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# INVESTIGATION OF SELF-HELP OIL-SPILL RESPONSE TECHNIQUES AND EQUIPMENT

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## EXECUTIVE SUMMARY

The U.S. Coast Guard commissioned Pacific Northwest Laboratory (PNL) to conduct this study of 45 self-help oil-spill response techniques and equipment for oceangoing tankers and inland tank barges to assess the potential effectiveness of the proposed countermeasure categories. The self-help countermeasure categories considered cover equipment stored on the vessel and deployed by the crew, operated automatically, or carried aboard and used by response crews in the case of unmanned barges. A basic requirement for the response equipment is that it be capable of retaining oil after the oil has escaped the confines of the vessel in all expected environmental conditions.

This study considers the hypothetical outflow of oil in the case of side damage and bottom damage to single-hull designs. The results will be considered by the Coast Guard in drafting regulations pertaining to the requirement for tanker vessels to carry oil pollution response equipment (i.e., in response to the oil Pollution Act of 1990).

PNL's approach to this investigation included:

- assessing time-dependent oil outflow in the cases of collision and grounding of both tankers and barges
- identifying environmental constraints on self-help countermeasure operation
- identifying human factor issues, such as crew performance, safety, and training requirements for the self-help countermeasures considered
- assessing each self-help countermeasure with respect to its potential for minimizing oil loss to the environment.

Results from the time-dependent oil outflow, environmental limitations, and human factors requirements were input into a simulation model. From the simulation runs made in this study, no self-help countermeasure emerges as clearly superior to the others. However, the results do suggest that a pumping solution in conjunction with some form of containment has the most promise in the near term. In addition, this study produced results that are

essential to future modeling efforts, including the fact that ground plugging has a significant effect on oil outflow in the case of grounding.

Based on the findings of this investigation, it is recommended that research pertaining to onboard self-help countermeasures focus on the pumping-containment category of concepts. Other recommendations include further developing the model used in this study to obtain more realistic oil outflow times, especially in the case of grounding; combining the simulation models used in this study into one global model; and making a more in-depth investigation of the environmental data.

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This project was unique in that it involved the combined talents of Battelle staff from many different offices, including the Marine Sciences Laboratory (MSL) in Sequim, Washington; the Battelle Ocean Sciences (BOS) Laboratory in Duxbury, Massachusetts; the Human Affairs Research Center (HARC) in Seattle, Washington; the Corporate Office (BCO) in Columbus, Ohio; and Pacific Northwest Laboratory (PNL) in Richland, Washington.

The project manager, Walt Enderlin, would like to acknowledge the following contributors to each section of the report:

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| 6.0 | Recommendations for Future Research (PNL) | Walter I. Enderlin |

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# 1.0 INTRODUCTION

The Coast Guard Marine Environmental Protection Division of Coast Guard Headquarters has determined that an in-depth investigation of feasible self-help countermeasures will assist in formulating Oil Pollution Act of 1990 (OPA 90) mandated regulations regarding oceangoing tank vessels. Currently, no regulation requires tank vessels to carry onboard equipment capable of responding to an oil spill from the vessel. Section 4115 of OPA 90 mandates that tank vessels be required to have double hulls by the year 2010 (with a few exceptions, by 2015), and vessels under 5,000 gross tons are required to have a double-hull or double containment system by 2015. In addition, OPA 90 requires the investigation of economical and technologically feasible structural and operational features to provide substantial environmental protection for single-hull vessels until 2015.

The Federal Water Pollution Control Act (FWPCA), 33 USC 1321, as amended by OPA 90, sets forth the requirements for tank vessel response plans and oil-spill response equipment. Under Section 311(j)(6) of the FWPCA, as amended by Section 4202(a) of OPA 90, vessels operating on navigable waters and carrying oil in bulk as cargo must also carry appropriate removal equipment. This equipment is to employ the best technology that is both economically feasible and compatible with the safe operation of the vessel. Section 311(j)(5) of the FWPCA, as amended by Section 4202(b)(4) of OPA 90, requires owners and operators of tank vessels, as defined in 46 USC 2101, to prepare and submit individual response plans to the President for approval. Consequently, in anticipation of this authority being delegated to the Commandant, the Coast Guard is developing proposed rules to implement requirements for tank vessel response plans, and the carriage and inspection of oil-spill response equipment. As a part of this effort, the Coast Guard is currently attempting to identify equipment and techniques that will increase the effectiveness of a tank vessel to mitigate a spill through engineering designs and the vessel's own actions and to establish those conditions under which its carriage and deployment are appropriate.

Pacific Northwest Laboratory (PNL) has been commissioned by the Coast Guard to conduct a comprehensive investigation of feasible self-help spill response techniques and equipment for 5,000 through 250,000 deadweight ton (DWT) oceangoing tankers and for oceangoing and inland tank barges ranging from 300 to 3,000 gross tons (GT). These self-help countermeasures will consist of equipment stored on the vessel and deployed by the crew, operated automatically, or carried aboard and used by response crews in the case of unmanned barges. The response equipment will be required to deal with oil once it has escaped the confines of the vessel in all expected environmental conditions. This study considers the hypothetical outflow of oil in the case of side damage and bottom damage to single hull designs consistent with the assumptions made in MARPOL (1985).[a]

The objective of the PNL investigation is to evaluate approximately 45 countermeasure concepts provided to PNL by the Coast Guard. These concepts have been grouped according to type and ranked according to effectiveness in mitigating oil spillage from a vessel. The results of this evaluation will be considered by the Coast Guard in drafting future regulations pertaining to the requirement for tanker vessels to carry oil pollution response equipment.

PNL's approach to this investigation included:

- assessing time-dependant oil outflow in the cases of collision and grounding of both tankers and barges
- identifying environmental constraints on countermeasure system operation
- identifying human factor issues, such as crew performance, safety, and training requirements for the countermeasure system types considered
- assessing each self-help category under consideration with respect to its potential for minimizing loss of oil to the environment.

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(a) MARPOL is the International Convention for the Prevention of Pollution from Ships, adopted in 1973 and amended in 1978. It constitutes the basic international law for limiting all ship-source pollution, including structural and operational provisions for tank vessel pollution control; the term is used in this study to describe the current standard for vessel design.

The regulations currently being considered by the Coast Guard would address the type, quantity, and capacity of the oil-spill response equipment to be carried on tank vessels. To adequately address this issue, a number of questions must be answered.

- Questions concerning time-dependant oil outflow:
  - What is an acceptable response time for spills?
  - How large a discharge should the equipment be capable of handling?
- Questions concerning environmental constraints on countermeasure system operation:
  - Should the area of the vessel's operation or the regional availability of support equipment affect the onboard equipment-carriage requirements?
  - What are the desired capabilities of this equipment?
- Questions concerning crew performance, safety, and training requirements:
  - Will sufficient qualified vessel crew be available to operate the equipment when needed?
  - How many crew members will be required for a given system?
  - What mariner training in the use of the equipment should be required?
  - Should the crew be required to do more than attempt to control or stop the discharge and report the incident to the proper authorities?
  - Who should be the "qualified individual" for directing the operation of equipment for a fleet of barges?

The assessment of self-help categories was performed using a simulation model. The results of the studies of time-dependent oil outflow, environmental limitations, and human factors requirements were input to this model. The findings of this assessment address the following questions:

- Should tank vessels carry equipment for containment and recovery?
- Which, if any, of the onboard self-help countermeasure categories considered is appropriate for tank vessels to carry?
- Which, if any, of the onboard self-help countermeasure categories considered is appropriate for barges to carry?

## 1.1 LITERATURE SEARCH

PNL conducted a literature search of papers and reports that describe the deployment and operation of self-help equipment. PNL also reviewed approximately 45 proposals and suggestions submitted to the Coast Guard Research and Development Center for potential merit. This review provided a basis for identifying techniques and equipment that have been investigated in past studies, and provided insight to problem areas and constraints that state-of-the-art countermeasures will need to overcome. In reviewing this material, PNL focused on understanding the engineering aspects of each proposed or actual system and identifying their key features. The systems under consideration were then categorized for subsequent evaluation.

The following summarizes the literature review. Also discussed are PNL's accomplishments in obtaining data that are critical to this study and not available in the open literature.

A review of the literature initially provided to PNL by the Coast Guard was completed (MARPOL 1985; NAS 1991; Ross 1983; Kohler and Jorgensen 1990; USCG 1989). In addition, PNL performed a computer search of the open literature using the following key words: tankers, barges, collision, grounding, oil pollution, oil spill countermeasures. The files searched included NTIS, COMPENDEX PLUS, and Water Resources Abstract. This search yielded an additional six citations.

Source literature pertaining to human factors was also identified through a search on the DIALOG system, and through a bibliographic search in the University of Washington library system. Documents were retrieved through the Battelle Human Affairs Research Center (HARC) library, and through contacts with the Marine Board of the National Academy of Sciences. The literature review revealed that while there is a respectable amount of human factors literature covering general shipboard operations, and by implication a portion of tanker and barge operations, there have been very few human factors studies specifically directed at tanker safety. Moreover, the literature review revealed virtually no information concerning the functions and tasks of crew members during emergency operations on any ship, including tankers. As a result, interviews with experts were also set up through a process of networking through the Seattle maritime community, based on initial contacts with the Coast Guard 13th District, the Seattle Community College Maritime Training Program, and contacts within the maritime industry.

Much of the critical data required to perform a time-dependent outflow analysis in the cases of grounding and collision are not available in the open literature (i.e., specifically data pertaining to vessel design and penetration sizes for the sizes of vessels specified for this investigation by the Coast Guard). Dimensions and configurations for 5,000 and 150,000 DWT tankers listed in the original scope of work have not been located within the open literature. Furthermore, no dimension or configuration information has been located in the open literature for any barges that represent those specified by the Coast Guard for this investigation. Moreover, no method for determining penetration sizes for the case of collision has been found in the open literature.

The NAS study (NAS 1991) was not limited to double hull construction, but included inboard containment systems that may be as effective as a double hull in preventing oil spillage. However, outboard containment systems were not covered, and only one size of single hull tanker was considered. This was used as a basis for comparison for the double hull designs considered in this study.

The Ross study (Ross 1983) of onboard self-help countermeasures considered both inboard and outboard countermeasures, but concentrated on the unique specifications of arctic tankers and did not consider all oceangoing tanker vessels. No rationale is given in this report for the penetration sizes considered in the oil release calculations.

A report (Smedley et al. 1991) describing an ongoing Canadian evaluation of tanker self-help recovery systems was reviewed. The report considers all of the self-help options that are considered by PNL in this study. The report concludes that the most practical tanker self-help systems are internal oil transfer, hydrostatic loading, external oil lightering, and contingency planning. Booms and skimmers were not considered to be "stand-alone," practical self-help systems because sea conditions and ice would have prevented their deployment and effectiveness in over 50% of the tanker incidents that occurred in Canadian waters. Liner systems were regarded as a design modification and not a self-help system and hence were deemed to be outside the scope of the evaluation. Appendix A of the draft report is a comprehensive database of spills of crude and refined product from both tankers and barges throughout the world from 1974 through June 1990.

MARPOL (1985) was reviewed to determine assumptions required for outflow calculations. It was determined that the MARPOL assumptions were inadequate for determining penetration sizes. MARPOL only addresses damage dimensions and not actual penetration sizes. It would be impractical to use damage dimensions for the penetration sizes due to the extent of the damage assumptions. (That is, the vertical extent of side damage is assumed to be the entire height of the ship.) The hypothetical outflows assumed the entire contents of any tank damaged would be leaked. This assumption is made in MARPOL to aid in determining tank sizes for design purposes. In an accident scenario, not all of the cargo will leak from a penetrated tank. Depending on the hydrostatic balancing of the cargo, some penetrations due to grounding will result in less than 8% of the cargo in a tank being leaked.

The analysis performed by Det Norske Veritas (Kohler and Jorgensen 1990) was reviewed, and it was concluded that the Det Norske Veritas (DnVC) method for determining penetration sizes in the case of grounding can be reproduced. However, the DnVC method for determining penetration sizes in the case of collision was based on statistics for damage resulting from collisions of ships. No distinction is made between ship types or sizes in the statistical data. DnVC makes the assumption that the data are also valid for tankers. For dimensions that can not be determined from the statistical data, DnVC relies on MARPOL assumptions. They assume the vertical height of the penetration is equal to the ship's height. To gain a greater understanding of the DnVC method for determining penetration sizes, PNL contacted DnVC. DnVC made it clear to PNL that their determination of penetration sizes was only meant for comparing various tanker designs and not for modeling realistic time-dependent outflows. DnVC was unaware of any databases containing actual penetration sizes.

According to the Coast Guard Research and Development Office, a model (micro HACS) was developed for determining time-dependent outflow from chemical tankers. This model has been recently delivered to the Coast Guard National Response Center. The model is capable of being operated in either an emergency response mode or a contingency mode. Although any penetration size can be input to the model, the model does have default values for each of the operating modes. All penetration sizes are regarded by the model to be circular area. The default value for the contingency mode is a 10-in. diameter circle. In the case of emergency response, the model has four default values: 0.5 in. diameter for a crack, 2.0 in. diameter for a puncture, 4.0 in. diameter for a fill pipe rupture, and an entire tank release. The default tank size is 420 $M^3$, which is smaller than for a crude carrier. Coast Guard staff contacted by PNL stated that they were not aware of any database that would contain penetration size data. These staff further stated that the National Response Center would depend on an on-scene coordinator from the Marine Safety Office to provide actual penetration size data. To date, the model has not been used.

The American Bureau of Shipping (ABS), the Tanker Advisory Commission, the Coast Guard, and some tanker owners were contacted by PNL but none could provide detailed information pertaining to vessel layout and construction, required to facilitate the outflow analysis. The Maritime Administration (Division of Navel Architecture) was then contacted and information was collected for the following size tankers listed by DWT: 33,000; 34,000; 40,000; 89,700; 22,500; 262,000; 390,000. Of these tankers the 34,000; 89,700; 225,000; and 262,000 DWT were selected for performing the outflow calculations. The Maritime Administration only had information on ships they had built or renovated and had no information on barges. Therefore, information pertaining to barges was obtained by PNL directly from barge designers, owners, and operators located on both the West Coast and in the Mississippi Delta Region.

The Coast Guard's Marine Investigation Division's databases contained no information regarding penetration sizes. Their CASMAIN database identifies accidents of interest and identifies the report numbers containing the repair information. These repair reports are not held by the Coast Guard but must be obtained from the shipyard where the repairs were made. These reports contain information on the quantity of steel plate replaced on the ship during repairs, but no information pertaining to size or quantity of penetrations in the hull. PNL has not been able to obtain ship damage/repair or ship design information directly from the shipyards, as the yards are normally bound by a non-disclosure agreement with the ship owners.

The results of the literature search and discussions with experts are discussed in more detail throughout the report. The literature reviewed in this investigation is referenced at the end of each section of the report and in Section 7.0 (bibliography).

## 1.2 HISTORICAL PERSPECTIVE

The following discussion puts in perspective the issue of oil spills in U.S waters resulting from collisions and/or groundings of tank ships and barges. The information is useful in characterizing these accident scenarios and in bounding the performance requirements for onboard self-help counter-measure systems, including the concepts considered in this study.

A report describing a Canadian evaluation of tanker self-help recovery systems contains a comprehensive global database of spills of crude and refined product from both tankers and barges during 1974 through June 1990 (see Appendix A in Smedley et al. 1991). PNL used this database to develop the following historical perspective of spills resulting from collisions and groundings in U.S. waters.

There were 681 casualties worldwide involving tankers and barges carrying crude or refined petroleum product from 1974 through June 1990. Of these casualties, 57 resulted in spills of 15,000 tons or larger (220,279 tons being the largest). Tankers of U.S. flag were involved in the largest number of accidents (160). This resulted in the fourth largest aggregate spill volume (193,731 tons), exceeded by tankers of Liberian flag (1,090,862 tons in 99 accidents), tankers of Greek flag (802,331 tons in 77 accidents), and tankers of Spanish flag (319,918 tons in 6 accidents).

Of the 681 casualties worldwide, there were 42 tanker and 73 barge accidents that occurred in U.S. waters during this survey period that resulted from either collision or grounding.

Of the 42 tanker accidents occurring in U.S. waters, 15 involved vessels of U.S. flag. The majority (30) of these tankers were between 15,000 DWT and 85,000 DWT, with 9 in the range of 25,000-35,000 DWT and 10 in the range of 75,000-85,000 DWT. The smallest tanker involved was 5000 DWT and the largest was 211,000 DWT. These 42 tanker accidents were divided evenly between collisions and groundings. Two accidents (both collisions) occurred in "open water" (greater than 50 miles offshore), 16 accidents occurred in "restricted" waters (0-50 miles offshore), 19 accidents occurred in harbors, and 5 accidents occurred at piers. Based on these data, it is evident that 57% of the tanker accidents occurred in inland waterways.

A total of five accidents occurred in U.S. waters during this survey period that resulted in spills in excess of 15,000 tons; however, only three of these accidents resulted from collision and/or grounding of tankers, namely the Burmah Agate, EXXON Valdez, and Argo Merchant. The other two vessels, Grand Zenith and Spartan Lady, were victims of hull rupture during severe weather off the east coast of the United States resulting in fatalities and the loss of both ships and their cargo.

In 1979 the Burmah Agate (61,674 DWT - Liberian flag) collided with the Mimosa 4 miles from the entrance to Galveston Bay, Texas, and subsequently went aground. This accident resulted in a fire, an explosion, and a spill of approximately 34,661 tons (about 11.4 million gallons) of Nigerian light crude. This spill ranked 23rd in size, on a global basis, during the survey period.

In 1989 the EXXON Valdez (211,000 DWT - U.S. flag) went aground on Bligh Reef, Prince William Sound, Alaska. This accident resulted in a spill of approximately 32,721 tons (about 10.8 million gallons) of North Slope crude. This spill ranked 27th in size, on a global basis, during the survey period.

In 1976 the Grand Zenith (30,000 DWT - Panamanian flag) broke-up and sank in open water off the coast of Massachusetts. This accident resulted in

38 fatalities and a spill of approximately 28,921 tons (about 9.5 million gallons) of No. 6 fuel oil. This spill ranked 34th in size, on a global basis, during the survey period.

In 1976 the Argo Merchant (28,691 DWT - Liberian flag) went aground 40 miles South East of Nantucket, Massachusetts. This accident resulted in a spill of approximately 24,295 tons (about 8 million gallons) of No. 6 fuel/ naphtha. This spill ranked 40th in size, on a global basis, during the survey period.

In 1975 the Spartan Lady (20,724 DWT - Liberian flag) was scuttled in restricted water off the coast of New Jersey. This accident resulted in one fatality and a spill of approximately 19,436 tons (about 6.4 million gallons) of No. 6 fuel. This spill ranked 51st in size, on a global basis, during the survey period.

Each of the remaining 39 tanker accidents involving collision or grounding resulted in spills of less than 15,000 tons (less than 5 million gallons).

The database for barges was not as specific as for tankers. Of the 73 barges, only 14 were identified as to size. The sizes identified ranged from 1,000 GT to 33,700 GT. Many of the barges in the database were not identified as to name/number; however, the date and location of the accident and type of cargo spilled were given for most barges. Almost all barge accidents occurred in inland waters and resulted in spills of refined product.

In summary, during the survey period, 17% of the casualties worldwide involving tankers and barges carrying oil (crude and product) occurred in U.S waters, predominately in inland waters, and were the result of collision and/ or grounding. Of these casualties, 63% involved barges and resulted in relatively small spills of refined product, whereas 37% involved tank vessels. Most of the tank vessels (71%) contained crude, were in the size range of 15,000 DWT to 85,000 DWT, and involved tank vessels other than U.S. flag. Except for three tankers, all of the spills in U.S. waters resulting from collisions and/or groundings were less than 15,000 tons (5 million gallons). During this survey period, a total of 57 casualties occurred worldwide (8% of the total casualties) that resulted in spills of 15,000 tons or larger.

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# 2.0 OUTFLOW CALCULATIONS

Two parameters important to the evaluation of a self-help method are time and quantity of oil. Both the deployment and duration time are critical factors for any self-help method. A self-help method must be capable of being deployed in an amount of time that results in a majority of the oil being contained or retrieved. The system must also be capable of functioning for the entire duration of the event. The evaluation of a self-help method also requires an understanding of the quantity and rate at which the oil must be handled.

To obtain an understanding of the time and oil volumes associated with small, medium, and catastrophic accidents, an outflow analysis was performed for hypothetical accidents involving vessels carrying oil. The analysis was applied to various sizes of tankers and barges that transport oil through U.S. waters. This Section discusses the assumptions applied to the outflow analysis, describes the sources of data used and the specific ships analyzed, explains the computational method, and presents the overall results of the outflow calculations. Results for each case analyzed are included in Appendix A.

## 2.1 ASSUMPTIONS

This section describes and discusses the assumptions used in the outflow calculations. Any discussion regarding an assumption immediately follows the statement of the assumption. The assumptions that apply to both groundings and collisions are discussed first, followed by those pertaining only to cases of groundings and then those for collisions.

Unless otherwise stated, each assumption applies to both tankers and barges. Initially MARPOL assumptions were to be used in developing outflow calculations. However, not all MARPOL assumptions are applicable to time-dependent outflow calculations; therefore, they were only used if applicable.

### 2.1.1 General Assumptions

1. **The effects of turbulence, mixing, ship motion, and sloshing were neglected.**

This assumption was specified by the Coast Guard to simplify the problem. The inclusion of these factors would require a great deal more effort, and the impact of these factors varies from case to case.

2. **The draft and trim of the leaking vessel were held constant during oil outflow. Designer water lines were assumed.**

There was no way of properly accounting for the change of a penetration's position relative to the water line without accounting for any change in the vessel's trim. The modeling of any listing or load imbalance was beyond the scope of this analysis; therefore, the change in a vessel's displacement was neglected. In most cases, the actual change in a vessel's displacement was minimal due to the relatively small percentage of a vessel's overall mass lost (less than 2-3%). Some of the smaller barges leaked oil equivalent to 20% of their total weight; however, in these cases the barges took on an almost equivalent amount of water.

In some instances, the change of a vessel's trim could have a significant impact on the outflow of oil. The effects could result in either more or less oil being spilled at a faster or slower rate depending on the specific incident.

3. **No oil was transferred via pumping or any other method during an accident scenario.**

The purpose of these calculations was to determine outflow times assuming no action was taken to limit oil loss.

4. **Vessels were fully loaded at the time of an accident. Full loads consisted of cargo tanks 98% and 95% full for tankers and barges, respectively.**

These data were provided with vessel designs and confirmed by individuals in the industry.

5. **Any evaporation of the cargo within the cargo tanks was neglected.**

Oil is not a highly volatile substance, and any significant pressure changes within the tanks were small.

6. **The outflow of oil was considered an isothermal process. A constant temperature of 45°F was assumed.**

This assumption allowed the changes in gas temperatures within the tank to be neglected. The effect of this assumption on the overall results is negligible.

7. **Penetrations will be generally rectangular in shape with random petals jagged inward. A discharge coefficient of 0.61 was used. This value comes from experimental data obtained from Dodge et al. (19C0).**

Experimental work has shown that the discharge coefficient has little dependence on fluid viscosity and penetration size but varies substantially with penetration geometry (Dodge et al. 1980).

The shape of the penetration was assumed rectangular in the cases of collision because penetration was assumed to be due to the bow of a ship. A V-bowed vessel would tend to create a somewhat rectangular penetration when it penetrated the side of a tanker assuming the striking vessel had a velocity perpendicular to the tanker.

In the cases of grounding, the rectangular shaped penetration is assumed because of the assumptions made in determining the size of the penetration. These assumptions are explained in Section 2.1.2.

The assumption of random jagged petals inward was made because all breaches of the hull are assumed to be made by penetration.

The experimental work of Dodge et al. (1980) determined discharge coefficients ($C_D$) for a variety of orifice geometries. Discharge coefficients for geometries applicable to this analysis are listed below (Dodge et al. 1980).

| Orifice Shape | Edge Condition | $C_D$ |
|---|---|---|
| Rectangular | Random Petals Jagged Inward on the Horizontal Edges | 0.609 |
| Rectangular | Random Petals Jagged Inward on the Vertical Edges | 0.613 |
| Circular | Random Petals Jagged Inward | 0.577 |

**8. The following values were assumed:**

Specific gravity of seawater = 1.025
Specific gravity of freshwater = 1.0
Specific gravity of oceangoing vessel cargo = 0.86
Specific gravity of inland waterway vessel cargo = 0.92

The value for the specific gravity of seawater was the same throughout the literature.

A specific gravity of 1 was assumed for inland waterways. The actual value is slightly higher for many waterways due to silt and other material in the water.

The specific gravity of crude oil varies between 0.83 and 0.90, a common value being 0.86. This is the value used throughout all of the literature involving analyses of oceangoing vessels carrying crude oil.

Most inland waterway vessels do not carry crude oil. A common cargo on inland water ways is #2 diesel fuel; therefore, the inland waterway barges were assumed to carry a cargo with a specific gravity of 0.92.

**9. The penetration of ballast tanks was not considered in the analysis. Only the outflow of oil and/or fuel was considered.**

Outflow of ballast tanks would not directly effect the oil outflow. However, the penetration of ballast tanks could effect the vessel's trim and stability. Because changes in the vessel's trim were not modeled, the penetration of ballast tanks was ignored.

**10. Oil outflow is assumed to be initiated after the penetration has reached its final size. No leakage is accounted for during the actual accident event.**

To include this factor would require detailed, time-dependent modeling of the structural deformation occurring. This was beyond the scope of this analysis.

11. **The outflow area was assumed to be equal to the size of the penetration. The effects were neglected of the penetration being partially plugged due to the bow of the penetrating ship in the case of collision, the ground in the case of grounding, or deformed structural material in both cases.**

The impact of penetration blockage can be significant on oil outflow rates. It is unknown whether the effects of blockage can be generalized or depend entirely on individual cases. The effects of blockage would require experimental data or data from actual events, neither of which were obtained for this analysis. Therefore, to avoid producing optimistic times for oil outflow, the effects of blockage had to be neglected.

12. **The outflow was assumed to only occur through the assumed penetrations. Leakage through cracks, torn weld seams, and other damage associated with the accident were not taken into account.**

13. **When necessary, void pressures within the tanks were determined assuming ideal gas behavior.**

Refer to the Assumption 18.

14. **Tankers were assumed to have a nitrogen cover gas initially pressurized to 2 psig.**

The literature and individuals within the industry reported void pressures in tankers ranging from 1-2 psig during transport. The higher the void pressure the greater the initial hydrostatic head. A void pressure of 2 psig was assumed to ensure results were conservative.

15. **The cover gas system aboard tankers was assumed sealed off from any penetrated cargo tanks during an accident scenario.**

This assumption was made to be consistent with the assumption of no action being taken to limit the oil outflow. Industry individuals also stated that the cover gas systems on most oil tankers were not sophisticated on-line systems.

**16. Barges were assumed vented to the atmosphere.**

Little information was found in the literature regarding barges. Individuals within the industry reported that any relief valves used on barges vented the cargo tanks at maximum and minimum pressures close to atmospheric pressure. Refer to the discussion of Assumption 18.

**17. Initial void spaces were not penetrated during an accident.**

This assumption was made to keep initial conditions the same for all accidents and to maintain conservative results. Penetration of the void space in an accident would result in a lower initial hydrostatic head in the case of tankers.

**18. Minimum threshold pressures ($P_{Thres}$) for the relief valves on vessels were assumed to be atmospheric pressure ($P_{atm}$). The void pressure in all cargo tanks was assumed to never fall below $P_{atm}$.**

The program written to perform the outflow calculations is capable of modeling the venting through a relief valve. However, specific information was not obtained for the relief valves of the vessels analyzed. Incorrectly modeling the relief valve could result in optimistic outflow times.

For tankers, the pressure of the void space ($P_{void}$) was assumed to change assuming ideal gas behavior until the $P_{void}$ was equal to $P_{atm}$. Upon reaching $P_{atm}$, the $P_{void}$ was assumed to remain constant. No pressure loss was associated with the relief valve.

For barges, venting through the relief valve was completely neglected since the void space of barges is not initially pressurized.

Some analyses were conducted that modeled the relief valve and evaluated the qualitative affects of venting through the relief valve. The results are presented in Section 2.4.

The void spaces of cargo tanks may be individually vented with separate relief valves or manifolded into a single network containing a single relief valve. Details of the venting systems for the vessels analyzed were not obtained. To obtain a venting system for the qualitative analyses, details from other vessels were incorporated. The Code of Federal Regulations for tank ships was also consulted (46 CFR Part 32, Sections 32.55-20 and 32.55-25).

Both individual tank venting and manifold venting were analyzed. The modeling of the relief valve in both cases assumed the valve has a 10-inch diameter opening when the valve is open and a discharge coefficient of 0.8. No maximum threshold pressure was assumed. Calculations were performed assuming minimum threshold pressures of -0.25 psig and -0.5 psig.

The manifolded system assumed individual cargo tank vents 3 inches in diameter. The volume of the manifold system was assumed equal to the volume of the void spaces in the unpenetrated tanks. This is a valid assumption since the relative volume of the manifold piping is small compared to the cargo tank void spaces. No flow resistance was modeled from the intact cargo tank voids to the manifold. The flow resistance from the manifold to the penetrated tanks was modeled. Also taken into account was air flow into the manifold system via the penetration in cases where the oil level drops below the top of the penetration.

### 2.1.2 Assumptions for Cases of Grounding

Assumptions 19 through 30 apply to groundings only. The method for determining the penetration size in the case of grounding is similar to the method used by Det Norske Veritas (DnVC) in their comparative study of tanker designs (Kohler and Jorgensen 1990). This method was prescribed for this study by the Coast Guard.

19. **The vessel was assumed to have forward speed at the time of grounding. Damage caused by the grounding while the ship was adrift, executing a turn, or going astern was not considered.**

20. **Damage started at the forward perpendicular of the vessel and propagated toward the stern.**

21. **Only the center tanks were penetrated during the grounding of tankers.**

The longitudinal bulkheads separating the tanks are capable of absorbing a great deal of energy compared to the longitudinal stiffeners. Because of this, these bulkheads tend to limit the transverse propagation of a penetration. To ensure the largest penetration for a given ship speed, it was assumed that the longitudinal bulkheads absorb no energy during a grounding.

Because of the assumptions made in determining the size of the penetration created during a grounding, the penetration of only wing tanks would result in less oil being leaked than for the case of only center tanks; therefore, this case was neglected (refer to Assumption 28).

**22. Only one set of side tanks was penetrated during the grounding of an inland waterway barge.**

Inland waterway barges only have two tanks in the transverse direction. It was assumed that the center longitudinal bulkhead absorbed no energy during a grounding (refer to Assumption 21).

**23. Outflow from ballast tanks was neglected; however, damage to ballast tanks was not necessarily neglected. Therefore, if the bow contained ballast tanks, it was possible for a grounding calculation to yield no damage to cargo tanks and no outflow.**

**24. The ship's trim did not change as a result of the grounding.**

Any lifting of the vessel as a result of the vessel contacting the ground was neglected.

**25. Penetration sizes were calculated for tanker speeds of 5 knots (low-energy case) and 10 knots (high-energy case) and barge speeds of 4 knots (low-energy case) and 8 knots (high-energy case).**

The Coast Guard prescribed the values of 5 and 10 knots for low- and high-energy cases, respectively. The speeds were changed to 4 and 8 knots for barges because the barges analyzed traveled at maximum speeds of 8 knots.

**26. The ship was grounded on a wedge-shaped rock that did not crush, and a constant breadth was assumed during the grounding process.**

This is an assumption made by DnVC and is consistent with other analyses. Groundings on sand or mud bottoms were not considered. This assumption means the ground did not absorb any of the energy during the collision.

**27. The vertical extent of damage due to grounding is determined from statistical information. The maximum extent of vertical damage is assumed for the entire length of the penetration. The damage height was calculated from the following relationship:**

$$\text{Damage Height} = 0.60512 * (Br)/15 \qquad (2.1)$$

where Br = Vessel's Breadth (m)

The damage height was calculated to determine the damage breadth.

This equation was developed from statistical data on bottom damage (Card 1975). The data consisted of 30 cases, of groundings resulting in cargo outflow. Most of the cases involved vessels less than 40,000 DWT with only four vessels being greater. The vertical extent of the damage ranged from 0.16 - 8.2 ft. The mean value was 1.985 ft (0.60512 m) with a standard deviation of 1.25 ft.

Card's work showed that 90% of the 30 cases would have resulted in no outflow if the vessels had contained double bottoms with a depth equal to Br/15. It is from Card's work that the MARPOL assumption of vertical damage equal to Br/15 is used in determining hypothetical outflow of oil for bottom damage.

Card (1975) also pointed out that the 11 cases involving vessels below 3,000 DWT had an average vertical penetration of 1.3 ft, and the 19 ships greater than 10,000 DWT had an average vertical damage of 2.5 ft. However, Card also states that "the amount of vertical damage sustained by a tanker involved in a bottom damaging casualty is not related to the size of the tanker" (Card 1975). Card did not discuss the relationship between tanker velocity and bottom damage or bottom damage and damage length.

The work of DnVC (Kohler and Jorgensen 1990) uses Card's work to estimate the vertical damage in cases of grounding, but it was not clear exactly how Card's work is used. DnVC may have set the damage height equal to Br/15 or just used the average, which is 1.985 ft. DnVC's analysis is applied to 40,000 DWT tankers.

Because it was not clear exactly how DnVC calculated vertical damage, a reasonable method had to be selected. Because the vertical damage is assumed to be constant for the entire length of the penetration, increasing or decreasing the damage height shortens or lengthens the penetration for the same initial vessel energy. The majority of Card's data fell in the range of Br/15 = 0.5 - 1.7; therefore, it was decided to set the vertical damage equal to the mean at Br/15 = 1.0. This resulted in the vertical damage for the four tankers and four barges evaluated ranging from 3.3 ft to 7.1 ft and 1.5 ft to 3.06 ft, respectively.

The actual extent of vertical damage in a grounding depends on the vessel velocity, the structural design, the ground surface conditions, and the ground position with respect to the vessel bottom. It is difficult to use statistics from groundings occurring over a wide range of conditions to accurately determine the vertical damage caused by a wedged rock that does not yield.

The equation used for determining the vertical damage height predicts damage heights within the range of those observed from past groundings.

**28. The damage breadth is 2.5 times the damage height. This is an assumption made by MARPOL.**

This is an assumption also used by DnVC. This damage breadth is assumed constant over the entire length of the penetration. The origin of this value for damage width is unknown to PNL.

**29. The damage length is determined from the following relationship:**

$$L_d = 0.5\ m_s\ V^2 / \left(93369\ \ B_d\ t_{pe} + 33422\ \ t_{pa}\right) \tag{2.2}$$

where $L_d$ = length of damage in longitudinal direction (m)

$B_d$ = breadth of damage (m)

$V$ = ship's velocity (m/s)

$m_s$ = ship's mass (kg)

$t_{pa}$ = actual thickness of bottom plating (mm)

$t_{pe}$ = equivalent thickness of bottom plating (mm) (accounts for longitudinal stiffeners and supporting beams and flanges).

The constants in Equation (2.2) have been converted from those used in the original references (Kohler and Jorgensen 1990; Vaughan 1978) to account for a change in units.

Equation (2.2) is known as the Vaughan Formula and was used by DnVC to predict damage lengths in cases of grounding. The Vaughan Formula was developed from an analysis of the kinetic energy lost during the collision of two ships (Minorsky 1959). Minorsky's work developed an empirical correlation between the resistance to penetration and the energy absorbed in a collision. His work was intended to be used as an aid for ship design. Minorsky's analysis did not develop a relationship for the kinetic energy absorbed by either the struck or striking ship; it only related the total kinetic energy absorbed by both vessels.

Vaughan used Minorsky's work as a basis for relating the initial kinetic energy of a vessel to the damage sustained from the grounding of the vessel. Vaughan's Formula equates the kinetic energy of the ship with the work required to deform the ship's structure. The amount of work required to penetrate the ship's hull is assumed to consist of the work required to tear or fracture the bottom plating of the ship and the work required to move and bend the plating and supporting structure as the ground enters the penetration.

$$\text{The kinetic energy (Ke) of the ship} = 0.5\ m_s\ V^2 \qquad (2.3)$$

$$\text{The work required to penetrate the hull (W)} = C_1 A_s + C_2 Vol \qquad (2.4)$$

where $A_s$ = the area of the fracture

$Vol$ = the volume of the plating and supporting structure moved

$C_1$ = the constant based on the energy function per unit length fractured hull plating

$C_2$ = the constant based on the energy function per unit volume of moved and bent (displaced) material.

$$A_s = L_d t_{pa} \qquad (2.5)$$

$$Vol = L_d B_d t_{pe} \qquad (2.6)$$

Therefore,

$$0.5\ m_s V^2 = C_1 L_d B_d t_{pe} + C_2 L_d t_{pa} \tag{2.7}$$

The solution of $C_1$ and $C_2$ requires the aid of experimental data. Experimental work performed in Japan simulating actual ships (Akita and Kitamura 1972) produced data that allowed Vaughan to solve for the necessary constants, $C_1$ = 352 ton-knot$^2$/m$^2$·mm (93,369 N/m·mm), $C_2$ = 126 ton-knot$^2$/m·mm (33,422 N/mm). These constants are only applicable assuming steel structures.

Vaughan's analysis and DnVC's work have recently been compared to a more extensive analysis of ship damage resulting from grounding (Wierzbicki et al. 1990). Wierzbicki's analysis takes a more detailed look at the various modes of structural failure occurring during a grounding. The predictions of this analysis correlated well with Vaughan's and Minorsky's empirical formulas, but only for specific ratios of the width to damage height (height of the wedged-shaped rock).

Wierzbicki et al. (1990) also conclude that by proving the correctness of Vaughan's methodology, further support is added to DnVC's study. However, in Wierzbicki's analysis it is pointed out that by assuming a damage breadth ($B_d$) equal to 2.5 times the damage height (Assumption 27), it appears DnVC's analysis underestimates the resisting force of the bottom structure by a factor of 1.9 (Wierzbicki 1990). This almost doubles the predicted damage length.

However, DnVC's analysis assumes the damage height is constant throughout the grounding. Card's (1975) investigation of actual accidents along with other data from actual groundings has shown that the maximum damage height is not maintained for the entire length of bottom damage. DnVC's damage height assumption clearly tends to reduce the predicted damage length. Despite the discrepancies discussed, DnVC's work is still considered valid since it was a comparative study of various ship designs.

Most of the work done to date analyzing ship damage has been initiated to aid in the design of ships. Previously mentioned works have provided useful information in understanding and predicting vessel damage for design purposes. However, the application of the present methods is uncertain for predicting penetration sizes for outflow calculations.

Present methods for making damage estimates are concerned with sizes and extent of structural damage. The problem with using the estimates of damage size is that the size of damage is not necessarily correlated to the size of the penetration. Even if a large portion of a vessel's structure has been damaged to the point of having no structural integrity, it may still provide a substantial amount of flow blockage. Leaking may occur through numerous cracks, but oil outflow is entirely different if the entire damaged area is void of structural material. The use of the entire damaged area for the penetration size should tend to greatly overestimate the outflow area.

**30. After running aground over the wedge-shaped rock the ship was adrift.**

No plugging due to the ground was assumed. In many grounding cases, the vessel is stranded with a portion of its hull still resting on the bottom. In cases such as this, it is not unreasonable to assume the ground may plug as much as 90% of the outflow area of a penetration.

### 2.1.3 Assumptions for Cases of Collisions

Assumptions 31 through 34 apply only to cases of collision.

**31. All penetrations were assumed at the water line.**

A penetration at the water line gives worst-case results for oil outflow. A worst-case condition was defined as one in which the outflow rate of oil is highest and the largest cumulative amount of oil is leaked. Only when the penetration is at the water line will all of the oil be leaked from a tank (Assumption 1 is assumed). If the bottom of the penetration is above the water line, all of the oil below the penetration will remain in the tank. If the top of the penetration is below the water line, a column of oil extending from the height at which hydrostatic balancing occurred down to the top of the penetration will remain in the tank.

The largest initial flow rate will result for a penetration with its bottom positioned slightly below the water line. The specific distance depends on the ratio of the oil and water densities.

If it is assumed that a penetration has its top above the water line and its bottom below the water line, the lower the penetration is positioned the smaller the initial outflow rate. This is because the average back pressure due to the water is increased with increasing depth. The higher the penetration is positioned, the smaller the outflow rate during water ingestion. This is because the available penetration area available for fluid transfer is reduced as the height of the penetration is increased.

The position of the penetration at the water line does not affect the oil outflow for small holes (>2 $ft^2$). The significance of the penetration's position increases with penetration size.

For this analysis, the center of the penetration was positioned approximately at the water line. This condition allows for the outflow to be approximately a worst-case condition while at the same time reasonably assumes the position of a penetration created by a striking vessel.

**32. Penetrations will be positioned at the longitudinal locations that yield worst-case conditions (i.e., result in the largest oil outflow). A worst-case condition is also considered to be the case that yields the largest initial flow rate (refer to Assumption 31).**

Because all tanks are loaded to the same height, the largest oil outflow case will also yield the maximum initial outflow. Therefore, penetrations were longitudinally placed so that the two adjacent tanks with the largest cumulative volume were penetrated with a single hole. The penetrations were centered between the two breached tanks.

**33. Due to a lack of an applicable method of determining penetration sizes, outflow calculations were performed over a range of penetration sizes.**

For tankers, the penetration size varied from 0.5 to 72 $ft^2$. For barges, the penetration size varied from 0.5 to 8 $ft^2$. The range of penetration sizes applied to barges was smaller due to the smaller size of the barges. Barge penetration sizes could not be increased without neglecting Assumption 18.

If a method had been found for predicting actual collision damage for the struck vessel, it would be difficult to determine for what general conditions the analysis should be performed. Parameters to be determined include striking vessel speed, bow shape, bow strength, mass, and draft.

**34. All penetrations had a height-to-length ratio equal to 2.**

This ratio was selected for a reasonable ratio that might be produced when a V-bowed vessel collided with a tanker. This assumption assumes the struck tanker has no velocity and that the velocity of the striking ship is perpendicular to the struck tanker.

## 2.2 DATA SOURCES

Most of the information regarding ship damage resulting from accidents came from technical literature. Telephone conversations were held with several individuals of DnVC. The methodology used for determining damage sizes in the case of groundings was taken from previous work done by DnVC (see Section 2.1.1).

For collisions, very little information, which was applicable to this study, was found in the literature. Therefore, information from individuals within the industry was used to help determine the range of penetration sizes to be evaluated in the study.

The methods used in modeling the oil outflow came from basic fluid dynamics and work done by Franklin T. Dodge (Dodge et al. 1980).

The most difficult information to obtain was that regarding actual tanker designs and specifications. Most of the individuals contacted regarded this information as proprietary and hence declined to provide the information to PNL. Sincere appreciation is given to the Maritime Administration's Division of Naval Architecture in assisting to make this information available. The four tanker designs used for the analysis are ships that were either built or renovated for the United States Government. The tanker sizes were selected to cover the range of tanker sizes for which data were available. The specific tankers chosen were selected because all of the necessary data were obtained. The four tankers evaluated were of the following sizes: 34,000 DWT; 89,700 DWT; 225,000 DWT; and 262,000 DWT. Schematics of the four tankers are shown in Figures 2.1 through 2.4.

The barge designs used in the analysis were provided to PNL by private shipping companies operating in the Gulf region and on the west coast. The specific barge designs evaluated were selected the same as those for the tankers. The four barge designs evaluated consisted of the following sizes: 628 GT; 1,182 GT; 1,769 GT; and 2,713 GT. The first three barge sizes listed are those of inland waterway vessels. The last barge listed is that of an oceangoing barge. Two cases were evaluated for the 2,713 GT barge. The amount of cargo that this design can carry depends on its certification date. Those barges that have been grandfathered can carry cargo in all 15 cargo tanks. Barges built after the regulation must not carry cargo in the three bow tanks. (The exact date of the grandfather clause was not obtained). Schematics of the four barges evaluated are shown in Figures 2.5 through 2.8.

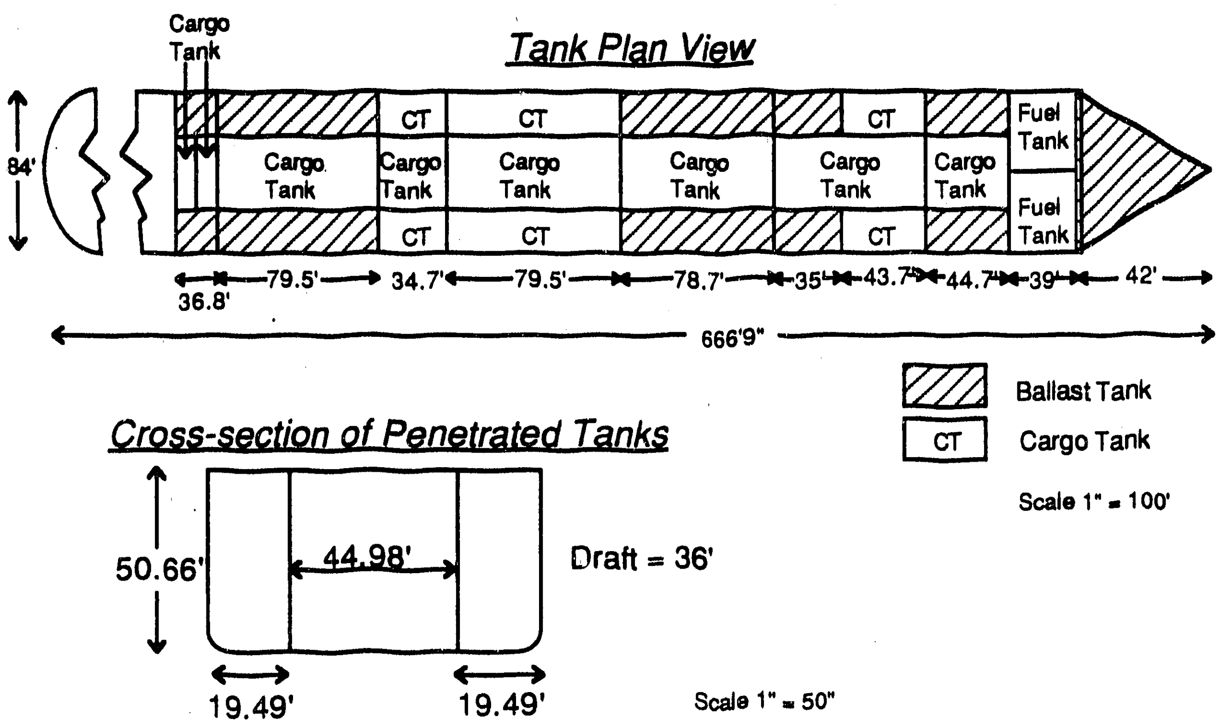



FIGURE 2.1. 34,000 DWT Tanker

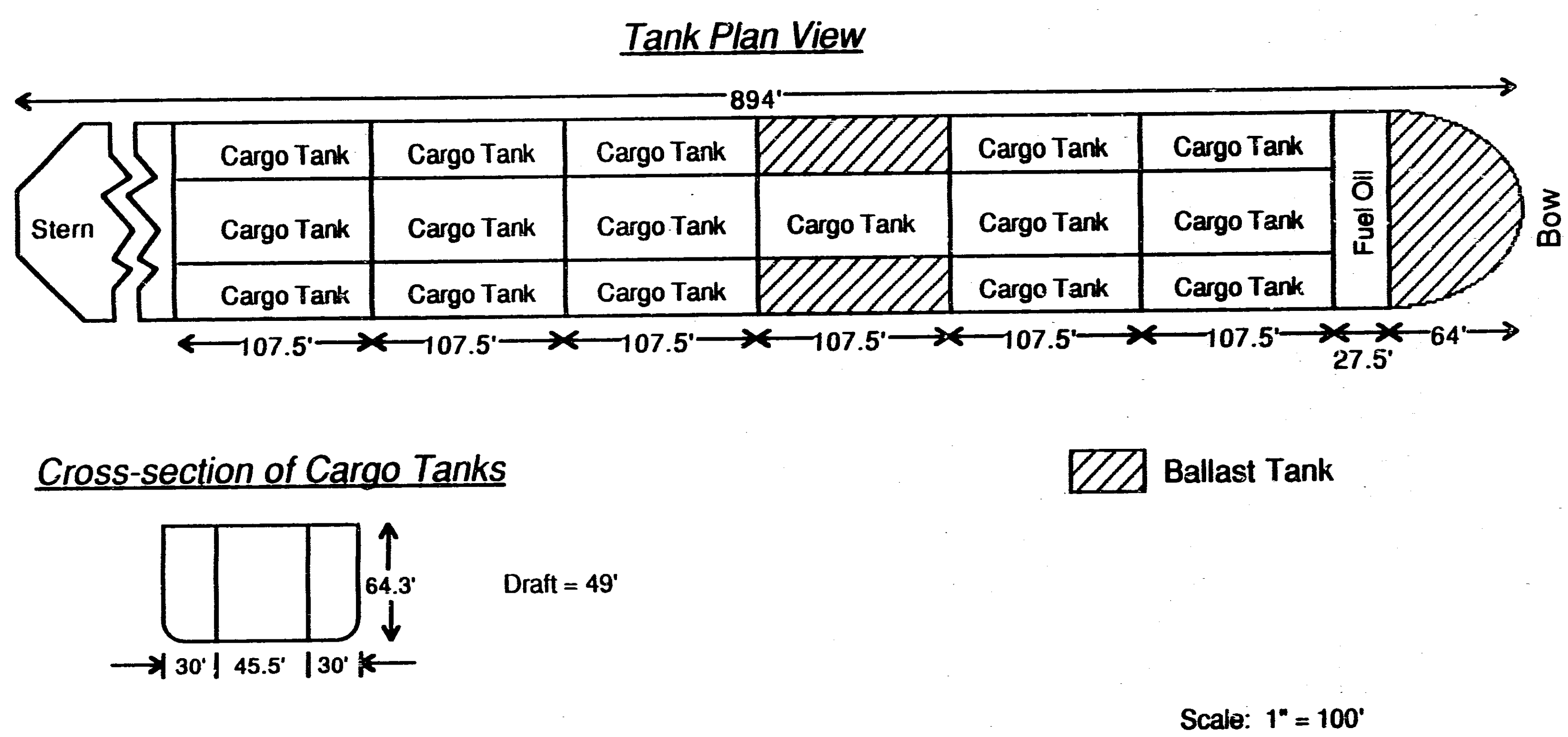



FIGURE 2.2. 89,700 DWT Tanker

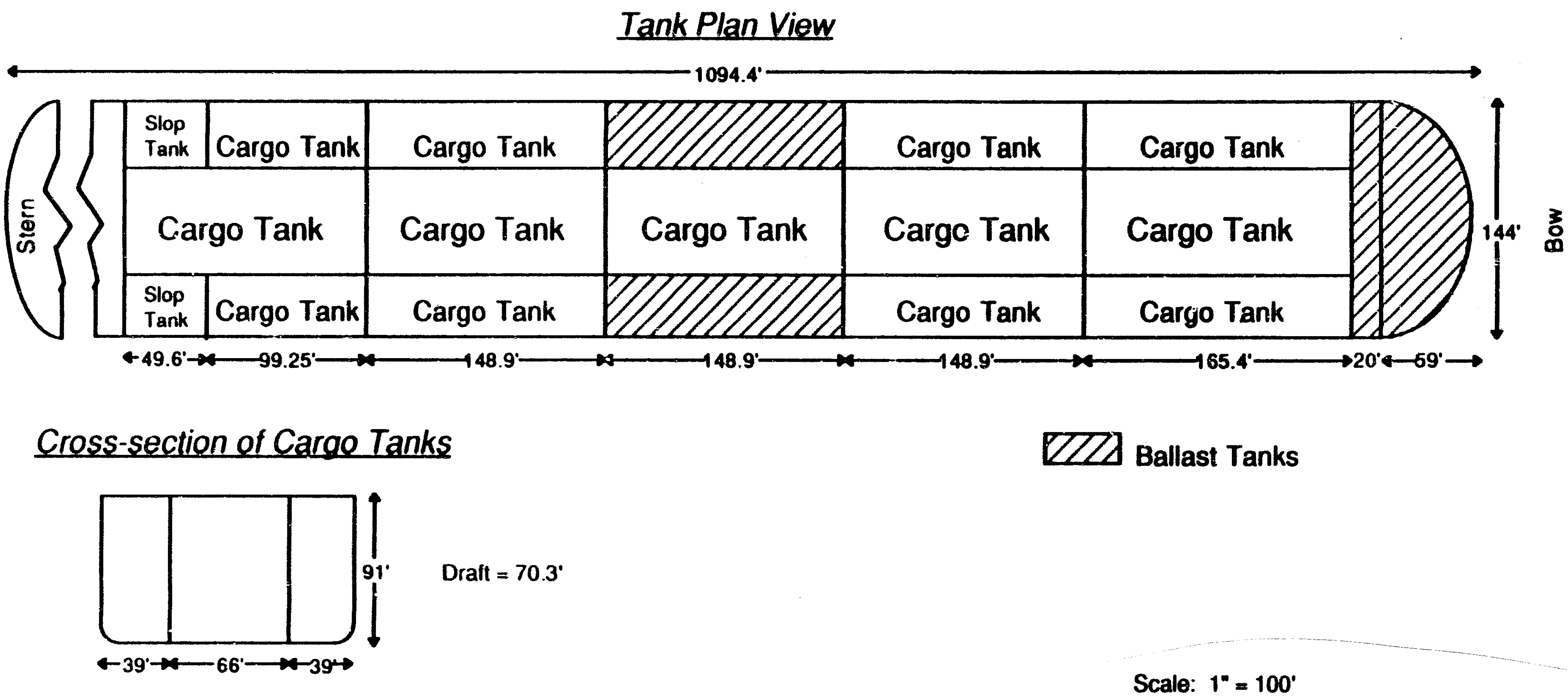



FIGURE 2.3. 225,000 DWT Tanker

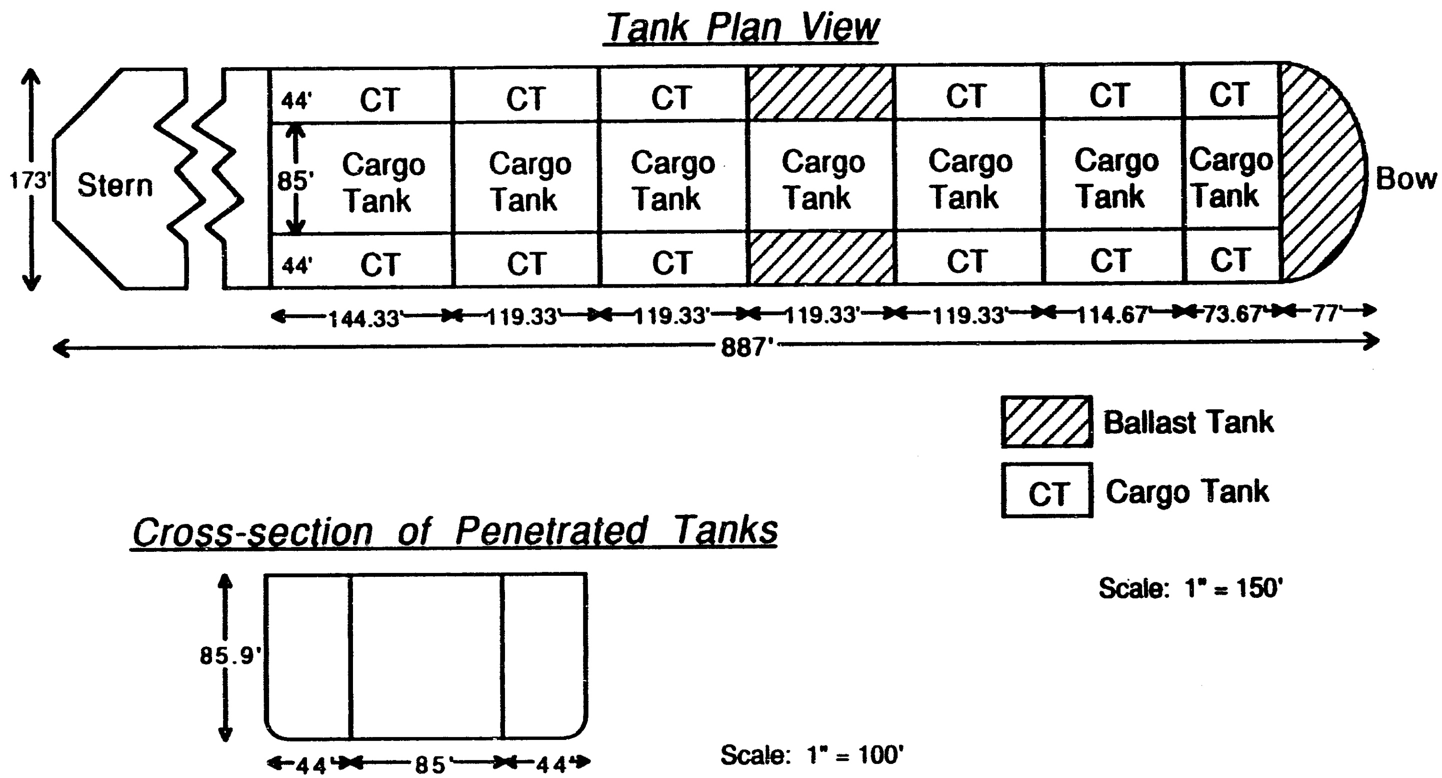



FIGURE 2.4. 262,000 DWT Tanker

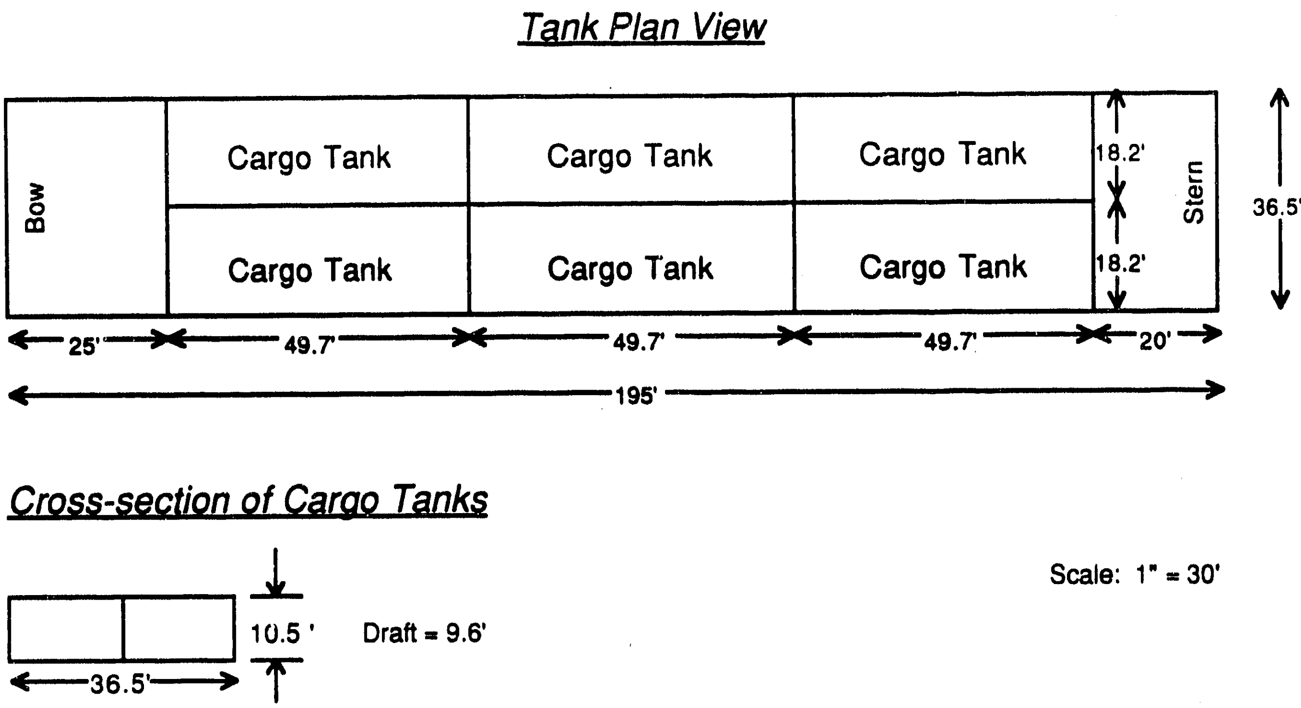



FIGURE 2.5. 628 GT Inland Waterway Barge

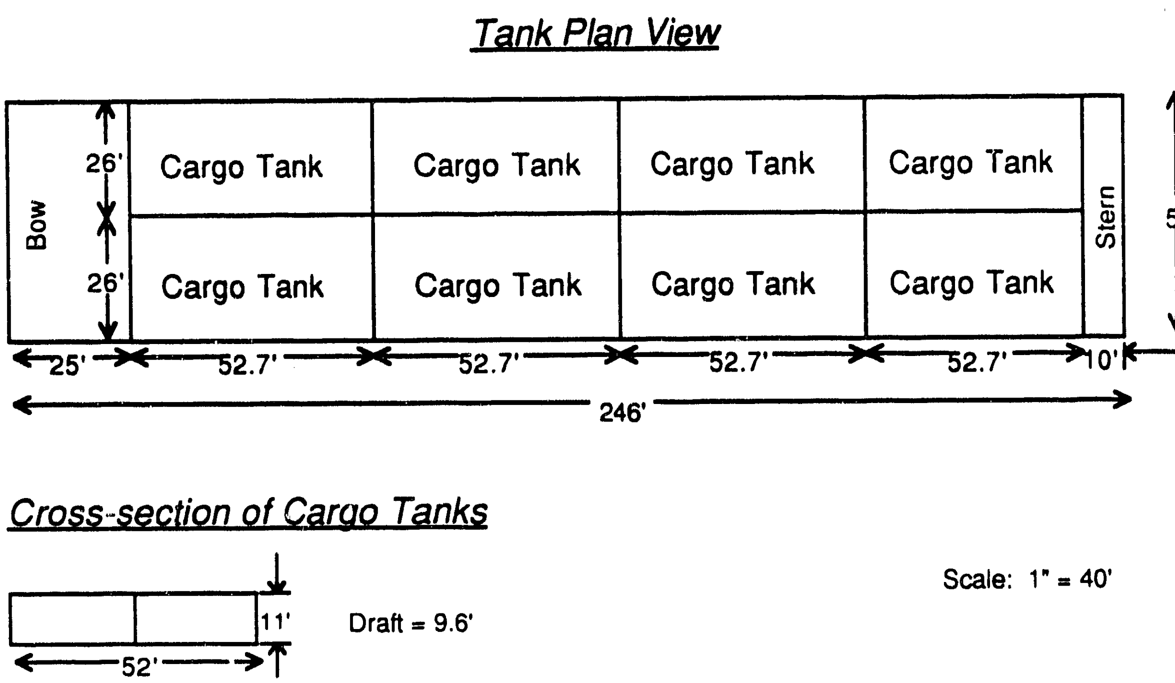



FIGURE 2.6. 1,182 GT Inland Waterway Barge

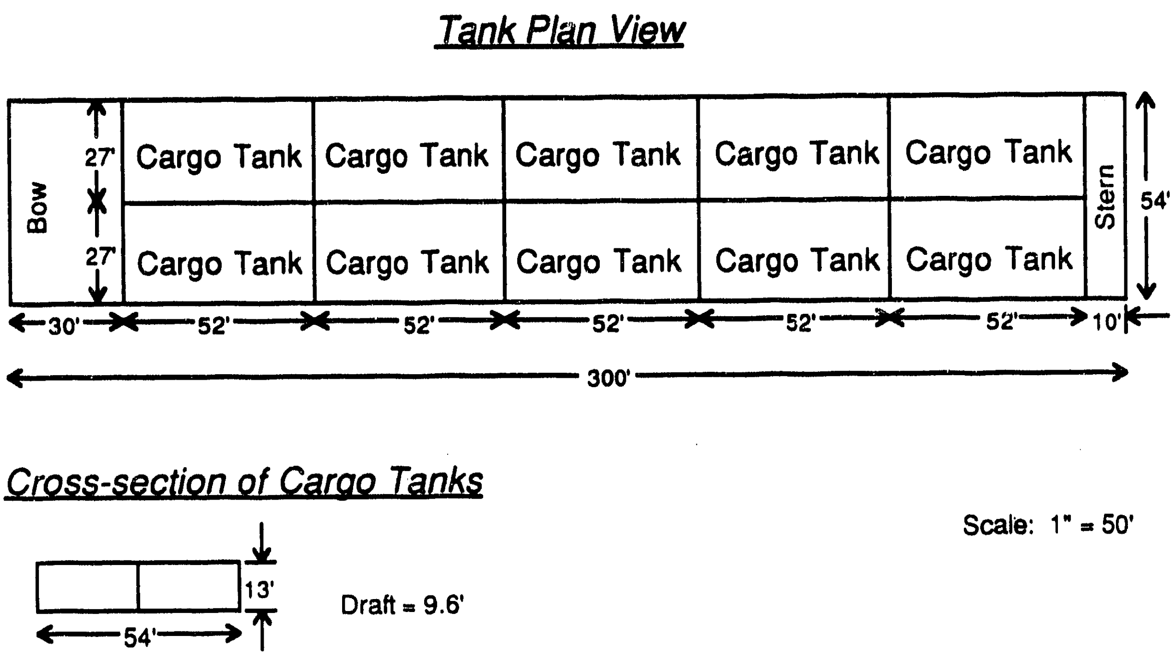
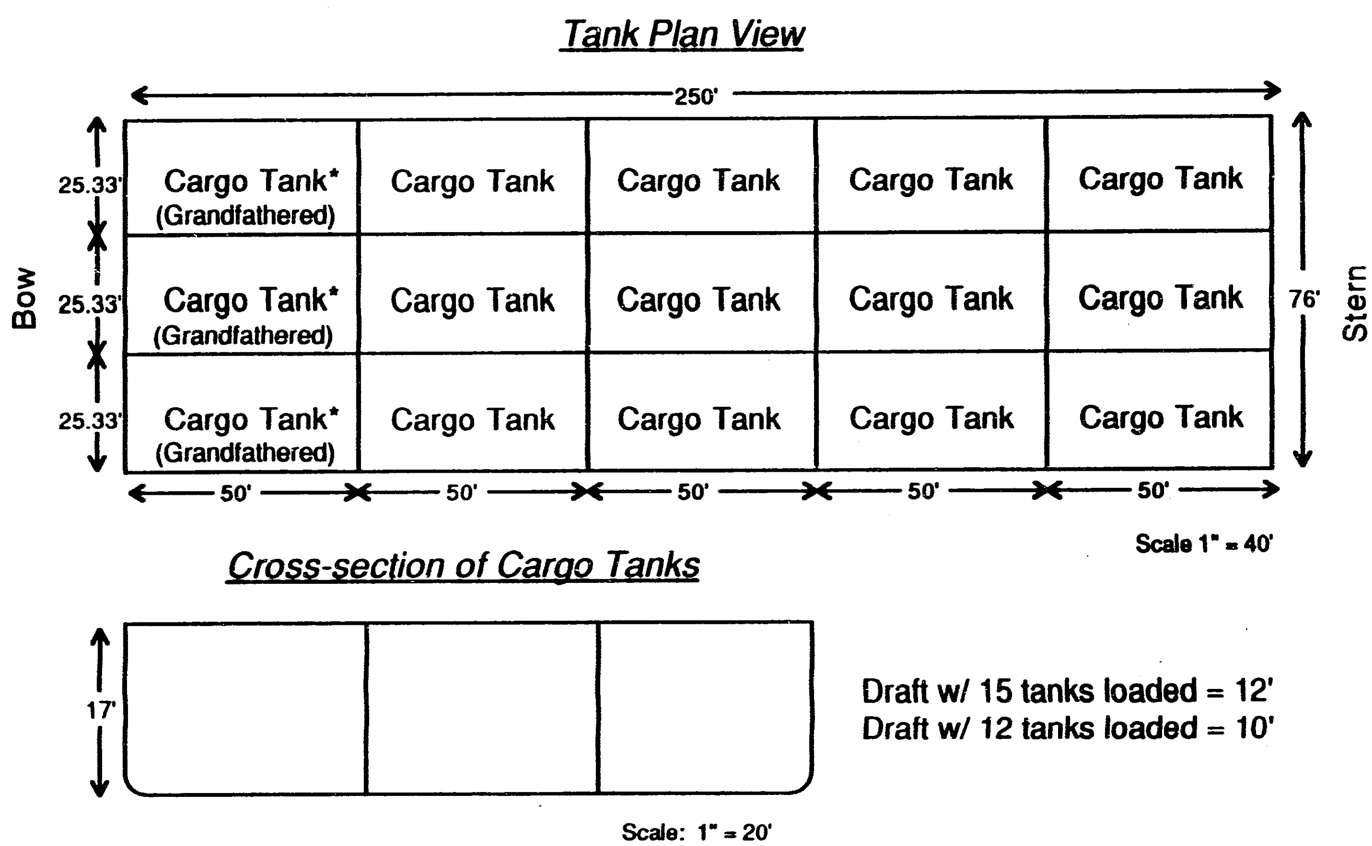



FIGURE 2.7. 1,769 GT Inland Waterway Barge




*Barges that are grandfathered with regard to loading regulations may carry cargo in all fifteen tanks. Otherwise, the bow tanks must be used as a rake and remain empty.

FIGURE 2.8. 2,713 GT Oceangoing Barge

## 2.3 COMPUTATIONAL METHOD

The cumulative oil outflow and the oil outflow rate from the penetrated tanks were determined by computing the transient conditions of the oil within the tank. This was accomplished by balancing the mass and energy of the tank throughout the transient event. The assumptions described in Section 2.1 were applied.

Oil outflow is dependent on the pressure difference across the penetration. The initial outflow of oil is caused by the difference in hydrostatic pressure between the oil inside the tank and water or air outside the tank. If the bottom of the penetration is below the water line, than water ingestion will occur when the pressure difference across the penetration approaches zero. The water ingestion is due to the buoyancy of oil in water. Water ingestion will be completed when the water level in the tank reaches the top of the penetration if the penetration is completely submerged, or the outside water level if the penetration is only partially submerged.

In the case of grounding, water ingestion will not occur. If the bottom penetration is assumed level, then there is no path for the oil to rise to the top. In this case, oil outflow will cease when hydrostatic balancing is achieved and the pressure difference across the penetration is zero. Only the outflow of oil was a concern in this study; water inflow was not calculated. Depending on initial conditions, it is possible for the water to flow into the tank when the pressure outside the penetration exceeds the inside pressure. In this study, such an event would simply result in no oil outflow.

To generate the time-dependent curves of the oil outflow and oil outflow rate, a fortran program was written and run on a Sun Sparc-2 work station. The program produced a detailed output file, a one-page summary of the output file, and a plot of the cumulative oil volume lost and oil outflow rate with respect to time. The plot was generated utilizing the UNIRAS™ graphics package.

In the case of grounding, the program calculates the penetration size and determines the outflow area in each of the penetrated tanks. In the case of collision, the total penetration size is input and the program determines the outflow area in each of the penetrated tanks.

The time step is determined from an input value for the maximum fraction of the tank's volume that is allowed to be discharged in a single time step and from the initial mass flow rate calculated. The maximum allowable volume is divided by the initial flow rate. This initial time step is then held constant throughout the calculation. The time step could be optimized, but it was not necessary. The sensitivity of the results with respect to the time step was evaluated. It was found that maximum volume fractions less than 0.002 showed negligible differences in the results. These results assume that the effects of the relief valve are ignored. The mass flow of air into the tank is much more sensitive to the size of the time step. Therefore, a smaller time step was applied to gas flows.

Water ingestion was assumed to commence when the pressure difference across the penetration was equal to one hundredth of the atmospheric pressure. This driving force for water ingestion was assumed to allow for a simple numerical solution of the problem and comes from previous experimental work on the subject (Dodge et al. 1980). During the numerical solution of the problem, all parameters were assumed constant throughout an entire time step. A quasi-equilibrium was assumed in which water enters the tank lifting the oil, increasing the hydrostatic head of the oil, and thus increasing the pressure difference across the penetration. In response to the increased pressure difference, oil flows out of the tank.

The same method of calculating oil outflow was employed by Ross Environmental Research LTD of Canada in their study of self-help countermeasures for Arctic tankers (Ross 1983) Results from the calculations used in this study agreed with those from the Ross study for similar cases.

The pressure difference across the penetration was calculated at the center of the penetration. To allow for larger penetration sizes, the program adjusted the assumed penetration size when the outflow area was reduced, such as when the oil level fell below the top of the penetration.

Calculations were only performed for side penetrations at the water line. The program is capable of positioning the penetration at any elevation; however, the program does not include an air ingestion model.

## 2.4 RESULTS

The following two sections present the results of the outflow calculations and discuss the qualitative effects of the relief valve venting. The results presented in this section have been summarized for all eight vessels evaluated. Results for individual vessels are included in Appendix A.

### 2.4.1 Grounding

Figure 2.9 shows an example of the curves generated by this study. The dotted-lined curve plots the oil outflow rate. The flow rate declines rapidly as the void pressure decreases assuming ideal gas behavior. The void pressure reaches atmospheric pressure and the void space is assumed vented to the atmosphere with no limitations on the air inflow rate. The flow rate declines linearly until the two tanks with penetrations running their entire length become hydrostatically balanced. The flow rate continues to decline until the final cargo tank, with a smaller penetration in the bottom, is hydrostatically balanced. The solid line plots the cumulative oil outflow with respect to time. Similar plots with corresponding tables for each vessel evaluated can be found in Appendix A. However, if no oil leaked, there is no outflow plot.

Calculations for cases of grounding were performed for all eight vessels. Each vessel was evaluated for a low- and a high-energy grounding. Table 2.1 presents the results for groundings of tankers. The results show that no cargo tanks were penetrated for the low-energy cases of the 34,000 and 89,700 DWT tankers while the high-energy case resulted in penetrated cargo tanks for all the tankers.

The number of tanks penetrated depends not only on the energy dissipated during the grounding but also on the configuration of the tanks. A vessel could have three tanks penetrated and still sustain half the damage of another with only one tank penetrated. A better comparison of damage is found by comparing damage areas. The damage widths and lengths can be obtained from the

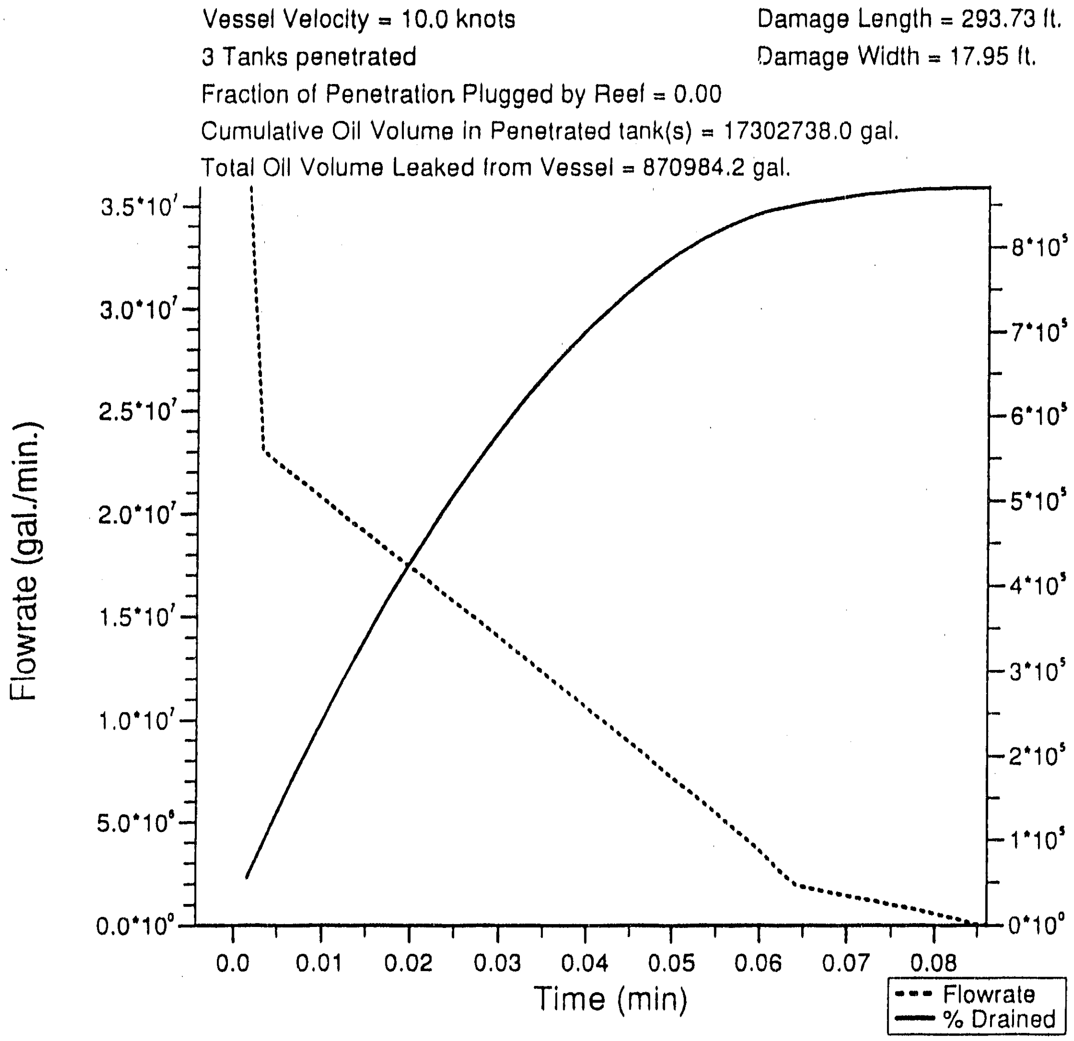



FIGURE 2.9. Outflow Plot for Individual High-Energy Case of Vessel Grounding for 262,000 DWT Tanker

individual plots of each case found in Appendix A. Since this study was only interested in oil outflow, damage length refers to the length of damage in the penetrated tanks and does not account for damage to any bow ballast tanks. However, the energy absorbed by these tanks is accounted for in the calculation of the damage length.

The penetration areas estimated in this study are quite large. They are also assumed free of any obstructions that would reduce the flow (see Section 2.1.1). This is the reason for the very short times required for hydrostatic balancing to be achieved. The effects of no blockage can be

TABLE 2.1. Grounding Results for Tankers

| Tanker DWT | Damage Extent: Low-Energy Velocity = 5 knots | Damage Extent: High-Energy Velocity = 10 knots | % of Cargo Lost High Energy | Total Volume of Cargo Lost High Energy (gallons) | Time Required for Hydrostatic Balancing to be Achieved: Low Energy (seconds) | Time Required for Hydrostatic Balancing to be Achieved: High Energy (seconds) |
|---|---|---|---|---|---|---|
| 34,000 | No Cargo Tanks Penetrated | 2 Tanks Penetrated | 13.4 | 187,000 | N/A | 7.8 |
| 89,700 | No Cargo Tanks Penetrated | 2 Tanks Penetrated | 7.1 | 205,000 | N/A | 3.9 |
| 225,000 | 1 Tank Penetrated | 3 Tanks Penetrated | 7.0 | 1,445,000 | 22.9 | 194 |
| 262,000 | 1 Tank Penetrated | 3 Tanks Penetrated | 5.0 | 552,000 | 6.5 | 5.2 |

compensated for by assuming a certain fraction of the flow area is plugged. The outflow time is inversely proportional to the area of the penetration (i.e., reducing the penetration size by 90% increases the outflow time by a factor of 10).

Very little data are available on actual penetration sizes resulting from grounding or collision. Some idea of penetration size was obtained through discussions with individuals in the industry. For instance, one of the most catastrophic tanker groundings to date resulted in a conservative estimate of the sum of the ship's penetration areas being approximately 1,000 $ft^2$; its damaged areas were considerably larger. It was also stated that the largest of these holes, of which there were several, was approximately 120 $ft^2$. For a similar size ship, moving at approximately the same speed, assuming a design similar to the vessels evaluated in this study, the model predicted a penetration area of 7,500 $ft^2$. In comparing these values, it should be noted that the model estimates damage assuming no longitudinal bulkheads absorb any energy.

While the predicted penetration sizes and thus the estimated outflow times are questionable, these parameters are independent of the estimation of the total cargo volume lost. The percent of cargo lost in the Table 2.1 refers to the percentage of the total cargo contained in the penetrated tanks. The percentage of cargo lost is also independent of the number of tanks penetrated as long as one tank is penetrated. The driving force for oil outflow in the case of grounding is entirely due to the difference in hydrostatic pressure between the oil and water. Since all of the tanks are loaded to the same height, hydrostatic balancing in each tank will occur when the oil reaches the same level. The size of the penetration has no effect on the volume of oil that will leak from a single tank. It only determines the time required for outflow and the number of tanks that are penetrated.

It is worth noting that the time required for hydrostatic balancing to be achieved is somewhat independent of the penetration size. As the penetration size in a single tank increases, the time required for hydrostatic balancing will be reduced. However, this does not continually hold for multiple tanks. An example of this can be seen in Table 2.1 for the case of the

22,500 DWT tanker. In the lower-energy case, one tank is penetrated. In the high-energy case, the penetration is larger and three tanks are penetrated. However, it takes 8.5 times longer, 194 seconds compared to 23 seconds, for hydrostatic balancing to occur in the high-energy case. The outflow time is dictated by the size of the penetration in the tank with only a fraction of its length penetrated. Given two different size holes that penetrate multiple tanks, the penetration that results in the smallest penetration to a single tank relative to the single tank's cross-sectional area will yield the longest outflow time.

Table 2.2 shows the results obtained for the barges evaluated. The same results with respect to penetration sizes were obtained for barges as were obtained for tankers. The amount of damage sustained in terms of the number of tanks penetrated was less for the barges than for the tankers. Only the grandfathered case of the 2,713 GT barge had cargo tanks penetrated during the low-energy collision. No more than one tank was penetrated under any of the conditions evaluated, and the 2,713 GT (not grandfathered) barge never had a cargo tank penetrated. The reduced damage can be contributed to several factors. All of the barges except for the grandfathered 2,713 GT have forward rakes. The length of these rakes allow for a good deal of energy to be absorbed before the cargo tanks are reached. Another factor contributing to the reduced damage is the reduced mass with respect to cargo. A barge contains no engines, crew, or supporting facilities; therefore, a larger percentage of its total mass is made up of cargo. This reduced mass with respect to the size of the vessel results in the barge having less kinetic energy at the time of grounding.

The smaller two barges resulted in no cargo being lost even when cargo tanks were penetrated. This is because the cargo tanks were loaded to a level that resulted in the hydrostatic pressure of the water at the bottom of the barge being greater than the hydrostatic pressure inside the tank. In such a case, the tanks are referred to as being hydrostatically balanced. The barges that did lose cargo lost cargo percentages similar to those of the tankers.

TABLE 2.2. Grounding Results for Barges

| Barge (GT) | Damage Extent: Low-Energy Velocity = 4 knots | Damage Extent: High-Energy Velocity = 8 knots | % of Cargo Lost High Energy | Total Volume of Cargo Lost High Energy (gallons) | Time Required for Hydrostatic Balancing to be Achieved: Low Energy (seconds) | Time Required for Hydrostatic Balancing to be Achieved: High Energy (seconds) |
|---|---|---|---|---|---|---|
| 628 | No Cargo Tanks Penetrated | 1 Tank Penetrated[a] | 0.0[a] | 0.0[a] | N/A | N/A |
| 1,182 | No Cargo Tanks Penetrated | 1 Tank Penetrated[a] | 0.0[a] | 0.0[a] | N/A | N/A |
| 1,769 | No Cargo Tanks Penetrated | 1 Tank Penetrated Cargo Leaked | 7 22 | 9,364 | N/A | 3.5 |
| 2,713 (Grand-fathered Bow Tanks Carry Cargo) | 1 Tank Penetrated Cargo Leaked | 1 Tank Penetrated Cargo Leaked | 11.45 | 17,516 | 8.3 | 2.1 |
| 2,713 Bow Tanks are Empty | No Cargo Tanks Penetrated | No Cargo Tanks Penetrated | -- | -- | N/A | N/A |

(a) Cargo height in tanks is less than that required for hydrostatic balancing. Water enters Cargo Tanks.

The relief valves found on tankers were not modeled; some calculations were performed assuming a specific relief valve (refer to Assumption 18) so that the qualitative effects of modeling the relief valve could be observed.

The inclusion of the venting model to the tanker grounding cases had a large impact on the outflow times. The outflow time increased anywhere from 2 to 30 times as long. The main reason for the large difference was due to the size of the hole. The large hole size results in an extremely high initial flow rate of oil. The change in volume within the tank is much too large for the relief valve to compensate; therefore, the pressure of the void space is reduced rapidly, and the oil outflow becomes dependent on the inflow of air through the relief valve. If the penetration size is reduced by assuming blockage, the effects of the relief valve are greatly reduced.

The relief valve does reduce the amount of oil leaked from the cargo tank in the case of grounding. The lower the valve threshold pressure the lower the amount of oil released. The lower void pressure reduces the hydrostatic pressure of the oil at the penetration and allows a higher column of oil to exist when hydrostatic balancing is achieved. In most cases, a threshold pressure of -0.25 psig resulted in 10% to 15% less oil being reduced.

The actual penetration sizes calculated using the DnVC method are associated with a lot of uncertainty. The results do predict the amount of oil that may be leaked in the case of grounding. The grounding results also show which vessels are less likely to result in cargo spillage in the event of a grounding.

### 2.4.2 Collision

The plots of collision results for individuals cases are similar to those found in Figure 2.9. This section contains the overall results obtained from the parametric study with respect to penetration size. Plots and corresponding tables for penetration sizes of 2, 8, and 50 $ft^2$ for each tanker are included in Appendix A. The same plots are included in Appendix A for barges with penetration sizes of 0.5, 2, and 8 $ft^2$.

For the tankers, calculations were performed for penetration sizes ranging from 2 $ft^2$ to 72 $ft^2$. The results are presented in Figures 2.10 through 2.13 and Tables 2.3 through 2.6. Each plot relates the outflow time to the penetration size for a specific percentage of cargo lost from the penetrated tanks. The penetration size in each plot still refers to the total penetration size. The actual penetration area in each tank is half of this value. The summation of the results in this form was done to aid in using the results if additional penetration size data should become available in the future. The plots allow outflow times to be predicted for a given quantity of oil and a specified penetration area. Estimations of allowable damage can also be determined if a specified time limit is given to save a corresponding amount of oil.

Tables 2.3 through 2.6 correspond to Figures 2.10 through 2.13, respectively. Each table lists the points used to generate the plots. The rapid discharge of the first 20% of oil in the penetrated tanks is the result of the hydrostatic head present in the tank initially. By the time 30% of the oil in the penetrated tanks has been discharged, oil outflow is the result of water ingestion. The driving force behind the water ingestion is much less than the initial driving force.

Figures 2.14 through 2.17 and Tables 2.7 through 2.10 show the results obtained for barges. As with the tankers, Tables 2.7 through 2.10 correspond to Figures 2.14 through 2.17, respectively. A significant difference found with some of the barges is that the first 20% is not lost as quickly when compared to the total outflow time. This is because some of the barges are hydrostatically loaded; therefore, the initial hydrostatic pressure found at the water line is less compared to that of tanker loads. This means water ingestion occurs after a smaller percentage of cargo has leaked.

Table 2.11 lists the frequency of hole occurrence for six penetration size ranges. Data related to actual penetration and frequency of occurrence were found to be scarce. The actual source of data used to develop this distribution is based on unpublished data provided to PNL by the Coast Guard.

Table 2.11 shows that 55% of the penetrations are less than 5 $ft^2$. These statistical data are very useful in helping to determine ranges of times

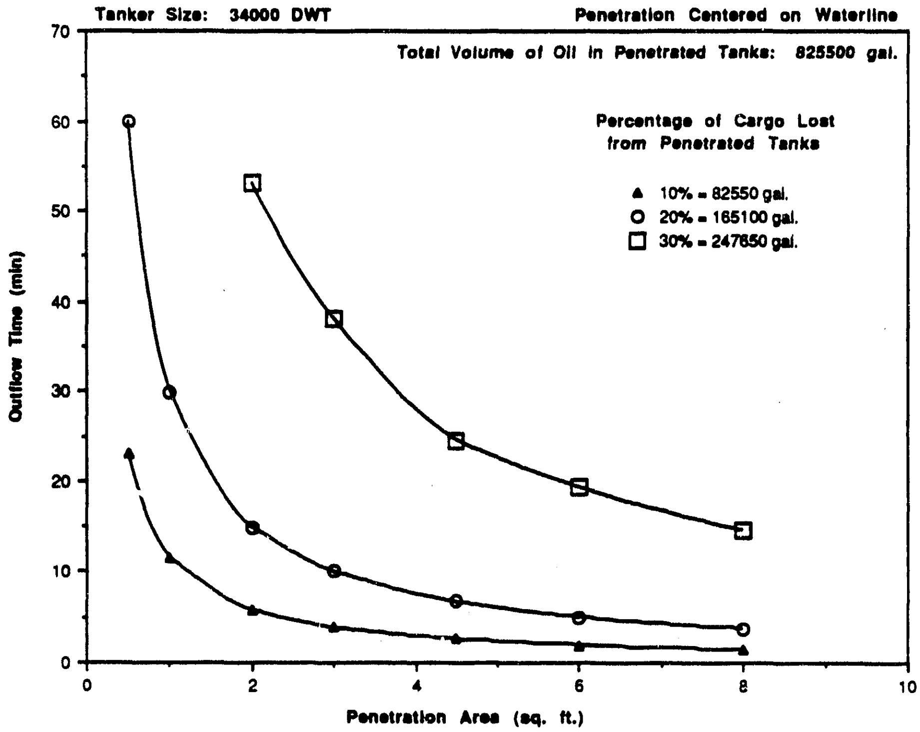



FIGURE 2.10. Plots of Outflow Time vs. Penetration Area for a 34,000 DWT Tanker in the Case of Collision (with the penetration on the waterline)

TABLE 2.3. Calculated Outflow Time for a 34,000 DWT Tanker in the Case of Collision (with penetration on the waterline)

| | Percentage of Cargo Lost from Penetrated Tanks[a] | | | |
|---|---|---|---|---|
| Penetration Area (ft$^2$) | 10%[b] (min) | 20%[c] (min) | 30%[d] (min) | 50%[e] (min) |
| 0.500 | 23.0 | 60.0 | 194 | 781 |
| 1.000 | 11.6 | 29.9 | 96.6 | 382 |
| 2.000 | 5.77 | 14.9 | 53.1 | 224 |
| 3.000 | 3.85 | 10.0 | 38.0 | 170 |
| 4.500 | 2.6 | 6.7 | 24.6 | 105 |
| 6.000 | 1.94 | 5.0 | 19.3 | 85.0 |
| 8.000 | 1.44 | 3.76 | 14.6 | 64.0 |

(a) Total Volume of Oil in Penetrated Tanks: 825,000 gal
(b) 10% = 82,550 gal
(c) 20% = 165,100 gal
(d) 30% = 247,650 gal
(e) 50% = 412,750 gal

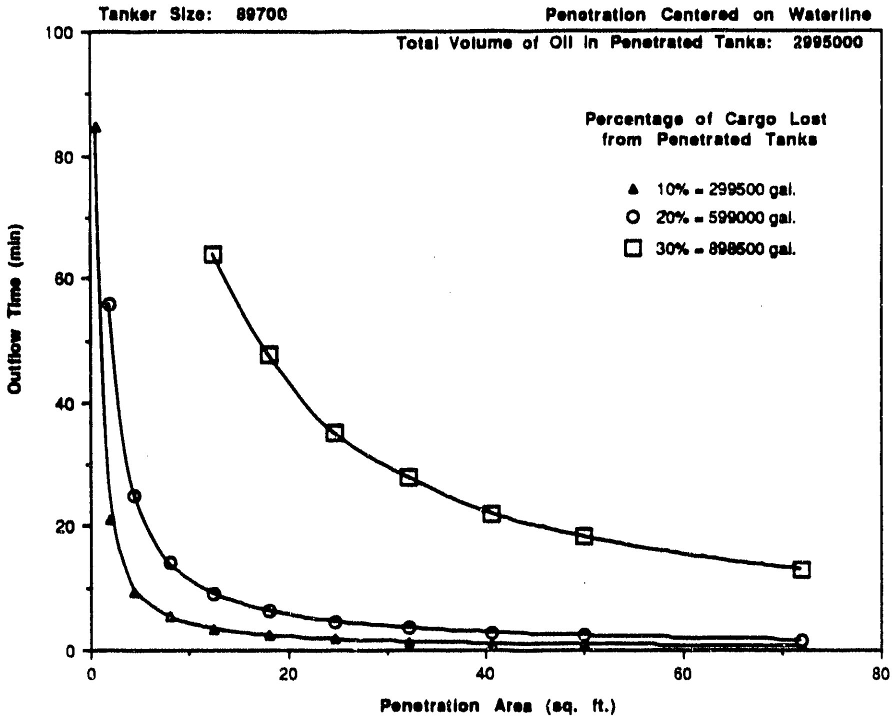



FIGURE 2.11. Plot of Outflow Time vs. Penetration Area for a 89,700 DWT Tanker in the Case of Collision (with penetration on the waterline)

TABLE 2.4. Calculated Outflow Time for a 89,700 DWT Tanker in the Case of Collision (with penetration on the waterline)

| | Percentage of Cargo Lost from Penetrated Tanks[a] | | | |
|---|---|---|---|---|
| Penetration Area (ft$^2$) | 10%[b] (min) | 20%[c] (min) | 30%[d] (min) | 50%[e] (min) |
| 0.500 | 84.6 | 224 | 1,158 | 3,228 |
| 2.000 | 21 | 55.9 | 375 | 1,096 |
| 4.000 | 9.3 | 25 | 157 | 450 |
| 8.000 | 5.3 | 14 | 95 | 276 |
| 12.500 | 3.4 | 9.1 | 64 | 187 |
| 18.000 | 2.3 | 6.3 | 47 | 141 |
| 24.500 | 1.7 | 4.6 | 35 | 102 |
| 32.000 | 1.3 | 3.6 | 27 | 83 |
| 40.500 | 1.0 | 2.8 | 22 | 67 |
| 50.000 | 0.85 | 2.3 | 18 | 54 |
| 72.000 | 0.59 | 1.6 | 13 | 38 |

(a) Total Volume of Oil in Penetrated Tanks: 2,995,000 gal
(b) 10% = 299,500 gal
(c) 20% = 599,000 gal
(d) 30% = 898,500 gal
(e) 50% = 1,497,500 gal.

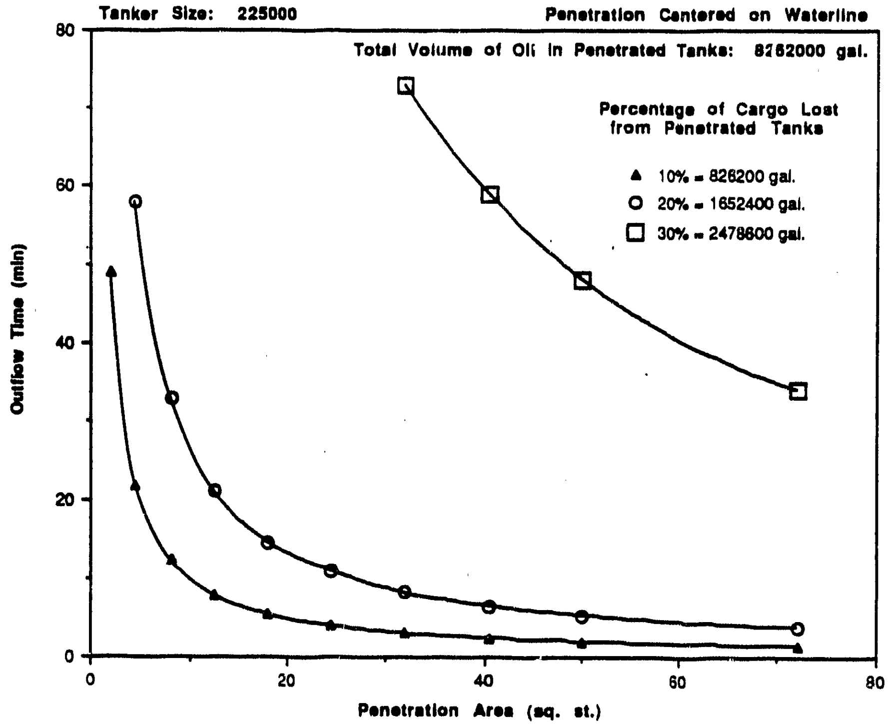



FIGURE 2.12. Plot of Outflow Time vs. Penetration Area for a 225,000 DWT Tanker in the Case of Collision (with penetration on the waterline)

TABLE 2.5. Calculated Outflow Time for a 225,000 DWT Tanker in the Case of Collision (with penetration on the waterline)

| | Percentage of Cargo Lost from Penetrated Tanks[a] | | | |
|---|---|---|---|---|
| Penetration Area ($ft^2$) | 10%[b] (min) | 20%[c] (min) | 30%[d] (min) | 50%[e] (min) |
| 0.500 | 195.8 | 521 | 3,056 | 8,773 |
| 2.000 | 48.9 | 130 | 934 | 2,763 |
| 4.000 | 21.7 | 58 | 430 | 1,275 |
| 8.000 | 12.2 | 33 | 260 | 777 |
| 12.500 | 7.8 | 21 | 174 | 522 |
| 18.000 | 5.4 | 14.5 | 124 | 375 |
| 24.500 | 4.0 | 11 | 94 | 284 |
| 32.000 | 3.0 | 8.2 | 73 | 222 |
| 40.500 | 2.4 | 6.5 | 59 | 178 |
| 50.000 | 1.95 | 5.3 | 48 | 146 |
| 72.000 | 1.4 | 3.7 | 34 | 104 |

(a) Total Volume of Oil in Penetrated Tanks: 8,262,000 gal
(b) 10% = 826,200 gal
(c) 20% = 1,652,400 gal
(d) 30% = 2,478,600 gal
(e) 50% = 4,131,000 gal.

