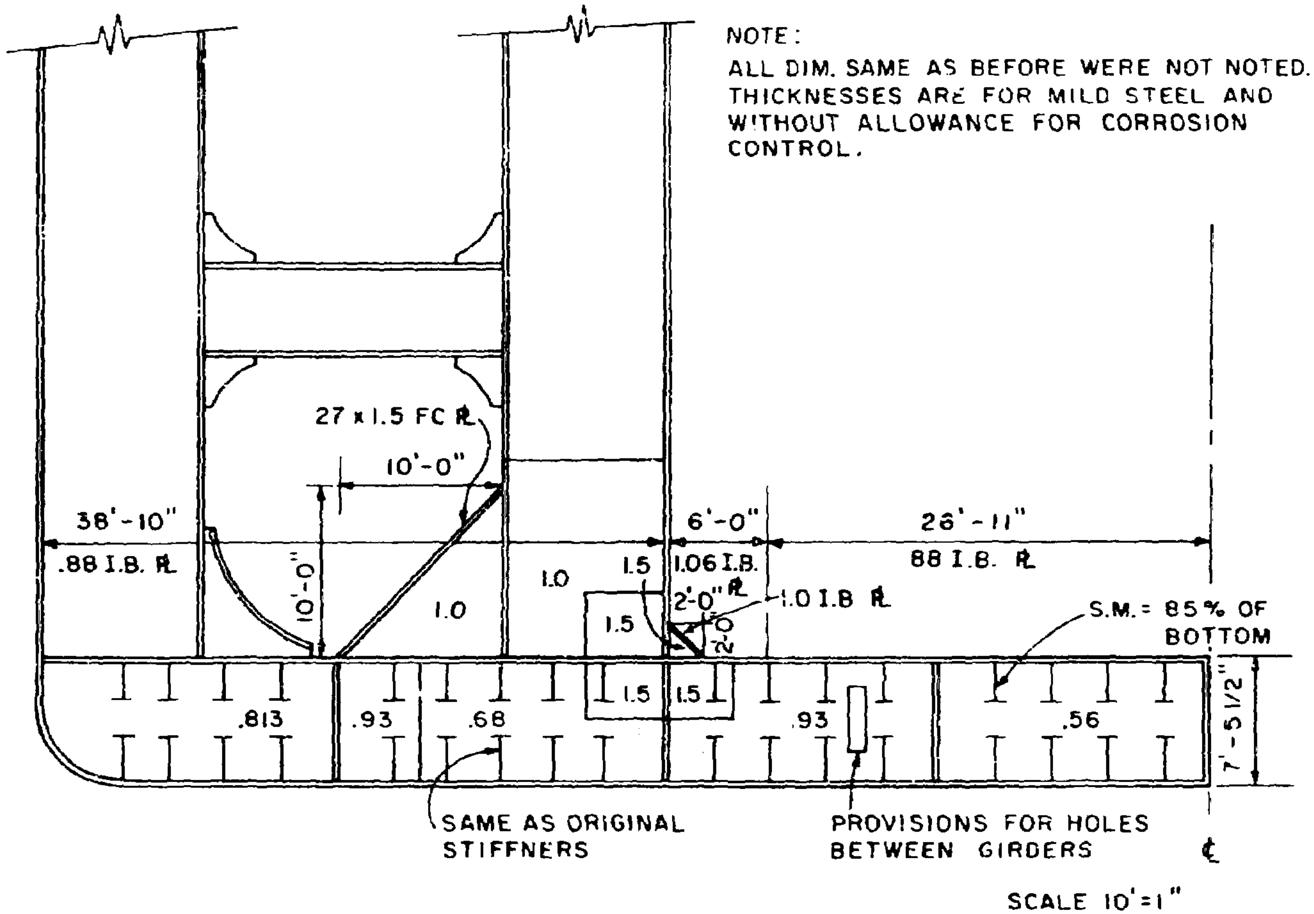

FIGURE 9.6 MINIMUM BRACKETS WEB FRAME - BOTTOM SECTION

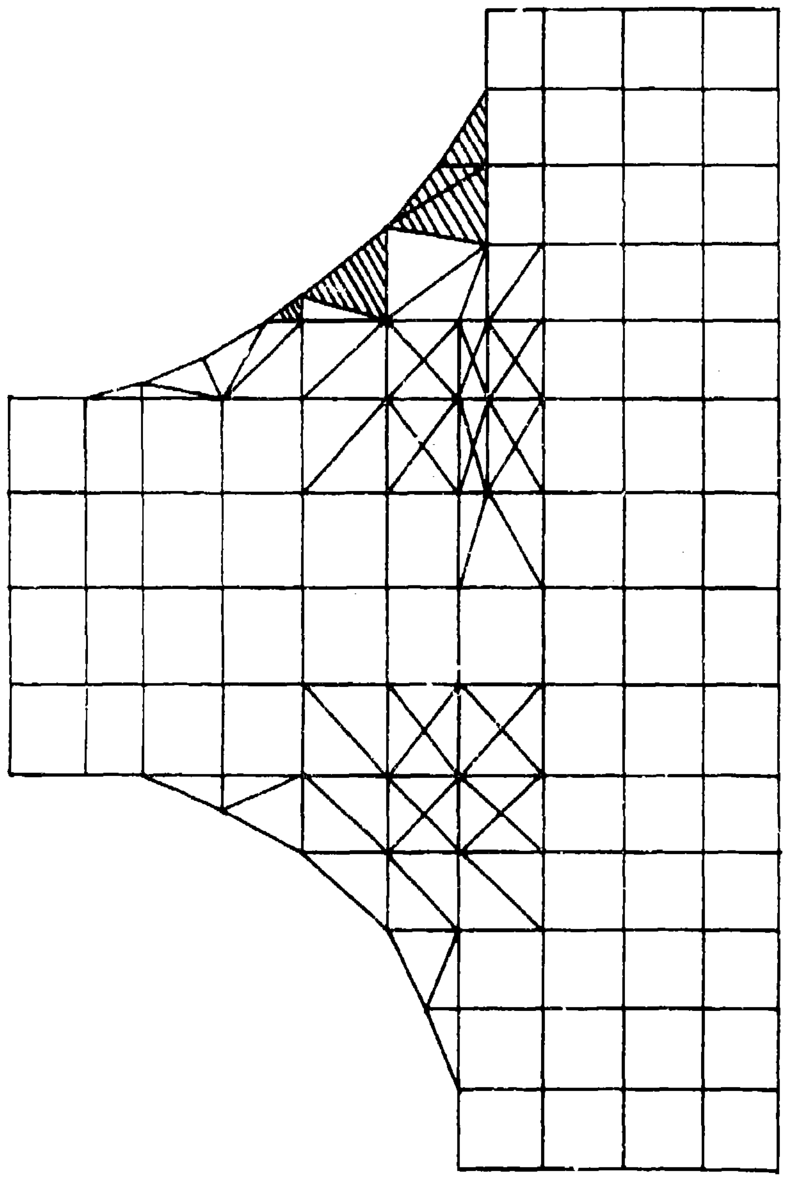

FIGURE 9.7 YIELDED ELEMENTS - EXISTING WEB FRAME
LOAD 6

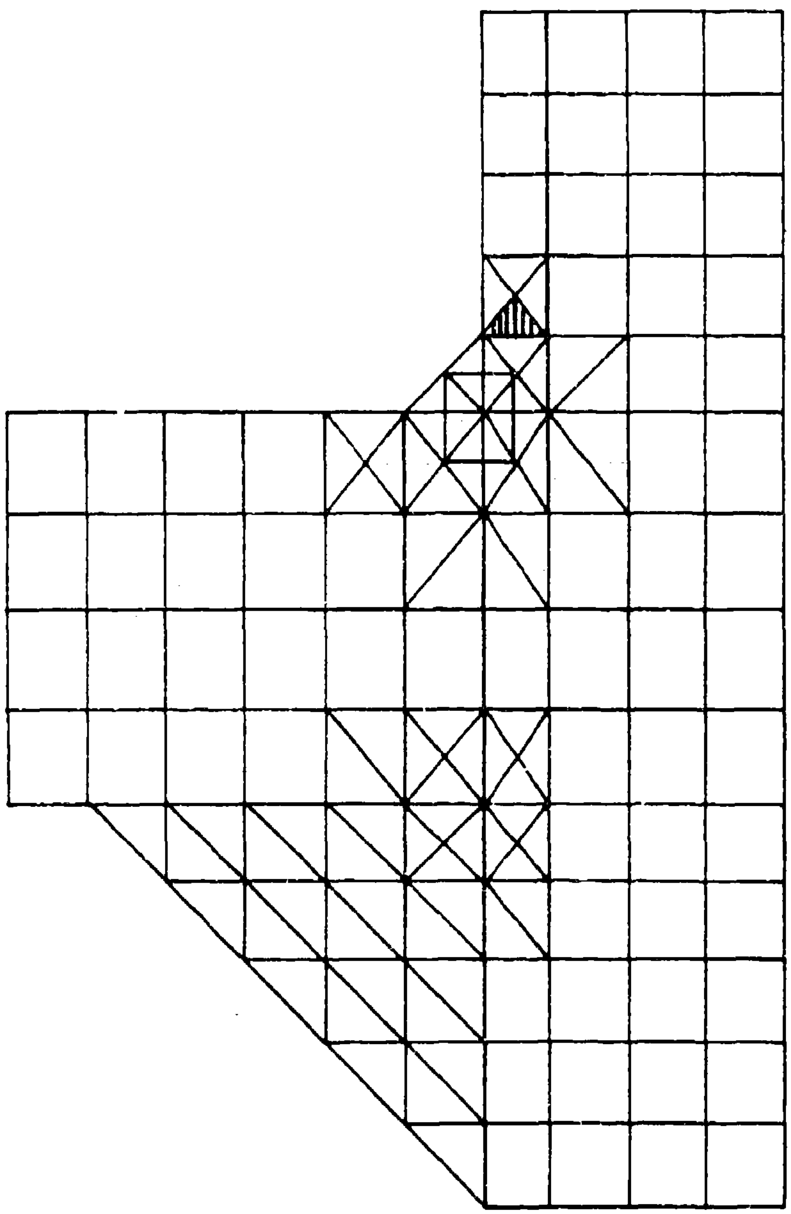

FIGURE 9.8 YIELDED ELEMENT - MINIMUM BRACKETS WEB FRAME