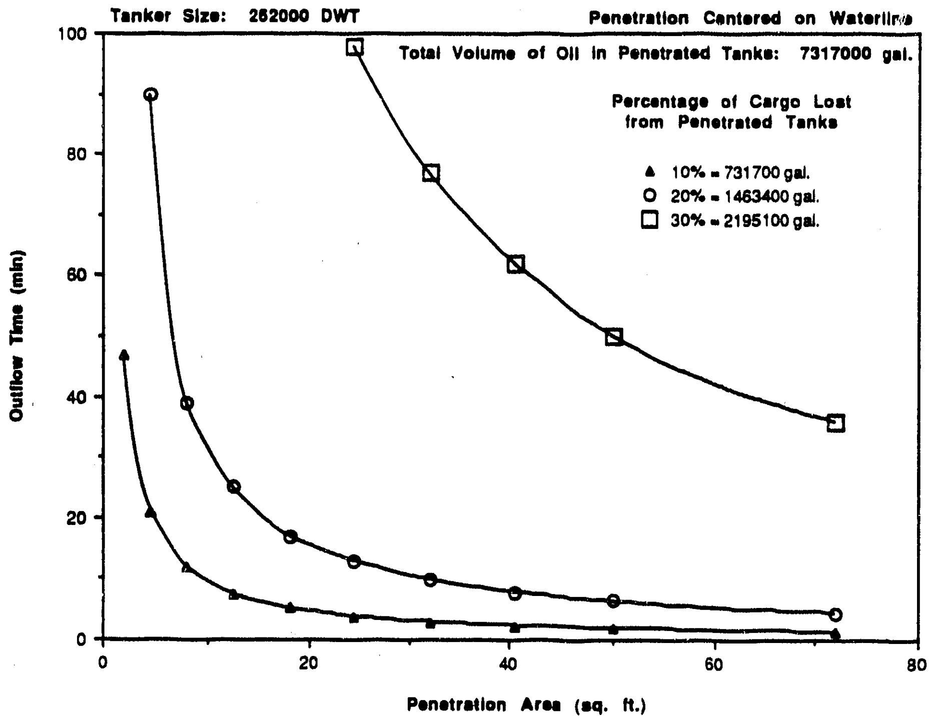



FIGURE 2.13. Plot of Outflow Time vs. Penetration Area for a 262,000 DWT Tanker in the Case of Collision (with penetration on the waterline)

TABLE 2.6. Calculated Outflow Time for a 262,000 DWT Tanker in the Case of Collision (with penetration on the waterline)

| | Percentage of Cargo Lost from Penetrated Tanks[a] | | | |
|---|---|---|---|---|
| Penetration Area ($ft^2$) | 10%[b] (min) | 20%[c] (min) | 30%[d] (min) | 50%[e] (min) |
| 0.500 | 187 | 600 | 3,223 | 8,484 |
| 2.000 | 47 | 152 | 907 | 2,419 |
| 4.000 | 21 | 90 | 561 | 1,504 |
| 8.000 | 12 | 39 | 274 | 745 |
| 12.500 | 7.4 | 25 | 184 | 501 |
| 18.000 | 5.2 | 17 | 131 | 357 |
| 24.500 | 3.8 | 13 | 98 | 270 |
| 32.000 | 2.9 | 9.9 | 77 | 211 |
| 40.500 | 2.3 | 7.8 | 62 | 169 |
| 50.000 | 1.9 | 6.3 | 50 | 138 |
| 72.000 | 1.3 | 4.4 | 36 | 98 |

(a) Total Volume of Oil in Penetrated Tanks: 7,317,000 gal
(b) 10% = 731,700 gal
(c) 20% = 1,463,400 gal
(d) 30% = 2,195,100 gal
(e) 50% = 3,658,500 gal.

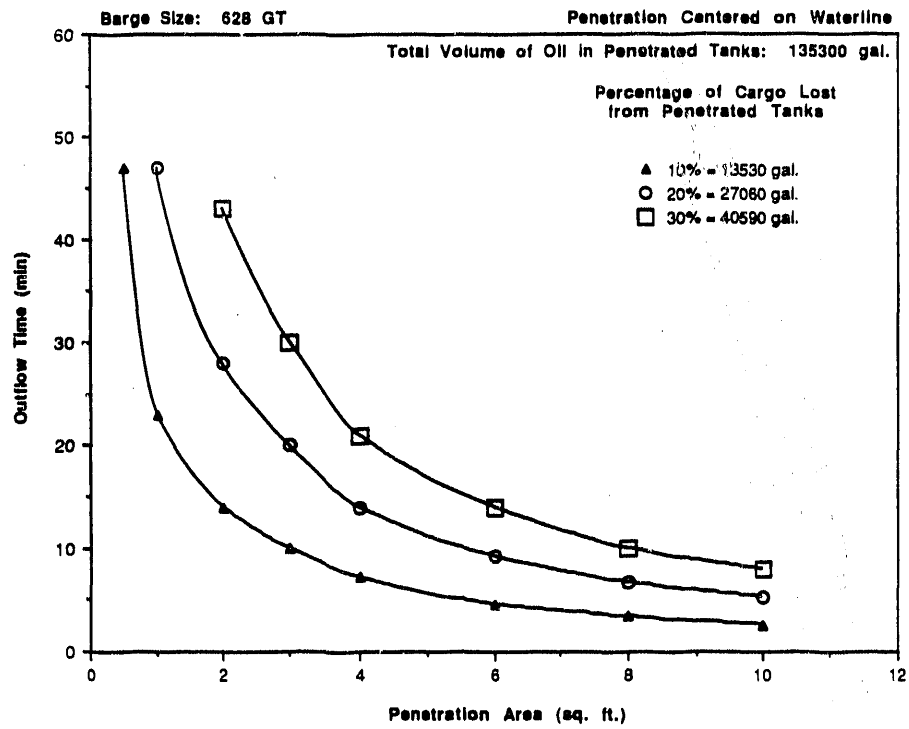



FIGURE 2.14. Plot of Outflow Time vs. Penetration Area for a 628 GT Barge (with penetration on the waterline)

TABLE 2.7. Calculated Outflow Time for a 628 GT Barge in the Case of Collision (with penetration on the waterline)

| | Percentage of Cargo Lost from Penetrated Tanks[a] | | | |
|---|---|---|---|---|
| Penetration Area ($ft^2$) | 10%[b] (min) | 20%[c] (min) | 30%[d] (min) | 50%[e] (min) |
| 0.500 | 47 | 93 | 140 | 234 |
| 1.000 | 23 | 47 | 70 | 117 |
| 2.000 | 14 | 28 | 43 | 71 |
| 3.000 | 9.9 | 20 | 30 | 50 |
| 4.000 | 7.2 | 14 | 21 | 36 |
| 6.000 | 4.6 | 9.2 | 14 | 23 |
| 8.000 | 3.4 | 6.7 | 10 | 17 |
| 10.000 | 2.6 | 5.3 | 8.0 | 13 |

(a) Total Volume of Oil in Penetrated Tanks: 135,300 gal
(b) 10% = 13,530 gal
(c) 20% = 27,060 gal
(d) 30% = 40,590 gal
(e) 50% = 67,650 gal.

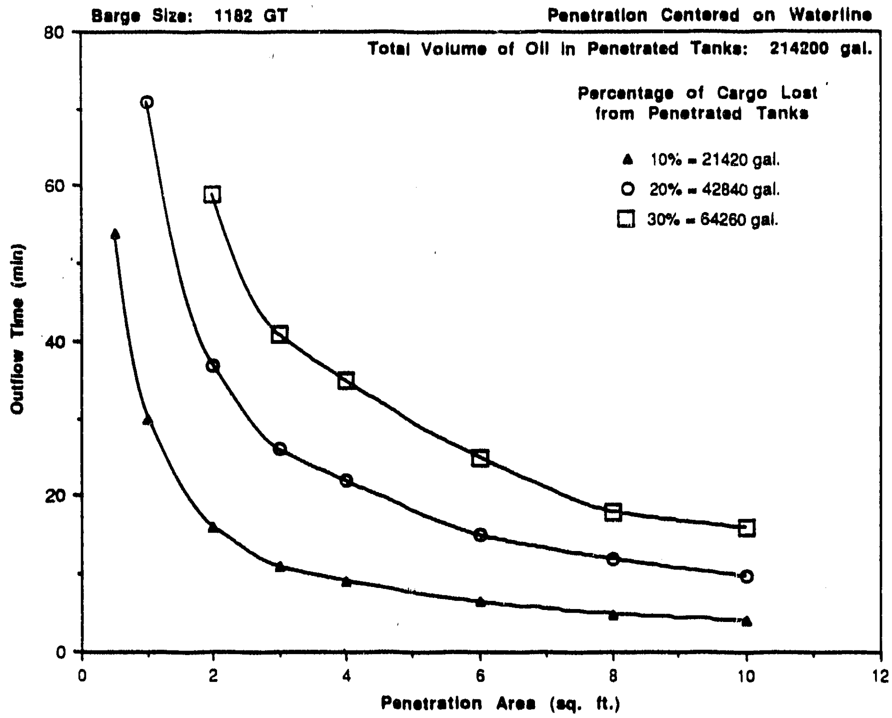



FIGURE 2.15. Plot of Outflow Time vs. Penetration Area for a 1,182 GT Barge (with penetration on the waterline)

TABLE 2.8. Calculated Outflow Time for a 1,182 GT Barge in the Case of Collision (with penetration on the waterline)

| | Percentage of Cargo Lost from Penetrated Tanks[a] | | | |
|---|---|---|---|---|
| Penetration Area ($ft^2$) | 10%[b] (min) | 20%[c] (min) | 30%[d] (min) | 50%[e] (min) |
| 0.500 | 54 | 128 | 202 | 351 |
| 1.000 | 30 | 71 | 112 | 194 |
| 2.000 | 16 | 37 | 59 | 102 |
| 3.000 | 11 | 26 | 41 | 71 |
| 4.000 | 9.2 | 22 | 35 | 60 |
| 6.000 | 6.4 | 15 | 25 | 43 |
| 8.000 | 4.9 | 12 | 18 | 32 |
| 10.000 | 4.0 | 9.8 | 16 | 27 |

(a) Total Volume of Oil in Penetrated Tanks: 214,200 gal
(b) 10% = 21,420 gal
(c) 20% = 42,840 gal
(d) 30% = 64,260 gal
(e) 50% = 107,100 gal.

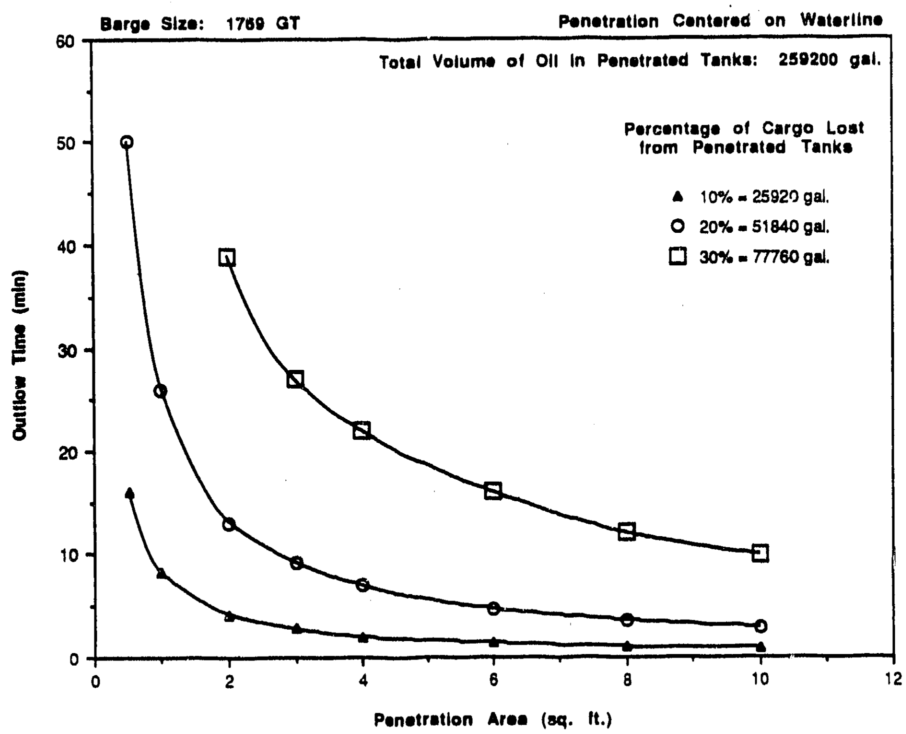



FIGURE 2.16. Plot of Outflow Time vs. Penetration Area for a 1,769 GT Barge (with penetration on the waterline)

TABLE 2.9. Calculated Outflow Time for a 1,769 GT Barge in the Case of Collision (with penetration on the waterline)

| | Percentage of Cargo Lost from Penetrated Tanks[a] | | | |
|---|---|---|---|---|
| Penetration Area ($ft^2$) | 10%[b] (min) | 20%[c] (min) | 30%[d] (min) | 50%[e] (min) |
| 0.500 | 16 | 50 | 139 | 318 |
| 1.000 | 8.2 | 26 | 75 | 175 |
| 2.000 | 4.2 | 13 | 39 | 91 |
| 3.000 | 2.8 | 9.2 | 27 | 63 |
| 4.000 | 2.0 | 7.0 | 22 | 53 |
| 6.000 | 1.4 | 4.7 | 16 | 38 |
| 8.000 | 1.0 | 3.6 | 12 | 28 |
| 10.000 | 0.85 | 2.9 | 9.9 | 24 |

(a) Total Volume of Oil in Penetrated Tanks: 259,200 gal
(b) 10% = 25,920 gal
(c) 20% = 51,840 gal
(d) 30% = 77,760 gal
(e) 50% = 129,600 gal.

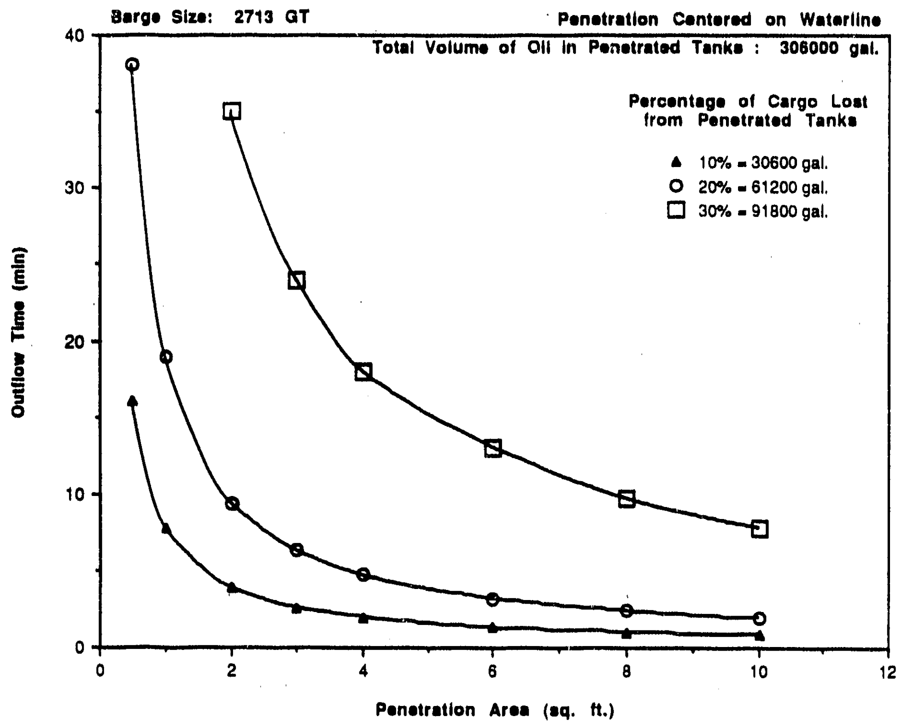



FIGURE 2.17. Plot of Outflow Time vs. Penetration Area for a 2,713 GT Barge (with penetration on the waterline)

TABLE 2.10. Calculated Outflow Time for a 2,713 GT Barge in the Case of Collision (with penetration on the waterline)

| | Percentage of Cargo Lost from Penetrated Tanks[a] | | | |
|---|---|---|---|---|
| Penetration Area ($ft^2$) | 10%[b] (min) | 20%[c] (min) | 30%[d] (min) | 50%[e] (min) |
| 0.500 | 16 | 38 | 122 | 333 |
| 1.000 | 7.8 | 19 | 62 | 170 |
| 2.000 | 3.9 | 9.4 | 35 | 99 |
| 3.000 | 2.6 | 6.3 | 24 | 69 |
| 4.000 | 2.0 | 4.7 | 18 | 53 |
| 6.000 | 1.3 | 3.2 | 13 | 38 |
| 8.000 | 1.0 | 2.4 | 9.7 | 28 |
| 10.000 | 0.8 | 1.9 | 7.8 | 23 |

(a) Total Volume of Oil in Penetrated Tanks: 306,000 gal
(b) 10% = 30,600 gal
(c) 20% = 61,200 gal
(d) 30% = 91,800 gal
(e) 50% = 153,000 gal.

available in deploying self-help methods. It must be emphasized that the outflow predictions obtained from the parametric study of penetration size are best utilized in conjunction with either statistical data or some method of predicting penetration size. Despite the short outflow times estimated for some penetration sizes, Table 2.11 shows the probability of actually obtaining these very short times is low.

Due to insufficient data, relief valves were not modeled for cases of collision. Calculations were performed so that the qualitative effects of relief valves could be observed for both cases of independently vented tanks and manifolded tanks. Relief valves help to lower the hydrostatic head of the oil by reducing the gas pressure in the cargo tank's void space. Therefore, the effects of the relief valve should only be observed prior to water ingestion.

For this study, the initial flow rate will be the same regardless of the relief valve because all tanks are assumed pressurized to 2 psig; therefore, the same initial hydrostatic pressure at the penetration is present for all relief valve scenarios. As oil leaks from a cargo tank, the void pressure of the tank is reduced. When the void pressure reaches the relief valve's minimum threshold pressure, the valve opens. The lower the threshold pressure the lower the hydrostatic pressure of the tank.

Once the valve is open, outside air will enter the tank until the threshold pressure is reached again, at which time the valve will close. The air will not necessarily flow into the tank at the same volume flow rate as the fluid flows out of the tank. This factor partially depends on the size of the penetration with respect to the size of the relief valve flow area and the pressure drop across the valve. The larger the penetration the harder it is for the air flow to maintain the void pressure. In some cases the void pressure will continue to drop even though the valve is open.

If the void pressure drops far enough, the pressure difference across the penetration may approach zero even though the oil level is still above that required for hydrostatic balancing. As the pressure difference approaches zero, water ingestion may begin. The lower flow rate of oil, due to water ingestion, or the reduction in hydrostatic head, allows the air flow through the valve to increase the void pressure. Eventually, the threshold pressure of the valve will be reached and the valve will close. In some instances the outflow may oscillate between, or be due to both, water ingestion and hydrostatic balancing until steady water ingestion commences.

Table 2.12 shows the results of calculations performed for the 89,700 DWT tanker for three different relief valve conditions for independently vented tanks. The venting conditions that neglect the relief valve assume the same conditions used to calculate all the results in this study. The void space is assumed initially pressurized at 2 psig. When the void pressure drops to atmospheric pressure, the relief valve is assumed open and no restrictions on the air inflow exists. The second and third cases model the valve according to Assumption 18. Only the threshold pressure is different between these two cases.

The values calculated for Table 2.12 are only meant for qualitative purposes. The actual design of the relief valves on the 89,700 DWT are unknown. As expected, the differences in outflow time occur in the range of hydrostatic balancing. Differences in the outflow times for 30% and 90% of the cargo are just constant lag times carried over from the delays created during hydrostatic balancing.

Little difference is seen for the times required to leak the first 10% of the oil. This lack of significant difference is because the initial flow rate is the same for all three cases, and no difference in the flow rate occurs until the void pressure reaches atmospheric pressure.

It is during the time between the leaking of 10% and 30% of the cargo that the most significant differences are found in the results for the modeled relief valve. Despite the fact that for some cases the relative time differences are significant, there are no large real-time differences. It is real time that is a factor in evaluating self-help methods.

Table 2.13 shows the results of calculations performed assuming all of the tank void spaces are manifolded together. Much of the discussion regarding the results presented in Table 2.12 is also applicable to Table 2.13. Very little difference is seen between the results of the two tables for

TABLE 2.11. Distribution of Penetration Sizes in Actual Accidents

| Penetration Area ($ft^2$) | Frequency of Hole Occurrence (%) |
|---|---|
| < 1 | 40.8 |
| 1-2 | 4.1 |
| 2-3 | 3.2 |
| 3-5 | 6.7 |
| 5-10 | 12.9 |
| 10-100 | 32.3 |

TABLE 2.12. Qualitative Effects of Venting on Oil Outflow Time for Individually Vented Cargo Tanks[a]

| | | % of Cargo Leaked from Penetrated Tanks | | | |
|---|---|---|---|---|---|
| Venting Conditions | Penetration Area ($ft^2$) | 10%[b] (min) | 20%[c] (min) | 30%[d] (min) | 90%[e] (min) |
| Relief valve not modeled | 2 | 21 | 57 | 292 | 1846 |
| $P_{Thresh} = P_{Atm}$ | 8 | 5.3 | 14 | 75 | 463 |
| | 50 | 0.9 | 2.5 | 13 | 75 |
| Relief valve | 2 | 21 | 60 | 314 | 1868 |
| $C_D = 0.8$ | 8 | 5.5 | 16 | 81 | 469 |
| Diameter = 10 inches | 50 | 1.3 | 4.6 | 15 | 77 |
| $P_{Thresh}$ = -0.25 psig | | | | | |
| Relief valve | 2 | 22 | 80 | 338 | 1892 |
| $C_D = 0.8$ | 8 | 5.7 | 22 | 87 | 475 |
| Diameter = 10 inches | 50 | 1.3 | 5.3 | 16 | 78 |
| $P_{Thresh}$ = -0.5 psig | | | | | |

(a) This is for a 89,700 DWT Tanker in the case of collision with penetration on the waterline. The initial void pressure is 2 psig.
(b) 10% = 299,500 gal
(c) 20% = 599,000 gal
(d) 30% = 898,500 gal
(e) 90% = 2,695,500 gal.

TABLE 2.13. Qualitative Effects of Venting on Oil Outflow Time for Tanks with Manifolded Void Spaces[a]

| Venting Conditions | Penetration Area ($ft^2$) | % of Cargo Leaked from Penetrated Tanks: 10%[b] (min) | 20%[c] (min) | 30%[d] (min) | 90%[e] (min) |
|---|---|---|---|---|---|
| Relief valve | 2 | 21 | 62 | 316 | 1870 |
| $C_D$ = 0.8 | 8 | 5.5 | 16 | 81 | 469 |
| Diameter = 10 inches | 50 | 1.5 | 6.7 | 17 | 79 |
| $P_{Thresh}$ = -0.25 psig | | | | | |
| | 2 | 22 | 83 | 341 | 1895 |
| Relief valve | 8 | 5.7 | 23 | 87 | 476 |
| $C_D$ = 0.8 | 50 | 1.5 | 6.9 | 17 | 79 |
| Diameter = 10 inches | | | | | |
| $P_{Thresh}$ = -0.5 psig | | | | | |

(a) This is for a 89,700 DWT Tanker in the case of collision with penetration on the waterline. The initial void pressure is 2 psig.
(b) 10% = 299,500 gal
(c) 20% = 599,000 gal
(d) 30% = 898,500 gal
(e) 90% = 2,695,500 gal.

similar relief valve conditions. One might expect the manifolded void spaces to yield smaller outflow times due to the increased volume of cover gas initially at 2 psig. However, the tank vent leading to the manifold creates a large enough pressure drop to negate the effects of the increased pressurized volume as a driving force. The flow resistance of the tank vent results in conditions similar to that of a tank with an independent relief valve.

Although the manifold system used in the calculations was not designed specifically for the 89,700 DWT, it is similar to systems aboard other vessels and complies with 46 CFR Part 32, Sections 32.55-20 and 32.55-25.

## 2.5 CONCLUSIONS

The outflow calculations provide relationships between penetration size and time-dependent outflow and information to aid in determining the requirements of self-help methods.

In the case of groundings, the outflow times are extremely short due to overly conservative methods of predicting penetration sizes. The outflow analysis clearly demonstrates the importance of distinguishing between damage size and penetration size. The cumulative oil outflows calculated do provide good estimates of the quantity of oil released in the event of a grounding.

The results of the collision analysis yields useful relationships between penetration size and oil outflow that can be used with present or future statistical studies of penetration sizes. These relationships along with statistical data allow the prediction of outflows associated with small, medium, and catastrophic accidents.

The outflow times calculated for collisions are conservative but realistic. The assumptions tend to use realistic parameters that yield conservative results, but no factors of safety were included in the modeling.

Modeling of the relief valve venting would further reduce conservatism. Preliminary analyses show that predicted flow rates are conservative but comparable to those obtained assuming various relief valve configurations.

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# 3.0 ENVIRONMENTAL LIMITATIONS FOR SELF-HELP COUNTERMEASURES

This section discusses typical environmental conditions that might limit the effectiveness of self-help countermeasures to control the spread of oil from tanker or tank barge spills. The section describes general physical parameters and environmental scenarios representing typical conditions encountered along tanker routes and near oil terminals in U.S. waters. These scenarios were developed for the analysis performed in Section 5.0.

Because the effectiveness of self-help countermeasures are location and situation specific, U.S. navigable waters are divided into nine zones that include the estuaries where major oil terminals are located, offshore waters from Demarcation Bay in the Alaskan Beaufort Sea to the Gulf of Maine, the great lakes, and intracoastal waterways (see Section 3.2.3).

The environmental conditions for tankers and tank barges in each zone are identical. The differences between the operational and safety characteristics of tankers and tank barges are explained in detail elsewhere in this report. In summary, the main differences are: 1) barges cannot maneuver without a towing/pushing vessel, 2) they have less freeboard than most tankers working offshore waters, and 3) barges carry limited auxiliary equipment for handling topside or over-the-side gear.

## 3.1 COUNTERMEASURE TYPES

Table 3.1 lists 45 countermeasures proposed to the U.S. Coast Guard Research and Development Center subsequent to the EXXON Valdez spill in 1989. These proposals were divided into six generic types and were given names to identify them in this report. General descriptions of the generic types and the environmental conditions that might reduce their effectiveness are given below. Figure 3.1 is a graphic representation of these countermeasures.

Booms are flexible or segmented barriers for containing and limiting the spread of oil slicks. They have flotation at the top and are weighted at the bottom so they will remain vertical when deployed. Spilled oil trapped by a boom can be pumped into empty onboard or external tankage. Twenty of the 46

TABLE 3.1. Self-Help Countermeasures Proposed to the Coast Guard Research and Development Center 1989-1991

| Prop No. | PNL Classification | Comments |
|---|---|---|
| 1 | Boom | Boom encircles tanker, skimmers remove oil |
| 4 | Boom | Place absorbent material into ruptured tank & deploy boom |
| 12 | Boom | Booms, internal & external. Pumps & bladders |
| 14 | Boom | Curtain dropped from deck & fastened to deck edge |
| 15 | Boom | Encircling boom tethered to tanker |
| 17 | Boom | Boom tethered to deck |
| 18 | Boom | Encircling boom |
| 21 | Boom | Encircling boom/envelope |
| 23 | Boom | Tethered boom |
| 25 | Boom | Encircling boom |
| 28 | Boom | Tethered encircling boom |
| 29 | Boom | Boom deployed by a small boat |
| 32 | Boom | Boom & onboard skimmer |
| 33 | Boom | Boom |
| 34 | Boom | Tethered boom |
| 36 | Boom | Encircling boom |
| 41 | Boom | Booms |
| 42 | Boom | Booms |
| 44 | Boom | Encircling boom |
| 45 | Boom | Encircling boom |
| 3 | Envelope | Booms deployed by lifeboats & ocean surface pumps used to pick up spilled oil |
| 9 | Envelope | Boom (w/o vertical extension) tethered to tanker |
| 11 | Envelope | External lining enveloping tanker |
| 22 | Envelope | N/A |
| 31 | Envelope | Encircling boom |
| 13 | Skirt | Curtain dropped from deck & fastened to deck edge |

TABLE 3.1. (contd)

| Prop No. | PNL Classification | Comments |
| --- | --- | --- |
| 26 | Skirt | Skirt |
| 5 | Bladder | Pump oil from ruptured tank into external bladder so net flow is into tank |
| 6 | Bladder | Pump oil from ruptured tank into external bladder |
| 16 | Bladder | Pump oil out of ruptured container so that net flow is into tank. Pumped oil is stored internally or externally |
| 20 | Bladder | Oil transferred to other on deck tank or external bladder |
| 19 | Patch with Plumb | Pump attached to outside of tanker rupture |
| 2 | Liner | Hull liner |
| 10 | Liner | Hull design with trailing skimmer |
| 40 | Adsorbent | Absorbent material used to immobilize oil |
| 7 | Unclassified | N/A |
| 8 | Unclassified | Not sufficiently described |
| 24 | Unclassified | N/A |
| 27 | Unclassified | N/A |
| 30 | Unclassified | N/A |
| 35 | Unclassified | Not sufficiently described |
| 37 | Unclassified | Not sufficiently described |
| 38 | Unclassified | Boom |
| 39 | Unclassified | Not sufficiently described |
| 43 | Unclassified | Pumps & bladders supplied by another vessel |

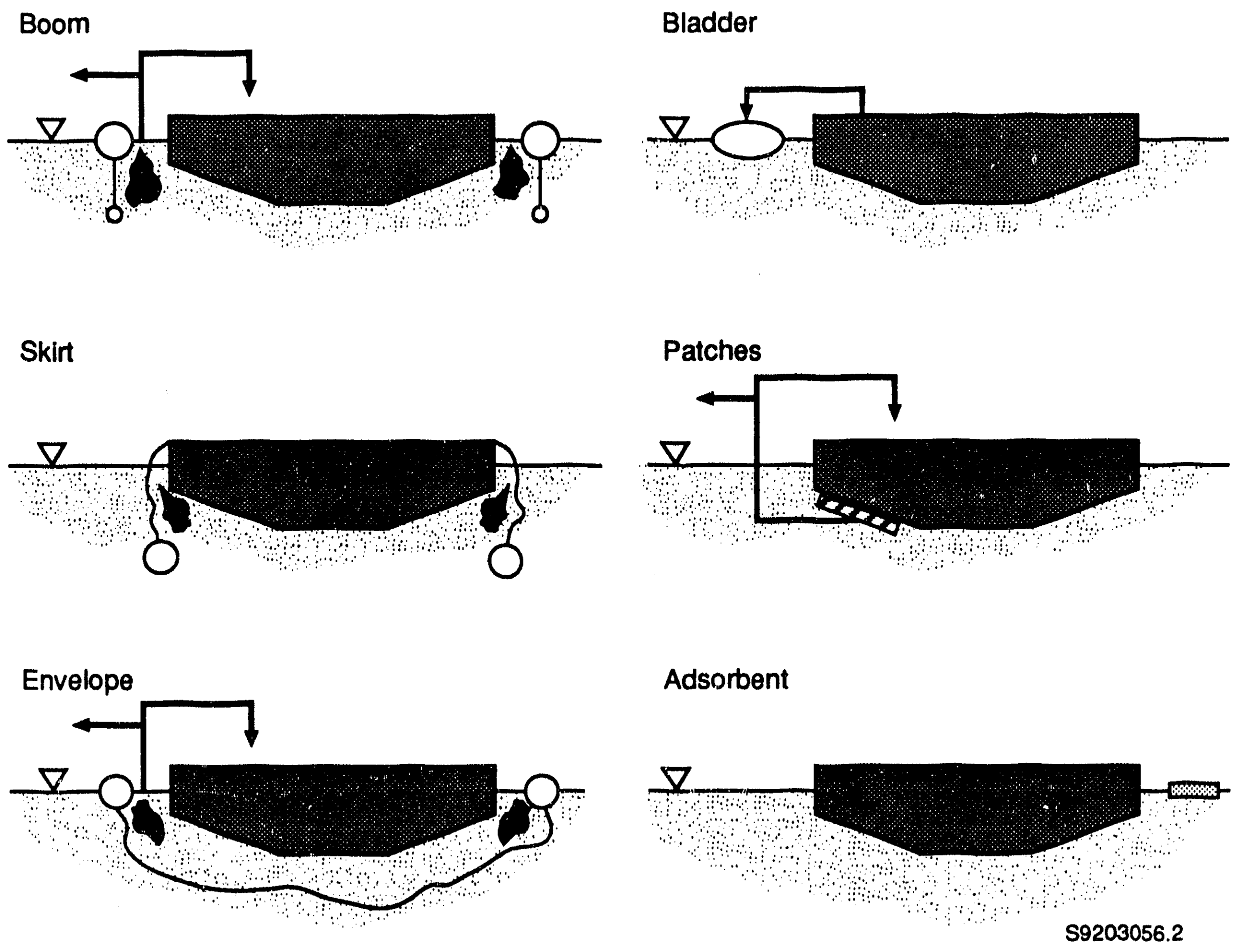


FIGURE 3.1. Self-Help Countermeasure Classifications

proposed technologies are of this generic type. Oceanographic and meteorological conditions that may negatively impact the effectiveness of booms are strong currents, stormy winds, breaking waves, and ice. Strong currents and breaking waves can mix oil and water below the boom, and allow it to escape containment. The depth to which oil mixes is a function of oil properties, mainly density and viscosity, water temperature, wave height, and current speed.

To be effective, a boom must be placed so that spilled oil surfaces within its perimeter. Factors that must be taken into consideration when deploying booms include the location(s) of punctured tankage with respect to the water surface; the velocity of oil flow; the current, wind, and wave directions; and vessel motion.

Skirts are flexible barriers deployed from the perimeter of a tanker that remain attached to it. Two proposed technologies are of this generic type. Unlike booms and envelopes, skirts are attached to and move with a tanker and shield spilled oil from wind and wave action. Consequently, there is nothing to prevent oil from escaping from the bottom of the skirt. Like booms, skirts may not be effective if the oil surfaces beyond the perimeter of the skirt.

Envelopes are flexible membranes that are deployed around the submerged vessel hull. Oil trapped between the hull and the envelop can be pumped to onboard or external tankage. Five proposed technologies are of this generic type. Unlike booms and skirts, envelopes prevent oil from escaping at depth. Envelopes are more complicated to deploy than booms and skirts, and they are more difficult to control in currents and waves because they have larger surface areas. Deployment in a grounding situation or when thick ice is present would be very difficult.

Bladders provide a receptacle for oil pumped from punctured tankage or spill containment devices. Four proposed technologies are of this generic type. Successful use of bladders requires over-the-side deployment of equipment (e.g., hoses, pipes), plumbing between the bladder and punctured tankage, or spill containment devices (e.g., booms, skirts, envelopes). Current and wave forces on a bladder can be large, particularly when it is nearly full. Controlling a bladder in strong currents, large waves, and ice would require special rigging and deck equipment (e.g., winches and cranes).

Patches with Plumbing. This type of countermeasure involves placing a patch, with fittings for pump intakes, over punctures and pumping oil into emergency tankage. One system of this generic type was proposed. The placement of the pump may be difficult in rough seas or when thick ice is present. Keeping a patch in place without auxiliary vessel support could be difficult in rough seas and strong currents.

Adsorbents are materials designed to immobilize spilled oil in or near a vessel. One proposed technology is of this generic type. The effectiveness of adsorbent materials depends on water temperature and salinity, as well as the type of spilled oil and its weathered state. Maintaining contact between adsorbents and spilled oil depends on wind, wave, and current conditions. Absorbents used without some form of containment system (a boom, skirt, or envelope) might not contact oil long enough to adsorb it.

## 3.2 SCENARIO DEVELOPMENT

The working definition of an environmental scenario is: a set of prescribed conditions that have a high probability of occurring and could reduce the effectiveness of self-help measures. An example scenario for Norton Sound in the Bering Sea in January is: 1/2-m thick first-year ice (30% coverage), winds averaging 25 knots, air temperature -15°C, blowing snow, 1-m wind waves, and 4 hours of daylight. The scenarios are intended to represent oceanographic conditions for the coastal waters of the United States out to 200 nm, the Economic Exclusion Zone (EEZ), estuaries, intracoastal waterways, major rivers, and parts of the Great Lakes where oil is transported by tanker or barge. Because U.S. coastal waters encompass oceanographic regimes ranging from ice-infested arctic seas (Beaufort, Chukchi, and Bering Seas) to the tropical waters of southern Florida, a range of scenarios is required. In addition, scenarios must represent conditions that are likely to occur. For these reasons, oceanographic and climate statistics provide the basis for scenario development.

Conditions that reduce the ability of the crew to operate deck equipment, deploy and operate small boats, or to visually assess the immediate surroundings of the vessel and extent of hull damage will reduce the effectiveness of all the countermeasures described here to some degree. These conditions include low visibility because of fog, rain, and snow and superstructure icing. Other conditions affect specific countermeasures.

In developing scenarios, primary and secondary environmental conditions were defined. Primary conditions limit the selection of equipment that can be deployed and operated to contain spilled oil and have first-order effects on the behavior, spreading, and transport of the spilled oil. Secondary conditions do not preclude specific countermeasures but may decrease their effectiveness or make spilled oil difficult to track, contain, or recover.

### 3.2.1 Primary Environmental Conditions

Wind speed. The speed of spilled oil transport away from a leaking vessel and the surface current is directly related to wind speed. A method used in oil-spill trajectory and surface-current forecasting is that the speed of oil transport and the surface current (neglecting tidal and other forces) is 2% to 3% of the wind speed. The rate of oil-water emulsification (mousse formation) also increases with wind speed. Oil-water emulsification will change the flow characteristics of spilled oil (Bridie et al. 1980) and limit the selection of oil-recovery equipment. In addition, equipment handling characteristics, deck and small boat safety, visibility, and local sea state are also strongly influenced by wind conditions.

Sea state (sea and swell) influences vertical mixing of oil and water, oil-water emulsification, dynamic loads on gear deployed over the side, and personnel safety.

Current speed is a major environmental factor in transport, spreading, and dispersion of spilled oil. Loads on gear deployed over the side and handling equipment required to control ground tackle and rigging are also affected by currents and can make certain countermeasure equipment impossible to operate. Flow drag on submerged and floating equipment will increase by a factor of about four as the current speed doubles. High current speeds can carry oil away from the vicinity of a leaking vessel before it can be contained. The effects of currents are most serious when a vessel is grounded, but even a vessel adrift will have to contend with rapid oil dispersion and unpredictable transport in a swift current.

Sea and lake ice also affect oil transport and dispersion, and handling gear over the side. When thick ice is in contact with a vessel, it will be extremely difficult to access the submerged hull. In addition to distributed loads from hydrodynamic forces, ice can produce concentrated stresses approaching the failure strength of ice, 50 to 1,000 psi (API 1982). These loads can cause fittings, lines, cables, and flexible barriers to fail and allow oil to escape containment.

Superstructure icing can render equipment inoperable or hazardous to deck personnel. Icing occurs when air temperature is below freezing, wind speed is high, and there is sufficient moisture and sea spray to add freeze to vessel structures. Ice adds topside weight, covers equipment controls, and makes rigging difficult to handle. In addition, icing of countermeasure equipment deployed in the water can cause it to submerge or cease to operate as designed.

### 3.2.2 Secondary Environmental Conditions

Tidal range and short-term water-level fluctuations (a few meters in 12 hours). Water-level fluctuations mainly effect grounded vessels. For example, the pressure head in a leaking or receptacle tankage will change with water level causing problems with fluid handling systems. In addition, the handling of booms, skirts, envelopes, and bladders can be adversely affected by water-level fluctuations. For example, grounding during a falling tide can make placement of countermeasure equipment difficult.

Low visibility and limited daylight negatively affect visual identification of outflow points, tracking of spilled oil, and crew efficiency and safety.

Precipitation (heavy snowfall, rain, or hail) contributes to low visibility, hazards on deck, and affects the consistency of spilled oil.

Sea surface and air temperature affect oil evaporation, viscosity, and gravitational spreading (Fay 1971).

### 3.2.3 Geographic Areas

U.S. coastal waters were divided into nine zones for the purpose of gathering data. The zones are illustrated in Figure 3.2 and are as follows:

- Zone 1, Eastport, Maine, to Cape Hatteras
- Zone 2, Cape Hatteras to Key West, Florida

- Zone 3, Key West, Florida, to Brownsville, Texas
- Zone 4, San Diego to Eureka, California
- Zone 5, Eureka, California to Ketchikan, Alaska
- Zone 6, Ketchikan to Dutch Harbor
- Zone 7, Dutch Harbor to Demarcation Bay (Alaskan Beaufort Sea)
- Zone 8, The Great Lakes
- Zone 9, Intracoastal waterways and rivers.

The Intracoastal Waterway connects centers of maritime commerce from New York to Brownsville, Texas, with a system of protected channels more than 2,700 nm long. Major oil terminals exist at a few locations along the waterway (e.g., the lower Delaware, Atchafalaya and Calcasieu Rivers, Port Arthur, and Galveston Bay, Texas). The scenario for Zone 9 was developed for the lower Delaware River because the largest volumes of crude oil are conveyed there (Waterbourne Commerce 1989a).

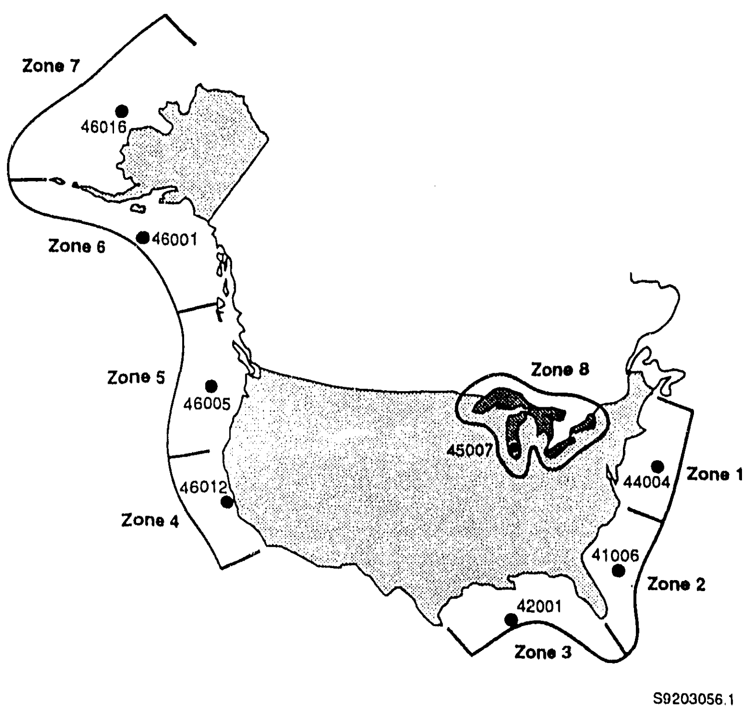


FIGURE 3.2. Nine Zones of U.S. Coastal Waters

Very little crude oil and only limited quantities of refined product are transported by tankers and tank barges on the Great Lakes (Waterbourne Commerce 1989b). Lake Michigan was selected for scenario development because it is large, exposed to severe winter storms, and has sea states not unlike those in coastal ocean waters.

### 3.2.4 Statistics and Data Sources

In mid- to high-latitudes, the severity of oceanographic and weather conditions will depend strongly on the season. Generally, conditions at sea will be less favorable for navigation, safe operation of small boats, deck equipment, and rigging from late fall to early spring. Conditions for these activities improve during the summer. Scenarios were developed to distinguish two general situations that a tanker or barge crew could expect to cope with during fair (summer) and inclement (winter) conditions at sea.

Oceanographic and climate statistics for each zone were extracted from readily available data such as climate and oceanographic atlases, NOAA National Data Buoy Center (NDBC) data summaries, and the U.S. Coast Pilots. Whenever possible, statistics for currents, waves, and winds were derived from multi-year records to avoid bias resulting from year-to-year variability. Surface current statistics are the most unreliable in this regard because long-term, near-surface measurements are not routinely made.

The basic statistical procedures for selecting wind speeds, current speeds, and wave heights for most zones are the same. Cumulative frequency distributions (CFDs) for these parameters were generated from observations at fixed locations central to each zone. For example, Figure 3.3 shows wave height CDFs for the Gulf of Alaska and the Gulf of Mexico. When several current meter records from several locations over a multiyear period were available, the current speed CFDs were constructed from near-surface current meter records ranging from a few months to 6 months. The CFDs for individual meters were weighted by record length and combined to form a single CFD for the zone. The combined CFDs thus represent a spatial and temporal average surface current for the entire zone.

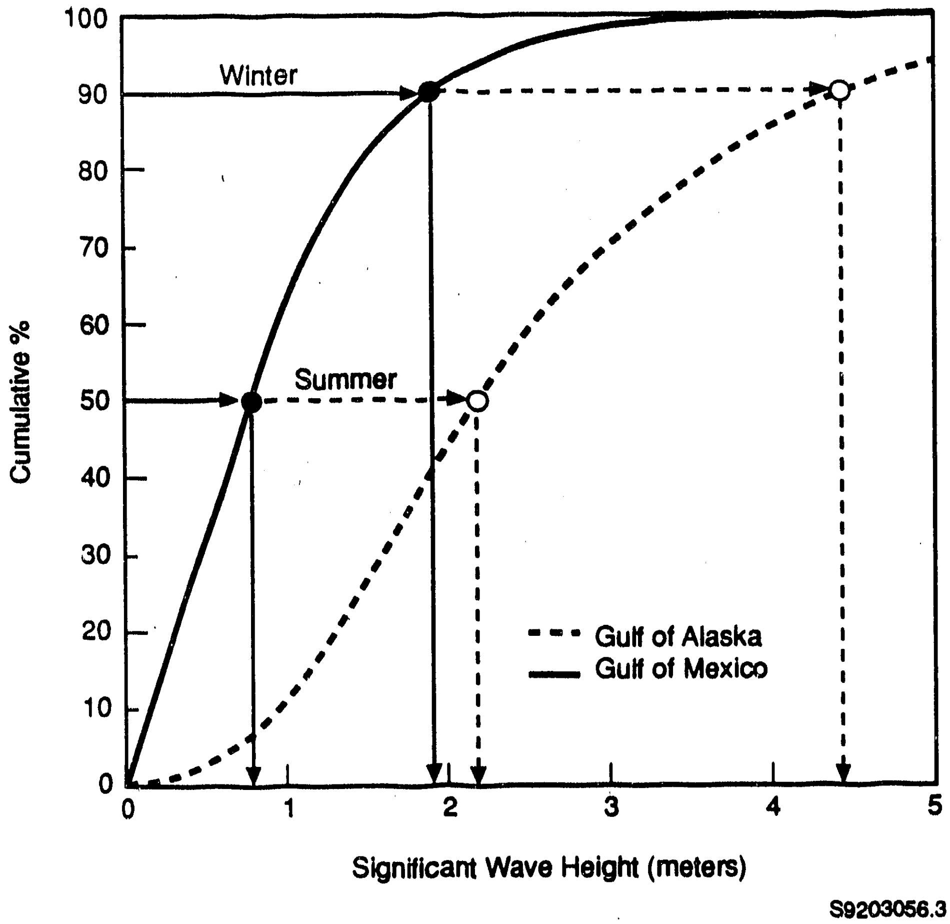


FIGURE 3.3. Wave Height Cumulative Frequency Distributions for the Gulf of Alaska and the Gulf of Mexico

Summer (fair) conditions were represented by the 50th percentiles of the CFDs, and winter (inclement) conditions were represented by the 90th percentiles. The 50th percentile is the wind/current speed, or wave height, that was exceeded during half of the observations. The 90th percentile is the value that was exceeded during 10% of the observations. CFDs provide a good base function for evaluating success and failure. For example, based on engineering data, a threshold parameter value can be selected for a piece of equipment which if exceeded will cause it to fail or become ineffective. The CFD for that parameter can then be used to estimate the percent of time the failure condition or inefficient operation will likely occur.

Wind Speed: Cumulative frequency distributions for winds recorded by NDBC buoys (NOAA 1990a) were used to estimate probable winter and summer wind speeds. Summer wind speeds were estimated by the 50th cumulative percentile, and winter wind speeds were estimated by the 90th cumulative percentile. Because buoy data were not available for January and February for the Great Lakes, annual CFDs could not be generated. Winter and summer wind and wave statistics were, therefore, estimated with the 50th percentiles for December and August data, respectively.

Wave Height: Cumulative frequency distributions for significant wave heights recorded by NDBC buoys in offshore waters were used to estimate probable summer and winter wave heights for each zone. Significant wave height is the average height of the one-third largest waves in a sea. Summer wave heights were estimated by the 50th cumulative percentile, and winter wave heights were estimated by the 80th cumulative percentile. Wave data of the sort used to develop the offshore scenarios are not routinely measured in protected waters and were not readily available. The wave heights in the Zone 9 scenario are, therefore, based on personal observations.

Wave conditions are less important than wind and current speeds in evaluating self-help measures for river navigation. On rivers and the intracoastal waterway, the sea state will depend heavily on local wind and fetch conditions. Fetch lengths can easily vary from several hundred to several thousand meters over a period of a day or more as storm systems transit a navigation area. But fetch length usually limited wave growth, and wind-wave periods are generally less than 3 seconds in protected waters.

Surface Currents: Cumulative current-speed frequency distributions were developed from multi-year, near-surface current meter records. Summer current speeds were estimated by the 50th cumulative percentile, and winter current speeds were estimated by the 90th percentile.

Surface current data of the type used to analyze offshore and tidal current speed statistics are limited for the Great Lakes. It was, therefore, not possible to generate CFDs. Surface circulations in the Great Lakes differ from offshore waters because there are no density gradients caused by salinity variation or significant astronomical tides. Surface currents in the Great

Lakes are driven mainly by the wind. Therefore, surface currents strong enough to hinder self-help measures rarely occur in the absence of strong winds, stormy weather, and moderate wind waves. During storms, surface current velocities will be approximately 2% to 3% of the local wind velocity. For example, when the average wind speed is 15 knots, the surface current will be the range from 0.15 to 0.23 m/s (0.29 to 0.45 knots). The current speeds given in the scenario for Zone 8 were estimated in this way with wind statistics from NDBC Buoy data.

River currents flow in one direction, and current speed increases with river stage dependent on the surface water hydrology of headwater and tributary rivers and streams. In general, the higher the river stage the higher the average current speed will be. Very large changes in stage and current speed can occur within a period of days when storms cause severe runoff and flooding. Variations in surface currents from one location to another are tremendous along a river navigation channel. The values given in the scenarios for Zone 9 represent 50% and 100% bank-full surface current estimates obtained from the U.S. Army Corps of Engineers measurements at Greenville, Mississippi. This station is upstream from tidal influences during low-flow. The Mississippi River was selected because it has a large volume of crude oil transported by barges compared to other navigable, nontidal rivers.

Tidal Current speed statistics at harbor entrances leading to oil terminal locations were with the program TIDE 2 (Micronautics 1991). Because the year-to-year variation of tidal forces is very small, one year of predicted data is sufficient to characterize current speeds for all years. TIDE 2 was run to make hourly predictions for 1991, and a CFD was calculated from the resultant 8,760 speeds. The 50th percentiles for each location with heavy tanker and barge traffic were determined from the CFDs and used in the scenario descriptions. Although the analysis was not made for the Intracoastal Waterway, tidal current speeds for the Waterway can be expected to fall within the range of values for Zones 1 through 3.

Sea Ice: NASA satellite passive-microwave observations were used to assess sea ice coverage (Parkinson et al. 1987). Ice thickness data were also used (Bilello 1980; Bauer and Martin 1980).

Air and Sea-Surface Temperatures: The mean monthly temperatures recorded by NDBC buoys for January (March for Lake Michigan) and August were used to estimate winter and summer values, respectively.

Visibility, Precipitation, Superstructure Icing: The climatological tables in the U.S. Coast Pilots were used to determine if low visibility (fog) and precipitation are likely conditions in each zone. These conditions were considered likely if either occur more than 50% of the days in December, January, and February (winter), or July, August, September (summer). For example, frequent summertime precipitation is common in the Gulf of Mexico (Zone 3). It rains more than 0.01 inches in 24 hours 52 out of 92 days at Fort Myers, Florida, during an average summer according to the Coast Pilot Climatological summary. Therefore, precipitation was included in the summer scenario for Zone 3. Likewise, fog is common in the Alaskan Bering Sea, Zone 7. Saint Paul Island has fog 69 out of 92 days during an average summer; therefore, fog is included in the summer scenario. There are no climatological data for superstructure icing in the Coast Pilots. However, the Coast Pilots indicate that it should be of concern to mariners in the Bering Sea and northern Great Lakes. For this reason, superstructure icing is included in Zones 7 and 8.

Water-Level Fluctuations: TIDE 1 software was used to generate tidal range statistics. The values given in the scenarios are the maximum tidals at locations for each scenario. In the case of Zones 1 and 3, the minimum and maximum tidal ranges for inlets with significant tanker traffic are given. In the case of Zone 2 and 7, there are no tidal inlets with significant tanker traffic; therefore, no tidal ranges are given. The remaining zones have only one inlet with significant tanker traffic.

## 3.3 SCENARIO DESCRIPTIONS

This section presents the scenario descriptions developed from oceanographic and weather statistics discussed above (see Tables 3.2 through 3.10). The descriptions for each zone are divided into winter and summer conditions. This was done because countermeasures that might be effective for a particular zone during the summer may be marginally or completely ineffective, or too hazardous to consider in the winter. Conditions that have a low probability of occurring in a zone, such as sea ice, superstructure icing, and low visibility, are not listed.

The tables presented in this section list weather and oceanographic conditions that are considered likely for U.S. navigable waters. They provide a way to factor physical conditions into analyses of the effectiveness of self-help countermeasures.

It is important to know the limitations of these tables. First, the numbers for wind and current speeds, wave heights, etc., do not represent forecasts for a particular location or time. Second, winter and summer are generic scenarios because it is generally true that inclement weather and sea conditions occur in winter, and milder conditions occur in summer in the mid latitudes. Hurricanes, persistent dense fog, and torrential rains are three obvious exceptions to the generic association of summer with mild conditions. The main utility of the tables is for the selection parameter ranges for analyzing how well a particular countermeasure might perform in a particular geographic area. For example, skimmers do not operate efficiently in waves greater than about 2.0 ft or currents faster than about 0.9 knots; however, these conditions can be expected in many zones. It is therefore reasonable to expect inefficient skimmer operations at many potential spill sites in exposed U.S. waters. Section 5.0 and the model runs in Appendix D provide a more detailed treatment of how the information in Tables 3.2 through 3.10 can be used in the evaluation of countermeasures.

## 3.4 SEA AND LAKE ICE

Zone 7 is ice infested every winter. Oil from Prudhoe Bay is conveyed by the Alyeska pipeline to the terminal at Valdez, Alaska, where glacial ice, but no significant sea ice, is present. Although oil tankers and barges do not currently service U.S. oil terminals in Zone 7, operations may occur in the Bering, Chukchi, or Beaufort Seas if offshore reserves are developed, and barge traffic on the Great Lakes may increase in the future. For these reasons, a general assessment of the effects of sea ice on countermeasure effectiveness is provided in this section.

TABLE 3.2. Zone 1, Eastport, Maine to Cape Hatteras

| | Winter | Summer |
|---|---|---|
| **Primary Conditions** | | |
| Wind Speed[a] | 24 kn | 13.5 kn |
| Sea State ($H_s$)[a] | 3.57 m | 1.5 m |
| Current Speed[b] | 0.46 m/s (0.89 kn) | 0.22 m/s (0.43 kn) |
| **Secondary Conditions** | | |
| Air Temperature[a] | 7.5°C | 23.8°C |
| Sea Surface Temperature[a] | 14.8°C | 25.5°C |
| Daylight[c] | 9.3 h/d | 15.0 h/d |
| Tidal Range[c] | 1.3 - 4.2 m | |
| Tidal Current Speed[c] | 0.33 - 0.64 m/s (0.64 - 1.24 kn) | |

(a) NDBC Buoy No. 44004 (NOAA 1990a).
(b) 106-mile Site. Battelle Ocean Sciences. Draft. Winter Survey of Selected Areas in the New York Night in Support of Designation of an Alternative Mud Dump Site.
(c) TIDE 1 and 2 (Micronautics 1991).

TABLE 3.3. Zone 2, Cape Hatteras to Key West, Florida

| | Winter | Summer |
|---|---|---|
| **Primary Conditions** | | |
| Wind Speed[a] | 18 kn | 9.7 kn |
| Sea State ($H_s$)[a] | 2.6 m | 1.3 m |
| Current Speed[b] | No Data | 0.33 m/s (0.64 kn) |
| **Secondary Conditions** | | |
| Air Temperature[a] | 19.5°C | 27.9°C |
| Sea Surface Temperature[a] | 23.0°C | 28.9°C |
| Daylight[c] | 10 h/d | 14 h/d |
| Precipitation[d] | - | >0.01 in. in 24 h |

(a) NDBC Buoy No. 41006 (NOAA 1990a).
(b) Battelle Ocean Sciences. Draft Final Report. The Physical Oceanography of the U.S. Atlantic and Eastern Gulf of Mexico. Volume II.
(c) TIDE 1 (Micronautics 1991).
(d) NOAA 1989a.

TABLE 3.4. Zone 3, Key West, Florida to Brownsville, Texas

| | Winter | Summer |
|---|---|---|
| **Primary Conditions** | | |
| Wind Speed[a] | 19 kn | 10 kn |
| Sea State ($H_s$)[a] | 1.9 m | 0.7 m |
| Current Speed[b] | 0.40 m/s (0.78 kn) | 0.26 m/s (0.51 kn) |
| **Secondary Conditions** | | |
| Air Temperature[a] | 20.5°C | 28.7°C |
| Sea Surface Temperature[a] | 23.8°C | 29.6°C |
| Daylight[c] | 10.3 h/d | 14 h/d |
| Precipitation[d] | - | >0.01 in. in 24 h |
| Tidal Range[c] | 0.7 - 1.0 m | |
| Tidal Current Speed[c] | 0.34 - 0.46 m/s (0.66 - 0.89 kn) | |

(a) NDBC Buoy No. 42001 (NOAA 1990a).
(b) SAIC (1986, 1987, 1988, 1989).
(c) TIDE 1 and 2, Houston & New Orleans (Micronautics 1991).
(d) NOAA 1989b.

TABLE 3.5. Zone 4, San Diego to Eureka, California

| | Winter | Summer |
|---|---|---|
| **Primary Conditions** | | |
| Wind Speed[a] | 17.5 kn | 8.5 kn |
| Sea State ($H_s$)[a] | 3.0 m | 1.6 m |
| Current Speed[b] | 0.61 m/s (1.19 kn) | 0.36 m/s (0.70 kn) |
| **Secondary Conditions** | | |
| Air Temperature[a] | 11.1°C | 13.7°C |
| Sea Surface Temperature[a] | 11.9°C | 14.4°C |
| Daylight[c] | 9.5 h/d | 15.0 h/d |
| Tidal Range[c] | 2.7 m | |
| Tidal Current Speed[c] | 0.81 m/s (1.57 kn) | |

(a) NDBC Buoy No. 46012 (NOAA 1990a).
(b) EG&G (1989, 1990a, 1990b).
(c) TIDE 1 and 2, Golden Gate, CA, (Micronautics 1991).

TABLE 3.6. Zone 5, Eureka, California to Ketchikan, Alaska

| | Winter | Summer |
|---|---|---|
| **Primary Conditions** | | |
| Wind Speed[a] | 23.5 kn | 13.5 kn |
| Sea State ($H_s$)[a] | 4.4 m | 2.1 m |
| Current Speed | No data | No data |
| **Secondary Conditions** | | |
| Air Temperature[a] | 8.9°C | 15.3°C |
| Sea Surface Temperature[a] | 10.0°C | 16.1°C |
| Daylight[b] | 8.4 h/d | 16.2 h/d |
| Tidal Range[b] | 3.3 m | |
| Tidal Current Speed[b] | 0.36 m/s (0.70 kn) | |

(a) NDBC Buoy No. 46005 (NOAA 1990a).
(b) TIDE 1 and 2, Strait of Juan de Fuca, WA (Micronautics 1991).

TABLE 3.7. Zone 6, Ketchikan to Dutch Harbor, Alaska

| | Winter | Summer |
|---|---|---|
| **Primary Conditions** | | |
| Wind Speed[a] | 27 kn | 17 kn |
| Sea State ($H_s$)[a] | 4.5 m | 2.2 m |
| Current Speed | No data | No data |
| **Secondary Conditions** | | |
| Air Temperature[a] | 3.3°C | 12.4°C |
| Sea Surface Temperature[a] | 4.7°C | 12.9°C |
| Daylight[b] | 6.8 h/d | 18 h/d |
| Tidal Range[b] | 5.4 m | |
| Tidal Current Speed[b] | 0.31 m/s (0.60 kn) | |

(a) NDBC Buoy No. 46001 (NOAA 1990a).
(b) TIDE 1 and 2, Prince William Sound entrance, Cape Bear, Alaska (Micronautics 1991).

TABLE 3.8. Zone 7, Dutch Harbor to Demarcation Bay (Alaskan Beaufort Sea)

| | Winter | Summer |
|---|---|---|
| Primary Conditions | | |
| Wind Speed[a] | 23 kn | 13 kn |
| Sea State ($H_s$)[b] | No Data | 2.2 m |
| Current Speed[b] | No Data | 0.25 m/s (0.49 kn) |
| Superstructure Icing | Yes | No Data |
| Sea Ice[c] | 1 m/60% | No Data |
| Secondary Conditions | | |
| Air Temperature[a] | -14.1°C | 7.4°C |
| Sea Surface Temperature[d] | 2.5°C | 11.0°C |
| Daylight[e] | 4 h/d | 22 h/d |
| Visibility[d] | - | Fog |
| Precipitation[d] | - | >0.01 in. in 24 h |
| Snow | Yes | - |

(a) NDBC Buoy No. 46016 (NOAA 1990a).
(b) EG&G. 1985. Meteorological and Oceanographic Monitoring in St. George Basin, Summer-Fall 1984 RAT No. 1 Well. ARCO Alaska, Inc., Anchorage, Alaska.
NORTEC. 1985. Meteorological & Oceanographic Data Acquisition Program. OCS-Y-586, Package #1 Navarin Basin, Bering Sea, Alaska ARCO Alaska, Inc., Anchorage, Alaska.
(c) Parkinson et al. 1987.
(d) NOAA 1989c.
(e) TIDE 1 (Micronautics 1991).

TABLE 3.9. Zone 8, Great Lakes

| | Winter | Summer |
|---|---|---|
| Primary Conditions | | |
| Wind Speed[a] | 13.4 kn | 8.2 kn |
| Sea State ($H_s$)[a] | 1.1 m | <0.5 m |
| Current Speed[b] | 0.20 m/s (0.29 kn) | 0.12 m/s (0.23 kn) |
| Superstructure Icing | Yes | - |
| Ice[c] | 0.3 m/20% | - |
| Secondary Conditions | | |
| Air Temperature[a] | 2.3°C | 21.5°C |
| Water Temperature[a] | 2.6°C | 22.0°C |
| Daylight[d] | 9 h/d | 13.5 h/d |
| Snow[e] | Yes | - |

(a) NDBC Buoy No. 45007 (NOAA 1990a).
(b) Average Wind Speed X 0.03.
(c) NOAA 1983.
(d) TIDE 1 (Micronautics 1991).
(e) NOAA 1991b.

TABLE 3.10. Zone 9, Intracoastal Waterways and Rivers

| | Winter | Summer |
|---|---|---|
| Primary Conditions | | |
| Wind Speed[a] | 13.4 kn | 8.2 kn |
| Sea State ($H_s$)[b] | <0.5 m | <0.25 m |
| Current Speed[c] (m/s) | 0.50 m/s (2.4 m/s[d]) | 0.50 m/s (2.4 m/s[d]) |
| Current Speed[c] (kn) | 0.97 kn (4.66 kn[d]) | 0.97 kn (4.66 kn[d]) |
| Secondary Conditions | | |
| Air Temperature[a] | 0.8°C | 23.8°C |
| Water Temperature[a] | 2.3°C | 26.0°C |
| Daylight[c] | 9.4 h/d | 13.1 h/d |

(a) NOAA 1991a.
(b) Personal Observations.
(c) TIDE 1 & 2, Wilmington, Delaware (Micronautics 1991).
(d) Median surface current speed of the lower Mississippi River; Ron Wooley, WES, Personal communication.

The effectiveness of countermeasures on the behavior of oil spilled in ice-infested waters depends on ice thickness, coverage, motion, as well as the type and amount of spilled oil. The annual cycle of sea ice formation begins when ice crystals and snow consolidate into 0.01- to 0.1-m thick elastic sheets, called grease ice. Wave and current action break these sheets into circular pieces 0.3 to 3 m in diameter called pancake ice. Once ice reaches a thickness of approximately 0.3 m it is called first-year ice and becomes a significant hazard to navigation. Ice that survives for more than one season is called multiyear ice.

First-year and multiyear ice break into irregular masses called floes. Maximum first-year thickness in Alaskan arctic seas ranges from 1.75 to 2.25 m (Bilello 1980). Multi-year ice attains an equilibrium thickness of approximately 3 m in the central Arctic Ocean (Maykut and Untersteiner 1971). Pressure ridging and rafting can locally thicken sea ice to as much as ten times the equilibrium thickness. Melting and breakup begins in April in the southern Bering Sea, and the western Beaufort Sea is free of shorefast ice by late July during most years.

### 3.4.1 Sea Ice Distribution in the Bering, Chukchi, and Beaufort Seas

Winter in the Arctic lasts for 8 months (November-June) during which time multiyear ice covers most of the area between the North Pole and the North America (Parkinson et al. 1987). Ice thickness and coverage in the Beaufort Sea varies form year-to-year, but minimum ice coverage usually occurs in September.

Approximately a third of the Bering Sea is ice infested from January to May. Ice formation begins in the northern regions of the Bering as early as November. Ice coverage grows rapidly during the months of December and January; the maximum extent of ice coverage is reached during March and April. Ice coverage decreases rapidly after April, and by June only traces of ice remain in the northern coastal regions of Norton Sound. At the maximum coverage, ice thickness ranges from about 1.5 m at the northern boundary to 0.2 m at the southern edge of pack ice (Bauer and Martin 1980). The ice thickness in Cook Inlet is highly variable as a result of continuous motion and interaction with the bottom caused by very strong tidal current and an extreme tidal range. Dynamic forces resulting from such motion are a major safety factor navigation and vessel engineering. In Prince William Sound there is no significant sea ice formation. However, icebergs calved from several glaciers flowing into the Sound are a safety concern for both navigation and the operation of self-help countermeasures.

### 3.4.2 Ice in The Great Lakes

Ice begins to form in shallow coves and inlets of the Great Lakes beginning in December and persists until early April. Winter winds blow ice floes offshore where they can be a hazard to navigation. Average ice thickness and percent coverage in the offshore waters are considerably less severe than for Zone 7; however, the possibility of encountering ice during winter should be considered in the evaluating self-help measures for Zone 8. In shallow, protected waters, ice concentrations can exceed 50% and ice can be as much as 1 m thick as a result of rafting and ridging (NOAA 1983).

### 3.4.3 Oil Behavior in Ice-Infested Waters

In ice-free waters, the major processes effecting spilled-oil behavior are gravitational spreading, advection by surface currents, transport by wind stress, and evaporation (Payne et al. 1987). Because it forms a partial barrier to spreading and wind transport, sea ice has a major effect on the oil behavior when the percent coverage is larger than about 30%. Oil composition, air and water temperature, and near-surface turbulence all exert secondary effects on oil transport when there is wind, waves, and currents at a spill site. Evaporative losses of fuels and volatile components of crude oil are substantial within the first 24-48 hours following a spill.

Sea ice is a major factor in countermeasure design because of its direct effect on spilled-oil behavior and the limitations it imposes on the selection and deployment of equipment over the side. Each prospective self-help technology must be evaluated for multiple scenarios where the surface extent, thickness, and mixture of ice types are varied. The proximity of the sea ice to the tanker may bar deployment and/or effective operation of a given countermeasure. Moreover, the efficacy of a particular technology may depend on whether oil is spilled directly onto, beneath, or immediately adjacent to an ice floe.

The spreading behavior of oil spilled directly onto ice is affected primarily by the surface roughness of the ice and the volume of spilled oil. In the case of small spills, the oil may be adequately contained by surface irregularities. The effects of low temperature and/or ice salinity may be important for self-help technologies which are sensitive to changes in oil viscosity. Oil released beneath ice tends to float into cavities in ice bottom. Within a matter of only a few days this oil will be entombed by the growth of new ice and will remain essentially unweathered until the ice begins melt and breakup (Ross 1983; NORCOR 1975). At this time, trapped oil will migrate to the surface through fractures and channels. Effective containment of oil spilled onto or underneath of ice may be further confounded by the movement of the floe.[a] Temporal and spatial variability in the formation and breakup of ice and the velocity and trajectory of floe movement contribute additional uncertainty in planning effective countermeasure strategies.

In the absence of waves and high currents, oil spilled in open water will not be carried beneath floes, but rather will be herded against the ice resulting in a relatively greater thickness of oil than that which would be achieved when ice is not present (Ross 1983). The extent to which this may aid in the initial containment of oil depends largely on whether subsequent efforts to recover the oil are physically inhibited by the nature and proximity of the ice.

Turbulence generated by wind stresses, waves, and currents produce a stable oil-water emulsion called "mousse." Mousse can be produced within a matter of hours following a spill (Bridie et al. 1980). The processes associated with ice formation and movement may enhance both the rates of dispersion

(a) Information obtained from a presentation handout prepared in 1989 by Engineering Computer Optecnomics, Inc., for the Alaska Oil Spill Commission, Anchorage, Alaska. The handout title is "An Overview of Spill Response in the Alaska Arctic-Bering Strait to the Canadian Border."

and emulsification, while at the same time inhibiting rates of microbial degradation (Payne et al. 1987). The physical properties and spreading behavior of mousse are substantially different than those of fresh crudes and must be considered in evaluating different self-help alternatives (Payne et al. 1987).

The net impact of sea ice-oil interactions on the utility of different containment/cleanup technologies is difficult to predict. Much of this uncertainty can be attributed to the variable effect of sea ice on oil movement. Ice can act as a physical barrier effectively restraining the movement of oil, or greatly enhance transport and dispersion in cases where oil is entrained within moving ice floes. Effects of temperature and brine incorporation on the chemical and physical properties of oil may be important for some countermeasures, especially those which are based on oil absorption.

## 3.5 DISCUSSION

Environmental scenarios for U.S. offshore, inland, and intracoastal waters represent a wide range of environmental conditions that can be factored into evaluations of self-help countermeasures. Wind, waves, currents, sea ice, and superstructure icing could have the most significant influence on countermeasure effectiveness. The ranges of primary conditions for U.S. waters (all zones and all seasons) are shown in Table 3.11.

Upper values of the ranges for winds, waves, and currents have about a 10% chance of occurring in certain zones based on the data analyzed. The minimum values for these conditions will be exceeded about 50% of the time in U.S. waters.

Two conditions, low visibility and superstructure icing, will reduce the performance of all the proposed countermeasures to some degree. The fate and physical consistency of spilled oil, as well as oil transport, spreading, and vertical mixing, are driven by environmental conditions that ships crew will be unable to control. In addition, wind, current, and ice loads could prohibit effective deployment and control of self-help equipment and ultimately lead to equipment and rigging failure in some situations.

TABLE 3.11. The Ranges of Primary Conditions for U.S. Waters

| Primary Conditions | Ranges |
|---|---|
| Wind Speed | 8.2 to 27 kn |
| Sea State ($H_s$) | <0.5 to 4.5 m |
| Current speed | 0.12 to 2.4 m/s (0.23 to 4.66 kn) |
| Sea/lake ice | None to 60% coverage of 1-m ice |
| Superstructure Icing | None to 50% chance of occurrence |

Seasonal and geographic variation of conditions in U.S. waters probably warrants region-specific system designs. Systems that will be effective for all seas and all seasons seem impractical. The determination of critical environmental conditions that could render the performance of a particular countermeasure unacceptable involves complex and interrelated system and design attributes. For this reason, the environmental scenarios developed for this study should be used with other criteria, including flow rates, navigation situation, and human factors to evaluate countermeasure efficacy.

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# 4.0 HUMAN FACTORS

This section of the report discusses the human factors engineering aspects of onboard countermeasures. As defined by the Coast Guard Navigation and Inspection Circular 4-89, human factors engineering is the discipline devoted to safe and effective human-machine systems. Proper human factors will ensure that equipment and software are designed to match the capabilities and limitations of personnel who operate them. Since a number of the proposed countermeasure technologies involve intervention by the crew, a human factors assessment is necessary.

It is particularly important to conduct such an assessment in the early stages of countermeasure development to identify potential mismatches between countermeasure requirements and crew knowledge, skill, and ability. An overriding question in this study is the extent to which existing or reduced crew would be able to perform additional pollution control tasks during damage control.

## 4.1 APPROACH

The principal aim of the human factors portion of this study is to determine the extent to which proposed countermeasure technologies can be employed by the existing crew of a tanker or tug. A corresponding goal is to determine the impact of reduced manning scales on the potential utility of onboard countermeasures.

To address these questions, it was necessary to undertake a preliminary function and task analysis of emergency operations as conducted aboard tankers and barges. Function and task analysis identifies the major activities and their components performed by various crew members during "damage control and salvage operations." Further, such an analysis can be used to identify safety and training issues associated with performance, and any new requirements that may result from onboard countermeasures. The general process of function and task analysis is shown in Figure 4.1.

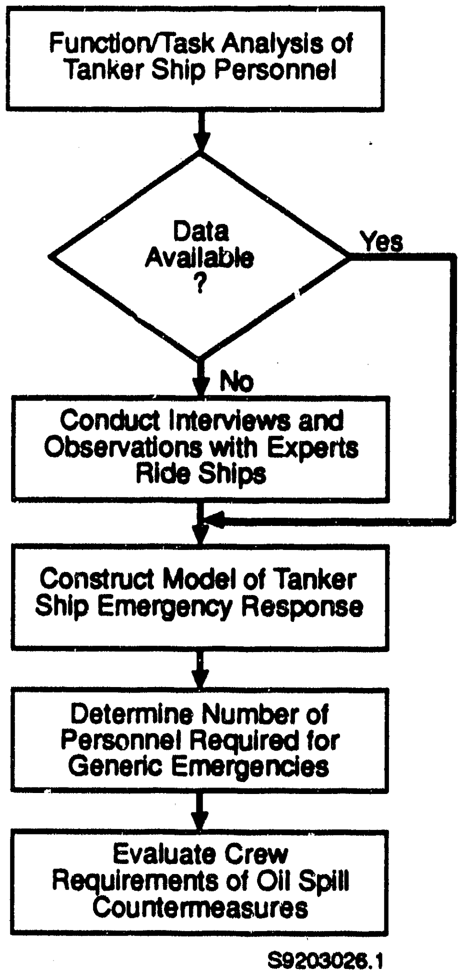


FIGURE 4.1. Human Factors Approach to Oil Spill Countermeasure Evaluation

The main tools employed in the preliminary function and task analysis were literature review, interviews with experts, and human factors analysis of the proposed technologies. Source literature was identified through a search on the DIALOG system and through a bibliographic search in the University of Washington library system. Documents were retrieved by staff in the Human Affairs Research Center (HARC) library and through contacts with the Marine Board of the National Academy of Sciences.

Interviews with experts were set up through a process of networking through the Seattle maritime community, based on initial contacts with the

Coast Guard 13th District, the Seattle Community College Maritime Training Program, and personal contacts within the maritime industry. The following personnel were interviewed:

- newly licensed chief mate unlimited with tanker experience
- area operations coordinators of two major oil shipping companies (one former master unlimited)
- one 2nd mate unlimited with tanker experience
- one master unlimited with primarily cargo ship experience
- one master unlimited employed by a major oil shipping company (onboard tanker interview)
- the fleet services manager, senior marine advisor, engineering and electrical support head, the regulatory compliance and environmental coordinator advisor, and the government relations head of a major oil shipping company (group telephone interview)
- the assistant fleet manager and the safety, training, and environment manager of a major oil shipping company (group telephone interview)
- Chief of the Marine Safety Division, Marine Safety Office, Seattle
- Chief of the Inspections Department, Marine Safety Office, Seattle
- Captain of the Port, U.S. Coast Guard 13th District
- president of a Seattle-based marine salvage company
- tug boat captain with extensive barge and cleanup experience
- director of bulk petroleum products for a major towing company
- safety and training director for a major towing company.

The interview format evolved from a fairly unstructured discussion, in order to learn what questions to ask, to a structured protocol. The questions from this protocol are as follows:

1. What is the typical crew structure of your company's tankers (tugs)? Please also consider potential reductions in manning as a result of automation.
2. What damage control and salvage activities do each of the crew members perform in the event of an emergency, such as a collision or grounding?

3. What types of training are provided to the various crew members in the area of emergency response and pollution control?

4. In the event that shipboard damage has been controlled, what activities would the crew be engaged in?

5. Does your company currently utilize any onboard self-help oil spill countermeasures?

6. What are the physical limitations (e.g., ship size, structure) in the use of potential onboard countermeasures? Where is the limitation in crew structure--supervision or labor?

7. Are there any potential onboard self-help countermeasures that you can suggest, and under what circumstances would they be employed?

The following sections present the results of the literature review and the interviews that have been conducted to date. Appendix B contains details of the human factors analysis of the proposed countermeasures.

## 4.2 HUMAN FACTORS AND SAFETY IN MARITIME OPERATIONS

The literature review identified a large number of sources concerned with the general issue of human factors and safety in maritime operations. While a complete review of this material is beyond the scope of the current project, it is worthwhile to briefly consider some of the major human factors issues associated with maritime operations, since these will have a bearing on the safety of tanker operations.

Safety analyses conducted by the Maritime Administration and the National Research Council in the middle 1970s and early 1980s suggest that human error contributes to 85% of maritime accidents. In 1976, the Maritime Transportation Research Board reported an initial investigation into human factors in marine accidents (MTRB 1976). Inattention was listed on a survey of mariners as an important cause of accidents. Thirteen categories of human error were identified, but were not ranked according to frequency of the cause or the types of accidents most likely to result. A subsequent study by the same organization published in 1981 developed more detail on maritime tasks, the potential human errors, and research requirements to alleviate error potential (MTRB 1981).

An analysis of maritime accidents by the National Transportation Safety Board (1981) analyzed the causes of 82 major marine accidents, and recommended an enhanced research program to better identify the contribution of the human operator. More recent work by the National Research Council (1991) indicates that overall safety in the maritime industry is improving, but the human factor remains largely ignored. Despite the earlier demonstrations of the need for research to develop solutions to human factors problems, government and industry did not respond with a vigorous program. The 1991 report reiterates the need for such research-based solutions and proposes a relatively comprehensive approach. The basis of the research program would be a functional analysis of shipboard operations, development of a task-based tool for manning decisions, development of user-centered automation to ensure proper operation, and implementation of watch assignments that would reduce fatigue.

### 4.2.1 Shipboard Operations

Research into shipboard operations has focused almost exclusively on the physical tasks performed by the crew, such as cargo loading and unloading, record keeping, equipment maintenance, and navigation. However, as previous research has shown, cognitive factors are often implicated in groundings and collisions. For example, inattention during a watch or the improper plotting of a course or position can have disastrous consequences. Similarly, operation of highly sophisticated equipment that has multiple modes (e.g., autopilot) can lead to errors due to lack of proper feedback or misinterpretation of operation. Future research in hur n factors in maritime operations will need to focus more on the cognitive tasks involved in operations such as navigation and tank loading that may lead to groundings, collisions, or pollution. The following paragraphs briefly discuss the impact of manning scales, automation, and fatigue on shipboard operations.

#### 4.2.1.1 Manning Scales

Shipboard manning is an area of developing concern with the increasing economic and technological pressure to reduce crew size; however, relatively little information is available with which to make decisions. Over the past 30 years, crew sizes have decreased from the mid 40s to the low 20s on American ships, and are substantially smaller on some modern foreign vessels.

Table 4.1 illustrates the manning levels for typical American, German and Japanese ships. The primary areas where American ships differ from the foreign counterparts are in the assignment of unlicensed deck and engine room personnel, and in junior-level licensed positions in the deck and engineering departments. In all these areas, the radio officer function will likely be assumed by another crew member, since communications equipment now requires relatively little training. The training requirements for the licensed and rating level personnel are specified in 46 CFR parts 10-12.

The crew levels shown for U.S. ships are deemed necessary to meet the regulatory requirements of the three watch system. Ironically, foreign ships entering U.S. waters are required to be sufficiently manned for safe operation, but the country of certification determines watch systems and positions for the particular ship. One of the most important unresolved question in the area of manning scales has to do with emergency operations (i.e., in an "all hands" type of situation such as fire or flood, are a sufficient number of crew members available to respond effectively?). Recent analyses of several fire scenarios on U.S. tanker and cargo ships suggest that a crew size of 14 would be sufficient to handle the emergencies, although no details were given regarding the source of the data (NRC 1991). At present, the Marine Board recommends that an internationally applicable task analytic tool be developed so that manning scales can be designed on a more rational basis. It should also be pointed out that Coast Guard manning standards are designed to ensure safe navigation of the vessel, and do not account for the many other job functions performed by crew members when not on watch (USCG 1989b).

#### 4.2.1.2 Automation

One of the driving factors in manning scale reduction has been the introduction of automation over the past 35 years. Goldenschuh (1991) provides a summary of manning reductions related to automation introduced since the 1950s; it is clear from his discussion that the staff reductions are related principally to the reduced need for engine room personnel, because of the development of technologies such as self-regulating steam boilers, fully automated boilers with pilothouse controls, and the replacement of steam

TABLE 4.1. Manning Scales for United States, Federal Republic of Germany, and Japan (NRC 1991)

| | German "Ship of the Future Design" Early 1980s | | |
|---|---|---|---|
| | Federal Republic of Germany | United States | Japanese "Pioneer" Ship Design Late 1980s |
| Master | 1 | 1 | 1 |
| Chief Mate | 1 | 1 | |
| 2nd Mate | 1 | 1 | |
| 3rd Mate | | 1 | |
| Unlicensed deck personnel | | 6 | |
| Chief Engineer | 1 | 1 | 1 |
| 1st Asst. Eng. | 1 | 1 | |
| 2nd Asst. Eng. | | 1 | |
| 3rd Asst. Eng. | | 1 | |
| Electrician | 1 | | |
| Boatswain | 1 | | |
| Unlicensed eng. personnel | | 3 | |
| Maintenance personnel | | | |
| General purpose crew | 4 | | 4 |
| Dual-licensed officer | | | 4 |
| Stewards/catering personnel | 2 | 3 | 1 |
| Radio officer | 1 | 1 | |
| TOTAL | 14 | 21 | 11 |

propulsion with diesel. Deck department reductions have been achieved principally through the introduction of maintenance personnel (Qualified Members of the Engineering Department (QMEDs).

These advances in engine room automation have reduced the number of personnel necessary to physically monitor and operate ship propulsion equipment. However, there appears to have been a corresponding increase in the number of monitoring activities and the number of potential decisions required by deck officers. This is in addition to an increased mental workload resulting from new navigation electronics, automated steering systems, and collision avoidance radar. Additional automation that is specific to tankers includes such systems as centralized pumprooms and cargo loading computers. These systems are typically the responsibility of licensed deck officers. Thus, while the actual number of personnel may be reduced, it appears that the technological changes over the years have actually increased the mental workload of deck officers.

One potential implication of the engine department staff reductions is that the increase in automated systems will overload the deck officers, whose numbers have remained constant. A number of interview respondents have reported that there is little training associated with the introduction of automation. Similarly, in situations where a reduced engineering staff leads to more frequent monitoring of propulsion system data by deck officers, potential anomalies may be undetected or misinterpreted. This can be especially important during emergency operations, where the deck officers take charge of response teams.

#### 4.2.1.3 Fatigue

While the aforementioned increase in mental workload for deck officers applies to ships in general, the implications are perhaps more important for tankers. This is because the deck officers are responsible for cargo operations, which is a protracted task. As described in the National Transportation Safety Board (NTSB) analysis of the Exxon Valdez accident, there were no deck officers available for departure that were considered fully rested, because of the activities they were engaged in during port operations. Fatigue is a commonly reported problem among mariners, that can lead to degraded performance.

The recent introduction of the work hour limitations of the Oil Pollution Act of 1990 (OPA 1990) for tankship personnel should have a positive effect on this situation, by generally limiting to 12 hours (as implemented by the shipping companies) the time worked during any 24-hour period. However, work hour limitations do not apply during emergency operations, with the potential for acute fatigue to develop. This must be a consideration when evaluating potential self-help countermeasures, since the complexity and riskiness of the technology may be exacerbated by a fatigued operator. For example, many boom systems require the launching of a work boat over the side of the vessel to emplace and connect boom segments. This strenuous and dangerous activity can be much more dangerous if performed by a fatigued crew, and could lead to personnel injury or fatality.

## 4.3 HUMAN FACTORS AND SAFETY IN TANKER AND TUG/BARGE OPERATIONS

While a respectable amount of human factors literature describes general shipboard operations, and by implication a portion of tanker and barge operations, there have been very few human factors studies specifically directed at tanker safety. This is reflected in the more general lack of published descriptions of tanker and barge operations. It appears that many of the operational practices aboard ships are grounded in experience that is passed along to new crew members who are trained in individual company and ship procedures. The discussion that follows is based both on the few published sources available and interviews.

### 4.3.1 Tanker Manning Scales

The manning scales for tanker ships are similar to those previously discussed and illustrated in Table 4.1. On a tanker, it is a requirement that a certain number of crew members (specified on the vessel's certificate of inspection) have additional training as tankermen, as specified in 46 CFR part 12.10, although by virtue of having a master or mate certified for vessels over 200 tons, ships are exempted from this requirement. Thus, the tankerman training requirement applies to barges, in practice. No additional certifications are required for officer licensing beyond the 1600 GT level. As a recent study by the Tanker Safety Study Group (USCG 1989b) points out, it is no longer the case that a master of a coastal tanker is qualified to command a liquid natural gas (LNG) or ultra-large crude carrier (ULCC) ship. Thus, the current licensing system "does not reflect the qualifications of the individual holding the license." The shipping industry has taken responsibility for ensuring that the crew is qualified for their positions.

Tanker size has little impact on the crew size of U.S. ships. The tankers observed for this study were 70,000 DWT and 810 feet long, and maintained a crew of 24 (2 more steward department personnel than typical); this crew size may be the same or smaller on more modern larger ships, since newer ships can be certified for unattended engine room operation, and would have more modern cooking facilities.

Discussions with the various interviewees indicated that they did not anticipate any reductions in manning scales for their ships in the near future. The largest crew size observed was the one mentioned above--24 (Company A); the other two oil shipping companies maintained crew sizes of 19--25 (Company B and C), depending on ship design, trade location, and trading pattern. Company C had recently added three crew members (an able-bodied seaman, engineer, and steward) to reach the crew size of 19; this recent addition of crew members was done in order to meet the requirements of OPA 1990 stating that no crew member shall work more than 15 hours within a 24-hour period, or 36 hours within a 72-hour period. Company A maintains a maximum 12-hour day for all personnel in order to accommodate the OPA 1990 requirement.

The Tanker Safety Study Group (USCG 1989b) discussed some of the problems with current manning practices based on the changing task demands of navigation and cargo operations. For example, a two-man bridge team (watch officer and helmsman) may be sufficient for open sea sailing, but may be quickly overloaded by information in areas where a pilot is not required. Such information would include small craft traffic, vessel traffic system

(VTS) communications, radar tracking, and maintaining a navigational fix. Transitions from information underload to overload particularly can lead to errors.

### 4.3.2 Tug/Barge Manning Scales

The manning scales applied to tugs are much more complex than those applied to tankers. As mentioned above, the crew size of a tanker depends more on automation than size. This is not the case with tug boats. The Coast Guard Marine Safety Manual delineates three principal types of vessels that may be engaged in transporting oil via barge: Inspected Tugs and Dual-Mode Integrated Tug-Barges, Inspected Push-Mode Integrated Tug-Barges, and Uninspected Tugs and Integrated Tug-Barges.

For the size of barge being considered in this study, the uninspected tugs are the most relevant. Typical manning for an oceangoing vessel includes a captain, a mate, an engineer, two able-bodied seamen, a cook, and a tankerman.

Smaller tugs for coastal runs use a combined deckhand/engineer and deckhand/cook, plus captain, mate, and tankerman. Of those interviewed, the minimum crew size used on the tugs is four persons, with a tankerman who travels by land or air between load and offload points. Additional modifications to crew size may occur on the basis of voyage length (i.e., less than or greater than 600 miles).

### 4.3.3 Normal Cargo Operations for Tankers

Normal cargo operations on a crude oil tanker fall into three functional categories: 1) loading, 2) discharging, and 3) tank cleaning. Most tanker spills occur during loading (Hayler 1989). In general, normal cargo operations are among the most crew intensive activities, because of the requirement for rapid turn-around times in port and because of crew structures that lead to crew shortages during round-the-clock cargo operations. The cycle of normal operations for a tanker is shown in Figure 4.2 (USCG 1989a).

A self-help measure that would reduce spillage from normal cargo operations is a pump and piping system designed to remove spills from the afterdeck of the ship. Current Coast Guard regulations require a barrier on the aft end

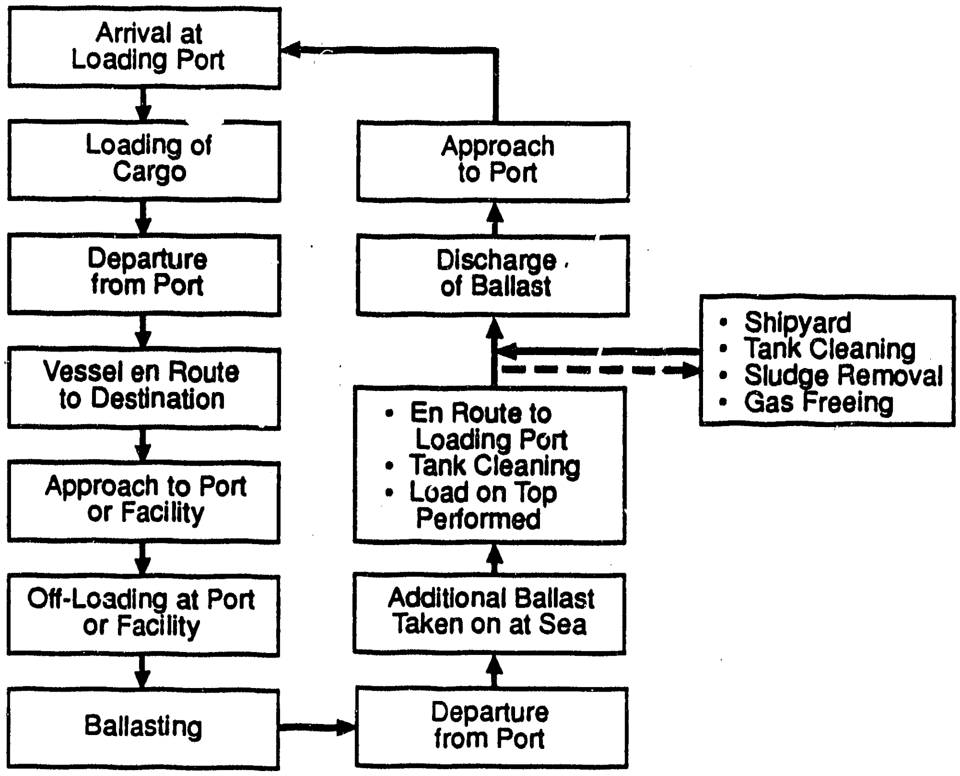


FIGURE 4.2. Flow Diagram of Normal Operations of an Oil Tanker (USCG 1989a)

of the ship to contain spillage, but these are easily breached, and a great deal of time is required to pump the oil from the deck to slop tanks. One captain suggested a retrofit system involving a below-deck piping arrangement that would be relatively low-cost.

#### 4.3.4 Normal Cargo Operations for Tug/Barges

As with normal tanker operations, cargo activities for tug/barges involve the activities of loading and discharging. After the barge is secured to the terminal by the tug crew, the tankerman lines up the barge manifolds with the refinery header, ensuring that a proper fit is achieved. Improper fitting of these couplings is the single largest cause of spills. A filling sequence is established by the tankerman (this is much less complex than for tank ships, which use computers), and communication is established between the tank barge and pump operators. Communication is critical because the flow must be reduced and then stopped as the cargo reaches the top of the tanks.

During the filling procedure, the tankerman monitors the tank filling, and as the tanks approach their capacity, he opens relief valves to bleed pressure.

### 4.3.5 Emergency Operations and Pollution Control for Tankers

The conditions under which self-help measures would be employed (i.e., groundings and collisions) would result in the mobilization of emergency operating procedures aboard ships. One of the primary issues investigated in the interviews was the nature of these emergency operations, and the potential availability of crew for the operation of self-help measures.

According to long-held tradition in the maritime industry, the master of the vessel responds in an emergency according to three priorities: 1) saving human life, 2) saving the ship, and 3) saving the cargo, or in the case of tankers, pollution control (Hayler 1989). These priorities dictate the actions taken by vessel captains in emergency circumstances. Any procedure or regulation that interferes with these priorities is likely to result in "selective compliance."

The literature review revealed virtually no information concerning the functions and tasks of crew members during emergency operations on <u>any</u> ship, including tankers. Further, discussions with industry personnel stress that most of the training and drilling focuses on <u>prevention</u> of accidents and pollution, rather than response to pollution as a result of an accident. Therefore, the interviews focused on investigating the damage control actions and limited salvage activities taken by tanker crews in the event of an accident. This took the form of discussing the general functions performed by each of the crew members, developing a function and task list, and reviewing the station bills of crew members during an emergency.

The main steps in emergency response for tanker accidents are shown in Figure 4.3. Specific crew activities and the crew members performing emergency response tasks are shown in Table 4.2. This Table identifies major functional areas of tanker emergency response, component tasks to accomplish those functions, and the crew members likely to be performing those functions. As outlined in Figure 4.3, initially the crew is mustered into damage control teams at designated locations (e.g., the damage control lockers). There are

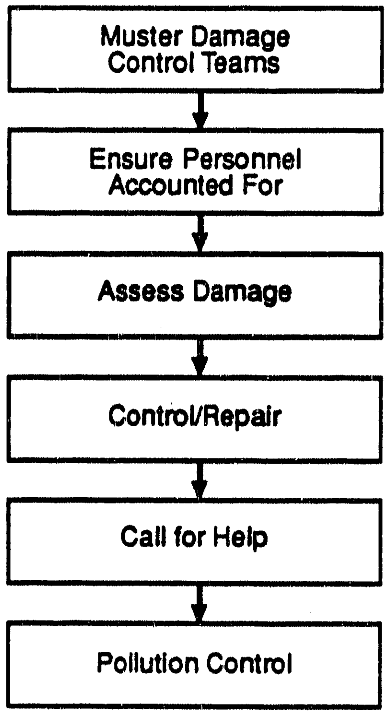


FIGURE 4.3. Stages of Emergency Response for Tanker Accidents

variations in the number and composition of teams from one company to the next. Some are organized into port and starboard teams, with deck, engineering, and rating personnel on each team. Others are organized into similarly composed primary, secondary, and tertiary teams. Finally, another company is organized into a seamanship/deck team composed of members of the deck department, a technical team composed of members of the engineering department, and a health and welfare support team with multiple specialties. In this latter organization, cross training of the crew members for each of the teams is done.

The next step shown in Figure 4.3 (i.e., assessment of damage) involves personnel from both the engineering and deck departments. The master of the ship will be on the bridge, usually with another licensed officer (e.g., the third mate). On most ships, the chief engineer and an assistant will be stationed in the engine room. Damage assessment may involve an on-site evaluation of the problem, in which case the chief mate, assisted by engineering

TABLE 4.2. Functional Analysis of Crew Activities During Tanker Emergency Operations

| | Personnel | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Deck Department | | | | Engine Department | | | | |
| Emergency Operations | Master | Chief Mate | 2nd Mate | 3rd Mate | AB(x6) | Chief Engineer | 1st Asst. | 2nd Asst. | 3rd Asst. | Unlicensed (x3) |
| Assessment & Control | | | | | | | | | | |
| Decision-making/bridge | X | | | X | | | | | | |
| Engine room | | | | | | X | | | X | |
| Onsite damage evaluation | | X | X | | X | | X | X | | X |
| Ballast shifting | | X | | | | | | | | |
| Soundings | | | | | X | | | | | |
| Communication | | | | | | | | | | |
| Radio | X | X | | | | | | | | |
| Hard line | | X | | | X | | | | | |
| Walkie talkie | | X | | | X | | | | | |
| Messenger network | | X | | | X | | | | | |
| Equipment Movement & Control | | | | | | | | | | |
| Electrical | | X | | | X | | X | | | X |
| Physical | | | | | | | X | | | X |
| Fire Control | | | | | | | | | | |
| Isolate electrical | | X | | | X | | X | | | X |
| Isolate steam/hydraulic | | X | | | X | | X | | | X |
| Ensure water lines intact | | X | | | X | | X | | | X |
| Ensure pumps operational | | X | | | X | | X | | | X |
| Ensure firemain & bilge lines intact | | X | | | X | | X | | | X |
| Pollution Control | | | | | | | | | | |
| Tank pumpout to alternate tank | | X | | | X | | | | | |
| Stress measurements | | X | | | | | | | | |

personnel and seamen, would physically move to the site to observe it. It should be noted that since tankers are essentially sealed containers, any damage below decks would need to be inferred from indicators in the pumproom. Additional "executive" activities involved in damage assessment and control include specifying the equipment needed for repair, supervising repair/salvage, and shifting ballast to alleviate stress on the vessel. It may also be necessary to take soundings to verify depth.

Additional functions shown in Table 4.2 include communications by various means, which will depend on personnel location and the power situation. The movement and operation of equipment for repair/salvage will involve both deck and engineering personnel. In the domain of fire control (really a subfunction of damage assessment and control, but sufficiently important to classify on its own), both deck and engineering licensed and rating personnel are involved. The entire cycle of emergency response operations depicted in Figure 4.3 is estimated to require approximately 25 minutes, possibly less depending on damage severity and environmental conditions. This estimate is based on the timeline of the Exxon Valdez accident, in which the grounding occurred shortly after midnight, and by 12:30 a.m., the chief mate had assessed the damage and made initial stability calculations. Although a general alarm mustering of the crew was not initiated in this accident, that would likely be the step accomplished most quickly, if the Exxon Valdez crew followed the procedure outlined in Figure 4.3.

In the area of pollution control, the principal activity performed by the crew is to pump oil from a damaged tank to an alternate tank, if one is available, and to prepare for the emergency transfer of cargo to another vessel. All three oil shipping companies interviewed carry onboard response equipment for the cleanup of small deck spills, and one company carries oil sorbent disposable booms to be used in the event of a small spill alongside the ship, presumably in port. The description of the operation of these booms is that they are to be lowered over the side, supported at each end, and agitated in any oil lying alongside the ship. They would then be brought back aboard and stowed in drums for subsequent disposal ashore. Since this type of operation is intended to be done from the ship, such a technology and its crew requirements may be extended to larger spills resulting from groundings and collisions.

One of the companies interviewed provided a copy of its contingency plan for oil spills. The following action list describes what the master must do:

1. ensure that steps are taken to minimize the oil spill, including
   - confirming that the ship is stable and not in danger of foundering
   - segregating the source of the oil spill from the remainder of the oil on board
2. notify the local government
3. notify the Fleet Manager
4. contain as much of the spill on board as possible.

The oil shipping industries have recently provided responses to the Coast Guard in response to an Advance Notice of Proposed Rulemaking under 33 CFR Part 155, covering Vessel Response Plans and Carriage and Inspection of Discharge-Removal Equipment. The interviews with oil company personnel indicated a uniform opinion that ship crews not be required to carry out any actions other than controlling or stopping the discharge and reporting the incident. It is believed that existing countermeasure technologies would be largely ineffective and potentially unsafe if the ship crew were required to use them. However, it was clear from the interviews that if properly engineered technologies were available crews would be available to operate the technologies if they could be used from the ship. The interview with a current tanker master also indicated an availability of crew. This conclusion can be reached by reviewing the manning structure for emergency operations depicted in Table 4.2. Even with three emergency teams of 3 persons each with the master on the bridge with a helmsman (11 total), there would be 10 crew members available to perform some function. It was also stated by one of the respondents that while his company felt that the crew should not be involved in spill containment/mitigation, that more time could be spent training the crew in damage control (i.e., problem identification and mitigation). This latter suggestion was also contained in a Coast Guard study (1989a) entitled

"Development and Assessment of Measures to Reduce Accidental Oil Outflow From Tank Ships," and was described as an initial step toward requiring onboard response equipment.

The foregoing analysis of emergency response crew structure was based on a current standard crew size of 21 persons. The reduced manning scales shown in Table 4.1 (i.e., 14 and 11) would be less likely to result in available personnel to operate pollution control equipment. The scale of 14 crew members would result in 3 available persons, assuming current damage control team structures were used. However, the manning scale of 11 used by the Japanese offers no spare manpower for pollution control or other unforeseen emergency response requirements.