LOAD 6

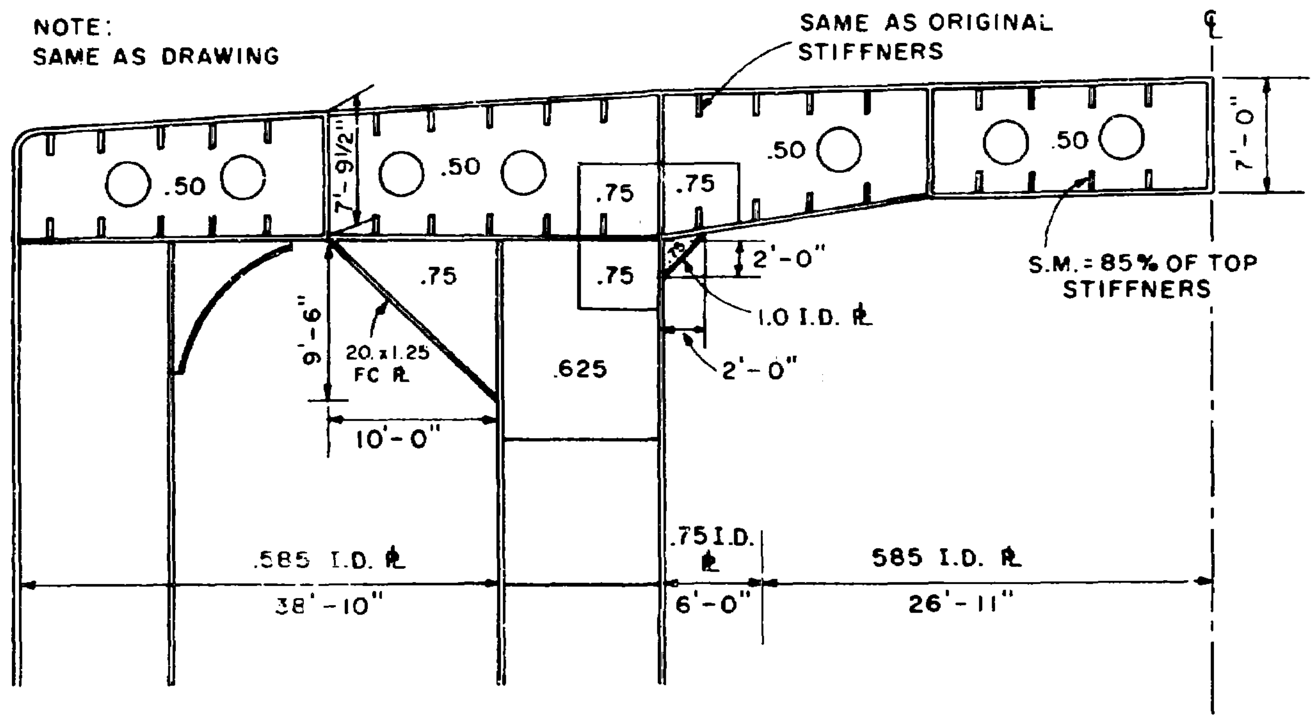

FIGURE 9.9 MINIMUM BRACKET WEB FRAME - DECK SECTION

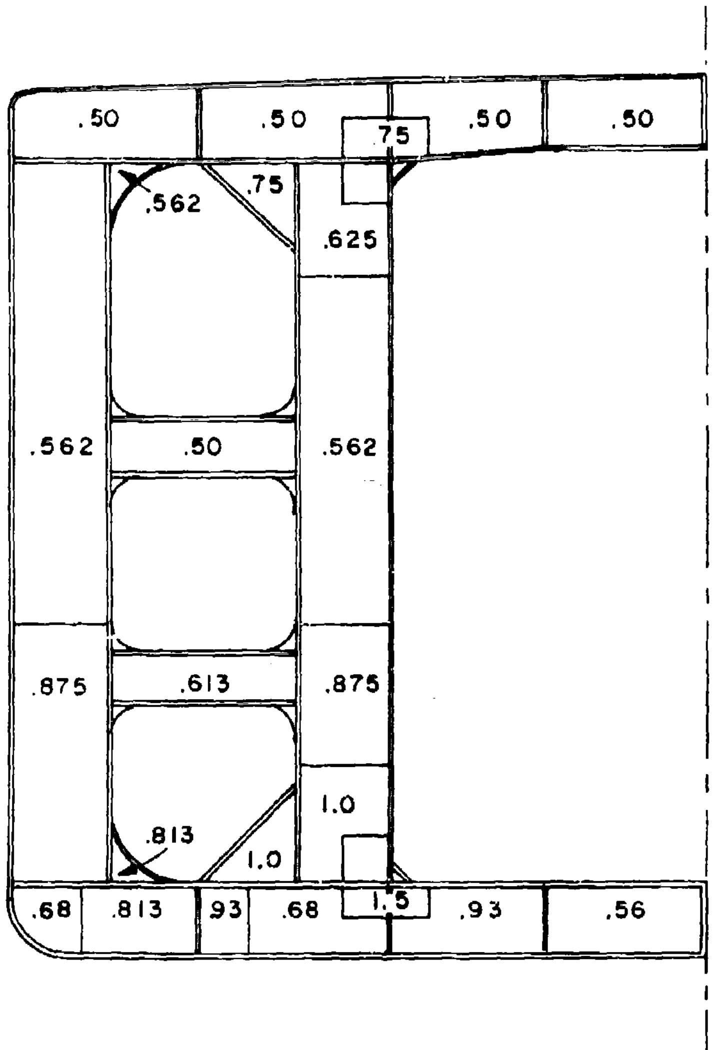

FIGURE 9.10 PLATE THICKNESSES OF INITIAL WEB FRAME

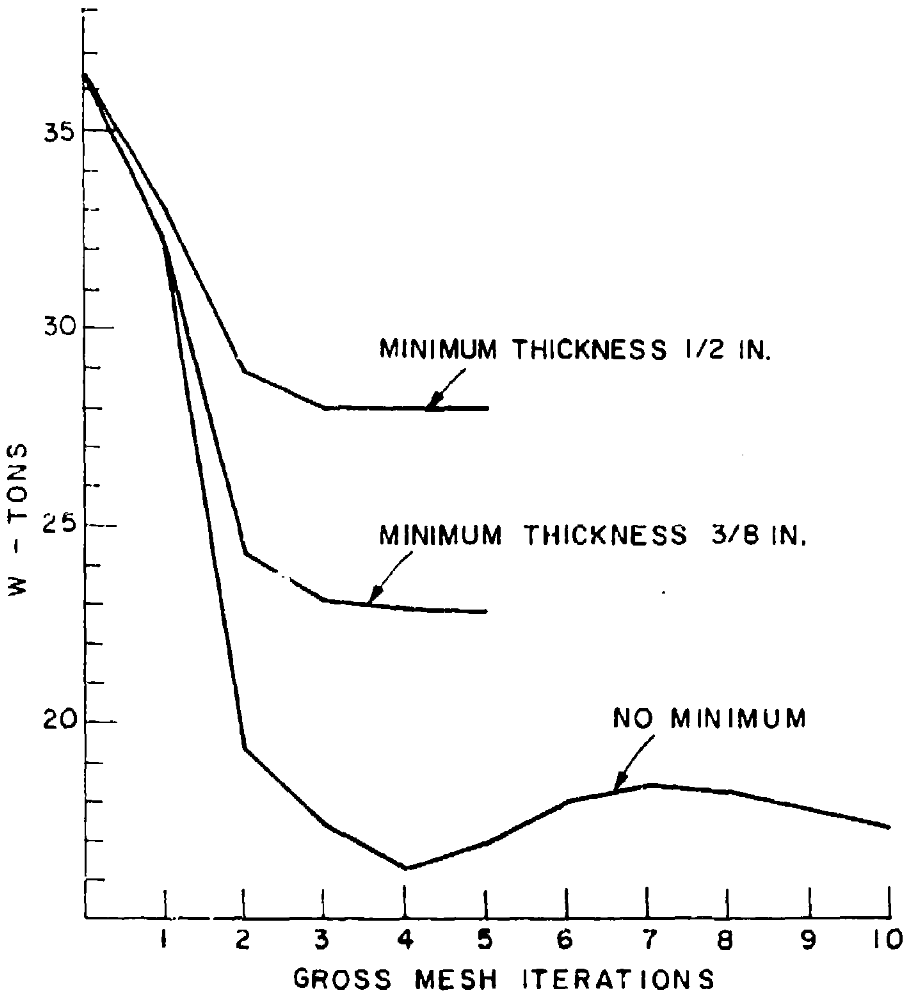

FIGURE 9.11 INFLUENCE OF