#### 4.3.6 Emergency Response and Pollution Prevention for Tug/Barges

As in the case of tankers, the primary emphasis in training for tug crews is pollution prevention. However, unlike tankers, the tugs employed by the companies interviewed in the Northwest carry pollution abatement packages. These packages are not a response to regulation, but instead the result of increasing public and industry concern about pollution. Additionally, because tug boats are more maneuverable and closer to the water, it is generally more feasible to use self-help oil spill countermeasures. While there are a variety of shore-based cleanup cooperatives that can be mobilized depending on the spill size, it was unnecessary to investigate these in the context of the current work, since the towing companies are implementing self-help measures.

The pollution abatement equipment is generally carried in a container stored on the barge. A generic list of equipment includes a containment boom, oil sorbents, oil skimmers, pumps and hoses, and hand tool kits. Work boats are carried on the tug, or as part of the containerized package on the barge. Training in the use of the pollution abatement equipment is provided on a semi-annual basis.

The operational sequence of activities in the event of a spill from a barge is similar to that of a tanker spill, with the addition of deploying pollution control measures. The following sequence is from one of the towing companies interviewed:

1. evaluate any potential safety risks
2. establish safety zone and level of personal protection equipment
3. stop source of spill, if possible
4. shut down and isolate operations
5. notify Coast Guard, state, and company response teams
6. initiate containment and recovery procedures.

The personnel involved in this type of response will be virtually everyone on the tugboat. The captain stays on the tug, with an engineer, to maintain a command center and maneuver as necessary. Two or more deckhands board the barge and open the container of pollution control equipment. Details of equipment deployment depend on the nature of the spill.

Two persons, preferably three, are the minimum crew required for deployment of the self-help measures. One crew member lifts and manipulates equipment, while another operates the workboat. Since the smallest crew size for a tug reported in this study was five persons, it appears that tugs are adequately manned for deploying self-help oil spill countermeasures.

## 4.4 CONCLUSIONS OF HUMAN FACTORS ANALYSIS

The human factors analysis of the proposed countermeasures was conducted by a human factors engineering expert familiar with crew structures and functions aboard tankers and tugs. The analysis was guided by existing maritime industry human factors guidelines and standards. The conclusions are presented here. Specific details of the analysis are given in Appendix B. (Table 3.1 in Section 3.0 contains the classification number, classification and comments for each countermeasure.)

The Coast Guard provided descriptions of 45 self-help oil spill countermeasures. Of these, 37 were reviewed for potential applicability. The remaining 8 were not classified into any particular category because of lack of detail. The 37 countermeasures reviewed from the human factors standpoint yielded 13 with insufficient detail for evaluation (i.e., no description of how the technology operates, making a crew resource assessment impossible);

10 countermeasures required a workboat, and 14 appeared to be operable from the deck of the ship, if they required human intervention at all.

Use of a workboat for countermeasure deployment is not considered to be a problem by the tug/barge industry. This is a standard procedure that is routinely trained in existing pollution prevention and mitigation programs. It is clear that there will be limits on the utility of workboats, primarily in the form of weather. Although specific thresholds for prohibiting the deployment of workboats were not identified in the course of this work, the judgment of the tug master prevails. If the safety of the crew were to be threatened by deployment of countermeasure technologies, then the prudent course will be adopted of waiting for shore-based assistance.

There is considerable sentiment within the tank ship industry that putting crew members over the side of the ship is unacceptable in any conditions. This relates principally to the amount of freeboard that would have to be negotiated and the potential impact of weather. Additionally, launching a workboat from a tanker not equipped to do so would require rigging a boom. However, it may be feasible to establish guidelines for countermeasure deployment that take both weather and workboat storage/launching into account. For example, refitting tankers with workboats for easy deployment would cost relatively little; of course, this would increase the routine maintenance load.

Of the 14 countermeasures that appeared to be operable from the deck of the ship, two seemed to offer some immediate potential. Countermeasure No. 14 requires minimal crew training, can be activated by 2 persons (one on either side of the ship), and requires no active control, since the curtain is held in place by bottom weights. Countermeasure No. 23 involves a similar mechanism, although the boom is composed of self-inflating segments. It requires the additional crew intervention of tethering the boom to the ship, which would likely require periodic attention. With both countermeasures, there are issues of safety associated with entrapping significant quantities of oil next to the ship, both in terms of fire hazards and toxic fumes. The remaining 12 countermeasures operable from the deck represent either variants of these two technologies, or do not require much human intervention, as with hull liners.

The results of the analysis presented in this chapter suggest that self-help oil spill countermeasures are a viable technology from a human factors perspective, although further engineering is required for unobtrusive introduction aboard tanker ships. One of the principal goals of such design should be to minimize the exposure requirements of the crew, since rough weather is highly likely. Since it is unlikely that one countermeasure will encompass all situations, it would be worthwhile to consider developing a series of countermeasures that have applicability in different situations. From the standpoint of crew resources, there are personnel available to operate countermeasures, assuming that other damage assessment and control activities have been accommodated.

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## 5.0 ASSESSMENT OF TANKER SELF-HELP OIL SPILL CONTROL SYSTEMS

The objective of this effort is to review and evaluate self-help concepts for oil tankers, to eliminate or reduce their spillage following an accident.

### 5.1 APPROACH

To aid in reviewing the large number of self-help concepts proposed for oil tankers, the concepts were grouped into categories based on similar traits. During the categorizing process, concepts were reviewed to verify that they were indeed self-help concepts, and not actually tanker vessel design. Those concepts that required substantial modification to the tanker were not considered for this evaluation. The resulting self-help categories are shown in Table 5.1. (Note that each category is further divided according to whether the concept acts inside or outside the ship.)

Once categorized, a more detailed review was conducted. Since the concepts within a category were similar, they could be easily compared and evaluated against each other. During this comparison, superior features of

TABLE 5.1. Categories of Self-Help Oil Spill Concepts

| Category | Internal Equipment | External Equipment |
|---|---|---|
| Containment | None | Booms<br>Skirts |
| Bulk Treatment | Gels<br>Absorbing Material | Absorbing Material<br>Gels/Dispersants/Sinking Agents<br>Combustion<br>Bioremediation |
| Closure | Clogging/Jamming<br>Patch<br>Local Sheet<br>Liner | Patch<br>Clogging/Jamming<br>Local Sheet (Diaper) |
| Collection | Tank to Tank<br>Tank to Bladder | External to Tank<br>External to External Bladder |

concepts within a category were identified. Also identified were those concepts with features considered as possessing major engineering or safety constraints.

"Notional" concepts were created for each category by comparing concepts. These notional concepts are self-help systems thought to best represent their particular category. These notional concepts have drawn heavily from related ideas found in the literature and in the Coast Guard submissions, and they have been put together incorporating the needed and superior features, while avoiding obvious pitfalls.

Next, the notional systems were defined in enough detail to allow their evaluation. This was an important requirement for the notional systems as none of the systems encountered in the literature, nor those supplied by the Coast Guard, were sufficiently detailed for this purpose. It should be noted, however, that no claim is made that these notional systems are optimal. The intent has been to establish a baseline for further evaluation, by experts in the field, of the relative merits of one or another of the techniques described.

Finally, the ability of each of the notional systems to contain oil spills was evaluated using a computer simulation. This simulation was performed for several spill scenarios, ranging over a variety of environmental conditions. Graphs illustrating the total volume of oil released as a function of time are included in Appendix D.

The notional concept must be evaluated in a context. We define this context as the combination of three sets of data; one of which describes the ship on which equipment is mounted and its cargo (Ship Data Set); the second for the location and conditions at, and just after, the time of the casualty (casualty Scene Data Set); and the last, the information which describes the extent of the damage (Casualty Severity Data Set). Figure 5.1 illustrates how the various sub-categories within the data sets combine to form scenarios. In particular, the heavy line that traverses the chart indicates the actual combinations of conditions for which we conducted simulations. These combinations were selected so as to present cases that were both real and severe,

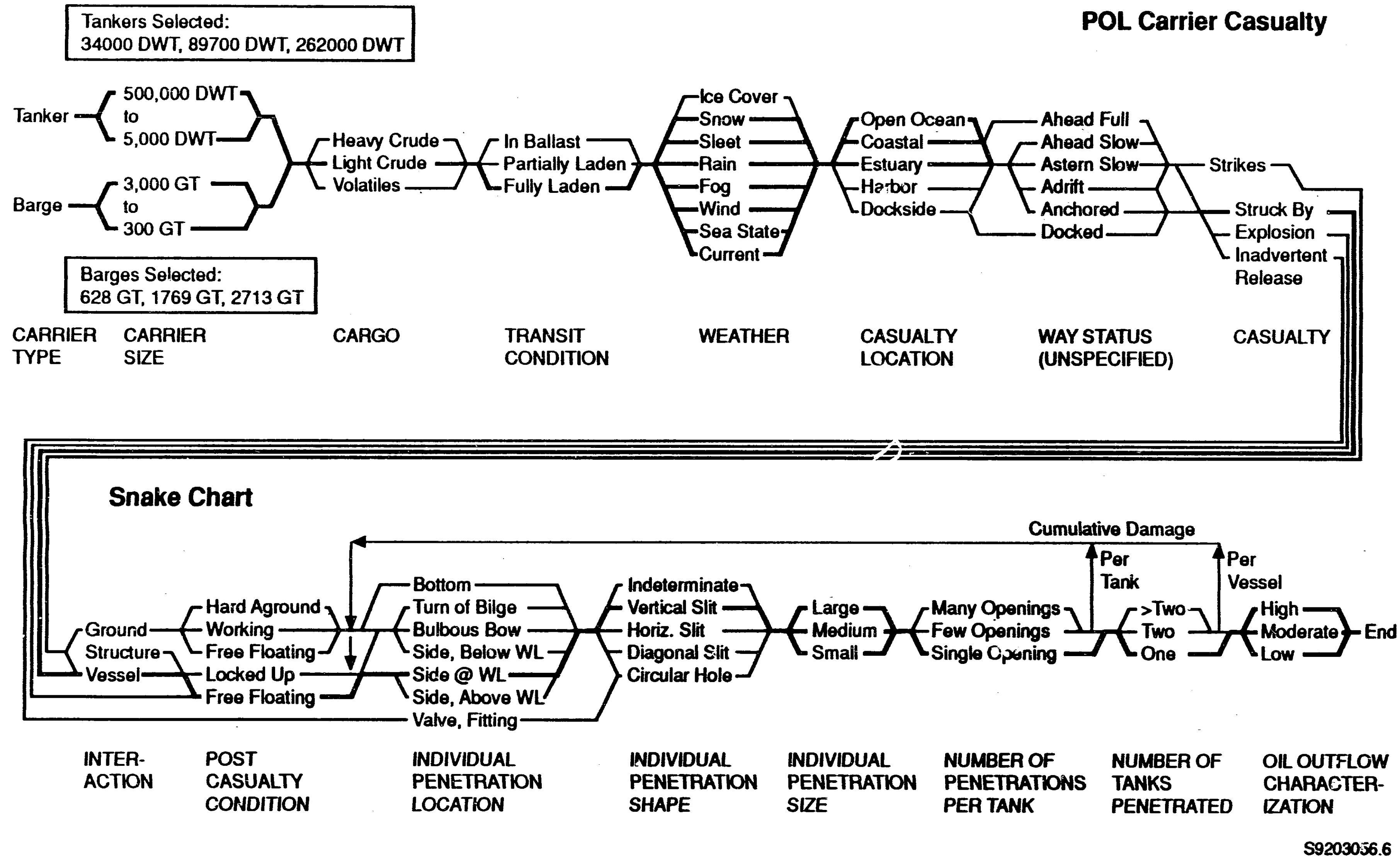


FIGURE 5.1. Various Sub-Categories to Form Scenarios

thus groudings were not studied, since a more severe case is a hole at the waterline, which has the potential for releasing all of the stored oil.

## 5.2 CONTAINMENT

In this report, "oil containment" means the equipment and/or procedures used to sequester spilled oil (or oil in danger of being spilled) in some form of enclosure, thereby preventing (or at the least, retarding) the spread of oil into the environment.

In this study, there are four main types of external containment: boom, skirt, curtain, and bladder. A description of each type is given in Table 5.2. The first three are size scaled variants of one another. These three "fence" type barriers can remain completely passive, once deployed. The fourth type (bladder) must have an auxiliary power source working to pump oil into it, and unless coupled with another containment means would only retard oil flow into the environment. The bladder has fundamental differences from the "fence" type systems, so it will be discussed separately (under the heading "pumping").

TABLE 5.2. Outboard Containment Types

| Name | Characteristics |
|---|---|
| Boom | • Essentially a line of buoyancy<br>• traps thin layer of oil: thickness < 1 ft<br>• Encloses large pond area<br>• Current/Sea State limited |
| Skirt | • Boom plus short width of pendant material<br>• Traps moderate layer of oil: 1 ft < thickness < 5 ft<br>• Encloses moderate pond area<br>• Primarily current limited |
| Curtain | • Boom plus wide pendant material<br>• Traps very deep volume of oil: 5 ft < thickness < 20 ft<br>• Pond area only slightly larger than ship platform<br>• Only moderately sensitive to current |
| Bladder | • Alternative storage reservoir(s) for oil from damaged holds |

In the following, we commonly use the term "boom" as a generic name for any of the fence-type containment systems not otherwise specified.

Oil booms have been in use for decades, but typically have been staged and deployed from shore. Since tankers congregate at ports, harbors, estuaries, and offshore loading facilities, it was natural to concentrate the pollution control equipment in contiguous areas. The question to be answered here is: does a role exist for onboard booms or similar equipment in pollution control?

Most of the oil boom systems built to date were made to address the need for containment or oil exclusion in relatively calm or protected waters that could be subjected to high currents. As a result, these systems tend to be fairly shallow draft, modular, stoutly built, meant to be anchored, and frequently deployed by hand, or by power assist from alongside work boats (with notable air dropped and other automatic deployment exceptions). Analysis, experience, and trial and error have led to designs that function reasonably well in calm conditions.

The conditions on a tanker in distress (i.e., just after a collision or grounding) that is rapidly losing oil will influence containment system design. For one, the ship itself will act as an "anchor," as far as the containment means is concerned, even if both are drifting, and so bottom interaction is neither necessary nor desired. Also, it seems impossible to guarantee that there will be ample man-power available to help with the physical deployment and securing of the gear; most or all of this part of the evolution must be done automatically and very reliably. It is also unlikely that there will be time or wherewithal to assemble modules of gear together to attack the specific casualty; the system must be preassembled, and sufficiently general in configuration and capacity to handle accidents wherever they may occur up to the design maximum size. Finally, the gear must not hamper the safe evacuation of crew from the stricken vessel, neither by requiring too much attention during and after deployment, nor by blocking free passage of life boats, nor finally by impeding rescue efforts.

### 5.2.1 Storage

The various concepts investigated for outboard containment of oil vary widely in the manner in which they store the containment equipment. Figure 5.2 provides a concise view of the options encountered.

#### 5.2.1.1 Continuous and Circumferential

Continuous and circumferential storage was the most frequently cited preferred method for storage of containment equipment. It involves completely surrounding the ship near the gunwale with a connected length of boom, skirt, or curtain. Some concepts advocated storage outboard of the deck edge, which avoids deck obstruction, but puts the containment in jeopardy during a collision. Other systems utilize deck-edge space for storage, and the efficacy of this approach is not established, given the need for clear passage of people and equipment over the side.

#### 5.2.1.2 Multiple Equipment Caches

Some of the literature researched advocated multiple equipment caches. With caches, the deployment is heavily dominated by manual activities. On larger ships, the amount of boom that must be handled is substantial, and dividing the boom into 10 boxes means no box need be over about 10 $ft^3$. This method allows for free passage of equipment and personnel over the side. This may be a cost-effective way of handling small spills in stable, protected conditions; however, for spills of considerable magnitude, the need for considerable manned interaction limits the effectiveness of this storage method.

#### 5.2.1.3 Single-Point Storage Locker

The single locker described in some concepts was usually located at the stern, either on the fantail, or in a special purpose hold below the main deck; (some concepts deployed two booms from the same general location at the stern, to port and starboard). In either case, long lengths of boom must be pulled from one location, so some form of mechanical power augmentation was necessary. This was frequently in the form of an auxiliary boat, or by means of a tugger cable led along the gunwale from a winch at the bow.

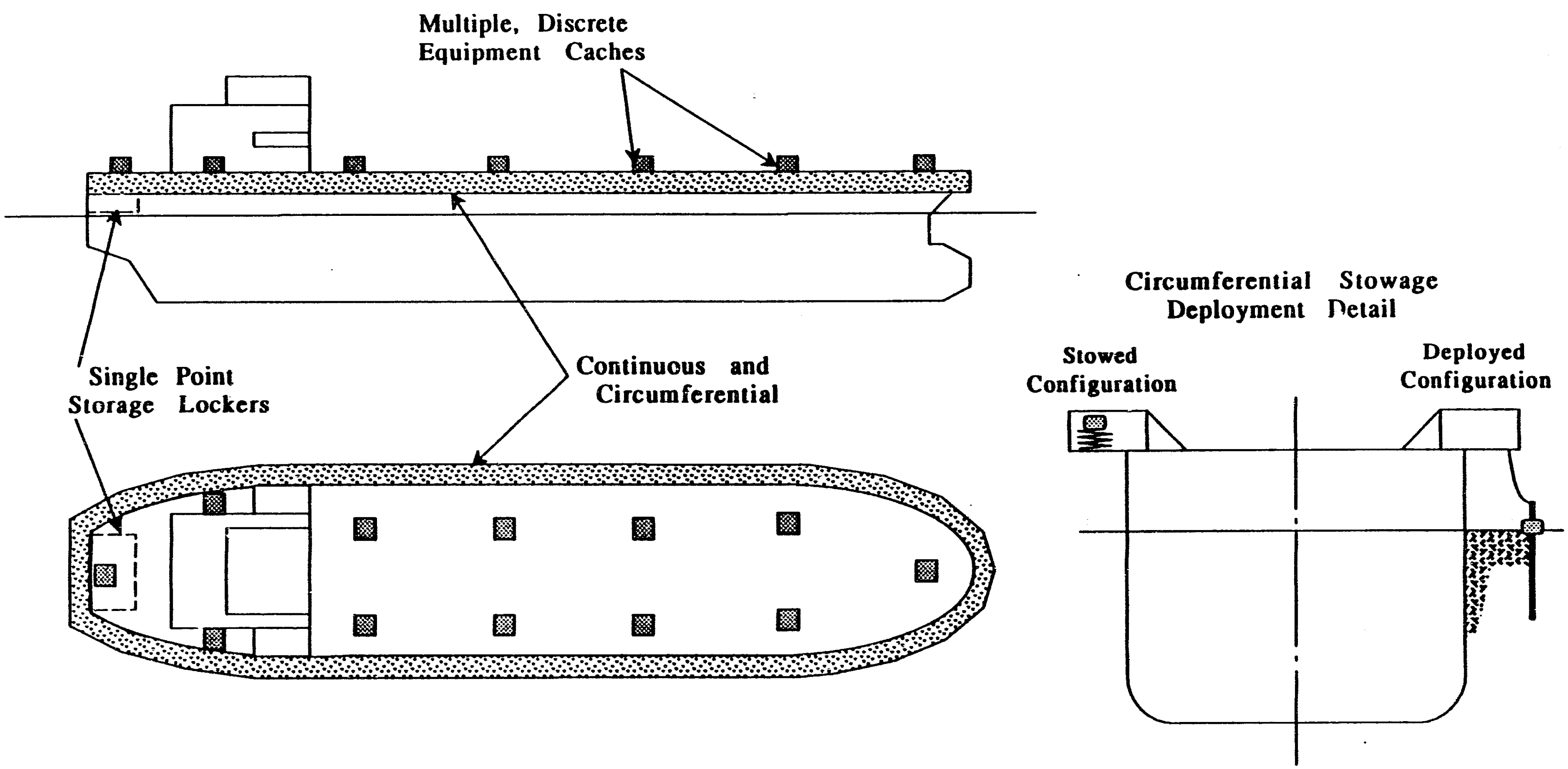


FIGURE 5.2. Containment Storage Options

5.2.2 Deployment

Although the mode of storage will have logistical and operational implications, deployment has the potential to cause the most problems. Figure 5.3 shows the most commonly proposed methods in schematic form.

5.2.2.1 Gravity

In the gravity deployment methods, the containment is stored either overhanging the gunwale, fastened to the hull outboard of the gunwale, or slightly inboard on a downwardly slanting platform, so that when some form of trigger is actuated, the boom-retaining means is released, and the equipment falls free to the ocean surface. The general idea is attractive for a number of reasons: first, a single conscious decision by a responsible member of the crew can set in motion the most difficult part of containing spilled oil; second, the actuation means (gravity) is always present and cannot deteriorate; and third, deployment goes to completion without human intervention. On the other hand, some issues need to be researched and refined such as the difficulty of simultaneous deployment all around the ship; the problem of tumbling, fouling, and tearing of the containment means during descent along the side of the ship; a reliable way to handle embedded slack; and a method for freeing hang-ups.

5.2.2.2 Propelled

Propelled systems are similar to gravity systems, except that the containment means is forcibly pushed away from the side of the ship, so that the system hits the water at a distance from the side of the ship, closer to its final configuration. The presumed advantage of this approach is that oil that has begun to leak will more likely be captured by a widely flung net than one dropped along side. The mechanisms presented seem to be relatively far fetched (e.g., cannon balls attached at intervals along the boom, fired simultaneously). A fast-acting gravity system, with even moderate depth should capture most of the initial outflow of oil, whose pressure should push it slowly away from ship side. It may prove useful to ensure that a modest clearance distance is maintained, primarily as a way of regularizing the

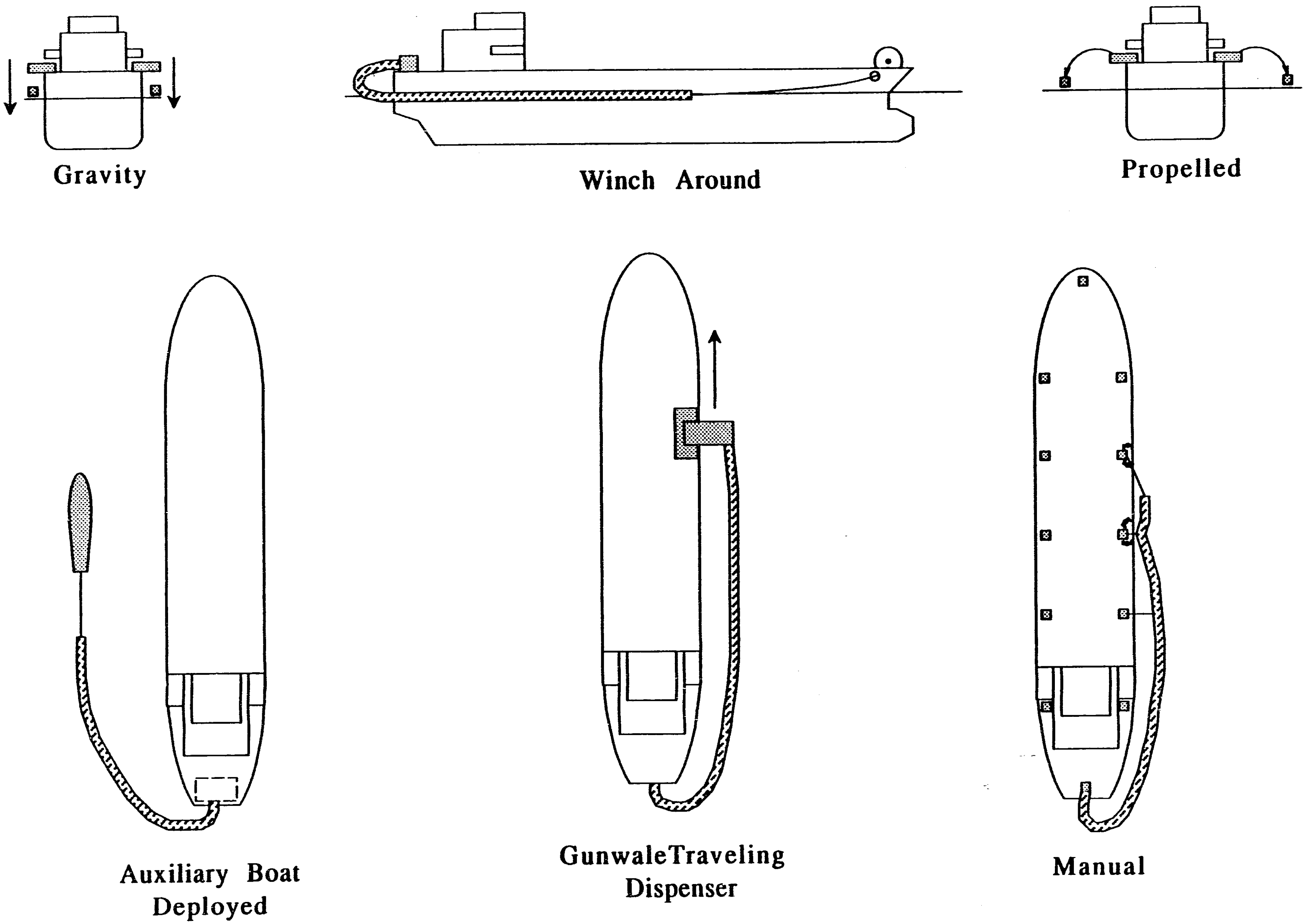


FIGURE 5.3. Containment Deployment Options

deployment, avoiding unpredictable interaction with the hull on descent, and avoiding the worst of the existing oil jet.

5.2.2.3 <u>Winch-around</u>

In the winch-around concept, a leader wire is permanently installed just outboard each gunwale and retained in breakaway clips. When triggered, two winches mounted in the bow pull the port and starboard wires forward along the ship, breaking free of the clips as they go. The aft end of each wire is attached to the forward end of a containment boom, stored in a protected bin in the fantail area. A variation of this method could include paravanes at the leading end of the containment boom, to tend it out from the hull. Deployment seems to rely too heavily on tenuous features. For example, a boom pulled along the length of the tanker for such a long deployment would put the containment in danger of tumbling, fouling, tangling, or tearing, so that once established around the tanker, it might not be rigged out properly. The general idea of collecting all of the containment gear in one protected place is attractive, but the deployment schemes reviewed to date are not thoroughly convincing.

5.2.2.4 <u>Auxiliary Boat</u>

A number of concepts utilize small boats, lowered from the deck of the tanker, to actually deploy the containment. A variant would provide a small boat with a cargo of containment boom so that the bitter end may be fixed to the tanker, and the small boat pays it out as it goes, thus avoiding the problems associated with dragging the boom. Modular lengths could be loaded out on each boat, such that, for example, two boats would provide a tight containment for small leaks, and four or six would be used to enclose large spills. This technique is probably the closest to existing boom deployment methods, and so has the advantage of prior experience. On the other hand, deploying auxiliary boats will be difficult at best in heavy seas and high winds. Also, dragging a boom 360$^{\circ}$ around a large tanker without causing damage will be nearly impossible to guarantee; accordingly, either two lengths (port and starboard) and two boats, or two excursions with a link up will be needed as a minimum. The most serious concerns with using these boats are the high level of crew involvement required and the time required for deployment.

#### 5.2.2.5 Traveling Dispenser

A variant of the winch-around and auxiliary boat deployment concepts involves the movement of a container holding the boom around the periphery of the ship at (or just outboard of) the deck edge, that pays out the boom as it moves. For the larger super tankers this would be a sizable container (on the order of a 24 $ft^3$), although it could be split into two units, port and starboard. Mechanization of such a system to move along an at-side track is certainly possible, but cumbersome, and problems of interference with the ship's routine and logistics would have to be worked out. Such a system seems to offer few advantages over the winch-around concept.

#### 5.2.2.6 Manual

A few deployment concepts relied on crew members to handle, couple, and deploy the containment gear. Members of the crew would unload, connect, and deploy segments of containment over the side from discrete lockers arranged along the deck just inboard of the gunwale. Most manual methods use some kind of power assist, such as air tugger winches, but still require men doing the actual work. A problem with manual deployment is that an accident may place the lives of the crew in immediate danger (e.g., a fire), where such lengthy boom deployment procedures would simply be out of the question. Similarly, heavy seas, high winds, precipitation, fog, or other weather conditions, which might well have been proximate causes of the accident, could make a largely manual deployment nearly impossible, or slow it sufficiently as to render it ineffective. Therefore, such a labor-intensive method will not be a general deployment solution.

### 5.2.3 Operation

The containment systems reviewed are essentially passive devices, acting only to corral the spilled oil, but most also allow for additional remediation, such as skimming or pumping of the oil out of the impoundment area. Some concepts gave considerable attention to tending the boom once installed so that it remained located properly with respect to the tanker. This was accomplished usually by a network of tether lines running from the ship to locations along the length of the boom. Some even brought lines back to the ship from the keel of the boom to help maintain the proper shape of the underwater portion of the skirt or curtain against the disruptive forces of current. Those systems installed in segments usually provided accommodation for boat passage by means of opening and re-sealing the containment, but most descriptions did not include this important point. In most cases, the concepts were acknowledged to be temporary, useful until more rugged and permanent containment can be deployed from a land-based depot. None described the process of replacing their temporary containment with a more permanent system.

### 5.2.4 Recovery

Almost all concepts reviewed either did not mention salvage and recovery of the boom or expected that the system would be recovered, cleaned, and reused. None expected their system to be expendable. Only one concept (for an existing boom) was complete enough to include details on reel-up, cleaning, and refurbishment. Expendable systems may be cost effective, especially considering that these systems may not be as rugged as a land-based system. A life-cycle cost analysis could show that a less rugged, disposable system is cheaper in the long run than the cost of designing one to withstand rough handling and refurbishment, plus the costs of returning it to service. This option merits further exploration.

### 5.2.5 Size Optimization Analysis

In order to gain some insight into the possible optimal configurations, volumes, and lengths of containment booms, skirts, and curtains, we conducted a parametric analysis of the variation of the shape, circumference, and total volume of these various containment configurations as a function of ship and oil spill size. This analysis is first order only, and involves a number of assumptions, detailed below. It does not purport to be definitive, but merely gives some idea of trends and order of magnitude sizes. Ship sizes examined were: 628; 1,182; and 2,113 GT coastal barges; and 34,000; 89,700; and 262,000 DWT tankers. In each case, it was assumed that the "design spill" (i.e., the amount to be contained) was represented by the total loss of all oil in the two largest tanks on the vessel. The general configuration of the containment was uniform throughout, and as follows: each is fitted with a buoyancy float of 4-$ft^2$ cross-sectional area, a below water skirt of depth

130% of the still water depth of the trapped oil, and an above water height of 130% of the height of the oil above the sea surface. The thickness of the skirt was taken as 3-inches, partly to account for packing inefficiency. A computer program then figured out the volume, perimeter, and depth of the containment needed to satisfy all conditions.

An interesting result is that, even though the oil spill volume varies by a factor of over 50:1 (from about 20,000 $ft^3$ on the coastal barge to almost 1,000,000 $ft^3$ on the DWT tanker), the volume of containment varies only by a factor of 7. The boom cross section (stowed) is close to 5 $ft^2$ in all cases. Clearly, this is a very readily manageable unit volume, even at double this value. This optimization routine is imbedded in the simulation, which is described later.

5.2.6 Containment Notional Concept Description

A containment system must be designed to handle a variety of spills in a variety of environments. Figure 5.4 shows our notional concept for the containment system to be evaluated in the barge simulation. Figure 5.5 shows our notional concept for the containment system to be evaluated in the tanker simulation.

Table 5.3 is an attribute comparison chart that enumerates the various features found in the containment concepts reviewed, and briefly states their advantages and disadvantages, and whether they have been included in the notional concept.

In summary, the containment scheme modeled consists of a completely circumferential "fence" (i.e., medium depth skirt) barrier that will be stored in a protective housing just inboard of the gunwale, using gravity for the primary motive deployment force. A boom, each to port and starboard, helps to keep the deployed system away from contact with the hull, at least in the forward area. This general description applies to both tanker and barge, but the barge also would utilize a riser curtain from the waterline to the gunwale in an attempt to trap more outflowing oil. While such a system would work best on a single barge, rafts of barges could still be protected by a similar system where the curtain on each barge would be segmented, and all

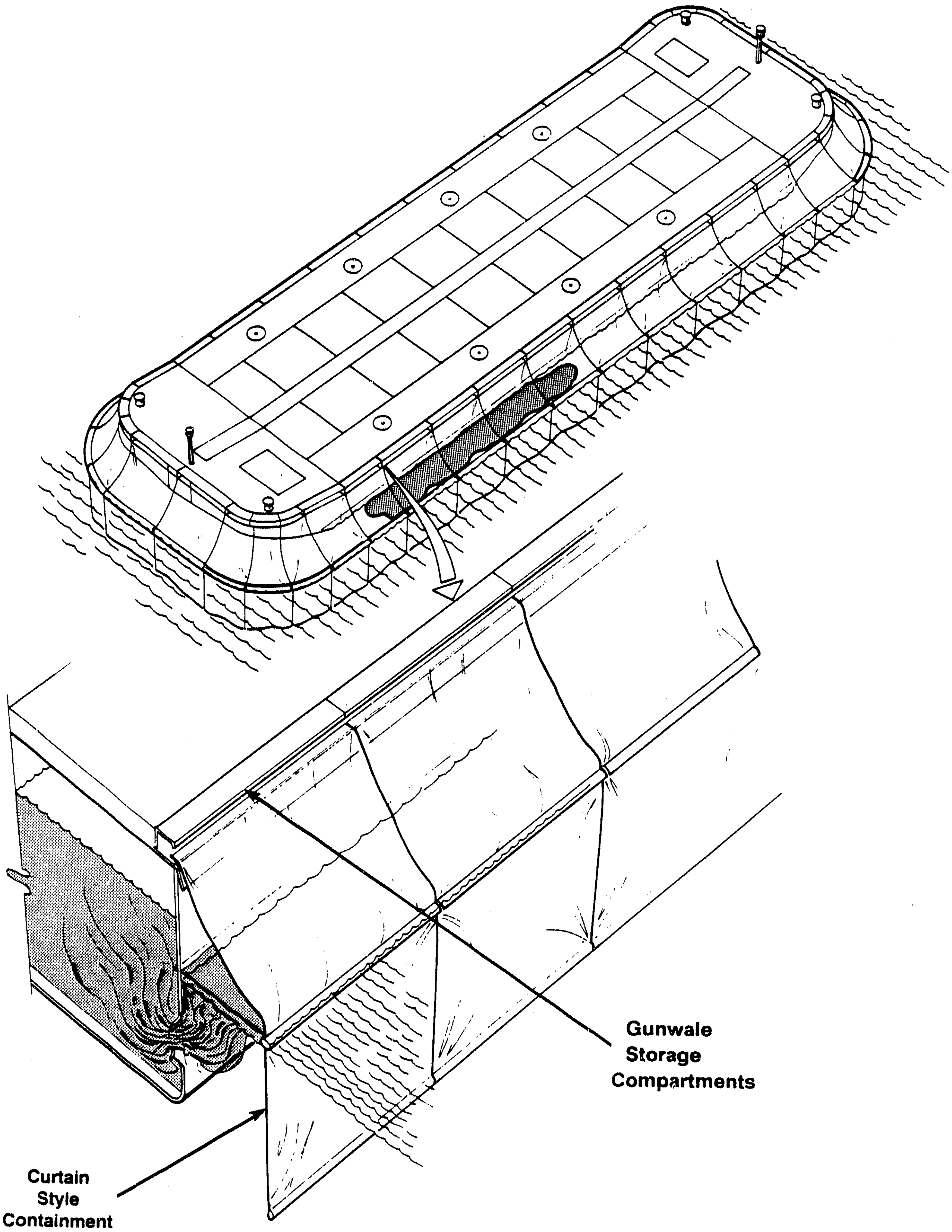


FIGURE 5.4. Barge Containment Notional Concept

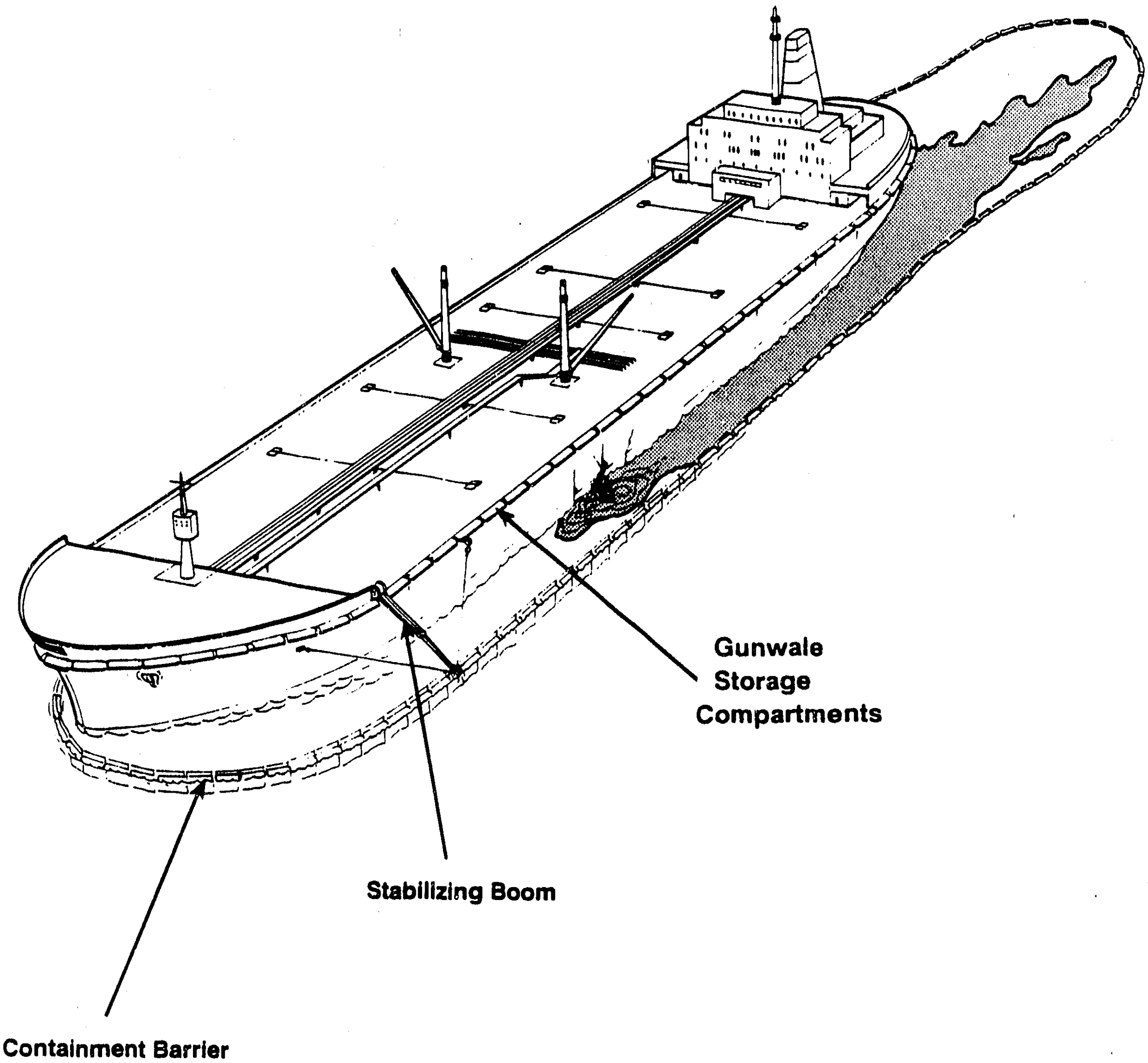


FIGURE 5.5. Containment Notional Concept

of the outboard segments ranged along the gunwales of each barge would be coupled together forming a closed periphery around the raft.

## 5.3 BULK TREATMENT

Bulk treatment of oil is here-in defined as all those methods of responding to an oil spill that mitigate the impacts through the immobilization, dispersal, or compositional change of the oil. Several methods of bulk

## TABLE 5.3. Containment Notional Concept Downselect Chart

| Containment Feature | Advantages | Disadvantages | Used? |
|---|---|---|---|
| • Partial circumference | Modest size and weight | Incomplete coverage | No |
| • Complete circumferential | Best coverage for arbitrary damage | Large, bulky costly | Yes |
| • Air filled tubes, stacked | Good reserve buoyancy; wave follower | Sinkage may req. heavy weights, windage | No |
| • Standoff outrigger beams at bow | Prevents oil outflow overtopping boom | May be difficult, dangerous to deploy | Yes |
| • Outriggers all along boom | Assures hull clearance all around | Multiplied difficulty | No |
| • Shallow booms | Small storage vol., weight, tension | Easily swamped in modest seas | No |
| • Medium depth skirts | Hold more oil, readily deployed, handled | High drag loads, more storage vol. | Yes |
| • Deep curtains | Largest oil capture in least area | Extreme loads, may only work drifting | No |
| • Curtains, attached at gunwale | Traps oil from any outflow | Very large surface areas, controllability | No |
| • Gunwale storage, peripheral | Immediately ready to deploy | May be damaged, accessibility issues | Yes |
| • Stern deck compact storage | Localized storage and transportation | Lost time in deployment | No |
| • Pull around from stern to bow | Readily automated | May subject boom to high deploy loads | No |
| • Gravity deployment | Simple, reliable, automatic | Falls close to ship | Yes |
| • Boom radially propelled out from side | Captures more leaked oil | Inherently unreliability | No |

treatment have been developed for mitigating the effects of oil spills; some development has been limited to laboratory testing and analysis, while others have actually been used in the field. Those treatment methods which fall within the classification of bulk treatments are:

- Sorbent Material
- Gels/Coagulants
- Dispersants
- Sinking Agents
- Combustion
- Bioremediation

An overview of each of these bulk treatment methods, a description of the performance attributes, and an analysis of the current state of development are included in the following sections.

### 5.3.1 Sorbent Material

Absorbents soak up oil and adsorbents fix oil on the surface of particles. Collectively, absorbents and adsorbents are referred to as sorbent materials, which include straw, polyurethane foams, sawdust, and rubber. Sorbents can be divided into three categories: natural products, modified or treated natural products, and synthetic or manmade products. In general it has been found that the lower the density of the sorbent material, the more oil it can pick up per unit weight (Mile 1970).

#### 5.3.1.1 Performance Attributes

Large-scale tests have been performed on numerous candidate sorbent materials (Mile 1970). The most effective sorbent material identified during these tests was polyurethane foam scraps 1 to 2 inches thick in various shapes and sizes up to 1 ft by 4 ft. The oil-to-sorbent ratio by weight was 46:1. Polyurethane, which has been ground to particles approximately 1/2 inch in diameter, proved effective in oil removal as well, with ratios of at least 28:1, although insufficient oil was present to completely characterize the total oil absorption capacity for these particles.

The following key factors should be considered for sorbent material usage:

- The sorbent must be distributed over the floating oil and, in all probability, agitated so that it absorbs the maximum amount of oil. Wind can be a deterrent to the spreading of the sorbent material.

- Sorbents can present pollution problems if not removed from the water.

- Polyurethane in its unmixed state (polyol and MDI components) presents a health hazard.

- Onboard storage requirements of the sorbent materials must be considered.

- The ability of a particular sorbent to pick up oil may be a function of the weight/type of oil.

- Some sorbents need to be treated prior to use to cause them to have a higher affinity for oil than water.

- Many sorbents absorb water and become waterlogged with time, and some actually sink (closed-cell polyurethane foam is an exception).

- Compared with other oil spill cleanup techniques, sorbents are costly (although cost varies with the efficiency and type of the sorbent material used).

5.3.1.2 State of Development

Internal Usage - The idea of using sorbent pillows that drop into the interior of an oil holding tank from the deck above has been patented. A description of the patent is included in Appendix C. This patent description does not specify a particular type of sorbent material to be used in the pillows. No evidence of implementation of this system onto a tanker or barge could be found.

External Usage - Testing and evaluation of numerous sorbent materials have been performed. Implementation of sorbent material has occurred in actual spill scenarios. Straw was used extensively to clean the beaches at Santa Barbara, where it was applied by blowing it out from straw mulching machines. The straw was removed from the beach by hand, which was a very labor intensive process. Sorbents are not generally being used for oil spills at sea.

### 5.3.2 Gels/Coagulants/Solidifying Agents

Gelling agents or coagulants have been considered for preventing the rapid spread of oil. In the ideal case, the oil becomes thick enough to stop up the rupture or hole from which it is spilling. In general, the formation of a gel requires the addition of an appropriate chemical agent (i.e., fatty acids, treated colloidal silicas, polymer systems) to the oil.

#### 5.3.2.1 Performance Attributes

In addition, for any of these agents to be effective, they must take action rapidly (e.g., between 5 to 10 minutes). For a gelling agent to be effective generally requires that it be well mixed in the oil. It takes approximately 10 hours before the oil starts to set when mixed with gelling agents. This time restriction would make it nearly impossible to develop a gelling system that could be used after the oil is actually spilled onto the water surface, and for internal usage a gelling system would be effective only for combating small openings with a very slow leak rate from the ship.

In the report A Study of Onboard Self-Help Oil Spill Countermeasures for Arctic Tankers, the conclusion was made that solidifying agents may be of some use because of their fast-acting nature (Ross 1983). Solidifiers cause oil to begin solidifying within about 10 minutes. Again, the solidifying agents must be well mixed with the oil, and they require a mixing ratio of approximately 30% to 40% polymer and other additives by weight be added to the oil.

#### 5.3.2.2 State of Development

Internal Use - Gelling agents have not been used operationally for the treatment of oil, but British Petroleum is investigating the use of solidifying agents at or near leaks in tank walls. Analysis indicates that mixing solidifying agents through the use of air sparging or nozzle jets could result in solidification in 20 to 70 minutes. This solidified oil will not flow from holes with an area of approximately 0.01 $m^2$ or less.

External Use - It is felt that the external treatment of oil on the surface of water would not be feasible because of the need to thoroughly mix the chemical agent with the oil to cause gelling. No research was found discussing the feasibility of treating oil using a gelling or solidifying agent while the oil is contained within a boom or skirt. It has been noted that gelled oil would present additional difficulties in clean-up.

### 5.3.3 Dispersants

The purpose of dispersing oil is to minimize damage from an unrecoverable oil spill. When a volume of oil is spilled onto the surface of water, the oil has a driving force to spread. The tendency to spread is affected by the surface tension of the water, oil, and interfacial tension between the two. Dispersants tend to lower the interfacial tension between the oil and water (surface active agent or "surfactant"). For the surfactant to be effective, it must also prevent the coalescence of the dispersed oil droplets after they are formed. Oil that is properly dispersed with a chemical surfactant will not stick to solid surfaces.

Where the recovery of oil is not feasible, the following incentives exist for chemically dispersing oil:

- The rate of biodegradation of oil is increased (1 to 2 orders of magnitude).
- Damage to marine life is minimized.
- The fire hazard is minimized.
- The spilled oil is prevented from wetting beach sand.
- The formation of tar-like residue is prevented.
- The formation of gelatinous water-in-oil emulsions is prevented.

#### 5.3.3.1 Performance Attributes

To be effective, the dispersant must be well mixed with the oil. Wind and wave action is sometimes sufficient for mixing. The manufacturers listed the volume to volume ratio of dispersants to oil as approximately 1:10, but EPA field experience indicates that the necessary dosage is often 1:1 or 1:2. There is significant concern over the toxicity of the chemicals that are used as dispersants. United States regulations forbid the use of chemicals except in unusual circumstances (Miles 1970). On-Scene Coordinators of the cleanup operation have the authority to approve the use of chemical agents if the spill will endanger human life or waterfowl, or presents a fire hazard.

Some form of solvent generally needs to be added to the surfactant to reduce its viscosity to allow application. Stabilizers are also added, which help to fix the emulsion once it is formed and increase stability of the mixture. The cost of dispersants is about $2.00 to $5.00 a gallon.

Figure 5.6 shows the relative effectiveness for various oils and four different dispersants. It can be seen that the effectiveness for these tests can be as low as 5% to as high as 90%, depending on the dispersant and oil involved in the testing.

5.3.3.2 State of Development

Internal Use - The injection of chemical dispersants into a cargo tank will not stop the outflow of oil, but most likely will reduce the amount of

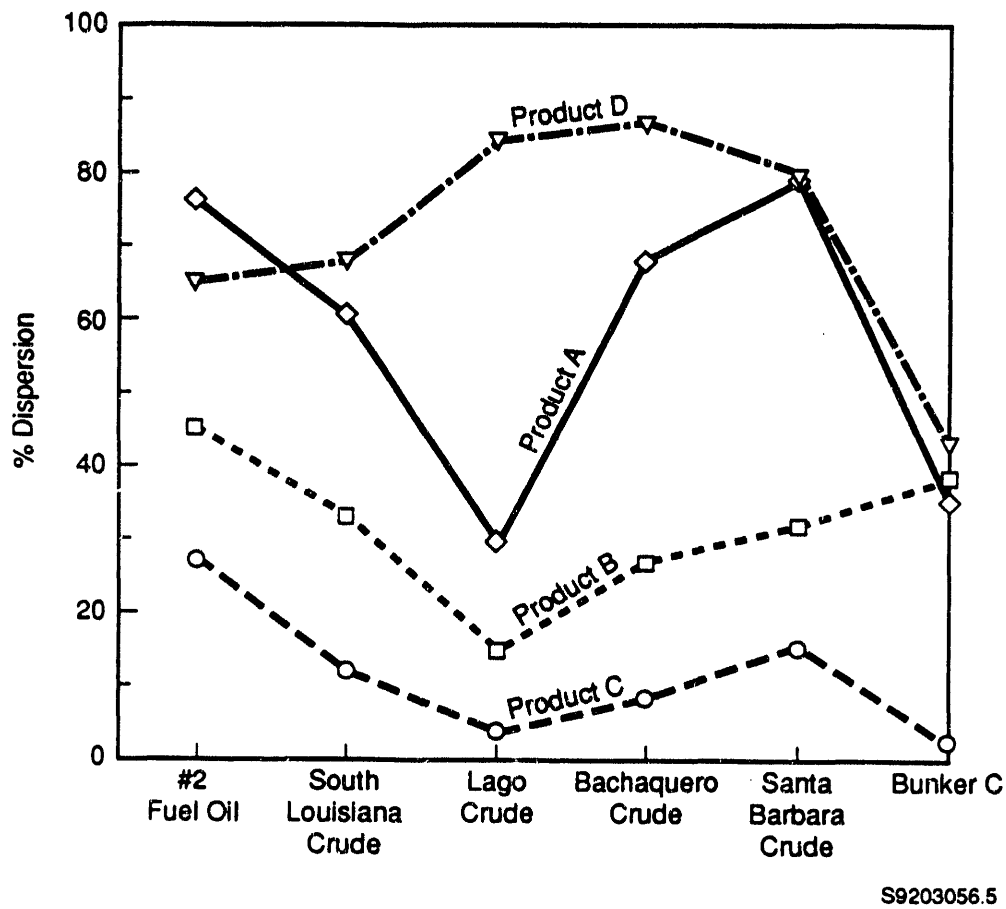


FIGURE 5.6. Effectiveness of Four Oil Dispersants

dispersant required outside of the tank. As with solidifying agents, it would take between 10 and 60 minutes to achieve the desired mixing level. An alternate proposed method is to locate distribution piping within the cargo hold, which would break when the ship ran aground or was involved in a collision. This piping would then automatically distribute the dispersant at the point of tank/hull rupture.

External Use - External application is possible, but the required application rate of the dispersant will be a function of the leak size, thereby necessitating knowledge of the leak size and adequate operator training. External application systems generally use spray application techniques. These may not be effective where there are large variations in the thicknesses of the oil layer.

### 5.3.4 Sinking Agents

Common sinking agents include sand, cement, ash, and clay. The oil adheres to the surface of these agents that then sink to the sea floor. Environmental concerns exist due to the deleterious effect the oil has on marine life at the sea floor.

#### 5.3.4.1 Performance Attributes

Sinking agents require a weight of sinking agent to weight of oil treated application ratios of 1:1 or higher. As with dispersants, sinking agents are not to be used without approval of the On-Scene Coordinator (due to the hazard to marine life caused by oil on the sea floor). Sinking agents are most efficient on thick, heavy, and weathered oil. Many sinking agents release oil after sinking; therefore, sinking may extend the time that aquatic life is exposed to oil.

#### 5.3.4.2 State of Development

Internal Use - Not Viable.

External Use - The French used sinking agents to sink oil that had escaped the Torrey Canyon in the Bay of Biscay. Three thousand tons of calcium carbonate were applied to the sea surface with some success. The long-term effects on the bottom life in this area have not been adequately analyzed (Mile 1970). The existing EPA policy restricts their use to waters exceeding 100 m in depth.

5.3.5 Combustion

One method proposed for the removal of oil from water is by burning. For this method of removal to be successful, the fire must be provided with sufficient oxygen to burn and must be kept hot enough to sustain burning.

5.3.5.1 Performance Attributes

The burning of oil from the surface of the water:

- can result in complete removal/elimination of oil spilled
- results in air pollution
- may create a fire hazard
- is difficult for thin layers of oil due to the cooling effect of water sublayers (0.12 inches or more required)
- may be difficult as time progresses because the material quickly loses its volatile components and ignition is difficult; (the heavier crude is most difficult to burn, and it is also the most difficult to remove from beaches and the environment.)
- may result in death, injury, or loss of ship.

5.3.5.2 State of Development

Internal - Not viable.

External - Burning has been used for stricken tankers (i.e., Torrey Canyon in 1967) with effectiveness. It was used as a "last resort" by the British Government to remove the 15,000 to 20,000 tons of crude oil from the severely damaged tanker. Air dropped starters were used that contained sodium metal, calcium carbide, and oil impregnated sawdust. There were no crew members onboard the tanker when the burning of the oil was initiated.

Commercial burning agents are available for promoting combustion of an oil slick, and patents have been filed for wick type devices that can be placed on a floating oil mass to provide sustained burning points. Although burning may be an effective way to dispose of oil on the water in certain special cases, it is impossible to conclude that this method would ever be willingly used by crew aboard a tanker leaking oil as the self-help method of choice.

### 5.3.6 Bioremediation

The process of bioremediation for oil spill treatment involves the injection of cultured bacteria, nutrients, or both to convert oil into a neutral substance. Oil is broken down when the enzymatic protein-like substances in the cells of bacteria act as organic catalysts in initiating the chemical reactions that break down hydrocarbon chains. Bioremediation was employed in the marine environment for the first time for the shoreline cleanup in Galveston Bay, Texas, and Prince William Sound, Alaska, and on crude oil spilled on the open sea of Galveston from the Mega Borg. Some people project that bioremediation will be the primary or secondary treatment method for both small and large oil spills in the marine environment (LeBlance and Fitzgerald 1990).

#### 5.3.6.1 Performance Attributes

Questions and concerns relating to the bioremediation process include the following:

- The possible toxic effect of additives (i.e., nutrients, surfactants, emulsifiers) has not been fully explored.
- The effectiveness and behavior of microbes are unknown when applied to oil that has had a dispersant previously applied to it.
- The nutrients and agents that promote or retard the growth of the bacteria have not been fully defined.
- Some concern exists that the introduction of bacteria into an area may cause harmful environmental effects.

For the bacteria to multiply and continue the breakdown of the hydrocarbon chain, a supply of nitrogen, phosphorous, and oxygen must be present. If the hydrocarbon material or any of these elements becomes unavailable, the population will decline and the break-down will cease. In marine applications, usually sufficient amounts of nitrogen and phosphorus are dissolved in the seawater to sustain the reaction (LeBlance and Fitzgerald 1990) which allows the application of three product formulations: (1) bacteria only, which would use existing nutrients; (2) nutrients, only which would cause the indigenous species to multiply more rapidly; or (3) both.

In controlled testing done on products from the Mega Borg spill, a bacteria and nutrient mixture was applied at a rate of 3 lb/acre with good success in breaking down weathered mousse.[a]

Different types of bacteria degrade oil compounds with varying efficiency depending on the type of oil compound. There are nearly 200,000 different compounds in crude oil, and fewer and fewer species of bacteria are able to consume the hydrocarbons as the molecular chain lengths of the hydrocarbons increase (LeBlance and Fitzgerald 1990).

#### 5.3.6.2 State of Development

Internal - No systems have been developed to apply this technology to internal use.

External - Bioremediation was used successfully for the removal of oil during shoreline testing at Prince William Sound, Alaska, and also in the Gulf of Mexico following the spill from the Mega Borg.

### 5.3.7 Bulk Treatment Notional System Selection

As previously discussed, several methods can be used for the bulk treatment of oil. Of these, several are not viable tanker self-help methods due to logistic, technological, regulatory, or operational issues. The bulk treatment systems that are deemed unfeasible are gels/coagulants, dispersants, sinking agents, and combustion (which are discussed previously).

Sorbent material and bioremediation are the two bulk treatment processes deemed worthy of further investigation as tanker self-help systems. The two notional systems are similar in many regards, but the logistics associated with handling the raw product, the amount of product required, and the

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(a) This information is referenced in Mega Borg Spill off the Texas Coast: An Open Water Bioremediation Test by the Texas General Land Office (Grary Mauro, Commissioner; Texas Water Commission, B. J. Wynne, III, Chairman).

notional methods of application are different enough to warrant that these methods be analyzed individually.

#### 5.3.7.1 Sorbent Notional System

Based on the test data reviewed, the sorbent notional system initially selected for analysis is a polyurethane foam system that dispenses chopped/shredded closed-cell foam over the edge of a ship or barge. A polyurethane foam dispensing machine was selected because it has a high oil to sorbent absorption ratio. (Ratios of 46:1 by weight have been observed during large-scale tests in which polyurethane foam chunks were used.)

The notional system consists of the following components:

- heated holding tanks for the raw chemicals (polyol and isocyanate) that mix to form polyurethane foam
- pumps and mixing heads to mix the chemicals into a foam that expands to about 30 times the volume of the unmixed chemicals
- shredding equipment to apply the polyurethane foam to the spill over the side of the ship.

The mixing machine selected for this notional system is a 60 horsepower delivery system that processes a maximum of 260 lb/min of raw chemicals. Given an absorbent ratio of 46:1, a single foam dispensing system operating at 100% efficiency could distribute enough foam to absorb oil leaking at a rate of about 24,000 lb/min (3,200 gal/min). The ratio of 46:1 has been selected for this notional system, as it is the best representation to date. For higher initial oil flow rates, multiple systems could be used to increase the application rate. The ability to apply the foam evenly to the surface of a spill is affected by weather conditions such as wind and rain. It was assumed for this system that the polyurethane chips would be blown through a large diameter hose from the foam generator/shredder to the point of application.

The attributes of this system are as follows:

Performance Characteristics (per mixing unit)

| | |
|---|---|
| Chemical Storage Requirements | 2% of volume of spill |
| Maximum Application Rate (Per Applicator) | 70 gpm (520 lbm/min) |
| Absorption Ratio (weight oil:weight sorbent) | 46:1 |
| Power (Per Applicator) | 60 Horsepower |
| Time to Deploy Estimate | 25 minutes |

Non-Performance Factors

- Chemicals are toxic in unmixed form.
- Chemical viscosity presents a pumping problem if temperatures are too low.
- Some degree of training will be required to operate the application machinery.
- Three people may be required to operate each pumping machine.
- Clean-up of the sorbent material is necessary following application.
- Wind or rain could hamper the effectiveness with which the sorbent is applied.

Notwithstanding the potential for reasonably successful bulk treatment using polyurethane sorbents, the fact that the chemicals are toxic in their unmixed form, makes this system questionable for self-help use. The risks to both the environment and personnel that are associated with potential chemical spillage are high, and the need to heat the chemicals and to clean up the polyurethane following application also complicate this notional system. The polyurethane foam system can be considered a contender pending further development but not as the most recommended bulk treatment concept.

5.3.7.2 Bioremediation Notional System

As previously discussed, bioremediation of spilled oil makes use of bacteria to transform hydrocarbons to a non-oil substance via microbial action. When bioremediation is used as an oil treatment, no attempt is made to physically remove the bacteria from the sea following application. The product that is applied to the spilled oil consists of a mixed culture of naturally occurring hydrocarbon degrading bacteria, inorganic nutrients, and growth factors. This mixture has a shelf life of up to a year, and can be applied as either a powder or mixed with water and applied to the surface of the oil (i.e., via a firefighting system).

Several factors affect the performance of the bioremediation process, and thus the system design. The decomposition reactions require the presence of hydrocarbons, microbes, nutrients, water, and oxygen. If any of these are present in inadequate amounts, the bacteria will die. The application ratio (i.e., weight of microbes and nutrients to weight of oil) is also important. If there are insufficient bioremediation products, the spill will not be efficiently converted to a non-oil substance, as there is a symbiotic relationship between the bacteria which enhances reproduction and oil decomposition. If too much product is applied to the oil spill, the reactions can become self-limiting (i.e., anoxic conditions could result which would result in the death of the microbes). The results of the research performed on bioremediation do not conclusively indicate what the proper application ratio for the bioproducts should be, although one manufacturer stated that it should be possible to treat oil with a weight percentage of bioproduct to oil of 2%.

In addition, the bioproducts can be applied either by premixing with water and spraying over the spill, or the powder can be applied directly to the surface. The product typically is in the form of a corn-meal textured powder, thus factors such as wind or rain could degrade the application effectiveness if applied in the powder form.

Since the bioproducts are cultured on a given type of oil, they are more effective on that specific type of oil than on others. This means that for maximum effectiveness, the microbes should be cultured on the specific type of oil in each ship. The application ratios will also be adjusted depending on what type of oil is spilled.

For the notional system developed and for the simulation, the assumptions were made that the application ratio of 2% is valid, and also that the bacteria were cultured for the type of oil transported.

The notional system consists of the following elements.

- A deck-mounted container or containers which would hold the bio-products. These containers could be changed out if the ship was moved to a different shipping region and thus needed different microbes for optimization of the bioremediation process.

- A feed system that would meter out the product at a controlled rate. The optimal rate of metering and the application pattern (i.e, large area application versus small area application) would be a function of the spill rate and manner in which the oil is leaking from the ship. A control system for both metering and adjusting the application pattern would therefore be required to optimize this system. A venturi feed system that uses high-pressure seawater as the motive force for the movement of the bacteria/nutrients from the storage container was selected as the physical method of dispensing the product as shown in Figure 5.7

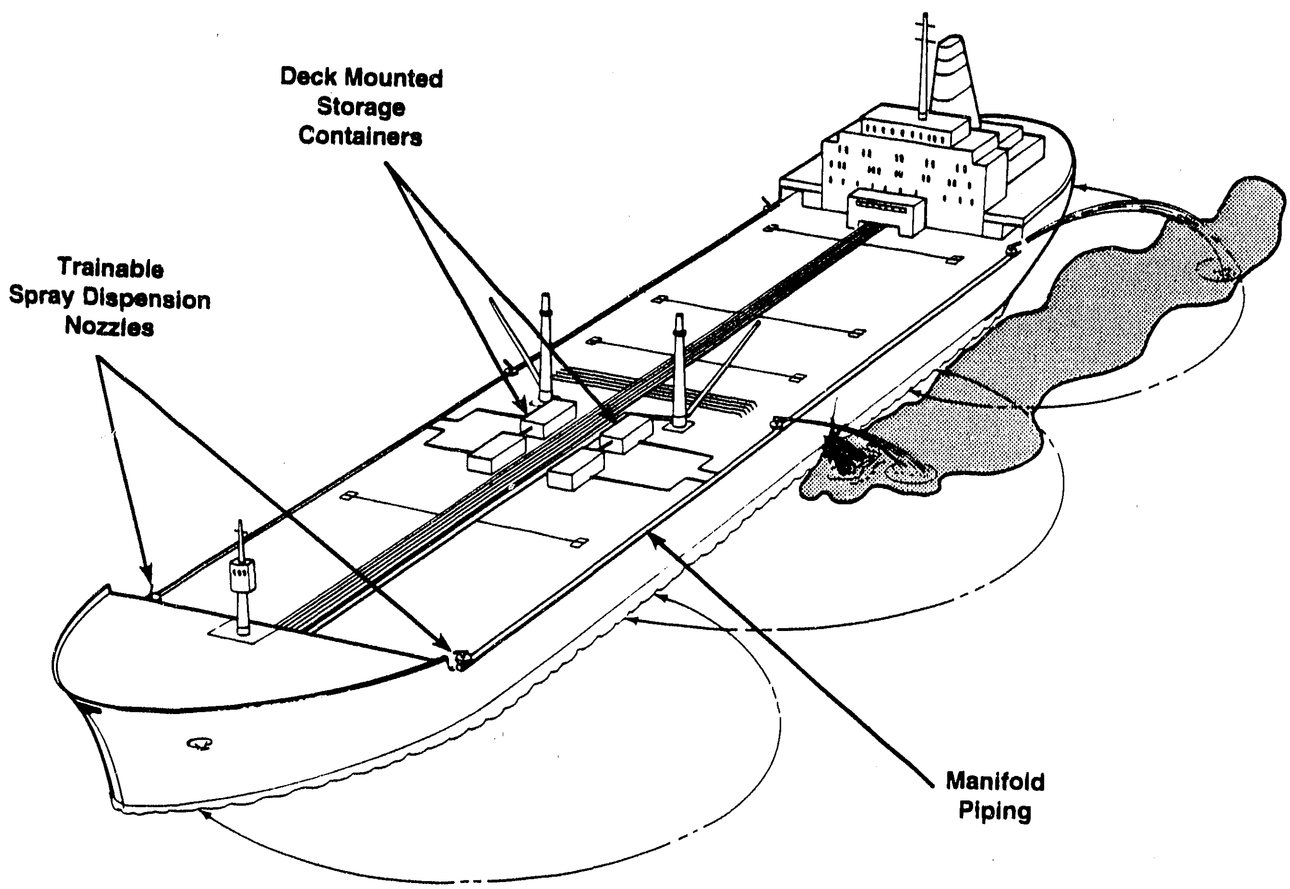


FIGURE 5.7. Bulk Treatment Notional Concept

The attributes and operating sequence of this system are as follows:

Performance Characteristics

| | |
|---|---|
| Chemical Storage Requirements | 2% of spill volume |
| Bioproduct Application Rate (Per Applicator) | 480 lbm/min |
| Time to Deploy Estimate | 25 minutes |
| Horsepower Estimate | 90 Horsepower |
| Application Range (Per Applicator) | 200 Feet |

Non-Performance Factors

- Microbes can be stored for up to 1 year.
- Manufacturer states that the bioproducts are not hazardous to personnel.
- Some training will be required to operate the application machinery.
- Estimated that two people will be required for system operation.
- Wind or rain could hamper the effectiveness with which the bacteria are applied.

5.3.7.2.1 Prerequisites. The following requirements are expected to be met to ensure that the system operates properly when required for treatment of an oil spill.

- Periodic maintenance must be performed on pumping and storage equipment.
- Bioproduct "expiration" dates will not be exceeded. The bioproducts must be replaced within the shipboard containers as required by manufacturers' recommendations.
- A supervisor trained in bioproduct application must be onboard whenever the ship is underway.
- Periodic training exercises will have been performed to ensure all personnel are able to respond properly to the spill.

5.3.7.2.2 Operating Sequence. The following steps are envisioned as occurring in order to apply the bioproducts to the spill:

- The extent of damage and estimates of the leak rate must be determined prior to the initiation of treatment.

- The bioproduct feed rate into the application stream must be set based on the spill rate. It is envisioned that this would require one operator located at the bioproduct storage/feed station.

- The application stations must be manned. It is anticipated that a maximum of three spray application stations would be manned at a time. These application stations are located along the gunwales of the ship.

- Supervisory control of the application will be required to ensure the application is occurring in an optimum fashion. The supervisor will maintain the local decision-making responsibility regarding the spray/application technique to be used. The supervisor must be trained in all factors affecting bioproduct application including coverage patterns, volume, and location.

## 5.4 CLOSURE MECHANISMS

Closure mechanisms are defined as those devices or systems that act to stop the flow of oil at a localized point of rupture or mechanical failure. The methods of closure typically involve plugging or patching at the point of failure. Proposed methods of plugging or patching a hole typically use devices that either act from the inside of the tank or are applied from the outside of the tank. Examples of proposed patching methods are included in Appendix C.

Various concepts for patching and plugging of holes in a tanker were reviewed, and a technical assessment of the merits of these concepts was performed. Of the concepts reviewed, it was concluded that manual localized patching or plugging of holes in a tanker was not viable. The problems associated with localized plugging or patching include:

- Significant pressure can be exerted on an external patch by small holes, thus making the patch difficult to install. For example, given an oil level within a hold 7 ft above the waterline, a hole with an area of 5 $ft^2$ will exert a force of over 2,500 lb against an externally applied patch. The pressure applied by the oil on this patch requires that reactionary forces be generated to hold it tightly against the ship. If the hydrostatic head of the oil has equilibrated with the hydrostatic head of the surrounding water, the driving forces against an externally applied patch will be minimal.

- The geometry of a tear, hole, or rupture is generally unknown following a collision or grounding. Patches and plugs typically have a geometry that does not make them suitable for all types of leaks.

- The location of the tear, hole, or rupture must be determined prior to the application of a patch. For leaks occurring below the waterline, the only indication of the leak location may be the presence or flow of oil on the surface of the water. This will be affected by the local water conditions such as current and waves.

- Internally applied patches also require knowledge of the leak location, and must be configured to cover the leak area. Unlike externally applied patches, the flow of oil from the ship could actually be used to seat the plug or patch.

The concept of using a high-strength tank liner, which is permanently located in a tank and acts passively to patch a hole, has been proposed in numerous forms. The National Research Council assessed the practical obstacles associated with such a liner or membrane to be insurmountable. Internal tank structure and equipment are not physically conducive to the fitting of liners. The presence of piping, pumps, heating coils, washing machinery, and ladders interfere with the incorporation of such a system. Cargo pumping and crude oil wash systems could damage such liners. Liners could also inhibit the performance of normal hull inspections. The National Research Council did conclude that liners could possibly be incorporated into tanks that have fewer obstructions or operating constraints than cargo tanks. For this report, liners will not be further analyzed as they are not seen as self-help systems, but as a large-scale tanker design modification.

## 5.5 PUMPING/COLLECTION

The major category of pumping/collection was selected as a self-help concept for spill minimization. Included in this major category are all concepts that attempt to collect the oil and deposit it in a storage reservoir.

Pumping oil from a damaged cargo tank into a secure holding location is a very basic approach to minimizing oil spill size. This operation is performed on most oil spills by "lightering," or transferring the oil from the damaged tanker to an empty tanker ship prior to moving the damaged tanker.

Some of the self-help collection/pumping concepts use the ship's existing cargo transfer pumps and piping. Other systems operate using a hydrostatic head to pump the oil. Still other approaches employ pumps (and power) that are completely independent of the ship's existing equipment in case the ship's systems are damaged during the accident.

Various containers have been proposed for temporary storage reservoirs for the pumping systems. Some of the concepts depend on the availability of additional storage space in the ship's ballast tanks or in other empty (and undamaged) cargo tanks. Other system concepts provide this storage volume with expandable bladders.

For the purposes of this review, two major subcategories (and thus two notional systems) were created; one that collects the oil from inside the damaged cargo tank, and a second that collects the oil from the surface of the water beside the tanker. For both of these concepts pumping is provided by pumping and power systems that are independent of the ship's systems, to provide some additional assurance that the equipment will not be damaged during the accident. Also, for both concepts a temporary storage reservoir is assumed to be carried on the ship, so that it too will be available when needed.

### 5.5.1 Interior Collection/Pumping

This concept is made up of the following equipment:

- one or more deepwell pumps, which are sized such that they can be manually lowered through the standard tank openings into the damaged cargo tank
- a combination of hose and hard piping (pre-plumbed) to carry the pumped oil to the temporary storage reservoir
- a temporary storage reservoir for holding the oil until it can be off-loaded to another tanker. This bladder is stored compressed in a container at the stern of the ship. Upon activation, the reservoir is self-deploying with gravity.

The flowrate of existing self-powered pumping systems (e.g., ADAPTS) is in the range of 1200-1500 gal/min, when drawing out of a cargo tank and through a reasonable run of piping to a storage reservoir. In order to accommodate various amounts of oil, multiple storage reservoirs may be carried on large tankers. For those tankers with multiple storage reservoirs, a distribution valve at the stern of the ship selects which reservoir is being filled.

### 5.5.2 Pumping/Skimming Methods

One method of dealing with oil after a leak occurs as a result of grounding, collision, or structural failure is to move the oil from its existing location (i.e., the tank from which it is leaking, the volume contained behind a boom, or directly from the sea surface) to a storage location. This movement of oil can take place by directly pumping from one location to another, or in the case of removal from the sea surface, removal may be coupled with skimming devices that concentrate the oil prior to pumping.

For the purpose of this study, pumping has been divided into distinct categories. The first category analyzed for tanker self-help is pumping from a location external to the ship's hull to a holding tank or bladder (the holding tank or bladder existing either internal or external to the ship), and the second category is the pumping from the leaking tank(s) to a holding tank or bladder. Each of these categories possesses unique capabilities.

Pumping oil that has escaped from the confines of the ship to a storage location typically requires that the oil be concentrated prior to pumping, in order to avoid pumping large quantities of water to the holding location. Mechanical treatment includes such techniques as:

- skimming/pumping with a suction device
- skimming/pumping with a weir
- pickup via rotating drums or endless belt sorbent devices.

The descriptions of several patented systems and concepts that perform these functions are contained in Appendix C. The ideal oil skimmer should be designed for:

- easy handling
- easy operation

- low maintenance
- ability to withstand rough handling
- versatility to operate in various wave and current situations
- ability to skim oil at a high oil-to-water ratio.

Skimmers generally consist of a pickup head, a pumping section, and an oil/water separator. The most significant variation in these systems is the pickup head configuration. The three most popular pickup heads (that part of the oil removal device in contact with the oil) for oil skimmers are the weir, floating suction, and adsorbent surface types. One state-of-the-art weir system is said to be able to collect oil at a rate of 400 gpm (Machine Design 1991). For a weir system to operate efficiently, the oil slick thickness should be maintained at greater than 0.25 inches, and the water must typically be calm to prevent water from spilling over the weir. A weir skimmer is not as sensitive to variations in the oil type as long as the oil thickness can be maintained and the seas are relatively calm. Floating suction devices are sensitive to the type of oil they are pumping. Heavy oils tend to clog intakes and flow passages, thereby rendering the devices inoperable. Again the operation depends on having a sufficient thickness of oil to prevent water entrainment. Sufficient lift must be provided to move the oil from the sea surface to the point where oil/water separation takes place.

Adsorbent surface types of skimmers require relatively calm seas to operate efficiently. The oleophilic properties of the sorbent are degraded by the continuous wetting with water, which may occur in the presence of waves. Sorbent skimmers are usually more expensive and as with the previously mentioned pickup heads, the mechanical complexity may require that the system be operated by adequately trained personnel.

Off-hull skimming devices are only marginally suitable as self-help countermeasures. Tests and experiences have indicated that skimmers generally do not operate efficiently in wave heights greater than 1.5 to 2.0 ft or in currents greater than 1.0 to 1.5 ft/s (0.6 to 0.9 knots). This limitation limits their use to calm or protected areas. Other detrimental aspects of skimming systems that make them unattractive as self-help devices are their cost, complexity, difficulty in deployment, and low-volumetric removal rates.

There may be some merit in using skimming devices in conjunction with containment devices that are able to concentrate the oil, thereby increasing its thickness to the point where efficient pumping could occur, but the complexity and coordination necessary would probably not make this a realistic self-help approach for ships to undertake.

State of Development

Internal Use - Not Applicable

External Use - Skimmers have most often been used for oil removal in protected areas such as harbors and estuaries, but they have been developed for open ocean use as well. One skimmer (BP Vikoma Skimmer) is said to have a recovery rate of 100 tons per hour with oils of medium viscosity. The unit is suitable for attachment to the deck of a small tanker or tug, and is designed to work in conjunction with a boom that can increase the thickness of the oil to several inches.

### 5.5.3 Pumping Notional System

This concept shown in Figure 5.8 is made up of the following equipment:

- one or more skimmers, attached to self-powered portable pumps located on the deck
- a combination of hose and hard piping (pre-plumbed) to carry the pumped oil to the temporary storage reservoir
- a temporary storage reservoir for holding the oil until it can be offloaded to another tanker. This bladder is the same one as was described for the interior pumping notional concept.

The flowrate selected for the self-powered pumps of this concept is the same as that of the internal pumping concept. Similar to the internal pumping concept, multiple storage reservoirs may be carried on large tankers.

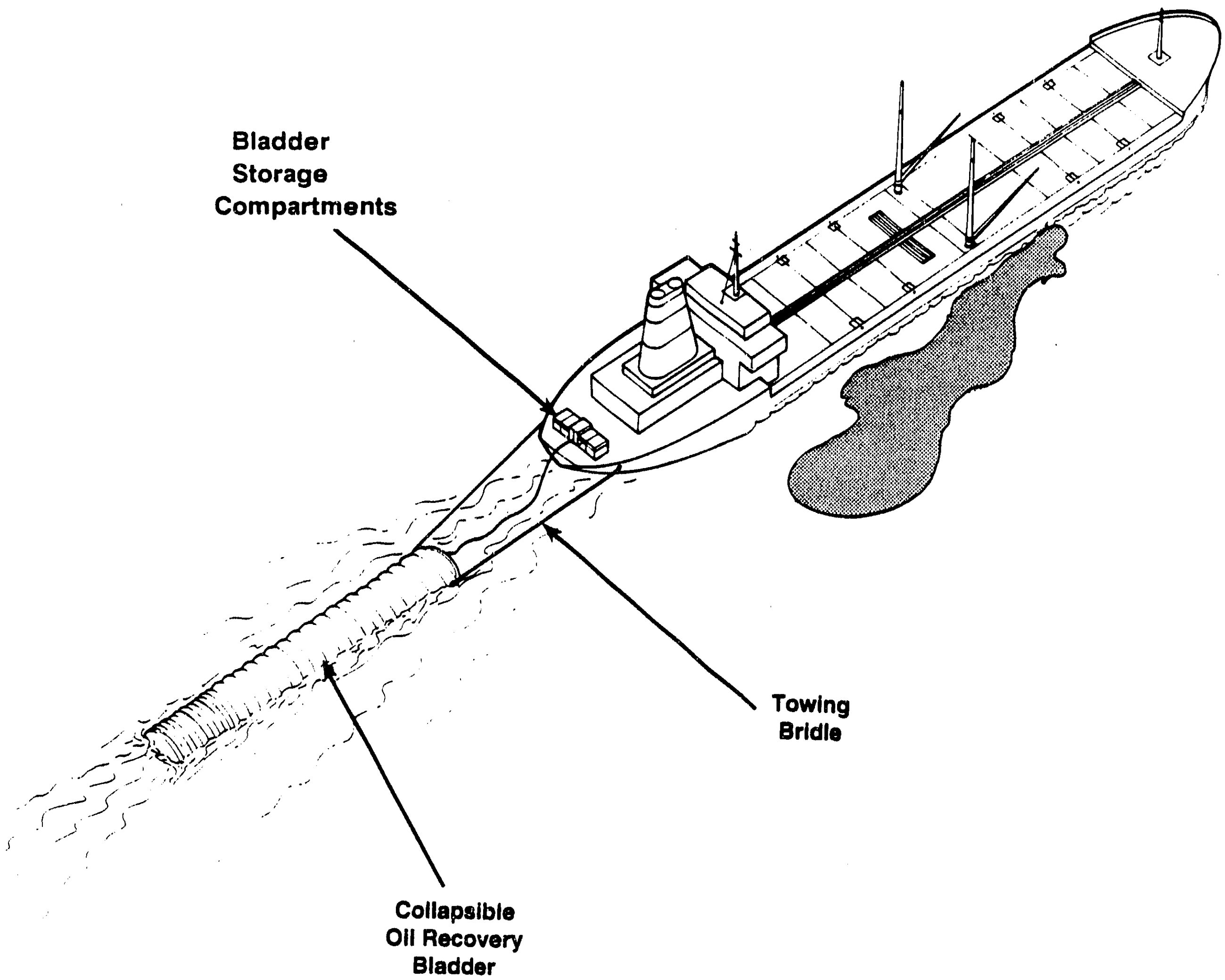


FIGURE 5.8. Pumping/Recovery Notional Concept

Tests and experiences indicate that skimmers generally do not operate efficiently in wave heights greater than 1.5 to 2.0 ft or in currents greater than 0.6 to 0.9 knots. Overtipping of the device is the primary cause of performance degradation; therefore, the device is more sensitive to wave action and rocking than to increases in current. Both of these influences on skimmer effectiveness have been approximated by curves, and are included in the computer simulation of the self-help system.

A third pumping concept was modeled and simulated but found to be relatively ineffective. It has been suggested that pumping from the spill pool back into the damaged hold, in lieu of any other locations, might be a useful stop gap measure. The modeling suggests that this is actually counterproductive.

## 5.6 SIMULATION DESCRIPTION

The analysts decided early in the study that definitive evaluation of self-help concepts would be premature, given the state of development of this technology, but categorization into meaningful groups was possible. The construction of "notional concepts," combining features of specific concepts by category, was also possible; parametric comparisons among and between these notional concepts should yield insights, and possibly point the way toward optimizing strategies. The simulation model developed here can be continuously refined and upgraded, becoming a powerful evaluation tool, when real-world systems must be considered.

The objective has been to develop a realistic means of simulating tankers using self-help methods to limit oil lost to the environment. The simulation should account for first-order relevant physical and human phenomenon. It must operate over the range of specified carriers, cargos, environments, and casualty scenarios. The amount of oil that escapes, untreated, into the environment was chosen as the singular evaluation criteria, since other possible parameters, such as life cycle costs, reliability, development risk, and safety were judged too difficult to quantify with confidence at this level of analysis.

As part of our study, especially in the simulation, it was important to know what was happening to the oil and to be able to trace its history from the tank through the various self help devices, until finally it was lost to the environment, or recaptured. Figure 5.9 portrays, by means of a Venn

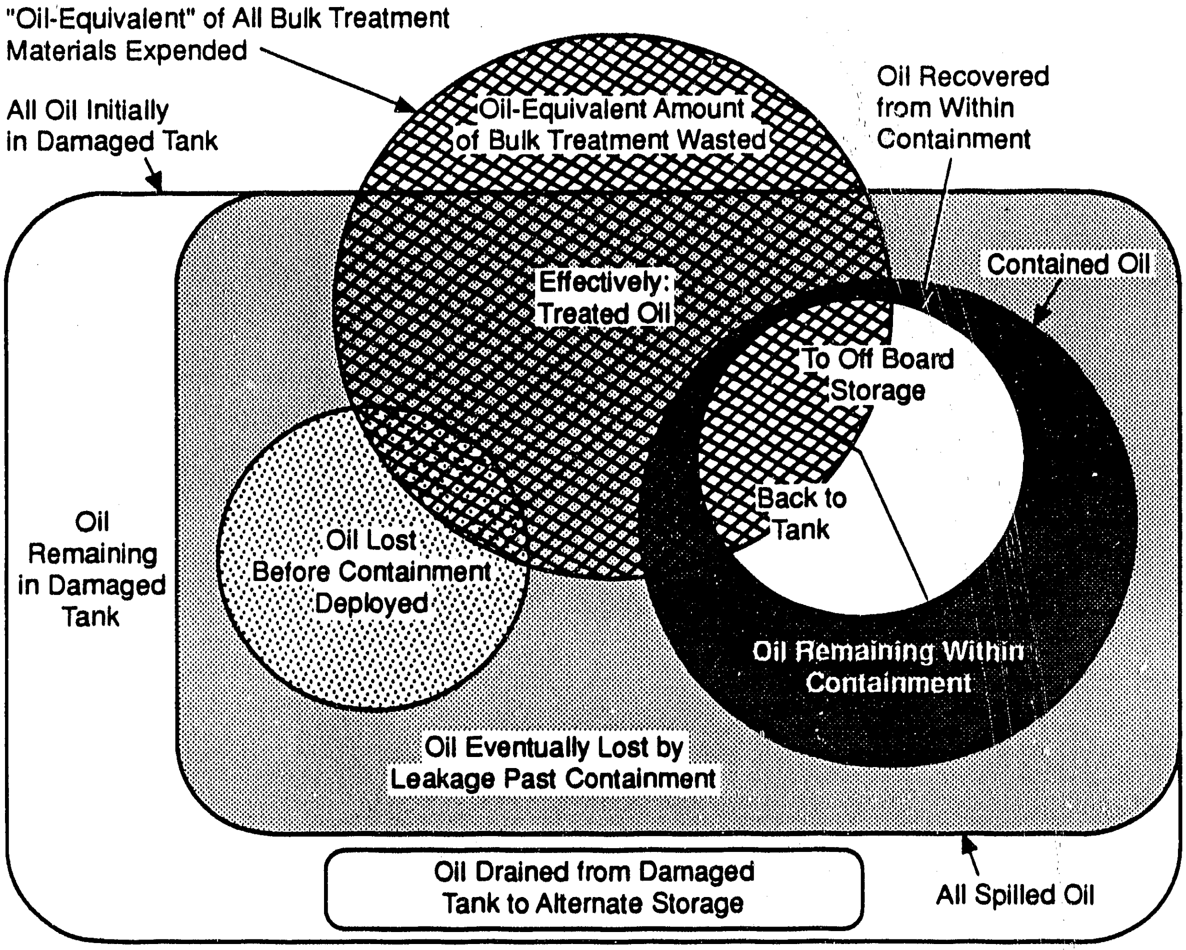


FIGURE 5.9. Oil Spill Venn Diagram

diagram, the multiplicity of states in the which the oil can exist throughout the spill event. All such conditions have been captured in the simulation model.

The simulations have been limited to the three categories established earlier; Containment, Bulk Treatment, and Pumping. Figure 5.1 illustrates the large number of potential scenarios that could develop in an arbitrary casualty situation. In order to limit the amount of simulation to a useful level, we have selected one set of conditions, representing worst-case conditions; specifically:

- All accidents are breaches at the waterline, since this always results in complete loss of oil in the tank if no action is taken.
- Two adjacent tanks are taken to be holed.
- The carrier is assumed to be free of any entanglements, at least by the time the self-help system has been actuated.
- The carrier is assumed to be holding station in the water, head to current and wind.
- The self-help system is evaluated as to total loss of untreated oil for 10 hours after the casualty.
- All self-help equipment has been assumed undamaged by the event.

The notional concepts are each modeled on the Macintosh computer, using the simulation program ithink™ by High Performance Systems, Inc. As shown in Appendix D, the process is represented diagrammatically by a series of interconnected "reservoirs" (rectangles). The reservoirs are fed and drained by flows (double line arrows), which are in turn regulated by "valves" (circles with handles). "Converters" (other circles) specify functionality. In Appendix D, the diagrams are broken into functional groupings called sectors. The model tracks the flow of oil from the damaged tank, out the puncture, into the water, and then through any containment, skimming, or bulk treatment processes employed, until it is finally recaptured, treated, or lost. Processes may be discrete, or continuous and functionally controlled. Even ill-defined or poorly understood causal relationships may be included as "sketched-in" functions, and refined as more data become available. Simulations may be run with explicit input data sets (as used here), or by using statistical protocols, such as Monte Carlo simulation, Normal or Poisson distribution, etc. Output may be either graphical or tabular.

Three separate models were constructed, one for each of the three main self-help methods: Containment, Bulk Treatment, and Pumping. These models were then exercised in simulation runs over a reduced design space to capture the essence of the variations caused by environment, carrier, and self-help methodology. Table 5.4 shows the data sets used in the runs.

## TABLE 5.4. Self-Help Casualty and Notional Concept Data Sets

**Self Help Casualty Data Sets**

| Parameters | Descriptors | Units | Data Sets | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Environmental Parameters** | (Data Sets) | | Fresh (I) | Fresh (II) | Fresh (III) | S/W ' | S/W (II) | S/W (III) | | |
| Wind speed | Wind | knots | 8.2 | 13.4 | 13.4 | [illegible] | 17.5 | 27 | | |
| Current speed | Current | ft/sec | 0.4 | 0.66 | 7.8 | 0.85 | 2 | | | |
| Tidal current speed | Tide | ft/sec | 0 | 0 | 0 | 1.1 | 2.7 | 1 | | |
| Wave height | Wave height | ft | 1.6 | 3.6 | 1.6 | 2.3 | 9.8 | 14.8 | | |
| Wave period | Period | sec | 3 | 3 | 3 | 3 | 6 | 8 | | |
| Water Type | Water type | -- | Fresh | Fresh | Fresh | s/w | s/w | s/w | | |
| Snow or ice | Snow ice | -- | No | Yes | No | No | No | Yes | | |
| Air temperature | Temperature | deg $^oF$ | 70.7 | 36.1 | 32.5 | 83.7 | 52 | 37.9 | | |
| Acceleration of gravity | g | ft/sec$^2$ | 32.2 | | | | | | | |
| **Ship Parameters** | | | | | | | | | | |
| Carrier ship | Tonnage | GT/DWT | 628 | 1,182 | 1,769* | 2,713 | 34,000 | 89,700 | 225,000* | 262,000* |
| Carrier type | Carrier type | -- | Barge | Barge | Barge* | Barge | Tanker | Tanker | Tanker* | Tanker |
| Length of ship | Lship | ft | 195 | 246 | 300* | 250 | 666.75 | 894 | 1094.37* | 1100 |
| Beam of ship | Wship | ft | 36.5 | 52 | 54* | 76 | 84 | 105.75 | 143.5* | 178 |
| Tank height | Tank height | ft | 10.5 | 11 | 13* | 17 | 50.7 | 64.3 | 92* | 86 |
| (Tank Length) | (Tank Length) | ft | 99.4 | 105.4 | 104* | 100 | 114.4 | 211.4 | 314.4* | 263.7 |
| (Tank Width) | (Tank Width) | ft | 18.2 | 26 | 27* | 25.3 | 19.5 | 30 | 39* | 44 |
| Tank area | Tank area | ft | 1,809.08 | 2,740.4 | 2,808* | 2,530 | 2,230.8 | 6,342 | 12,261.6* | 11,602.8 |
| Height of waterline | Zw | ft | 9.6 | 9.6 | 9.6 | 12 | 36 | 49.1 | 70.3 | 67.2 |
| **Puncture Parameters** | | | | | | | | | | |
| Height of puncture | H puncture | ft | 2 | 4.9 | 12 | | | | | |
| Length of puncture | L puncture | ft | 1 | 2.45 | 6 | | | | | |
| (Area of puncture) | (A puncture) | ft$^2$ | 2 | 12 | 72 | | | | | |
| Outflow orifice coefficient | Cd | -- | 0.61 | | | | | | | |

Fresh (I) Benign (zone 9, summer)
Fresh (II) Moderate (zone 8, winter)
Fresh (III) Severe (zone 9, winter)
S/W (I) Benign (zone 3, summer)
S/W (II) Strong current (zone 4, winter)
S/W (III) High wind (zone 6, winter)
NOTES: 1) All tankers operate in s/w; only 2713 GT barge operates in s/w; 2) Asterisks show other available data not used in simulations; 3) () Parameters shown for ref. only.

## TABLE 5.4. (contd)

**Notional Concept Data**

| Parameters | Descriptors | Units | Data Sets | | |
|---|---|---|---|---|---|
| **Bulk Treatment Parameters** | | | | | |
| Start time of treatment (nominal) | Tt | min | 25 | | |
| Start time (if "automatic") | Tt | min | 5 | | |
| Treatment spray rate | Treat spray rate | lb/min | 480 | | |
| Conversion efficiency | Conver factor | lb/lb | 50 | | |
| **Pumping Parameters** | | | | | |
| Start drain time (nominal) | Tdr | min | 25 | | |
| Drain rate | Drain rate | GPM | 0 | 600 | 1200 |
| Start return pumping time (nominal) | Trp | min | 25 | | |
| Return pumping rate | RP rate | GPM | 0 | 600 | 1200 |
| Start off-board pumping time (nominal) | Tobp | min | 25 | | |
| Off-board pumping rate | OBP rate | GPM | 0 | 600 | 1200 |
| **Containment Parameters** | | | | | |
| Deployment complete time (nominal) | Td | min | 25 | | |

Inputs for each of the data sets were obtained from: the outflow calculations, representative environmental scenarios, manning and response time estimates, and the nature of the notional concepts. Both quantitative relationships from the technical literature as well as more qualitative relationships, where precise mathematical equations were unavailable, were set up in the model.

The same set of environmental conditions, tankers, barges, cargo mixes, and casualties were used to exercise the model for all self-help systems. A short description of each of the major data sets is included below.

### 5.6.1 Environmental Data Set Selection

The environmental data collected from nine geographic areas were used to analyze the various notional systems. The data sets used for analysis were selected to ensure the concepts were analyzed over the full range of environmental conditions that could realistically be encountered. The data sets were compiled, and environmental scenarios were selected for analysis that represented the most benign, most severe, and also moderate conditions for both freshwater and saltwater, providing us with six zones for analysis (see Table 5.5). Details of the environmental conditions associated with these areas can be found in Section 3.0.

TABLE 5.5. Six Analysis Zones

| Scenario | Locale |
|---|---|
| 1. Benign Freshwater | Intracoastal Waterways and Rivers, Summer |
| 2. Moderate Freshwater | Great Lakes, Winter |
| 3. Severe Freshwater | Intracoastal Waterways and Rivers, Winter |
| 4. Benign Saltwater | Key West, FL to Brownsville, TX, Summer |
| 5. Moderate Saltwater | San Diego, CA to Eureka, CA, Winter |
| 6. Severe Saltwater | Ketchikan, AK to Dutch Harbor, AK, Winter |

5.6.2 Model Parameters

Ship parameters describe the essential elements of the carrier and the cargo hold which were modeled as breached. The actual carriers used are the same as selected for the outflow analysis. As above, we have selected fewer carriers to investigate, and the inactive cases are shown with asterisks in Table 5.4.

For the simulations, all punctures are rectangular, centered slightly below the waterline, and of aspect ratio 2 (height/width) which is the same modeling approach used by the engineers who calculated the outflow results. The flow area increases by a factor of six with each scale increment. A flow coefficient of 0.61, as in the outflow calculations, has been used. A slight departure, of no ultimate significance to the evaluation, is that only one tank has been punctured for the simulation, whereas in the earlier outflow calculations, two tanks were assumed breached. The configuration and size of the single tank is equal to both tanks, which are treated as one in the outflow calculations.

"Bulk treatment" is conceived of as generic enough that the model may be used whether for the application of bio-remediation products, or sorbents. In either case, parameters affecting the ability to apply these materials will have to be built into the model, as well as a "conversion efficiency" which is expressed as a ratio of weight of successfully treated oil to weight of applied bulk treatment product. For the present, it is assumed that the agents are sprayed from high-pressure nozzles out onto the slick using a water carrier, and that these nozzles, however arranged, can cover an area from the breach (taken as amidship) to the stern and 200 ft out from the side of the ship. Other parameters used as input include the assumed time to start application under ideal conditions, and the length of time for which spraying can continue.

Three types of pumping are provided, and in each case we have set a nominal start time and a pumping rate in gallons per minute (GPM). Each pump may be set on or off on any given simulation run. A "Drain" pump may be operating, which pumps oil from the holed tank to some other (unspecified) location. The second pump is one which moves oil, as a stop gap measure, from the spilled pool back into the stricken tank, and the third pump moves oil from the pool to some other location (unspecified). (Note that pumping back into the damaged tank had been suggested in some of the submissions; therefore, the model was constructed to evaluate this concept.)

An optimization subroutine established the length, height, draft, and freeboard of a notional containment barrier, which is taken to go completely around the carrier. The only input for this sector is the nominal time to complete deployment of the system in ideal conditions. Operation by a crew of men or by automatic means may be selected, and this will affect the deployment time used by the model.

### 5.6.3 Model Characterizations

Each of the three models developed is broken up into linked "sectors." The following describes the key assumptions made in the modeling, features modeled, and aspects not modeled.

#### Outflow Characterization Sector

Key modeling premises:

- A single tank is punctured slightly (1 ft) below water line.
- Tank overpressure is vented when it reaches atmospheric.
- Cargo tank is taken to be a rectangular prism.
- Puncture is rectangular with height-to-width = 2.
- Discharge coefficient = 0.61.
- Water flows into the tank and settles to the bottom (driving out more oil) when the driving pressure differential reaches 0.01 ATA.

Key features:

- tankage overpressure (or underpressure) as a function of oil level and/or time
- bi-modal outflow: gravity driven (stage 1), density difference driven (stage 2)
- type of cargo keyed to carrier type and water of operation (i.e., fresh or salt).

Effects not modeled:

- effects of variations in oil viscosity
- effects of multiple, arbitrary holes
- effect of plugging of hole (e.g., as by a colliding vessel).

Containment Characterization Sector

Key modeling premises:

- Barrier behavior and environmental effects are taken from the technical literature.
- Carrier is streamed into current.
- Containment encloses carrier and forms an oblong shape down stream.
- If carrier is assumed to be moored, then current is true maximum current; if carrier is taken to be drifting, then current is relative current at the containment.
- Deep water conditions apply.
- Deployment is not complicated by the presence of vessel or other obstruction.

Key features:

- time to complete deployment of containment
- current induced set up against barrier
- effect of waves on degrading performance of barrier
- Containment failure mode checking and consequent oil loss calculation:
  - drainage under the barrier
  - Entrainment of oil by current.

Effects not modeled:

- flow field distortion caused by carrier
- full three-dimensional effects around barrier
- wave overtopping
- loads or mechanical failure.

Pumping Sector

Key modeling premises:

- Once started, pumping is continuous until oil available to pump is gone.
- All pumping nominal rates set to 600 GPM or 1200 GPM.

Key features:

- Three modes available: Drainage of the damaged tank to another tank onboard or a storage bladder; pumping from the contained oil pool back into the damaged tank; and pumping from the pool to an off-board storage site (e.g., Dracone, or bladder, or another tanker).
- Environment affects both response time of men on deck, as well as efficiency of the skimmers working in the spill pool.

Effects not modeled:

- flow variations with head
- passive drainage from damaged tank into separate holding tank.

Bulk Treatment Sector

Key modeling premises:

- The bulk treatment medium is sprayed out over the spilling oil.
- Oil that has spilled and spread beyond the spray envelope is counted lost and untreated at the time spraying begins.
- Oil lost from the ship after spraying stops is counted as lost and untreated.
- A fixed stock of treatment material is available.
- Oil jetting from the side forms a plume that moves to the side and aft with the current.
- Oil spreading relations taken from the literature.
- The puncture occurs amidship.
- Spray coverage is uniform over a rectangular area equal to the half length of the ship and 200 ft out from the side in no wind.

Key features:

- "Treatment" is envisaged to be bioremediation, but may be other.
- Efficiency of distribution depends on wind and waves.
- Conversion efficiency (weight of oil "neutralized"/weight of treatment applied) is taken as 50:1.

Effects not modeled:

- post deposition spreading of treatment on oil or into water.
- how well the treatment actually mixes with and neutralizes the oil.

Oil Fate Tracking Sector (will be somewhat different for each concept modeled)

Key modeling premises:

- All oil will be accounted for.
- Oil does not change its character by evolving volatiles, weathering, or sinking up to the point it is lost irretrievably.
- A shore based response time of 10 hours is assumed for all simulations for comparing amount of total lost oil.

Key features:

- Both treated and untreated oil are tracked.
- Treated oil pumped back into the tank loses its treated attribute.

Effects not modeled:

- As above, no degradation or water column dispersion of oil is modeled.
- Spreading pattern after escape not modeled in either the Containment or the Pumping case, and is modeled as a current swept plume in the Bulk Treatment case.

Input Control Panel

Key modeling premises:

- "Ghosted" elements are simply displaced clones of original entry elements and are a programming device to reduce diagram clutter.
- All data entry takes place in the parameter boxes, not the Functional Relation spaces.

Key features:

- pumping parameters
  - start times for all pumps (min)
  - all pump rates (GPM)
- Containment parameters
- Deployment time under ideal conditions (min)
- Environment
  - wind speed in knots
  - relative current at the containment in ft/sec
  - tidal current in ft/sec
  - significant wave height (ft)
  - temperature of air ($^oF$)
  - water type (fresh/salt) with conversion to weight density ($lb/ft^3$)
  - snow and ice marker establishes presence or absence of same
- Ship parameters
  - Carrier type - barge or tanker. Has connections to: ullage space overpressure determination (2 psig for tankers, 0 psig for barges); Sp. Gr. of cargo oil: (keyed to carrier - 0.86 for tankers, 0.92 for barges); Ullage Fraction: (keyed to carrier - 2% for tankers, 5% for barges).
  - Zw: Height of W.L. above tank bottom in ft
  - Lship: Length of carrier in ft
  - Wship: Max. beam of carrier in ft
  - Tank Height: total internal height of damaged tank in ft
  - Tank Area: total plan area of spilling oil in damaged tank(s) in $ft_2$
  - V oil init: a calculated volume of oil available to spill in gal.

- Bulk Treatment parameters
  - Tt: Time to start spraying under ideal conditions (min)
  - Treatment spray rate: (lbm/min) of active ingredient in spray
  - Conversion factor: lbm of oil "neutralized"/lbm of active ingredient used, applied under ideal conditions.
- Puncture Characteristics
  - Zp: Height of top of puncture above bottom of tank in ft
  - H puncture: Vertical extent of puncture in ft
  - L puncture: Horizontal extent of puncture in ft
  - Cd: Coefficient of discharge.
- Containment Functional Relations
  - automatic: toggle that designates method of deployment as "automatic" or "manual"
  - containment length and depth optimization subroutine, based on minimizing volume of material used
  - actual flowing area of puncture subroutine to account for oil levels dropping below top of penetration
  - effects of waves and currents on ability of boom to retain oil
  - effects of wind, temperature, snow and ice on personnel response times.
  - sizing subroutine to determine maximum amount of oil that can be contained behind a boom, and compare against actual volume available
  - degradation effects for containment calculated from technical literature.
- Pumping Functional Relations
  - effects of waves and current on ability of pumps deployed in the spilled oil pool to move oil
  - human factors effects due to wind, temperature and snow or ice on response times; human factors degradation effects due to wind, temperature, snow and ice are "sketched-in" at this point

- degradation effects for pumping estimated from reports in the literature.

- Bulk Treatment Functional Relations
  - Automatic: toggle that designates method of deployment as "automatic" or "manual." Human factors degradation effects due to wind, temperature, snow and ice are "sketched-in" at this point.
  - Effects of wind and waves on spray effectiveness. Degradation relations for spray effects have been estimated based on simple dispersion models.

## 5.7 SIMULATION RESULTS

### 5.7.1 General

The results of the simulation runs are in Appendix D. The graphs in the appendix show the amount of oil that has escaped to the environment for each scenario. In the Bulk Treatment case, the amount of untreated oil that escapes is reported. At the top of each page is the graphical output for the run set, and beneath it is a tabular summary of the key variables that have been changed between each run. Usually, four runs have been made, and the results superimposed on one graph. In all cases run #1 represents the case without any form of self-help being applied. (This is accomplished by setting the response time to 10,000 minutes.) All runs on one sheet of paper share at least two common attributes: they are for the same carrier (and damaged tank), and for the same sized hole. Thus, curve number "1" shows the outflow characteristics for that carrier and the hole size, and if there is sufficient time within the 10-hour cut off, a flat top represents the capacity of that tank, since all oil will be lost eventually from a waterline holing. Run #2 represents the most benign case in the run set, and can be interpreted as representing the most optimistic results for likely scenarios. Runs #3 and #4 are the moderate and most severe environmental cases examined. It must be stressed that "moderate" and "severe" are nominal; in any situation the scheme being modeled might react more unfavorably to the "moderate" environment than to the "severe" environment.

The abscissa is the elapsed time from the casualty in minutes, and the ordinate of the graph represents the amount of oil lost in gallons. The lower a numbered run is on the graph relative to the line for run #1, the more effective the system for that set of environmental conditions. The Appendix is arranged in three packets, by category: Containment, Bulk Treatment, and Pumping. Within each packet, sheets progress by groups based on tonnage, with the smallest carrier first. Within each carrier size, there will be at least three sheets for the three nominal hole sizes (2,12, and 72 $ft^2$). More sheets are occasionally included to examine sensitivity to other parameter variations not otherwise explored.

Some similarities in the graphs need to be understood. Each of the unimpeded outflow lines consists of three parts. The first is a swift outflow until the oil inside the tank is just a little above the water outside. (Sometimes this is so fast that, at the scale shown for 600 minutes it is indistinguishable from the ordinate.) Next comes a slower loss representing the outflow due to density difference between water and oil, in which water flows into the tank and sinks to the bottom, displacing oil and pushing it out through the hole; this is the diagonal line visible on most graphs. The last portion of the curve is a flat horizontal line, showing that all oil has been lost. For the smallest holes, this point is occasionally not reached in 10 hours.

5.7.2 Containment Evaluation

From consultation with our Human Factors engineers, a value of 25 minutes seemed a reasonable nominal time at which to activate most systems, and this has been pre-set into the model. Graphs D.6 - D.29 illustrate the following:

- The small hole in the benign environment can be handled reasonable well (only about 25% of oil lost).
- On the small carriers, anything bigger than the smallest hole is a severe challenge to the system; the only way to get ahead is to respond more rapidly. Even this is almost hopeless on the largest hole.

- The more severe environments, especially those with high currents, will fail the containment by drainage or entrainment of oil under the lower edge, although it will remain partially effective if it can be deployed early.

- The largest carriers will swamp the containment in almost all cases, but usually after a considerable time. They are effective, but time to bring in outside help is critical.

- In the large carrier case, a more rapid response in setting the containment in place will only delay the inevitable loss of a certain amount of oil, not prevent it.

5.7.3 Bulk Treatment Evaluation

(Note: a computational problem seems to be occurring with the largest hole, and these results are not to be trusted.)

- Bulk treatment is most heavily dependent on speed of response. Oil spilled in the first few minutes will move rapidly away from the ship and be unreachable by the spray system.

- The outflow from smaller holes will, of course, be the easiest to treat, except that if the bulk treatment material is not managed properly, it can be exhausted while oil is still leaking out. A dual set point flow might be adequate at an early high rate to catch the initial outflow, and then cut back to cope with the density flow.

5.7.4 Pumping Evaluation

- A characteristic of many of the charts in this segment of Appendix D is that oil can be seen being recovered after having been "lost." This is certainly encouraging, but note that the model is not constructed to assess how well the oil may be pulled back up from a slick that is still spreading, so curves which return to the abscissa are clearly too optimistic; some degradation in effectiveness is to be anticipated. Note also that curve #4 in most cases levels out, either at the full tank capacity (i.e., completely ineffective) or somewhat below. We believe this effect represents the situation where the head of oil inside the tank has been drained down below the lip of the puncture (by the internal "draining" pump) faster than the water can back flow into the tank and displace the oil out into the environment.

- Another seemingly anomalous effect can be seen in a graph in Appendix D. The pumping system in the most benign environment appears to be performing more poorly than the same system in the more severe environments! We believe that the model is showing that as oil is pumped back into the damaged tank, it inadvertently keeps the relative oil-to-water head higher than it would otherwise be. Thus, the flow remains in the higher flow rate regime for longer. As the environment worsens, the ability of return (and off-board) pumps to be effective is significantly degraded, so less and less oil is available to "top off" the tank, and the onboard drain pump has a chance to stay up with the outflow. This effect may benefit from a more thorough study. With the return pumping shut off, the more benign environment results in the most oil saved.

### 5.7.5 Summary Discussion

The simulation model and results described above are early indications of the eventual utility of such a system. The simulation is a tool that can be refined and updated as more theoretical and empirical results are reported, and used as a common yardstick of performance. At this stage in its development, it should be viewed as a prototype. Validation and checking of results by independent parties would be desirable, and a number of the special purpose relationships "sketched" into the model should be investigated. For example, the loss of efficiency of skimming equipment is known to depend on both wind and waves, but we could not uncover an explicit relationship that handled the interaction effects. Finally, the models for each of the main categories should be combined into one global model, so that the effect of using combined systems may be investigated.

No clear winner was apparent in these simulation runs, but the following has emerged:

- Containment is extremely sensitive to relative current. In simulations, it was assumed that full environmental currents would be acting on the containment, whereas in many cases, the ship might well be drifting and net relative current would be low. In these circumstances, a containment barrier seems attractive, at least as an interim measure.

- Bulk treatment, especially bio-remediation, may offer the best hope for long-term solution, through genetic engineering of more effective microbes, and better dispersal equipment and methods.

- Pumping is the only method with at least the chance of recovering some of the oil inside the (self-imposed) 10-hour time limit for self help. But it is unlikely to be effective by itself; combining a pumping solution with some form of containment holds the most promise for achieving a real capability for ships within the next decade and should be the first system to be investigated using a global model.

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## 6.0 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Based on the information provided in the foregoing sections, the following is concluded:

- Most spills in U.S. waters occur in inland waters.
- No analytical method appears to be readily available for predicting the penetration size in a vessel as a result of collision, given currently available casualty data.
- The parametric approach based on hole size, as used in this study to determine oil outflow in the case of collision, appears to be validated for small holes by the results obtained independently by S. L. Ross (Ross 1983).
- MARPOL assumptions are not applicable to time-dependent oil outflow analysis.
- In cases of grounding, the oil outflow rates determined in this study are probably overly conservative. The methodology developed by DnVC for predicting bottom damage when performing design comparisons was prescribed by the Coast Guard as a means of analyzing both the high-energy and low-energy grounding cases. DnVC's equations for determining penetration size depend on a vessel's kinetic energy and structural design, and they apply MARPOL assumptions for determining the extent of vertical and transverse damage. MARPOL assumptions for bottom damage are not dependent on a vessel's structural design or its kinetic energy at the time of grounding, so the methodology was used in this study for the lack of a better approach. Because this methodology was not intended for this application, no allowance was made for the energy that is dissipated in breaking/deforming the ground or in changing the trim of the vessel as it rides up and becomes hard aground. Consideration of these factors would result is a smaller hole size. Also, no allowance was made for the plugging action of the ground. Consideration of this factor would also result in a smaller hole size and hence further reduce the rate of outflow. Moreover, this methodology does not distinguish between damage area and penetration area. Only penetration area is significant in this case.
- Ground plugging has a significant effect on oil outflow in the case of grounding.
- Sea ice is a major factor in countermeasure design; however, the net impact of interactions between sea ice and oil on the utility of different containment/cleanup technologies is difficult to predict.

- Two conditions, low visibility and superstructure icing, will reduce the performance of all proposed countermeasures to some degree.

- Seasonal and geographic variation of conditions in U.S. waters may warrant region-specific system designs.

- Based on a standard crew size of 21 persons, personnel would be available on tankers to operate properly engineered countermeasures from the ship, assuming other damage assessment and control activities have been accommodated. However, if the manning scale is reduced, sufficient personnel may not be available. In the case of barges, personnel would also be available to operate countermeasures. Crew training would be required in the case of some countermeasure concepts.

- The simulation model used in this study appears to be a viable tool for predicting the performance of self-help countermeasures. However, at this stage of development, it should be viewed as a prototype. This tool can be refined and updated as more theoretical and empirical results are reported. One such refinement would be the incorporation of an improved/refined model for determining the time-dependant outflow of oil, which would improve the accuracy of the countermeasure performance prediction.

- No clear winner is apparent from the simulation runs made in the course of this study. However, the results do suggest that a pumping solution in conjunction with some form of containment has the most promise for achieving a real self-help capability for ships within the near term.

## 6.1 RECOMMENDATIONS FOR FUTURE RESEARCH

### 6.1.1 Pumping-Containment

Based on the findings of this investigation, it is recommended that research pertaining to onboard self-help countermeasure concepts focus on the pumping-containment category of concepts.

A pumping-containment concept that holds considerable promise as a near-term solution is *internal transfer*. Strong justification exists for exploring in detail the feasibility of pumping oil from a penetrated cargo tank(s) to some other compartment within the vessel (e.g., undamaged dedicated clean ballast tanks, slop tanks, and/or other available onboard containment, such as the ullage of undamaged cargo tanks, in the case of vessels that are hydrostatically loaded). At an information exchange meeting in Toronto, Canada, representatives of the tanker industry expressed an interest in this concept. Moreover, one of these representatives stated that his company was currently transporting crude in tank vessels that were hydrostatically loaded.

Another pumping-containment concept that should be explored further is *pumping-over-the-top* from a penetrated cargo tank to overboard containment (DRACONES/bladder) that has been deployed from the vessel. The representatives of the tanker industry at the Toronto meeting preferred the internal transfer concept to this concept; however, they agreed with PNL that this concept may be applicable to barges.

It is recommended that a research program designed to explore in detail the feasibility of each of the two foregoing concepts be conducted and that it include the following elements:

- Concept Analysis and Technical Considerations: This element would include identifying functional requirements; determining extent of retrofit required; and conducting an assessment of potential reliability, inspectibility, and maintainability, together with an assessment of the potential effectiveness (based on amount of oil retained) of each concept.

- Benefit-Cost Analysis: This element would compare the estimated life-cycle cost for each concept with the estimated potential cost avoidance realized.

- Safety Considerations: This element would assess the potential for fire and explosion together with ship stability and structure considerations associated with the concepts.

- Human Factors Considerations: This element would cover the requirements for manning, training, and skills/seamanship and would include a function and task analysis for each concept considered.

- Regulatory Constraints: This element would consider the regulatory requirements/constraints applicable to the proposed concepts as set forth in U.S. Code of Federal Regulations, 33 CFR Subchapter O and 46 CFR Subchapter D.

- Operational Considerations: This element would consider the impact of the proposed concepts on the ability to perform damage assessment, salvage, lightering, removal and recovery of oil from the water, and subsequent cleaning of contaminated areas, such as dedicated clean ballast and pumping systems.

- Environmental Constraints: This element would assess the effectiveness of the proposed concepts in relation to the environmental scenarios set forth in this report.

### 6.1.2 Develop the Oil Outflow Model

To obtain more realistic oil outflow times, especially in the case of grounding, it is recommended that the oil outflow model employed in support of this study be further developed. This development would include replacing the existing method for computing outflow in the case of grounding with a parametric approach, similar to what is used for collision. In addition, the revision would expand the model to consider manifolding tank vents, ground plugging effect, and dissipation of energy in breaking/deforming the ground and in altering the trim of the ship. The model would also be provided with a capability for distinguishing between hull penetration and hull damage. Also, during the course of development, the model would be made more user friendly.

To facilitate assessment of the potential effectiveness of the proposed pumping-containment self-help scenarios, and associated contingency plans, the enhanced outflow model would be used to determine the maximum allowable response time and corresponding hole size as a result of grounding and/or collision. A database containing casualty (ship damage) data would also be developed to support this assessment. This database would be used in determining the most probable range of hole sizes that should be considered for various tanker/barge sizes. Also, this database would be used in validating/verifying the enhanced model.

### 6.1.3 Develop Functional Criteria for Onboard Self-Help Countermeasure Systems

Based on the findings of this study, development of functional criteria for onboard self-help countermeasures is recommended. These criteria would provide a basis for developing and evaluating conceptual designs of onboard self-help countermeasure systems, including the aforementioned proposed concepts.

### 6.1.4 Develop a Global Simulation Model

The simulation models developed for assessing each of the self-help categories considered in this study would be combined into a global simulation model to assess the effectiveness of combining self-help categories/system types. The resulting global model would incorporate the proposed enhanced oil outflow model and would subsequently be used to evaluate the proposed combined pumping and containment categories.

### 6.1.5 Assess Environmental Data

A comprehensive set of wind, wave, ice and current data for U.S. waters was assembled for this study. Although this was essential to provide a sound statistical basis for the development of the scenarios for broad geographical regions, only a small fraction of the total amount of data collected was used in this study and included in this report. It is recommended that the scenarios be refined for specific areas where oil commerce is concentrated or the risk of accidents is anomalously high. In this way, self-help measures could be designed for specific regions, perhaps making them more effective and less costly. This effort would also have direct application to rule making, as it would address the following three fundamental questions:

- What removal equipment is appropriate for tank vessels to carry?
- What removal equipment should be carried on tank barges?
- Should the area of the vessel's operation or the regional availability of support equipment affect the onboard equipment-carriage requirements?

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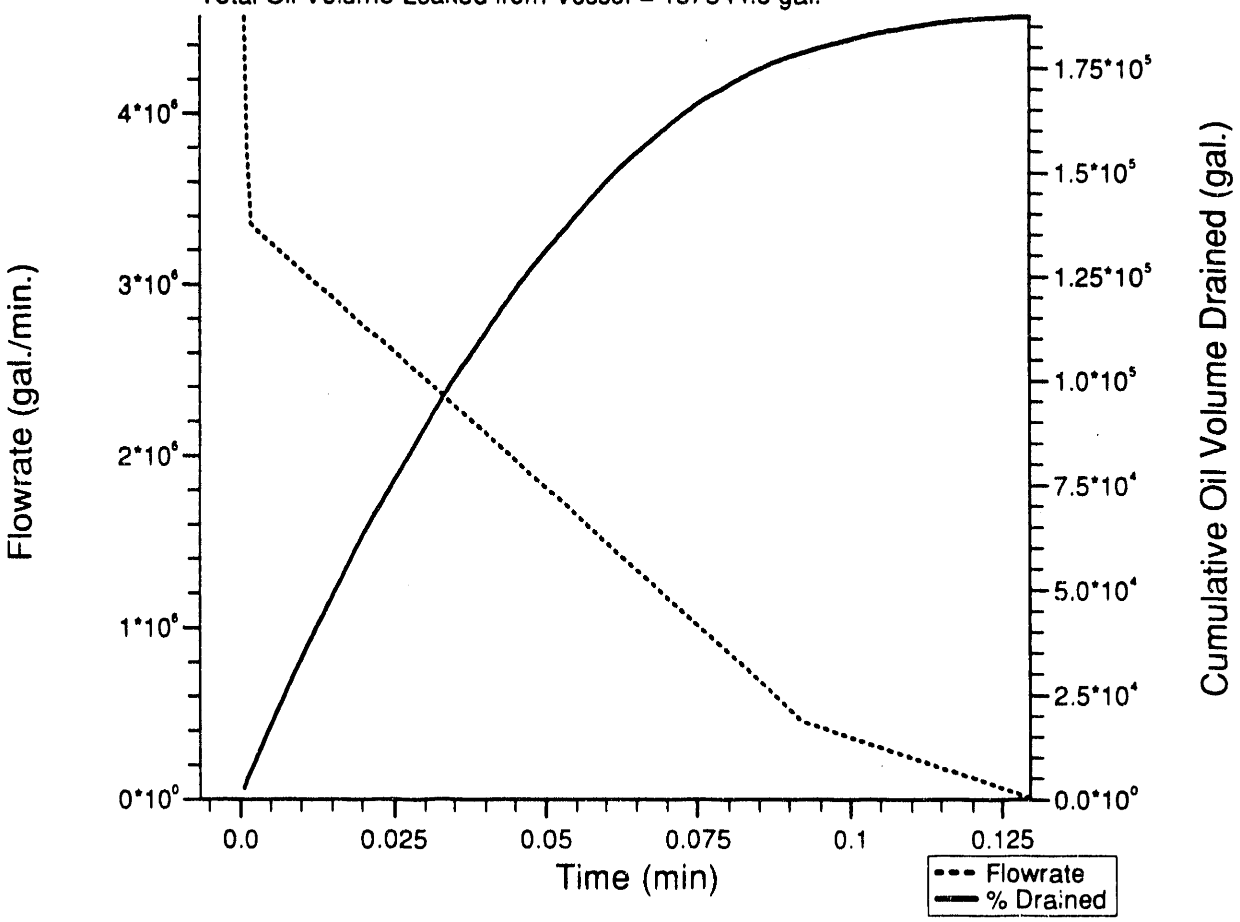
# APPENDIX A

## RESULTS OF OUTFLOW CALCULATIONS

## Oil Outflow in Case of Vessel Grounding
## for 34000 DWT Tanker

Vessel Velocity = 10.0 knots
Damage Length = 70.81 ft.
2 Tanks penetrated
Damage Width = 8.47 ft.
Fraction of Penetration Plugged by Reef = 0.00
Cumulative Oil Volume in Penetrated tank(s) = 1396765.6 gal.
Total Oil Volume Leaked from Vessel = 187344.8 gal.



Tanker Grounding Tanker DWT = 34000. tons

Accident Occurred in Salt Water Cargo Specific Gravity = .86

Draft = 36.0 ft Ship Velocity = 10.0 knots

Penetration Width = 8.47 ft Penetration Length = 70.81 ft

Penetration Area = 599.8 sq. ft No. Tanks Penetrated = 2

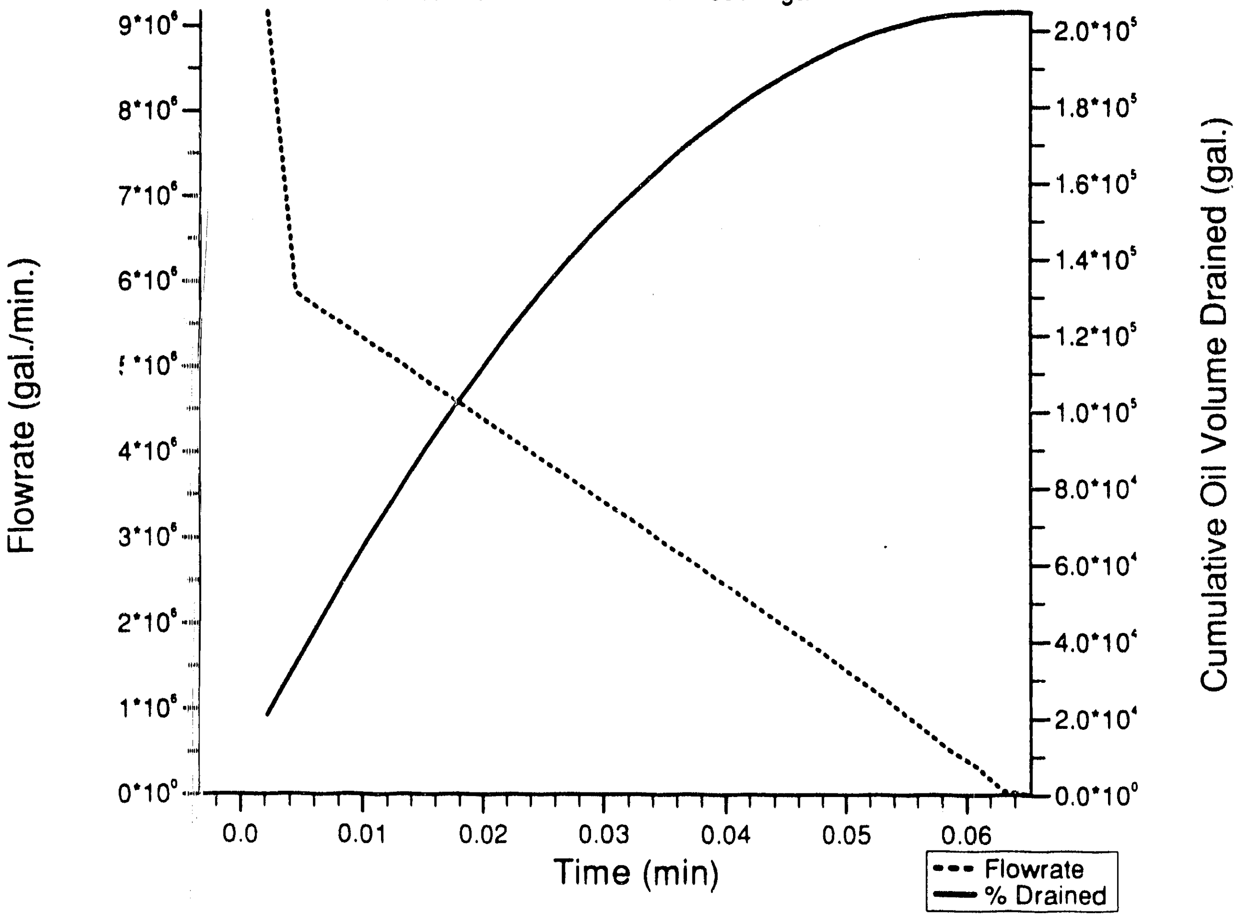
Fraction of Penetration Plugged by Reef = 0.00

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.00 | 2705.77 | 0.19 | 4565316.00 |
| 0.00 | 10876.92 | 0.78 | 3312035.25 |
| 0.01 | 18617.19 | 1.33 | 3236694.50 |
| 0.01 | 28041.36 | 2.01 | 3142511.25 |
| 0.01 | 35379.72 | 2.53 | 3067157.50 |
| 0.01 | 44301.44 | 3.17 | 2972957.00 |
| 0.02 | 51237.82 | 3.67 | 2897589.50 |
| 0.02 | 57995.51 | 4.15 | 2822214.25 |
| 0.02 | 66191.31 | 4.74 | 2727985.50 |
| 0.02 | 72546.90 | 5.19 | 2652590.50 |
| 0.03 | 80240.02 | 5.74 | 2558338.75 |
| 0.03 | 86193.38 | 6.17 | 2482928.25 |
| 0.03 | 93383.66 | 6.69 | 2388645.25 |
| 0.03 | 98934.70 | 7.08 | 2313208.00 |
| 0.04 | 104306.88 | 7.47 | 2237760.00 |
| 0.04 | 110770.53 | 7.93 | 2143430.25 |
| 0.04 | 115740.17 | 8.29 | 2067954.62 |
| 0.05 | 121700.55 | 8.71 | 1973581.12 |
| 0.05 | 126267.47 | 9.04 | 1898066.50 |
| 0.05 | 131724.33 | 9.43 | 1803646.50 |
| 0.05 | 135888.31 | 9.73 | 1728086.00 |
| 0.06 | 139873.12 | 10.01 | 1652498.75 |
| 0.06 | 144602.08 | 10.35 | 1557976.38 |
| 0.06 | 148183.52 | 10.61 | 1482329.00 |
| 0.06 | 152408.05 | 10.91 | 1387715.25 |
| 0.07 | 155585.73 | 11.14 | 1311977.12 |
| 0.07 | 159305.20 | 11.41 | 1217228.25 |
| 0.07 | 162078.53 | 11.60 | 1141360.38 |
| 0.07 | 164671.89 | 11.79 | 1065415.75 |
| 0.08 | 167660.16 | 12.00 | 970347.94 |
| 0.08 | 169847.69 | 12.16 | 894132.00 |
| 0.08 | 172327.59 | 12.34 | 798601.88 |
| 0.08 | 174107.19 | 12.47 | 721838.12 |
| 0.09 | 176074.61 | 12.61 | 625103.00 |
| 0.09 | 177440.06 | 12.70 | 546168.25 |
| 0.09 | 178874.95 | 12.81 | 450180.00 |
| 0.09 | 179901.14 | 12.88 | 422462.38 |
| 0.10 | 180861.56 | 12.95 | 394728.88 |
| 0.10 | 181969.61 | 13.03 | 360036.00 |
| 0.10 | 182782.02 | 13.09 | 332260.19 |
| 0.11 | 183704.84 | 13.15 | 297506.62 |
| 0.11 | 184368.89 | 13.20 | 269666.12 |
| 0.11 | 184966.89 | 13.24 | 241793.55 |
| 0.11 | 185621.36 | 13.29 | 206884.25 |
| 0.12 | 186070.34 | 13.32 | 178882.44 |
| 0.12 | 186538.05 | 13.35 | 143757.11 |
| 0.12 | 186837.03 | 13.38 | 115511.78 |
| 0.12 | 187116.03 | 13.40 | 79852.60 |
| 0.13 | 187262.44 | 13.41 | 50804.93 |
| 0.13 | 187344.83 | 13.41 | 0.00 |

# Oil Outflow in Case of Vessel Grounding

## for 89700 DWT Tanker

Vessel Velocity = 10.0 knots  
Damage Length = 124.72 ft.  
2 Tanks penetrated  
Damage Width = 10.65 ft.  
Fraction of Penetration Plugged by Reef = 0.00  
Cumulative Oil Volume in Penetrated tank(s) = 2867224.5 gal.  
Total Oil Volume Leaked from Vessel = 204690.7 gal.



Tanker Grounding    Tanker DWT = 89700. tons

Accident Occurred in Salt Water    Cargo Specific Gravity = .86

Draft = 49.1 ft    Ship Velocity = 10.0 knots

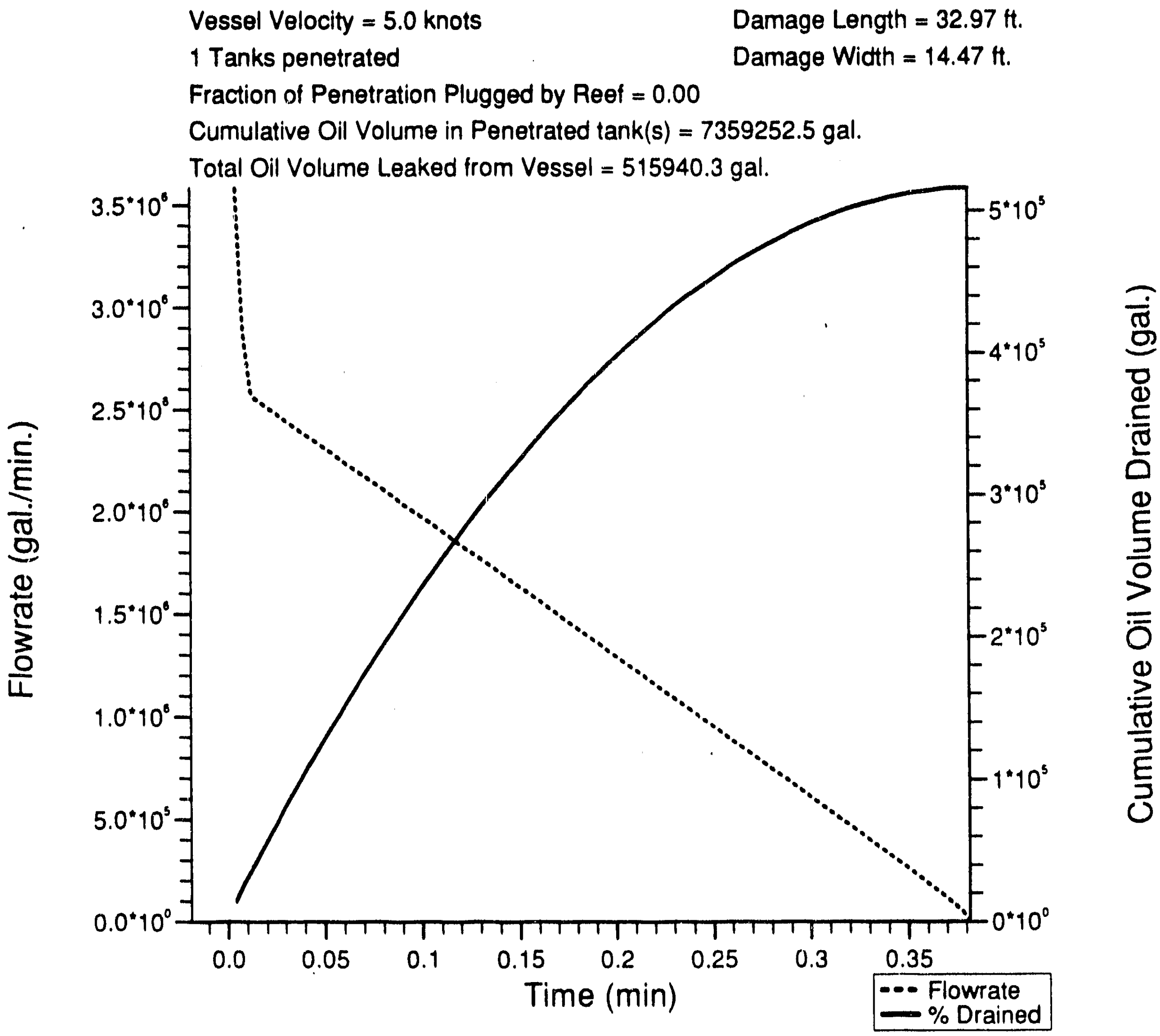
Penetration Width = 10.65 ft    Penetration Length = 124.72 ft

Penetration Area = 1328.8 sq. ft    No. Tanks Penetrated = 2

Fraction of Penetration Plugged by Reef = 0.00

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.00 | 20645.35 | 0.72 | 9163997.00 |
| 0.00 | 33862.56 | 1.18 | 5866818.50 |
| 0.01 | 46595.29 | 1.63 | 5651766.00 |
| 0.01 | 58843.18 | 2.05 | 5436554.50 |
| 0.01 | 70605.84 | 2.46 | 5221178.00 |
| 0.01 | 81882.87 | 2.86 | 5005613.50 |
| 0.02 | 92673.82 | 3.23 | 4789852.50 |
| 0.02 | 102978.16 | 3.59 | 4573863.50 |
| 0.02 | 112795.38 | 3.93 | 4357637.50 |
| 0.02 | 122124.84 | 4.26 | 4141138.00 |
| 0.02 | 130965.90 | 4.57 | 3924339.25 |
| 0.03 | 139317.78 | 4.86 | 3707209.50 |
| 0.03 | 147179.66 | 5.13 | 3489700.75 |
| 0.03 | 154550.52 | 5.39 | 3271754.25 |
| 0.03 | 161429.30 | 5.63 | 3053330.75 |
| 0.04 | 167814.66 | 5.85 | 2834313.75 |
| 0.04 | 173705.11 | 6.06 | 2614636.25 |
| 0.04 | 179098.83 | 6.25 | 2394148.50 |
| 0.04 | 183993.62 | 6.42 | 2172688.00 |
| 0.05 | 188386.75 | 6.57 | 1950009.62 |
| 0.05 | 192274.70 | 6.71 | 1725776.12 |
| 0.05 | 195652.81 | 6.82 | 1499460.25 |
| 0.05 | 198514.33 | 6.92 | 1270159.88 |
| 0.05 | 200848.62 | 7.00 | 1036141.88 |
| 0.06 | 202633.84 | 7.07 | 792422.12 |
| 0.06 | 203827.58 | 7.11 | 529865.94 |
| 0.06 | 204573.55 | 7.13 | 331121.69 |
| 0.06 | 204690.73 | 7.14 | 52015.82 |
| 0.07 | 204690.73 | 7.14 | 0.00 |

## Oil Outflow in Case of Vessel Grounding
## for 225000 DWT Tanker



Tanker Grounding Tanker DWT = 225000. tons

Accident Occurred in Salt Water Cargo Specific Gravity = .86

Draft = 70.3 ft Ship Velocity = 5.0 knots

Penetration Width = 14.47 ft Penetration Length = 32.97 ft

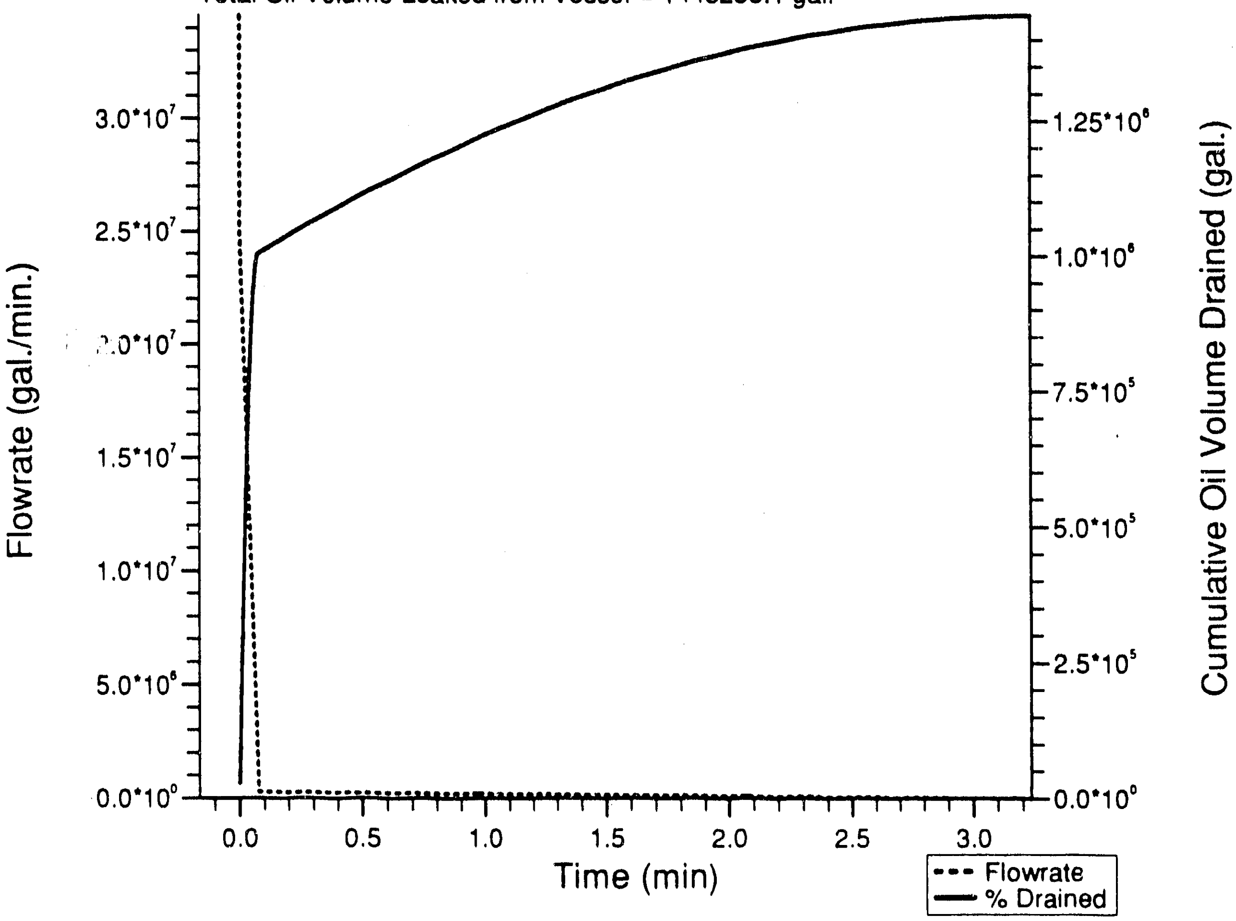
Penetration Area = 477.2 sq. ft No. Tanks Penetrated = 1

Fraction of Penetration Plugged by Reef = 0.00

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.00 | 14718.51 | 0.20 | 3583040.50 |
| 0.01 | 26513.55 | 0.36 | 2871358.75 |
| 0.02 | 47487.29 | 0.65 | 2539002.50 |
| 0.02 | 68004.21 | 0.92 | 2483394.75 |
| 0.03 | 88064.25 | 1.20 | 2427781.25 |
| 0.04 | 107667.35 | 1.46 | 2372162.00 |
| 0.05 | 126813.45 | 1.72 | 2316535.50 |
| 0.06 | 145502.48 | 1.98 | 2260899.25 |
| 0.06 | 154675.59 | 2.10 | 2233080.00 |
| 0.07 | 172678.91 | 2.35 | 2177430.25 |
| 0.08 | 190224.97 | 2.58 | 2121771.25 |
| 0.09 | 207313.72 | 2.82 | 2066109.38 |
| 0.09 | 223945.06 | 3.04 | 2010427.50 |
| 0.10 | 240118.92 | 3.26 | 1954741.00 |
| 0.11 | 255835.23 | 3.48 | 1899046.00 |
| 0.12 | 263521.75 | 3.58 | 1871192.50 |
| 0.12 | 278551.53 | 3.79 | 1815475.50 |
| 0.13 | 293123.44 | 3.98 | 1759740.00 |
| 0.14 | 307237.41 | 4.17 | 1703999.62 |
| 0.15 | 320893.31 | 4.36 | 1648237.38 |
| 0.16 | 334091.00 | 4.54 | 1592464.12 |
| 0.16 | 346830.34 | 4.71 | 1536669.62 |
| 0.17 | 353028.09 | 4.80 | 1508768.62 |
| 0.18 | 365079.66 | 4.96 | 1452949.38 |
| 0.18 | 376672.50 | 5.12 | 1397107.75 |
| 0.19 | 387806.44 | 5.27 | 1341241.12 |
| 0.20 | 398481.25 | 5.41 | 1285351.62 |
| 0.21 | 408696.72 | 5.55 | 1229435.88 |
| 0.22 | 418452.69 | 5.69 | 1173495.75 |
| 0.22 | 423158.25 | 5.75 | 1145515.38 |
| 0.23 | 432224.41 | 5.87 | 1089519.62 |
| 0.24 | 440830.31 | 5.99 | 1033494.00 |
| 0.25 | 448975.69 | 6.10 | 977426.88 |
| 0.25 | 456660.06 | 6.21 | 921303.06 |
| 0.26 | 463883.12 | 6.30 | 865134.88 |
| 0.27 | 470644.38 | 6.40 | 808913.00 |
| 0.28 | 473851.66 | 6.44 | 780771.81 |
| 0.28 | 479919.16 | 6.52 | 724436.00 |
| 0.29 | 485523.31 | 6.60 | 668026.88 |
| 0.30 | 490663.31 | 6.67 | 611502.62 |
| 0.31 | 495338.25 | 6.73 | 55[illegible]851.62 |
| 0.32 | 499546.88 | 6.79 | 498057.88 |
| 0.32 | 503287.88 | 6.84 | 441096.38 |
| 0.33 | 504982.41 | 6.86 | 412514.81 |
| 0.34 | 508018.25 | 6.90 | 355163.00 |
| 0.35 | 510580.44 | 6.94 | 297415.69 |
| 0.35 | 512664.81 | 6.97 | 239070.31 |
| 0.36 | 514264.59 | 6.99 | 179841.89 |
| 0.37 | 515367.75 | 7.00 | 118862.97 |
| 0.38 | 515940.34 | 7.01 | 0.00 |

## Oil Outflow in Case of Vessel Grounding
## for 225000 DWT Tanker

Vessel Velocity = 10.0 knots
Damage Length = 317.92 ft.
3 Tanks penetrated
Damage Width = 14.47 ft.
Fraction of Penetration Plugged by Reef = 0.00
Cumulative Oil Volume in Penetrated tank(s) = 20614960.0 gal.
Total Oil Volume Leaked from Vessel = 1445258.1 gal.



Tanker Grounding Tanker DWT = 225000. tons

Accident Occurred in Salt Water Cargo Specific Gravity = .86

Draft = 70.3 ft Ship Velocity = 10.0 knots

Penetration Width = 14.47 ft Penetration Length = 317.92 ft

Penetration Area = 4601.2 sq. ft No. Tanks Penetrated = 3

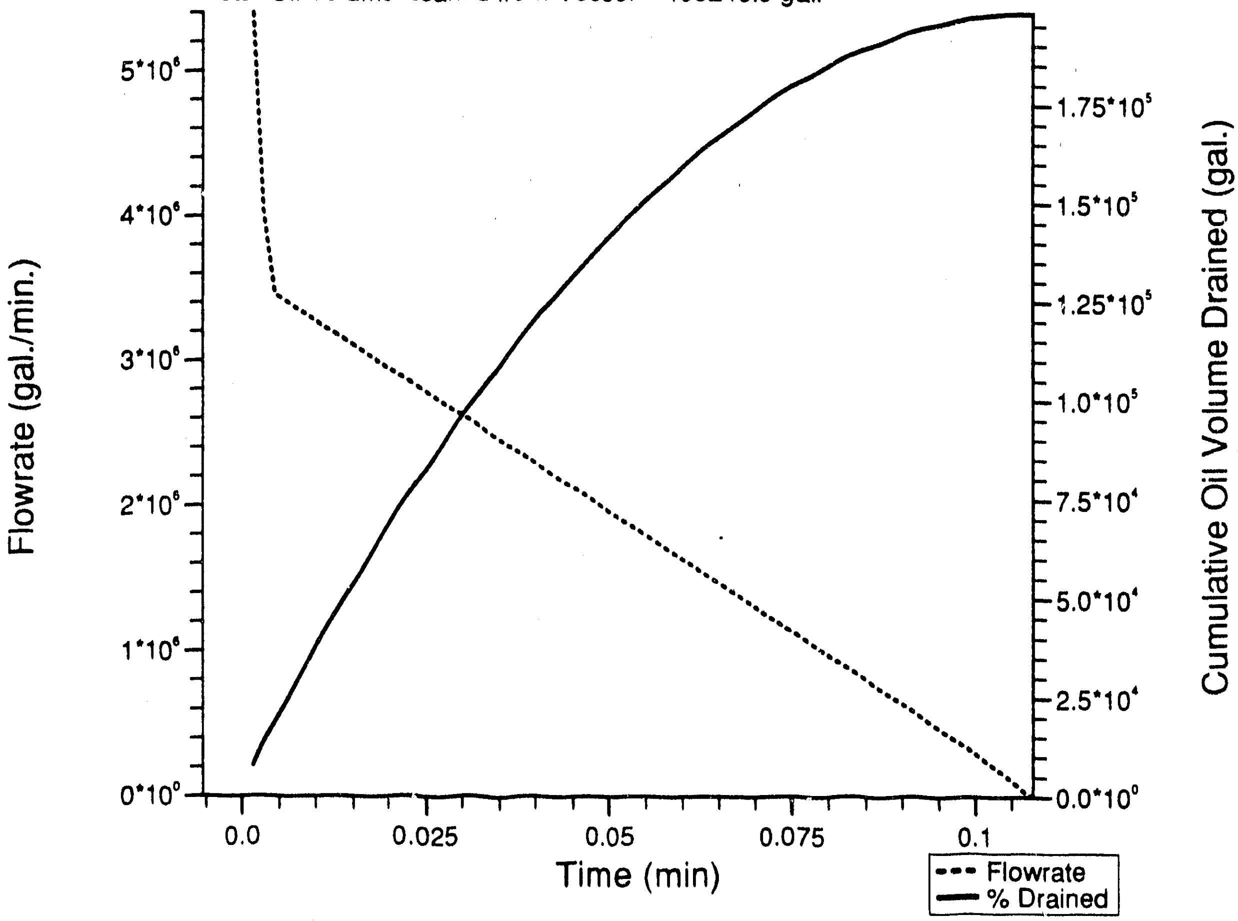
Fraction of Penetration Plugged by Reef = 0.00

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.00 | 28292.70 | 0.14 | 34546532.00 |
| 0.07 | 984282.81 | 4.77 | 3938944.25 |
| 0.13 | 1020451.31 | 4.95 | 273566.31 |
| 0.20 | 1038183.44 | 5.04 | 267797.28 |
| 0.26 | 1055752.12 | 5.12 | 261956.39 |
| 0.33 | 1072723.75 | 5.20 | 256187.47 |
| 0.40 | 1089522.12 | 5.29 | 250346.55 |
| 0.46 | 1105933.12 | 5.36 | 244505.41 |
| 0.53 | 1121761.38 | 5.44 | 238736.14 |
| 0.59 | 1137402.25 | 5.52 | 232895.28 |
| 0.66 | 1152469.62 | 5.59 | 227126.12 |
| 0.73 | 1167340.38 | 5.66 | 221285.20 |
| 0.79 | 1181647.25 | 5.73 | 215516.22 |
| 0.86 | 1195747.88 | 5.80 | 209674.45 |
| 0.92 | 1209460.88 | 5.87 | 203833.50 |
| 0.99 | 1222624.25 | 5.93 | 198064.09 |
| 1.06 | 1235567.00 | 5.99 | 192223.06 |
| 1.12 | 1247969.88 | 6.05 | 186453.86 |
| 1.19 | 1260142.38 | 6.11 | 180612.72 |
| 1.25 | 1271784.38 | 6.17 | 174842.73 |
| 1.32 | 1283186.62 | 6.22 | 169001.45 |
| 1.39 | 1294201.50 | 6.28 | 163160.30 |
| 1.45 | 1304700.00 | 6.33 | 157390.19 |
| 1.52 | 1314944.62 | 6.38 | 151548.86 |
| 1.58 | 1324682.38 | 6.43 | 145779.39 |
| 1.65 | 1334156.75 | 6.47 | 139937.31 |
| 1.72 | 1343133.88 | 6.52 | 134168.56 |
| 1.78 | 1351838.00 | 6.56 | 128325.63 |
| 1.85 | 1360154.50 | 6.60 | 122483.94 |
| 1.91 | 1367988.00 | 6.64 | 116714.47 |
| 1.98 | 1375534.38 | 6.67 | 110871.80 |
| 2.05 | 1382607.00 | 6.71 | 105101.73 |
| 2.11 | 1389383.00 | 6.74 | 99259.34 |
| 2.18 | 1395694.88 | 6.77 | 93489.35 |
| 2.24 | 1401700.38 | 6.80 | 87646.47 |
| 2.31 | 1407318.50 | 6.83 | 81803.52 |
| 2.38 | 1412486.75 | 6.85 | 76032.96 |
| 2.44 | 1417334.38 | 6.88 | 70191.43 |
| 2.51 | 1421741.38 | 6.90 | 64418.51 |
| 2.57 | 1425818.62 | 6.92 | 58576.17 |
| 2.64 | 1429465.00 | 6.93 | 52803.94 |
| 2.71 | 1432771.62 | 6.95 | 46958.72 |
| 2.77 | 1435690.50 | 6.96 | 41114.66 |
| 2.84 | 1438192.88 | 6.98 | 35341.38 |
| 2.90 | 1440341.00 | 6.99 | 29494.14 |
| 2.97 | 1442081.75 | 7.00 | 23717.67 |
| 3.04 | 1443458.38 | 7.00 | 17869.86 |
| 3.10 | 1444437.50 | 7.01 | 12082.23 |
| 3.17 | 1445042.25 | 7.01 | 6220.72 |
| 3.23 | 1445258.12 | 7.01 | 0.00 |

## Oil Outflow in Case of Vessel Grounding for 262000 DWT Tanker

Vessel Velocity = 5.0 knots
1 Tanks penetrated
Fraction of Penetration Plugged by Reef = 0.00
Cumulative Oil Volume in Penetrated tank(s) = 3938834.8 gal.
Total Oil Volume Leaked from Vessel = 198219.8 gal.

Damage Length = 44.20 ft.
Damage Width = 17.95 ft.



Tanker Grounding    Tanker DWT = 262000. tons

Accident Occurred in Salt Water    Cargo Specific Gravity = .86

Draft = 67.2 ft    Ship Velocity = 5.0 knots

Penetration Width = 17.95 ft    Penetration Length = 44.20 ft

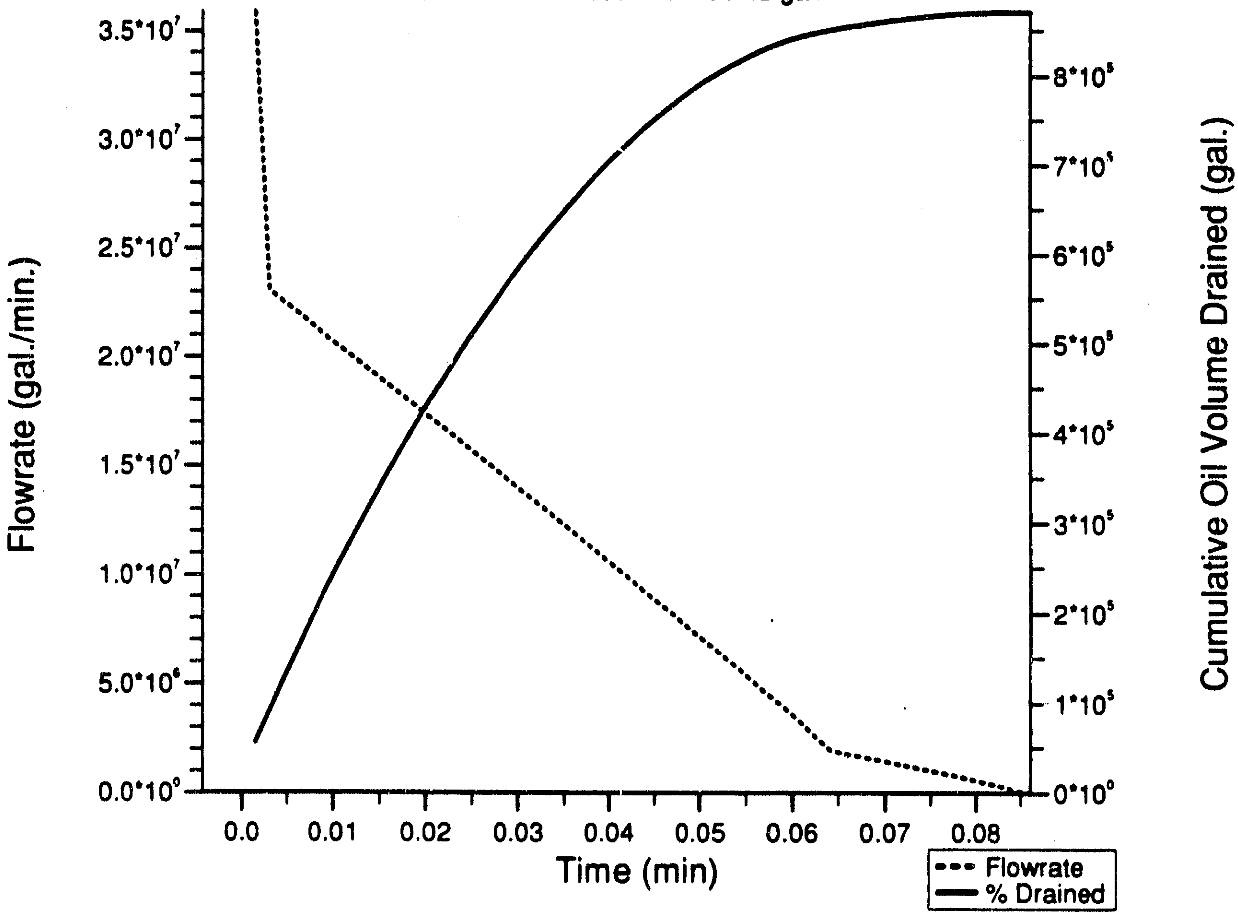
Penetration Area = 793.4 sq. ft    No. Tanks Penetrated = 1

Fraction of Penetration Plugged by Reef = 0.00

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.00 | 7877.67 | 0.20 | 5401056.50 |
| 0.00 | 13751.19 | 0.35 | 4026983.50 |
| 0.00 | 18801.23 | 0.48 | 3462384.75 |
| 0.01 | 28692.43 | 0.73 | 3366911.75 |
| 0.01 | 33533.59 | 0.85 | 3319176.50 |
| 0.01 | 43006.99 | 1.09 | 3223682.00 |
| 0.01 | 47639.21 | 1.21 | 3175926.75 |
| 0.02 | 56694.66 | 1.44 | 3080395.00 |
| 0.02 | 61117.88 | 1.55 | 3032629.75 |
| 0.02 | 69755.23 | 1.77 | 2937062.00 |
| 0.02 | 73969.36 | 1.88 | 2889271.25 |
| 0.02 | 82188.45 | 2.09 | 2793669.00 |
| 0.03 | 86193.41 | 2.19 | 2745862.75 |
| 0.03 | 93994.08 | 2.39 | 2650212.75 |
| 0.03 | 97789.77 | 2.48 | 2602382.00 |
| 0.03 | 105171.78 | 2.67 | 2506690.50 |
| 0.04 | 108758.09 | 2.76 | 2458830.25 |
| 0.04 | 112274.59 | 2.85 | 2410968.50 |
| 0.04 | 119098.09 | 3.02 | 2315203.00 |
| 0.04 | 122405.05 | 3.11 | 2267304.75 |
| 0.04 | 128809.32 | 3.27 | 2171476.50 |
| 0.05 | 131906.61 | 3.35 | 2123552.50 |
| 0.05 | 137891.39 | 3.50 | 2027657.12 |
| 0.05 | 140778.84 | 3.57 | 1979682.88 |
| 0.05 | 146343.78 | 3.72 | 1883704.25 |
| 0.05 | 149021.20 | 3.78 | 1835687.88 |
| 0.06 | 154165.89 | 3.91 | 1739616.00 |
| 0.06 | 156633.08 | 3.98 | 1691546.88 |
| 0.06 | 161357.00 | 4.10 | 1595344.38 |
| 0.06 | 163613.69 | 4.15 | 1547218.88 |
| 0.07 | 167916.34 | 4.26 | 1450898.50 |
| 0.07 | 169962.22 | 4.32 | 1402698.88 |
| 0.07 | 173842.89 | 4.41 | 1306191.88 |
| 0.07 | 175677.61 | 4.46 | 1257905.88 |
| 0.07 | 177441.81 | 4.50 | 1209569.12 |
| 0.08 | 180758.52 | 4.59 | 1112783.50 |
| 0.08 | 182310.88 | 4.63 | 1064324.25 |
| 0.08 | 185203.28 | 4.70 | 967259.38 |
| 0.08 | 186543.16 | 4.74 | 918637.94 |
| 0.08 | 189009.73 | 4.80 | 821164.94 |
| 0.09 | 190136.20 | 4.83 | 772331.94 |
| 0.09 | 192174.75 | 4.88 | 674293.88 |
| 0.09 | 193086.48 | 4.90 | 625089.50 |
| 0.09 | 194693.73 | 4.94 | 526206.62 |
| 0.09 | 195388.69 | 4.96 | 476468.66 |
| 0.10 | 196559.16 | 4.99 | 376056.31 |
| 0.10 | 197033.48 | 5.00 | 325206.38 |
| 0.10 | 197755.45 | 5.02 | 221325.88 |
| 0.10 | 197999.59 | 5.03 | 167385.42 |
| 0.11 | 198219.78 | 5.03 | 0.00 |

## Oil Outflow in Case of Vessel Grounding
## for 262000 DWT Tanker

Vessel Velocity = 10.0 knots
Damage Length = 293.73 ft.
3 Tanks penetrated
Damage Width = 17.95 ft.
Fraction of Penetration Plugged by Reef = 0.00
Cumulative Oil Volume in Penetrated tank(s) = 17302738.0 gal.
Total Oil Volume Leaked from Vessel = 870984.2 gal.



Tanker Grounding Tanker DWT = 262000. tons

Accident Occurred in Salt Water Cargo Specific Gravity = .86

Draft = 67.2 ft Ship Velocity = 10.0 knots

Penetration Width = 17.95 ft Penetration Length = 293.73 ft

Penetration Area = 5272.6 sq. ft No. Tanks Penetrated = 3

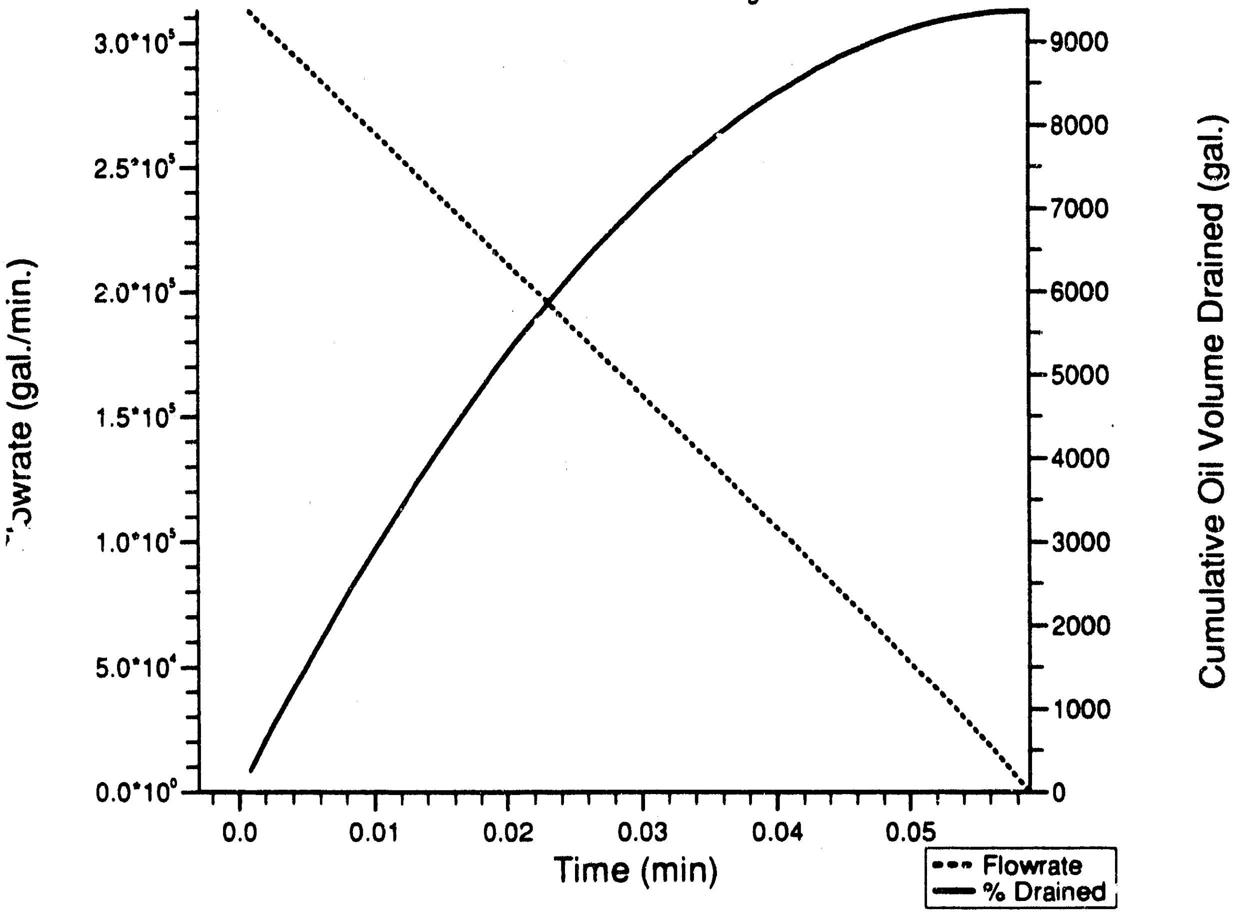
Fraction of Penetration Plugged by Reef = 0.00

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.00 | 56224.99 | 0.32 | 35892176.00 |
| 0.00 | 92366.16 | 0.53 | 23071336.00 |
| 0.00 | 127655.52 | 0.74 | 22527550.00 |
| 0.01 | 162119.69 | 0.94 | 22000790.00 |
| 0.01 | 195758.39 | 1.13 | 21473834.00 |
| 0.01 | 228571.38 | 1.32 | 20946722.00 |
| 0.01 | 260558.39 | 1.51 | 20419456.00 |
| 0.01 | 291719.16 | 1.69 | 19892004.00 |
| 0.01 | 322053.28 | 1.86 | 19364308.00 |
| 0.02 | 351560.53 | 2.03 | 18836468.00 |
| 0.02 | 380240.56 | 2.20 | 18308374.00 |
| 0.02 | 408092.88 | 2.36 | 17780022.00 |
| 0.02 | 435117.28 | 2.51 | 17251480.00 |
| 0.02 | 486680.34 | 2.81 | 16193518.00 |
| 0.03 | 511218.03 | 2.95 | 15664044.00 |
| 0.03 | 534925.88 | 3.09 | 15134292.00 |
| 0.03 | 557803.25 | 3.22 | 14604149.00 |
| 0.03 | 579849.56 | 3.35 | 14073650.00 |
| 0.03 | 601064.12 | 3.47 | 13542674.00 |
| 0.03 | 621446.19 | 3.59 | 13011254.00 |
| 0.03 | 640995.06 | 3.70 | 12479354.00 |
| 0.04 | 659709.81 | 3.81 | 11946855.00 |
| 0.04 | 677589.38 | 3.92 | 11413748.00 |
| 0.04 | 694632.94 | 4.01 | 10880012.00 |
| 0.04 | 710839.00 | 4.11 | 10345427.00 |
| 0.04 | 740733.38 | 4.28 | 9273581.00 |
| 0.05 | 754418.44 | 4.36 | 8736095.00 |
| 0.05 | 767259.31 | 4.43 | 8197154.00 |
| 0.05 | 779253.62 | 4.50 | 7656768.50 |
| 0.05 | 790398.19 | 4.57 | 7114292.00 |
| 0.05 | 800689.50 | 4.63 | 6569636.00 |
| 0.05 | 810123.00 | 4.68 | 6022056.50 |
| 0.05 | 818692.44 | 4.73 | 5470454.50 |
| 0.06 | 826390.19 | 4.78 | 4913964.00 |
| 0.06 | 833203.69 | 4.82 | 4349558.00 |
| 0.06 | 839114.06 | 4.85 | 3772971.25 |
| 0.06 | 844083.38 | 4.88 | 3172229.75 |
| 0.06 | 851026.69 | 4.92 | 1938781.25 |
| 0.07 | 853855.44 | 4.93 | 1805783.38 |
| 0.07 | 856475.25 | 4.95 | 1672412.25 |
| 0.07 | 858885.50 | 4.96 | 1538620.12 |
| 0.07 | 861085.31 | 4.98 | 1404286.25 |
| 0.07 | 863073.62 | 4.99 | 1269297.62 |
| 0.07 | 864849.44 | 5.00 | 1133618.50 |
| 0.08 | 866411.19 | 5.01 | 996967.12 |
| 0.08 | 867756.75 | 5.02 | 858966.50 |
| 0.08 | 868883.19 | 5.02 | 719048.19 |
| 0.08 | 869786.25 | 5.03 | 576465.50 |
| 0.08 | 870458.69 | 5.03 | 429265.34 |
| 0.09 | 870984.25 | 5.03 | 0.00 |

## Oil Outflow in Case of Vessel Grounding for 1769 GT Barge

Vessel Velocity = 8.0 knots
1 Tanks penetrated
Fraction of Penetration Plugged by Reef = 0.00
Cumulative Oil Volume in Penetrated tank(s) = 129626.2 gal.
Total Oil Volume Leaked from Vessel = 9363.8 gal.

Damage Length = 27.67 ft.
Damage Width = 5.45 ft.



Barge Grounding     Barge GT = 1769.

Accident Occurred in Fresh Water     Cargo Specific Gravity = .92

Draft = 9.6 ft     Ship Velocity = 8.0 knots

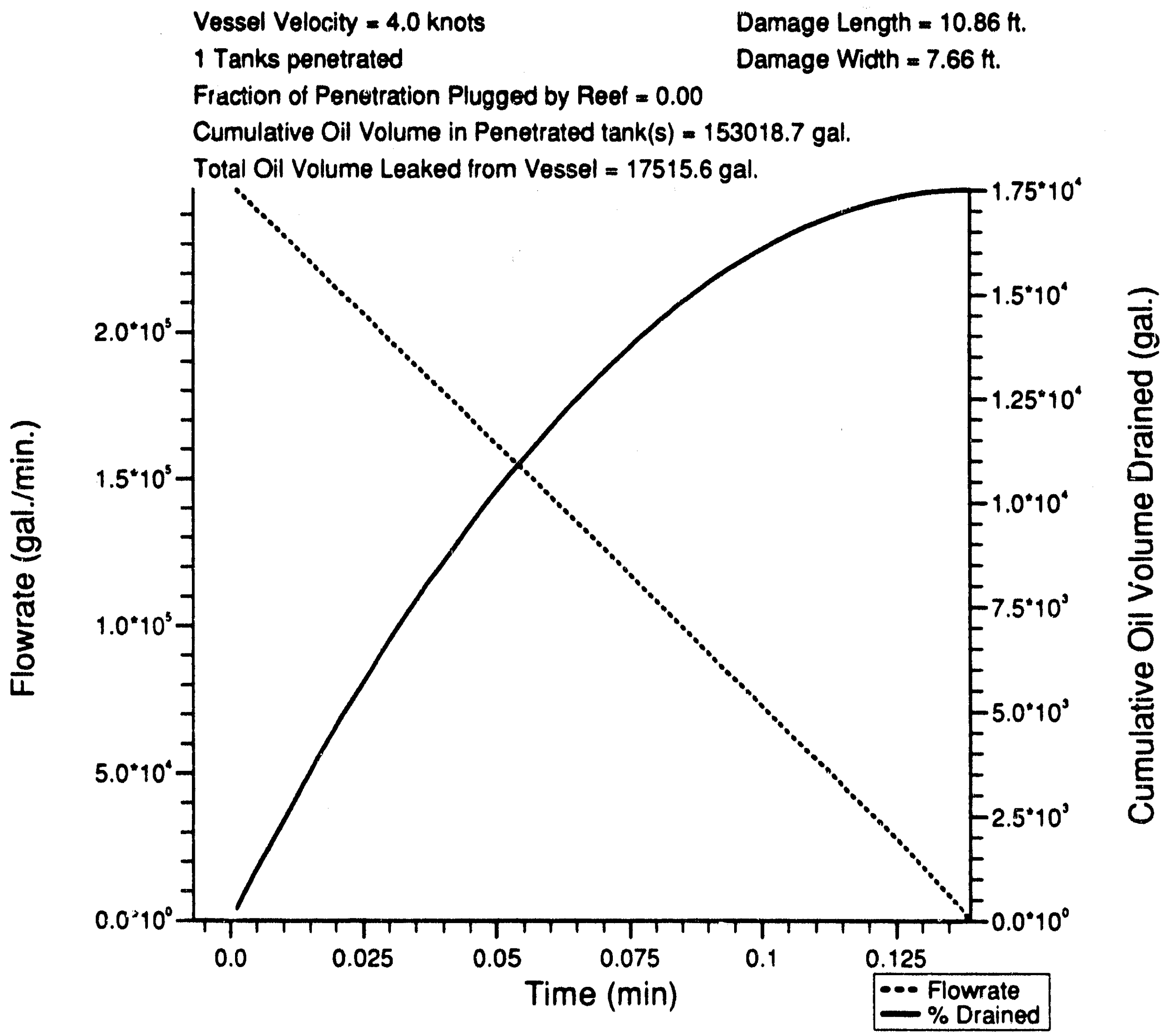
Penetration Width = 5.45 ft     Penetration Length = 27.67 ft

Penetration Area = 150.7 sq. ft     No. Tanks Penetrated = 1

Fraction of Penetration Plugged by Reef = 0.00

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.00 | 259.25 | 0.20 | 312672.31 |
| 0.00 | 514.89 | 0.40 | 308313.41 |
| 0.00 | 766.91 | 0.59 | 303952.25 |
| 0.00 | 1260.11 | 0.97 | 295230.69 |
| 0.00 | 1501.29 | 1.16 | 290870.34 |
| 0.01 | 1972.78 | 1.52 | 282145.75 |
| 0.01 | 2203.11 | 1.70 | 277782.56 |
| 0.01 | 2429.81 | 1.87 | 273419.19 |
| 0.01 | 2872.37 | 2.22 | 264690.56 |
| 0.01 | 3088.22 | 2.38 | 260325.23 |
| 0.01 | 3509.05 | 2.71 | 251592.39 |
| 0.01 | 3714.04 | 2.87 | 247224.75 |
| 0.01 | 3915.41 | 3.02 | 242856.78 |
| 0.02 | 4307.27 | 3.32 | 234119.55 |
| 0.02 | 4497.77 | 3.47 | 229750.25 |
| 0.02 | 4867.89 | 3.76 | 221007.22 |
| 0.02 | 5047.51 | 3.89 | 216634.81 |
| 0.02 | 5223.51 | 4.03 | 212261.72 |
| 0.02 | 5564.62 | 4.29 | 203511.91 |
| 0.02 | 5729.73 | 4.42 | 199135.00 |
| 0.02 | 6049.07 | 4.67 | 190380.11 |
| 0.02 | 6203.29 | 4.79 | 186000.33 |
| 0.03 | 6353.88 | 4.90 | 181619.44 |
| 0.03 | 6644.16 | 5.13 | 172854.02 |
| 0.03 | 6783.85 | 5.23 | 168469.30 |
| 0.03 | 7052.31 | 5.44 | 159695.30 |
| 0.03 | 7181.08 | 5.54 | 155305.73 |
| 0.03 | 7427.70 | 5.73 | 146520.80 |
| 0.03 | 7545.54 | 5.82 | 142125.03 |
| 0.03 | 7659.73 | 5.91 | 137726.81 |
| 0.04 | 7877.18 | 6.08 | 128927.06 |
| 0.04 | 7980.43 | 6.16 | 124522.67 |
| 0.04 | 8175.96 | 6.31 | 115703.08 |
| 0.04 | 8268.24 | 6.38 | 111291.51 |
| 0.04 | 8356.85 | 6.45 | 106873.91 |
| 0.04 | 8523.08 | 6.58 | 98029.17 |
| 0.04 | 8600.69 | 6.63 | 93599.37 |
| 0.04 | 8744.87 | 6.75 | 84724.94 |
| 0.04 | 8811.44 | 6.80 | 80280.75 |
| 0.05 | 8874.31 | 6.85 | 75826.42 |
| 0.05 | 8988.95 | 6.93 | 66896.69 |
| 0.05 | 9040.71 | 6.97 | 62418.26 |
| 0.05 | 9133.03 | 7.05 | 53422.93 |
| 0.05 | 9173.58 | 7.08 | 48902.35 |
| 0.05 | 9210.36 | 7.11 | 44364.03 |
| 0.05 | 9272.55 | 7.15 | 35201.98 |
| 0.05 | 9297.90 | 7.17 | 30574.44 |
| 0.06 | 9336.87 | 7.20 | 21116.77 |
| 0.06 | 9350.31 | 7.21 | 16209.73 |
| 0.06 | 9363.79 | 7.22 | 0.00 |

## Oil Outflow in Case of Vessel Grounding for 2713 GT Barge



Barge Grounding Barge GT = 2713.

Accident Occurred in Salt Water Cargo Specific Gravity = .86

Draft = 12.0 ft Ship Velocity = 4.0 knots

Penetration Width = 7.66 ft Penetration Length = 10.86 ft

Penetration Area = 83.2 sq. ft No. Tanks Penetrated = 1

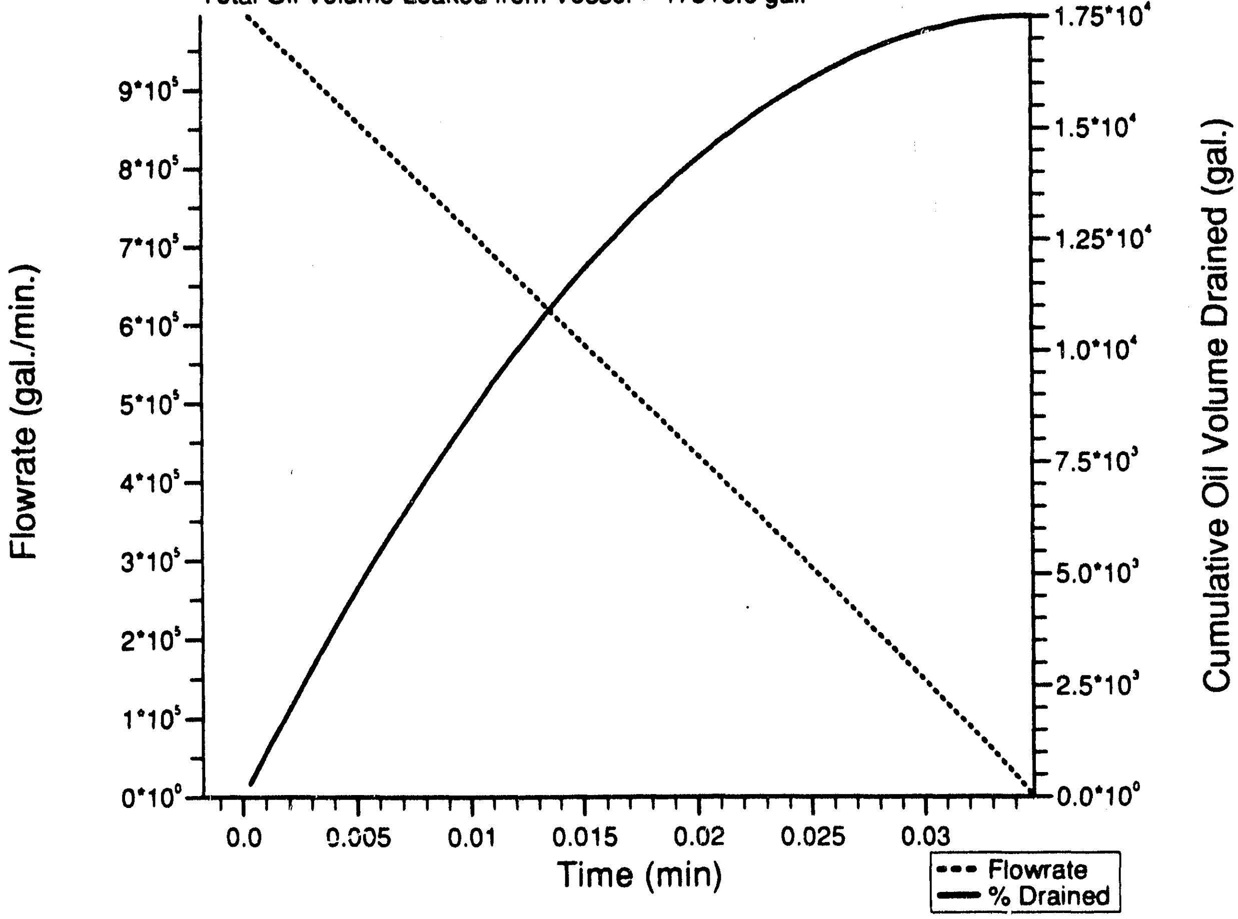
Fraction of Penetration Plugged by Reef = 0.00

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.00 | 306.04 | 0.20 | 248577.62 |
| 0.00 | 910.06 | 0.59 | 244215.19 |
| 0.01 | 1503.33 | 0.98 | 239852.16 |
| 0.01 | 2085.86 | 1.36 | 235488.52 |
| 0.01 | 2939.51 | 1.92 | 228942.56 |
| 0.01 | 3495.18 | 2.28 | 224578.16 |
| 0.02 | 4040.10 | 2.64 | 220213.50 |
| 0.02 | 4574.28 | 2.99 | 215848.08 |
| 0.02 | 5355.38 | 3.50 | 209299.36 |
| 0.03 | 5862.67 | 3.83 | 204932.94 |
| 0.03 | 6359.22 | 4.16 | 200566.12 |
| 0.03 | 6845.01 | 4.47 | 196198.41 |
| 0.03 | 7553.53 | 4.94 | 189646.52 |
| 0.04 | 8012.43 | 5.24 | 185277.36 |
| 0.04 | 8460.57 | 5.53 | 180908.30 |
| 0.04 | 8897.95 | 5.81 | 176538.08 |
| 0.05 | 9533.84 | 6.23 | 169981.84 |
| 0.05 | 9944.32 | 6.50 | 165610.31 |
| 0.05 | 10344.03 | 6.76 | 161237.47 |
| 0.05 | 10923.40 | 7.14 | 154676.84 |
| 0.06 | 11296.18 | 7.38 | 150302.11 |
| 0.06 | 11658.19 | 7.62 | 145926.42 |
| 0.06 | 12009.42 | 7.85 | 141549.62 |
| 0.07 | 12516.06 | 8.18 | 134983.20 |
| 0.07 | 12840.35 | 8.39 | 130603.64 |
| 0.07 | 13153.84 | 8.60 | 126222.57 |
| 0.07 | 13456.55 | 8.79 | 121841.55 |
| 0.08 | 13890.38 | 9.08 | 115265.31 |
| 0.08 | 14166.10 | 9.26 | 110880.04 |
| 0.08 | 14431.02 | 9.43 | 106492.54 |
| 0.08 | 14685.13 | 9.60 | 102103.52 |
| 0.09 | 15046.02 | 9.83 | 95515.61 |
| 0.09 | 15273.10 | 9.98 | 91120.63 |
| 0.09 | 15489.34 | 10.12 | 86723.12 |
| 0.10 | 15793.40 | 10.32 | 80121.76 |
| 0.10 | 15982.55 | 10.44 | 75717.24 |
| 0.10 | 16160.85 | 10.56 | 71308.44 |
| 0.10 | 16328.28 | 10.67 | 66896.05 |
| 0.11 | 16559.04 | 10.82 | 60266.63 |
| 0.11 | 16699.27 | 10.91 | 55842.07 |
| 0.11 | 16828.[illegible]8 | 11.00 | 51406.16 |
| 0.11 | 16946.96 | 11.08 | 46966.49 |
| 0.12 | 17103.98 | 11.18 | 40284.63 |
| 0.12 | 17194.91 | 11.24 | 35810.56 |
| 0.12 | 17274.81 | 11.29 | 31323.24 |
| 0.13 | 17343.61 | 11.33 | 26812.26 |
| 0.13 | 17425.83 | 11.39 | 19979.03 |
| 0.13 | 17466.48 | 11.41 | 15350.49 |
| 0.13 | 17495.54 | 11.43 | 10608.35 |
| 0.14 | 17515.63 | 11.45 | 0.00 |

## Oil Outflow in Case of Vessel Grounding
## for 2713 GT Barge

Vessel Velocity = 8.0 knots
1 Tanks penetrated
Fraction of Penetration Plugged by Reef = 0.00
Cumulative Oil Volume in Penetrated tank(s) = 153018.7 gal.
Total Oil Volume Leaked from Vessel = 17515.6 gal.

Damage Length = 43.45 ft.
Damage Width = 7.66 ft.



Barge Grounding Barge GT = 2713.

Accident Occurred in Salt Water Cargo Specific Gravity = .86

Draft = 12.0 ft Ship Velocity = 8.0 knots

Penetration Width = 7.66 ft Penetration Length = 43.45 ft

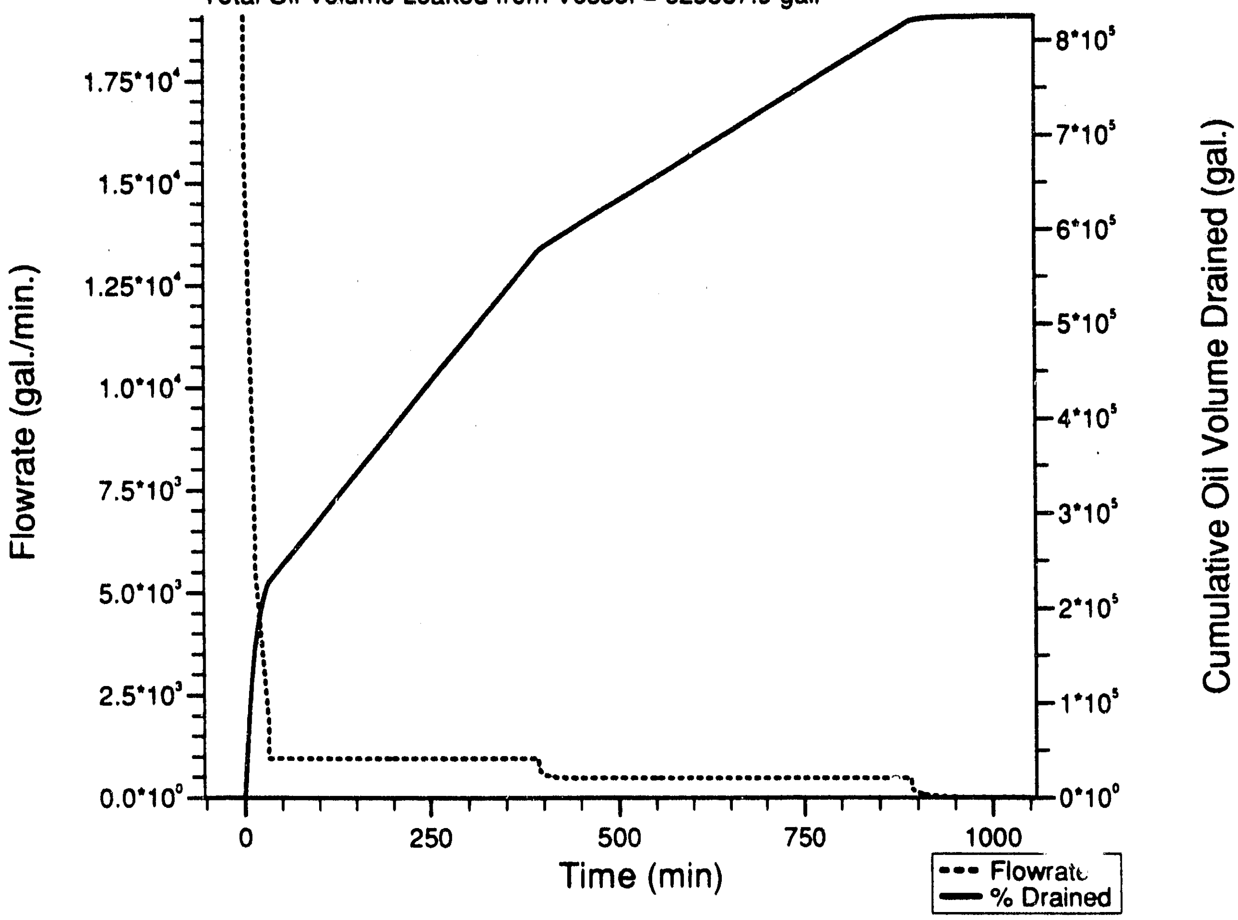
Penetration Area = 332.9 sq. ft No. Tanks Penetrated = 1

Fraction of Penetration Plugged by Reef = 0.00

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.00 | 306.04 | 0.20 | 994310.50 |
| 0.00 | 910.06 | 0.59 | 976860.75 |
| 0.00 | 1503.33 | 0.98 | 959408.62 |
| 0.00 | 2085.86 | 1.36 | 941954.06 |
| 0.00 | 2939.51 | 1.92 | 915770.25 |
| 0.00 | 3495.18 | 2.28 | 898312.62 |
| 0.00 | 4040.10 | 2.64 | 880854.00 |
| 0.00 | 4574.28 | 2.99 | 863392.31 |
| 0.01 | 5355.38 | 3.50 | 837197.44 |
| 0.01 | 5862.67 | 3.83 | 819731.75 |
| 0.01 | 6359.22 | 4.16 | 802264.50 |
| 0.01 | 6845.01 | 4.47 | 784793.62 |
| 0.01 | 7553.53 | 4.94 | 758586.06 |
| 0.01 | 8012.43 | 5.24 | 741109.44 |
| 0.01 | 8460.57 | 5.53 | 723633.19 |
| 0.01 | 8897.95 | 5.81 | 706152.31 |
| 0.01 | 9533.84 | 6.23 | 679927.38 |
| 0.01 | 9944.32 | 6.50 | 662441.25 |
| 0.01 | 10344.03 | 6.76 | 644949.88 |
| 0.01 | 10923.40 | 7.14 | 618707.38 |
| 0.01 | 11296.18 | 7.38 | 601208.44 |
| 0.01 | 11658.19 | 7.62 | 583705.69 |
| 0.02 | 12009.42 | 7.85 | 566198.50 |
| 0.02 | 12516.06 | 8.18 | 539932.81 |
| 0.02 | 12840.35 | 8.39 | 522414.56 |
| 0.02 | 13153.84 | 8.60 | 504890.28 |
| 0.02 | 13456.55 | 8.79 | 487366.19 |
| 0.02 | 13890.38 | 9.08 | 461061.25 |
| 0.02 | 14166.10 | 9.26 | 443520.16 |
| 0.02 | 14431.02 | 9.43 | 425970.16 |
| 0.02 | 14685.13 | 9.60 | 408414.09 |
| 0.02 | 15046.02 | 9.83 | 382062.44 |
| 0.02 | 15273.10 | 9.98 | 364482.53 |
| 0.02 | 15489.34 | 10.12 | 346892.47 |
| 0.02 | 15793.40 | 10.32 | 320487.03 |
| 0.02 | 15982.55 | 10.44 | 302868.97 |
| 0.03 | 16160.85 | 10.56 | 285233.75 |
| 0.03 | 16328.28 | 10.67 | 267584.19 |
| 0.03 | 16559.04 | 10.82 | 241066.53 |
| 0.03 | 16699.27 | 10.91 | 223368.28 |
| 0.03 | 16828.58 | 11.00 | 205624.64 |
| 0.03 | 16946.96 | 11.08 | 187865.95 |
| 0.03 | 17103.98 | 11.18 | 161138.53 |
| 0.03 | 17194.91 | 11.24 | 143242.23 |
| 0.03 | 17274.81 | 11.29 | 125292.98 |
| 0.03 | 17343.61 | 11.33 | 107249.05 |
| 0.03 | 17425.83 | 11.39 | 79916.13 |
| 0.03 | 17466.48 | 11.41 | 61401.95 |
| 0.03 | 17495.54 | 11.43 | 42433.42 |
| 0.03 | 17515.63 | 11.45 | 0.00 |

## Oil Outflow in Case of Vessel Collision
## for 34000 DWT Tanker

Penetration Area = 2.00 sq. ft. Damage Length = 1.00 ft.
2 Tanks penetrated Damage Height = 2.00 ft.
Height of Penetration Center with respect to Waterline = -0.2 ft.
Cumulative Oil Volume in Penetrated tank(s) = 825524.2 gal.
Total Oil Volume Leaked from Vessel = 825587.9 gal.



Tanker Collision Tanker DWT = 34000. tons

Accident Occurred in Salt Water Cargo Specific Gravity = .86

Draft = 36.0 ft

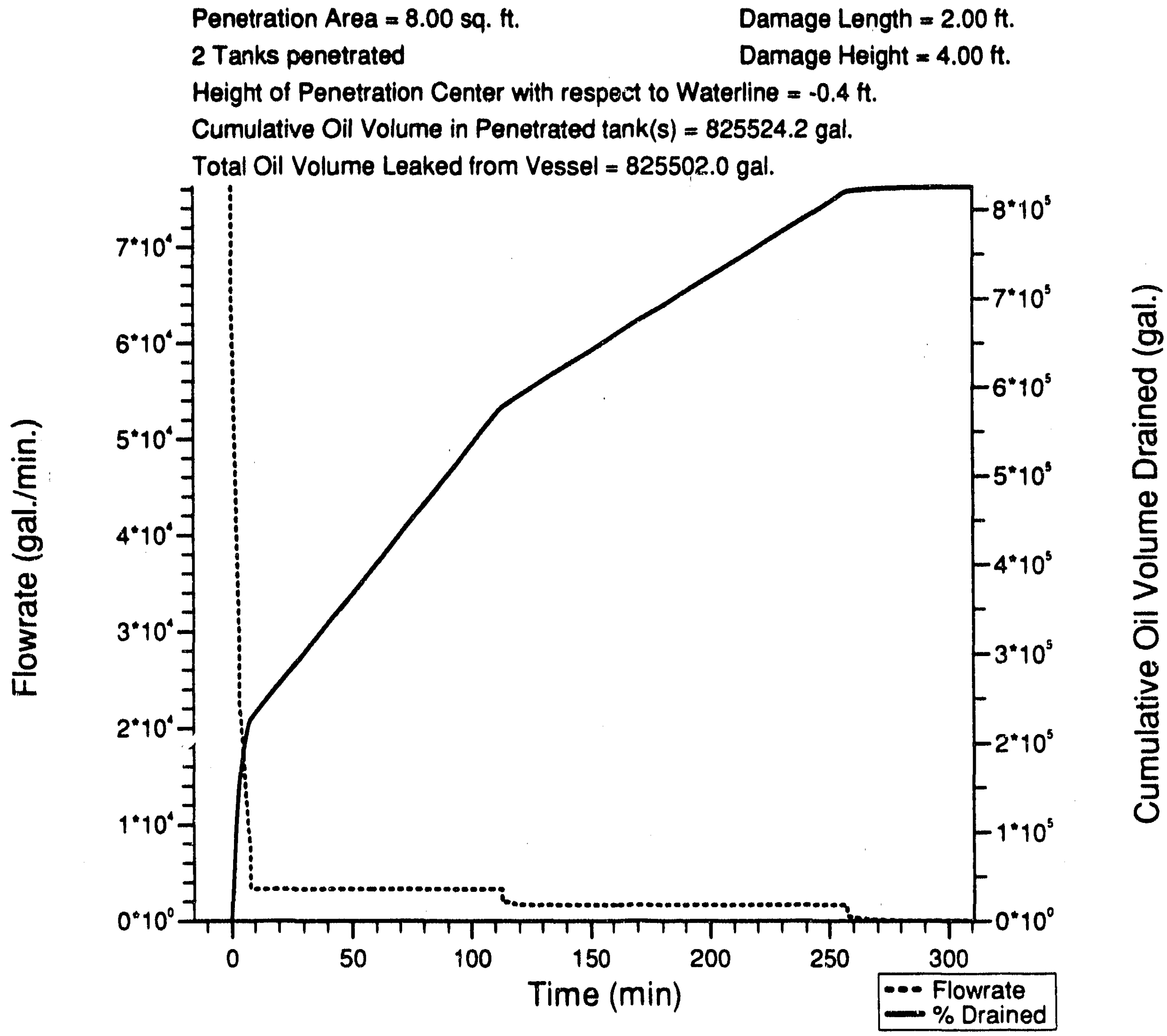
Penetration Height = 2.00 ft Penetration Length = 1.00 ft

Penetration Area = 2.0 sq. ft No. Tanks Penetrated = 2

Penetration Center w.r.t. Water Line = -0.2 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.12 | 2293.65 | 0.28 | 19081.83 |
| 21.64 | 196588.12 | 23.81 | 4053.39 |
| 43.27 | 238172.81 | 28.85 | 967.17 |
| 64.79 | 258982.06 | 31.37 | 967.17 |
| 86.42 | 279907.59 | 33.91 | 967.17 |
| 108.06 | 300833.09 | 36.44 | 967.17 |
| 129.58 | 321642.34 | 38.96 | 967.17 |
| 151.21 | 342567.84 | 41.50 | 967.17 |
| 172.85 | 363493.38 | 44.03 | 967.17 |
| 194.36 | 384302.62 | 46.55 | 967.17 |
| 216.00 | 405228.12 | 49.09 | 967.17 |
| 237.51 | 426037.41 | 51.61 | 967.17 |
| 259.15 | 446962.91 | 54.14 | 967.17 |
| 280.78 | 467888.41 | 56.68 | 967.17 |
| 302.30 | 488697.66 | 59.20 | 967.17 |
| 323.94 | 509623.19 | 61.73 | 967.17 |
| 345.58 | 530548.69 | 64.27 | 967.17 |
| 367.09 | 551360.81 | 66.79 | 967.17 |
| 388.73 | 572292.12 | 69.32 | 967.17 |
| 410.37 | 586702.56 | 71.07 | 520.42 |
| 431.89 | 597520.00 | 72.38 | 493.37 |
| 453.52 | 608122.56 | 73.67 | 487.89 |
| 475.04 | 618581.50 | 74.93 | 484.45 |
| 496.68 | 629064.56 | 76.20 | 484.45 |
| 518.31 | 639547.62 | 77.47 | 484.45 |
| 539.83 | 649972.50 | 78.73 | 484.45 |
| 561.46 | 660455.56 | 80.00 | 484.45 |
| 583.09 | 670938.62 | 81.27 | 484.45 |
| 604.60 | 681363.44 | 82.54 | 484.45 |
| 626.23 | 691846.50 | 83.81 | 484.45 |
| 647.75 | 702271.38 | 85.07 | 484.45 |
| 669.38 | 712754.44 | 86.34 | 484.45 |
| 691.01 | 723237.50 | 87.61 | 484.45 |
| 712.52 | 733662.31 | 88.87 | 484.45 |
| 734.15 | 744145.38 | 90.14 | 484.45 |
| 755.79 | 754628.44 | 91.41 | 484.45 |
| 777.30 | 765053.31 | 92.67 | 484.45 |
| 798.93 | 775536.38 | 93.94 | 484.45 |
| 820.56 | 786019.44 | 95.21 | 484.45 |
| 842.07 | 796444.25 | 96.48 | 484.45 |
| 863.71 | 806927.31 | 97.75 | 484.45 |
| 885.22 | 817352.19 | 99.01 | 484.45 |
| 906.85 | 822905.44 | 99.68 | 98.72 |
| 928.48 | 824255.75 | 99.85 | 38.74 |
| 949.99 | 824843.62 | 99.92 | 19.08 |
| 971.63 | 825154.12 | 99.96 | 10.73 |
| 993.26 | 825337.00 | 99.98 | 6.63 |
| 1014.77 | 825453.00 | 99.99 | 4.38 |
| 1036.41 | 825532.31 | 100.00 | 3.05 |
| 1058.17 | 825587.88 | 100.00 | 0.00 |

## Oil Outflow in Case of Vessel Collision for 34000 DWT Tanker



Tanker Collision Tanker DWT = 34000. tons

Accident Occurred in Salt Water Cargo Specific Gravity = .86

Draft = 36.0 ft

Penetration Height = 4.00 ft Penetration Length = 2.00 ft

Penetration Area = 8.0 sq. ft No. Tanks Penetrated = 2

Penetration Center w.r.t. Water Line = -0.4 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.03 | 2293.65 | 0.28 | 76245.13 |
| 6.38 | 209456.22 | 25.37 | 12677.03 |
| 12.72 | 241421.12 | 29.24 | 3344.84 |
| 19.07 | 262653.81 | 31.82 | 3344.84 |
| 25.42 | 283884.38 | 34.39 | 3344.84 |
| 31.77 | 305113.66 | 36.96 | 3344.84 |
| 38.11 | 326342.94 | 39.53 | 3344.84 |
| 44.46 | 347572.22 | 42.10 | 3344.84 |
| 50.81 | 368801.50 | 44.67 | 3344.84 |
| 57.16 | 390030.78 | 47.25 | 3344.84 |
| 63.50 | 411260.06 | 49.82 | 3344.84 |
| 69.85 | 432489.34 | 52.39 | 3344.84 |
| 76.20 | 453718.62 | 54.96 | 3344.84 |
| 82.55 | 474947.91 | 57.53 | 3344.84 |
| 88.89 | 496177.19 | 60.10 | 3344.84 |
| 95.24 | 517406.47 | 62.68 | 3344.84 |
| 101.59 | 538635.75 | 65.25 | 3344.84 |
| 107.97 | 559965.69 | 67.83 | 3344.84 |
| 114.31 | 579245.12 | 70.17 | 2024.15 |
| 120.66 | 590981.50 | 71.59 | 1755.84 |
| 127.01 | 601919.19 | 72.91 | 1701.99 |
| 133.36 | 612658.25 | 74.21 | 1684.57 |
| 139.70 | 623288.06 | 75.50 | 1668.05 |
| 146.05 | 633875.44 | 76.78 | 1668.05 |
| 152.39 | 644462.88 | 78.07 | 1668.05 |
| 158.74 | 655050.31 | 79.35 | 1668.05 |
| 165.08 | 665637.75 | 80.63 | 1668.05 |
| 171.43 | 676225.19 | 81.91 | 1668.05 |
| 177.78 | 686812.56 | 83.20 | 1668.05 |
| 184.12 | 697400.00 | 84.48 | 1668.05 |
| 190.47 | 707987.44 | 85.76 | 1668.05 |
| 196.81 | 718574.88 | 87.04 | 1668.05 |
| 203.16 | 729162.31 | 88.33 | 1668.05 |
| 209.54 | 739799.88 | 89.62 | 1668.05 |
| 215.88 | 750387.31 | 90.90 | 1668.05 |
| 222.23 | 760974.75 | 92.18 | 1668.05 |
| 228.57 | 771562.19 | 93.46 | 1668.05 |
| 234.92 | 782149.56 | 94.75 | 1668.05 |
| 241.26 | 792737.00 | 96.03 | 1668.05 |
| 247.61 | 803324.44 | 97.31 | 1668.05 |
| 253.96 | 813911.88 | 98.59 | 1668.05 |
| 260.30 | 821380.38 | 99.50 | 388.67 |
| 266.65 | 823115.69 | 99.71 | 190.27 |
| 273.00 | 824023.88 | 99.82 | 106.92 |
| 279.35 | 824558.06 | 99.88 | 65.95 |
| 285.70 | 824898.50 | 99.92 | 43.51 |
| 292.05 | 825128.75 | 99.95 | 30.20 |
| 298.40 | 825291.75 | 99.97 | 21.81 |
| 304.75 | 825411.75 | 99.99 | 16.25 |
| 311.16 | 825502.00 | 100.00 | 0.00 |

Oil Outflow in Case of Vessel Collision

for 89700 DWT Tanker

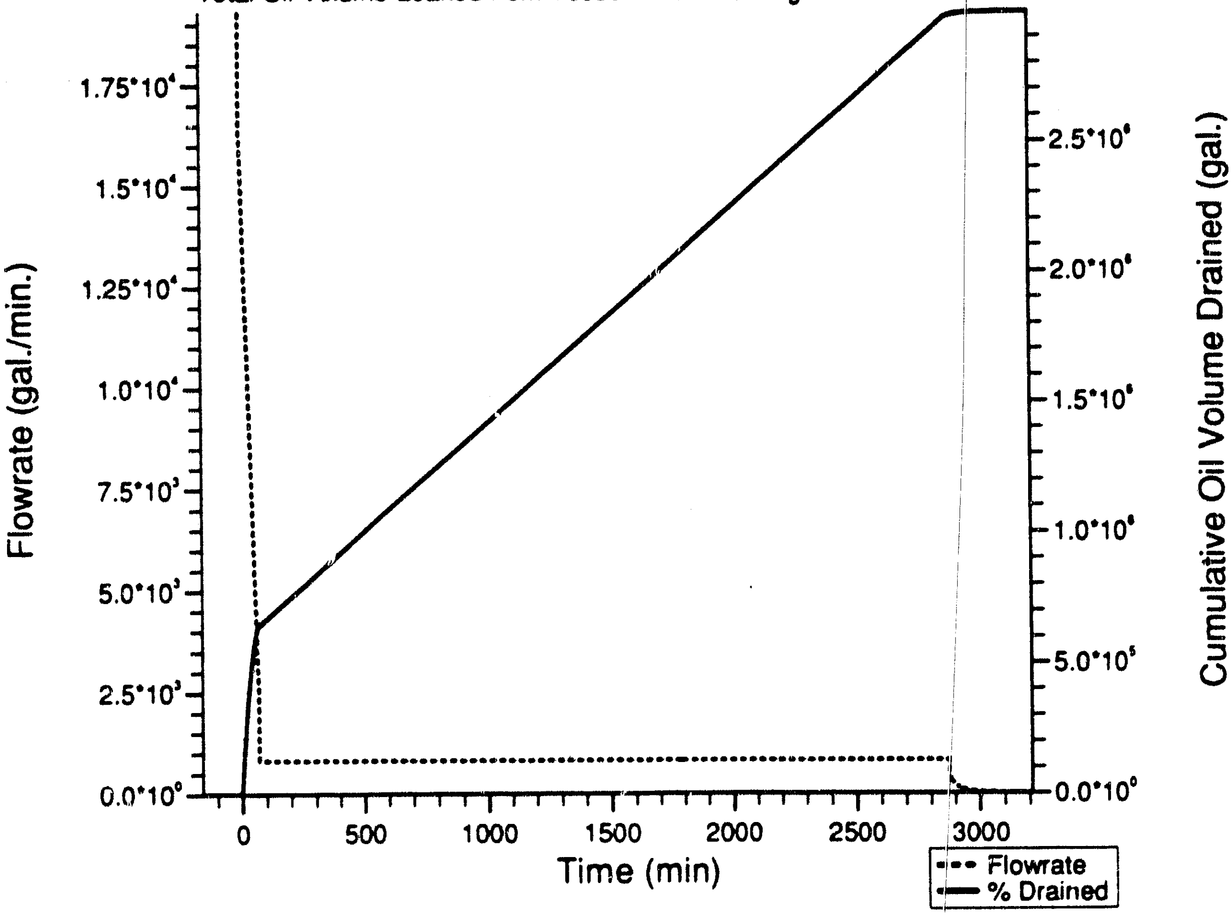
Penetration Area = 2.00 sq. ft. Damage Length = 1.00 ft.