THE MINIMUM THICKNESS ON THE OPTIMIZATION

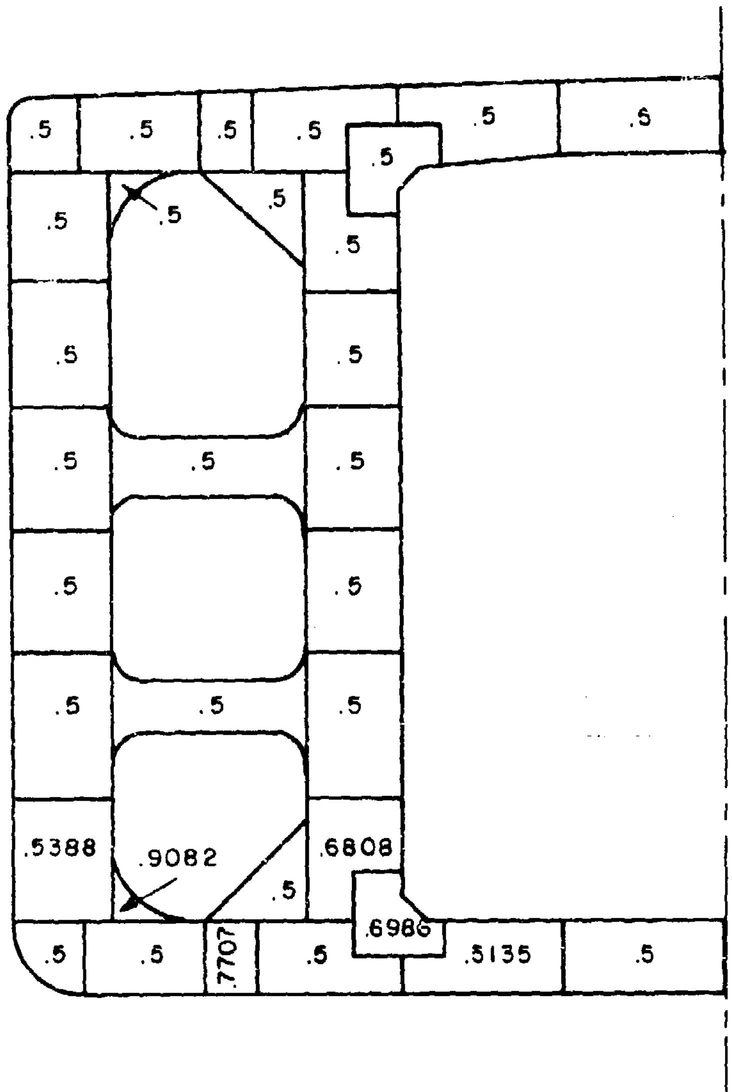

FIGURE 9.12 FINAL DESIGN - MINIMUM THICKNESS 1/2 IN.