2 Tanks penetrated Damage Height = 2.00 ft.

Height of Penetration Center with respect to Waterline = -0.0 ft.

Cumulative Oil Volume in Penetrated tank(s) = 2994851.2 gal.

Total Oil Volume Leaked from Vessel = 2994935.5 gal.



Tanker Collision    Tanker DWT = 89700. tons

Accident Occurred in Salt Water    Cargo Specific Gravity = .86

Draft = 49.1 ft

Penetration Height = 2.00 ft    Penetration Length = 1.00 ft

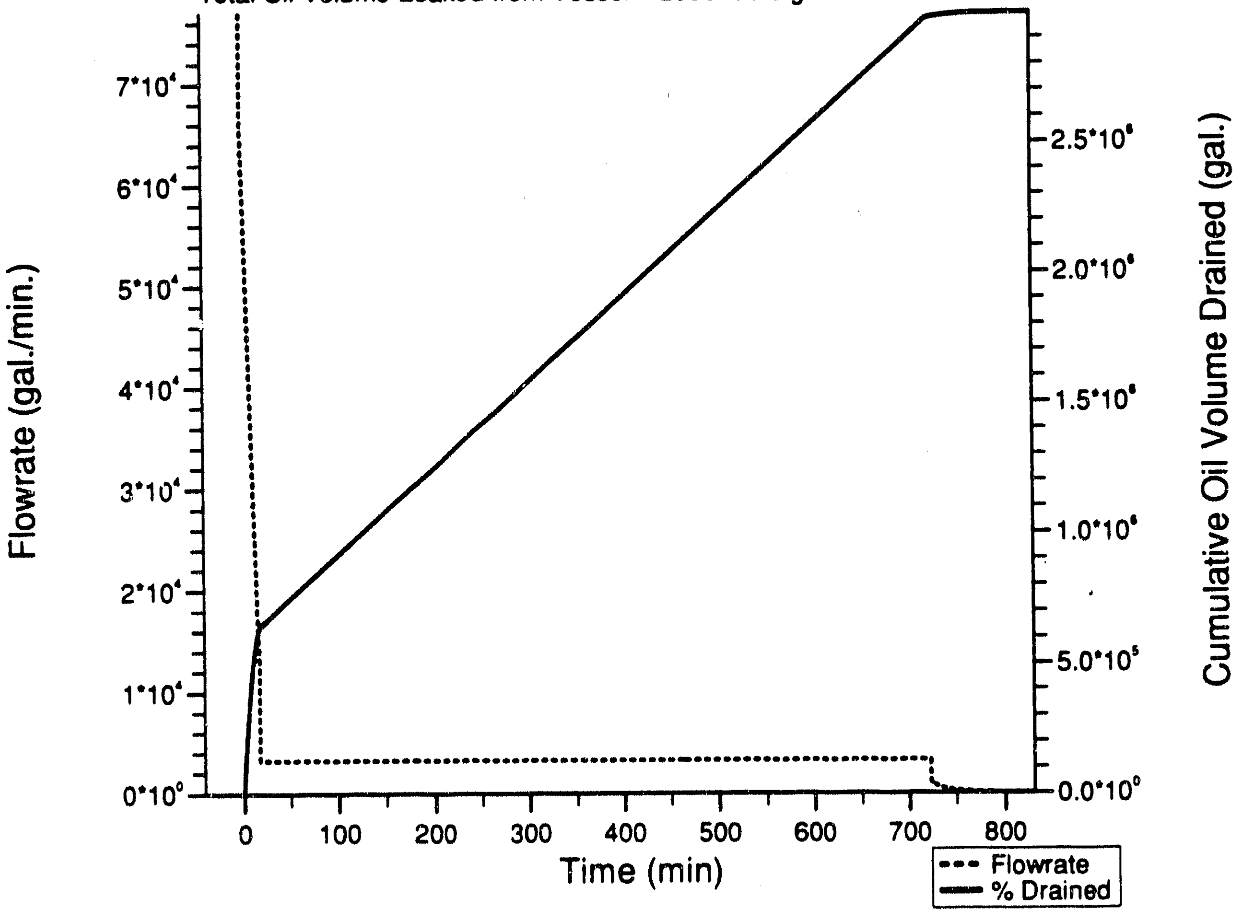
Penetration Area = 2.0 sq. ft    No. Tanks Penetrated = 2

Penetration Center w.r.t. Water Line = 0.0 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.31 | 5989.70 | 0.20 | 19282.39 |
| 65.85 | 638717.69 | 21.33 | 2864.80 |
| 131.40 | 696084.06 | 23.24 | 830.73 |
| 196.94 | 750531.75 | 25.06 | 830.73 |
| 262.48 | 804979.38 | 26.88 | 830.73 |
| 328.02 | 859427.06 | 28.70 | 830.73 |
| 393.57 | 913874.75 | 30.51 | 830.73 |
| 459.11 | 968322.38 | 32.33 | 830.73 |
| 524.66 | 1022770.06 | 34.15 | 830.73 |
| 590.20 | 1077217.75 | 35.97 | 830.73 |
| 655.73 | 1131677.75 | 37.79 | 830.73 |
| 721.27 | 1186139.00 | 39.61 | 830.73 |
| 786.81 | 1240600.38 | 41.42 | 830.73 |
| 852.35 | 1295061.62 | 43.24 | 830.73 |
| 917.89 | 1349522.88 | 45.06 | 830.73 |
| 983.43 | 1403984.12 | 46.88 | 830.73 |
| 1048.97 | 1458445.50 | 48.70 | 830.73 |
| 1114.83 | 1513164.88 | 50.53 | 830.73 |
| 1180.38 | 1567626.12 | 52.34 | 830.73 |
| 1245.93 | 1622087.38 | 54.16 | 830.73 |
| 1311.48 | 1676548.62 | 55.98 | 830.73 |
| 1377.04 | 1731010.00 | 57.80 | 830.73 |
| 1442.59 | 1785471.25 | 59.62 | 830.73 |
| 1508.14 | 1839932.50 | 61.44 | 830.73 |
| 1573.69 | 1894393.75 | 63.26 | 830.73 |
| 1639.24 | 1948855.00 | 65.07 | 830.73 |
| 1704.79 | 2003316.38 | 66.89 | 830.73 |
| 1770.34 | 2057777.62 | 68.71 | 830.73 |
| 1835.89 | 2112239.00 | 70.53 | 830.73 |
| 1901.44 | 2166698.75 | 72.35 | 830.73 |
| 1967.00 | 2221132.75 | 74.17 | 830.73 |
| 2032.55 | 2275566.75 | 75.98 | 830.73 |
| 2098.08 | 2330001.00 | 77.80 | 830.73 |
| 2163.91 | 2384693.00 | 79.63 | 830.73 |
| 2229.44 | 2439127.00 | 81.44 | 830.73 |
| 2294.96 | 2493561.00 | 83.26 | 830.73 |
| 2360.49 | 2547995.25 | 85.08 | 830.73 |
| 2426.02 | 2602429.25 | 86.90 | 830.73 |
| 2491.54 | 2656863.25 | 88.71 | 830.73 |
| 2557.07 | 2711297.25 | 90.53 | 830.73 |
| 2622.59 | 2765731.25 | 92.35 | 830.73 |
| 2688.12 | 2820165.50 | 94.17 | 830.73 |
| 2753.64 | 2874599.50 | 95.98 | 830.73 |
| 2819.17 | 2929033.50 | 97.80 | 830.73 |
| 2884.69 | 2979507.75 | 99.49 | 316.93 |
| 2950.22 | 2989726.75 | 99.83 | 72.85 |
| 3015.74 | 2992681.25 | 99.93 | 27.30 |
| 3081.27 | 2993924.75 | 99.97 | 13.05 |
| 3146.79 | 2994563.50 | 99.99 | 7.22 |
| 3212.94 | 2994935.50 | 100.00 | 0.00 |

## Oil Outflow in Case of Vessel Collision
## for 89700 DWT Tanker

Penetration Area = 8.00 sq. ft. | Damage Length = 2.00 ft.
2 Tanks penetrated | Damage Height = 4.00 ft.
Height of Penetration Center with respect to Waterline = -0.4 ft.
Cumulative Oil Volume in Penetrated tank(s) = 2994851.2 gal.
Total Oil Volume Leaked from Vessel = 2995155.8 gal.



Tanker Collision Tanker DWT = 89700. tons

Accident Occurred in Salt Water Cargo Specific Gravity = .86

Draft = 49.1 ft

Penetration Height = 4.00 ft Penetration Length = 2.00 ft

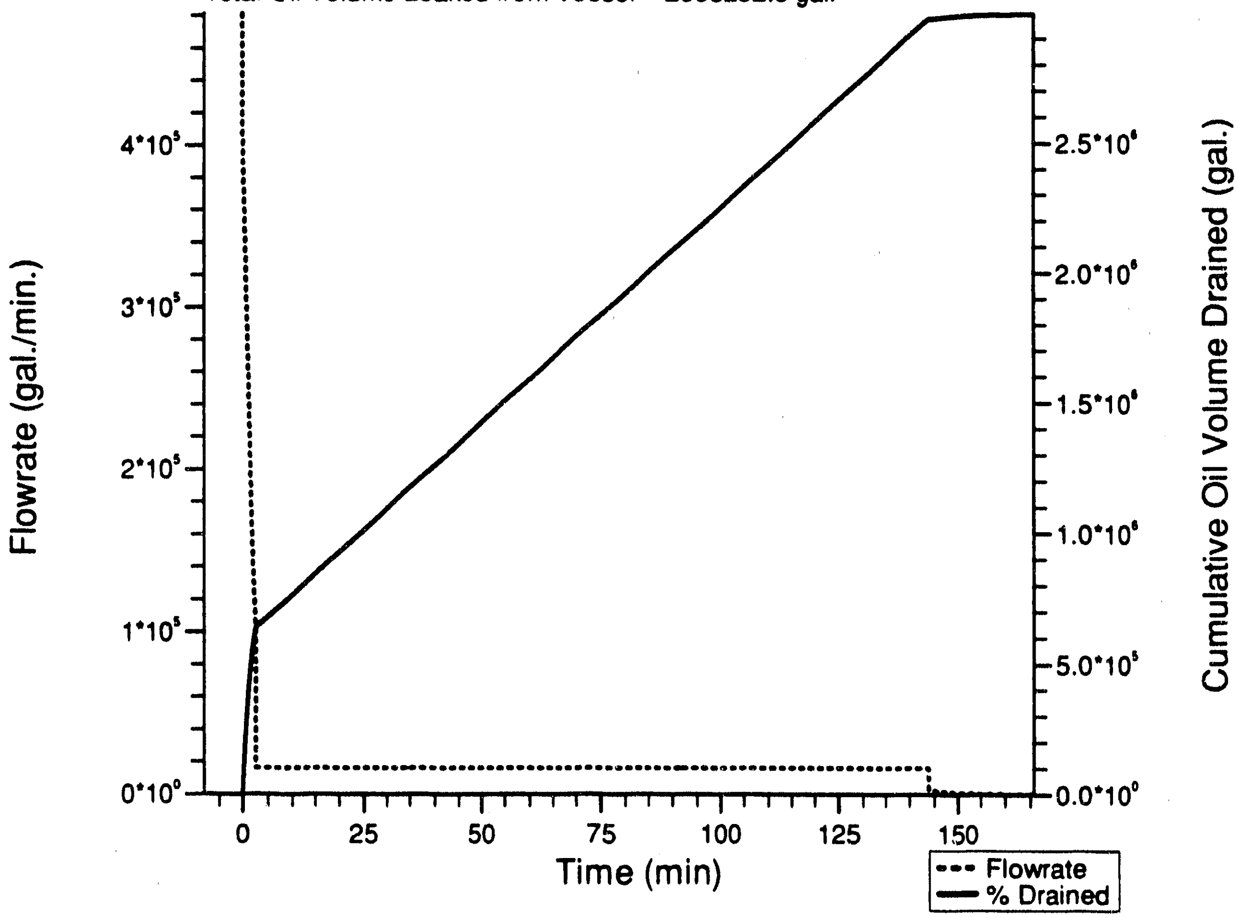
Penetration Area = 8.0 sq. ft No. Tanks Penetrated = 2

Penetration Center w.r.t. Water Line = -0.4 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.08 | 5989.70 | 0.20 | 76984.88 |
| 17.04 | 640515.38 | 21.39 | 3305.19 |
| 34.00 | 696572.56 | 23.26 | 3305.19 |
| 51.04 | 752886.81 | 25.14 | 3305.19 |
| 68.00 | 808944.00 | 27.01 | 3305.19 |
| 84.96 | 865001.12 | 28.88 | 3305.19 |
| 102.00 | 921315.44 | 30.76 | 3305.19 |
| 118.96 | 977372.56 | 32.64 | 3305.19 |
| 135.92 | 1033429.75 | 34.51 | 3305.19 |
| 152.96 | 1089745.88 | 36.39 | 3305.19 |
| 169.92 | 1145817.12 | 38.26 | 3305.19 |
| 186.96 | 1202145.50 | 40.14 | 3305.19 |
| 203.93 | 1258216.75 | 42.01 | 3305.19 |
| 220.89 | 1314287.88 | 43.88 | 3305.19 |
| 237.93 | 1370616.38 | 45.77 | 3305.19 |
| 254.89 | 1426687.50 | 47.64 | 3305.19 |
| 271.85 | 1482758.75 | 49.51 | 3305.19 |
| 288.88 | 1539087.12 | 51.39 | 3305.19 |
| 305.84 | 1595158.38 | 53.26 | 3305.19 |
| 322.80 | 1651229.62 | 55.14 | 3305.19 |
| 339.83 | 1707558.00 | 57.02 | 3305.19 |
| 356.79 | 1763629.25 | 58.89 | 3305.19 |
| 373.83 | 1819957.62 | 60.77 | 3305.19 |
| 390.79 | 1876028.88 | 62.64 | 3305.19 |
| 407.74 | 1932100.00 | 64.51 | 3305.19 |
| 424.78 | 1988428.50 | 66.39 | 3305.19 |
| 441.74 | 2044499.75 | 68.27 | 3305.19 |
| 458.70 | 2100571.00 | 70.14 | 3305.19 |
| 475.73 | 2156899.25 | 72.02 | 3305.19 |
| 492.69 | 2212970.50 | 73.89 | 3305.19 |
| 509.73 | 2269299.00 | 75.77 | 3305.19 |
| 526.69 | 2325370.25 | 77.65 | 3305.19 |
| 543.65 | 2381441.25 | 79.52 | 3305.19 |
| 560.70 | 2437769.75 | 81.40 | 3305.19 |
| 577.66 | 2493841.00 | 83.27 | 3305.19 |
| 594.63 | 2549912.25 | 85.14 | 3305.19 |
| 611.67 | 2606240.50 | 87.02 | 3305.19 |
| 628.63 | 2662311.75 | 88.90 | 3305.19 |
| 645.60 | 2718383.00 | 90.77 | 3305.19 |
| 662.64 | 2774711.50 | 92.65 | 3305.19 |
| 679.61 | 2830782.75 | 94.52 | 3305.19 |
| 696.65 | 2887111.00 | 96.40 | 3305.19 |
| 713.61 | 2943182.25 | 98.27 | 3305.19 |
| 730.58 | 2979931.00 | 99.50 | 674.49 |
| 747.62 | 2987442.50 | 99.75 | 283.32 |
| 764.58 | 2990898.00 | 99.87 | 145.13 |
| 781.55 | 2992776.00 | 99.93 | 84.04 |
| 798.59 | 2993913.00 | 99.97 | 52.83 |
| 815.56 | 2994648.00 | 99.99 | 35.41 |
| 832.68 | 2995155.75 | 100.00 | 0.00 |

## Oil Outflow in Case of Vessel Collision
## for 89700 DWT Tanker

Penetration Area = 50.00 sq. ft.　　Damage Length = 5.00 ft.
2 Tanks penetrated　　Damage Height = 10.00 ft.
Height of Penetration Center with respect to Waterline = -0.3 ft.
Cumulative Oil Volume in Penetrated tank(s) = 2994851.2 gal.
Total Oil Volume Leaked from Vessel = 2995252.8 gal.



Tanker Collision     Tanker DWT = 89700. tons

Accident Occurred in Salt Water     Cargo Specific Gravity = .86

Draft = 49.1 ft

Penetration Height = 10.00 ft     Penetration Length = 5.00 ft

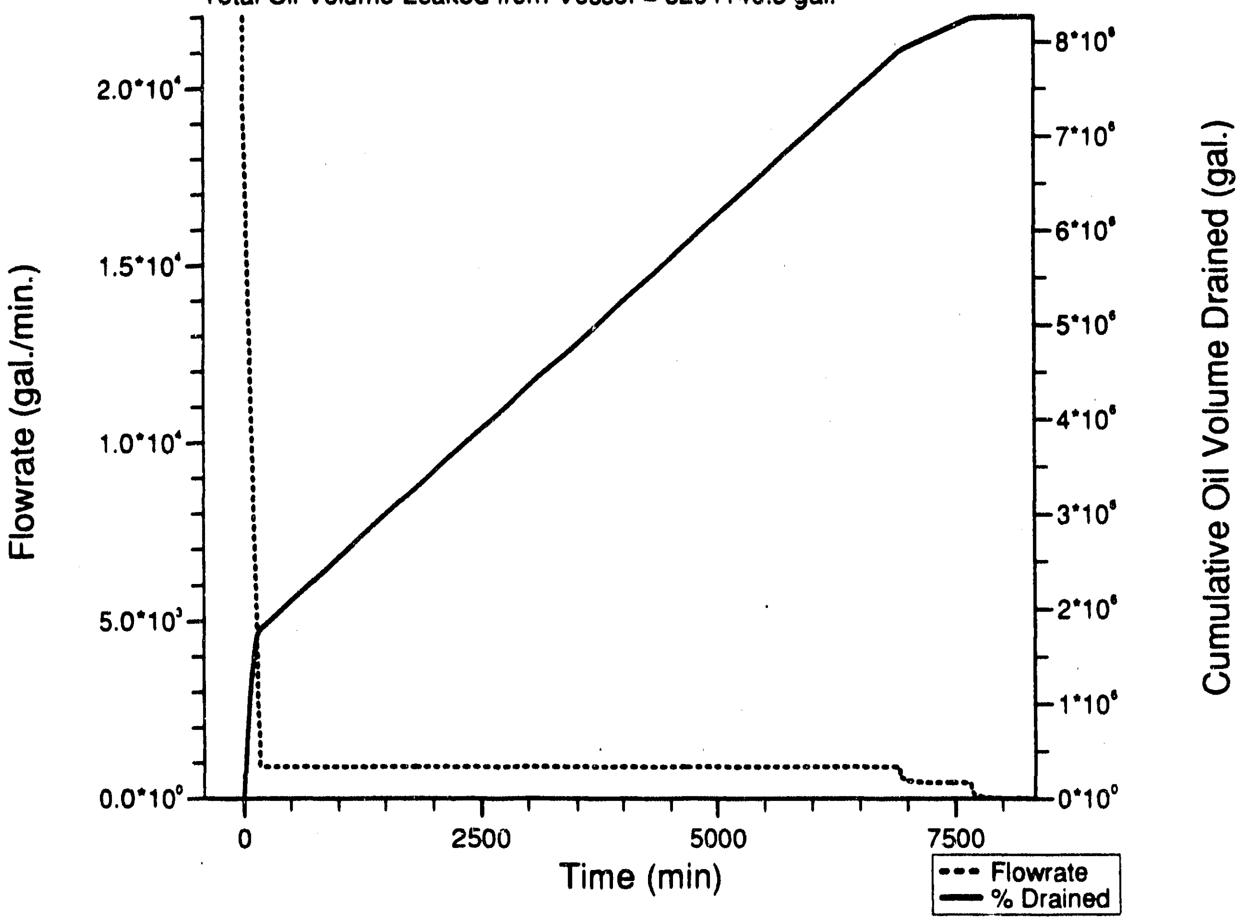
Penetration Area = 50.0 sq. ft     No. Tanks Penetrated = 2

Penetration Center w.r.t. Water Line = -0.3 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.01 | 5989.70 | 0.20 | 481514.53 |
| 3.40 | 652799.12 | 21.80 | 16527.81 |
| 6.78 | 708725.31 | 23.66 | 16527.81 |
| 10.16 | 764651.56 | 25.53 | 16527.81 |
| 13.55 | 820577.75 | 27.40 | 16527.81 |
| 16.93 | 876504.00 | 29.27 | 16527.81 |
| 20.31 | 932430.25 | 31.13 | 16527.81 |
| 23.71 | 988562.06 | 33.01 | 16527.81 |
| 27.09 | 1044488.31 | 34.88 | 16527.81 |
| 30.48 | 1100414.50 | 36.74 | 16527.81 |
| 33.86 | 1156340.62 | 38.61 | 16527.81 |
| 37.24 | 1212266.88 | 40.48 | 16527.81 |
| 40.63 | 1268193.12 | 42.35 | 16527.81 |
| 44.01 | 1324119.38 | 44.21 | 16527.81 |
| 47.41 | 1380251.12 | 46.09 | 16527.81 |
| 50.79 | 1436177.38 | 47.95 | 16527.81 |
| 54.17 | 1492103.62 | 49.82 | 16527.81 |
| 57.56 | 1548029.88 | 51.69 | 16527.81 |
| 60.94 | 1603956.12 | 53.56 | 16527.81 |
| 64.33 | 1659882.25 | 55.42 | 16527.81 |
| 67.71 | 1715808.50 | 57.29 | 16527.81 |
| 71.10 | 1771940.38 | 59.17 | 16527.81 |
| 74.49 | 1827866.62 | 61.03 | 16527.81 |
| 77.87 | 1883792.75 | 62.90 | 16527.81 |
| 81.25 | 1939719.00 | 64.77 | 16527.81 |
| 84.63 | 1995645.25 | 66.64 | 16527.81 |
| 88.02 | 2051571.50 | 68.50 | 16527.81 |
| 91.40 | 2107497.75 | 70.37 | 16527.81 |
| 94.79 | 2163629.50 | 72.24 | 16527.81 |
| 98.18 | 2219555.75 | 74.11 | 16527.81 |
| 101.56 | 2275482.00 | 75.98 | 16527.81 |
| 104.94 | 2331408.25 | 77.85 | 16527.81 |
| 108.32 | 2387334.50 | 79.71 | 16527.81 |
| 111.71 | 2443260.75 | 81.58 | 16527.81 |
| 115.09 | 2499186.75 | 83.45 | 16527.81 |
| 118.48 | 2555318.75 | 85.32 | 16527.81 |
| 121.87 | 2611245.00 | 87.19 | 16527.81 |
| 125.25 | 2667171.25 | 89.06 | 16527.81 |
| 128.63 | 2723097.50 | 90.93 | 16527.81 |
| 132.01 | 2779023.50 | 92.79 | 16527.81 |
| 135.40 | 2834949.75 | 94.66 | 16527.81 |
| 138.78 | 2890876.00 | 96.53 | 16527.81 |
| 142.17 | 2947008.00 | 98.40 | 16527.81 |
| 145.56 | 2978953.75 | 99.47 | 2293.26 |
| 148.94 | 2984990.00 | 99.67 | 1380.92 |
| 152.32 | 2988757.50 | 99.80 | 895.01 |
| 155.70 | 2991267.25 | 99.88 | 612.83 |
| 159.09 | 2993020.50 | 99.94 | 437.83 |
| 162.47 | 2994295.75 | 99.98 | 323.53 |
| 165.88 | 2995252.75 | 100.00 | 0.00 |

## Oil Outflow in Case of Vessel Collision
## for 225000 DWT Tanker

Penetration Area = 2.00 sq. ft. Damage Length = 1.00 ft.
2 Tanks penetrated Damage Height = 2.00 ft.
Height of Penetration Center with respect to Waterline = -0.1 ft.
Cumulative Oil Volume in Penetrated tank(s) = 8262895.0 gal.
Total Oil Volume Leaked from Vessel = 8264140.5 gal.



Tanker Collision Tanker DWT = 225000. tons

Accident Occurred in Salt Water Cargo Specific Gravity = .86

Draft = 70.3 ft

Penetration Height = 2.00 ft Penetration Length = 1.00 ft

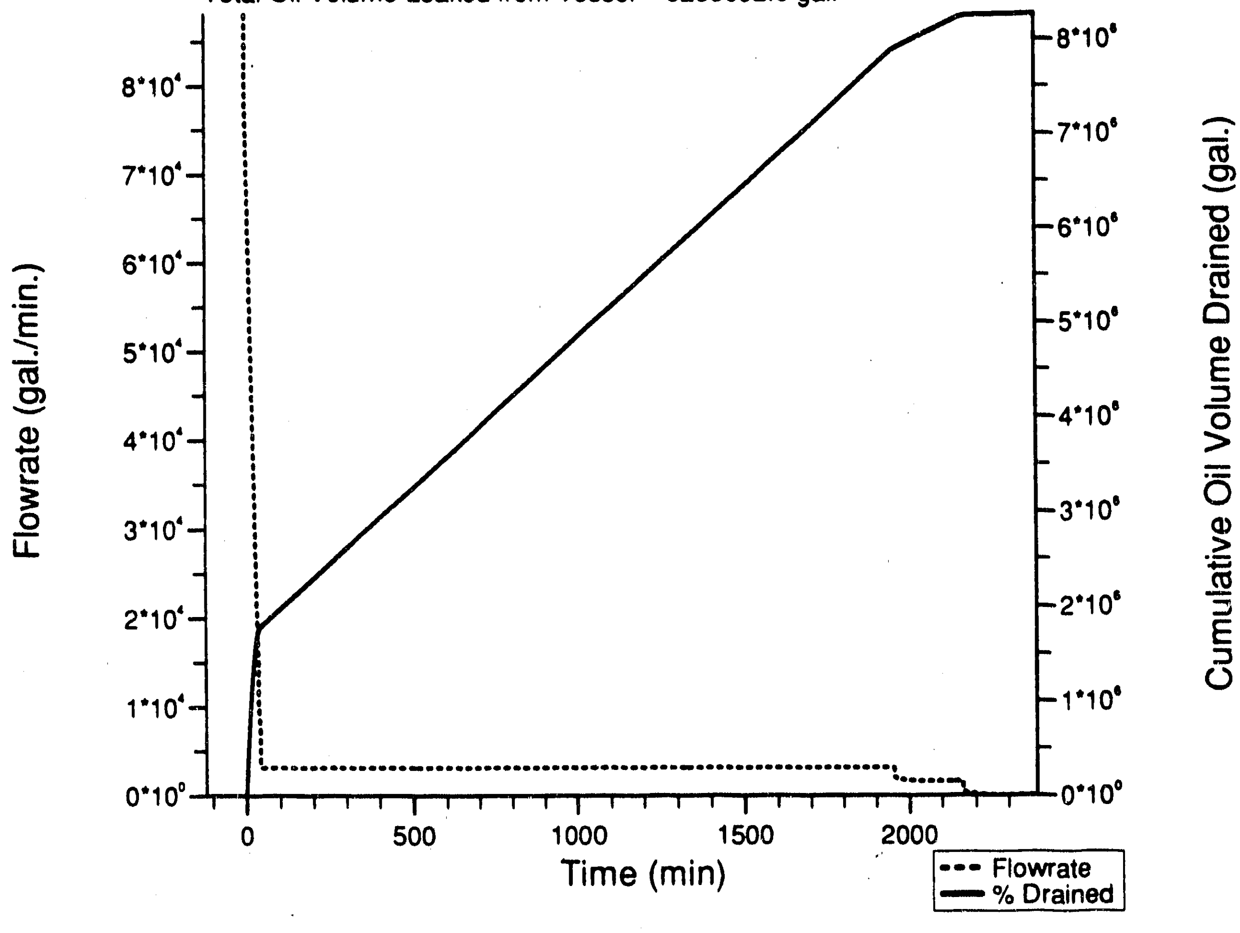
Penetration Area = 2.0 sq. ft No. Tanks Penetrated = 2

Penetration Center w.r.t. Water Line = -0.1 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.79 | 17389.94 | 0.21 | 22032.39 |
| 170.49 | 1788384.62 | 21.64 | 903.77 |
| 340.97 | 1942461.38 | 23.51 | 903.77 |
| 511.46 | 2096538.12 | 25.37 | 903.77 |
| 681.95 | 2250615.00 | 27.24 | 903.77 |
| 852.44 | 2404691.75 | 29.10 | 903.77 |
| 1022.93 | 2558768.50 | 30.97 | 903.77 |
| 1193.42 | 2712845.25 | 32.83 | 903.77 |
| 1363.91 | 2866922.00 | 34.70 | 903.77 |
| 1534.40 | 3020998.75 | 36.56 | 903.77 |
| 1704.89 | 3175075.50 | 38.43 | 903.77 |
| 1875.38 | 3329152.25 | 40.29 | 903.77 |
| 2045.87 | 3483229.00 | 42.16 | 903.77 |
| 2216.36 | 3637305.75 | 44.02 | 903.77 |
| 2386.85 | 3791382.50 | 45.88 | 903.77 |
| 2557.34 | 3945459.25 | 47.75 | 903.77 |
| 2727.83 | 4099536.00 | 49.61 | 903.77 |
| 2897.53 | 4252899.50 | 51.47 | 903.77 |
| 3068.02 | 4407004.50 | 53.33 | 903.77 |
| 3238.51 | 4561137.00 | 55.20 | 903.77 |
| 3409.00 | 4715269.50 | 57.07 | 903.77 |
| 3579.49 | 4869402.00 | 58.93 | 903.77 |
| 3749.98 | 5023534.50 | 60.80 | 903.77 |
| 3920.47 | 5177667.00 | 62.66 | 903.77 |
| 4090.96 | 5331799.50 | 64.53 | 903.77 |
| 4261.40 | 5485932.00 | 66.39 | 903.77 |
| 4431.84 | 5640064.50 | 68.26 | 903.77 |
| 4602.28 | 5794197.00 | 70.12 | 903.77 |
| 4772.71 | 5948329.50 | 71.99 | 903.77 |
| 4943.15 | 6102462.00 | 73.85 | 903.77 |
| 5113.59 | 6256594.50 | 75.72 | 903.77 |
| 5284.03 | 6410727.00 | 77.58 | 903.77 |
| 5454.46 | 6564859.50 | 79.45 | 903.77 |
| 5624.11 | 6718278.50 | 81.31 | 903.77 |
| 5794.55 | 6872411.00 | 83.17 | 903.77 |
| 5964.99 | 7026543.50 | 85.04 | 903.77 |
| 6135.42 | 7180676.00 | 86.90 | 903.77 |
| 6305.86 | 7334808.50 | 88.77 | 903.77 |
| 6476.30 | 7488941.00 | 90.63 | 903.77 |
| 6646.74 | 7643073.50 | 92.50 | 903.77 |
| 6817.17 | 7797206.00 | 94.36 | 903.77 |
| 6987.61 | 7929934.00 | 95.97 | 533.74 |
| 7158.05 | 8013414.00 | 96.98 | 468.44 |
| 7328.49 | 8092186.50 | 97.93 | 458.09 |
| 7498.92 | 8169981.00 | 98.88 | 455.07 |
| 7669.36 | 8245514.50 | 99.79 | 203.54 |
| 7839.80 | 8259554.50 | 99.96 | 30.51 |
| 8010.24 | 8262523.00 | 100.00 | 9.65 |
| 8180.67 | 8263618.50 | 100.00 | 4.21 |
| 8351.90 | 8264140.50 | 100.00 | 0.00 |

## Oil Outflow in Case of Vessel Collision
## for 225000 DWT Tanker

Penetration Area = 8.00 sq. ft. — Damage Length = 2.00 ft.
2 Tanks penetrated — Damage Height = 4.00 ft.
Height of Penetration Center with respect to Waterline = -0.3 ft.
Cumulative Oil Volume in Penetrated tank(s) = 8262895.0 gal.
Total Oil Volume Leaked from Vessel = 8263092.0 gal.



Tanker Collision     Tanker DWT = 225000. tons

Accident Occurred in Salt Water     Cargo Specific Gravity = .86

Draft = 70.3 ft

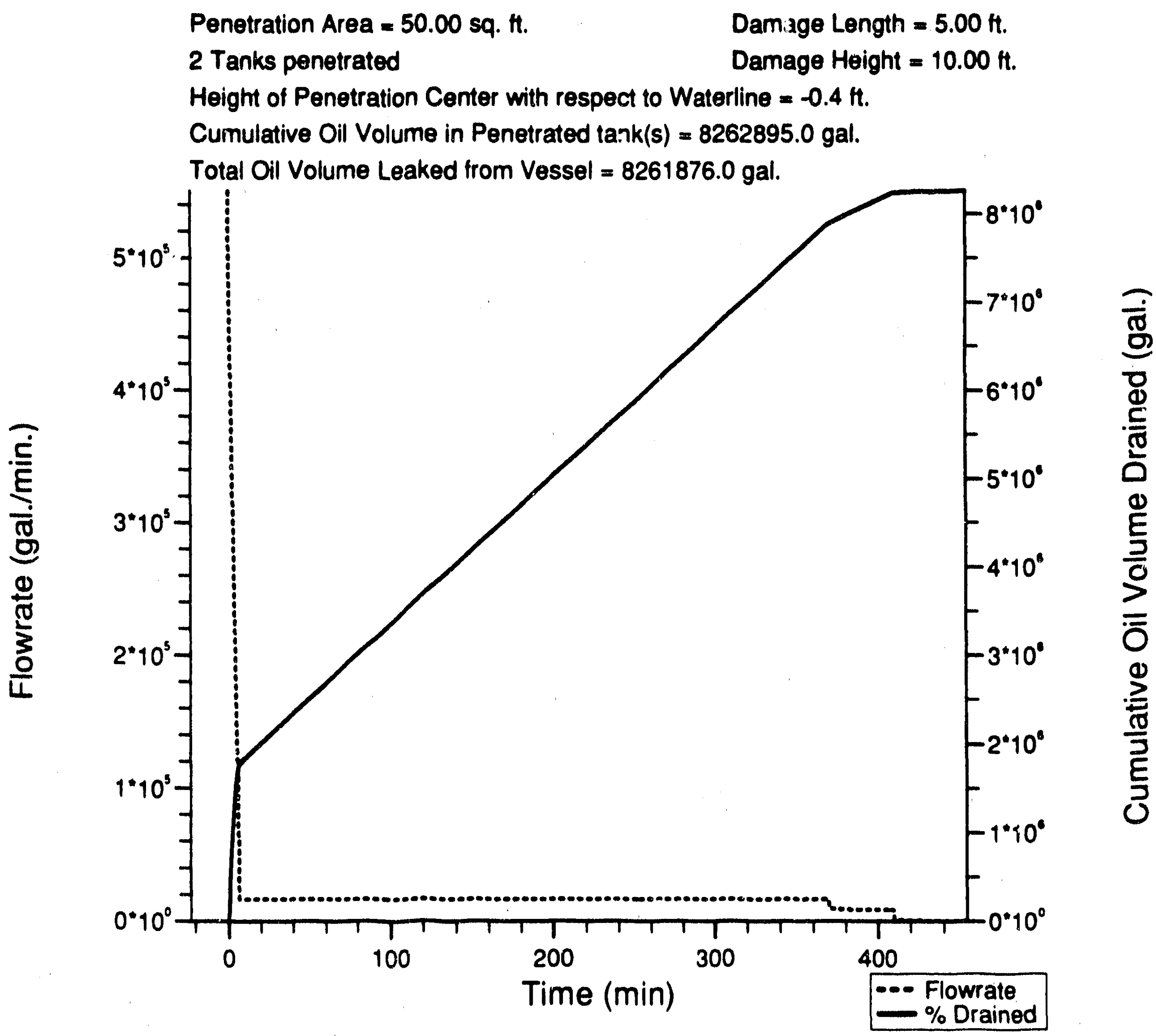
Penetration Height = 4.00 ft     Penetration Length = 2.00 ft

Penetration Area = 8.0 sq. ft     No. Tanks Penetrated = 2

Penetration Center w.r.t. Water Line = -0.3 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.20 | 17389.94 | 0.21 | 88054.78 |
| 48.78 | 1805039.75 | 21.85 | 3192.88 |
| 97.36 | 1960144.25 | 23.72 | 3192.88 |
| 146.14 | 2115879.50 | 25.61 | 3192.88 |
| 194.73 | 2270984.00 | 27.48 | 3192.88 |
| 243.51 | 2426719.25 | 29.37 | 3192.88 |
| 292.09 | 2581823.75 | 31.25 | 3192.88 |
| 340.87 | 2737558.75 | 33.13 | 3192.88 |
| 389.45 | 2892663.25 | 35.01 | 3192.88 |
| 438.22 | 3048398.50 | 36.89 | 3192.88 |
| 486.80 | 3203503.00 | 38.77 | 3192.88 |
| 535.58 | 3359238.00 | 40.65 | 3192.88 |
| 584.17 | 3514342.50 | 42.53 | 3192.88 |
| 632.96 | 3670077.75 | 44.42 | 3192.88 |
| 681.54 | 3825182.25 | 46.29 | 3192.88 |
| 730.33 | 3980917.25 | 48.18 | 3192.88 |
| 778.92 | 4136022.00 | 50.06 | 3192.88 |
| 827.50 | 4291126.50 | 51.93 | 3192.88 |
| 876.29 | 4446862.00 | 53.82 | 3192.88 |
| 924.88 | 4601966.50 | 55.69 | 3192.88 |
| 973.66 | 4757701.50 | 57.58 | 3192.88 |
| 1022.25 | 4912806.00 | 59.46 | 3192.88 |
| 1071.03 | 5068541.00 | 61.34 | 3192.88 |
| 1119.62 | 5223645.50 | 63.22 | 3192.88 |
| 1168.40 | 5379380.50 | 65.10 | 3192.88 |
| 1216.99 | 5534485.50 | 66.98 | 3192.88 |
| 1265.78 | 5690220.50 | 68.86 | 3192.88 |
| 1314.36 | 5845325.00 | 70.74 | 3192.88 |
| 1363.15 | 6001060.00 | 72.63 | 3192.88 |
| 1411.74 | 6156164.50 | 74.50 | 3192.88 |
| 1460.52 | 6311899.50 | 76.39 | 3192.88 |
| 1509.11 | 6467004.00 | 78.27 | 3192.88 |
| 1557.89 | 6622739.00 | 80.15 | 3192.88 |
| 1606.48 | 6777844.00 | 82.03 | 3192.88 |
| 1655.07 | 6932948.50 | 83.90 | 3192.88 |
| 1703.85 | 7088683.50 | 85.79 | 3192.88 |
| 1752.44 | 7243788.00 | 87.67 | 3192.88 |
| 1801.23 | 7399523.00 | 89.55 | 3192.88 |
| 1849.81 | 7554627.50 | 91.43 | 3192.88 |
| 1898.60 | 7710362.50 | 93.31 | 3192.88 |
| 1947.19 | 7865467.50 | 95.19 | 3192.88 |
| 1995.97 | 7964852.50 | 96.39 | 1740.22 |
| 2044.56 | 8046737.00 | 97.38 | 1650.52 |
| 2093.34 | 8126457.00 | 98.35 | 1622.77 |
| 2141.93 | 8204985.50 | 99.30 | 1611.57 |
| 2190.72 | 8251131.50 | 99.86 | 241.29 |
| 2239.30 | 8258137.50 | 99.94 | 84.00 |
| 2288.09 | 8260929.00 | 99.98 | 38.45 |
| 2336.67 | 8262306.00 | 99.99 | 20.75 |
| 2385.66 | 8263092.00 | 100.00 | 0.00 |

## Oil Outflow in Case of Vessel Collision
## for 225000 DWT Tanker



Tanker Collision      Tanker DWT = 225000. tons

Accident Occurred in Salt Water      Cargo Specific Gravity = .86

Draft = 70.3 ft

Penetration Height = 10.00 ft      Penetration Length = 5.00 ft

Penetration Area = 50.0 sq. ft      No. Tanks Penetrated = 2

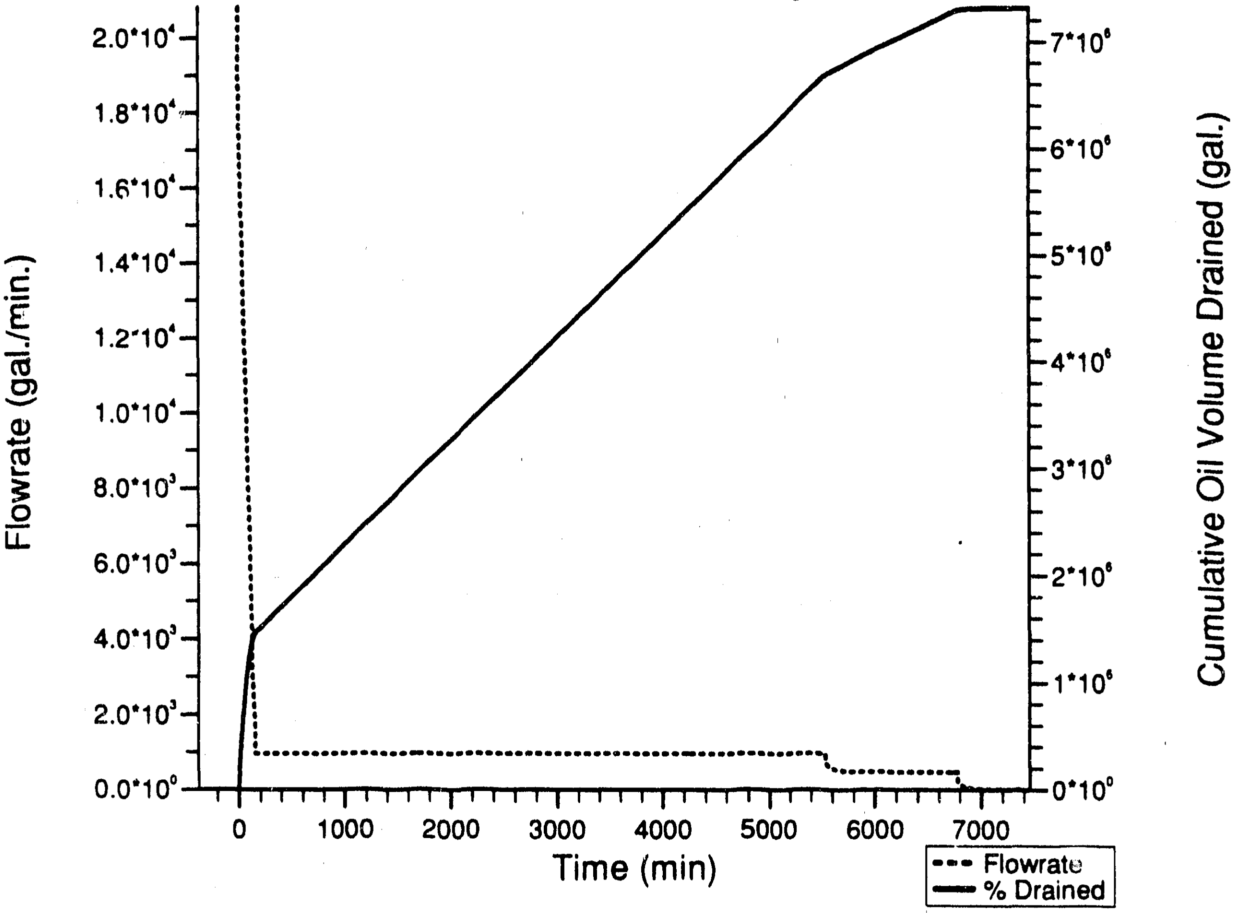
Penetration Center w.r.t. Water Line = -0.4 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.03 | 17389.94 | 0.21 | 550332.75 |
| 9.29 | 1826167.88 | 22.10 | 16809.14 |
| 18.58 | 1982335.88 | 23.99 | 16809.14 |
| 27.87 | 2138503.75 | 25.88 | 16809.14 |
| 37.16 | 2294671.75 | 27.77 | 16809.14 |
| 46.42 | 2450308.50 | 29.65 | 16809.14 |
| 55.71 | 2606476.50 | 31.54 | 16809.14 |
| 65.00 | 2762644.25 | 33.43 | 16809.14 |
| 74.29 | 2918812.25 | 35.32 | 16809.14 |
| 83.58 | 3074980.25 | 37.21 | 16809.14 |
| 92.84 | 3230617.00 | 39.10 | 16809.14 |
| 102.13 | 3386785.00 | 40.99 | 16809.14 |
| 111.42 | 3542953.00 | 42.88 | 16809.14 |
| 120.71 | 3699121.00 | 44.77 | 16809.14 |
| 130.00 | 3855289.00 | 46.66 | 16809.14 |
| 139.26 | 4010925.75 | 48.54 | 16809.14 |
| 148.55 | 4167093.75 | 50.43 | 16809.14 |
| 157.84 | 4323261.50 | 52.32 | 16809.14 |
| 167.13 | 4479356.00 | 54.21 | 16809.14 |
| 176.42 | 4635448.00 | 56.10 | 16809.14 |
| 185.68 | 4791009.50 | 57.98 | 16809.14 |
| 194.97 | 4947101.50 | 59.87 | 16809.14 |
| 204.26 | 5103193.50 | 61.76 | 16809.14 |
| 213.55 | 5259285.50 | 63.65 | 16809.14 |
| 222.84 | 5415378.00 | 65.54 | 16809.14 |
| 232.10 | 5570939.00 | 67.42 | 16809.14 |
| 241.39 | 5727031.00 | 69.31 | 16809.14 |
| 250.68 | 5883123.50 | 71.20 | 16809.14 |
| 259.97 | 6039215.50 | 73.09 | 16809.14 |
| 269.26 | 6195307.50 | 74.98 | 16809.14 |
| 278.51 | 6350868.50 | 76.86 | 16809.14 |
| 287.80 | 6506961.00 | 78.75 | 16809.14 |
| 297.09 | 6663053.00 | 80.64 | 16809.14 |
| 306.37 | 6819145.00 | 82.53 | 16809.14 |
| 315.66 | 6975237.00 | 84.42 | 16809.14 |
| 324.91 | 7130798.50 | 86.30 | 16809.14 |
| 334.20 | 7286890.50 | 88.19 | 16809.14 |
| 343.49 | 7442982.50 | 90.08 | 16809.14 |
| 352.77 | 7599074.50 | 91.97 | 16809.14 |
| 362.06 | 7755167.00 | 93.86 | 16809.14 |
| 371.31 | 7897248.50 | 95.57 | 9685.93 |
| 380.60 | 7983526.00 | 96.62 | 9004.38 |
| 389.89 | 8065737.50 | 97.61 | 8731.80 |
| 399.17 | 8146185.00 | 98.59 | 8602.07 |
| 408.46 | 8225747.50 | 99.55 | 8532.61 |
| 417.71 | 8249311.50 | 99.84 | 842.11 |
| 427.00 | 8255105.00 | 99.91 | 458.18 |
| 436.28 | 8258419.00 | 99.95 | 276.32 |
| 445.57 | 8260490.50 | 99.97 | 179.28 |
| 454.89 | 8261876.00 | 99.99 | 0.00 |

Oil Outflow in Case of Vessel Collision

for 262000 DWT Tanker

Penetration Area = 2.00 sq. ft. Damage Length = 1.00 ft.
2 Tanks penetrated Damage Height = 2.00 ft.
Height of Penetration Center with respect to Waterline = -0.2 ft.
Cumulative Oil Volume in Penetrated tank(s) = 7317069.0 gal.
Total Oil Volume Leaked from Vessel = 7317117.5 gal.



Tanker Collision Tanker DWT = 262000. tons

Accident Occurred in Salt Water Cargo Specific Gravity = .86

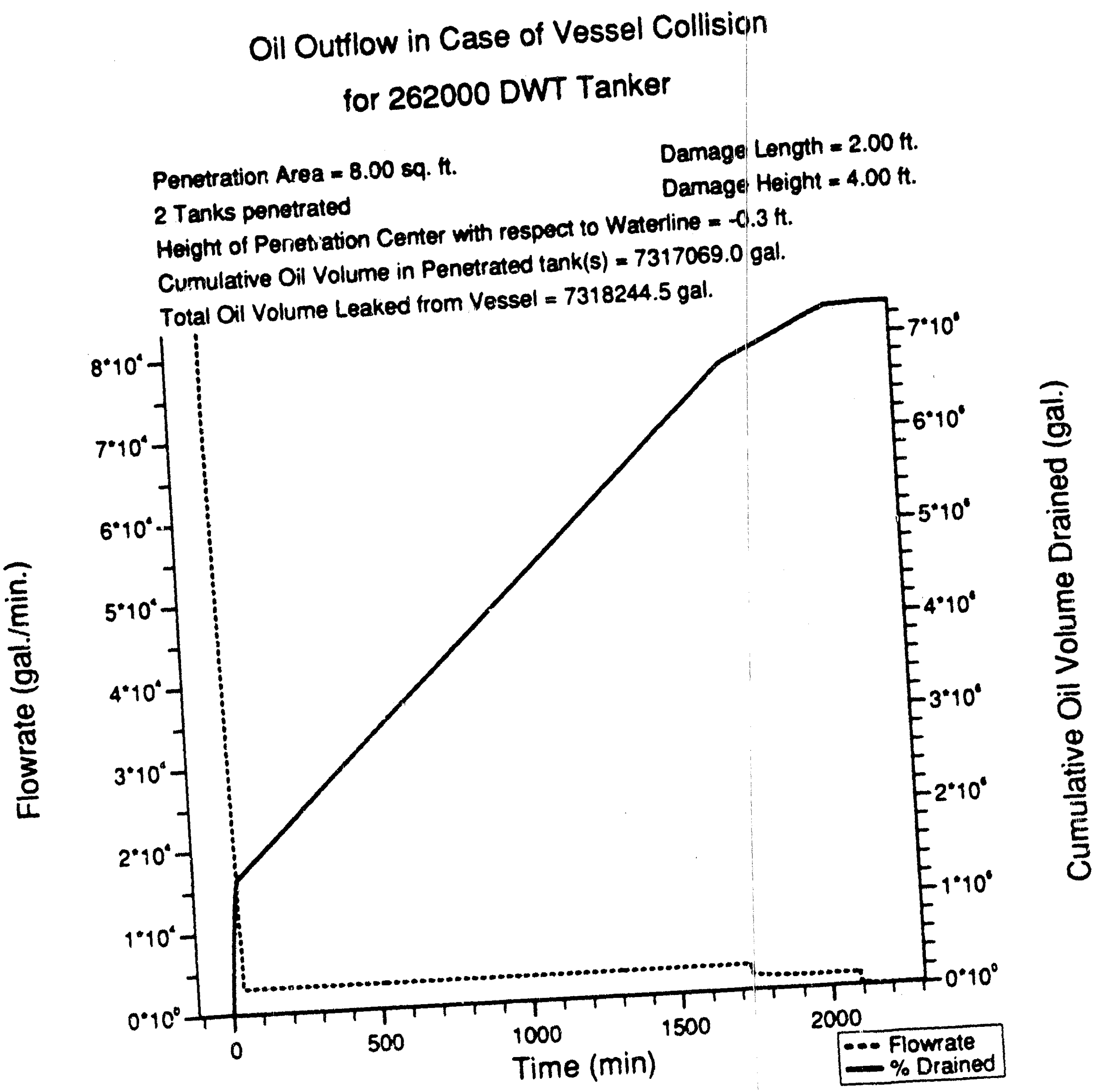
Draft = 67.2 ft

Penetration Height = 2.00 ft Penetration Length = 1.00 ft

Penetration Area = 2.0 sq. ft No. Tanks Penetrated = 2

Penetration Center w.r.t. Water Line = -0.2 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.77 | 16017.46 | 0.22 | 20811.96 |
| 152.39 | 1463441.50 | 20.00 | 968.77 |
| 304.77 | 1611063.62 | 22.02 | 968.77 |
| 457.16 | 1758685.62 | 24.04 | 968.77 |
| 609.55 | 1906307.75 | 26.05 | 968.77 |
| 761.94 | 2053929.75 | 28.07 | 968.77 |
| 913.56 | 2200806.50 | 30.08 | 968.77 |
| 1065.95 | 2348428.50 | 32.10 | 968.77 |
| 1218.34 | 2496050.50 | 34.11 | 968.77 |
| 1370.73 | 2643672.75 | 36.13 | 968.77 |
| 1523.12 | 2791294.75 | 38.15 | 968.77 |
| 1674.75 | 2938171.25 | 40.16 | 968.77 |
| 1827.14 | 3085793.25 | 42.17 | 968.77 |
| 1979.53 | 3233415.50 | 44.19 | 968.77 |
| 2131.91 | 3381037.50 | 46.21 | 968.77 |
| 2284.27 | 3528659.50 | 48.23 | 968.77 |
| 2436.64 | 3676281.50 | 50.24 | 968.77 |
| 2588.24 | 3823158.25 | 52.25 | 968.77 |
| 2740.61 | 3970780.25 | 54.27 | 968.77 |
| 2892.97 | 4118402.25 | 56.28 | 968.77 |
| 3045.34 | 4266024.50 | 58.30 | 968.77 |
| 3197.71 | 4413646.50 | 60.32 | 968.77 |
| 3349.31 | 4560523.00 | 62.33 | 968.77 |
| 3501.67 | 4708145.50 | 64.34 | 968.77 |
| 3654.04 | 4855767.50 | 66.36 | 968.77 |
| 3806.41 | 5003389.50 | 68.38 | 968.77 |
| 3958.77 | 5151011.50 | 70.40 | 968.77 |
| 4111.14 | 5298633.50 | 72.41 | 968.77 |
| 4262.74 | 5445510.00 | 74.42 | 968.77 |
| 4415.11 | 5593132.00 | 76.44 | 968.77 |
| 4567.47 | 5740754.00 | 78.46 | 968.77 |
| 4719.84 | 5888376.50 | 80.47 | 968.77 |
| 4872.21 | 6035998.50 | 82.49 | 968.77 |
| 5023.81 | 6182875.00 | 84.50 | 968.77 |
| 5176.17 | 6330497.00 | 86.52 | 968.77 |
| 5328.54 | 6478119.00 | 88.53 | 968.77 |
| 5480.91 | 6625741.00 | 90.55 | 968.77 |
| 5633.27 | 6738902.00 | 92.10 | 537.48 |
| 5785.64 | 6816462.50 | 93.16 | 494.26 |
| 5937.24 | 6890653.00 | 94.17 | 486.17 |
| 6089.61 | 6964513.00 | 95.18 | 483.62 |
| 6241.97 | 7037895.00 | 96.18 | 481.27 |
| 6394.34 | 7111246.50 | 97.19 | 481.27 |
| 6546.71 | 7184598.00 | 98.19 | 481.27 |
| 6698.31 | 7257578.50 | 99.19 | 481.27 |
| 6850.67 | 7307137.00 | 99.86 | 86.46 |
| 7003.04 | 7313793.50 | 99.96 | 21.06 |
| 7155.41 | 7315803.50 | 99.98 | 8.10 |
| 7307.77 | 7316667.50 | 99.99 | 3.93 |
| 7460.91 | 7317117.50 | 100.00 | 0.00 |



Oil Outflow in Case of Vessel Collision
for 262000 DWT Tanker
Penetration Area = 8.00 sq. ft.
2 Tanks penetrated
Damage Length = 2.00 ft.
Damage Height = 4.00 ft.
Height of Penetration Center with respect to Waterline = -0.3 ft.
Cumulative Oil Volume in Penetrated tank(s) = 7317069.0 gal.
Total Oil Volume Leaked from Vessel = 7318244.5 gal.
Flowrate (gal./min.)
Cumulative Oil Volume Drained (gal.)
Time (min)
Flowrate
% Drained

Tanker Collision    Tanker DWT = 262000. tons

Accident Occurred in Salt Water    Cargo Specific Gravity = .86

Draft = 67.2 ft

Penetration Height = 4.00 ft    Penetration Length = 2.00 ft

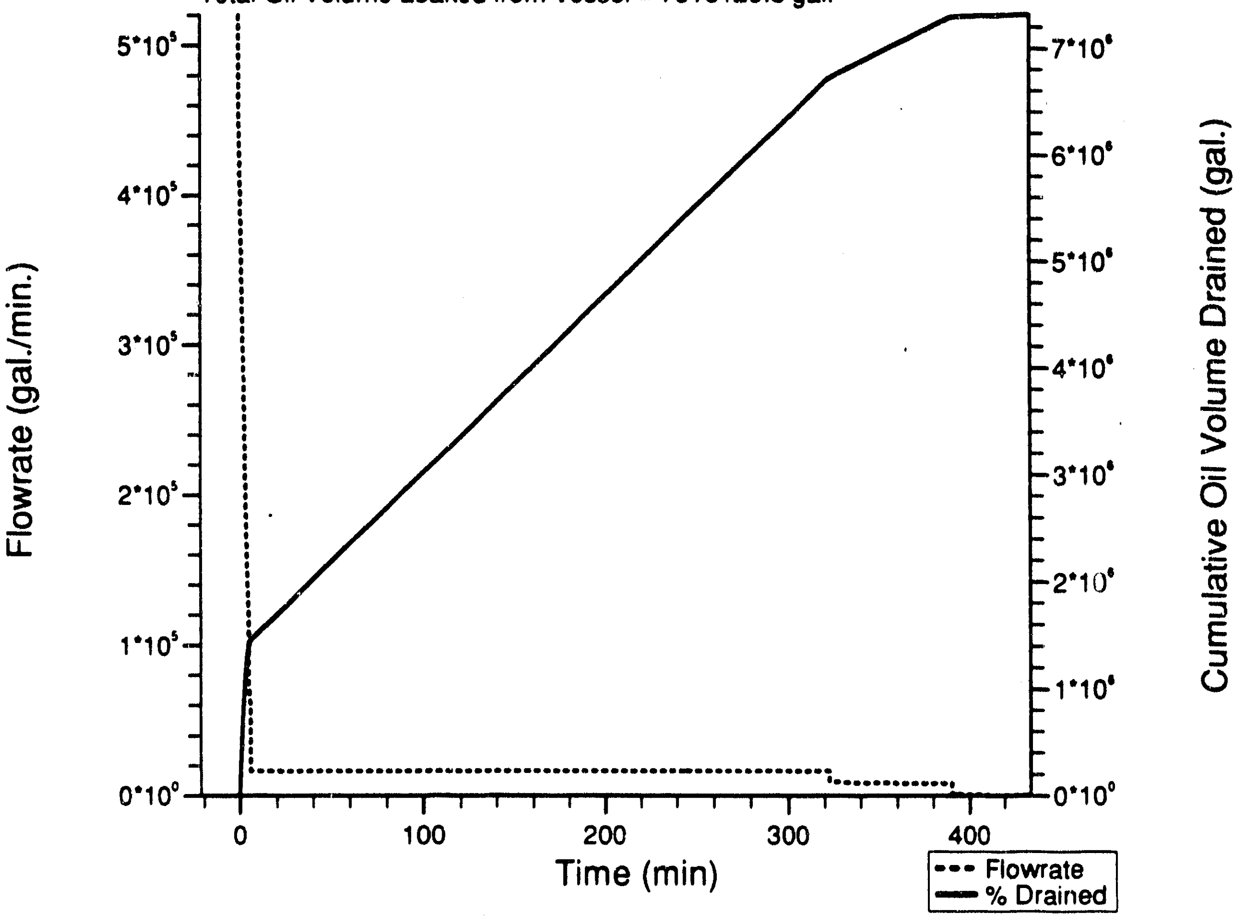
Penetration Area = 8.0 sq. ft    No. Tanks Penetrated = 2

Penetration Center w.r.t. Water Line = -0.3 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.19 | 16017.47 | 0.22 | 83228.70 |
| 47.15 | 1488727.38 | 20.35 | 3106.02 |
| 94.30 | 1635174.38 | 22.35 | 3106.02 |
| 141.26 | 1781023.62 | 24.34 | 3106.02 |
| 188.41 | 1927470.62 | 26.34 | 3106.02 |
| 235.36 | 2073319.88 | 28.34 | 3106.02 |
| 282.51 | 2219766.75 | 30.34 | 3106.02 |
| 329.66 | 2366213.75 | 32.34 | 3106.02 |
| 376.62 | 2512063.00 | 34.33 | 3106.02 |
| 423.77 | 2658510.00 | 36.33 | 3106.02 |
| 470.72 | 2804359.25 | 38.33 | 3106.02 |
| 517.87 | 2950806.25 | 40.33 | 3106.02 |
| 565.02 | 3097253.00 | 42.33 | 3106.02 |
| 611.98 | 3243102.25 | 44.32 | 3106.02 |
| 659.13 | 3389549.25 | 46.32 | 3106.02 |
| 706.08 | 3535398.50 | 48.32 | 3106.02 |
| 753.23 | 3681845.50 | 50.32 | 3106.02 |
| 800.38 | 3828292.50 | 52.32 | 3106.02 |
| 847.34 | 3974141.75 | 54.31 | 3106.02 |
| 894.48 | 4120588.75 | 56.31 | 3106.02 |
| 941.44 | 4266438.00 | 58.31 | 3106.02 |
| 988.59 | 4412921.00 | 60.31 | 3106.02 |
| 1035.74 | 4559431.50 | 62.31 | 3106.02 |
| 1082.71 | 4705343.50 | 64.31 | 3106.02 |
| 1129.88 | 4851854.00 | 66.31 | 3106.02 |
| 1176.85 | 4997766.00 | 68.30 | 3106.02 |
| 1224.01 | 5144276.00 | 70.31 | 3106.02 |
| 1270.98 | 5290188.50 | 72.30 | 3106.02 |
| 1318.15 | 5436698.50 | 74.30 | 3106.02 |
| 1365.31 | 5583208.50 | 76.30 | 3106.02 |
| 1412.28 | 5729121.00 | 78.30 | 3106.02 |
| 1459.44 | 5875631.00 | 80.30 | 3106.02 |
| 1506.42 | 6021543.00 | 82.29 | 3106.02 |
| 1553.58 | 6168053.50 | 84.30 | 3106.02 |
| 1600.74 | 6314563.50 | 86.30 | 3106.02 |
| 1647.71 | 6460475.50 | 88.29 | 3106.02 |
| 1694.88 | 6606986.00 | 90.30 | 3106.02 |
| 1741.85 | 6742814.00 | 92.15 | 1904.58 |
| 1789.01 | 6824703.50 | 93.27 | 1645.34 |
| 1836.18 | 6900723.00 | 94.31 | 1590.55 |
| 1883.15 | 6974921.00 | 95.32 | 1572.41 |
| 1930.31 | 7048652.00 | 96.33 | 1554.66 |
| 1977.28 | 7121671.00 | 97.33 | 1554.66 |
| 2024.45 | 7194989.50 | 98.33 | 1554.66 |
| 2071.60 | 7268307.50 | 99.33 | 1554.66 |
| 2118.54 | 7307253.00 | 99.87 | 220.49 |
| 2165.67 | 7313587.50 | 99.95 | 79.85 |
| 2212.61 | 7316174.00 | 99.99 | 37.55 |
| 2259.75 | 7317488.50 | 100.00 | 20.52 |
| 2307.07 | 7318244.50 | 100.00 | 0.00 |

## Oil Outflow in Case of Vessel Collision
## for 262000 DWT Tanker

Penetration Area = 50.00 sq. ft. Damage Length = 5.00 ft.
2 Tanks penetrated Damage Height = 10.00 ft.
Height of Penetration Center with respect to Waterline = -0.3 ft.
Cumulative Oil Volume in Penetrated tank(s) = 7317069.0 gal.
Total Oil Volume Leaked from Vessel = 7316120.5 gal.



Tanker Collision    Tanker DWT = 262000. tons

Accident Occurred in Salt Water    Cargo Specific Gravity = .86

Draft = 67.2 ft

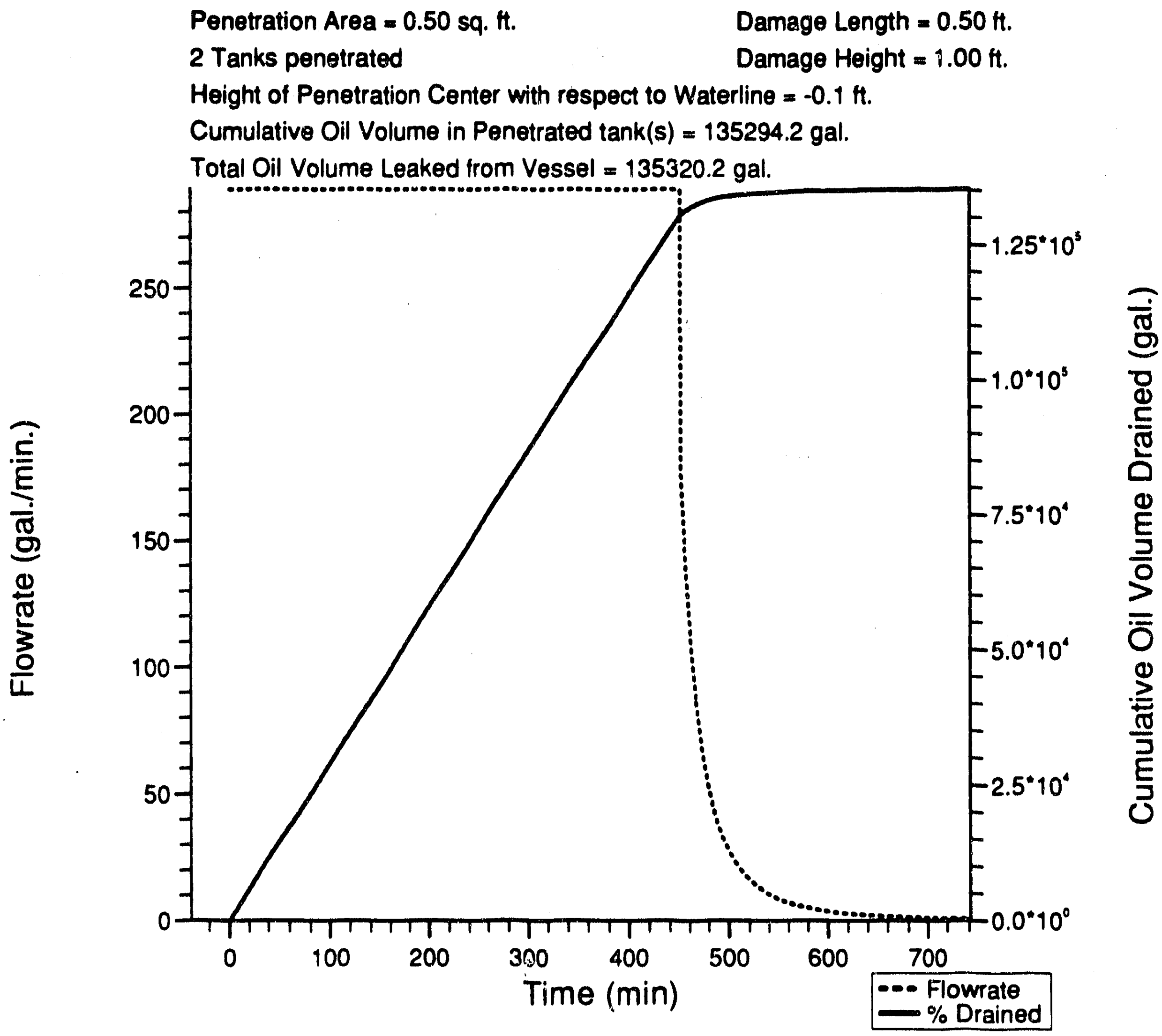
Penetration Height = 10.00 ft    Penetration Length = 5.00 ft

Penetration Area = 50.0 sq. ft    No. Tanks Penetrated = 2

Penetration Center w.r.t. Water Line = -0.3 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.03 | 16017.47 | 0.22 | 520159.00 |
| 8.87 | 1505349.62 | 20.57 | 16607.69 |
| 17.74 | 1652646.75 | 22.59 | 16607.69 |
| 26.61 | 1799943.75 | 24.60 | 16607.69 |
| 35.47 | 1947240.75 | 26.61 | 16607.69 |
| 44.31 | 2094026.25 | 28.62 | 16607.69 |
| 53.18 | 2241303.75 | 30.63 | 16607.69 |
| 62.05 | 2388563.75 | 32.64 | 16607.69 |
| 70.92 | 2535823.50 | 34.66 | 16607.69 |
| 79.75 | 2682572.25 | 36.66 | 16607.69 |
| 88.62 | 2829832.00 | 38.67 | 16607.69 |
| 97.49 | 2977091.75 | 40.69 | 16607.69 |
| 106.36 | 3124351.75 | 42.70 | 16607.69 |
| 115.23 | 3271611.50 | 44.71 | 16607.69 |
| 124.06 | 3418360.25 | 46.72 | 16607.69 |
| 132.93 | 3565620.00 | 48.73 | 16607.69 |
| 141.80 | 3712880.00 | 50.74 | 16607.69 |
| 150.67 | 3860139.75 | 52.76 | 16607.69 |
| 159.51 | 4006888.25 | 54.76 | 16607.69 |
| 168.37 | 4154148.25 | 56.77 | 16607.69 |
| 177.24 | 4301408.00 | 58.79 | 16607.69 |
| 186.11 | 4448668.00 | 60.80 | 16607.69 |
| 194.98 | 4595928.00 | 62.81 | 16607.69 |
| 203.82 | 4742676.50 | 64.82 | 16607.69 |
| 212.68 | 4889936.50 | 66.83 | 16607.69 |
| 221.55 | 5037196.50 | 68.84 | 16607.69 |
| 230.42 | 5184456.00 | 70.85 | 16607.69 |
| 239.26 | 5331204.50 | 72.86 | 16607.69 |
| 248.13 | 5478464.50 | 74.87 | 16607.69 |
| 256.99 | 5625724.50 | 76.88 | 16607.69 |
| 265.86 | 5772984.50 | 78.90 | 16607.69 |
| 274.73 | 5920244.00 | 80.91 | 16607.69 |
| 283.57 | 6066993.00 | 82.92 | 16607.69 |
| 292.44 | 6214252.50 | 84.93 | 16607.69 |
| 301.30 | 6361512.50 | 86.94 | 16607.69 |
| 310.17 | 6508772.50 | 88.95 | 16607.69 |
| 319.01 | 6655521.00 | 90.96 | 16607.69 |
| 327.88 | 6765510.00 | 92.46 | 9210.64 |
| 336.75 | 6844787.00 | 93.55 | 8743.32 |
| 345.61 | 6921346.50 | 94.59 | 8547.93 |
| 354.48 | 6996684.00 | 95.62 | 8452.18 |
| 363.32 | 7070631.50 | 96.63 | 8298.80 |
| 372.19 | 7144187.00 | 97.64 | 8298.80 |
| 381.06 | 7217742.50 | 98.64 | 8298.80 |
| 389.92 | 7291298.50 | 99.65 | 8298.80 |
| 398.76 | 7304666.50 | 99.83 | 774.78 |
| 407.63 | 7309835.00 | 99.90 | 435.20 |
| 416.50 | 7312873.00 | 99.94 | 268.40 |
| 425.37 | 7314812.50 | 99.97 | 177.00 |
| 434.26 | 7316120.50 | 99.99 | 0.00 |

## Oil Outflow in Case of Vessel Collision for 628 GT Barge



Barge Collision    Barge GT = 628.

Accident Occurred in Fresh Water    Cargo Specific Gravity = .92

Draft = 9.6 ft

Penetration Height = 1.00 ft    Penetration Length = 0.50 ft

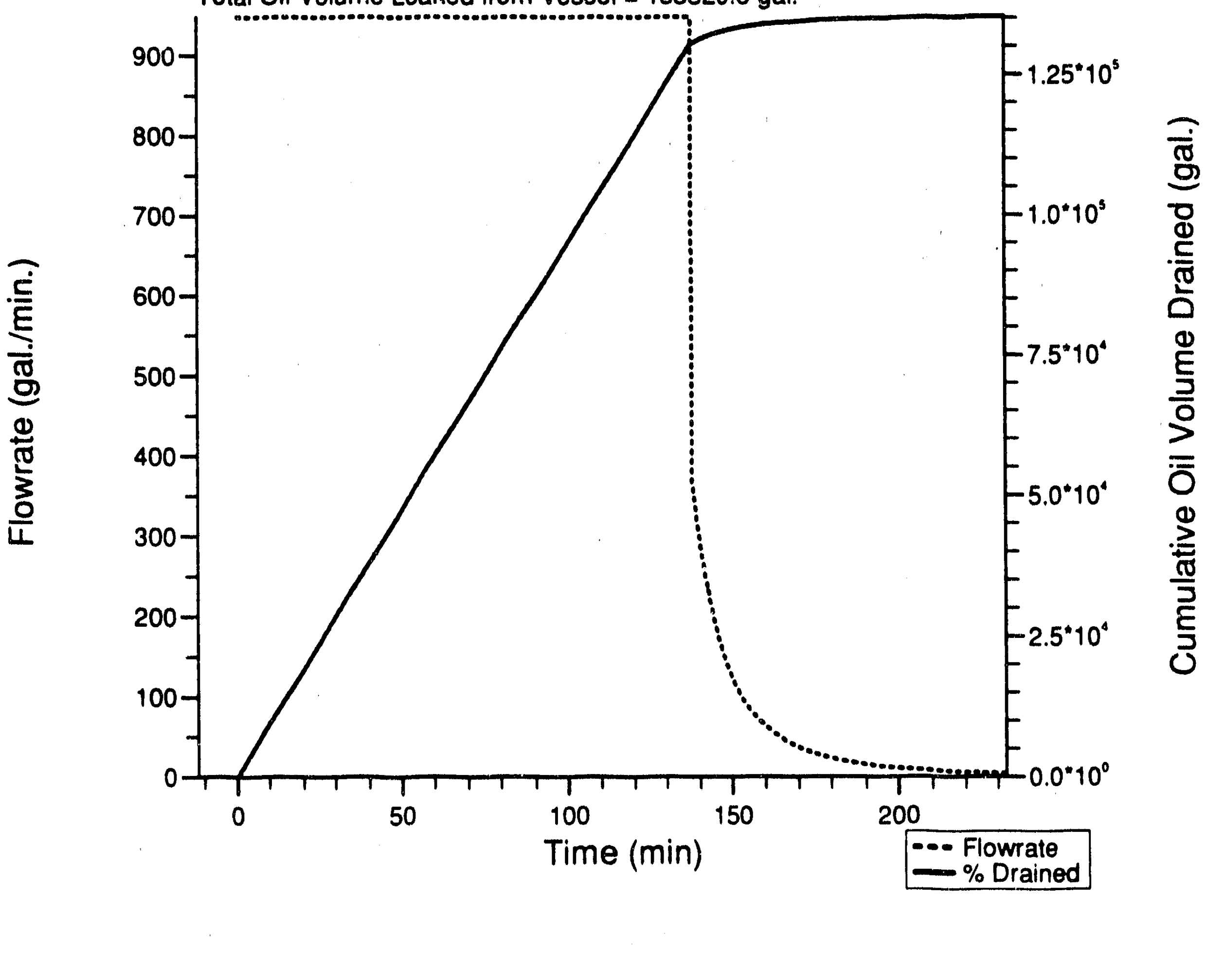
Penetration Area = 0.5 sq. ft    No. Tanks Penetrated = 2

Penetration Center w.r.t. Water Line = -0.1 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.94 | 270.59 | 0.20 | 289.19 |
| 15.91 | 4600.00 | 3.40 | 289.19 |
| 30.88 | 8929.42 | 6.60 | 289.19 |
| 45.85 | 13258.83 | 9.80 | 289.19 |
| 60.82 | 17588.24 | 13.00 | 289.19 |
| 75.79 | 21917.65 | 16.20 | 289.19 |
| 90.76 | 26247.06 | 19.40 | 289.19 |
| 106.67 | 30847.06 | 22.80 | 289.19 |
| 121.64 | 35176.48 | 26.00 | 289.19 |
| 136.61 | 39505.93 | 29.20 | 289.19 |
| 151.58 | 43835.37 | 32.40 | 289.19 |
| 166.55 | 48164.81 | 35.60 | 289.19 |
| 181.52 | 52494.25 | 38.80 | 289.19 |
| 196.49 | 56823.70 | 42.00 | 289.19 |
| 212.40 | 61423.73 | 45.40 | 289.19 |
| 227.37 | 65753.17 | 48.60 | 289.19 |
| 242.34 | 70082.61 | 51.80 | 289.19 |
| 257.31 | 74412.05 | 55.00 | 289.19 |
| 272.28 | 78741.49 | 58.20 | 289.19 |
| 287.25 | 83070.94 | 61.40 | 289.19 |
| 302.22 | 87400.38 | 64.60 | 289.19 |
| 318.13 | 92000.41 | 68.00 | 289.19 |
| 333.10 | 96329.86 | 71.20 | 289.19 |
| 348.07 | 100659.30 | 74.40 | 289.19 |
| 363.04 | 104988.74 | 77.60 | 289.19 |
| 378.01 | 109318.19 | 80.80 | 289.19 |
| 392.98 | 113647.62 | 84.00 | 289.19 |
| 407.95 | 117977.07 | 87.20 | 289.19 |
| 423.86 | 122577.10 | 90.60 | 289.19 |
| 438.83 | 126906.55 | 93.80 | 289.19 |
| 453.80 | 130893.24 | 96.75 | 158.94 |
| 468.77 | 132553.53 | 97.97 | 79.83 |
| 483.74 | 133445.75 | 98.63 | 45.71 |
| 498.71 | 133980.67 | 99.03 | 28.60 |
| 513.68 | 134326.75 | 99.28 | 19.08 |
| 529.59 | 134575.83 | 99.47 | 13.09 |
| 544.56 | 134741.78 | 99.59 | 9.55 |
| 559.53 | 134864.73 | 99.68 | 7.18 |
| 574.50 | 134958.38 | 99.75 | 5.53 |
| 589.47 | 135031.36 | 99.81 | 4.35 |
| 604.44 | 135089.33 | 99.85 | 3.49 |
| 619.41 | 135136.14 | 99.88 | 2.84 |
| 635.32 | 135176.67 | 99.91 | 2.31 |
| 650.29 | 135208.16 | 99.94 | 1.93 |
| 665.26 | 135234.56 | 99.96 | 1.63 |
| 680.23 | 135256.97 | 99.97 | 1.39 |
| 695.20 | 135276.11 | 99.99 | 1.19 |
| 710.17 | 135292.59 | 100.00 | 1.03 |
| 725.14 | 135306.92 | 100.00 | 0.90 |
| 741.99 | 135320.16 | 100.00 | 0.00 |

## Oil Outflow in Case of Vessel Collision for 628 GT Barge

Penetration Area = 2.00 sq. ft. Damage Length = 1.00 ft.
2 Tanks penetrated Damage Height = 2.00 ft.
Height of Penetration Center with respect to Waterline = -0.3 ft.
Cumulative Oil Volume in Penetrated tank(s) = 135294.2 gal.
Total Oil Volume Leaked from Vessel = 135320.6 gal.



Barge Collision Barge GT = 628.

Accident Occurred in Fresh Water Cargo Specific Gravity = .92

Draft = 9.6 ft

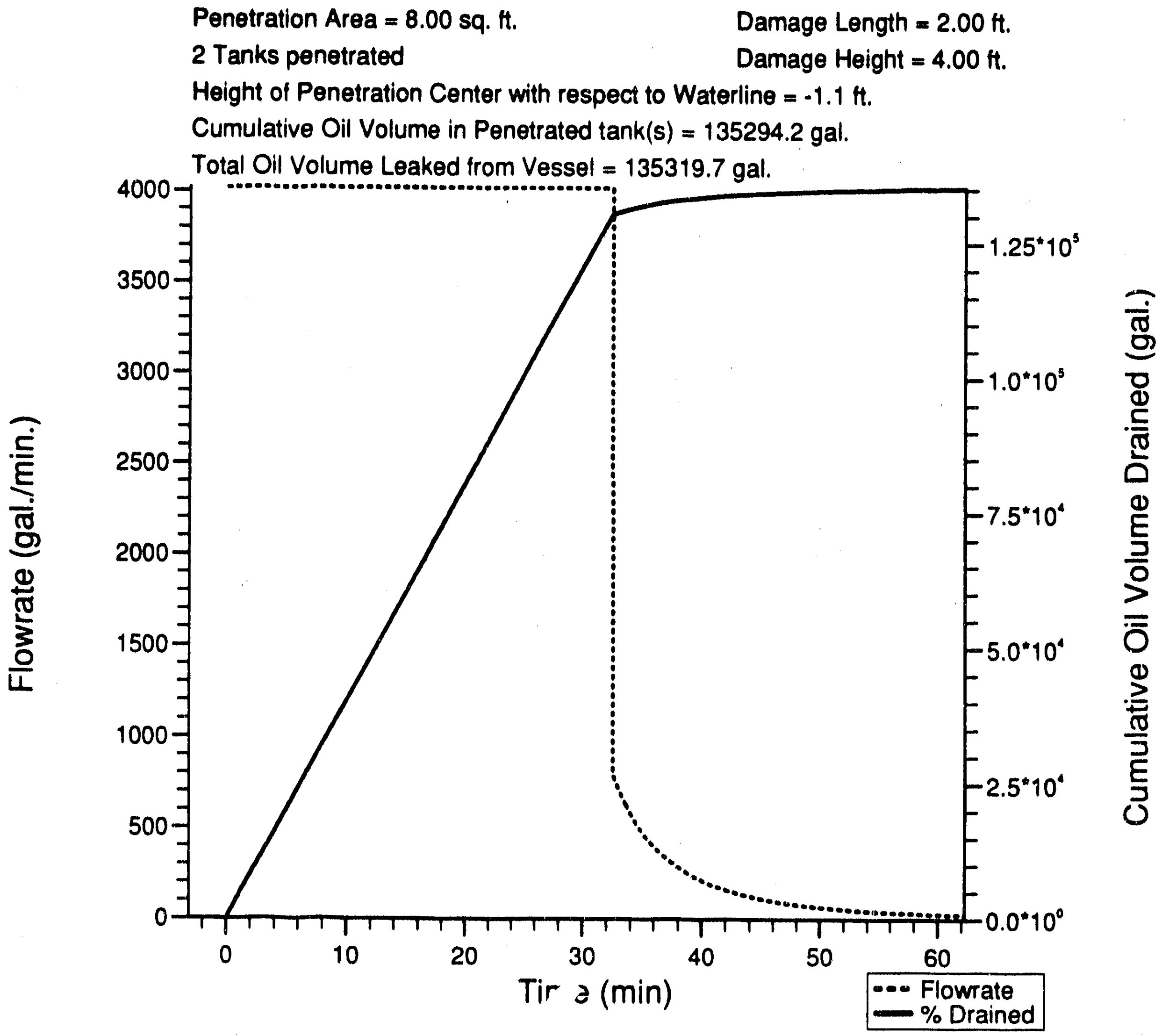
Penetration Height = 2.00 ft Penetration Length = 1.00 ft

Penetration Area = 2.0 sq. ft No. Tanks Penetrated = 2

Penetration Center w.r.t. Water Line = -0.3 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.29 | 270.59 | 0.20 | 948.03 |
| 4.85 | 4600.00 | 3.40 | 948.03 |
| 9.70 | 9200.01 | 6.80 | 948.03 |
| 14.27 | 13529.42 | 10.00 | 948.03 |
| 19.12 | 18129.42 | 13.40 | 948.03 |
| 23.69 | 22458.83 | 16.60 | 948.03 |
| 28.54 | 27058.83 | 20.00 | 948.03 |
| 33.39 | 31658.83 | 23.40 | 948.03 |
| 37.96 | 35988.25 | 26.60 | 948.03 |
| 42.81 | 40588.29 | 30.00 | 948.03 |
| 47.38 | 44917.73 | 33.20 | 948.03 |
| 52.23 | 49517.76 | 36.60 | 948.03 |
| 57.08 | 54117.79 | 40.00 | 948.03 |
| 61.65 | 58447.24 | 43.20 | 948.03 |
| 66.50 | 63047.27 | 46.60 | 948.03 |
| 71.07 | 67376.71 | 49.80 | 948.03 |
| 75.92 | 71976.74 | 53.20 | 948.03 |
| 80.77 | 76576.77 | 56.60 | 948.03 |
| 85.34 | 80906.22 | 59.80 | 948.03 |
| 90.19 | 85506.25 | 63.20 | 948.03 |
| 94.76 | 89835.70 | 66.40 | 948.03 |
| 99.61 | 94435.73 | 69.80 | 948.03 |
| 104.46 | 99035.76 | 73.20 | 948.03 |
| 109.03 | 103365.20 | 76.40 | 948.03 |
| 113.88 | 107965.23 | 79.80 | 948.03 |
| 118.45 | 112294.68 | 83.00 | 948.03 |
| 123.30 | 116894.71 | 86.40 | 948.03 |
| 127.87 | 121224.15 | 89.60 | 948.03 |
| 132.72 | 125824.19 | 93.00 | 948.03 |
| 137.57 | 130424.22 | 96.40 | 948.03 |
| 142.14 | 131775.42 | 97.40 | 237.93 |
| 146.99 | 132701.62 | 98.08 | 156.24 |
| 151.56 | 133295.72 | 98.52 | 110.35 |
| 156.41 | 133746.05 | 98.86 | 79.35 |
| 161.26 | 134075.48 | 99.10 | 58.98 |
| 165.83 | 134310.95 | 99.27 | 45.72 |
| 170.68 | 134505.58 | 99.42 | 35.65 |
| 175.25 | 134650.83 | 99.52 | 28.72 |
| 180.10 | 134775.33 | 99.62 | 23.19 |
| 184.95 | 134876.59 | 99.69 | 18.99 |
| 189.52 | 134955.61 | 99.75 | 15.92 |
| 194.37 | 135025.97 | 99.80 | 13.34 |
| 198.94 | 135082.03 | 99.84 | 11.40 |
| 203.79 | 135132.91 | 99.88 | 9.73 |
| 208.64 | 135176.48 | 99.91 | 8.37 |
| 213.21 | 135212.06 | 99.94 | 7.31 |
| 218.06 | 135245.09 | 99.96 | 6.38 |
| 222.63 | 135272.36 | 99.98 | 5.64 |
| 227.48 | 135297.97 | 100.00 | 4.97 |
| 232.62 | 135320.58 | 100.00 | 0.00 |

## Oil Outflow in Case of Vessel Collision for 628 GT Barge



Barge Collision Barge GT = 628.

Accident Occurred in Fresh Water Cargo Specific Gravity = .92

Draft = 9.6 ft

Penetration Height = 4.00 ft Penetration Length = 2.00 ft

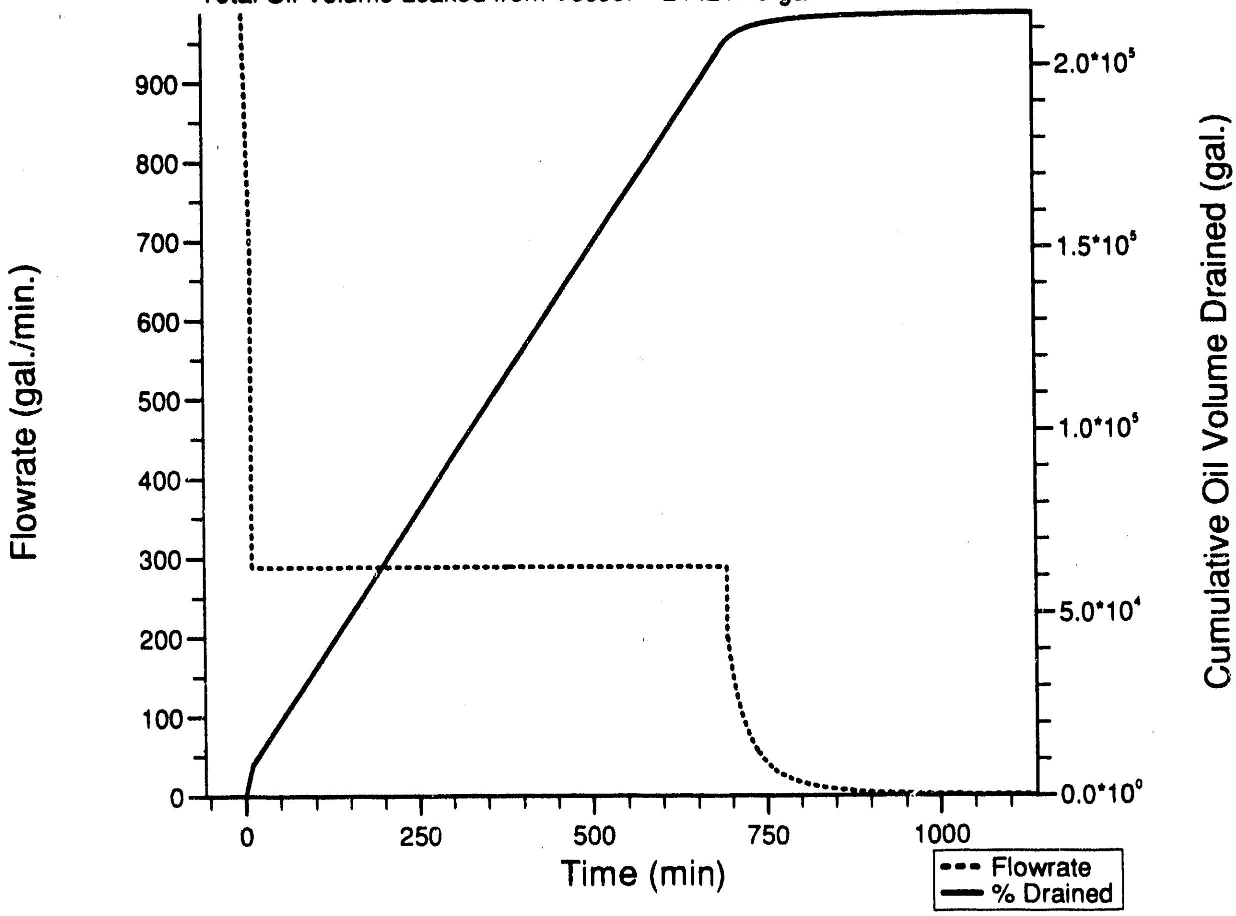
Penetration Area = 8.0 sq. ft No. Tanks Penetrated = 2

Penetration Center w.r.t. Water Line = -1.1 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.07 | 270.59 | 0.20 | 4019.07 |
| 1.28 | 5141.18 | 3.80 | 4019.07 |
| 2.56 | 10282.36 | 7.60 | 4019.07 |
| 3.84 | 15423.54 | 11.40 | 4019.07 |
| 5.12 | 20564.71 | 15.20 | 4019.07 |
| 6.40 | 25705.89 | 19.00 | 4019.07 |
| 7.68 | 30847.06 | 22.80 | 4019.07 |
| 8.89 | 35717.66 | 26.40 | 4019.07 |
| 10.17 | 40858.88 | 30.20 | 4019.07 |
| 11.45 | 46000.09 | 34.00 | 4019.07 |
| 12.72 | 51141.30 | 37.80 | 4019.07 |
| 14.00 | 56282.52 | 41.60 | 4019.07 |
| 15.28 | 61423.73 | 45.40 | 4019.07 |
| 16.49 | 66294.35 | 49.00 | 4019.07 |
| 17.77 | 71435.56 | 52.80 | 4019.07 |
| 19.05 | 76576.77 | 56.60 | 4019.07 |
| 20.33 | 81717.98 | 60.40 | 4019.07 |
| 21.61 | 86859.20 | 64.20 | 4019.07 |
| 22.89 | 92000.41 | 68.00 | 4019.07 |
| 24.10 | 96871.04 | 71.60 | 4019.07 |
| 25.38 | 102012.25 | 75.40 | 4019.07 |
| 26.66 | 107153.46 | 79.20 | 4019.07 |
| 27.94 | 112294.68 | 83.00 | 4019.07 |
| 29.22 | 117435.89 | 86.80 | 4019.07 |
| 30.50 | 122577.10 | 90.60 | 4019.07 |
| 31.71 | 127447.73 | 94.20 | 4019.07 |
| 32.99 | 130828.02 | 96.70 | 712.39 |
| 34.27 | 131623.80 | 97.29 | 549.69 |
| 35.55 | 132244.47 | 97.75 | 433.04 |
| 36.83 | 132737.98 | 98.11 | 347.24 |
| 38.11 | 133136.86 | 98.41 | 282.70 |
| 39.32 | 133448.12 | 98.64 | 235.54 |
| 40.60 | 133722.12 | 98.84 | 196.48 |
| 41.88 | 133951.94 | 99.01 | 165.62 |
| 43.16 | 134146.58 | 99.15 | 140.89 |
| 44.44 | 134312.88 | 99.27 | 120.86 |
| 45.71 | 134456.11 | 99.38 | 104.46 |
| 46.93 | 134574.20 | 99.47 | 91.55 |
| 48.21 | 134683.41 | 99.55 | 80.13 |
| 49.48 | 134779.28 | 99.62 | 70.53 |
| 50.76 | 134863.89 | 99.68 | 62.41 |
| 52.04 | 134938.97 | 99.74 | 55.49 |
| 53.32 | 135005.88 | 99.79 | 49.56 |
| 54.53 | 135062.73 | 99.83 | 44.69 |
| 55.81 | 135116.83 | 99.87 | 40.23 |
| 57.09 | 135165.61 | 99.90 | 36.34 |
| 58.37 | 135209.77 | 99.94 | 32.93 |
| 59.65 | 135249.84 | 99.97 | 29.94 |
| 60.93 | 135286.34 | 99.99 | 27.30 |
| 62.28 | 135319.66 | 100.00 | 0.00 |

## Oil Outflow in Case of Vessel Collision for 1182 GT Barge

Penetration Area = 0.50 sq. ft.
2 Tanks penetrated
Damage Length = 0.50 ft.
Damage Height = 1.00 ft.
Height of Penetration Center with respect to Waterline = -0.1 ft.
Cumulative Oil Volume in Penetrated tank(s) = 214108.3 gal.
Total Oil Volume Leaked from Vessel = 214211.9 gal.



Barge Collision     Barge GT = 1182.

Accident Occurred in Fresh Water     Cargo Specific Gravity = .92

Draft = 9.6 ft

Penetration Height = 1.00 ft     Penetration Length = 0.50 ft

Penetration Area = 0.5 sq. ft     No. Tanks Penetrated = 2

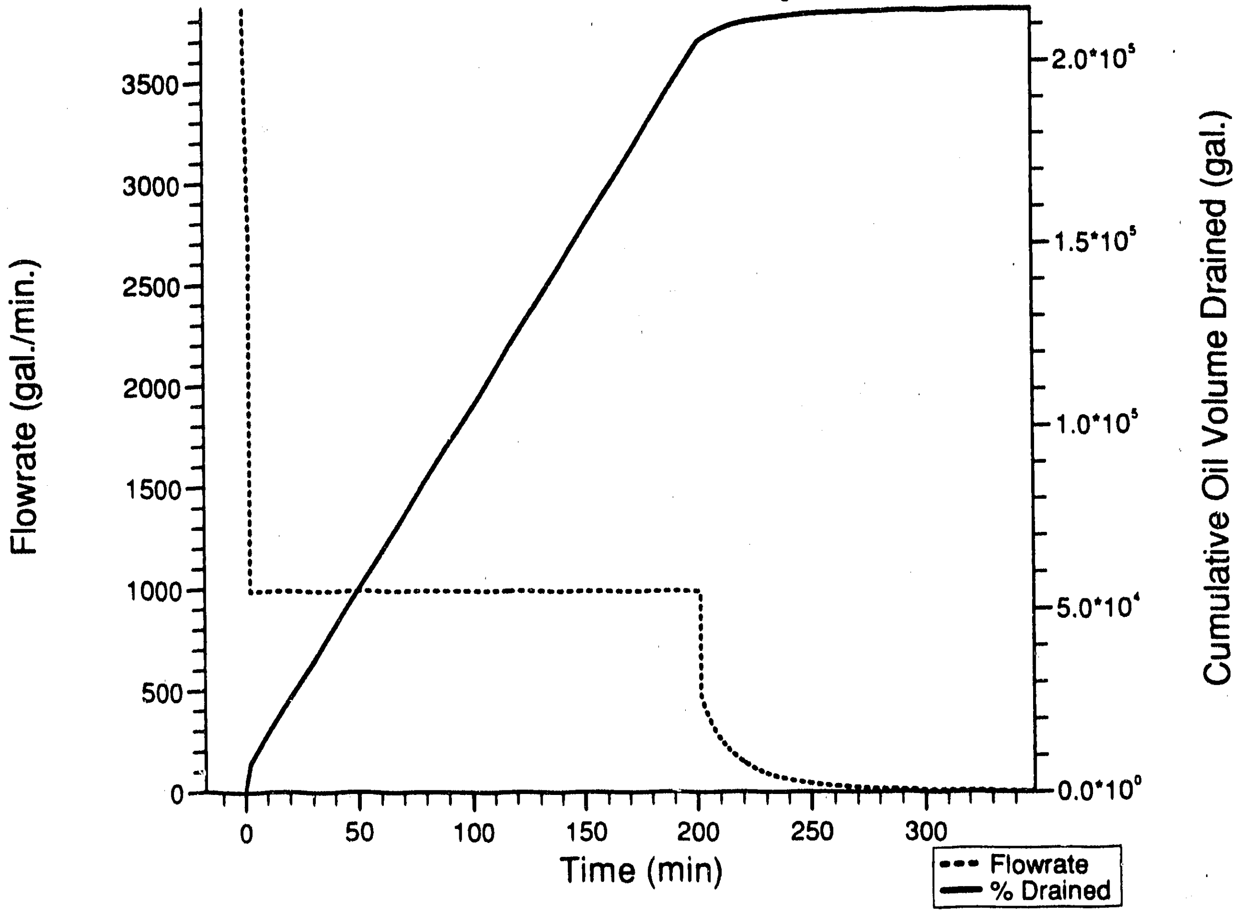
Penetration Center w.r.t. Water Line = -0.1 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.43 | 428.22 | 0.20 | 986.27 |
| 23.45 | 12502.72 | 5.84 | 289.19 |
| 46.46 | 19157.42 | 8.95 | 289.19 |
| 69.90 | 25937.67 | 12.11 | 289.19 |
| 92.91 | 32592.37 | 15.22 | 289.19 |
| 116.36 | 39372.63 | 18.39 | 289.19 |
| 139.37 | 46027.33 | 21.50 | 289.19 |
| 162.82 | 52807.59 | 24.66 | 289.19 |
| 185.83 | 59462.28 | 27.77 | 289.19 |
| 209.27 | 66242.54 | 30.94 | 289.19 |
| 232.28 | 72897.41 | 34.05 | 289.19 |
| 255.30 | 79552.31 | 37.16 | 289.19 |
| 278.74 | 86332.79 | 40.32 | 289.19 |
| 301.75 | 92987.70 | 43.43 | 289.19 |
| 325.20 | 99768.17 | 46.60 | 289.19 |
| 348.21 | 106423.09 | 49.71 | 289.19 |
| 371.65 | 113203.56 | 52.87 | 289.19 |
| 394.67 | 119858.47 | 55.98 | 289.19 |
| 418.11 | 126638.95 | 59.15 | 289.19 |
| 441.12 | 133293.86 | 62.26 | 289.19 |
| 464.13 | 139948.47 | 65.36 | 289.19 |
| 487.58 | 146728.50 | 68.53 | 289.19 |
| 510.59 | 153382.98 | 71.64 | 289.19 |
| 534.04 | 160163.03 | 74.80 | 289.19 |
| 557.05 | 166817.52 | 77.91 | 289.19 |
| 580.50 | 173597.55 | 81.08 | 289.19 |
| 603.51 | 180252.03 | 84.19 | 289.19 |
| 626.96 | 187032.08 | 87.35 | 289.19 |
| 649.97 | 193686.56 | 90.46 | 289.19 |
| 673.42 | 200466.59 | 93.63 | 289.19 |
| 696.43 | 206735.47 | 96.56 | 180.74 |
| 719.44 | 209642.53 | 97.91 | 88.28 |
| 742.89 | 211184.44 | 98.63 | 49.07 |
| 765.90 | 212070.48 | 99.05 | 30.30 |
| 789.35 | 212644.86 | 99.32 | 19.86 |
| 812.36 | 213025.36 | 99.49 | 13.81 |
| 835.81 | 213299.53 | 99.62 | 9.93 |
| 858.82 | 213496.67 | 99.71 | 7.42 |
| 882.27 | 213648.39 | 99.79 | 5.66 |
| 905.28 | 213763.48 | 99.84 | 4.43 |
| 928.29 | 213854.47 | 99.88 | 3.54 |
| 951.74 | 213928.95 | 99.92 | 2.86 |
| 974.75 | 213988.55 | 99.94 | 2.35 |
| 998.20 | 214038.69 | 99.97 | 1.95 |
| 1021.21 | 214079.75 | 99.99 | 1.64 |
| 1044.66 | 214115.09 | 100.00 | 1.39 |
| 1067.67 | 214144.64 | 100.00 | 1.19 |
| 1091.12 | 214170.50 | 100.00 | 1.02 |
| 1114.13 | 214192.42 | 100.00 | 0.89 |
| 1138.01 | 214211.88 | 100.00 | 0.00 |

Oil Outflow in Case of Vessel Collision

for 1182 GT Barge

Penetration Area = 2.00 sq. ft.
Damage Length = 1.00 ft.
2 Tanks penetrated
Damage Height = 2.00 ft.
Height of Penetration Center with respect to Waterline = -0.3 ft.
Cumulative Oil Volume in Penetrated tank(s) = 214108.3 gal.
Total Oil Volume Leaked from Vessel = 214160.8 gal.



Barge Collision Barge GT = 1182.

Accident Occurred in Fresh Water Cargo Specific Gravity = .92

Draft = 9.6 ft

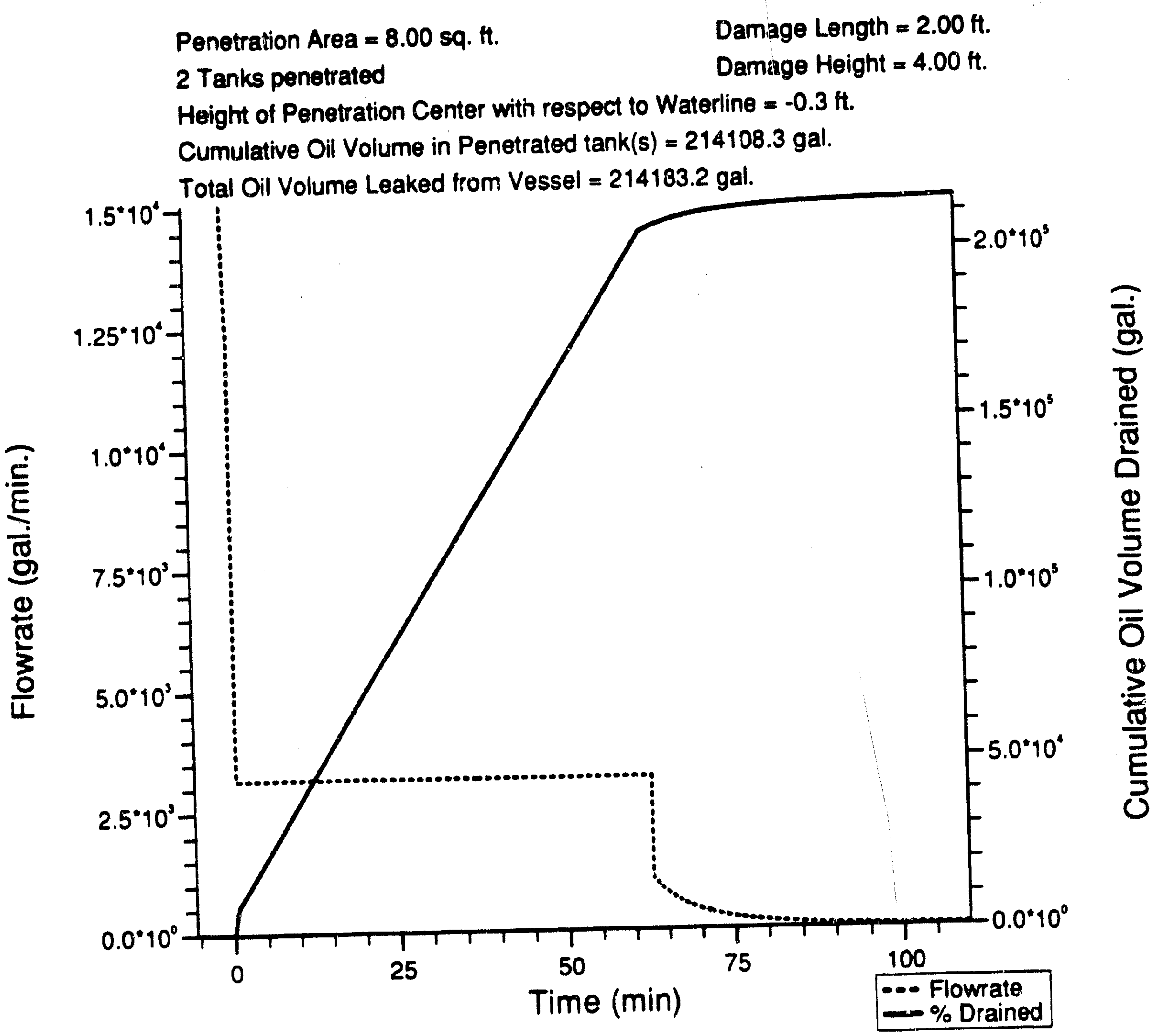
Penetration Height = 2.00 ft Penetration Length = 1.00 ft

Penetration Area = 2.0 sq. ft No. Tanks Penetrated = 2

Penetration Center w.r.t. Water Line = -0.3 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.11 | 428.22 | 0.20 | 3863.55 |
| 7.20 | 12764.63 | 5.96 | 990.66 |
| 14.30 | 19791.79 | 9.24 | 990.66 |
| 21.39 | 26818.94 | 12.53 | 990.66 |
| 28.48 | 33846.09 | 15.81 | 990.66 |
| 35.69 | 40983.05 | 19.14 | 990.66 |
| 42.78 | 48010.20 | 22.42 | 990.66 |
| 49.88 | 55037.35 | 25.71 | 990.66 |
| 56.97 | 62064.51 | 28.99 | 990.66 |
| 64.06 | 69091.71 | 32.27 | 990.66 |
| 71.27 | 76228.93 | 35.60 | 990.66 |
| 78.36 | 83256.34 | 38.89 | 990.66 |
| 85.45 | 90283.75 | 42.17 | 990.66 |
| 92.55 | 97311.16 | 45.45 | 990.66 |
| 99.64 | 104338.57 | 48.73 | 990.66 |
| 106.84 | 111475.79 | 52.07 | 990.66 |
| 113.94 | 118503.20 | 55.35 | 990.66 |
| 121.03 | 125530.61 | 58.63 | 990.66 |
| 128.12 | 132558.02 | 61.91 | 990.66 |
| 135.22 | 139585.42 | 65.19 | 990.66 |
| 142.42 | 146722.64 | 68.53 | 990.66 |
| 149.52 | 153750.05 | 71.81 | 990.66 |
| 156.61 | 160777.47 | 75.09 | 990.66 |
| 163.70 | 167804.88 | 78.37 | 990.66 |
| 170.80 | 174832.28 | 81.66 | 990.66 |
| 178.00 | 181969.50 | 84.99 | 990.66 |
| 185.10 | 188996.91 | 88.27 | 990.66 |
| 192.19 | 196024.33 | 91.55 | 990.66 |
| 199.28 | 203051.73 | 94.84 | 990.66 |
| 206.38 | 207204.70 | 96.78 | 336.90 |
| 213.58 | 209134.89 | 97.68 | 213.35 |
| 220.68 | 210378.67 | 98.26 | 144.38 |
| 227.77 | 211239.47 | 98.66 | 102.22 |
| 234.86 | 211859.86 | 98.95 | 75.00 |
| 241.96 | 212321.81 | 99.17 | 56.65 |
| 249.16 | 212679.77 | 99.33 | 43.67 |
| 256.25 | 212954.70 | 99.46 | 34.49 |
| 263.35 | 213173.80 | 99.56 | 27.71 |
| 270.44 | 213351.14 | 99.65 | 22.60 |
| 277.54 | 213496.72 | 99.71 | 18.67 |
| 284.74 | 213619.47 | 99.77 | 15.57 |
| 291.83 | 213720.83 | 99.82 | 13.14 |
| 298.93 | 213806.81 | 99.86 | 11.20 |
| 306.02 | 213880.38 | 99.89 | 9.62 |
| 313.12 | 213943.80 | 99.92 | 8.33 |
| 320.32 | 213999.66 | 99.95 | 7.24 |
| 327.41 | 214047.70 | 99.97 | 6.34 |
| 334.51 | 214089.92 | 99.99 | 5.59 |
| 341.60 | 214127.19 | 100.00 | 4.95 |
| 348.92 | 214160.81 | 100.00 | 0.00 |

## Oil Outflow in Case of Vessel Collision for 1182 GT Barge



Barge Collision Barge GT = 1182.

Accident Occurred in Fresh Water Cargo Specific Gravity = .92

Draft = 9.6 ft

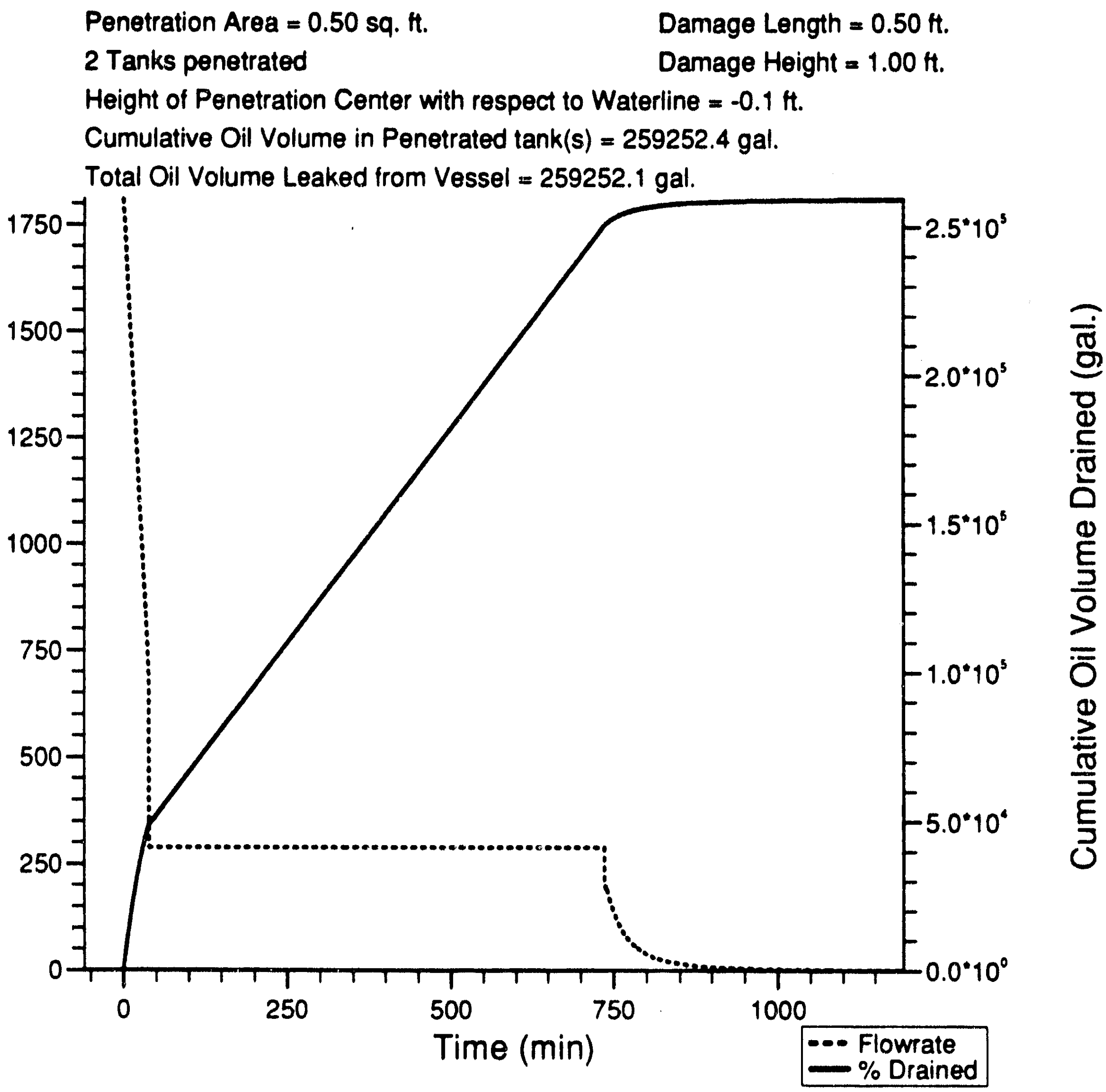
Penetration Height = 4.00 ft Penetration Length = 2.00 ft

Penetration Area = 8.0 sq. ft No. Tanks Penetrated = 2

Penetration Center w.r.t. Water Line = -0.3 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.03 | 428.22 | 0.20 | 15078.44 |
| 2.24 | 13058.34 | 6.10 | 3172.49 |
| 4.49 | 20175.92 | 9.42 | 3172.49 |
| 6.73 | 27293.50 | 12.75 | 3172.49 |
| 8.97 | 34411.08 | 16.07 | 3172.49 |
| 11.22 | 41528.66 | 19.40 | 3172.49 |
| 13.46 | 48646.24 | 22.72 | 3172.49 |
| 15.70 | 55763.82 | 26.04 | 3172.49 |
| 17.95 | 62881.40 | 29.37 | 3172.49 |
| 20.19 | 69999.09 | 32.69 | 3172.49 |
| 22.44 | 77116.98 | 36.02 | 3172.49 |
| 24.68 | 84234.88 | 39.34 | 3172.49 |
| 26.92 | 91352.78 | 42.67 | 3172.49 |
| 29.14 | 98380.59 | 45.95 | 3172.49 |
| 31.38 | 105498.48 | 49.27 | 3172.49 |
| 33.62 | 112616.38 | 52.60 | 3172.49 |
| 35.87 | 119734.27 | 55.92 | 3172.49 |
| 38.11 | 126852.17 | 59.25 | 3172.49 |
| 40.36 | 133970.08 | 62.57 | 3172.49 |
| 42.60 | 141087.97 | 65.90 | 3172.49 |
| 44.84 | 148205.88 | 69.22 | 3172.49 |
| 47.09 | 155323.77 | 72.54 | 3172.49 |
| 49.33 | 162441.67 | 75.87 | 3172.49 |
| 51.57 | 169559.56 | 79.19 | 3172.49 |
| 53.82 | 176677.47 | 82.52 | 3172.49 |
| 56.03 | 183705.27 | 85.80 | 3172.49 |
| 58.28 | 190823.16 | 89.12 | 3172.49 |
| 60.52 | 197941.06 | 92.45 | 3172.49 |
| 62.76 | 204999.05 | 95.75 | 1063.06 |
| 65.01 | 207012.45 | 96.69 | 758.49 |
| 67.25 | 208473.72 | 97.37 | 560.02 |
| 69.49 | 209567.75 | 97.88 | 425.19 |
| 71.74 | 210408.05 | 98.27 | 330.41 |
| 73.98 | 211067.47 | 98.58 | 261.84 |
| 76.22 | 211594.53 | 98.83 | 211.00 |
| 78.47 | 212022.30 | 99.03 | 172.52 |
| 80.71 | 212374.27 | 99.19 | 142.86 |
| 82.93 | 212663.97 | 99.33 | 119.89 |
| 85.17 | 212911.20 | 99.44 | 101.38 |
| 87.41 | 213121.16 | 99.54 | 86.50 |
| 89.66 | 213301.06 | 99.62 | 74.40 |
| 91.90 | 213456.34 | 99.70 | 64.44 |
| 94.14 | 213591.28 | 99.76 | 56.20 |
| 96.39 | 213709.30 | 99.81 | 49.29 |
| 98.63 | 213813.14 | 99.86 | 43.48 |
| 100.87 | 213904.91 | 99.90 | 38.55 |
| 103.12 | 213986.50 | 99.94 | 34.33 |
| 105.36 | 214059.30 | 99.98 | 30.71 |
| 107.60 | 214124.56 | 100.00 | 27.58 |
| 109.87 | 214183.25 | 100.00 | 0.00 |

## Oil Outflow in Case of Vessel Collision for 1769 GT Barge



Barge Collision      Barge GT = 1769.

Accident Occurred in Fresh Water      Cargo Specific Gravity = .92

Draft = 9.6 ft

Penetration Height = 1.00 ft      Penetration Length = 0.50 ft

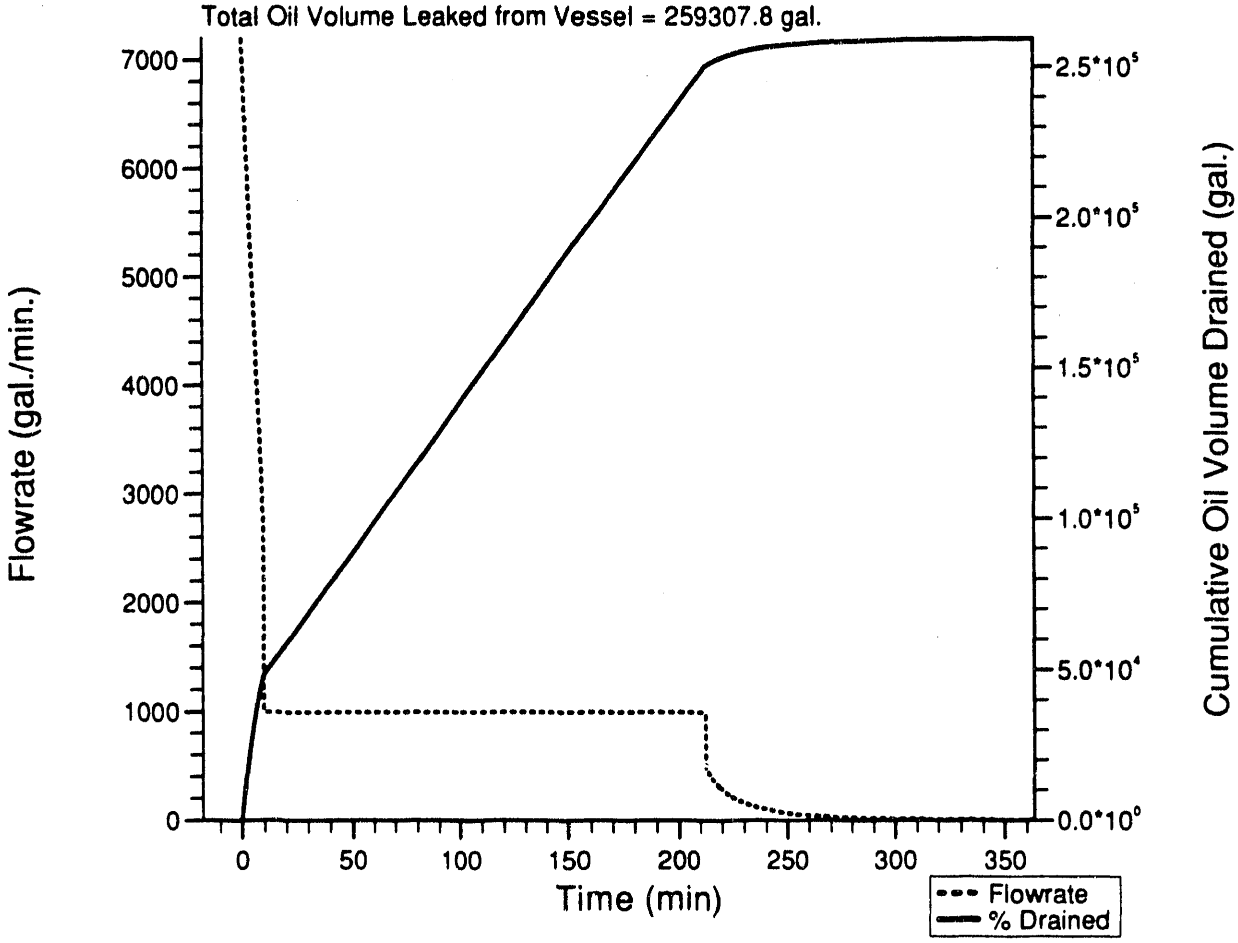
Penetration Area = 0.5 sq. ft      No. Tanks Penetrated = 2

Penetration Center w.r.t. Water Line = -0.1 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.29 | 518.50 | 0.20 | 1809.99 |
| 24.64 | 35951.25 | 13.87 | 1108.41 |
| 48.99 | 51708.00 | 19.95 | 289.19 |
| 73.34 | 58749.77 | 22.66 | 289.19 |
| 97.69 | 65791.52 | 25.38 | 289.19 |
| 122.04 | 72833.29 | 28.09 | 289.19 |
| 146.39 | 79875.05 | 30.81 | 289.19 |
| 170.74 | 86916.81 | 33.53 | 289.19 |
| 195.08 | 93958.57 | 36.24 | 289.19 |
| 219.43 | 101000.34 | 38.96 | 289.19 |
| 243.78 | 108042.09 | 41.67 | 289.19 |
| 268.13 | 115083.86 | 44.39 | 289.19 |
| 292.48 | 122125.62 | 47.11 | 289.19 |
| 316.83 | 129167.38 | 49.82 | 289.19 |
| 341.18 | 136209.14 | 52.54 | 289.19 |
| 365.53 | 143250.91 | 55.26 | 289.19 |
| 389.88 | 150292.67 | 57.97 | 289.19 |
| 414.23 | 157334.42 | 60.69 | 289.19 |
| 438.58 | 164376.19 | 63.40 | 289.19 |
| 462.93 | 171417.95 | 66.12 | 289.19 |
| 487.28 | 178459.72 | 68.84 | 289.19 |
| 511.63 | 185501.47 | 71.55 | 289.19 |
| 535.98 | 192543.23 | 74.27 | 289.19 |
| 560.33 | 199585.00 | 76.98 | 289.19 |
| 584.67 | 206626.75 | 79.70 | 289.19 |
| 609.02 | 213668.52 | 82.42 | 289.19 |
| 633.37 | 220710.28 | 85.13 | 289.19 |
| 657.72 | 227752.05 | 87.85 | 289.19 |
| 682.06 | 234793.80 | 90.57 | 289.19 |
| 706.41 | 241835.56 | 93.28 | 289.19 |
| 730.76 | 248877.33 | 96.00 | 289.19 |
| 755.11 | 253519.20 | 97.79 | 117.96 |
| 779.45 | 255600.23 | 98.59 | 61.69 |
| 803.80 | 256752.09 | 99.04 | 36.22 |
| 828.15 | 257455.78 | 99.31 | 23.05 |
| 852.49 | 257917.06 | 99.48 | 15.57 |
| 876.84 | 258235.77 | 99.61 | 11.01 |
| 901.19 | 258465.05 | 99.70 | 8.07 |
| 925.54 | 258635.52 | 99.76 | 6.09 |
| 949.88 | 258765.73 | 99.81 | 4.70 |
| 974.23 | 258867.41 | 99.85 | 3.71 |
| 998.58 | 258948.36 | 99.88 | 2.98 |
| 1022.92 | 259013.83 | 99.91 | 2.43 |
| 1047.28 | 259067.53 | 99.93 | 2.01 |
| 1071.63 | 259112.11 | 99.95 | 1.67 |
| 1095.98 | 259149.55 | 99.96 | 1.41 |
| 1120.33 | 259181.30 | 99.97 | 1.20 |
| 1144.69 | 259208.44 | 99.98 | 1.03 |
| 1169.04 | 259231.78 | 99.99 | 0.89 |
| 1193.68 | 259252.08 | 100.00 | 0.00 |

## Oil Outflow in Case of Vessel Collision for 1769 GT Barge

Penetration Area = 2.00 sq. ft. Damage Length = 1.00 ft.
2 Tanks penetrated Damage Height = 2.00 ft.
Height of Penetration Center with respect to Waterline = -0.3 ft.
Cumulative Oil Volume in Penetrated tank(s) = 259252.4 gal.
Total Oil Volume Leaked from Vessel = 259307.8 gal.



Barge Collision Barge GT = 1769.

Accident Occurred in Fresh Water Cargo Specific Gravity = .92

Draft = 9.6 ft

Penetration Height = 2.00 ft Penetration Length = 1.00 ft

Penetration Area = 2.0 sq. ft No. Tanks Penetrated = 2

Penetration Center w.r.t. Water Line = -0.3 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.07 | 518.50 | 0.20 | 7195.88 |
| 7.42 | 40833.79 | 15.75 | 3806.83 |
| 14.84 | 53283.16 | 20.55 | 996.31 |
| 22.27 | 60677.68 | 23.40 | 996.31 |
| 29.69 | 68072.19 | 26.26 | 996.31 |
| 37.11 | 75466.70 | 29.11 | 996.31 |
| 44.53 | 82861.21 | 31.96 | 996.31 |
| 51.95 | 90255.72 | 34.81 | 996.31 |
| 59.37 | 97650.23 | 37.67 | 996.31 |
| 66.80 | 105044.74 | 40.52 | 996.31 |
| 74.22 | 112439.25 | 43.37 | 996.31 |
| 81.64 | 119833.76 | 46.22 | 996.31 |
| 89.06 | 127228.27 | 49.08 | 996.31 |
| 96.48 | 134622.78 | 51.93 | 996.31 |
| 103.91 | 142016.53 | 54.78 | 996.31 |
| 111.33 | 149410.20 | 57.63 | 996.31 |
| 118.75 | 156803.89 | 60.48 | 996.31 |
| 126.17 | 164197.56 | 63.34 | 996.31 |
| 133.59 | 171591.25 | 66.19 | 996.31 |
| 141.02 | 178984.92 | 69.04 | 996.31 |
| 148.44 | 186378.61 | 71.89 | 996.31 |
| 155.86 | 193772.30 | 74.74 | 996.31 |
| 163.28 | 201165.97 | 77.59 | 996.31 |
| 170.70 | 208559.66 | 80.45 | 996.31 |
| 178.12 | 215953.33 | 83.30 | 996.31 |
| 185.47 | 223275.23 | 86.12 | 996.31 |
| 192.89 | 230668.91 | 88.97 | 996.31 |
| 200.31 | 238062.59 | 91.83 | 996.31 |
| 207.74 | 245456.27 | 94.68 | 996.31 |
| 215.16 | 251257.69 | 96.92 | 400.08 |
| 222.58 | 253590.77 | 97.82 | 246.56 |
| 230.00 | 255077.05 | 98.39 | 162.56 |
| 237.42 | 256082.03 | 98.78 | 112.78 |
| 244.84 | 256793.12 | 99.05 | 81.42 |
| 252.26 | 257314.67 | 99.25 | 60.69 |
| 259.69 | 257708.58 | 99.40 | 46.44 |
| 267.11 | 258013.30 | 99.52 | 36.33 |
| 274.53 | 258253.88 | 99.61 | 28.95 |
| 281.95 | 258447.12 | 99.69 | 23.44 |
| 289.37 | 258604.73 | 99.75 | 19.25 |
| 296.79 | 258734.95 | 99.80 | 16.00 |
| 304.21 | 258843.72 | 99.84 | 13.44 |
| 311.64 | 258935.55 | 99.88 | 11.40 |
| 319.06 | 259013.78 | 99.91 | 9.75 |
| 326.48 | 259080.97 | 99.93 | 8.41 |
| 333.90 | 259139.08 | 99.96 | 7.30 |
| 341.32 | 259189.73 | 99.98 | 6.38 |
| 348.74 | 259234.03 | 99.99 | 5.61 |
| 356.16 | 259273.14 | 100.00 | 4.95 |
| 363.66 | 259307.80 | 100.00 | 0.00 |

## Oil Outflow in Case of Vessel Collision

## for 1769 GT Barge

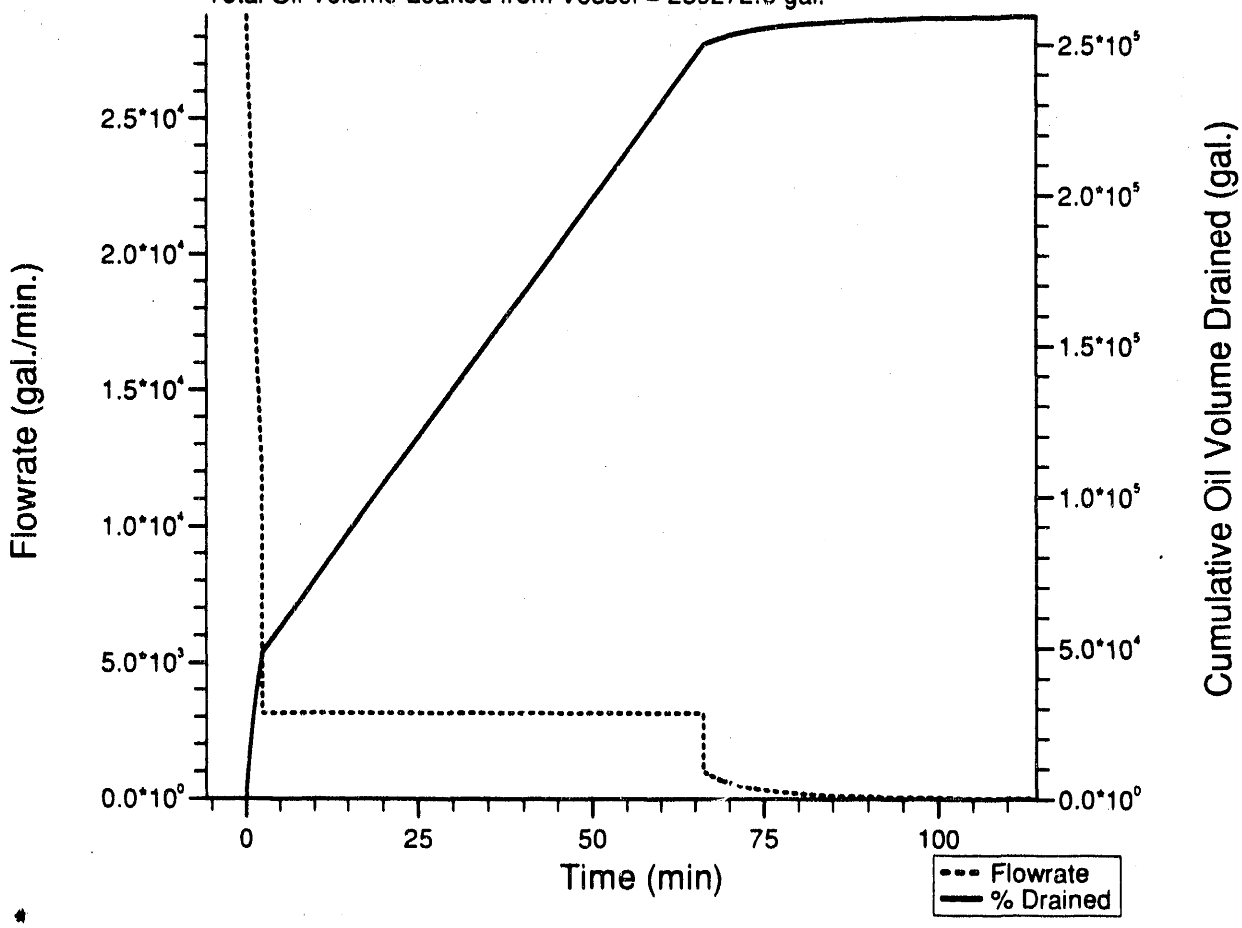
Penetration Area = 8.00 sq. ft. | Damage Length = 2.00 ft.

2 Tanks penetrated | Damage Height = 4.00 ft.

Height of Penetration Center with respect to Waterline = -0.3 ft.

Cumulative Oil Volume in Penetrated tank(s) = 259252.4 gal.

Total Oil Volume Leaked from Vessel = 259272.6 gal.



Barge Collision Barge GT = 1769.

Accident Occurred in Fresh Water Cargo Specific Gravity = .92

Draft = 9.6 ft

Penetration Height = 4.00 ft Penetration Length = 2.00 ft

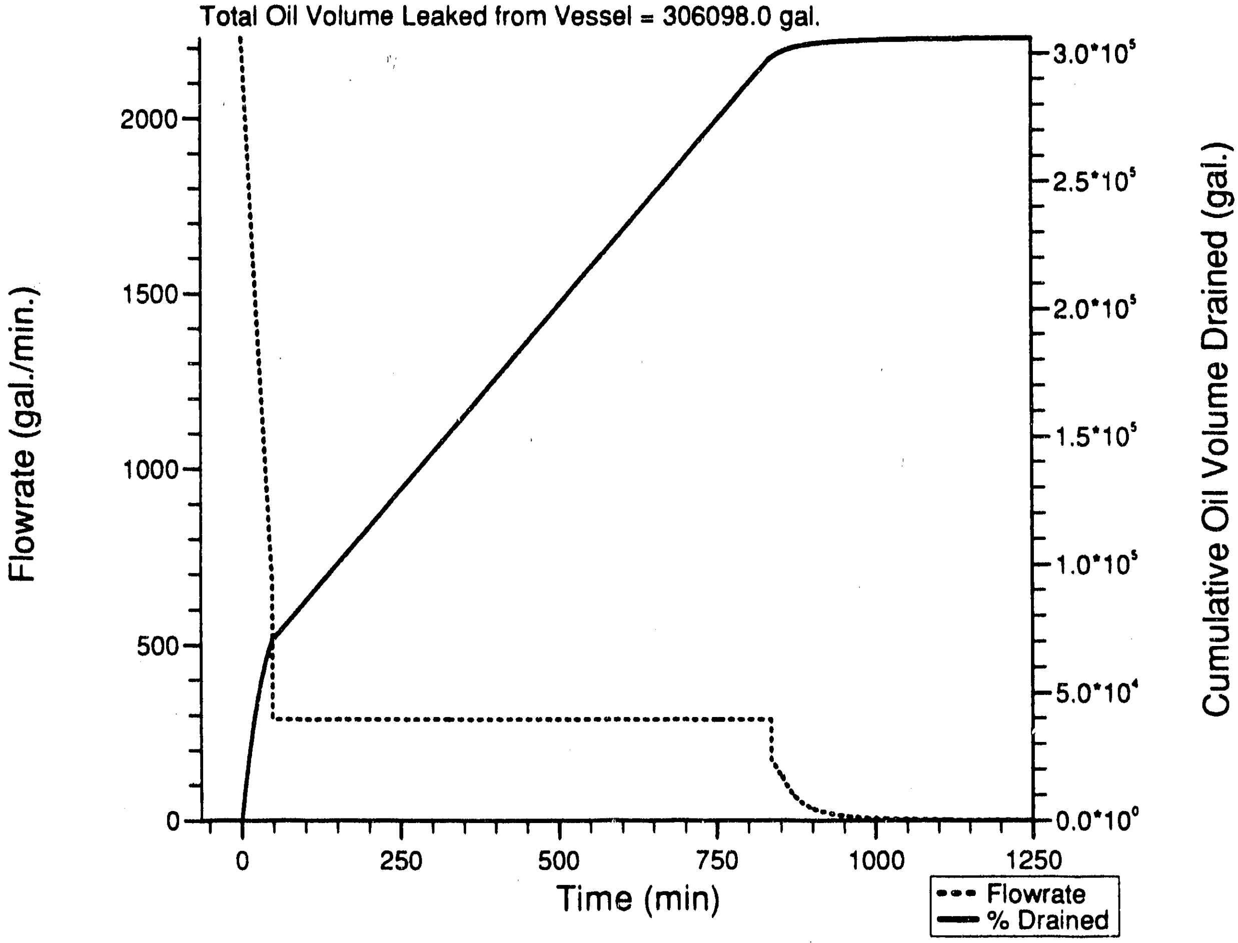
Penetration Area = 8.0 sq. ft No. Tanks Penetrated = 2

Penetration Center w.r.t. Water Line = -0.3 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.02 | 518.50 | 0.20 | 28762.92 |
| 2.34 | 47092.73 | 18.16 | 12583.66 |
| 4.67 | 55273.04 | 21.32 | 3161.83 |
| 7.01 | 62682.74 | 24.18 | 3161.83 |
| 9.34 | 70035.45 | 27.01 | 3161.83 |
| 11.68 | 77445.16 | 29.87 | 3161.83 |
| 14.01 | 84797.88 | 32.71 | 3161.83 |
| 16.33 | 92150.59 | 35.54 | 3161.83 |
| 18.68 | 99560.29 | 38.40 | 3161.83 |
| 21.00 | 106913.00 | 41.24 | 3161.83 |
| 23.34 | 114322.71 | 44.10 | 3161.83 |
| 25.67 | 121675.41 | 46.93 | 3161.83 |
| 28.00 | 129028.12 | 49.77 | 3161.83 |
| 30.34 | 136437.84 | 52.63 | 3161.83 |
| 32.66 | 143790.55 | 55.46 | 3161.83 |
| 35.01 | 151200.27 | 58.32 | 3161.83 |
| 37.33 | 158552.97 | 61.16 | 3161.83 |
| 39.66 | 165905.67 | 63.99 | 3161.83 |
| 42.00 | 173315.39 | 66.85 | 3161.83 |
| 44.33 | 180668.09 | 69.69 | 3161.83 |
| 46.67 | 188077.80 | 72.55 | 3161.83 |
| 49.00 | 195430.52 | 75.38 | 3161.83 |
| 51.32 | 202783.22 | 78.22 | 3161.83 |
| 53.67 | 210192.94 | 81.08 | 3161.83 |
| 55.99 | 217545.64 | 83.91 | 3161.83 |
| 58.34 | 224955.34 | 86.77 | 3161.83 |
| 60.66 | 232308.06 | 89.61 | 3161.83 |
| 63.01 | 239717.77 | 92.46 | 3161.83 |
| 65.33 | 247070.47 | 95.30 | 3161.83 |
| 67.66 | 251330.28 | 96.94 | 842.63 |
| 70.00 | 253013.72 | 97.59 | 612.18 |
| 72.33 | 254247.27 | 98.07 | 459.64 |
| 74.67 | 255191.56 | 98.43 | 353.18 |
| 77.00 | 255919.78 | 98.71 | 277.71 |
| 79.32 | 256497.44 | 98.94 | 222.30 |
| 81.67 | 256966.62 | 99.12 | 180.43 |
| 83.99 | 257347.38 | 99.27 | 148.66 |
| 86.33 | 257665.16 | 99.39 | 123.77 |
| 88.66 | 257929.23 | 99.49 | 104.27 |
| 90.99 | 258152.72 | 99.58 | 88.66 |
| 93.33 | 258344.97 | 99.65 | 75.93 |
| 95.66 | 258509.08 | 99.71 | 65.60 |
| 98.00 | 258652.36 | 99.77 | 57.00 |
| 100.32 | 258776.33 | 99.82 | 49.89 |
| 102.65 | 258885.14 | 99.86 | 43.92 |
| 104.99 | 258981.91 | 99.90 | 38.82 |
| 107.32 | 259067.03 | 99.93 | 34.52 |
| 109.66 | 259143.42 | 99.96 | 30.80 |
| 111.99 | 259211.20 | 99.98 | 27.62 |
| 114.35 | 259272.61 | 100.00 | 0.00 |

## Oil Outflow in Case of Vessel Collision
## for 2713 GT Barge

Penetration Area = 0.50 sq. ft. Damage Length = 0.50 ft.
2 Tanks penetrated Damage Height = 1.00 ft.
Height of Penetration Center with respect to Waterline = -0.2 ft.
Cumulative Oil Volume in Penetrated tank(s) = 306037.4 gal.
Total Oil Volume Leaked from Vessel = 306098.0 gal.



Barge Collision Barge GT = 2713.

Accident Occurred in Salt Water Cargo Specific Gravity = .86

Draft = 12.0 ft

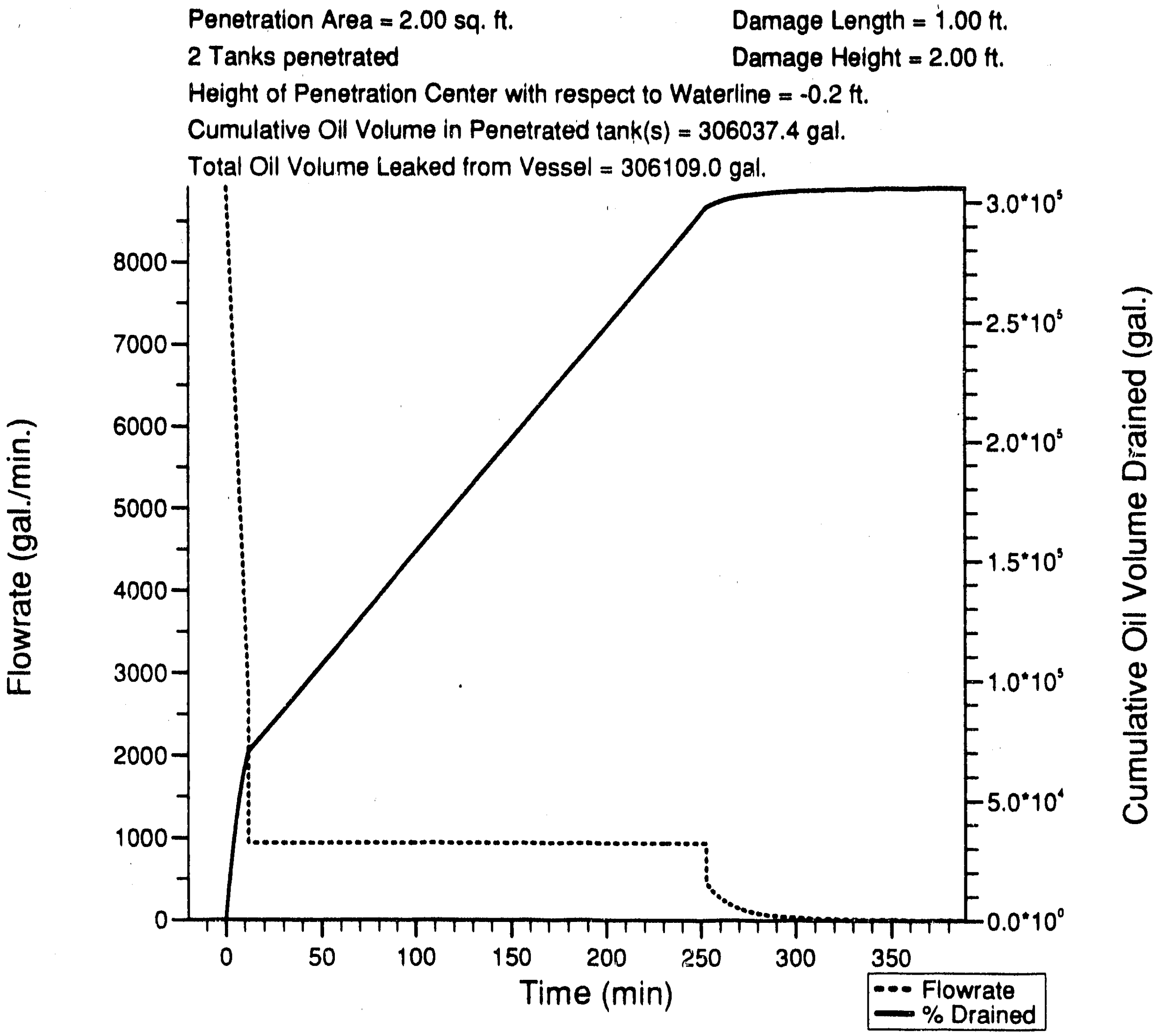
Penetration Height = 1.00 ft Penetration Length = 0.50 ft

Penetration Area = 0.5 sq. ft No. Tanks Penetrated = 2

Penetration Center w.r.t. Water Line = -0.2 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.27 | 612.07 | 0.20 | 2227.40 |
| 25.56 | 46618.92 | 15.23 | 1420.86 |
| 51.11 | 71410.83 | 23.33 | 289.19 |
| 76.67 | 78801.20 | 25.75 | 289.19 |
| 102.22 | 86191.56 | 28.16 | 289.19 |
| 127.78 | 93581.93 | 30.58 | 289.19 |
| 153.06 | 100892.83 | 32.97 | 289.19 |
| 178.62 | 108283.20 | 35.38 | 289.19 |
| 204.17 | 115673.56 | 37.80 | 289.19 |
| 229.73 | 123063.93 | 40.21 | 289.19 |
| 255.28 | 130454.30 | 42.63 | 289.19 |
| 280.56 | 137765.45 | 45.02 | 289.19 |
| 306.12 | 145156.56 | 47.43 | 289.19 |
| 331.67 | 152547.67 | 49.85 | 289.19 |
| 357.23 | 159938.80 | 52.26 | 289.19 |
| 382.78 | 167329.91 | 54.68 | 289.19 |
| 408.34 | 174721.03 | 57.09 | 289.19 |
| 433.62 | 182032.67 | 59.48 | 289.19 |
| 459.17 | 189423.78 | 61.90 | 289.19 |
| 484.73 | 196814.91 | 64.31 | 289.19 |
| 510.28 | 204206.02 | 66.73 | 289.19 |
| 535.84 | 211597.14 | 69.14 | 289.19 |
| 561.11 | 218908.78 | 71.53 | 289.19 |
| 586.67 | 226299.89 | 73.95 | 289.19 |
| 612.22 | 233691.02 | 76.36 | 289.19 |
| 637.78 | 241082.12 | 78.78 | 289.19 |
| 663.33 | 248473.25 | 81.19 | 289.19 |
| 688.89 | 255864.36 | 83.61 | 289.19 |
| 714.17 | 263176.00 | 85.99 | 289.19 |
| 739.72 | 270567.09 | 88.41 | 289.19 |
| 765.28 | 277956.72 | 90.82 | 289.19 |
| 790.83 | 285346.34 | 93.24 | 289.19 |
| 816.39 | 292735.97 | 95.65 | 289.19 |
| 841.67 | 299192.12 | 97.76 | 155.06 |
| 867.22 | 302170.44 | 98.74 | 79.26 |
| 892.77 | 303631.06 | 99.21 | 41.02 |
| 918.33 | 304432.25 | 99.48 | 23.91 |
| 943.88 | 304918.72 | 99.63 | 15.14 |
| 969.44 | 305236.09 | 99.74 | 10.19 |
| 994.72 | 305452.59 | 99.81 | 7.21 |
| 1020.27 | 305609.91 | 99.86 | 5.27 |
| 1045.83 | 305726.59 | 99.90 | 3.96 |
| 1071.38 | 305815.53 | 99.93 | 3.06 |
| 1096.94 | 305884.97 | 99.95 | 2.41 |
| 1122.22 | 305939.53 | 99.97 | 1.94 |
| 1147.77 | 305984.12 | 99.98 | 1.58 |
| 1173.33 | 306020.56 | 99.99 | 1.30 |
| 1198.88 | 306050.94 | 100.00 | 1.08 |
| 1224.43 | 306076.34 | 100.00 | 0.91 |
| 1250.26 | 306098.00 | 100.00 | 0.00 |

## Oil Outflow in Case of Vessel Collision
## for 2713 GT Barge



Barge Collision    Barge GT = 2713.

Accident Occurred in Salt Water    Cargo Specific Gravity = .86

Draft = 12.0 ft

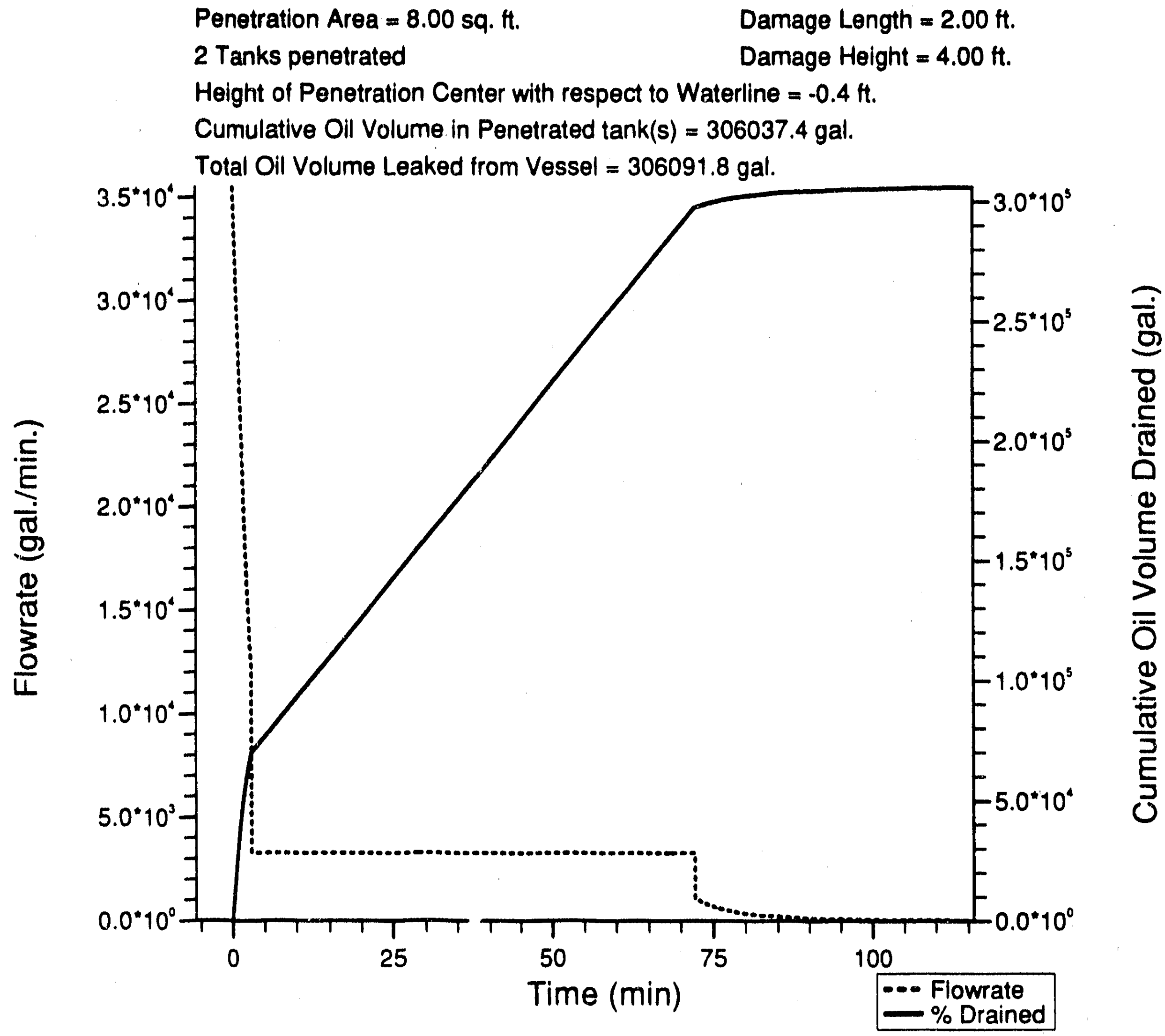
Penetration Height = 2.00 ft    Penetration Length = 1.00 ft

Penetration Area = 2.0 sq. ft    No. Tanks Penetrated = 2

Penetration Center w.r.t. Water Line = -0.2 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.07 | 612.07 | 0.20 | 8907.97 |
| 7.97 | 54927.73 | 17.95 | 4873.80 |
| 15.94 | 74136.79 | 24.22 | 944.43 |
| 23.84 | 81599.18 | 26.66 | 944.43 |
| 31.81 | 89126.46 | 29.12 | 944.43 |
| 39.71 | 96588.85 | 31.56 | 944.43 |
| 47.69 | 104116.13 | 34.02 | 944.43 |
| 55.59 | 111578.53 | 36.46 | 944.43 |
| 63.56 | 119105.81 | 38.92 | 944.43 |
| 71.46 | 126568.20 | 41.36 | 944.43 |
| 79.43 | 134095.48 | 43.82 | 944.43 |
| 87.33 | 141558.66 | 46.26 | 944.43 |
| 95.30 | 149086.88 | 48.72 | 944.43 |
| 103.20 | 156550.20 | 51.15 | 944.43 |
| 111.17 | 164078.41 | 53.61 | 944.43 |
| 119.08 | 171541.73 | 56.05 | 944.43 |
| 127.05 | 179069.95 | 58.51 | 944.43 |
| 134.95 | 186533.27 | 60.95 | 944.43 |
| 142.92 | 194061.48 | 63.41 | 944.43 |
| 150.82 | 201524.81 | 65.85 | 944.43 |
| 158.79 | 209053.02 | 68.31 | 944.43 |
| 166.69 | 216516.34 | 70.75 | 944.43 |
| 174.66 | 224044.56 | 73.21 | 944.43 |
| 182.56 | 231507.88 | 75.65 | 944.43 |
| 190.53 | 239036.09 | 78.11 | 944.43 |
| 198.44 | 246499.42 | 80.55 | 944.43 |
| 206.41 | 254027.64 | 83.01 | 944.43 |
| 214.31 | 261490.95 | 85.44 | 944.43 |
| 222.28 | 269019.16 | 87.90 | 944.43 |
| 230.18 | 276481.00 | 90.34 | 944.43 |
| 238.15 | 284007.34 | 92.80 | 944.43 |
| 246.05 | 291468.81 | 95.24 | 944.43 |
| 254.02 | 298451.56 | 97.52 | 431.25 |
| 261.93 | 301011.34 | 98.36 | 242.36 |
| 269.90 | 302527.66 | 98.85 | 148.94 |
| 277.80 | 303484.38 | 99.17 | 98.32 |
| 285.77 | 304136.56 | 99.38 | 68.08 |
| 293.68 | 304593.97 | 99.53 | 49.20 |
| 301.65 | 304932.28 | 99.64 | 36.61 |
| 309.55 | 305185.44 | 99.72 | 28.04 |
| 317.52 | 305382.94 | 99.79 | 21.91 |
| 325.43 | 305537.47 | 99.84 | 17.47 |
| 333.40 | 305662.66 | 99.88 | 14.13 |
| 341.30 | 305763.88 | 99.91 | 11.61 |
| 349.28 | 305848.31 | 99.94 | 9.64 |
| 357.18 | 305918.09 | 99.96 | 8.11 |
| 365.15 | 305977.62 | 99.98 | 6.87 |
| 373.05 | 306027.94 | 100.00 | 5.88 |
| 381.03 | 306071.28 | 100.00 | 5.07 |
| 389.07 | 306109.00 | 100.00 | 0.00 |

# Oil Outflow in Case of Vessel Collision
## for 2713 GT Barge



Barge Collision Barge GT = 2713.

Accident Occurred in Salt Water Cargo Specific Gravity = .86

Draft = 12.0 ft

Penetration Height = 4.00 ft Penetration Length = 2.00 ft

Penetration Area = 8.0 sq. ft No. Tanks Penetrated = 2

Penetration Center w.r.t. Water Line = -0.4 ft

| Time (min) | Total Outflow (gal) | % Outflow | Flowrate (gal/min) |
|---|---|---|---|
| 0.02 | 612.07 | 0.20 | 35476.57 |
| 2.38 | 61274.24 | 20.02 | 15954.38 |
| 4.74 | 75691.78 | 24.73 | 3285.56 |
| 7.11 | 83457.39 | 27.27 | 3285.56 |
| 9.47 | 91223.01 | 29.81 | 3285.56 |
| 11.84 | 98988.62 | 32.35 | 3285.56 |
| 14.20 | 106754.24 | 34.88 | 3285.56 |
| 16.56 | 114519.86 | 37.42 | 3285.56 |
| 18.93 | 122285.48 | 39.96 | 3285.56 |
| 21.29 | 130051.09 | 42.50 | 3285.56 |
| 23.67 | 137873.77 | 45.05 | 3285.56 |
| 26.04 | 145640.48 | 47.59 | 3285.56 |
| 28.40 | 153407.20 | 50.13 | 3285.56 |
| 30.76 | 161173.94 | 52.66 | 3285.56 |
| 33.13 | 168940.66 | 55.20 | 3285.56 |
| 35.49 | 176707.38 | 57.74 | 3285.56 |
| 37.85 | 184474.09 | 60.28 | 3285.56 |
| 40.22 | 192240.81 | 62.82 | 3285.56 |
| 42.58 | 200007.53 | 65.35 | 3285.56 |
| 44.95 | 207774.27 | 67.89 | 3285.56 |
| 47.33 | 215597.67 | 70.45 | 3285.56 |
| 49.69 | 223364.39 | 72.99 | 3285.56 |
| 52.05 | 231131.11 | 75.52 | 3285.56 |
| 54.42 | 238897.83 | 78.06 | 3285.56 |
| 56.78 | 246664.56 | 80.60 | 3285.56 |
| 59.15 | 254431.28 | 83.14 | 3285.56 |
| 61.51 | 262198.00 | 85.68 | 3285.56 |
| 63.87 | 269964.72 | 88.21 | 3285.56 |
| 66.24 | 277731.44 | 90.75 | 3285.56 |
| 68.60 | 285498.16 | 93.29 | 3285.56 |
| 70.98 | 293321.56 | 95.84 | 3285.56 |
| 73.34 | 298520.84 | 97.54 | 907.50 |
| 75.71 | 300310.69 | 98.13 | 631.11 |
| 78.07 | 301579.72 | 98.54 | 456.48 |
| 80.43 | 302512.28 | 98.85 | 340.79 |
| 82.80 | 303217.38 | 99.08 | 261.12 |
| 85.16 | 303763.44 | 99.26 | 204.47 |
| 87.52 | 304195.09 | 99.40 | 163.09 |
| 89.89 | 304542.12 | 99.51 | 132.17 |
| 92.25 | 304825.22 | 99.60 | 108.59 |
| 94.63 | 305060.84 | 99.68 | 90.19 |
| 96.99 | 305256.31 | 99.74 | 75.82 |
| 99.36 | 305421.34 | 99.80 | 64.34 |
| 101.72 | 305562.00 | 99.84 | 55.08 |
| 104.08 | 305682.88 | 99.88 | 47.50 |
| 106.45 | 305787.38 | 99.92 | 41.26 |
| 108.81 | 305878.56 | 99.95 | 36.06 |
| 111.17 | 305958.41 | 99.97 | 31.70 |
| 113.54 | 306028.84 | 100.00 | 28.02 |
| 115.93 | 306091.75 | 100.00 | 0.00 |

# APPENDIX B

## HUMAN FACTORS ANALYSIS OF PROPOSED COUNTERMEASURES

APPENDIX B

## HUMAN FACTORS ANALYSIS OF PROPOSED COUNTERMEASURES

As stated in Section 4.3, the human factors analysis of the proposed countermeasures was conducted by a human factors engineering expert familiar with crew structures and functions aboard tankers and tugs. The analysis was guided by existing maritime industry human factors guidelines and standards. A scheme for coding the human factors review was developed based on the potential findings of the review. Questions included the following:

1. Does the countermeasure appear to require crew members to operate it? If so, how many?

2. What general functions would the crew perform to operate the countermeasure? (Codes = Actuate, Emplace, Control, and Monitor).

3. Where would the crew be stationed in order to operate the countermeasure? Does the location adversely affect safety (e.g., foredeck operation in high seas)? (Codes = Deck, Bridge, Engine Room, Pump Room, Work Boat).

4. Does the countermeasure appear to require special training in addition to that already received by the licensed and unlicensed members of the crew? (Codes = Yes, No).

Assumptions: The following four functions have been identified as potentially being necessary to operate the oil spill countermeasure equipment described in the Coast Guard supplied concepts. The concepts have been reviewed for information pertinent to operation and evaluated in terms of the functions involved. The following definitions describe the type(s) of behavior associated with the functions:

- Actuate: Based on some external input, such as an alarm or spill team mustering, an operator manipulates a device in order to activate the countermeasure for operation. This might consist of releasing a hatch that is secured over a self-deployable boom, or simply pushing a button to activate electronically operated and deployed countermeasures. Additionally, it would consist of launching a workboat, if required.

- Emplace: Once a countermeasure is actuated, it must be put into proper position by some means. Crew members would be involved in the placement of the countermeasure in ways such as reeling the boom down from a work boat, throwing the boom over the side of a ship, or rigging skimming or pumping devices.

- Control: Control implies the use of feedback in order to manipulate the countermeasure so that it can achieve its designated purpose. This would include the use of lines to position and secure an overboard countermeasure, directing the flow of salvaged oil to selected locations, and performing and acting upon the results of stability calculations.

- Monitor: This function is somewhat more passive than the others, in that it involves watching the performance of the countermeasure to ensure proper operation. Examples include ensuring that tethered boom remains secured to the deck continue to operate, and salvage tanks do not exceed capacity. Periodic stability calculations would be included in this function.

The designation of numbers of crew required for countermeasure operation is based on the functions required and how these are carried out. Highly automated countermeasures, which simply require actuation by electronic means, may only require three crew members, one to actuate, and two to monitor on either side of the ship. More labor intensive deployment and operation requirements, such as launching of a work boat and operations on deck, would require more personnel. For example, a minimum of two persons is required to launch a workboat and deploy boom; additional personnel would be required to tether the boom to the ship (if that is required). The estimates of crew requirements for the countermeasure concepts are conservative from the standpoint of safety (always two crew members in a boat), but quite liberal from the standpoint of deck operations. Given the large surface area of tanker decks, it is quite likely that more personnel could be used if they were available; this depends on the conditions (weather, damage) prevailing at the time of the spill. The crew designations for tankers and tugs are virtually identical, since the countermeasures will require the same number of people to operate them unless there are design modifications made for each type of vessel. Tug/barge combinations are actually somewhat more complicated, since the tug crew needs to board the barges to actuate and deploy many of the countermeasures described.

The designation of the various countermeasures in the following analysis is based on a classification scheme developed by PNL in the early phases of the project.

**COUNTERMEASURE NUMBER AND TYPE:** 3, Envelope

DESCRIPTION: Booms deployed by workboats and ocean surface pumps in inflatable rafts used to pick up spilled oil.

RATINGS:

TANKERS: No. crew members required: 3+
Crew functions to operate: Actuate, Emplace, Control, Monitor
Crew stations: Deck, Work Boat
Training required: Yes

TUGS: No. crew members required: 3+
Crew functions to operate: Actuate, Emplace, Control, Monitor
Crew stations: Deck, Work Boat
Training required: Yes

COMMENTS: Pumping from inflatable rafts will require close deck and work boat coordination. Need to specify destination for pumped oil.

**COUNTERMEASURE NUMBER AND TYPE:** 9, Envelope

DESCRIPTION: Boom (w/o vertical extension) tethered to tanker

RATINGS:

TANKERS: No. crew members required: 3+
Crew functions to operate: Actuate, Emplace, Control, Monitor
Crew stations: Deck, Work Boat
Training required: Yes

TUGS: No. crew members required: 3+
Crew functions to operate: Actuate, Emplace, Control, Monitor
Crew stations: Deck, Work Boat
Training required: Yes

COMMENTS: Appears less feasible for barges because crew must activate from deck of tank vessel.

**COUNTERMEASURE NUMBER AND TYPE:** 11, Envelope

DESCRIPTION: External lining enveloping tanker

RATINGS: Insufficient detail provided

**COUNTERMEASURE NUMBER AND TYPE:** 22, Diaper

DESCRIPTION: Inflatable raft

RATINGS: Not applicable; concept requires helicopter and scuba diving team.

**COUNTERMEASURE NUMBER AND TYPE:** 31, Envelope

DESCRIPTION: Encircling boom

RATINGS:

TANKERS: No. crew members required: 3+
Crew functions to operate: Actuate, Emplace, Control, Monitor
Crew stations: Deck, Work Boat
Training required: Yes

TUGS: No. crew members required: 3+
Crew functions to operate: Actuate, Emplace, Control, Monitor
Crew stations: Deck, Work Boat
Training required: Yes

COMMENTS: Requires assembly of sections of desired length and blowing additional absorptive cork material over the oil. Also requires anchoring of boom sections.

**COUNTERMEASURE NUMBER AND TYPE:** 1, Boom

DESCRIPTION: Encircling boom and skimmers

RATINGS:

TANKERS: No. crew members required: 4+
Crew functions to operate: Assist in emplacement
Crew stations: Foredeck and Afterdeck
Training required: Yes

TUGS: No. crew members required: 4+
Crew functions to operate: Assist in emplacement
Crew stations: Foredeck and Afterdeck
Training required: Yes

COMMENTS: This countermeasure involves a cumbersome system of spars and guy wires to emplace and control the encircling boom. The written description suggested that the technology would be inappropriate for vessel storage and deployment, but it appears that crew assistance would be required, with 2 crew fore and aft for emplacement.

**COUNTERMEASURE NUMBER AND TYPE:** 4, Boom

DESCRIPTION: Absorbent material dropped into tank, boom encircles ship.

RATINGS:

TANKERS: No. crew members required: 3+
Crew functions to operate: Actuate, Monitor
Crew stations:
Bridge (actuate drop system), Aft Deck (actuate boom container), Fore Deck (operate winch), Main Deck (replace drop system)
Training required: Yes

TUGS: No. crew members required: 3+
Crew functions to operate: Actuate, Monitor
Crew stations:
Barge House (actuate drop system), Aft Deck (actuate boom container), Fore Deck (operate winch), Main Deck (replace drop system)
Training required: Yes

COMMENTS: May require stability calculations to be done in real-time in order to determine how much absorbent material to put into tank; if cables get "hung up" when being drawn around the hull, may require dangerous operation to free them (i.e., go over side)

**COUNTERMEASURE NUMBER AND TYPE:** 12, Boom

DESCRIPTION: Boom, pumps, skimmers, balloon storage for oil

RATINGS:

TANKERS: No. crew members required: 6+
Crew functions to operate:
Actuate, Emplace, Control and Monitor multiple pieces of equipment (tank openings, boom via work boat, skimmer and sea bag via work boat)
Crew stations: Deck, work boats
Training required: Yes

TUGS: No. crew members required: 6+
Crew functions to operate:
Actuate, Emplace, Control and Monitor multiple pieces of equipment (tank openings, boom via work boat, skimmer ana sea bag via work boat)
Crew stations: Deck, work boats
Training required: Yes

COMMENTS: This set of counter measures is very crew intensive because it requires carrying out multiple procedures simultaneously involving different pieces of equipment. It is probable that two work boats would be required, one for boom emplacement, the other for the sea pump/skimmer and balloon storage bag.

**COUNTERMEASURE NUMBER AND TYPE:** 14, Boom

DESCRIPTION: Curtain dropped from deck and fastened to deck edge.

RATINGS:

TANKERS: No. crew members required: 2+
Crew functions to operate: Actuate, Monitor
Crew stations: Deck
Training required: Minimal

TUGS: No. crew members required: 2+
Crew functions to operate: Actuate, Monitor
Crew stations: Deck
Training required: Minimal

COMMENTS: This boom appears to be stored in containers adjacent to the bulwarks, and activated manually or automatically; weights hold the material in place.

**COUNTERMEASURE NUMBER AND TYPE:** 15, Boom

DESCRIPTION: Encircling boom tethered to tanker

RATINGS:

TANKERS:
No. crew members required: 3+
Crew functions to operate: Actuate, Control, Monitor
Crew stations: Deck
Training required: Yes

TUGS:
No. crew members required: 3+
Crew functions to operate: Actuate, Control, Monitor
Crew stations: Barge deck
Training required: Yes

COMMENTS: The encircling boom would create difficulties for other craft and personnel getting close to a barge in order to continue cleanup operations.

**COUNTERMEASURE NUMBER AND TYPE:** 17, Boom

DESCRIPTION: Boom tethered to deck

RATINGS:

TANKERS:
No. crew members required: Nominally 2; Scenario illustrated with 8
Crew functions to operate:
Actuate, Emplace, Control, Monitor
Crew stations: Deck
Training required: Yes

TUGS:
No. crew members required: 2+
Crew functions to operate: Actuate, Emplace, Control, Monitor
Crew stations: Barge deck
Training required: Yes

COMMENTS: Individual sections of boom required inflation with compressed air prior to deployment over the side; they must also be attached to the end of a connecting section prior to inflation and deployment. This could lead to handling problems, since the inflated deployed section will drag the not yet deployed uninflated section.

**COUNTERMEASURE NUMBER AND TYPE:** 18, Boom

DESCRIPTION: Encircling boom

RATINGS: Insufficient detail provided

**COUNTERMEASURE NUMBER AND TYPE:** 21, Boom

DESCRIPTION: Encircling boom/envelope

RATINGS: Insufficient detail provided

**COUNTERMEASURE NUMBER AND TYPE:** 23, Boom

DESCRIPTION: Tethered boom

RATINGS:

TANKERS:
No. crew members required: 2+
Crew functions to operate: Actuate, Control, Monitor
Crew stations: Deck
Training required: Yes

TUGS:
No. crew members required: 2+
Crew functions to operate: Actuate, Control, Monitor
Crew stations: Deck
Training required: Yes

COMMENTS: This system is automatically emplaced, once actuated either manually or via a spill detection system. It would appear that the tether lines would require adjustment or securing, and that the ballast system would require operation, and possibly calculations to accommodate vessel stability and weather conditions.

**COUNTERMEASURE NUMBER AND TYPE:** 25, Boom

DESCRIPTION: Encircling boom

RATINGS: Insufficient detail provided

**COUNTERMEASURE NUMBER AND TYPE:** 28, Boom

DESCRIPTION: Tethered encircling boom

RATINGS:

TANKERS: No. crew members required: 2+
Crew functions to operate: Actuate, Control, Monitor
Crew stations: Deck
Training required: Yes

TUGS: No. crew members required: 2+
Crew functions to operate: Actuate, Control, Monitor
Crew stations: Deck
Training required: Yes

COMMENTS: Crew actuates by releasing door on storage container; it appears as if the barrier material is self-emplacing, via bottom weights and self-inflating buoys. The tether probably needs to be secured. It is not clear how many canisters are required (i.e., are multiple sheets of barrier material used? If so, how are they joined to prevent leakage?).

**COUNTERMEASURE NUMBER AND TYPE:** 29, Boom

DESCRIPTION: Boom deployed by small boat

RATINGS:

TANKERS: No. crew members required: 3+
Crew functions to operate: Actuate, Emplace, Control, Monitor
Crew stations: Deck, Work boat
Training required: Yes

TUGS: No. crew members required: 3+
Crew functions to operate: Actuate, Emplace, Control, Monitor
Crew stations: Deck, Work boat
Training required: Yes

COMMENTS: Work boat appears small enough to be stored on larger tugs, thus facilitating deployment for barges.

**COUNTERMEASURE NUMBER AND TYPE:** 32, Boom

DESCRIPTION: Boom and onboard skimmer

RATINGS:

TANKERS: No. crew members required: 6+
Crew functions to operate: Actuate, Emplace, Control, Monitor
Crew stations: Deck, Workboat
Training required: Yes

TUGS: No. crew members required: 6+
Crew functions to operate: Actuate, Emplace, Control, Monitor
Crew stations: Deck, Workboat
Training required: Yes

COMMENTS: The countermeasure involves boom placed via workboat and submersible skimmers lowered by boom from the tank vessel. Operation needs 3 crew members for the boom deployment, 1 for starboard and port pumps, and 1 for stripping pumps, plus supervision. On tankers, skimmed oil is pumped into a salvage tank, or the pump room (this latter destination could cause stability problems); a salvage location may not be available on barges.

**COUNTERMEASURE NUMBER AND TYPE:** 33, Boom

DESCRIPTION: Inflatable boom

RATINGS: Insufficient detail provided

COMMENTS: The invention description indicates requirements for determining in real-time how much ballast should be used for the different barrier sections. This increases the complexity of the operation. It is likely that workboats are required for emplacement, but this is not clear from the description.

**COUNTERMEASURE NUMBER AND TYPE:** 34, Boom

DESCRIPTION: Tethered boom

RATINGS:

TANKERS: No. crew members required: 2+
Crew functions to operate: Actuate, Monitor
Crew stations: Deck
Training required: Minimal

TUGS: No. crew members required: 2+
Crew functions to operate: Actuate, Monitor
Crew stations: Deck
Training required: Minimal

COMMENTS: Some control actions may be required to secure the tethering lines. The actual number of crew to operate depends on the number of containment system housings mounted on deck.

**COUNTERMEASURE NUMBER AND TYPE:** 36, Boom

DESCRIPTION: Encircling boom and remote control skimmer

RATINGS:

TANKERS: No. crew members required: 2+
Crew functions to operate: Actuate, Monitor
Crew stations: Bridge, After deck
Training required: Yes

TUGS: No. crew members required: 2+
Crew functions to operate: Actuate, Monitor
Crew stations: Deck
Training required: Yes

COMMENTS: Use of the remote controlled skimmer would increase the crew requirements, since it would need an operator and someone to monitor salvaged oil storage.

**COUNTERMEASURE NUMBER AND TYPE:** 38, Unclassified

DESCRIPTION: no detail provided

**COUNTERMEASURE NUMBER AND TYPE:** 41, Boom

DESCRIPTION: Boom and workboat

RATINGS: Insufficient detail; illegible copy

**COUNTERMEASURE NUMBER AND TYPE:** 42, Boom

DESCRIPTION: Roller mounted boom, stored in After deck space

RATINGS:

TANKERS:
No. crew members required: 4
Crew functions to operate: Actuate, Emplace, Control, Monitor
Crew stations: Deck, Work boat
Training required: Yes

TUGS:
No. crew members required: 4
Crew functions to operate: Actuate, Emplace, Control, Monitor
Crew stations: Deck, Work boat
Training required: Yes

COMMENTS: Hazard may exist involving connection of boom ends from work boat.

**COUNTERMEASURE NUMBER AND TYPE:** 44, Boom

DESCRIPTION: Encircling boom

RATINGS:

TANKERS:
No. crew members required: 3+
Crew functions to operate: Actuate, Control, Monitor
Crew stations: Deck
Training required: Yes

TUGS:
No. crew members required: 3+
Crew functions to operate: Actuate, Control, Monitor
Crew stations: Deck
Training required: Yes

COMMENTS: Crew actions would be required to ensure that threaded rope pays out appropriately (this is also a hazard concern, since it is launched by a harpoon gun). Is the 1/2 - 1 mile radius of boom realistic?

**COUNTERMEASURE NUMBER AND TYPE:** 45, Boom

DESCRIPTION: Encircling boom

RATINGS: Insufficient detail on operation provided

**COUNTERMEASURE NUMBER AND TYPE:** 2, Liner

DESCRIPTION: Hull Liner

RATINGS: Human intervention not required; liner responds flexibly to hard material, preventing escape of oil.

**COUNTERMEASURE NUMBER AND TYPE:** 10, Liner

DESCRIPTION: Hull design with liner, recovery ship with trailing skimmer

RATINGS: Insufficient detail provided. It appears that human intervention is required only on the recovery ship to deploy and operate the trailing skimmer.

**COUNTERMEASURE NUMBER AND TYPE:** 5, Bladder

DESCRIPTION: Pump oil from ruptured tank into external balloon

RATINGS:

TANKERS: No. crew members required: 3+
Crew functions to operate: Actuate, Control, Monitor
Crew stations: Deck
Training required: Yes

TUGS: No. crew members required: 3+
Crew functions to operate: Actuate, Control, Monitor
Crew stations: Deck
Training required: Yes

COMMENTS: Crew intervention is required to activate the pumps and bladder mechanism, and to secure the balloon after it has been deployed. Insufficient detail to determine if a work boat is required to emplace the balloon.

**COUNTERMEASURE NUMBER AND TYPE:** 6, Bladder

DESCRIPTION: Pump oil from ruptured tank into external balloon.

RATINGS:

TANKERS: No. crew members required: 3+
Crew functions to operate: Actuate, Emplace, Control, Monitor
Crew stations: Deck, Work boat
Training required: Yes

TUGS: No. crew members required: 3+
Crew functions to operate: Actuate, Emplace, Control, Monitor
Crew stations: Deck
Training required: Yes

COMMENTS: Placement of multiple bags, as suggested, would require additional crew members.

**COUNTERMEASURE NUMBER AND TYPE:** 16, Bladder

DESCRIPTION: Pump oil out of ruptured container so that net flow is into tank. Pumped oil is stored internally or externally.

RATINGS:

TANKERS: No. crew members required: 3+
Crew functions to operate: Actuate, Control, Monitor
Crew stations: Deck
Training required: Yes

TUGS: No. crew members required: 3+
Crew functions to operate: Actuate, Control, Monitor
Crew stations: Deck
Training required: Yes

COMMENTS: This countermeasure involves opening a series of valves, which must be done in the proper order to ensure safe salvage. The design of the valve controls should indicate their order in a salvage sequence.

**COUNTERMEASURE NUMBER AND TYPE:** 20, Bladder

DESCRIPTION: Oil transferred to other on-deck tank or external balloon.

RATINGS: Insufficient detail provided

**COUNTERMEASURE NUMBER AND TYPE:** 13, Skirt

DESCRIPTION: Curtain dropped from deck and fastened to deck edge

RATINGS: Insufficient detail provided

**COUNTERMEASURE NUMBER AND TYPE:** 26, Skirt

DESCRIPTION: Skirt

RATINGS: Insufficient detail provided

**COUNTERMEASURE NUMBER AND TYPE:** 26, Skirt

DESCRIPTION: Bulwark mounted skirt

RATINGS: Insufficient detail provided

**COUNTERMEASURE NUMBER AND TYPE:** 40, Absorbent

DESCRIPTION:

RATINGS: Insufficient detail provided

**COUNTERMEASURE NUMBER AND TYPE:** 19, Patch and Plumb

DESCRIPTION: Pump attached to outside of tanker rupture

COMMENTS: The many potential scenarios available for this device make a unitary rating meaningless. From the standpoint of self-help, this concept is not immediately useful, since it requires a scuba diver to attach the device. A ship that is retrofit with "THOR" may be more likely to recover oil from a self-caused spill, but this would still require sufficient storage capacity, which may not exist due to other full tanks, or stability problems.

# APPENDIX C

## BULK-OIL TREATMENT CONCEPTS, PROPOSED PATCHING METHODS, AND PUMPING/SKIMMING CONCEPTS

# APPENDIX C

## BULK-OIL TREATMENT CONCEPTS

EDIC II Z387B

4,981,097

ON-BOARD OIL SPILL PREVENTION AND RECOVERY SYSTEM

Louis Beyrouty, 88 Robin Dr., Mercerville, N.J. 08619

Filed Feb. 26, 1990, Ser. No. 484,977
Int. Cl.[5] B63B 43/16
U.S. Cl. 114—228 7 Claims

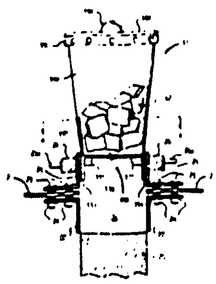
1. An on-board oil spill prevention and recovery system for an oil transporting vessel comprising

a pillow storage container;

JANUARY 1, 1991

a plurality of sorbent pillows disposed in said pillow storage container;

means to selectively release said pillows from said container to the interior of an oil holding tank of said vessel;

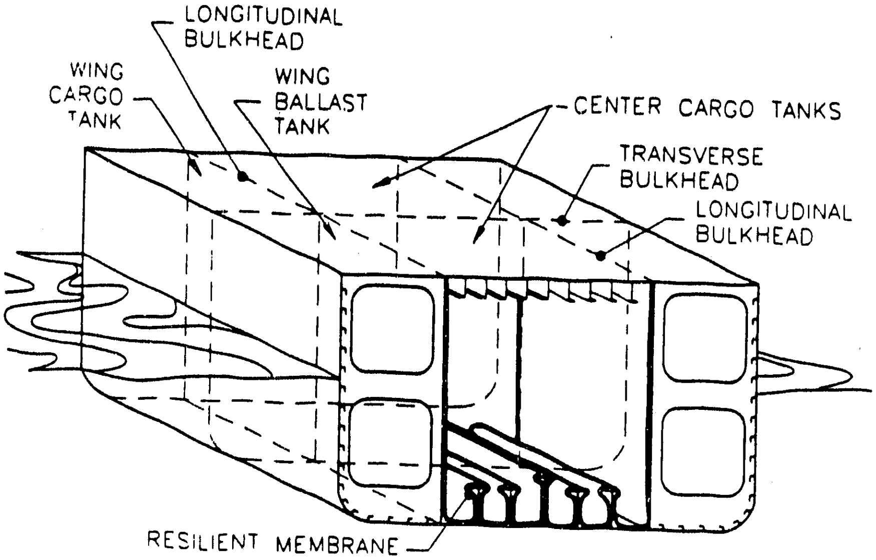


a sorbent boom; and

means to deploy said sorbent boom into the waters surrounding the vessel.

# APPENDIX C

## PATCHING AND PLUGGING CONCEPTS




Resilient membrane—a pliable, non-structural tank liner.

APRIL 23, 1991

LDIC # 24026

5,009,180

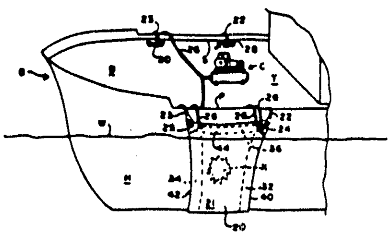
**HULL HOLE CLOSURE FOR AN OIL TANKER**

William T. Holt, 4610 Ellendale Rd., Memphis, Tenn. 38135

Filed Sep. 7, 1990, Ser. No. 579,365

Int. Cl.[5] B63B 43/16

U.S. Cl. 114—229 23 Claims



13. A hull hole closure, for use with an oil tanker having a hull hole, said closure comprising:

a. a flexible, substantially waterproof sheet, shaped substantially similar to the bow of the tanker, for covering said hull hole and for extending under the keel and around the bow of the tanker from the port side to the starboard side of the tanker, said sheet comprising:
   i. an aft edge, for location toward the stern of the tanker and passing under the keel of the tanker, said aft edge comprising a first end and a second end;
   ii. an upper portion for location substantially above the water line of the tanker, said upper portion extending substantially from the first end of the aft edge to the second end of the aft edge;
   iii. an inner surface for placement substantially adjacent the hull of the tanker; and, iv. an outer surface for placement away from the hull of the tanker;

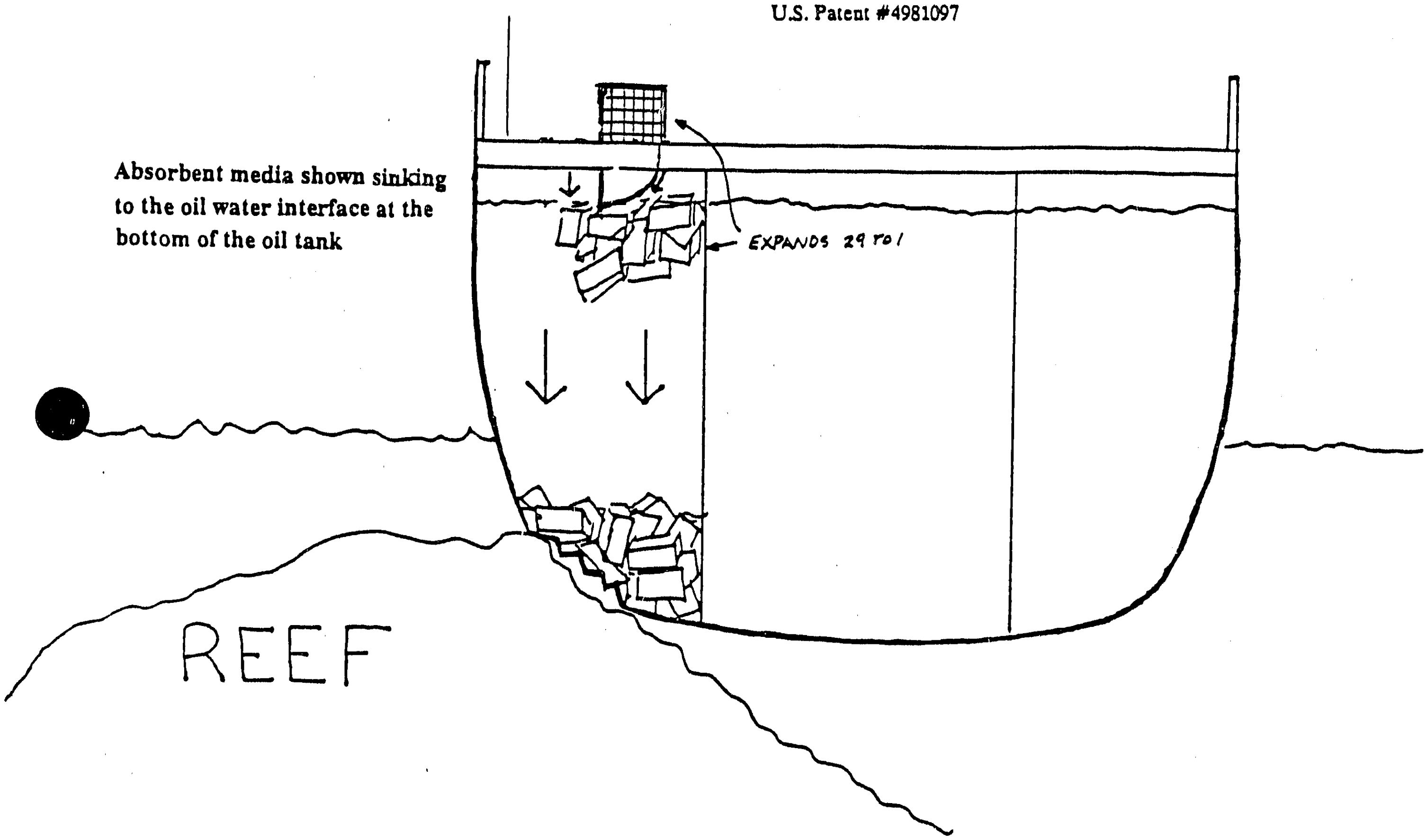
b. an aft belt, attached to the sheet substantially adjacent the aft edge of the sheet, said aft belt extending substantially from the first end of the aft edge to the second end of the aft edge, said aft belt comprising:
   i. a longitudinal reinforcing strap attached to the sheet; and,
   ii. a first longitudinal high pressure hose for inflation, located substantially parallel to the longitudinal reinforcing strap, and attached to the longitudinal reinforcing strap on the inner surface of the sheet;

c. an upper belt, attached to the upper portion of the sheet, comprising:
   i. a transverse reinforcing strap attached to the sheet, and
   ii. a transverse inflatable bladder attached to the upper belt on the inner surface of the sheet for inflation to substantially seal the upper portion of the sheet to the hull; and

d. means for securing the hull hole closure to the tanker.

**Oil Spill Containment And Retention System**

U.S. Patent #4981097



# APPENDIX C

## PUMPING/SKIMMING CONCEPTS

**Gulf Research and Development Company Device**

A device developed by *R.C. Amero and G.L. Karner; U.S. Patent 3,534,859; October 20, 1970; assigned to Gulf Research and Development Company* for removing and collecting oil floating on water contains a first inner member which serves as both a main flotation member and a notched weir, and an outer buoyancy member held above the flotation member and closely adjacent the surface of the oil. A flotsam screen is provided. An inflatable embodiment easily carried on vessels or other vehicles is also provided.

Figure 134 is a sectional perspective view of such a device. Referring to the drawing, 10 designates an oil recovery device which comprises an inner flotation member 12, an outer stabilizing and buoyancy member 14, and a plurality of rib members 16 interconnecting the members 12 and 14. Suspended from inner flotation member 12 is a combined tank and funnel assembly 18 which comprises a tank member 20 within which is nested a funnel member 22.

Suspended from outer buoyancy member 14 is a screen 24 which extends down from member 14 through the layer of oil 26 and into the water 28 below the level of the uppermost portion of inner member 12, or lower. The screen will surround the inner member even where the outer member is discontinuous, or provided with a gap or gaps, as described below.

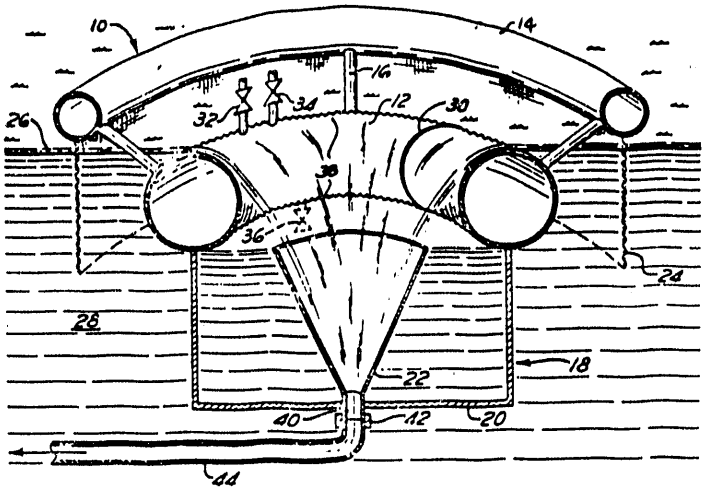
Means are provided to adjustably control the buoyancy of the overall device by controlling the amount of air and water within inner flotation member 12, and to also control the horizontal position of the device so as to keep the top surface of the flotation member 12 level. The buoyancy control permits location of the top surface of the inner member at a predetermined level with respect to the oil/water interface. To this end, flotation member 12 is divided into a plurality of separate compartments by a number of transverse dividing members 30.

Each compartment carries a first valve means 32 which may be a compressed air fitting to permit filling the compartment with compressed air; second valve means 34 which may comprise an air release valve; and a third valve means 36 which may comprise a combined water inlet and outlet valve. By manipulating the ratio of compressed air and water in each compartment of member 12, the overall buoyancy of the entire device may be controlled. Thus, by selectively changing the air to water ratio in the various compartments, the device may be caused to float with the top surface of the flotation member 12 both level and at any predetermined level with respect to the oil/water interface.

Means are provided to present a notched or irregular surface or weir to the liquid which is to flow into and be salvaged by the device 10. Such a surface provides advantages over a smooth surface in certain situations, which smooth surface is also operable particularly with thick layers of oil, because it is thought that a notched weir will improve buoyancy stability and improve the oil recovery efficiency of the device particularly while operating in thin oil films. The precise physics resulting in these advantages are not understood.

However, it is thought that the notched weir improves stability because the peaks serve as a part of the apparatus tending to be above the top of the water, and the valleys serve to promote cohesion of the droplets of oil making up a thin film into streamlets which flow more readily than the droplets to and then across the weir. To this end, flotation member 12 is torus-shaped and is provided with ridges 38 on its outside surface transverse to its circular axis.

FIGURE 134: GULF RESEARCH AND DEVELOPMENT COMPANY WEIR-TYPE OIL SKIMMER




Source: R.C. Amero and G.L. Karner; U.S. Patent 3,534,859; October 20, 1970

It will be understood by those skilled in the art that device **10** could have any configuration such as square or rectangular, or the like, so long as it closes on itself, and the round shape shown is by way of example only. Similarly, the outer buoyancy member **14** is shown as a closed torus by way of example only, and it is anticipated that gaps in the outer member could be provided so that particularly when operating with thick oil layers, the member **14** would not block the flow of oil into the device.

Means are provided to transport the oil collected by the apparatus to other locations. To this end, funnel member **22** comprises a neck **40** which passes through a suitably formed opening in the bottom of tank **20**, and suitable connecting means **42** are provided to connect neck **40** to a hose or other liquid transmission member **44**, to carry away the collected hydrocarbon liquids. A suitable pump, not shown, will be provided to draw the collected liquids away, after which they may be reprocessed, which reprocessing basically comprises removing any water collected with the oil. It is noteworthy that both the necessary pump and a source of compressed air or other gas are already available in virtually all locations where the device would be used.

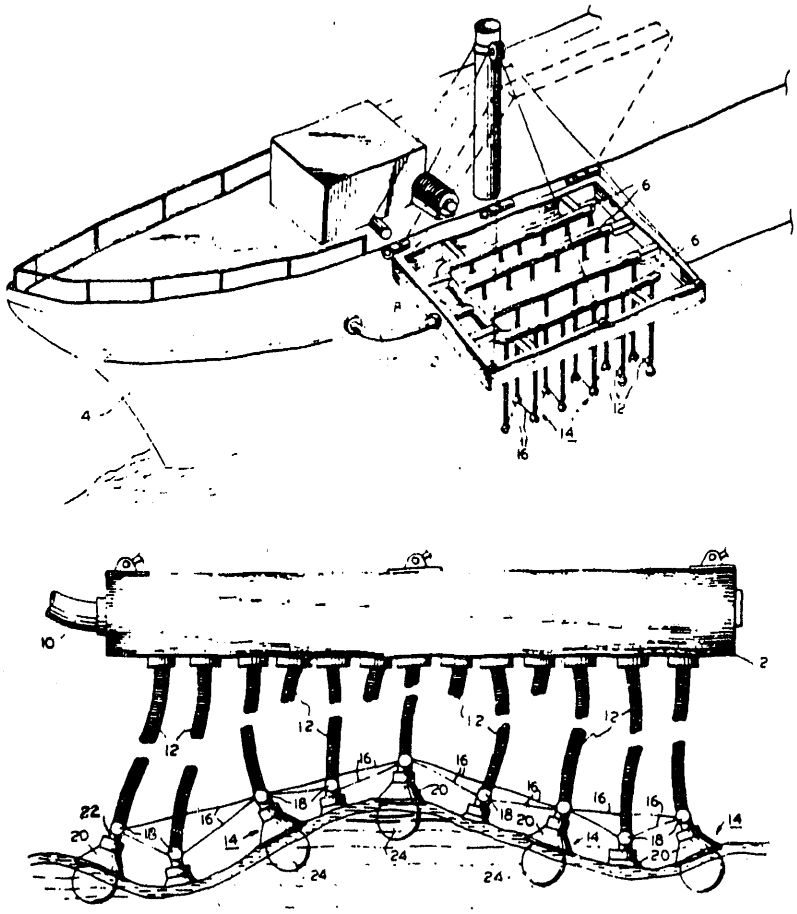
According to *B.J. Hoffman; U.S. Patent 3,753,497; August 21, 1973* this skimmer removes only oil and will not remove flotsam. Further the screen in this Amero et al device may become easily clogged and it is further claimed that the Amero et al device is not suitable for use in a moving body of water such as a stream.

**Harrington Device**

A device developed by *J.W. Harrington; U.S. Patent 3,534,858; October 20, 1970* consists of a flexible suction hose connected with a suitable vacuum source and a floatable skimmer capable of moving with varying wave motions in such manner that the suction apertures provided in the skimmer are maintained substantially at all times within the layer of pollutant. For sweeping operations to remove large bodies of oil or chemical pollutants on water surfaces, a bed comprising headers connected with a manifold to a common suction pump is utilized. A plurality of the skimmer apparatuses are connected to each header. The individual suction lines are then tied together in such manner as to allow freedom of movement by the individual units, but function as a sweeping unit to cover a large area.

Figure 145 shows this device mounted on a vessel ready for operational use (upper view) and in cross-sectional detail (lower view). This device is shown to comprise a frame 2 hingedly mounted on the side of a ship 4 and adapted to be lowered into operational position or raised when not in use by a conventional boom and pulley system.

FIGURE 145: HARRINGTON FLOATING SUCTION SKIMMER SYSTEM



Source: J.W. Harrington; U.S. Patent 3,534,858; October 20, 1970

It will be appreciated that when the apparatus is used with ocean sweeping or waterways subject to heavier wave motion, equipment means must be provided to maintain the frame support 2 at the same height above the surface of the water irrespective of wave amplitude. Mounted within frame 2 are a plurality of suction headers 6 connected to a manifold 8. A suction conduit 10 forms the connection between the manifold and a suction pump (not shown).