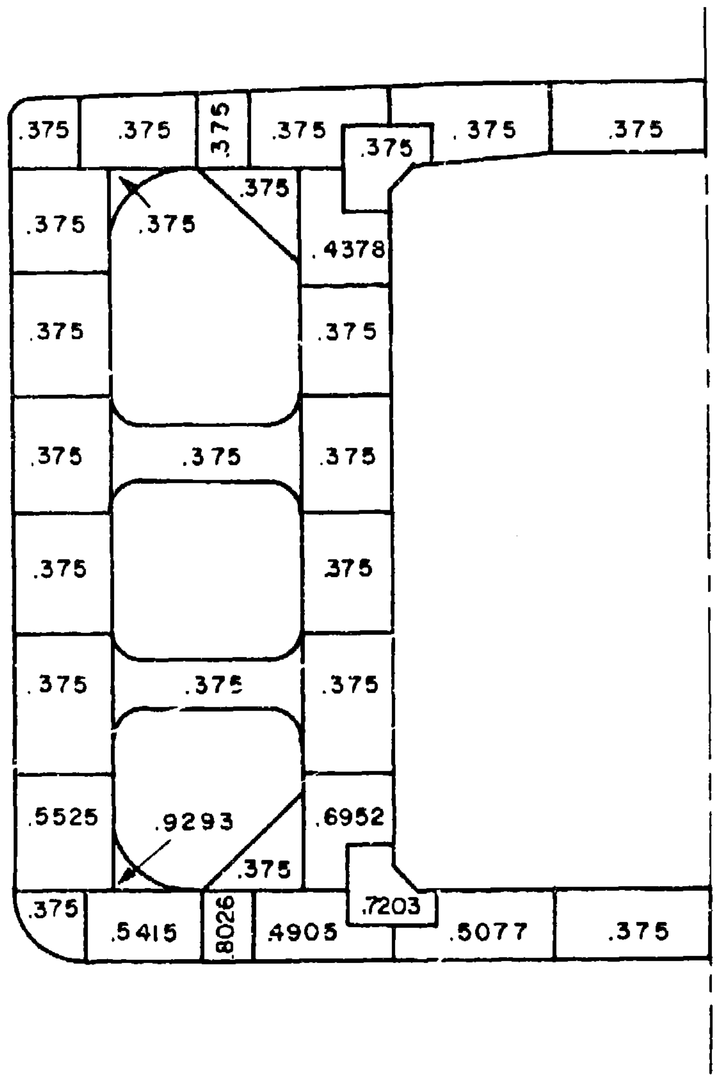

FIGURE 9.13 ALTERNATE DESIGN - MINIMUM THICKNESS 3/8 IN.

10. RECOMMENDATIONS

The engineering study of the membrane system has demonstrated the feasibility of isolating the cargo from seawater ballast in dual-purpose tanks. Several new features of design and operation were evolved in the study as described in the previous chapters of this report.

The constraints imposed on the ship design by the use of membranes in some of the tanks did not compromise the design of new tankers. The bending moment, shear force and trim conditions were acceptable and typical of conventional tankers.

The structural changes to the web frame resulting from the requirement for smooth walls in the dual purpose tanks were found to have little influence on the steel weight in new tankers. However, the conversion of existing tankers to accept membranes was somewhat more substantial because of the additional steel required to provide smooth skins to the insides of the dual-purpose tanks.

The proposed operational procedures utilize inert gas to assist in moving the membrane during filling and also as a measure to reduce wear due to abrasion. These operations are similar to the existing methods of providing inert gas as a safety precaution in many large tankers. A reliable inert gas system and fool proof operations, however, are necessary to insure the long service life of the membranes.

Model tests using a 1/20 scale model have provided the data on filling and emptying operations and on membrane conditions in a seaway. Although model testing in small models is a well established procedure in many fields of engineering, it is obviously necessary to demonstrate the operations on a full-size prototype.

The main engineering uncertainty in the proposed membrane system is probably associated with the integrity and life of the membrane. The membrane materials are to be utilized in a new application and environment, although there are similarities with other applications. Recommended areas of research and development are:

1. Testing of sample membrane materials in a simulated tank environment including immersion in oil and seawater, and contact with inert gas.
2. Testing of membrane materials including seams in tight folds under high hydrostatic pressures after cargo and seawater immersion.
3. Testing of membrane materials in association with attachment devices with simulated corner folds.

A single testing machine could be devised to accommodate these tests.