The suction pump may be conveniently mounted on the deck of the ship or within the hold of the ship. Any self-priming type vacuum pump of sufficient capacity may be satisfactorily used, for example, motor driven centrifugal high efficiency water pumps having hydraulically created vacuum systems that enable the pumps to continue operation when, on occasion, the skimmer aperture is prevented by wave motion from being completely immersed in the pollutant to be pumped. In other words, for most efficient operation, a pump is used which will not lose vacuum, when, for instance, because of sea turbulence, one or more of the vacuum hose inlets rises above the liquid surface and sucks air.

Connected with each of the suction headers are a plurality of flexible suction hoses 12. Frame 2, suction headers 6 and the manifold form so to speak, a bed horizontally disposed with respect to the liquid surface to be cleaned. The suction hoses hang downwardly from the bed for operational connection with a skimmer 14 mounted on the end of each suction hose. Adjacent to, but with allowance for freedom of movement of the skimmers, tie lines 16 are provided to allow the plurality of skimmers to sweep as a unit and additionally prevent blowing of the skimmer or skimmers out of the water in high winds.

As may be appreciated, the length of the suction hose is dependent upon many factors, e.g., state of movement of water to be swept, type of ship or barge used, or dock, speed of sweeping, ship, etc. In the preferred embodiment, and particularly where the device used to skim pollutants from the seas, each skimmer is joined with its respective suction hose 16 through a swivel joint 18 which allows a swinging movement of the skimmer throughout 360°.

As shown in the lower detail view in particular, nozzle 14 comprises a floatable hollow cone shaped member 20 slidably mounted on pipe section 22 and communicating with the interior of suction hose 12. A substantially spherical shaped float 24 is connected with pipe section 22.

Floatable hollow cone member 20 and float 24 are designed and constructed in such manner and of such material that the base edge of cone member 20 will float on the surface or just within the upper surface of the lighter liquid, e.g., oil, to be removed, while float 24 floats partially in the heavier liquid, to the end that a suction aperture is formed between the lower edge of cone member 20 and float 24, which aperture lies wholly within the layer of pollutant. The cone member being slidably mounted on pipe section 22 will allow the intake aperture to automatically adjust itself to the thickness of the floating pollutant.

**Olsen Device**

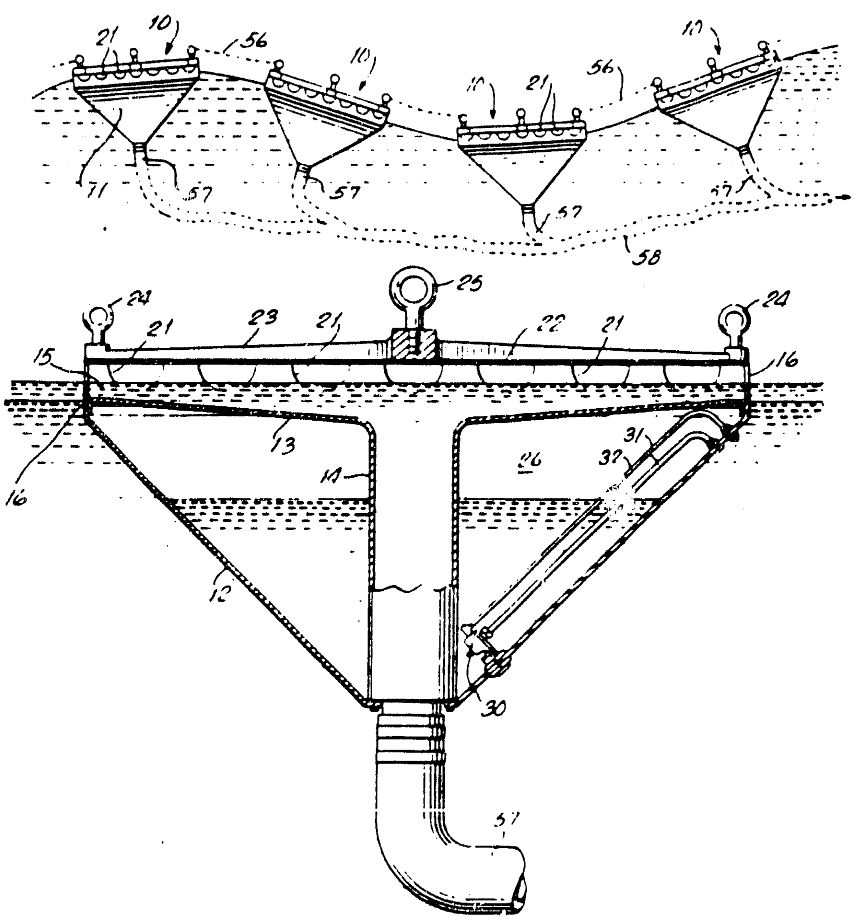
A device developed by *M.F. Olsen; U.S. Patent 3,745,115; July 10, 1973* is one in which one or more floats are provided for immersion in an oil-slick affected water area, the floats having a collecting compartment and a ballast compartment, and a limit valve for the ballast compartment, such that the floats will be partially submerged at the level of the collecting compartment so that the oil and water mixture may be collected.

Flexible tubes are also provided for the collecting compartment for transferring the collected oil and water mixture to a separation tank. The separation tank has two ball float control valves, one of which permits the clean water to drain back into the environmental water area and the other of which permits the collected oil to be drained off for further use or refinement.

Figure 147 shows such floats immersed in an oil-slick affected water area, and flexible tubing connected to the conical base of each float, and showing the floats accommodating to a moderate rolling sea, as well as an enlarged vertical sectional view of one of the floats. The device thus provides a plurality of floats **10** each having a hollow body portion **11** composed of an outer shell **12** and an inner shell **13**.

The latter, in turn, is connected to an inner tube **14**. The upper wall of the inner shell **13** constitutes the bottom of the oil and water collecting compartment **15** of the float **10**, such compartment being generally rectangular in plan view and having side walls **16**. Each side wall **16** is provided with a plurality of spaced semicircular cut outs **21** which approximate one-half the height of the side walls and extend downwardly from the upper edge of each such side wall. A cover plate **22** of rectangular shape in plan view, having crossed bracing ribs **23**, threaded eye bolts **24** at each corner and a lifting eye **25** is suitably mounted on top of the float to close the top of the oil and water collecting compartment, such cover plate being securely fastened to the side walls **16** and **17** by means of the eye bolts **24** which are threaded into the threaded holes **20**. With the cover plate **22** in place, the semicircular cut outs **21** constitute the only access of the oil and water mixture to the collecting compartment **15**.

**FIGURE 147: OLSEN FLOATING SUCTION SKIMMER SYSTEM**




Source: M.F. Olsen; U.S. Patent 3,745,115; July 10, 1973

The float 10 is so designed and constructed that the cut outs in the side walls of the collecting compartment will always be maintained partially submerged. This is accomplished by providing a ballast compartment 26 between the outer shell 12 and the inner shell 13 for receiving an adequate amount of water to provide the necessary ballast to assure that the collecting compartment is always at the proper water surface level.

There is provided in the ballast compartment 26 a ballast limit valve 30. Such ballast limit valve generally consists of a water intake conduit 31 and an air vent 32 both of which are disposed close to the inner shell 13 which forms the bottom of the collecting compartment 15, with the air vent tube disposed nearer to such collecting compartment. A plurality of floats 10 may be connected in spaced relationship by means of flexible chains or other connecting members 56 which are attached to the eye bolts 24 located at each of the corners of the floats. With such flexible connections a series of floats 10 can follow the surface of a moderately rolling sea and still perform their function and purpose of collecting the oil-slick with a minimum amount of water.

It will also be noted that each float 10 is provided with a flexible hose 57 and that each such flexible hose is in turn connected to a common hose 58 which, in turn, is connected to a pump provided on a ship, barge, or other structure, also having on board a separation tank.

**Smith Device**

A device developed by *M.F. Smith; U.S. Patent 3,556,301; January 19, 1971* is constructed of lightweight nonrigid materials and comprises two parallel-spaced sheets with flexible edges. The device floats on the surface of water and flexibly conforms to waves and swells on the water surface. Skimming is performed by exposing a negative pressure intake portal to a shallow skimming zone directly beneath the surface. The narrow elongated intake portal is defined between a flexible floating underflow edge of one sheet and a second flexible overflow edge of a second sheet spaced beneath the first sheet.

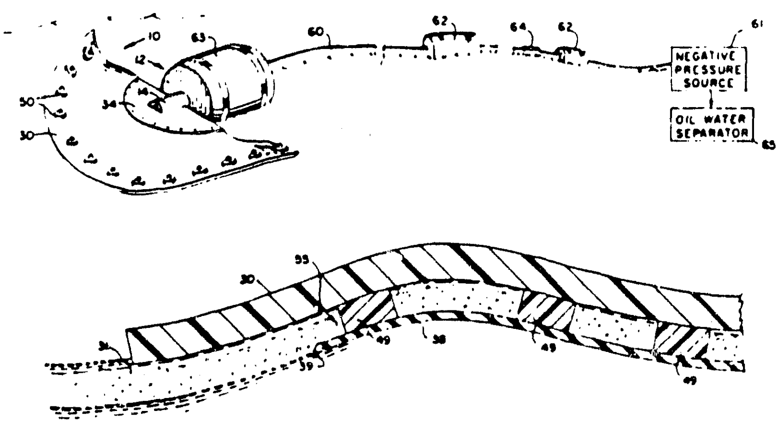
Figure 148 is a perspective view of this device and also shows a sectional view of construction and operation of the flexible skimmer head assembly. The floating flexible skimmer apparatus has two main components, one of which is the skimmer head assembly **10** and the other of which is a negative pressure source and delivery means **12**. The skimmer head assembly comprises first a section of aluminum conduit **14**.

The upper sheet **30** of the skimmer head is fabricated of closed-cell nitrile foam and is secured to the top face of the upper plate of the U-shaped plenum member. The sheet **30** is notched at **31** to accommodate the conduit **14**, which has already been welded to the plenum member. The sheet is anchored to the plenum member by sandwiching it between an upper plenum plate **22** and a correspondingly shaped plate **34**.

Positioned directly below the upper sheet **30** is a lower, less buoyant sheet **38** of nitrile rubber. It is also semicircular and is preferably shaped to correspond with the lower face of the upper sheet **30**. The facing areas of the two sheets **30** and **38** are held in spaced-apart relation by angularly separated spacer blocks **49** which may be either integral or cemented or heat fused to anchor them between the two sheets. The outermost semicircular ring of blocks are preferably spaced at 2½° intervals; the next three concentric rings of blocks are spaced at 5° intervals and the innermost ring of blocks are spaced apart at 10° intervals. The preferred material for these blocks, especially when used in an assembly with the removable ballast described above, is buoyant closed-cell nitrile foam.

The skimmer head assembly thus constructed is then connected by conduit **60** to a negative pressure source **61** preferably a diaphragm pump, and either disposal means, or an oil/water separation apparatus. The conduit may be fabricated in sections, all of which are supported on the surface of the water by a plurality of keg-shaped floats **62**. The several sections may be joined together by bellows like joints **64** which are extremely flexible.

FIGURE 148: SMITH FLOATING SUCTION SKIMMER SYSTEM



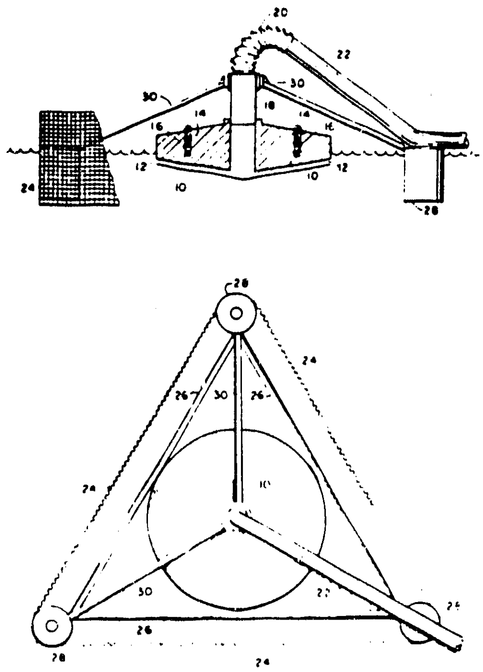

Source: M.F. Smith; U.S. Patent 3,556,301; January 19, 1971

The inside diameter of conduit **60** is telescoped over the mating outside diameter of conduit **14** extending from the skimming head assembly. Thus, the negative pressure source and conduit delivery means are connected to the skimming head assembly by slidingly engaging conduit **60** over conduit **14**. The other end of conduit **60** is sealably attached to the negative pressure source, thereby providing a closed vacuum delivery means connecting the negative pressure source to the skimmer head assembly. A large keg-shaped float **63** may be provided near the junction of conduits **60** and **14** to aid in buoyantly supporting the skimmer head assembly.

Because the intake portal **55** is defined between the two flexible, wave conforming sheets, the upper one of which floats on the surface, it is located immediately beneath the surface of the water regardless of the surface conditions. The elongated intake portal **55** is formed between the flexible underflow and overflow edges **31** and **39**, and is ideally positioned for the removal of waste from the surface of contaminated water.

The suction ports 12 are tapered and V-notched in order to help prevent mechanical emulsification of the oil/water mixture and thus aid in separation of the oil from the water. A debris screen 24 preferably of about ¾ inch mesh circumscribes the head 10 and is used to protect the ports 12 from clogging and other damage. The screen is supported independently of the head by the triangular shaped screen angles 26 which have a circular float 28 attached at each of three corners substantially as shown.

**FIGURE 150: U.S. NAVY FLOATING SUCTION SKIMMER SYSTEM**



Source: J.A. O'Brien; U.S. Patent 3,690,463; September 12, 1972

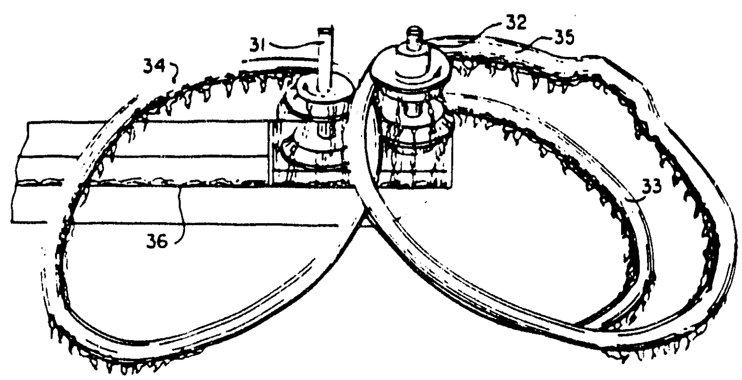
The frame angles 30 are attached to each float 28 and to the tube 18 thereby providing additional strength to the framework formed by angles 26. The angles 30 also support the flexible hose 20. In operation the oil/water mixture enters the head through the suction intake ports and is sucked through tube 18 by suitable pump means into hoses 20 and 22 then into a storage area. Through a series of weights 16 which are added to head 10 as is required the skimming depth is maintained at between about ¼ to 1 inch. This ability to adjust the skimming depth enhances the oil-to-water ratio so that the volume requirement for an oil/water separation system is reduced.

Three suction head assemblies may preferably be used simultaneously with the same source to increase oil pickup efficiency. In case of substantial decreased output flow, the head is easily cleaned by backflushing. Routine cleaning with diesel fuel or strong detergent and water effectively removes the sticky oil and small particles of debris that may plug the suction head after severe use.

## Brill Device

A device developed by *E.L. Brill and B.M. Brill; U.S. Patent 3,640,394; February 8, 1972* is a device for skimming oil or the like floating on a pool of water including an endless substantially rigid loop of uniform cross section, generally circular. The loop is gripped at its upper edge by a pair of rolls rotating in opposite directions and drivingly engaging the loop at one zone in diagonally opposed quadrants, one above and one below the center of a section of the loop. The rolls rotate the loop in its own plane causing it to pass continuously into and out of the pool of water or hydrophilic liquid and to attract hydrophobic material, such as oil or the like or finely divided or colloidal material, which material is lifted by the coil and squeezed out upon passing through the rolls or separated by a scraper or by a blast of air. The loop may oscillate about an axis substantially tangential the loop at the driving zone. A modification utilizes a brushlike surface on the loop and on the driving rolls. Figure 152 is a simplified schematic view of this general type of apparatus.

FIGURE 152: BRILL ENDLESS ABSORBENT LOOP SKIMMER




Source: E.L. Brill and B.M. Brill; U.S. Patent 3,640,394; February 8, 1972

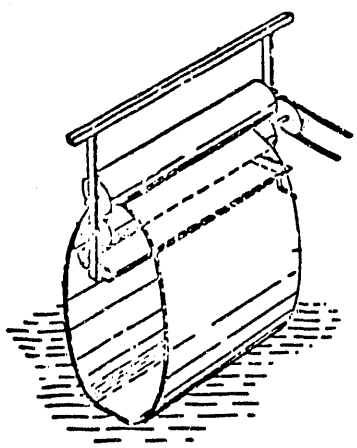
The figure shows diagrammatically a pair of spaced parallel drive shafts **31** and **32**, generally vertical, on which are mounted a plurality of rolls to provide pairs of coacting arcuately concave annular surfaces, each pair of such surfaces engaging a different one of the loops **33**, **34** and **35**, to drive each loop for rotation in its own plane into the polluted water to carry the hydrophobic material upwardly out of the water where the hydrophobic material is squeezed out between the coacting drive roll surfaces to be diverted into the trough **36**.

This device is commercially available from Oil Skimmers, Inc. of Cleveland, Ohio. This skimmer includes a long tube as a belt over a sprocket and past a cleaning point where the oil is scraped off and flows to a container. The tubular belt is made of an oil absorbent material and is long enough to wind about the oil-water surface. The oil is absorbed as the belt leaves the oil-water surface. The tubular belt is small enough in diameter so that debris on the oil-water surface does not interfere with the operation. The sprocket handling the tubular belt is driven by an electric motor.

#### British Petroleum Company Devices

One belt type skimmer developed by British Petroleum Company is described in British Patent 1,026,201; April 14, 1966. As shown in Figure 153, the device comprises an endless belt of resilient foam material, several rollers between which the belt passes at its upper end, and means for collecting and removing liquid squeezed from the strip by the rollers. The resilient foam material is comprised of a number of interconnected pores and is compressible so as to enable a liquid contained in the pores to be removed. A suitable material is a plastic foam such as polyurethane foam. The compression may be in the form of one or more pairs of rollers between which the resilient foam material is arranged to pass. The rollers may comprise the means for driving the endless band of resilient foam material.

FIGURE 153: BRITISH PETROLEUM COMPANY ABSORBENT BELT SKIMMER



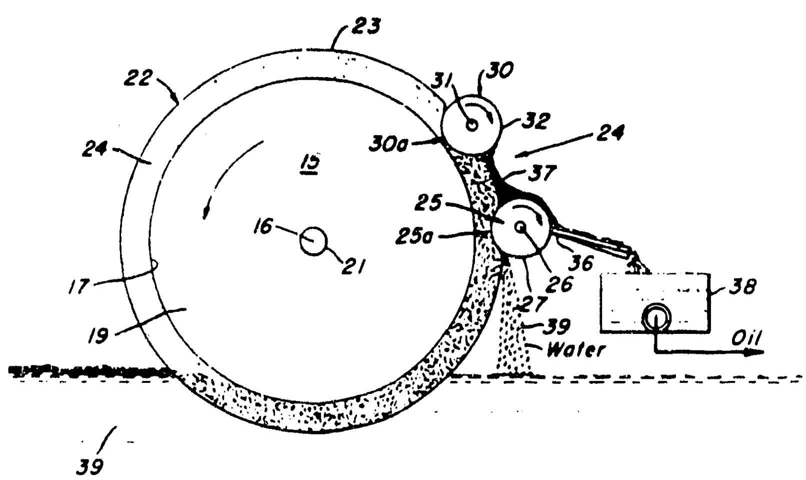
Source: Report PB 218,504

**Standard Oil Company Devices**

A device developed by *W.L. Bulkley, H.E. Ries, Jr. and R.G. Will; U.S. Patent 3,539,508; November 10, 1970; assigned to Standard Oil Company* is one in which at least one pair of spaced, revolving pickup members which dip into the liquid are used to recover the floating material. This material adheres to the members as they come into contact with the liquid, and means adjacent these members remove and collect the material adhering to them. The characterizing feature of this device is that the surface of one member is smooth and oleophilic, and the surface of the other member is porous and deformable. The member having a smooth, oleophilic surface is in advance of the member having the porous, deformable surface, so that the smooth surfaced member contacts the floating material before the porous surfaced member.

A device developed by *R.G. Will and W.F. Swiss, Jr.; U.S. Patent 3,546,112; December 8, 1970; assigned to Standard Oil Company* is a power driven apparatus having a rotation means with a closed supporting surface, absorber means for absorbing water and oil supported on the surface, removal means for sequentially removing water and oil from the absorber means, the removal means being a plurality of rollers exerting different pressures against the absorber means, and wiper means for effectuating the withdrawal of the oil. Figure 162 is an end elevation of such a device.

FIGURE 162: STANDARD OIL COMPANY ABSORBENT DRUM SKIMMER




Source: R.G. Will and W.F. Swiss, Jr.; U.S. Patent 3,546,112; December 8, 1970

# APPENDIX D

## RESULTS OF SIMULATION RUNS

| Figure No. | Run No. | Tonnage GT/DWT | Hole Size (sf) | Environmentai Data Set | Booms | Pumping | | | | | | Bulk Treatment | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Return | | Offboard | | Drain | | | |
| | | | | | Td (min) | Tr (min) | RP Rate (GPM) | TOBP (min) | OBP Rate (GPM) | Td (min) | Drain Rate (GPM) | Start t nom. (min) | Spray Duration (min) |
| D.6 | ALL | 628 | 2 | | | | | | | | | | |
| | 1 | | | Fresh I | 10000 | | | | | | | | |
| | 2 | | | Fresh I | 25 | | | | | | | | |
| | 3 | | | Fresh II | 25 | | | | | | | | |
| | 4 | | | Fresh III | 25 | | | | | | | | |
| | | | | | | | | | | | | | |
| D.7 | ALL | 628 | 12 | | | | | | | | | | |
| | 1 | | | Fresh I | 10000 | | | | | | | | |
| | 2 | | | Fresh I | 25 | | | | | | | | |
| | 3 | | | Fresh II | 25 | | | | | | | | |
| | 4 | | | Fresh III | 25 | | | | | | | | |
| | | | | | | | | | | | | | |
| D.8 | ALL | 628 | 72 | | | | | | | | | | |
| | 1 | | | Fresh I | 10000 | | | | | | | | |
| | 2 | | | Fresh I | 25 | | | | | | | | |
| | 3 | | | Fresh II | 25 | | | | | | | | |
| | 4 | | | Fresh III | 25 | | | | | | | | |
| | | | | | | | | | | | | | |
| D.9 | ALL | 628 | 72 | | | | | | | | | | |
| | 1 | | | Fresh I | 10000 | | | | | | | | |
| | 2 | | | Fresh I | 5 | | | | | | | | |
| | 3 | | | Fresh II | 5 | | | | | | | | |
| | 4 | | | Fresh III | 5 | | | | | | | | |
| | | | | | | | | | | | | | |
| D.10 | ALL | 1182 | 2 | | | | | | | | | | |
| | 1 | | | Fresh I | 10000 | | | | | | | | |
| | 2 | | | FreshII | 25 | | | | | | | | |
| | 3 | | | Fresh III | 25 | | | | | | | | |
| | 4 | | | Fresh III | 25 | | | | | | | | |
| | | | | | | | | | | | | | |
| D.11 | ALL | 1182 | 12 | | | | | | | | | | |
| | 1 | | | Fresh I | 10000 | | | | | | | | |
| | 2 | | | Fresh I | 25 | | | | | | | | |
| | 3 | | | Fresh II | 25 | | | | | | | | |
| | 4 | | | Fresh III | 25 | | | | | | | | |
| | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |

| Figure No. | Run No. | Tonnage GT/DWT | Hole Size (sf) | Environmental Data Set | Booms | Pumping | | | | | | Bulk Treatment | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Return | | Offboard | | Drain | | | |
| | | | | | Td (min) | Tr (min) | RP Rate (GPM) | TOBP (min) | OBP Rate (GPM) | Td (min) | Drain Rate (GPM) | Start t nom. (min) | Spray Duration (min) |
| D.12 | ALL | 1182 | 72 | | | | | | | | | | |
| | 1 | | | Fresh I | 10000 | | | | | | | | |
| | 2 | | | Fresh I | 25 | | | | | | | | |
| | 3 | | | Fresh II | 25 | | | | | | | | |
| | 4 | | | Fresh III | 25 | | | | | | | | |
| D.13 | ALL | 1182 | 72 | | | | | | | | | | |
| | 1 | | | Fresh I | 10000 | | | | | | | | |
| | 2 | | | Fresh I | 5 | | | | | | | | |
| | 3 | | | Fresh II | 5 | | | | | | | | |
| | 4 | | | Fresh III | 5 | | | | | | | | |
| D.14 | ALL | 2713 | 72 | | | | | | | | | | |
| | 1 | | | S/W I | 10000 | | | | | | | | |
| | 2 | | | S/W I | 25 | | | | | | | | |
| | 3 | | | S/W II | 25 | | | | | | | | |
| | 4 | | | S/W III | 25 | | | | | | | | |
| D.15 | ALL | 2713 | 72 | | | | | | | | | | |
| | 1 | | | S/W I | 10000 | | | | | | | | |
| | 2 | | | S/W I | 5 | | | | | | | | |
| | 3 | | | S/W II | 5 | | | | | | | | |
| | 4 | | | S/W III | 5 | | | | | | | | |
| D.16 | ALL | 2713 | 12 | | | | | | | | | | |
| | 1 | | | S/W I | 10000 | | | | | | | | |
| | 2 | | | S/W I | 5 | | | | | | | | |
| | 3 | | | S/W II | 5 | | | | | | | | |
| | 4 | | | S/W III | 5 | | | | | | | | |
| D.17 | ALL | 2713 | 2 | | | | | | | | | | |
| | 1 | | | S/W I | 10000 | | | | | | | | |
| | 2 | | | S/W I | 5 | | | | | | | | |
| | 3 | | | S/W II | 5 | | | | | | | | |
| | 4 | | | S/W III | 5 | | | | | | | | |

| Figure No. | Run No. | Tonnage GT/DWT | Hole Size (sf) | Environmental Data Set | Booms Td (min) | Pumping: Return Tr (min) | Pumping: Return RP Rate (GPM) | Pumping: Offboard TOBP (min) | Pumping: Offboard OBP Rate (GPM) | Pumping: Drain Td (min) | Pumping: Drain Drain Rate (GPM) | Bulk Treatment Start t nom. (min) | Bulk Treatment Spray Duration (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D.18 | | 34000 | 72 | S/W I | 10000 | | | | | | | | |
| D.19 | ALL | 34000 | 12 | | | | | | | | | | |
| | 1 | | | S/W I | 10000 | | | | | | | | |
| | 2 | | | S/W I | 25 | | | | | | | | |
| | 3 | | | S/W II | 25 | | | | | | | | |
| | 4 | | | S/W III | 25 | | | | | | | | |
| D.20 | ALL | 34000 | 12 | | | | | | | | | | |
| | 1 | | | S/W I | 10000 | | | | | | | | |
| | 2 | | | S/W I | 25 | | | | | | | | |
| | 3 | | | S/W II | 25 | | | | | | | | |
| | 4 | | | S/W III | 25 | | | | | | | | |
| D.21 | ALL | 89700 | 2 | | | | | | | | | | |
| | 1 | | | S/W I | 10000 | | | | | | | | |
| | 2 | | | S/W I | 5 | | | | | | | | |
| | 3 | | | S/W II | 5 | | | | | | | | |
| | 4 | | | S/W III | 5 | | | | | | | | |
| D.22 | ALL | 89700 | 2 | | | | | | | | | | |
| | 1 | | | S/W I | 10000 | | | | | | | | |
| | 2 | | | S/W I | 25 | | | | | | | | |
| | 3 | | | S/W II | 25 | | | | | | | | |
| | 4 | | | S/W III | 25 | | | | | | | | |
| D.23 | ALL | 89700 | 72 | | | | | | | | | | |
| | 1 | | | S/W I | 10000 | | | | | | | | |
| | 2 | | | S/W I | 5 | | | | | | | | |
| | 3 | | | S/W II | 5 | | | | | | | | |
| | 4 | | | S/W III | 5 | | | | | | | | |
| D.24 | ALL | 89700 | 72 | | | | | | | | | | |
| | 1 | | | S/W I | 10000 | | | | | | | | |
| | 2 | | | S/W I | 25 | | | | | | | | |
| | 3 | | | S/W II | 25 | | | | | | | | |
| | 4 | | | S/W III | 25 | | | | | | | | |

| Figure No. | Run No. | Tonnage GT/DWT | Hole Size (sf) | Environmental Data Set | Booms | Pumping | | | | | | Bulk Treatment | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Return | | Offboard | | Drain | | | |
| | | | | | Td (min) | Tr (min) | RP Rate (GPM) | TOBP (min) | OBP Rate (GPM) | Td (min) | Drain Rate (GPM) | Start t nom. (min) | Spray Duration (min) |
| D.25 | ALL | 89700 | 12 | | | | | | | | | | |
| | 1 | | | S/W I | 10000 | | | | | | | | |
| | 2 | | | S/W I | 5 | | | | | | | | |
| | 3 | | | S/W II | 5 | | | | | | | | |
| | 4 | | | S/W III | 5 | | | | | | | | |
| D.26 | ALL | 89700 | 12 | S/W I | 10000 | | | | | | | | |
| | 1 | | | S/W I | 25 | | | | | | | | |
| | 2 | | | S/W II | 25 | | | | | | | | |
| | 3 | | | S/W III | 25 | | | | | | | | |
| | 4 | | | | | | | | | | | | |
| D.27 | ALL | 262000 | 2 | | | | | | | | | | |
| | 1 | | | S/W I | 10000 | | | | | | | | |
| | 2 | | | S/W I | 25 | | | | | | | | |
| | 3 | | | S/W II | 25 | | | | | | | | |
| | 4 | | | S/W III | 25 | | | | | | | | |
| D.28 | ALL | 262000 | 12 | | | | | | | | | | |
| | 1 | | | S/W I | 10000 | | | | | | | | |
| | 2 | | | S/W I | 25 | | | | | | | | |
| | 3 | | | S/W II | 25 | | | | | | | | |
| | 4 | | | S/W III | 25 | | | | | | | | |
| D.29 | ALL | 262000 | 72 | | | | | | | | | | |
| | 1 | | | S/W I | 10000 | | | | | | | | |
| | 2 | | | S/W I | 25 | | | | | | | | |
| | 3 | | | S/W II | 25 | | | | | | | | |
| | 4 | | | S/W III | 25 | | | | | | | | |
| D.35 | ALL | 628 | 2 | | | | | | | | | | |
| | 1 | | | Fresh I | | | | | | | | 10000 | 360 |
| | 2 | | | Fresh I | | | | | | | | 25 | 360 |
| | 3 | | | Fresh II | | | | | | | | 25 | 360 |
| | 4 | | | Fresh III | | | | | | | | 25 | 360 |

| Figure No. | Run No. | Tonnage GT/DWT | Hole Size (sf) | Environmental Data Set | Booms | Pumping: Return | | Pumping: Offboard | | Pumping: Drain | | Bulk Treatment | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Td (min) | Tr (min) | RP Rate (GPM) | TOBP (min) | OBP Rate (GPM) | Td (min) | Drain Rate (GPM) | Start t nom. (min) | Spray Duration (min) |
| D.36 | ALL | 628 | 12 | | | | | | | | | | |
| | 1 | | | Fresh I | | | | | | | | 10000 | 360 |
| | 2 | | | Fresh I | | | | | | | | 25 | 360 |
| | 3 | | | Fresh II | | | | | | | | 25 | 360 |
| | 4 | | | Fresh III | | | | | | | | 25 | 360 |
| D.37 | ALL | 628 | 72 | | | | | | | | | | |
| | 1 | | | Fresh I | | | | | | | | 10000 | 360 |
| | 2 | | | Fresh I | | | | | | | | 25 | 360 |
| | 3 | | | Fresh II | | | | | | | | 25 | 360 |
| | 4 | | | Fresh III | | | | | | | | 25 | 360 |
| D.38 | ALL | 1182 | 2 | | | | | | | | | | |
| | 1 | | | Fresh I | | | | | | | | 10000 | 360 |
| | 2 | | | Fresh I | | | | | | | | 25 | 360 |
| | 3 | | | Fresh II | | | | | | | | 25 | 360 |
| | 4 | | | Fresh III | | | | | | | | 25 | 360 |
| D.39 | ALL | 1182 | 12 | | | | | | | | | | |
| | 1 | | | Fresh I | | | | | | | | 10000 | 360 |
| | 2 | | | Fresh I | | | | | | | | 25 | 360 |
| | 3 | | | Fresh II | | | | | | | | 25 | 360 |
| | 4 | | | Fresh III | | | | | | | | 25 | 360 |
| D.40 | ALL | 1182 | 72 | | | | | | | | | Computation Failure | |
| | 1 | | | Fresh I | | | | | | | | | |
| | 2 | | | Fresh I | | | | | | | | | |
| | 3 | | | Fresh II | | | | | | | | | |
| | 4 | | | Fresh III | | | | | | | | | |
| D.41 | ALL | 2713 | 2 | | | | | | | | | | |
| | 1 | | | S/W I | | | | | | | | 10000 | 360 |
| | 2 | | | S/W I | | | | | | | | 25 | 360 |
| | 3 | | | S/W II | | | | | | | | 25 | 360 |
| | 4 | | | S/W III | | | | | | | | 25 | 360 |

| Figure No. | Run No. | Tonnage GT/DWT | Hole Size (sf) | Environmental Data Set | Booms | Pumping | | | | | | Bulk Treatment | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Return | | Offboard | | Drain | | | |
| | | | | | Td (min) | Tr (min) | RP Rate (GPM) | TOBP (min) | OBP Rate (GPM) | Td (min) | Drain Rate (GPM) | Start t nom. (min) | Spray Duration (min) |
| D.42 | ALL | 2713 | 12 | | | | | | | | | | |
| | 1 | | | S/W I | | | | | | | | 10000 | 360 |
| | 2 | | | S/W II | | | | | | | | 25 | 360 |
| | 3 | | | S/W II | | | | | | | | 25 | 360 |
| | 4 | | | S/W III | | | | | | | | 25 | 360 |
| D.43 | ALL | 2713 | 72 | | | | | | | | | | |
| | 1 | | | S/W I | | | | | | | | Computation Failure | |
| | 2 | | | S/W II | | | | | | | | | |
| | 3 | | | S/W II | | | | | | | | | |
| | 4 | | | S/W III | | | | | | | | | |
| D.44 | ALL | 34000 | 2 | | | | | | | | | | |
| | 1 | | | S/W I | | | | | | | | 10000 | 360 |
| | 2 | | | S/W I | | | | | | | | 25 | 360 |
| | 3 | | | S/W II | | | | | | | | 25 | 360 |
| | 4 | | | S/W III | | | | | | | | 25 | 360 |
| D.45 | ALL | 34000 | 12 | | | | | | | | | | |
| | 1 | | | S/W I | | | | | | | | 10000 | 360 |
| | 2 | | | S/W I | | | | | | | | 25 | 360 |
| | 3 | | | S/W II | | | | | | | | 25 | 360 |
| | 4 | | | S/W III | | | | | | | | 25 | 360 |
| D.46 | ALL | 34000 | 72 | | | | | | | | | | |
| | 1 | | | S/W I | | | | | | | | Computation Failure | |
| | 2 | | | S/W I | | | | | | | | | |
| | 3 | | | S/W II | | | | | | | | | |
| | 4 | | | S/W III | | | | | | | | | |
| D.47 | ALL | 89700 | 2 | | | | | | | | | | |
| | 1 | | | S/W I | | | | | | | | 10000 | 360 |
| | 2 | | | S/W I | | | | | | | | 25 | 360 |
| | 3 | | | S/W II | | | | | | | | 25 | 360 |
| | 4 | | | S/W III | | | | | | | | 25 | 360 |

| Figure No. | Run No. | Tonnage GT/DWT | Hole Size (sf) | Environmental Data Set | Booms | Pumping | | | | | | Bulk Treatment | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Return | | Offboard | | Drain | | | |
| | | | | | Td (min) | Tr (min) | RP Rate (GPM) | TOBP (min) | OBP Rate (GPM) | Td (min) | Drain Rate (GPM) | Start t nom. (min) | Spray Duration (min) |
| D.48 | ALL | 89700 | 12 | | | | | | | | | | |
| | 1 | | | S/W I | | | | | | | | 10000 | 360 |
| | 2 | | | S/W II | | | | | | | | 25 | 360 |
| | 3 | | | S/W II | | | | | | | | 25 | 360 |
| | 4 | | | S/W III | | | | | | | | 25 | 360 |
| D.49 | ALL | 89700 | 72 | | | | | | | | | | |
| | 1 | | | S/W I | | | | | | | | Computation Failure | |
| | 2 | | | S/W II | | | | | | | | | |
| | 3 | | | S/W II | | | | | | | | | |
| | 4 | | | S/W III | | | | | | | | | |
| D.50 | ALL | 262000 | 2 | | | | | | | | | | |
| | 1 | | | S/W I | | | | | | | | 10000 | 360 |
| | 2 | | | S/W I | | | | | | | | 25 | 360 |
| | 3 | | | S/W II | | | | | | | | 25 | 360 |
| | 4 | | | S/W III | | | | | | | | 25 | 360 |
| D.51 | ALL | 262000 | 12 | | | | | | | | | | |
| | 1 | | | S/W I | | | | | | | | 10000 | 360 |
| | 2 | | | S/W I | | | | | | | | 25 | 360 |
| | 3 | | | S/W II | | | | | | | | 25 | 360 |
| | 4 | | | S/W III | | | | | | | | 25 | 360 |
| D.52 | ALL | 262000 | 72 | | | | | | | | | | |
| | 1 | | | S/W I | | | | | | | | Computation Failure | |
| | 2 | | | S/W I | | | | | | | | | |
| | 3 | | | S/W II | | | | | | | | | |
| | 4 | | | S/W III | | | | | | | | | |

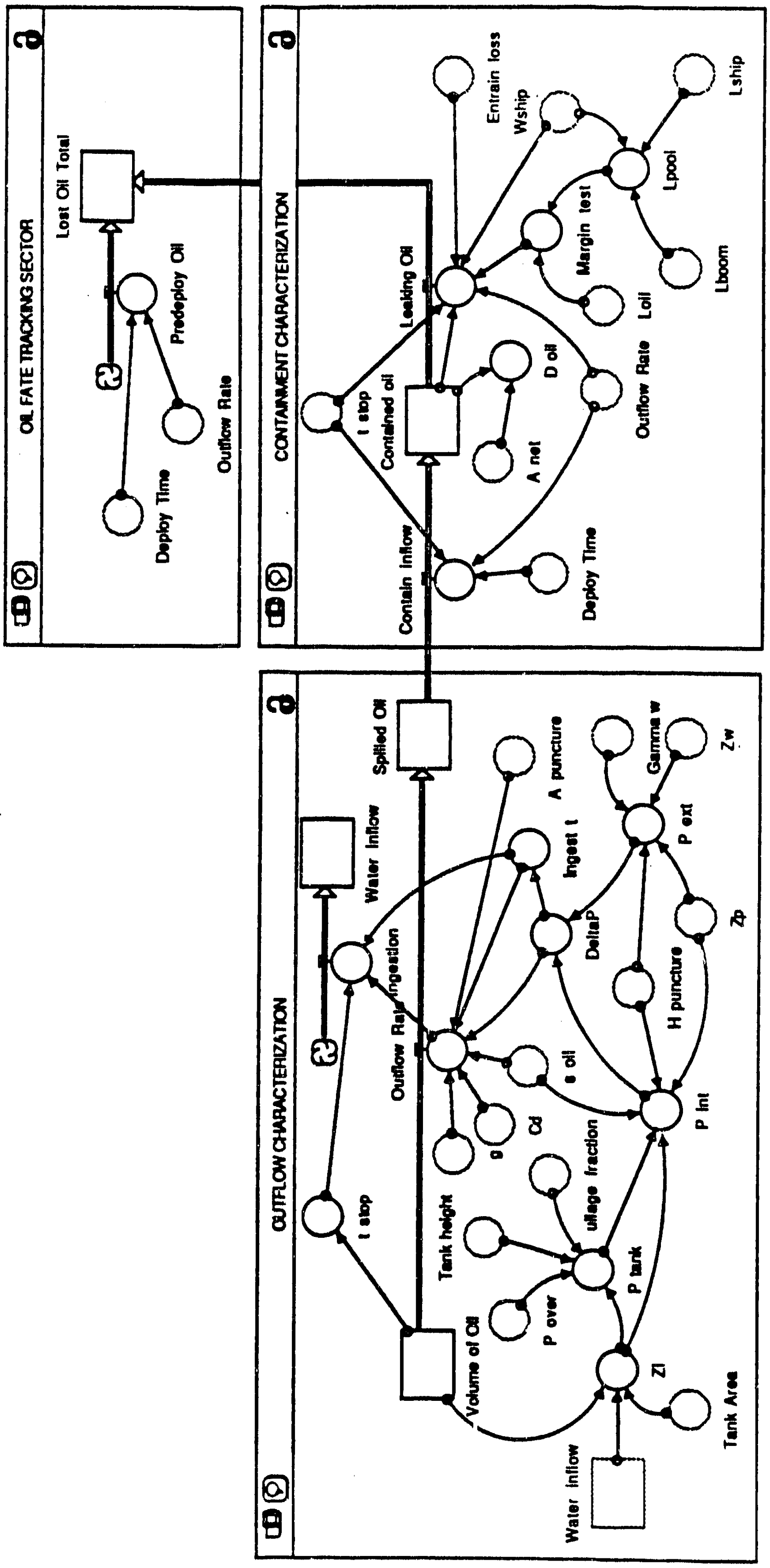
| Figure No. | Run No. | Tonnage GT/DWT | Hole Size (sf) | Environmental Data Set | Booms | Pumping | | | | | | Bulk Treatment | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Return | | Offboard | | Drain | | | |
| | | | | | Td (min) | Tr (min) | RP Rate (GPM) | TOBP (min) | OBP Rate (GPM) | Td (min) | Drain Rate (GPM) | Start t nom. (min) | Spray Duration (min) |
| D.58 | ALL | 628 | 2 | | | 25 | | 25 | | 25 | | | |
| | 1 | | | Fresh I | | | 0 | | 0 | | 0 | | |
| | 2 | | | Fresh I | | | 600 | | 600 | | 600 | | |
| | 3 | | | Fresh II | | | 600 | | 600 | | 600 | | |
| | 4 | | | Fresh III | | | 600 | | 600 | | 600 | | |
| D. 59 | ALL | 628 | 12 | | | 25 | | 25 | | 25 | | | |
| | 1 | | | Fresh I | | | 0 | | 0 | | 0 | | |
| | 2 | | | Fresh I | | | 600 | | 600 | | 600 | | |
| | 3 | | | Fresh II | | | 600 | | 600 | | 600 | | |
| | 4 | | | Fresh III | | | 600 | | 600 | | 600 | | |
| D.60 | ALL | 628 | 72 | | | 25 | | 25 | | 25 | | | |
| | 1 | | | Fresh I | | | 0 | | 0 | | 0 | | |
| | 2 | | | Fresh I | | | 600 | | 600 | | 600 | | |
| | 3 | | | Fresh II | | | 600 | | 600 | | 600 | | |
| | 4 | | | Fresh III | | | 600 | | 600 | | 600 | | |
| D.61 | ALL | 1182 | 2 | | | 25 | | 25 | | 25 | | | |
| | 1 | | | Fresh I | | | 0 | | 0 | | 0 | | |
| | 2 | | | Fresh I | | | 600 | | 600 | | 600 | | |
| | 3 | | | Fresh II | | | 600 | | 600 | | 600 | | |
| | 4 | | | Fresh III | | | 600 | | 600 | | 600 | | |
| D.62 | ALL | 1182 | 12 | | | 25 | | 25 | | 25 | | | |
| | 1 | | | Fresh I | | | 0 | | 0 | | 0 | | |
| | 2 | | | Fresh I | | | 600 | | 600 | | 600 | | |
| | 3 | | | Fresh II | | | 600 | | 600 | | 600 | | |
| | 4 | | | Fresh III | | | 600 | | 600 | | 600 | | |
| D.63 | ALL | 1182 | 72 | | | 25 | | 25 | | 25 | | | |
| | 1 | | | Fresh I | | | 0 | | 0 | | 0 | | |
| | 2 | | | Fresh I | | | 600 | | 600 | | 600 | | |
| | 3 | | | Fresh II | | | 600 | | 600 | | 600 | | |
| | 4 | | | Fresh III | | | 600 | | 600 | | 600 | | |

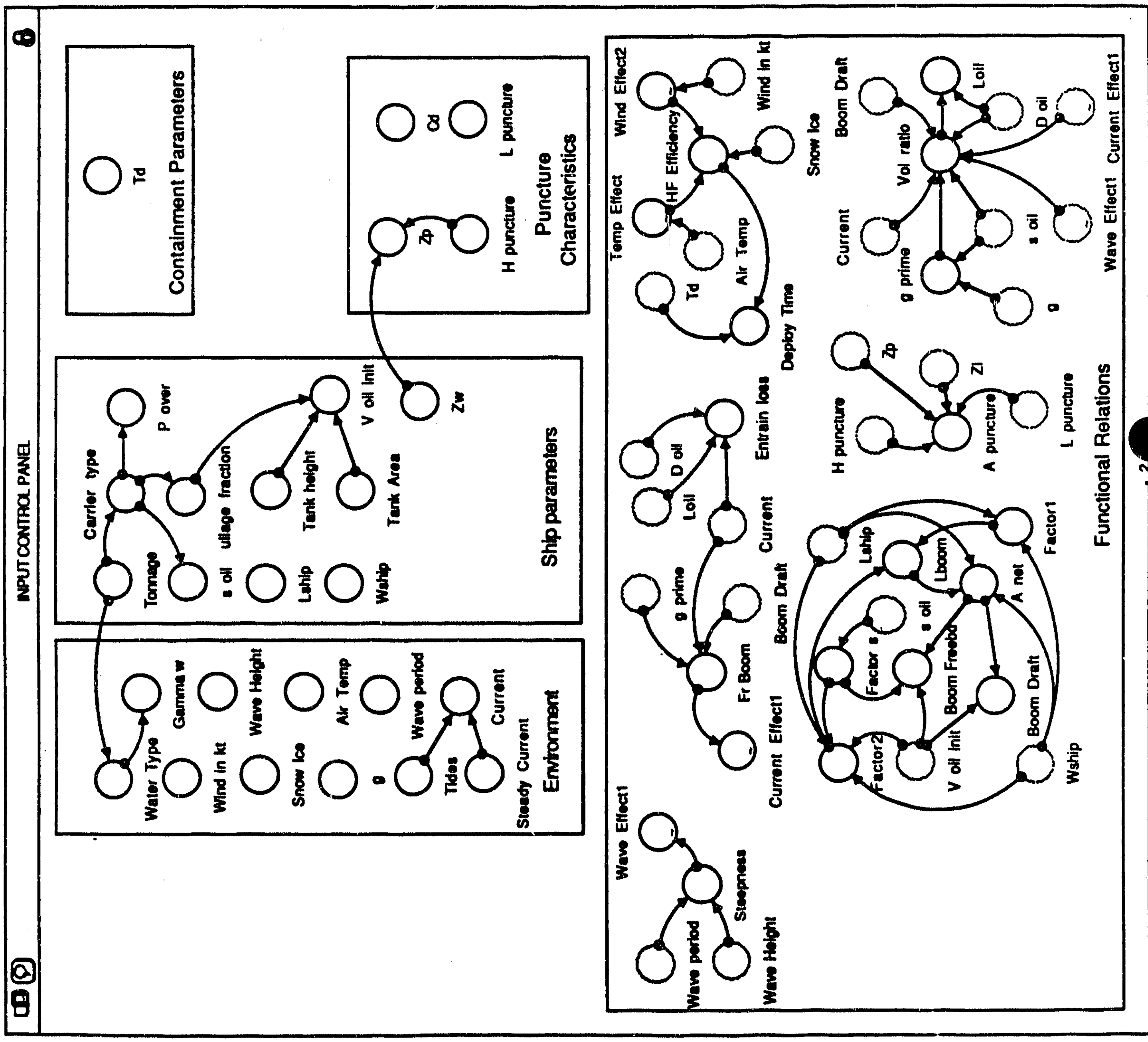
| Figure No. | Run No. | Tonnage GT/DWT | Hole Size | Environmental Data Set | Booms | Pumping | | | | | | Bulk Treatment | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Return | | Offboard | | Drain | | | |
| | | | | | Td (min) | Tr (min) | RP Rate (GPM) | TOBP (min) | OBP Rate (GPM) | Td (min) | Drain Rate (GPM) | Start t nom. (min) | Spray Duration (min) |
| D.64 | ALL | 2713 | 72 | | | 25 | | 25 | | 25 | | | |
| | 1 | | | S/W I | | | 0 | | 0 | | 0 | | |
| | 2 | | | S/W I | | | 600 | | 600 | | 600 | | |
| | 3 | | | S/W II | | | 600 | | 600 | | 600 | | |
| | 4 | | | S/W III | | | 600 | | 600 | | 600 | | |
| D.65 | ALL | 2713 | 12 | | | 25 | | 25 | | 25 | | | |
| | 1 | | | S/W I | | | 0 | | 0 | | 0 | | |
| | 2 | | | S/W I | | | 600 | | 600 | | 600 | | |
| | 3 | | | S/W II | | | 600 | | 600 | | 600 | | |
| | 4 | | | S/W III | | | 600 | | 600 | | 600 | | |
| D.66 | ALL | 2713 | 2 | | | 25 | | 25 | | 25 | | | |
| | 1 | | | S/W I | | | 0 | | 0 | | 0 | | |
| | 2 | | | S/W I | | | 600 | | 600 | | 600 | | |
| | 3 | | | S/W II | | | 600 | | 600 | | 600 | | |
| | 4 | | | S/W III | | | 600 | | 600 | | 600 | | |
| D.67 | ALL | 34000 | 2 | | | 25 | | 25 | | 25 | | | |
| | 1 | | | S/W I | | | 0 | | 0 | | 0 | | |
| | 2 | | | S/W I | | | 600 | | 600 | | 600 | | |
| | 3 | | | S/W II | | | 600 | | 600 | | 600 | | |
| | 4 | | | S/W III | | | 600 | | 600 | | 600 | | |
| D.68 | ALL | 34000 | 12 | | | 25 | | 25 | | 25 | | | |
| | 1 | | | S/W I | | | 0 | | 0 | | 0 | | |
| | 2 | | | S/W I | | | 600 | | 600 | | 600 | | |
| | 3 | | | S/W II | | | 600 | | 600 | | 600 | | |
| | 4 | | | S/W III | | | 600 | | 600 | | 600 | | |
| D.69 | ALL | 34000 | 72 | | | 25 | | 25 | | 25 | | | |
| | 1 | | | S/W I | | | 0 | | 0 | | 0 | | |
| | 2 | | | S/W I | | | 600 | | 600 | | 600 | | |
| | 3 | | | S/W II | | | 600 | | 600 | | 600 | | |
| | 4 | | | S/W III | | | 600 | | 600 | | 600 | | |

| Figure No. | Run No. | Tonnage GT/DWT | Hole Size (sf) | Environmental Data Set | Booms | Pumping | | | | | | Bulk Treatment | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Return | | Offboard | | Drain | | | |
| | | | | | Td (min) | Tr (min) | RP Rate (GPM) | TOBP (min) | OBP Rate (GPM) | Td (min) | Drain Rate (GPM) | Start t nom. (min) | Spray Duration (min) |
| D.70 | ALL | 34000 | 72 | | | 25 | 0 | 25 | | 25 | 0 | | |
| | 1 | | | S/W I | | | | | 0 | | | | |
| | 2 | | | S/W I | | | | | 600 | | | | |
| | 3 | | | S/W II | | | | | 600 | | | | |
| | 4 | | | S/W III | | | | | 600 | | | | |
| D.71 | ALL | 34000 | 72 | | | 25 | 0 | 25 | 0 | 25 | | | |
| | 1 | | | S/W I | | | | | | | 0 | | |
| | 2 | | | S/W I | | | | | | | 600 | | |
| | 3 | | | S/W II | | | | | | | 600 | | |
| | 4 | | | S/W III | | | | | | | 600 | | |
| D.72 | ALL | 89700 | 2 | | | 25 | | 25 | | 25 | | | |
| | 1 | | | S/W I | | | 0 | | 0 | | 0 | | |
| | 2 | | | S/W I | | | 600 | | 600 | | 600 | | |
| | 3 | | | S/W II | | | 600 | | 600 | | 600 | | |
| | 4 | | | S/W III | | | 600 | | 600 | | 600 | | |
| D.73 | ALL | 89700 | 12 | | | 25 | | 25 | | 25 | | | |
| | 1 | | | S/W I | | | 0 | | 0 | | 0 | | |
| | 2 | | | S/W I | | | 600 | | 600 | | 600 | | |
| | 3 | | | S/W II | | | 600 | | 600 | | 600 | | |
| | 4 | | | S/W III | | | 600 | | 600 | | 600 | | |
| D.74 | ALL | 89700 | 72 | | | 25 | | 25 | | 25 | | | |
| | 1 | | | S/W I | | | 0 | | 0 | | 0 | | |
| | 2 | | | S/W I | | | 600 | | 600 | | 600 | | |
| | 3 | | | S/W II | | | 600 | | 600 | | 600 | | |
| | 4 | | | S/W III | | | 600 | | 600 | | 600 | | |
| D.75 | ALL | 89700 | 72 | | | 25 | 0 | 25 | | 25 | | | |
| | 1 | | | S/W I | | | | | 0 | | 0 | | |
| | 2 | | | S/W I | | | | | 600 | | 600 | | |
| | 3 | | | S/W II | | | | | 600 | | 600 | | |
| | 4 | | | S/W III | | | | | 600 | | 600 | | |

| Figure No. | Run No. | Tonnage GT/DWT | Hole Size (sf) | Environmental Data Set | Booms | Pumping | | | | | | Bulk Treatment | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Return | | Offboard | | Drain | | | |
| | | | | | Td (min) | Tr (min) | RP Rate (GPM) | TOBP (min) | OBP Rate (GPM) | Td (min) | Drain Rate (GPM) | Start t nom. (min) | Spray Duration (min) |
| D.76 | ALL | 89700 | 72 | | | 25 | 0 | 25 | | 25 | 0 | | |
| | 1 | | | S/W I | | | | | 0 | | | | |
| | 2 | | | S/W I | | | | | 1200 | | | | |
| | 3 | | | S/W II | | | | | 1200 | | | | |
| | 4 | | | S/W III | | | | | 1200 | | | | |
| D.77 | ALL | 89700 | 72 | | | 25 | 0 | 25 | 0 | 25 | | | |
| | 1 | | | S/W I | | | | | | | 0 | | |
| | 2 | | | S/W I | | | | | | | 1200 | | |
| | 3 | | | S/W II | | | | | | | 1200 | | |
| | 4 | | | S/W III | | | | | | | 1200 | | |
| D.78 | ALL | 262000 | 2 | | | 25 | | 25 | | 25 | | | |
| | 1 | | | S/W I | | | 0 | | 0 | | 0 | | |
| | 2 | | | S/W I | | | 600 | | 600 | | 600 | | |
| | 3 | | | S/W II | | | 600 | | 600 | | 600 | | |
| | 4 | | | S/W III | | | 600 | | 600 | | 600 | | |
| D.79 | ALL | 262000 | 12 | | | 25 | | 25 | | 25 | | | |
| | 1 | | | S/W I | | | 0 | | 0 | | 0 | | |
| | 2 | | | S/W I | | | 600 | | 600 | | 600 | | |
| | 3 | | | S/W II | | | 600 | | 600 | | 600 | | |
| | 4 | | | S/W III | | | 600 | | 600 | | 600 | | |
| D.80 | ALL | 262000 | 72 | | | 25 | | 25 | | 25 | | | |
| | 1 | | | S/W I | | | 0 | | 0 | | 0 | | |
| | 2 | | | S/W I | | | 600 | | 600 | | 600 | | |
| | 3 | | | S/W II | | | 600 | | 600 | | 600 | | |
| | 4 | | | S/W III | | | 600 | | 600 | | 600 | | |
| D.81 | ALL | 262000 | 72 | | | 25 | | 25 | | 25 | | | |
| | 1 | | | S/W I | | | 0 | | 0 | | 0 | | |
| | 2 | | | S/W I | | | 1200 | | 1200 | | 1200 | | |
| | 3 | | | S/W II | | | 1200 | | 1200 | | 1200 | | |
| | 4 | | | S/W III | | | 1200 | | 1200 | | 1200 | | |

| Figure No. | Run No. | Tonnage GT/DWT | Hole Size (sf) | Environmental Data Set | Booms | Pumping | | | | | | Bulk Treatment | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Return | | Offboard | | Drain | | | |
| | | | | | Td (min) | Tr (min) | RP Rate (GPM) | TOBP (min) | OBP Rate (GPM) | Td (min) | Drain Rate (GPM) | Start t nom. (min) | Spray Duration (min) |
| D.82 | ALL | 262000 | 72 | | | 25 | 0 | 25 | | 25 | | | |
| | 1 | | | S/W I | | | | | 0 | | 0 | | |
| | 2 | | | S/W I | | | | | 1200 | | 1200 | | |
| | 3 | | | S/W II | | | | | 1200 | | 1200 | | |
| | 4 | | | S/W III | | | | | 1200 | | 1200 | | |
| D.83 | ALL | 262000 | 72 | | | 25 | 0 | 25 | | 25 | 0 | | |
| | 1 | | | S/W I | | | | | 0 | | | | |
| | 2 | | | S/W I | | | | | 1200 | | | | |
| | 3 | | | S/W II | | | | | 1200 | | | | |
| | 4 | | | S/W III | | | | | 1200 | | | | |


OIL FATE TRACKING SECTOR
Lost Oil Total
Predeploy Oil
Outflow Rate
Deploy Time
CONTAINMENT CHARACTERIZATION
Entrain loss
Wship
Lship
Lpool
Margin test
Lboom
Loil
Leaking Oil
D oil
Outflow Rate
t stop
Contained oil
A net
Contain Inflow
Deploy Time
OUTFLOW CHARACTERIZATION
Spilled Oil
Water Inflow
A puncture
Gamma w
Zw
P ext
Ingest t
DeltaP
Zp
H puncture
Ingestion
Outflow Rate
s oil
Cd
g
Tank height
t stop
ullage fraction
P int
P tank
P over
Volume of Oil
Zl
Tank Area
Water Inflow


INPUT CONTROL PANEL
Containment Parameters
Td
Puncture Characteristics
Zp
H puncture
Cd
L puncture
Ship parameters
Carrier type
P over
Tonnage
s oil
uillage fraction
V oil init
Lship
Tank height
Tank Area
Wship
Zw
Environment
Water Type
Gamma w
Wind in kt
Wave Height
Snow Ice
Air Temp
g
Wave period
Tides
Current
Steady Current
Functional Relations
Wave Effect1
Wave period
Steepness
Wave Height
g prime
Fr Boom
Boom Draft
Current Effect1
Loil
D oil
Current
Entrain loss
Factor2
Factor s
s oil
Boom Freebd
V oil init
Lship
Lboom
A net
Boom Draft
Wship
Factor1
Temp Effect
HF Efficiency
Td
Air Temp
Deploy Time
Wind Effect2
Wind in kt
Snow Ice
H puncture
Zp
Zl
A puncture
L puncture
Current
Vol ratio
Boom Draft
Loil
D oil
g prime
s oil
g
Wave Effect1
Current Effect1

**OIL FATE TRACKING SECTOR**
DOCUMENT:
Provides total amounts (in gal.) of treated and untreated oil lost for each scenario.

☐ Lost_Oil_Total(t) = Lost_Oil_Total(t - dt) + (Leaking_Oil + Predeploy_Oil) * dt
INIT Lost_Oil_Total = 0 {Total amount of oil lost to the environment, gal.}
INFLOWS:
- Leaking_Oil (IN SECTOR: CONTAINMENT CHARACTERIZATION)
- Predeploy_Oil = IF (TIME ≤ Deploy_Time) THEN Outflow_Rate ELSE 0{The flow rate of oil lost before the containment is completely deployed, GPM}

**INPUT CONTROL PANEL**
DOCUMENT:
Collects all input variables for the model

- ○ Air_Temp = 36.1 {air temp. deg F}
- ○ A_net = .5*Lboom*Wship - .6781*Wship^2 - Lship*Wship{ Place right hand side of equation here... }
- ○ A_puncture = IF (Zl > Zp) THEN (L_puncture*H_puncture) ELSE ((Zl - Zp + H_puncture)*L_puncture) {Area of puncture (if oil level above top of puncture) or area of flow (if oil level below top of puncture), sf. }
- ○ Boom_Draft = 1.3*(V_oil_init/A_net)/7.48 + .333{boom draft below WL optimized by calculation, ft.}
- ○ Boom_Freebd = (Factor_s - 1)*(1.3*(V_oil_init/A_net)/7.48 + .333){ Place right hand side of equation here... }
- ○ Carrier_type = IF (Tonnage ≥ 34000) THEN 1 ELSE 0 {0 means carrier is a barge; 1 means carrier is a tanker}
- ○ Cd = .61 {Oil discharge coefficient}
- ○ Current = Steady_Current + Tides {Total effective current, fps}
- ○ Deploy_Time = Td/HF_Efficiency {Actual time needed to deploy containment}
- ○ Entrain_loss = IF (Loil ≤ EXP(2*(Current - .6968))) THEN (.0075*Current*1.66*D_oil) ELSE 0 {Non dimensional volume leakage due to entrainment of oil drops driven under the boom, cf/ft-sec}
- ○ Factor1 = 1.356*Wship + 2*Lship{ Place right hand side of equation here... }
- ○ Factor2 = (15.6*Factor_s*V_oil_init/7.48)/((.6781*(Wship)^2 + Wship*Lship)*(Factor_s+48)) { Place right hand side of equation here... }
- ○ Factor_s = (s_oil- s_oil^2 + 1){ Place right hand side of equation here... }
- ○ Fr_Boom = Current/SQRT(Boom_Draft*g_prime) {Boom Froude no}
- ○ g = 32.2 {acceleration of gravity, fps}
- ○ Gamma_w = IF (Water_Type = 1) THEN 64 ELSE 62.4 { Establishes the weight density of the water of operation, pcf.}
- ○ g_prime = g*2*(64 - (s_oil*62.4))/(s_oil*62.4 + 64){Froude related reduced gravity constant}
- ○ HF_Efficiency = Temp_Effect*Wind_Effect2*Snow_Ice {Combined degradation effect of temperature, wind snow and ice on human performance on deck}
- ○ H_puncture = 12 {Height of puncture, ft.}
- ○ Lboom = Factor1*(1+SQRT(Factor2)){Boom length optimized by calculation, ft}
- ○ Loil = Vol_ratio/(1.667*D_oil) {max. length of stable oil pool upstream of boom, ft.}
- ○ Lship = 246 {length overall of ship, ft.}
- ○ L_puncture = 6 {Length of puncture, ft.}
- ○ P_over = IF (Carrier_type = 1) THEN 2 ELSE 0 {Initial ullage overpressure, psi; set at 2 psig. for tankers and 0 psig. for barges}
- ○ Snow_Ice = .75 {Set expression to degradation factor (suggest .75) if snow or ice is present, otherwise set to 1}

○ Steady_Current = .66 {Max. steady current, fps}
○ Steepness = Wave_Height/(5.12*Wave_period^2){Wave steepness, H/L }
○ s_oil = IF( Carrier_type = 1) THEN .86 ELSE .92 {specific gravity of cargo oil; =.86 for tankers (crude), or .92 for barges (diesel)}
○ Tank_Area = 2740.4 {Cross sectional area of cargo tank, sf.}
○ Tank_height = 11 {height of tank, ft.}
○ Td = 25 {Nominal time to deploy containment, min.}
○ Tides = 0 {Max. tidal current, fps}
○ Tonnage = 1182 {DWT for tankers or GT for barges}
○ ullage_fraction = IF (Carrier_type = 1) THEN .02 ELSE .05 {Fraction of tank height which is left as void above cargo; for barges = 5%, for tankers =2%}

○ Vol_ratio = MAX(0, Current_Effect1*((s_oil*g_prime)*((Boom_Draft/s_oil)^3 - .216*(1.66*Wave_Effect1*D_oil)^3)/(1.5*.002*Current^2) + 5.64*(1.66*Wave_Effect1*D_oil/Boom_Draft)^2)) {Max. vol of oil that can be contained without drainage failure per foot of boom width; Cf = 0.002. Boom height modified by effect of wind and waves}
○ V_oil_init = 7.48*(1-ullage_fraction)*Tank_height*Tank_Area {Initial volume of cargo in tank, gal}
○ Water_Type = IF (Tonnage ≥ 2713) THEN 1 ELSE 0 {1 means carrier operates in seawater; 0 in fresh water}
○ Wave_Height = 3.6 {Significant wave height in ft.}
○ Wave_period = 3 {Period in sec. of significant wave}
○ Wind_in_kt = 13.4 {Wind speed in kts.}
○ Wship = 52 {width of ship at midsection, ft.}
○ Zp = Zw -.4 + H_puncture/2 {Height of top of puncture above bottom of tank in ft. (center of puncture set equal to the height of the water -0.3 ft. for worst-case side puncture analysis)}
○ Zw = 9.6 {Height of the waterline above the tank bottom, ft.}
⊘ Current_Effect1 = GRAPH( Fr_Boom {Effect of current on boom failure})
(0.00, 1.00), (0.1, 1.00), (0.2, 1.00), (0.3, 1.00), (0.4, 1.00), (0.5, 1.00), (0.6, 1.00), (0.7, 1.00), (0.8, 1.00), (0.9, 1.00), (1, 1.00), (1.10, 0.89), (1.20, 0.65), (1.30, 0.26), (1.40, 0.055), (1.50, 0.00), (1.60, 0.00), (1.70, 0.00), (1.80, 0.00), (1.90, 0.00), (2.00, 0.00)
⊘ Temp_Effect = GRAPH( Air_Temp{ Place right hand side of equation here... })
(-40.0, 0.2), (-32.0, 0.215), (-24.0, 0.24), (-16.0, 0.28), (-8.00, 0.33), (0.00, 0.42), (8.00, 0.53), (16.0, 0.665), (24.0, 0.825), (32.0, 0.955), (40.0, 1.00), (48.0, 1.00), (56.0, 1.00), (64.0, 1.00), (72.0, 1.00), (80.0, 1.00), (88.0, 1.00), (96.0, 0.93), (104, 0.82), (112, 0.7), (120, 0.53)
⊘ Wave_Effect1 = GRAPH(Steepness{ Place right hand side of equation here... })
(0.00, 1.00), (0.01, 1.00), (0.02, 1.00), (0.03, 1.00), (0.04, 1.05), (0.05, 1.27), (0.06, 1.65), (0.07, 2.12), (0.08, 2.90), (0.09, 3.73), (0.1, 5.00)
⊘ Wind_Effect2 = GRAPH( Wind_in_kt{ Place right hand side of equation here... })
(0.00, 1.00), (1.00, 1.00), (2.00, 1.00), (3.00, 1.00), (4.00, 1.00), (5.00, 1.00), (6.00, 1.00), (7.00, 1.00), (8.00, 1.00), (9.00, 1.00), (10.0, 1.00), (11.0, 1.00), (12.0, 1.00), (13.0, 1.00), (14.0, 1.00), (15.0, 1.00), (16.0, 1.00), (17.0, 1.00), (18.0, 1.00), (19.0, 1.00), (20.0, 1.00), (21.0, 1.00), (22.0, 1.00), (23.0, 1.00), (24.0, 1.00), (25.0, 0.99), (26.0, 0.96), (27.0, 0.905), (28.0, 0.82), (29.0, 0.715), (30.0, 0.585)

**OUTFLOW CHARACTERIZATION**
DOCUMENT:
Describes the actual time history of the oil outflow for the selected carrier, casualty and environmental scenario.

☐ Spilled_Oil(t) = Spilled_Oil(t - dt) + (Outflow_Rate - Contain_inflow) * dt
INIT Spilled_Oil = 0 {gal.}
INFLOWS:
Outflow_Rate = IF (Ingest_t = 1) THEN (60*7.48*Cd*(A_puncture/2)*s_oil*SQRT((2*g*DeltaP/(s_oil*62.4)))) ELSE (60*7.48*Cd*A_puncture*SQRT(2*g*DeltaP/(s_oil*62.4))) {GPM}

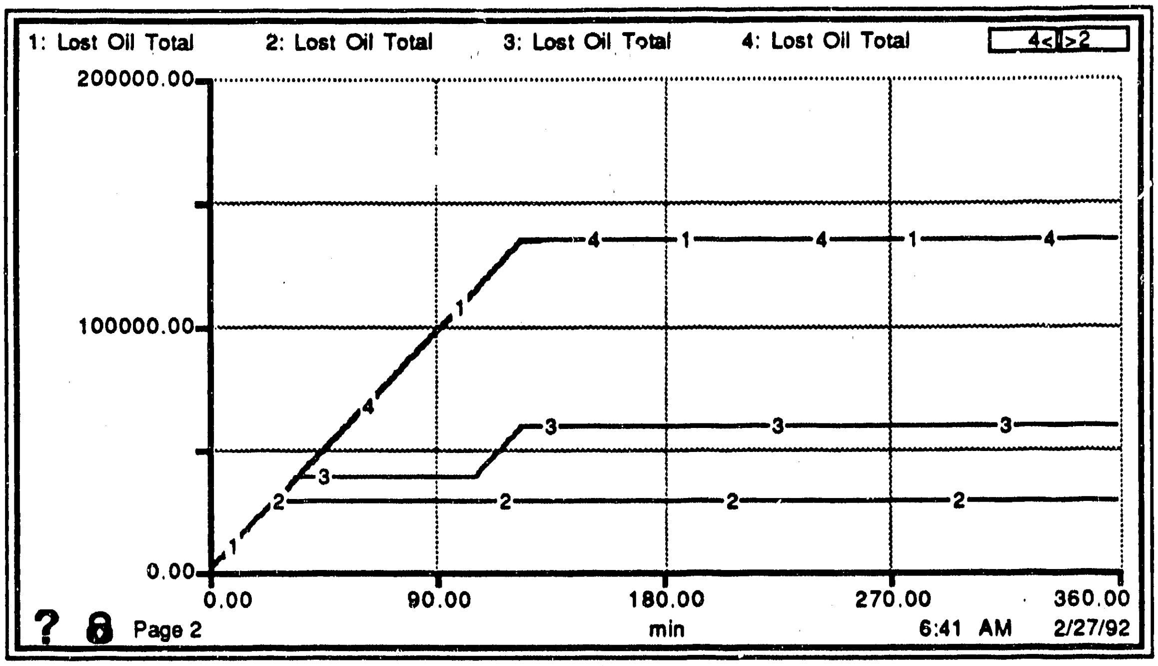
```
OUTFLOWS:
  Contain_Inflow (IN SECTOR:  CONTAINMENT CHARACTERIZATION)
☐ Volume_of_Oil(t) = Volume_of_Oil(t - dt) + (- Outflow_Rate) * dt
  INIT Volume_of_Oil =  V_oil_init(gal.)
  OUTFLOWS:
    Outflow_Rate = IF (Ingest_t = 1) THEN (60*7.48*Cd*(A_puncture/2)*s_oil*SQRT((2*g*DeltaP/(s_oil*62.4)))) ELSE
      (60*7.48*Cd*A_puncture*SQRT(2*g*DeltaP/(s_oil*62.4)))   {GPM}
☐ Water_inflow(t) = Water_inflow(t - dt) + (Ingestion) * dt
  INIT Water_inflow =  0{Amount of water ingested back into tank, gal}
  INFLOWS:
    Ingestion = IF (Ingest_t = 1) AND (t_stop ≠ 1) THEN Outflow_Rate ELSE 0 {Flow rate of water back into tank, GPM}
○ DeltaP = IF ((P_int - P_ext) ≥ (.01*14.7*144)) THEN (P_int - P_ext) ELSE (.01*14.7*144)  {Sets driving pressure difference, psf.}
○ Ingest_t = IF (DeltaP ≤ .01*14.7*144) THEN 1 ELSE 0{Captures start of water ingestion back into ruptured tank}
○ P_ext = 14.7*144 + Gamma_w*(Zw - Zp + (H_puncture/2)){External pressure of water acting on puncture, psf (absolute)}
○ P_int =  P_tank + 62.4*s_oil*(Zl - Zp + (H_puncture/2)) {Internal pressure of the oil acting on the puncture, psf (absolute)}
○ P_tank =  MAX( 14.7*144, (144*((P_over + 14.7)*(ullage_fraction)/(1 - (Zl/Tank_height))))) {Over pressure as a function of ullage, psf. (absolute)}
○ t_stop = IF (Volume_of_Oil ≥ 0) THEN 0 ELSE 1{Captures time at which all oil has flowed from the tank}
○ Zl = ((Volume_of_Oil + Water_inflow)/7.48)/Tank_Area {Height of oil above bottom, ft., including effect of backflowing water}
```

**CONTAINMENT CHARACTERIZATION**

DOCUMENT:

Characterizes how well any containment captures and retains (or leaks) oil spilled alongside the carrier.

```
☐ Contained_oil(t) = Contained_oil(t - dt) + (Contain_inflow - Leaking_Oil) * dt
  INIT Contained_oil = 0 {gal}
  INFLOWS:
    Contain_inflow = IF (TIME ≥ Deploy_Time) AND (t_stop = 0) THEN Outflow_Rate ELSE 0  {Starts accumulation of contained oil, GPM}
  OUTFLOWS:
    Leaking_Oil = IF (Contained_oil > 0) AND (Margin_test = 1) AND (t_stop = 0) THEN (Outflow_Rate + 7.48*60*Entrain_loss*Wship) ELSE
      7.48*60*Entrain_loss*Wship  {GPM}
○ D_oil = ((Contained_oil/7.48)/A_net)  {ft}
○ Lpool = .5*Lboom - .5708*Wship -Lship {aprox. length of impounding area downstream of ship}
○ Margin_test = IF (Loil ≤ Lpool) THEN 1 ELSE 0
  Contain_inflow = IF (TIME ≥ Deploy_Time) AND (t_stop = 0) THEN Outflow_Rate ELSE 0  {Starts accumulation of contained oil, GPM}
  OUTFLOW FROM:  Spilled_Oil (IN SECTOR:  OUTFLOW CHARACTERIZATION)
  INFLOW TO:
```




Setup #2 2/27/92 6:42 AM

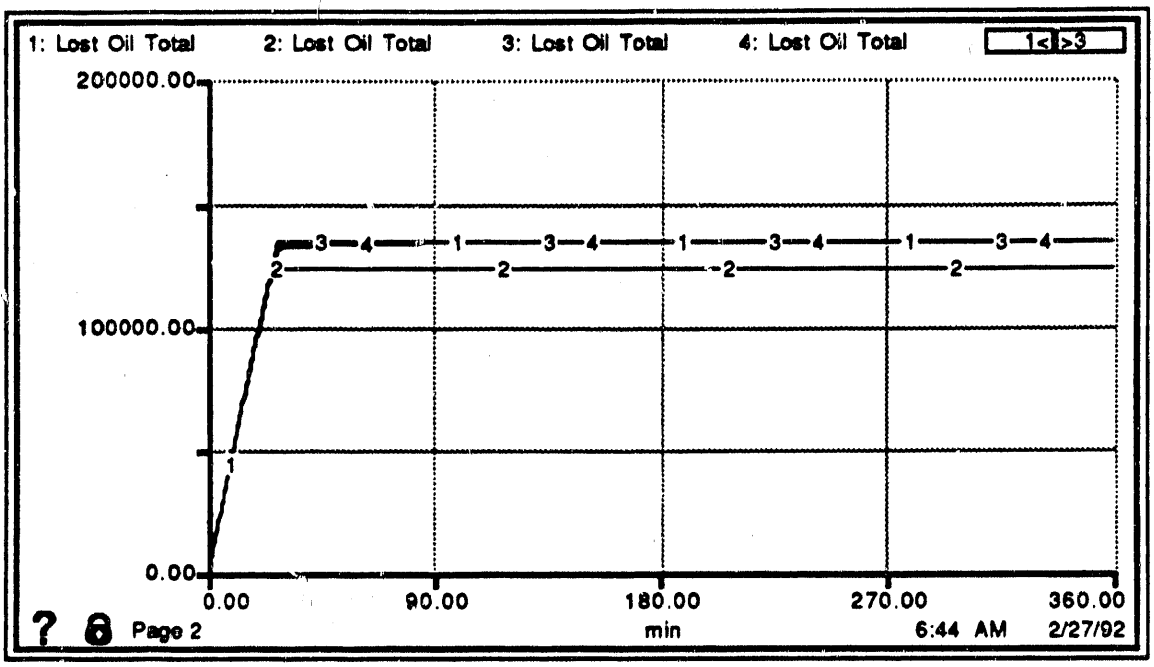
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 2.00 | 1.00 | 628 |
| 2 | 2.00 | 1.00 | 628 |
| 3 | 2.00 | 1.00 | 628 |
| 4 | 2.00 | 1.00 | 628 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 8.20 | 1.60 | 70.7 |
| 2 | 8.20 | 1.60 | 70.7 |
| 3 | 13.4 | 3.60 | 36.1 |
| 4 | 13.4 | 1.60 | 32.5 |

| Run # | Wave period | Steady Current | Tides |
|---|---|---|---|
| 1 | 3.00 | 0.4 | 0.00 |
| 2 | 3.00 | 0.4 | 0.00 |
| 3 | 3.00 | 0.66 | 0.00 |
| 4 | 3.00 | 7.80 | 0.00 |

| Run # | Td | Snow Ice |
|---|---|---|
| 1 | 10000 | 1.00 |
| 2 | 25.0 | 1.00 |
| 3 | 25.0 | 0.75 |
| 4 | 25.0 | 1.00 |




Setup #3 2/27/92 6:43 AM

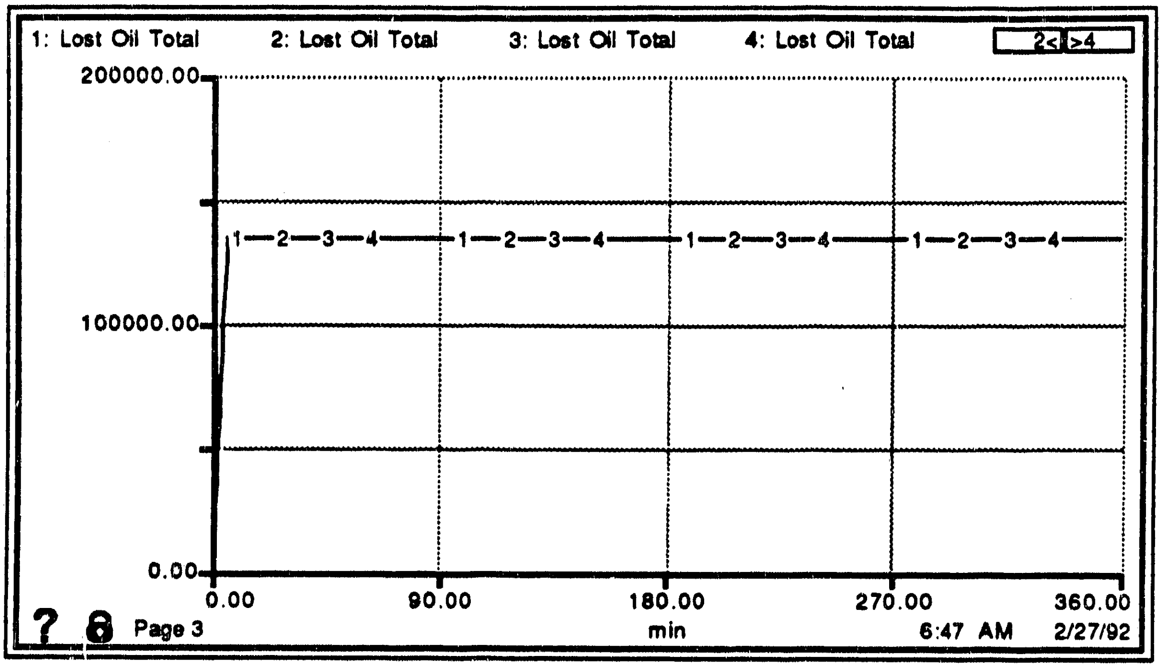
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 4.90 | 2.45 | 628 |
| 2 | 4.90 | 2.45 | 628 |
| 3 | 4.90 | 2.45 | 628 |
| 4 | 4.90 | 2.45 | 628 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 8.20 | 1.60 | 70.7 |
| 2 | 8.20 | 1.60 | 70.7 |
| 3 | 13.4 | 3.60 | 36.1 |
| 4 | 13.4 | 1.60 | 32.5 |

| Run # | Wave period | Steady Current | Tides |
|---|---|---|---|
| 1 | 3.00 | 0.4 | 0.00 |
| 2 | 3.00 | 0.4 | 0.00 |
| 3 | 3.00 | 0.66 | 0.00 |
| 4 | 3.00 | 7.80 | 0.00 |

| Run # | Td | Snow Ice |
|---|---|---|
| 1 | 10000 | 1.00 |
| 2 | 25.0 | 1.00 |
| 3 | 25.0 | 0.75 |
| 4 | 25.0 | 1.00 |




Setup #4 2/27/92 6:45 AM

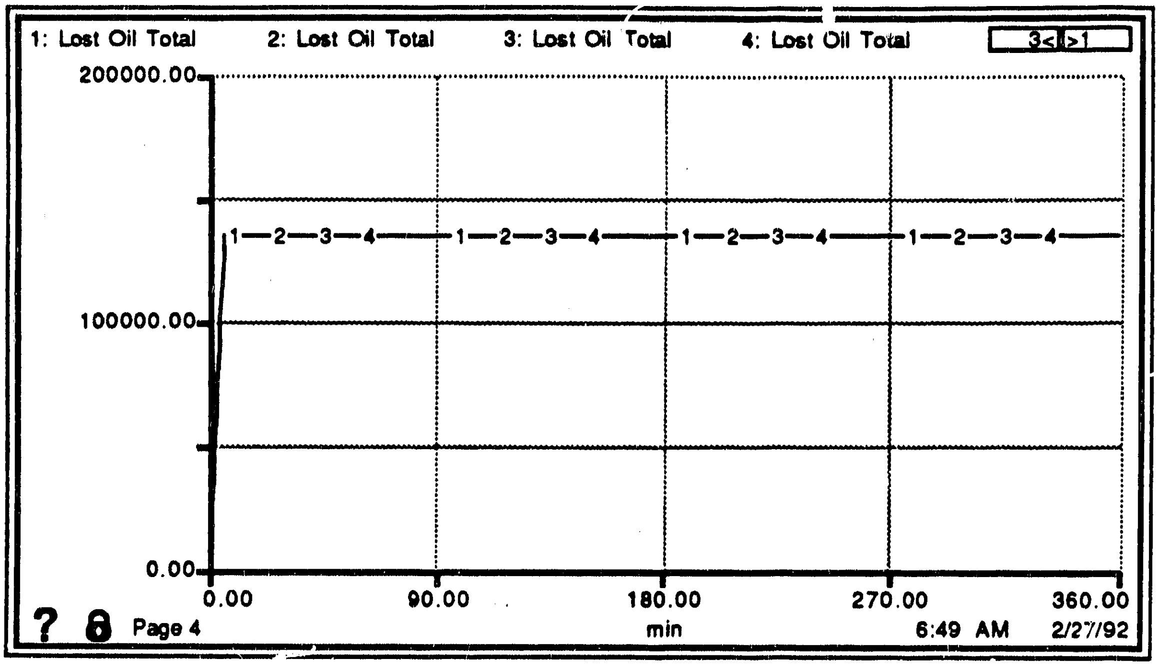
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 628 |
| 2 | 12.0 | 6.00 | 628 |
| 3 | 12.0 | 6.00 | 628 |
| 4 | 12.0 | 6.00 | 628 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 8.20 | 1.60 | 70.7 |
| 2 | 8.20 | 1.60 | 70.7 |
| 3 | 13.4 | 3.60 | 36.1 |
| 4 | 13.4 | 1.60 | 32.5 |

| Run # | Wave period | Steady Current | Tides |
|---|---|---|---|
| 1 | 3.00 | 0.4 | 0.00 |
| 2 | 3.00 | 0.4 | 0.00 |
| 3 | 3.00 | 0.66 | 0.00 |
| 4 | 3.00 | 7.80 | 0.00 |

| Run # | Td | Snow Ice |
|---|---|---|
| 1 | 10000 | 1.00 |
| 2 | 25.0 | 1.00 |
| 3 | 25.0 | 0.75 |
| 4 | 25.0 | 1.00 |




Setup #5 2/27/92 6:47 AM

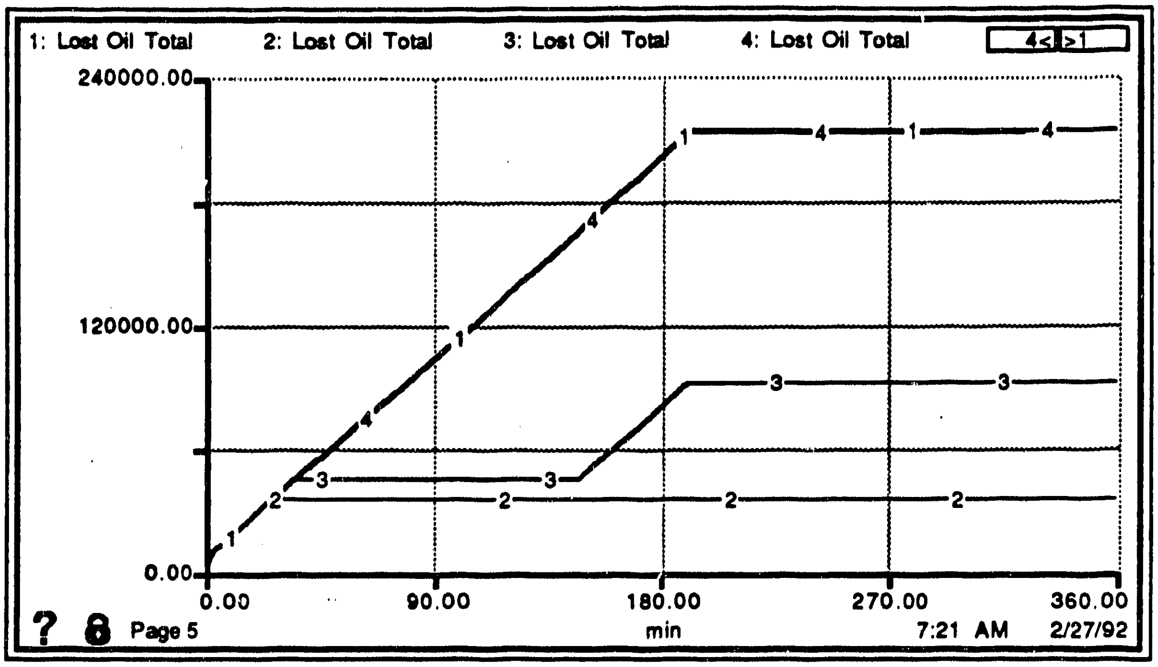
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 628 |
| 2 | 12.0 | 6.00 | 628 |
| 3 | 12.0 | 6.00 | 628 |
| 4 | 12.0 | 6.00 | 628 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 8.20 | 1.60 | 70.7 |
| 2 | 8.20 | 1.60 | 70.7 |
| 3 | 13.4 | 3.60 | 36.1 |
| 4 | 13.4 | 1.60 | 32.5 |

| Run # | Wave period | Steady Current | Tides |
|---|---|---|---|
| 1 | 3.00 | 0.4 | 0.00 |
| 2 | 3.00 | 0.4 | 0.00 |
| 3 | 3.00 | 0.66 | 0.00 |
| 4 | 3.00 | 7.80 | 0.00 |

| Run # | Td | Snow Ice |
|---|---|---|
| 1 | 10000 | 1.00 |
| 2 | 5.00 | 1.00 |
| 3 | 5.00 | 0.75 |
| 4 | 5.00 | 1.00 |




Setup #6 2/27/92 7:19 AM

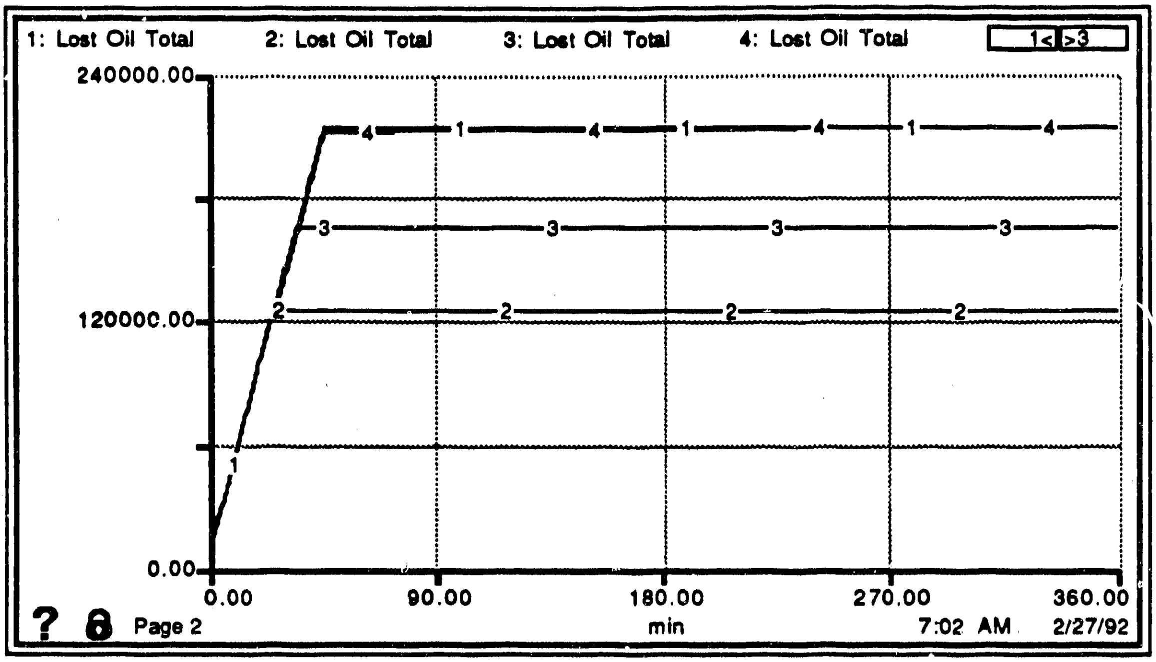
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 2.00 | 1.00 | 1182 |
| 2 | 2.00 | 1.00 | 1182 |
| 3 | 2.00 | 1.00 | 1182 |
| 4 | 2.00 | 1.00 | 1182 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 8.20 | 1.60 | 70.7 |
| 2 | 8.20 | 1.60 | 70.7 |
| 3 | 13.4 | 3.60 | 36.1 |
| 4 | 13.4 | 1.60 | 32.5 |

| Run # | Wave period | Steady Current | Tides |
|---|---|---|---|
| 1 | 3.00 | 0.4 | 0.00 |
| 2 | 3.00 | 0.4 | 0.00 |
| 3 | 3.00 | 0.66 | 0.00 |
| 4 | 3.00 | 7.80 | 0.00 |

| Run # | Td | Snow Ice |
|---|---|---|
| 1 | 10000 | 1.00 |
| 2 | 25.0 | 1.00 |
| 3 | 25.0 | 0.75 |
| 4 | 25.0 | 1.00 |




Setup #3 2/27/92 6:59 AM

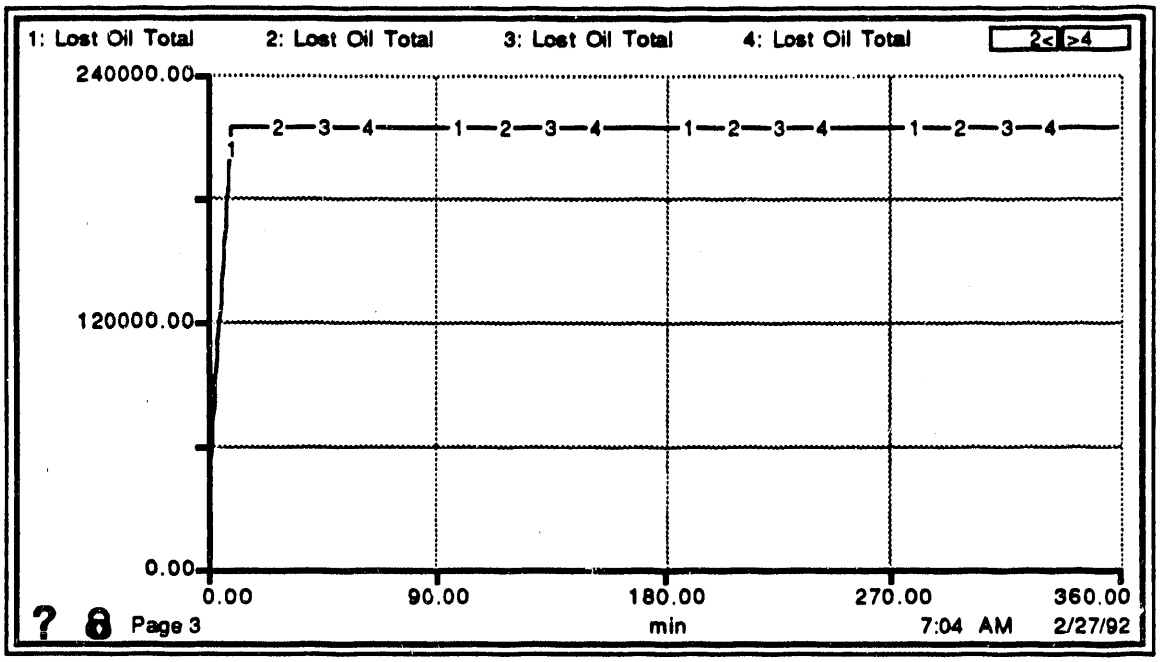
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 4.90 | 2.45 | 1182 |
| 2 | 4.90 | 2.45 | 1182 |
| 3 | 4.90 | 2.45 | 1182 |
| 4 | 4.90 | 2.45 | 1182 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 8.20 | 1.60 | 70.7 |
| 2 | 8.20 | 1.60 | 70.7 |
| 3 | 13.4 | 3.60 | 36.1 |
| 4 | 13.4 | 1.60 | 32.5 |

| Run # | Wave period | Steady Current | Tides |
|---|---|---|---|
| 1 | 3.00 | 0.4 | 0.00 |
| 2 | 3.00 | 0.4 | 0.00 |
| 3 | 3.00 | 0.66 | 0.00 |
| 4 | 3.00 | 7.80 | 0.00 |

| Run # | Td | Snow Ice |
|---|---|---|
| 1 | 10000 | 1.00 |
| 2 | 25.0 | 1.00 |
| 3 | 25.0 | 0.75 |
| 4 | 25.0 | 1.00 |




Setup #4 2/27/92 7:02 AM

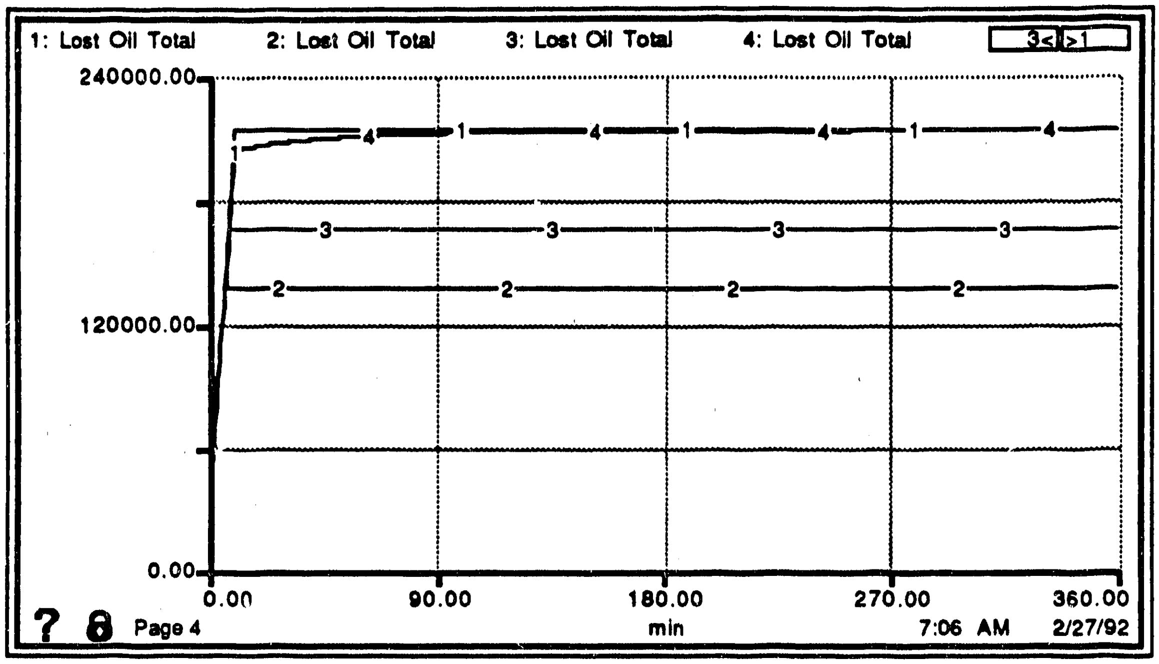
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 1182 |
| 2 | 12.0 | 6.00 | 1182 |
| 3 | 12.0 | 6.00 | 1182 |
| 4 | 12.0 | 6.00 | 1182 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 8.20 | 1.60 | 70.7 |
| 2 | 8.20 | 1.60 | 70.7 |
| 3 | 13.4 | 3.60 | 36.1 |
| 4 | 13.4 | 1.60 | 32.5 |

| Run # | Wave period | Steady Current | Tides |
|---|---|---|---|
| 1 | 3.00 | 0.4 | 0.00 |
| 2 | 3.00 | 0.4 | 0.00 |
| 3 | 3.00 | 0.66 | 0.00 |
| 4 | 3.00 | 7.80 | 0.00 |

| Run # | Td | Snow Ice |
|---|---|---|
| 1 | 10000 | 1.00 |
| 2 | 25.0 | 1.00 |
| 3 | 25.0 | 0.75 |
| 4 | 25.0 | 1.00 |




Setup #5 2/27/92 7:04 AM

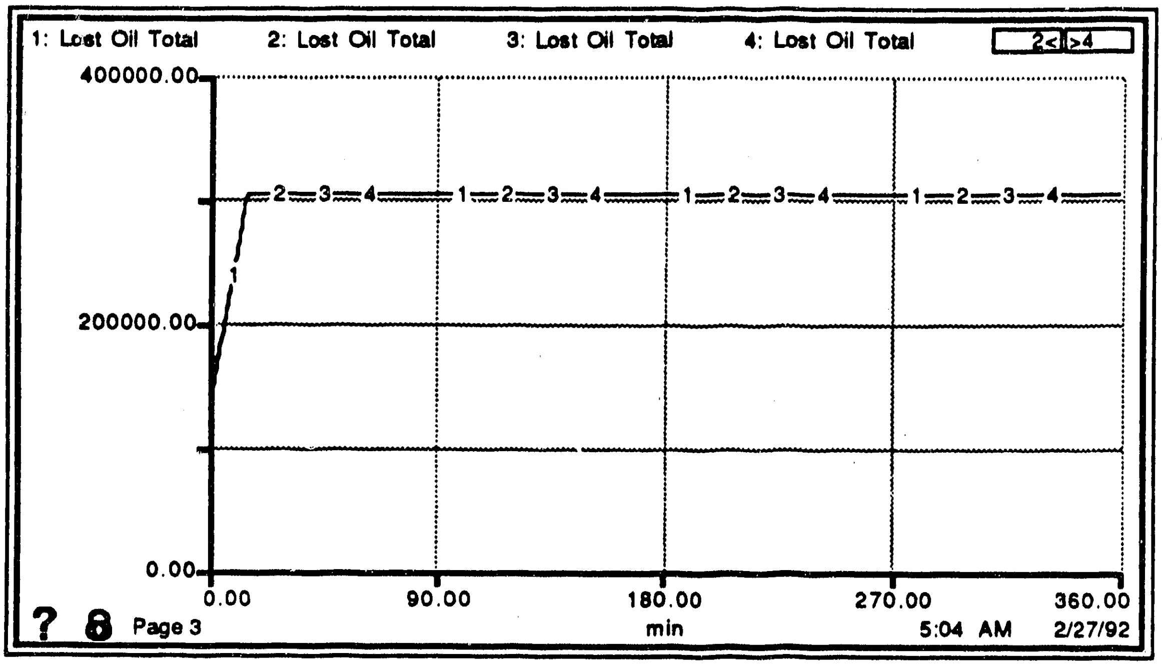
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 1182 |
| 2 | 12.0 | 6.00 | 1182 |
| 3 | 12.0 | 6.00 | 1182 |
| 4 | 12.0 | 6.00 | 1182 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 8.20 | 1.60 | 70.7 |
| 2 | 8.20 | 1.60 | 70.7 |
| 3 | 13.4 | 3.60 | 36.1 |
| 4 | 13.4 | 1.60 | 32.5 |

| Run # | Wave period | Steady Current | Tides |
|---|---|---|---|
| 1 | 3.00 | 0.4 | 0.00 |
| 2 | 3.00 | 0.4 | 0.00 |
| 3 | 3.00 | 0.66 | 0.00 |
| 4 | 3.00 | 7.80 | 0.00 |

| Run # | Td | Snow Ice |
|---|---|---|
| 1 | 10000 | 1.00 |
| 2 | 5.00 | 1.00 |
| 3 | 5.00 | 0.75 |
| 4 | 5.00 | 1.00 |




Setup #4 2/27/92 5:02 AM

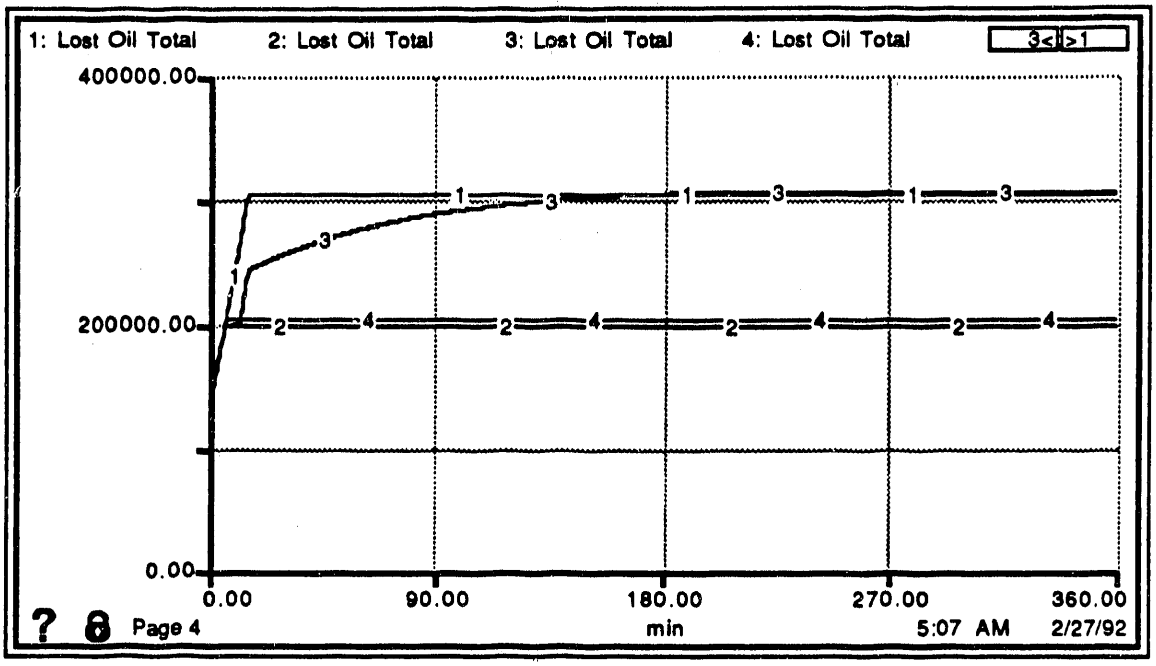
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 2713 |
| 2 | 12.0 | 6.00 | 2713 |
| 3 | 12.0 | 6.00 | 2713 |
| 4 | 12.0 | 6.00 | 2713 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 10.0 | 2.30 | 83.7 |
| 2 | 10.0 | 2.30 | 83.7 |
| 3 | 17.5 | 9.80 | 52.0 |
| 4 | 27.0 | 14.8 | 37.9 |

| Run # | Wave period | Steady Current | Tides |
|---|---|---|---|
| 1 | 3.00 | 0.85 | 1.10 |
| 2 | 3.00 | 0.85 | 1.10 |
| 3 | 6.00 | 2.00 | 2.70 |
| 4 | 8.00 | 0.00 | 1.00 |

| Run # | Td |
|---|---|
| 1 | 10000 |
| 2 | 25.0 |
| 3 | 25.0 |
| 4 | 25.0 |




Setup #5 2/27/92 5:05 AM

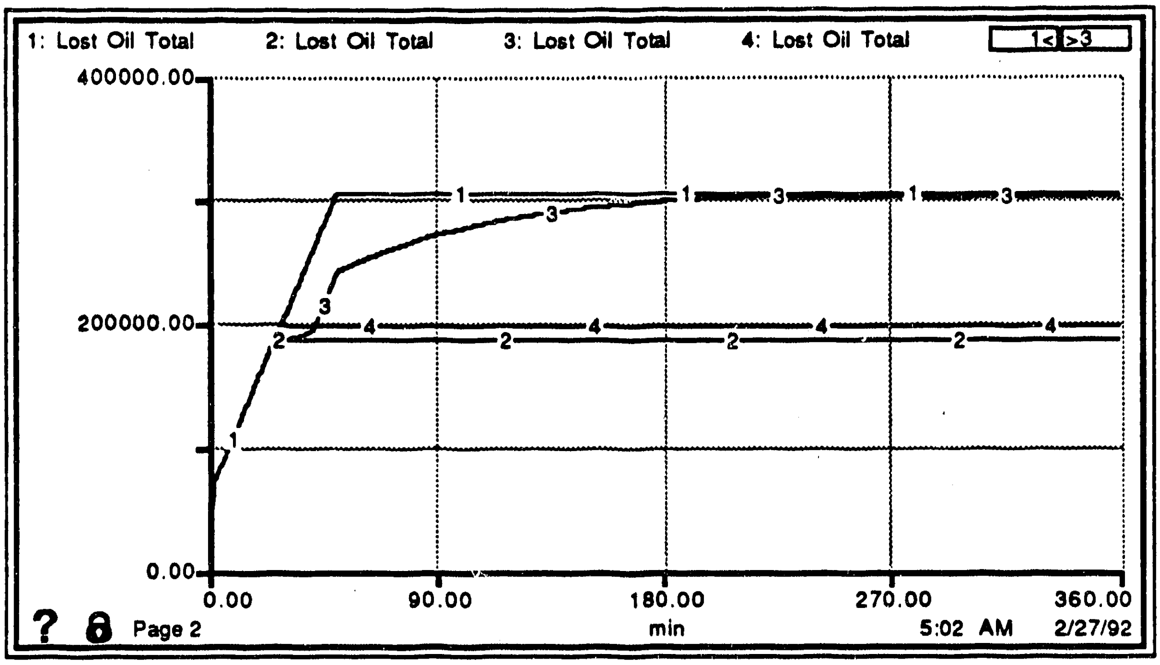
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 2713 |
| 2 | 12.0 | 6.00 | 2713 |
| 3 | 12.0 | 6.00 | 2713 |
| 4 | 12.0 | 6.00 | 2713 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 10.0 | 2.30 | 83.7 |
| 2 | 10.0 | 2.30 | 83.7 |
| 3 | 17.5 | 9.80 | 52.0 |
| 4 | 27.0 | 14.8 | 37.9 |

| Run # | Wave period | Steady Current | Tides |
|---|---|---|---|
| 1 | 3.00 | 0.85 | 1.10 |
| 2 | 3.00 | 0.85 | 1.10 |
| 3 | 6.00 | 2.00 | 2.70 |
| 4 | 8.00 | 0.00 | 1.00 |

| Run # | Td |
|---|---|
| 1 | 10000 |
| 2 | 5.00 |
| 3 | 5.00 |
| 4 | 5.00 |




Setup #3 2/27/92 5:00 AM

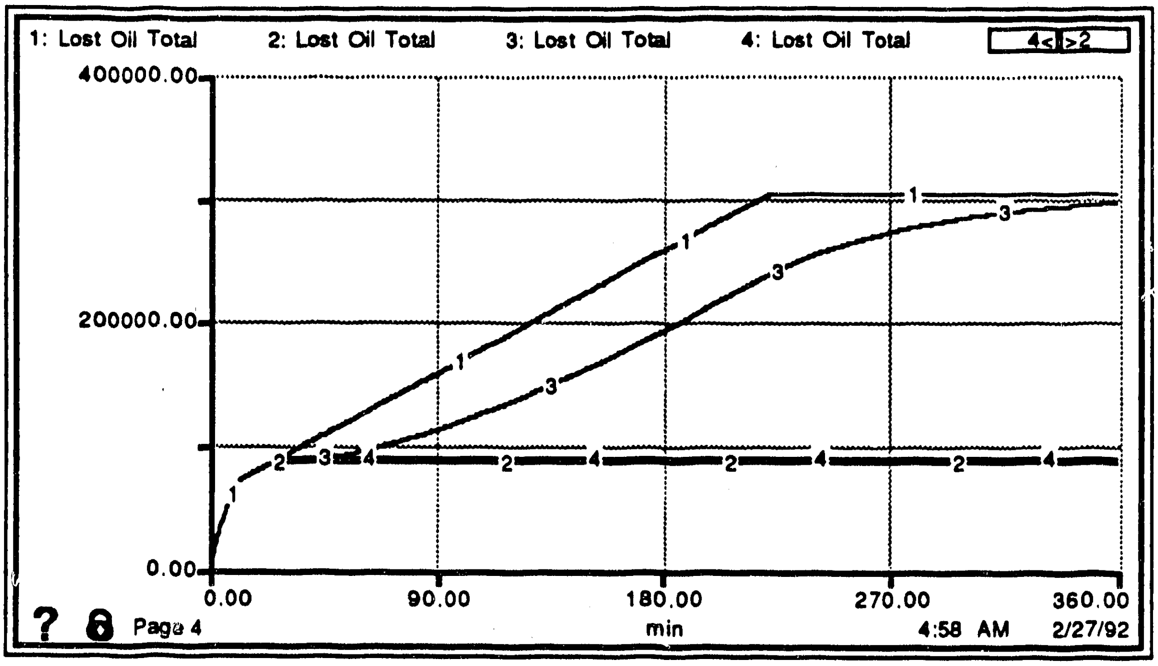
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 4.90 | 2.45 | 2713 |
| 2 | 4.90 | 2.45 | 2713 |
| 3 | 4.90 | 2.45 | 2713 |
| 4 | 4.90 | 2.45 | 2713 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 10.0 | 2.30 | 83.7 |
| 2 | 10.0 | 2.30 | 83.7 |
| 3 | 17.5 | 9.80 | 52.0 |
| 4 | 27.0 | 14.8 | 37.9 |

| Run # | Wave period | Steady Current | Tides |
|---|---|---|---|
| 1 | 3.00 | 0.85 | 1.10 |
| 2 | 3.00 | 0.85 | 1.10 |
| 3 | 6.00 | 2.00 | 2.70 |
| 4 | 8.00 | 0.00 | 1.00 |

| Run # | Td |
|---|---|
| 1 | 10000 |
| 2 | 25.0 |
| 3 | 25.0 |
| 4 | 25.0 |




Setup #2 2/27/92 4:59 AM

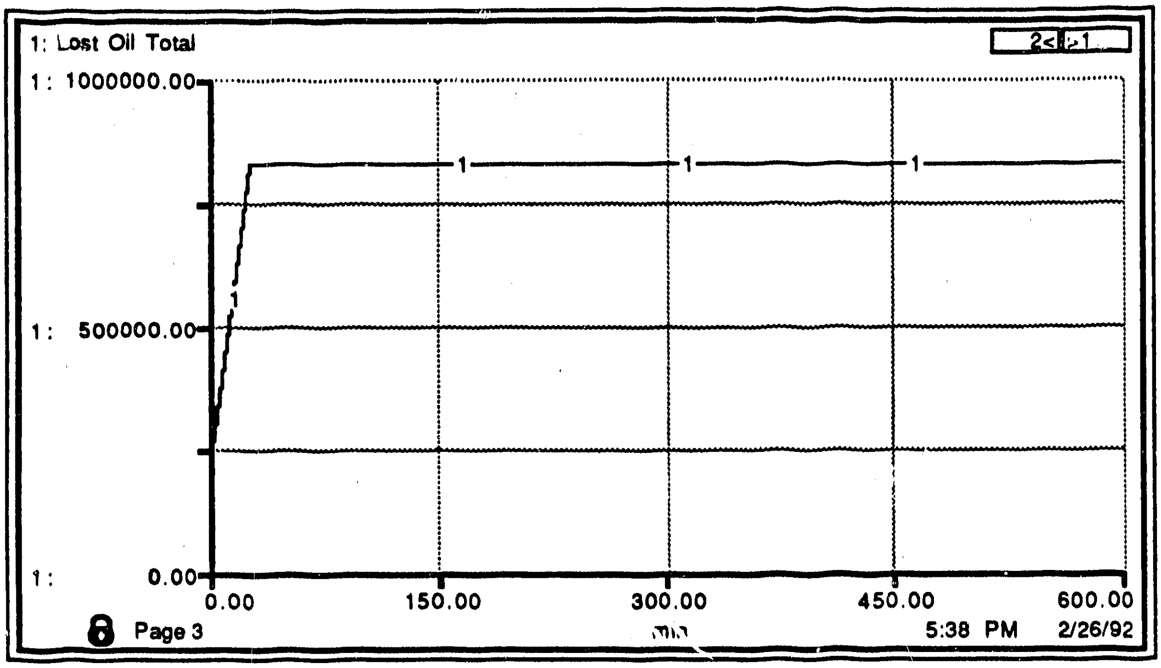
**Input Variables**

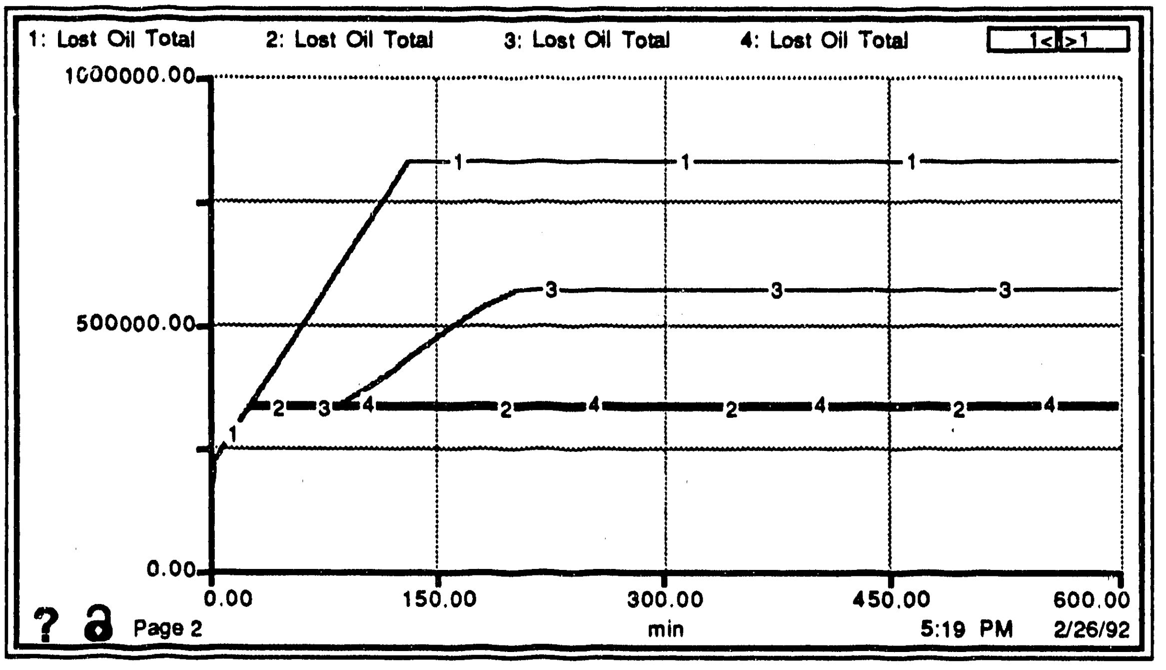
| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 2.00 | 1.00 | 2713 |
| 2 | 2.00 | 1.00 | 2713 |
| 3 | 2.00 | 1.00 | 2713 |
| 4 | 2.00 | 1.00 | 2713 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 10.0 | 2.30 | 83.7 |
| 2 | 10.0 | 2.30 | 83.7 |
| 3 | 17.5 | 9.80 | 52.0 |
| 4 | 27.0 | 14.8 | 37.9 |

| Run # | Wave period | Steady Current | Tides |
|---|---|---|---|
| 1 | 3.00 | 0.85 | 1.10 |
| 2 | 3.00 | 0.85 | 1.10 |
| 3 | 6.00 | 2.00 | 2.70 |
| 4 | 8.00 | 0.00 | 1.00 |

| Run # | Td |
|---|---|
| 1 | 10000 |
| 2 | 25.0 |
| 3 | 25.0 |
| 4 | 25.0 |


1: Lost Oil Total
2< >1
1: 1000000.00
1: 500000.00
1: 0.00
0.00
150.00
300.00
450.00
600.00
Page 3
min
5:38 PM
2/26/92




Setup #3 2/26/92 5:14 PM

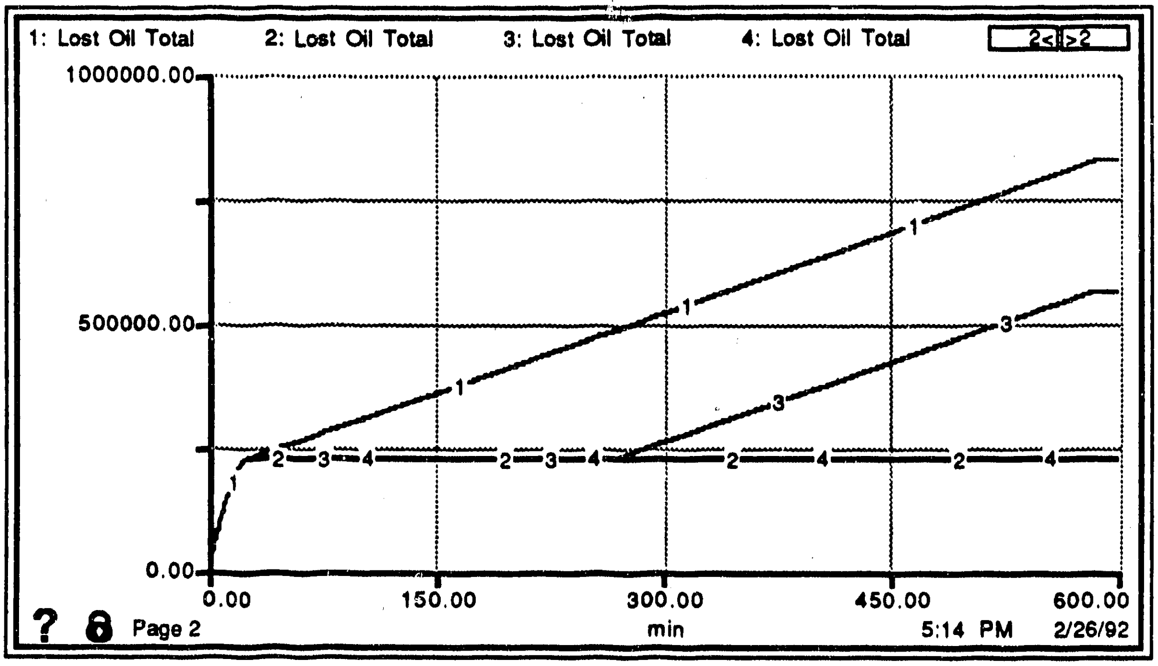
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 4.90 | 2.45 | 34000 |
| 2 | 4.90 | 2.45 | 34000 |
| 3 | 4.90 | 2.45 | 34000 |
| 4 | 4.90 | 2.45 | 34000 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 10.0 | 2.30 | 83.7 |
| 2 | 10.0 | 2.30 | 83.7 |
| 3 | 17.5 | 9.80 | 52.0 |
| 4 | 27.0 | 14.8 | 37.9 |

| Run # | Wave period | Steady Current | Tides |
|---|---|---|---|
| 1 | 3.00 | 0.85 | 1.10 |
| 2 | 3.00 | 0.85 | 1.10 |
| 3 | 6.00 | 2.00 | 2.70 |
| 4 | 8.00 | 0.00 | 1.00 |

| Run # | Td |
|---|---|
| 1 | 10000 |
| 2 | 25.0 |
| 3 | 25.0 |
| 4 | 25.0 |




Setup #2 — 2/26/92 5:10 PM

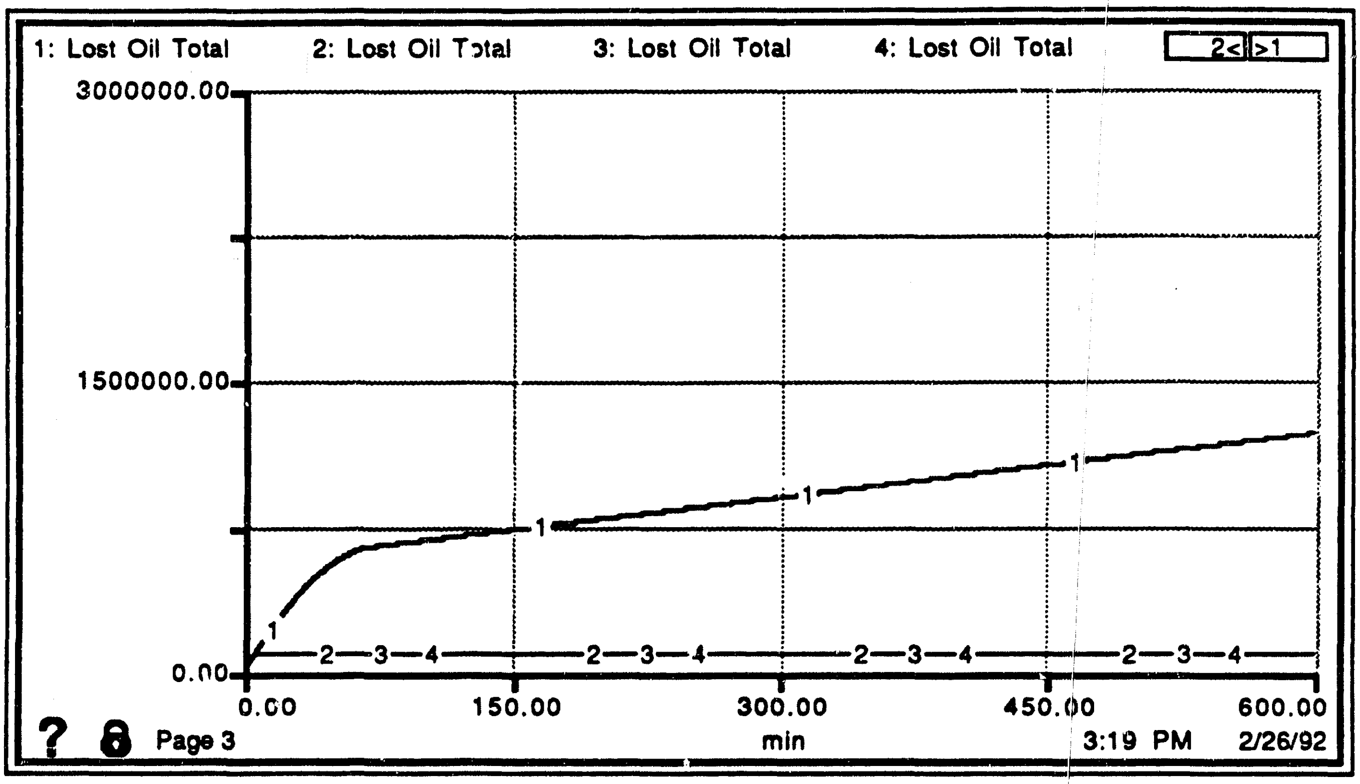
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 2.00 | 1.00 | 34000 |
| 2 | 2.00 | 1.00 | 34000 |
| 3 | 2.00 | 1.00 | 34000 |
| 4 | 2.00 | 1.00 | 34000 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 10.0 | 2.30 | 83.7 |
| 2 | 10.0 | 2.30 | 83.7 |
| 3 | 17.5 | 9.80 | 52.0 |
| 4 | 27.0 | 14.8 | 37.9 |

| Run # | Wave period | Steady Current | Tides |
|---|---|---|---|
| 1 | 3.00 | 0.85 | 1.10 |
| 2 | 3.00 | 0.85 | 1.10 |
| 3 | 6.00 | 2.00 | 2.70 |
| 4 | 8.00 | 0.00 | 1.00 |

| Run # | Td |
|---|---|
| 1 | 10000 |
| 2 | 25.0 |
| 3 | 25.0 |
| 4 | 25.0 |



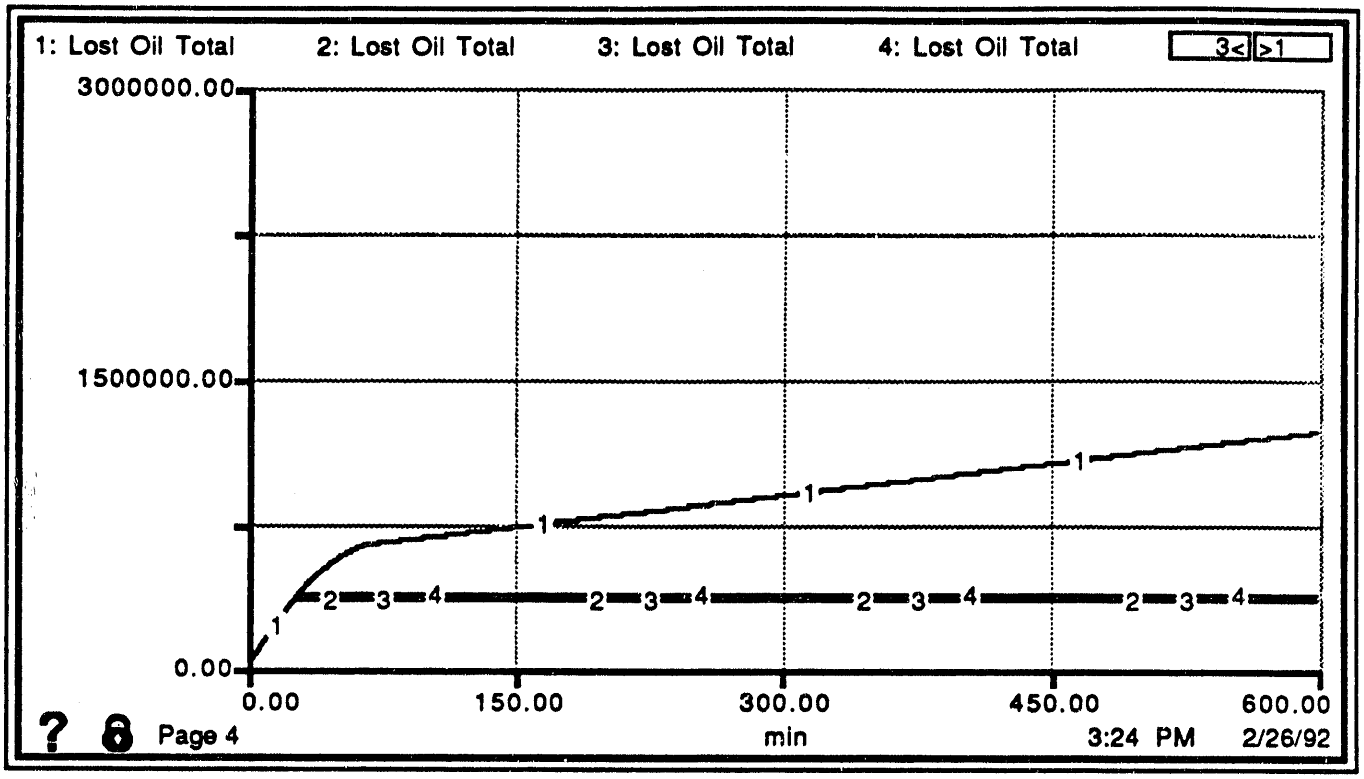

Setup #3 2/26/92 3:15 PM

**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 2.00 | 1.00 | 89700 |
| 2 | 2.00 | 1.00 | 89700 |
| 3 | 2.00 | 1.00 | 89700 |
| 4 | 2.00 | 1.00 | 89700 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 10.0 | 2.30 | 83.7 |
| 2 | 10.0 | 2.30 | 83.7 |
| 3 | 17.5 | 9.80 | 52.0 |
| 4 | 27.0 | 14.8 | 37.9 |

| Run # | Wave period | Td |
|---|---|---|
| 1 | 3.00 | 10000 |
| 2 | 3.00 | 5.00 |
| 3 | 6.00 | 5.00 |
| 4 | 8.00 | 5.00 |



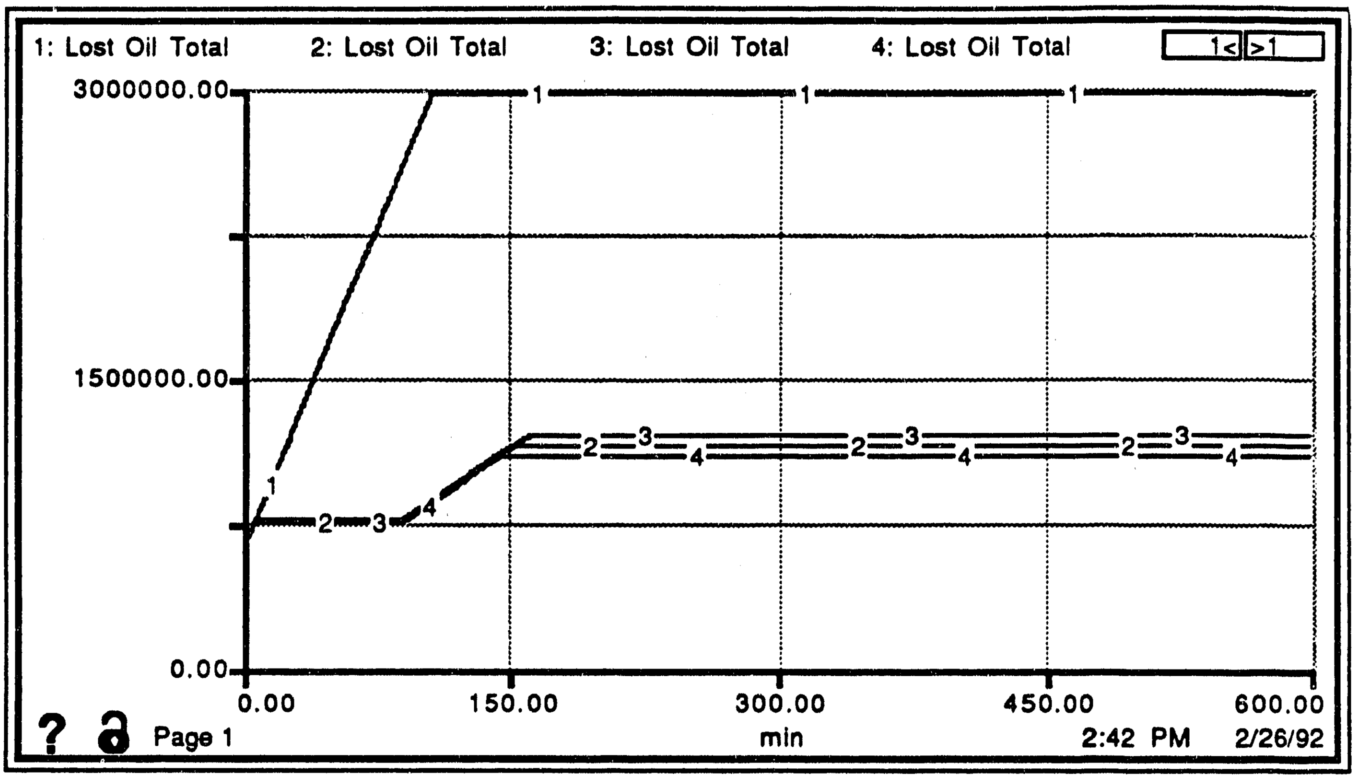

Setup #4 2/26/92 3:19 PM

**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 2.00 | 1.00 | 89700 |
| 2 | 2.00 | 1.00 | 89700 |
| 3 | 2.00 | 1.00 | 89700 |
| 4 | 2.00 | 1.00 | 89700 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 10.0 | 2.30 | 83.7 |
| 2 | 10.0 | 2.30 | 83.7 |
| 3 | 17.5 | 9.80 | 52.0 |
| 4 | 27.0 | 14.8 | 37.9 |

| Run # | Wave period | Td |
|---|---|---|
| 1 | 3.00 | 10000 |
| 2 | 3.00 | 25.0 |
| 3 | 6.00 | 25.0 |
| 4 | 8.00 | 25.0 |



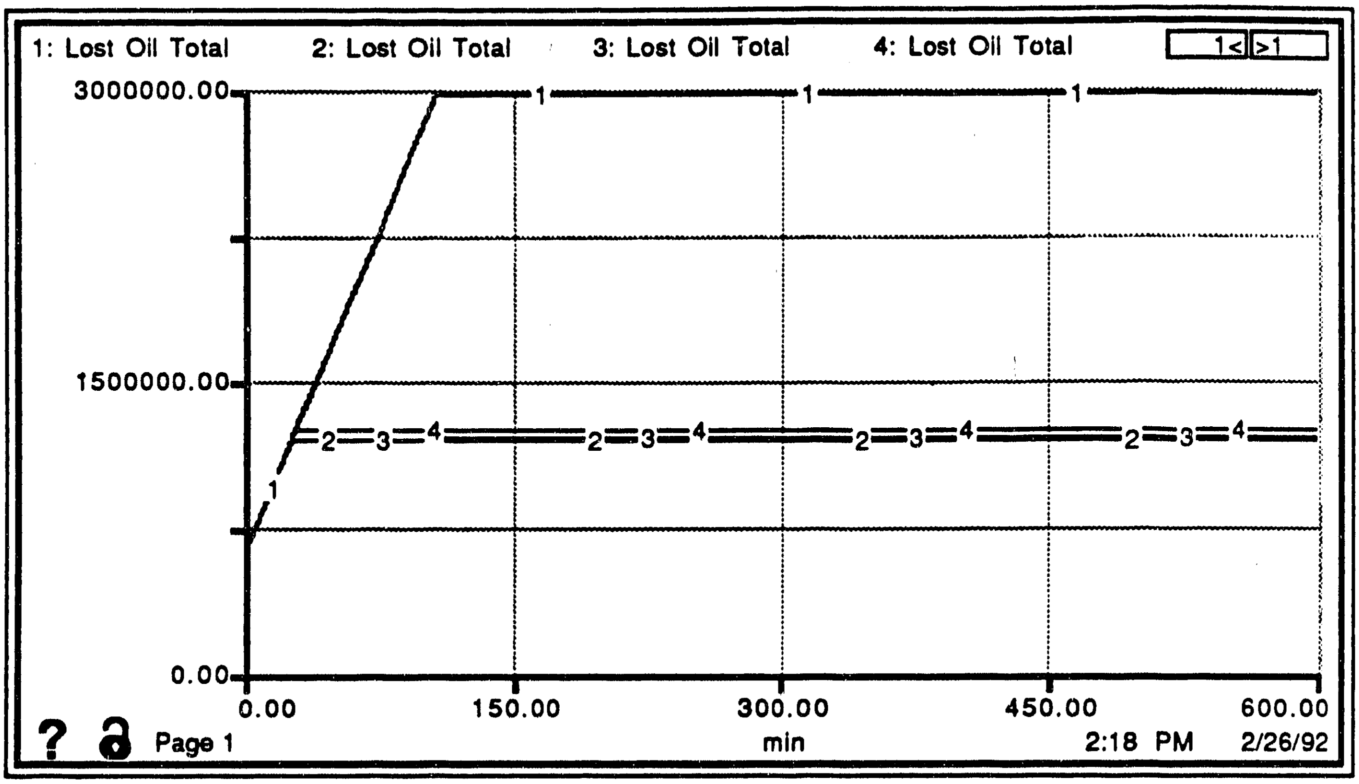

Setup #2 2/26/92 2:39 PM

**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 89700 |
| 2 | 12.0 | 6.00 | 89700 |
| 3 | 12.0 | 6.00 | 89700 |
| 4 | 12.0 | 6.00 | 89700 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 10.0 | 2.30 | 83.7 |
| 2 | 10.0 | 2.30 | 83.7 |
| 3 | 17.5 | 9.80 | 52.0 |
| 4 | 27.0 | 14.8 | 37.9 |

| Run # | Wave period | Td |
|---|---|---|
| 1 | 3.00 | 10000 |
| 2 | 3.00 | 5.00 |
| 3 | 6.00 | 5.00 |
| 4 | 8.00 | 5.00 |



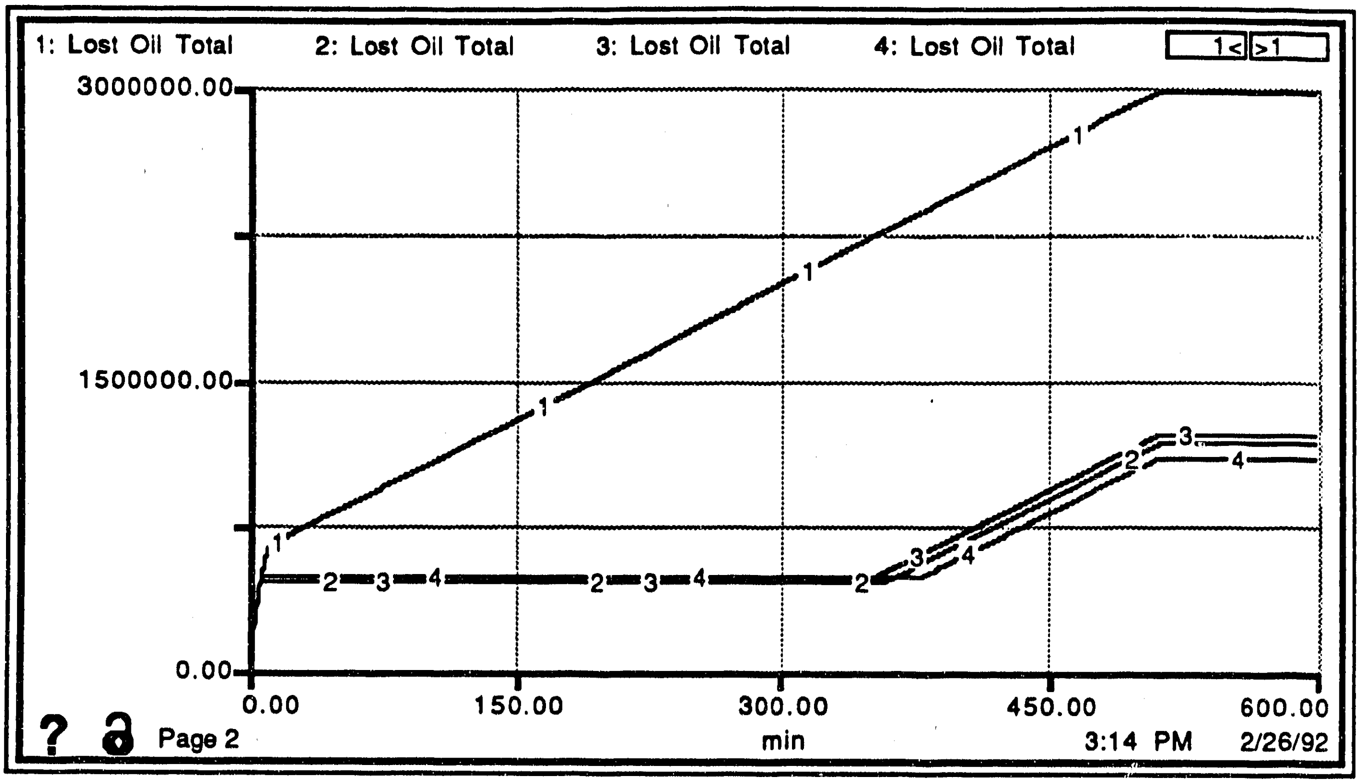

Setup #2 2/26/92 2:15 PM

**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 89700 |
| 2 | 12.0 | 6.00 | 89700 |
| 3 | 12.0 | 6.00 | 89700 |
| 4 | 12.0 | 6.00 | 89700 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 10.0 | 2.30 | 83.7 |
| 2 | 10.0 | 2.30 | 83.7 |
| 3 | 17.5 | 9.80 | 52.0 |
| 4 | 27.0 | 14.8 | 37.9 |

| Run # | Wave period | Td |
|---|---|---|
| 1 | 3.00 | 10000 |
| 2 | 3.00 | 25.0 |
| 3 | 6.00 | 25.0 |
| 4 | 8.00 | 25.0 |



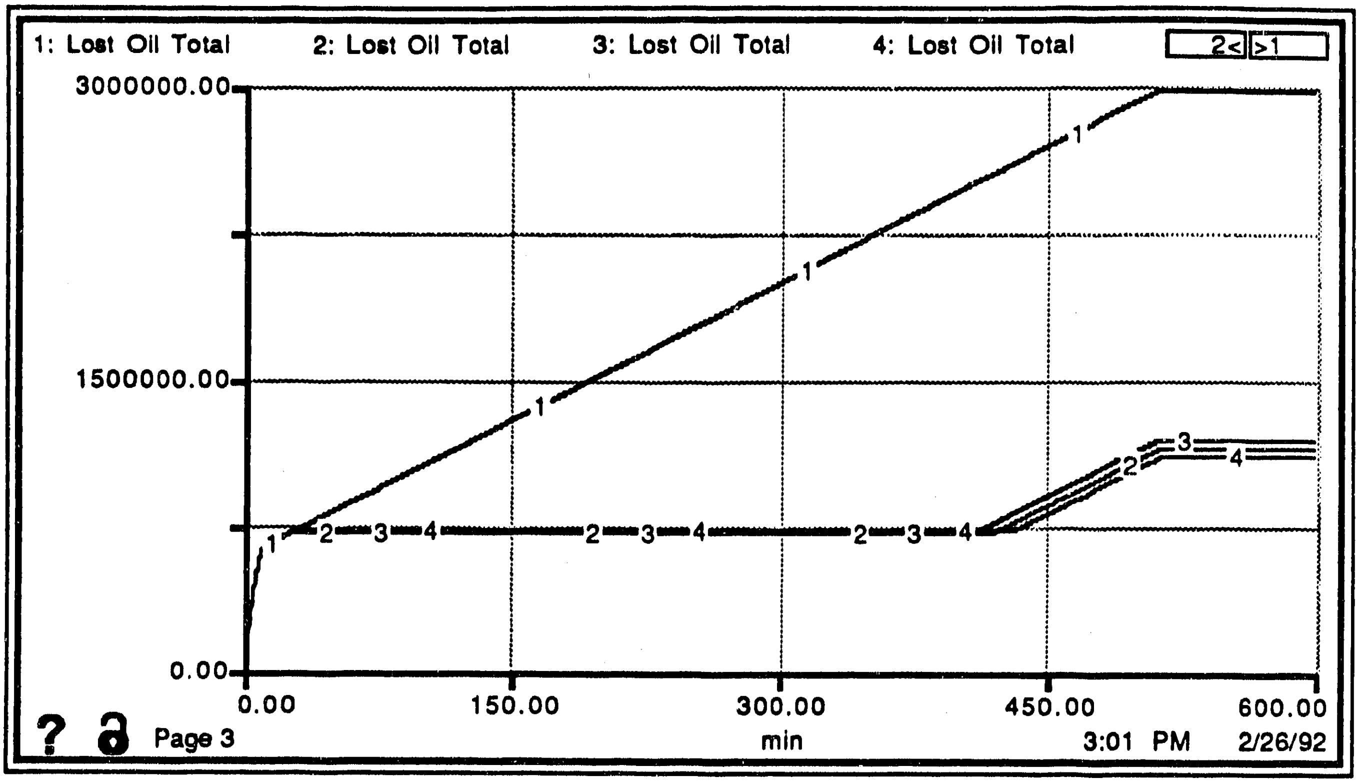

Setup #2 2/26/92 3:07 PM

**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 4.90 | 2.45 | 89700 |
| 2 | 4.90 | 2.45 | 89700 |
| 3 | 4.90 | 2.45 | 89700 |
| 4 | 4.90 | 2.45 | 89700 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 10.0 | 2.30 | 83.7 |
| 2 | 10.0 | 2.30 | 83.7 |
| 3 | 17.5 | 9.80 | 52.0 |
| 4 | 27.0 | 14.8 | 37.9 |

| Run # | Wave period | Td |
|---|---|---|
| 1 | 3.00 | 10000 |
| 2 | 3.00 | 5.00 |
| 3 | 6.00 | 5.00 |
| 4 | 8.00 | 5.00 |



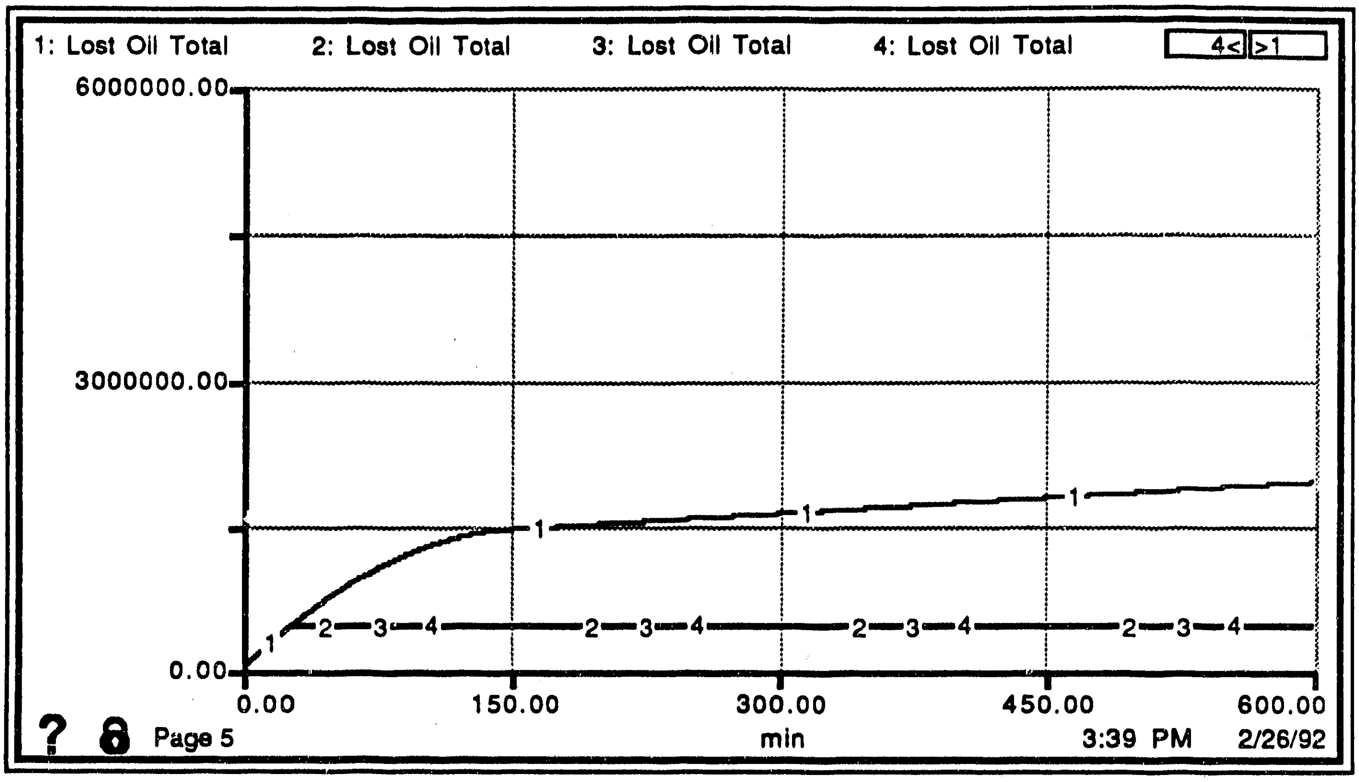

Setup #2 2/26/92 2:57 PM

**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 4.90 | 2.45 | 89700 |
| 2 | 4.90 | 2.45 | 89700 |
| 3 | 4.90 | 2.45 | 89700 |
| 4 | 4.90 | 2.45 | 89700 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 10.0 | 2.30 | 83.7 |
| 2 | 10.0 | 2.30 | 83.7 |
| 3 | 17.5 | 9.80 | 52.0 |
| 4 | 27.0 | 14.8 | 37.9 |

| Run # | Wave period | Td |
|---|---|---|
| 1 | 3.00 | 10000 |
| 2 | 3.00 | 25.0 |
| 3 | 6.00 | 25.0 |
| 4 | 8.00 | 25.0 |



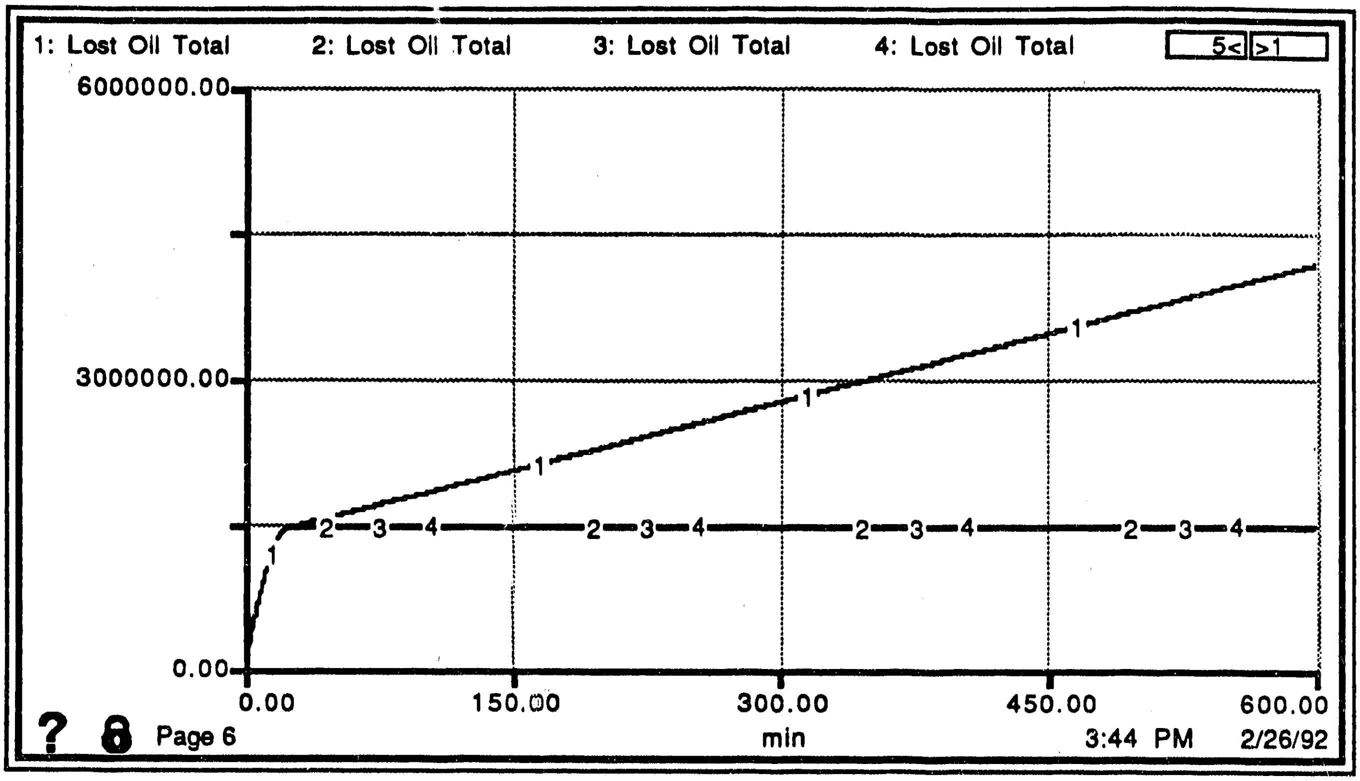

Setup #5 2/26/92 3:34 PM

## Input Variables

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 2.00 | 1.00 | 262000 |
| 2 | 2.00 | 1.00 | 262000 |
| 3 | 2.00 | 1.00 | 262000 |
| 4 | 2.00 | 1.00 | 262000 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 10.0 | 2.30 | 83.7 |
| 2 | 10.0 | 2.30 | 83.7 |
| 3 | 17.5 | 9.80 | 52.0 |
| 4 | 27.0 | 14.8 | 37.9 |

| Run # | Wave period | Td |
|---|---|---|
| 1 | 3.00 | 10000 |
| 2 | 3.00 | 25.0 |
| 3 | 6.00 | 25.0 |
| 4 | 8.00 | 25.0 |



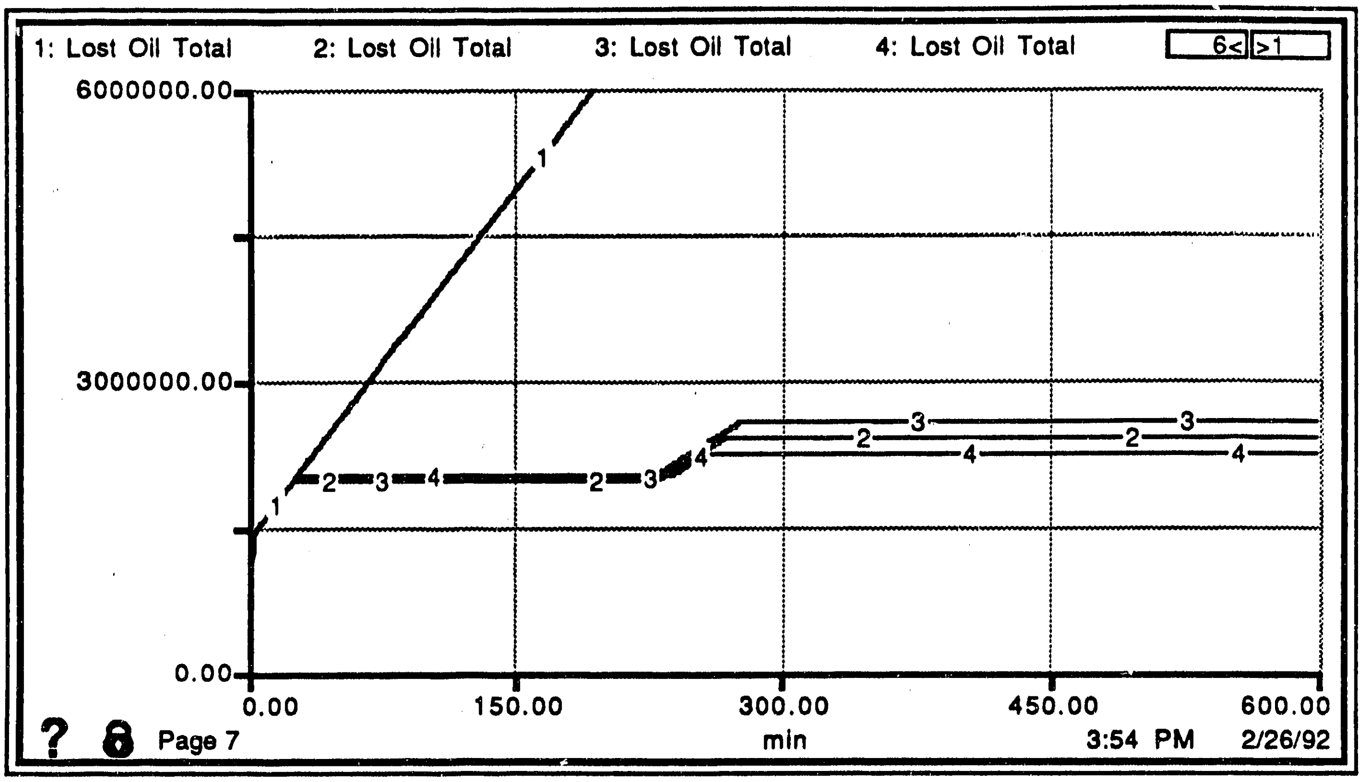

Setup #6 2/26/92 3:40 PM

**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 4.90 | 2.45 | 262000 |
| 2 | 4.90 | 2.45 | 262000 |
| 3 | 4.90 | 2.45 | 262000 |
| 4 | 4.90 | 2.45 | 262000 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 10.0 | 2.30 | 83.7 |
| 2 | 10.0 | 2.30 | 83.7 |
| 3 | 17.5 | 9.80 | 52.0 |
| 4 | 27.0 | 14.8 | 37.9 |

| Run # | Wave period | Td |
|---|---|---|
| 1 | 3.00 | 10000 |
| 2 | 3.00 | 25.0 |
| 3 | 6.00 | 25.0 |
| 4 | 8.00 | 25.0 |



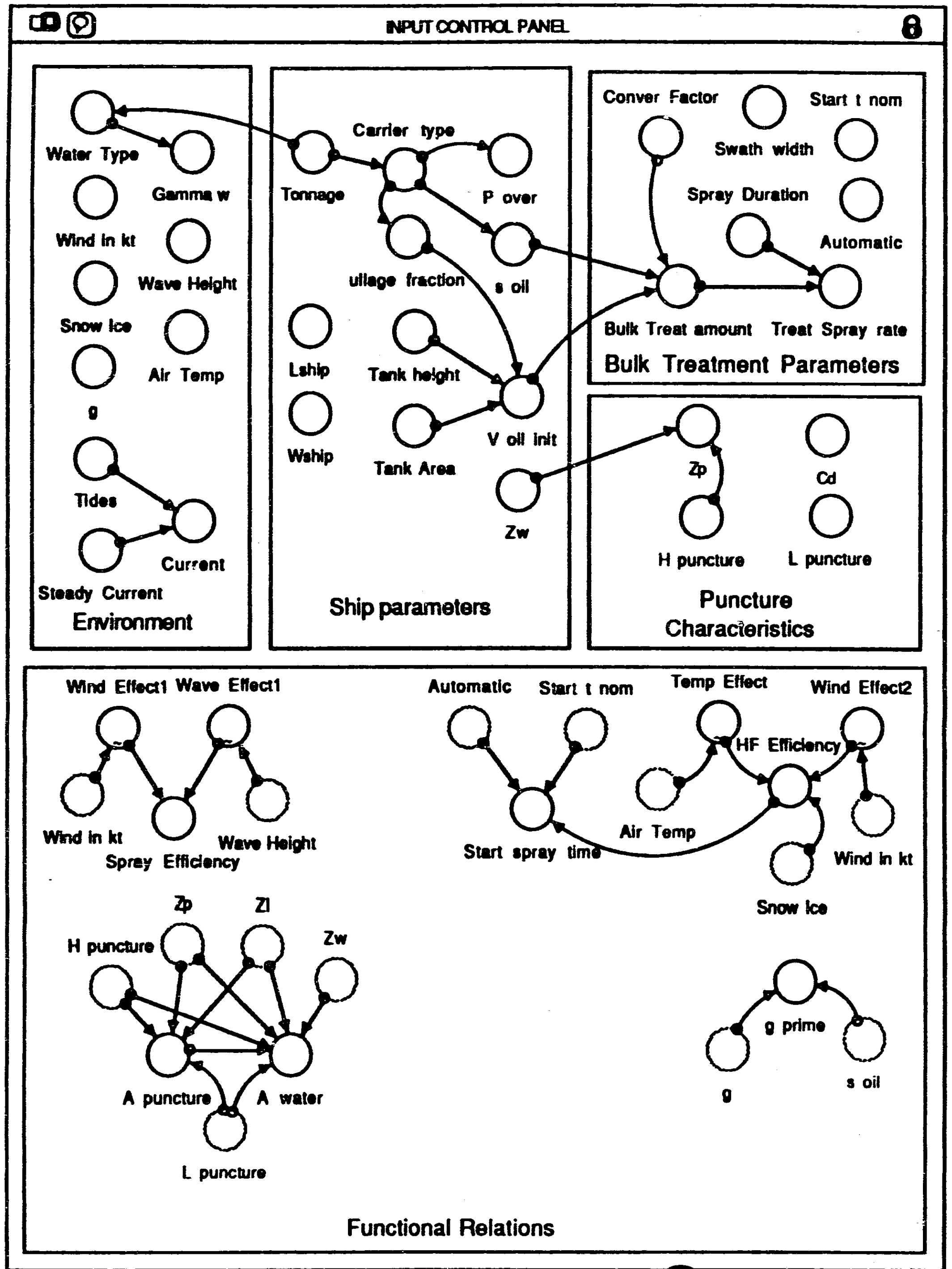

Setup #7 2/26/92 3:49 PM

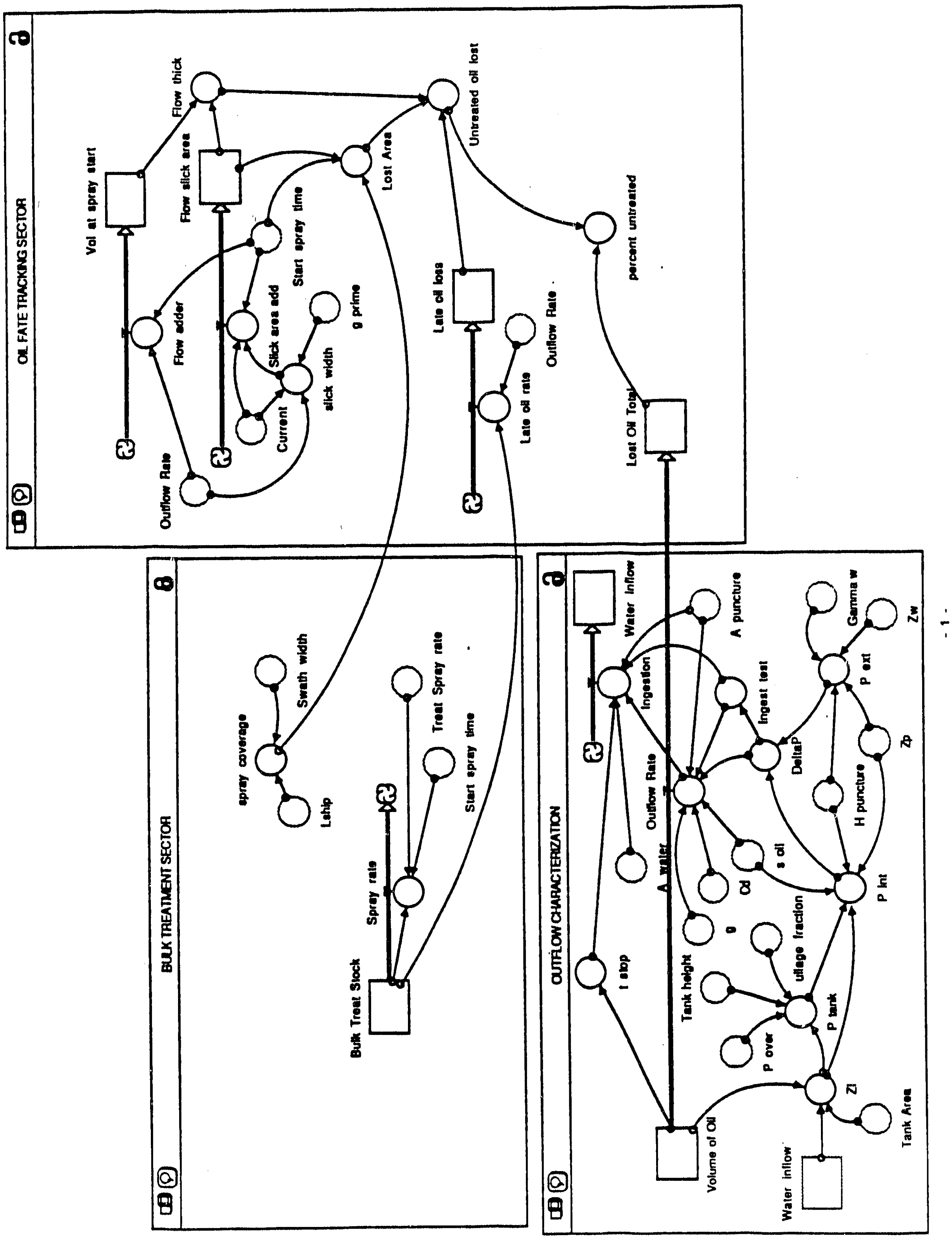
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 262000 |
| 2 | 12.0 | 6.00 | 262000 |
| 3 | 12.0 | 6.00 | 262000 |
| 4 | 12.0 | 6.00 | 262000 |

| Run # | Wind in kt | Wave Height | Air Temp |
|---|---|---|---|
| 1 | 10.0 | 2.30 | 83.7 |
| 2 | 10.0 | 2.30 | 83.7 |
| 3 | 17.5 | 9.80 | 52.0 |
| 4 | 27.0 | 14.8 | 37.9 |

| Run # | Wave period | Td |
|---|---|---|
| 1 | 3.00 | 10000 |
| 2 | 3.00 | 25.0 |
| 3 | 6.00 | 25.0 |
| 4 | 8.00 | 25.0 |


INPUT CONTROL PANEL
Water Type
Gamma w
Wind in kt
Wave Height
Snow Ice
Air Temp
g
Tides
Current
Steady Current
Environment
Carrier type
Tonnage
P over
ullage fraction
s oil
Lship
Tank height
V oil init
Wship
Tank Area
Zw
Ship parameters
Conver Factor
Start t nom
Swath width
Spray Duration
Automatic
Bulk Treat amount
Treat Spray rate
Bulk Treatment Parameters
Zp
Cd
H puncture
L puncture
Puncture Characteristics
Wind Effect1
Wave Effect1
Wind in kt
Wave Height
Spray Efficiency
Automatic
Start t nom
Start spray time
Temp Effect
Wind Effect2
HF Efficiency
Air Temp
Wind in kt
Snow Ice
Zp
Zl
Zw
H puncture
A puncture
A water
L puncture
g prime
g
s oil
Functional Relations



OIL FATE TRACKING SECTOR
Vol at spray start
Flow thick
Flow slick area
Lost Area
Untreated oil lost
Start spray time
percent untreated
Flow adder
Slick area add
g prime
slick width
Current
Outflow Rate
Late oil loss
Late oil rate
Outflow Rate
Lost Oil Total
BULK TREATMENT SECTOR
spray coverage
Swath width
Lship
Treat Spray rate
Start spray time
Spray rate
Bulk Treat Stock
OUTFLOW CHARACTERIZATION
Water Inflow
A puncture
Ingestion
Ingest test
Gamma w
P ext
Zw
Outflow Rate
DeltaP
Zp
H puncture
A water
Cd
s oil
P int
g
Tank height
ullage fraction
t stop
P tank
P over
Zl
Volume of Oil
Water inflow
Tank Area
- 1 -

**BULK TREATMENT SECTOR**
DOCUMENT:
Controls and dispenses the oil bulk treatment medium

☐ Bulk_Treat_Stock(t) = Bulk_Treat_Stock(t - dt) + (- Spray_rate) * dt
INIT Bulk_Treat_Stock = Bulk_Treat_amount{lbm of bulk treatment material needed to just neutralize the design spill of oil}
OUTFLOWS:
Spray_rate = IF (TIME > Start_spray_time) AND (Bulk_Treat_Stock > 0) THEN Treat_Spray_rate ELSE 0 {lbm/min}
○ spray_coverage = (Lship/2)*Swath_width {Spray coverage area, sf}

**INPUT CONTROL PANEL**
DOCUMENT:
Collects all input variables for the model

○ Air_Temp = 83.7 {air temp. deg F}
○ Automatic = 0 {Set = 1 for automatic triggering, set = 0 for crew operation.}
○ A_puncture = IF (Zl > Zp) THEN (L_puncture*H_puncture) ELSE (MAX (.01,((Zl - Zp + H_puncture)*L_puncture))) {Reference fluid flow area, sf. }
○ A_water = MAX (A_puncture/2, (Zw-Zl-(Zp-H_puncture)/2)*L_puncture) {Effective area of water backflow, sf}
○ Bulk_Treat_amount = (V_oil_Init/7.48)*(62.4*s_oil)/Conver_Factor {lbm of bulk treatment material needed to just neutralize the design spill of oil}
○ Carrier_type = IF (Tonnage ≥ 3400) THEN 1 ELSE 0 {0 means carrier is a barge; 1 means carrier is a tanker}
○ Cd = .61 {Oil discharge coefficient}
○ Conver_Factor = 50 {weight of oil rendered inert per dry weight of bulk treatment applied}
○ Current = Tides + Steady_Current {Net Current in fps}
○ g = 32.2 {fps^2}
○ Gamma_w = IF (Water_Type = 1) THEN 64 ELSE 62.4 { Establishes the weight density of the water of operation, pcf.}
○ g_prime = g*2*(64 - (s_oil*62.4))/(s_oil + 64) {Froude related reduced gravity constant}
○ HF_Efficiency = Temp_Effect*Wind_Effect2*Snow_Ice {Combined degradation effect of temperature, wind snow and ice on human performance on deck}
○ H_puncture = 4.9 {Height of puncture, ft.}
○ Lship = 666.75 {Length overall of ship, ft.}
○ L_puncture = 2.45 {Length of puncture, ft.}
○ P_over = IF (Carrier_type = 1) THEN 2 ELSE 0{Initial ullage overpressure, psi; set at 2 psig. for tankers and 0 psig. for barges}
○ Snow_Ice = 1 {Set expression to degradation factor (suggest .75) if snow or ice present, otherwise set to 1}
○ Spray_Duration = 360 {Pre-established elapsed time to spray all material, min.}
○ Spray_Efficiency = Wind_Effect1*Wave_Effect1{Performance degradation coefficient for combined action of wind and wave on bulk treatment by spraying}
○ Start_spray_time = IF (Automatic = 0) THEN Start_t_nom/HF_Efficiency ELSE Start_t_nom {Actual time needed to initiate spraying, min.}
○ Start_t_nom = 25 {Nominal time to start spraying, min. For triggering by officer of the deck, Tt = 5 min.; when a crew must deploy on deck, Tt = 25 min. nominal}
○ Steady_Current = .85 {Steady state current, fps}
○ Swath_width = 200 {Width of spray swath from side of ship, ft.}
○ s_oil = IF( Carrier_type = 1) THEN .86 ELSE .92 {specific gravity of cargo oil; =.86 for tankers (crude), or .92 for barges (diesel)}

○ Tank_Area = 2230.8 {Cross sectional area of cargo tank, sf.}
○ Tank_height = 50.7 {Height of tank, ft.}
○ Tides = 1.1 {Max tidal current, fps}
○ Tonnage = 34000 {DWT for tankers or GT for barges}
○ Treat_Spray_rate = Bulk_Treat_amount/Spray_Duration {lbm/min of bulk treatment spray, based on an estimated need to spray continuously for two hours}
○ ullage_fraction = IF (Carrier_type = 1) THEN .02 ELSE .05 {Fraction of tank height which is left as void above cargo; for barges = 5%, for tankers =2%}

○ V_oil_init = 7.48*(1-ullage_fraction)*Tank_height*Tank_Area {Initial volume of cargo in tank, gal}
○ Water_Type = IF (Tonnage ≥ 2713) THEN 1 ELSE 0 {1 means carrier operates in s/w; 0 in fresh water}
○ Wave_Height = 2.3 {significant wave height in ft.}
○ Wind_in_kt = 10 {Wind speed in kts.}
○ Wship = 84 {Width of ship at midsection, ft.}
○ Zp = Zw -.4 + H_puncture/2 {Height of top of puncture above bottom of tank in ft. (center of puncture set equal to the height of the water -0.3 ft. for worst-case side puncture analysis)}
○ Zw = 36 {Height of the waterline above the tank bottom, ft.}
⊘ Temp_Effect = GRAPH( Air_Temp{ Place right hand side of equation here... })
(-40.0, 0.2), (-32.0, 0.215), (-24.0, 0.24), (-16.0, 0.28), (-8.00, 0.33), (0.00, 0.42), (8.00, 0.53), (16.0, 0.665), (24.0, 0.825), (32.0, 0.955), (40.0, 1.00), (48.0, 1.00), (56.0, 1.00), (64.0, 1.00), (72.0, 1.00), (80.0, 1.00), (88.0, 1.00), (96.0, 0.93), (104, 0.82), (112, 0.7), (120, 0.53)
⊘ Wave_Effect1 = GRAPH(Wave_Height)
(0.00, 1.00), (1.00, 0.98), (2.00, 0.91), (3.00, 0.76), (4.00, 0.6), (5.00, 0.495), (6.00, 0.4), (7.00, 0.33), (8.00, 0.26), (9.00, 0.215), (10.0, 0.165), (11.0, 0.125), (12.0, 0.085)
⊘ Wind_Effect1 = GRAPH(Wind_in_kt)
(0.00, 1.00), (1.00, 1.00), (2.00, 1.00), (3.00, 1.00), (4.00, 1.00), (5.00, 0.99), (6.00, 0.96), (7.00, 0.915), (8.00, 0.875), (9.00, 0.815), (10.0, 0.755), (11.0, 0.695), (12.0, 0.615), (13.0, 0.535), (14.0, 0.435), (15.0, 0.35), (16.0, 0.245), (17.0, 0.125), (18.0, 0.00), (19.0, 0.00), (20.0, 0.00), (21.0, 0.00), (22.0, 0.00), (23.0, 0.00), (24.0, 0.00), (25.0, 0.00), (26.0, 0.00), (27.0, 0.00), (28.0, 0.00), (29.0, 0.00), (30.0, 0.00), (31.0, 0.00), (32.0, 0.00), (33.0, 0.00), (34.0, 0.00), (35.0, 0.00), (36.0, 0.00), (37.0, 0.00), (38.0, 0.00), (39.0, 0.00), (40.0, 0.00)
⊘ Wind_Effect2 = GRAPH( Wind_in_kt{ Place right hand side of equation here... })
(0.00, 1.00), (1.00, 1.00), (2.00, 1.00), (3.00, 1.00), (4.00, 1.00), (5.00, 1.00), (6.00, 1.00), (7.00, 1.00), (8.00, 1.00), (9.00, 1.00), (10.0, 1.00), (11.0, 1.00), (12.0, 1.00), (13.0, 1.00), (14.0, 1.00), (15.0, 1.00), (16.0, 1.00), (17.0, 1.00), (18.0, 1.00), (19.0, 1.00), (20.0, 1.00), (21.0, 1.00), (22.0, 1.00), (23.0, 1.00), (24.0, 1.00), (25.0, 0.99), (26.0, 0.96), (27.0, 0.905), (28.0, 0.82), (29.0, 0.715), (30.0, 0.585)

**OIL FATE TRACKING SECTOR**
DOCUMENT:
Provides total amounts (in gal.) of treated and untreated oil lost for each scenario.

□ Flow_slick_area(t) = Flow_slick_area(t - dt) + (Slick_area_add) * dt
INIT Flow_slick_area = 0{Cum area of slick, sf}
INFLOWS:
Slick_area_add = IF (TIME < Start_spray_time) THEN (slick_width*(Current*DT*60)) ELSE 0{Additional slick area added per time increment, sf}
□ Late_oil_loss(t) = Late_oil_loss(t - dt) + (Late_oil_rate) * dt
INIT Late_oil_loss = 0{Vol. of oil lost untreated after use of all bulk treatment, gal}
INFLOWS:
Late_oil_rate = IF (Bulk_Treat_Stock = 0) THEN Outflow_Rate ELSE 0 {Add'n untreated oil lost after all bulk treatment stock exhausted, gpm}

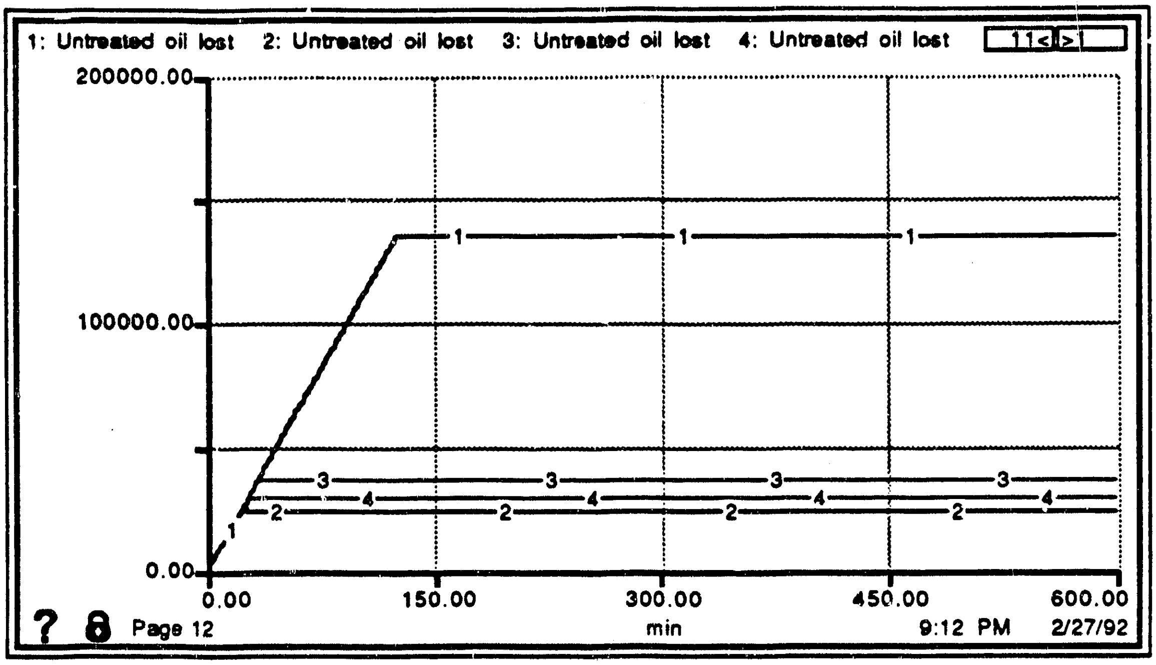
```
□ Lost_Oil_Total(t) = Lost_Oil_Total(t - dt) + (Outflow_Rate) * dt
    INIT Lost_Oil_Total =   0{ gal }
    INFLOWS:
      ⇝ Outflow_Rate (IN SECTOR: OUTFLOW CHARACTERIZATION)
□ Vol_at_spray_start(t) = Vol_at_spray_start(t - dt) + (Flow_adder) * dt
    INIT Vol_at_spray_start = 0 {Volume of oil in slick at time spraying starts, cf }
    INFLOWS:
      ⇝ Flow_adder =  IF (TIME < Start_spray_time) THEN (Outflow_Rate/(7.48)) ELSE 0 {rate of flow of oil, cf/min}
○ Flow_thick = Vol_at_spray_start/Flow_slick_area {Ave. thickness of slick, ft}
○ Lost_Area =  IF (TIME < Start_spray_time) THEN Flow_slick_area ELSE (Flow_slick_area - spray_coverage) {Area of slick which completely escapes
    any bulk treatment, sf}
○ percent_untreated =   (Untreated_oil_lost/Lost_Oil_Total)*100{ Place right hand side of equation here... }
○ slick_width = (1.5/2)*((2*g_prime*Outflow_Rate/(7.48*60*Current))^.33)*((60*TIME)^.66) {Width of slick in ft. as a function of time}
○ Untreated_oil_lost =   (Lost_Area*Flow_thick)*7.48 + Late_oil_loss {Volume of oil which completely escapes bulk treatment, gal}
```

**OUTFLOW CHARACTERIZATION**

DOCUMENT:

Describes the actual time history of the oil outflow for the selected carrier, casualty and environmental scenario.

```
□ Volume_of_Oil(t) = Volume_of_Oil(t - dt) + (- Outflow_Rate) * dt
    INIT Volume_of_Oil =   V_oil_init{gal.}
    OUTFLOWS:
      ⇝ Outflow_Rate = IF (Ingest_test = 1) THEN (60*7.48*Cd*(A_puncture/2)*s_oil*SQRT((2*g*DeltaP/(s_oil*62.4)))) ELSE
          (60*7.48*Cd*A_puncture*SQRT(2*g*DeltaP/(s_oil*62.4)))     {GPM}
□ Water_inflow(t) = Water_inflow(t - dt) + (Ingestion) * dt
    INIT Water_inflow =   0{Amount of water ingested back into tank, gal}
    INFLOWS:
      ⇝ Ingestion = IF (Ingest_test = 1) AND (t_stop ≠ 1) THEN (A_water*Outflow_Rate/(A_puncture/2)) ELSE 0 {Flow rate of water back into tank,
          GPM}
○ DeltaP =  IF ((P_int - P_ext) ≥ (.01*14.7*144)) THEN (P_int - P_ext) ELSE (.01*14.7*144)  {Sets driving pressure difference, psf.}
○ Ingest_test =  IF (DeltaP ≤ .01*14.7*144) THEN 1 ELSE 0 {Captures start of water ingestion back into ruptured tank}
○ P_ext = 14.7*144 + Gamma_w*(Zw - Zp + (H_puncture/2)){External pressure of water acting on puncture, psf (absolute)}
○ P_int =  P_tank + 62.4*s_oil*(Zl - Zp + (H_puncture/2)) {Internal pressure of the oil acting on the puncture, psf (absolute)}
○ P_tank =  MAX( 14.7*144, (144*((P_over + 14.7)*(ullage_fraction)/(1 - (Zl/Tank_height))))) {Over pressure as a function of ullage, psf. (absolute)}
○ t_stop =  IF (Volume_of_Oil ≥ 0) THEN 0 ELSE 1{Captures time at which all oil has flowed from the tank}
○ Zl = ((Volume_of_Oil + Water_inflow)/7.48)/Tank_Area {Height of oil above bottom, ft., including effect of backflowing water}
⇝ Outflow_Rate = IF (Ingest_test = 1) THEN (60*7.48*Cd*(A_puncture/2)*s_oil*SQRT((2*g*DeltaP/(s_oil*62.4)))) ELSE
    (60*7.48*Cd*A_puncture*SQRT(2*g*DeltaP/(s_oil*62.4)))     {GPM}
    OUTFLOW FROM:
    INFLOW TO: Lost_Oil_Total (IN SECTOR: OIL FATE TRACKING SECTOR)
```




Setup #13 2/27/92 9:11 PM

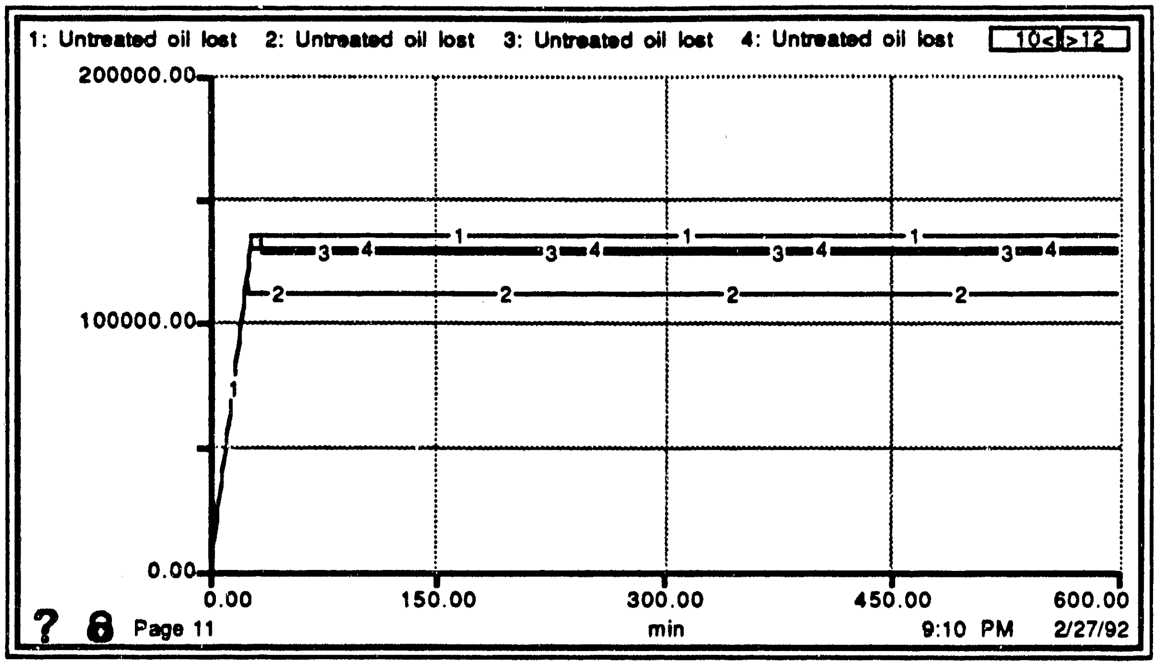
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 2.00 | 1.00 | 628 |
| 2 | 2.00 | 1.00 | 628 |
| 3 | 2.00 | 1.00 | 628 |
| 4 | 2.00 | 1.00 | 628 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 8.20 | 0.4 | 1.10 |
| 2 | 8.20 | 0.4 | 0.00 |
| 3 | 13.4 | 0.66 | 0.00 |
| 4 | 13.4 | 7.80 | 0.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 1.60 | 1.00 | 70.7 |
| 2 | 1.60 | 1.00 | 70.7 |
| 3 | 3.60 | 0.75 | 36.1 |
| 4 | 1.60 | 1.00 | 32.5 |

| Run # | Start t nom | Spray Duration |
|---|---|---|
| 1 | 10000 | 360 |
| 2 | 25.0 | 360 |
| 3 | 25.0 | 360 |
| 4 | 25.0 | 360 |




Setup #12 2/27/92 9:08 PM

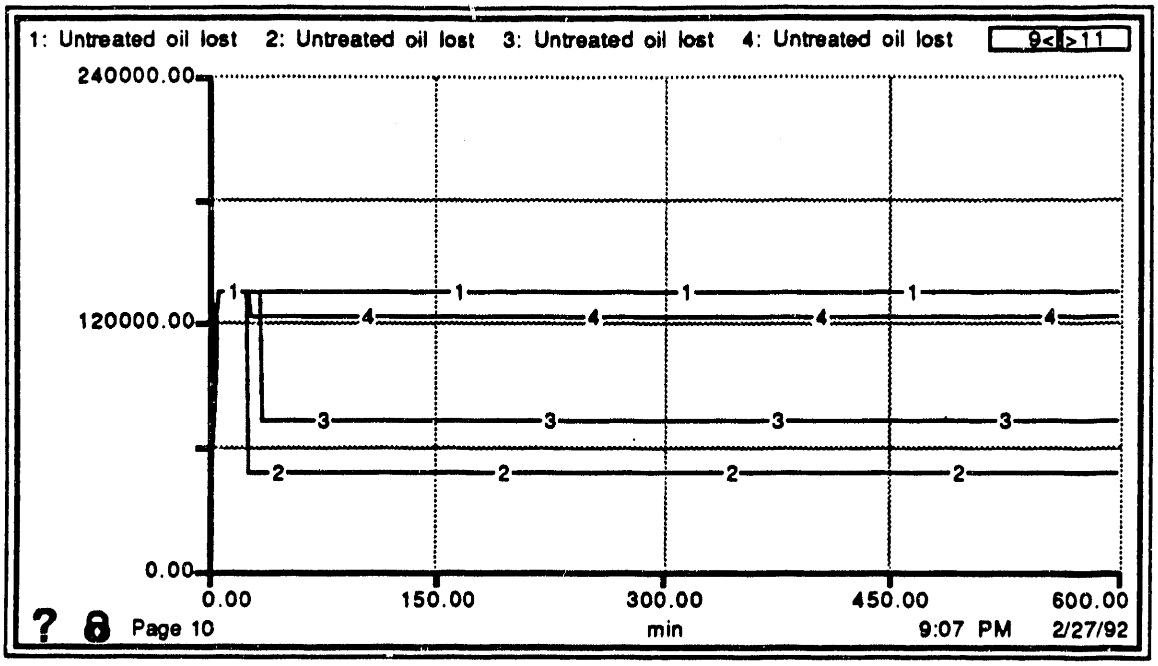
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 4.90 | 2.45 | 628 |
| 2 | 4.90 | 2.45 | 628 |
| 3 | 4.90 | 2.45 | 628 |
| 4 | 4.90 | 2.45 | 628 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 8.20 | 0.4 | 1.10 |
| 2 | 8.20 | 0.4 | 0.00 |
| 3 | 13.4 | 0.66 | 0.00 |
| 4 | 13.4 | 7.80 | 0.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 1.60 | 1.00 | 70.7 |
| 2 | 1.60 | 1.00 | 70.7 |
| 3 | 3.60 | 0.75 | 36.1 |
| 4 | 1.60 | 1.00 | 32.5 |

| Run # | Start t nom | Spray Duration |
|---|---|---|
| 1 | 10000 | 360 |
| 2 | 25.0 | 360 |
| 3 | 25.0 | 360 |
| 4 | 25.0 | 360 |




Setup #11 2/27/92 9:04 PM

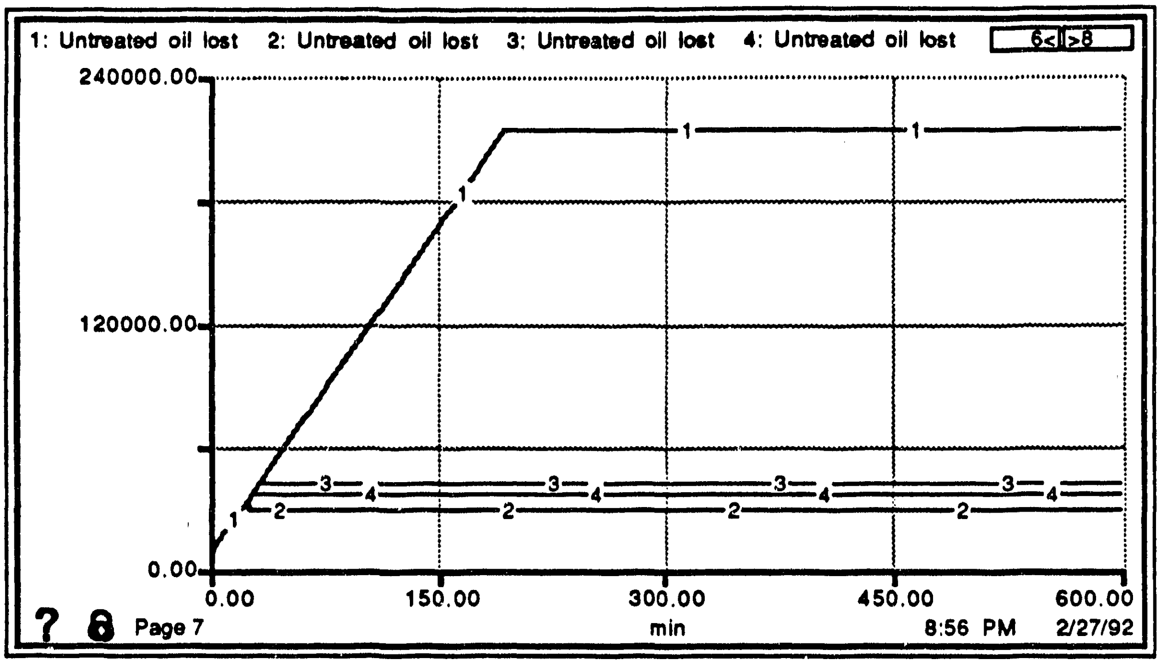
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 628 |
| 2 | 12.0 | 6.00 | 628 |
| 3 | 12.0 | 6.00 | 628 |
| 4 | 12.0 | 6.00 | 628 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 8.20 | 0.4 | 1.10 |
| 2 | 8.20 | 0.4 | 0.00 |
| 3 | 13.4 | 0.66 | 0.00 |
| 4 | 13.4 | 7.80 | 0.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 1.60 | 1.00 | 70.7 |
| 2 | 1.60 | 1.00 | 70.7 |
| 3 | 3.60 | 0.75 | 36.1 |
| 4 | 1.60 | 1.00 | 32.5 |

| Run # | Start t nom | Spray Duration |
|---|---|---|
| 1 | 10000 | 360 |
| 2 | 25.0 | 360 |
| 3 | 25.0 | 360 |
| 4 | 25.0 | 360 |




Setup #8 2/27/92 8:53 PM

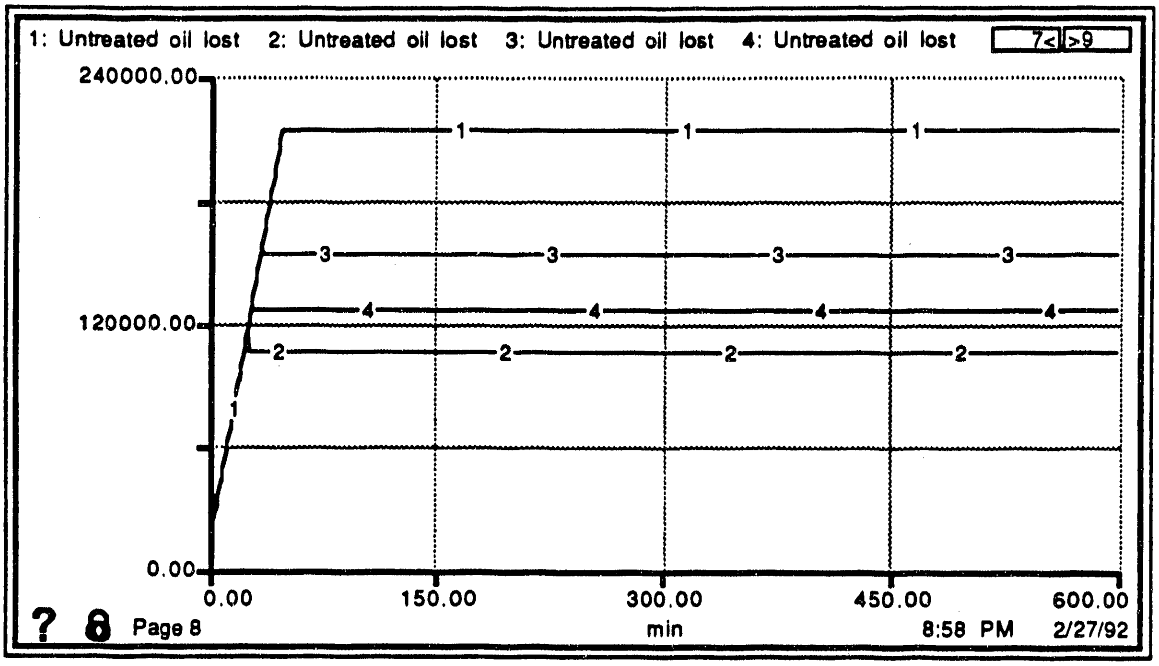
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 2.00 | 1.00 | 1182 |
| 2 | 2.00 | 1.00 | 1182 |
| 3 | 2.00 | 1.00 | 1182 |
| 4 | 2.00 | 1.00 | 1182 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 8.20 | 0.4 | 1.10 |
| 2 | 8.20 | 0.4 | 0.00 |
| 3 | 13.4 | 0.66 | 0.00 |
| 4 | 13.4 | 7.80 | 0.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 1.60 | 1.00 | 70.7 |
| 2 | 1.60 | 1.00 | 70.7 |
| 3 | 3.60 | 0.75 | 36.1 |
| 4 | 1.60 | 1.00 | 32.5 |

| Run # | Start t nom | Spray Duration |
|---|---|---|
| 1 | 10000 | 360 |
| 2 | 25.0 | 360 |
| 3 | 25.0 | 360 |
| 4 | 25.0 | 360 |




Setup #9 2/27/92 8:56 PM

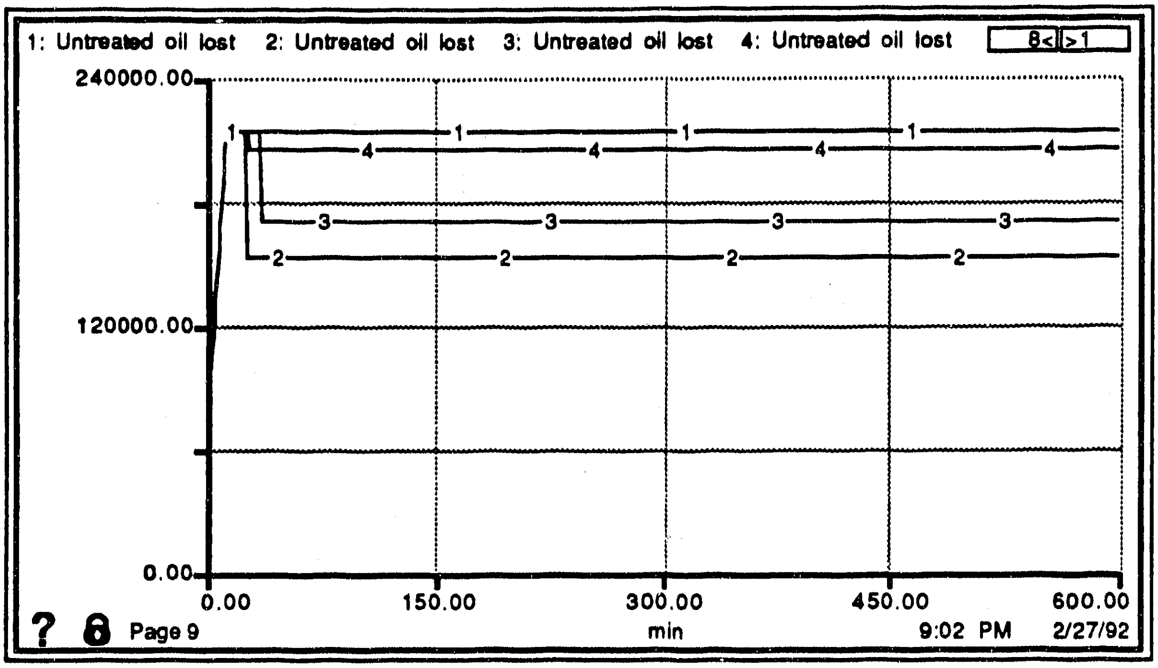
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 4.90 | 2.45 | 1182 |
| 2 | 4.90 | 2.45 | 1182 |
| 3 | 4.90 | 2.45 | 1182 |
| 4 | 4.90 | 2.45 | 1182 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 8.20 | 0.4 | 1.10 |
| 2 | 8.20 | 0.4 | 0.00 |
| 3 | 13.4 | 0.66 | 0.00 |
| 4 | 13.4 | 7.80 | 0.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 1.60 | 1.00 | 70.7 |
| 2 | 1.60 | 1.00 | 70.7 |
| 3 | 3.60 | 0.75 | 36.1 |
| 4 | 1.60 | 1.00 | 32.5 |

| Run # | Start t nom | Spray Duration |
|---|---|---|
| 1 | 10000 | 360 |
| 2 | 25.0 | 360 |
| 3 | 25.0 | 360 |
| 4 | 25.0 | 360 |




Setup #10 2/27/92 9:01 PM

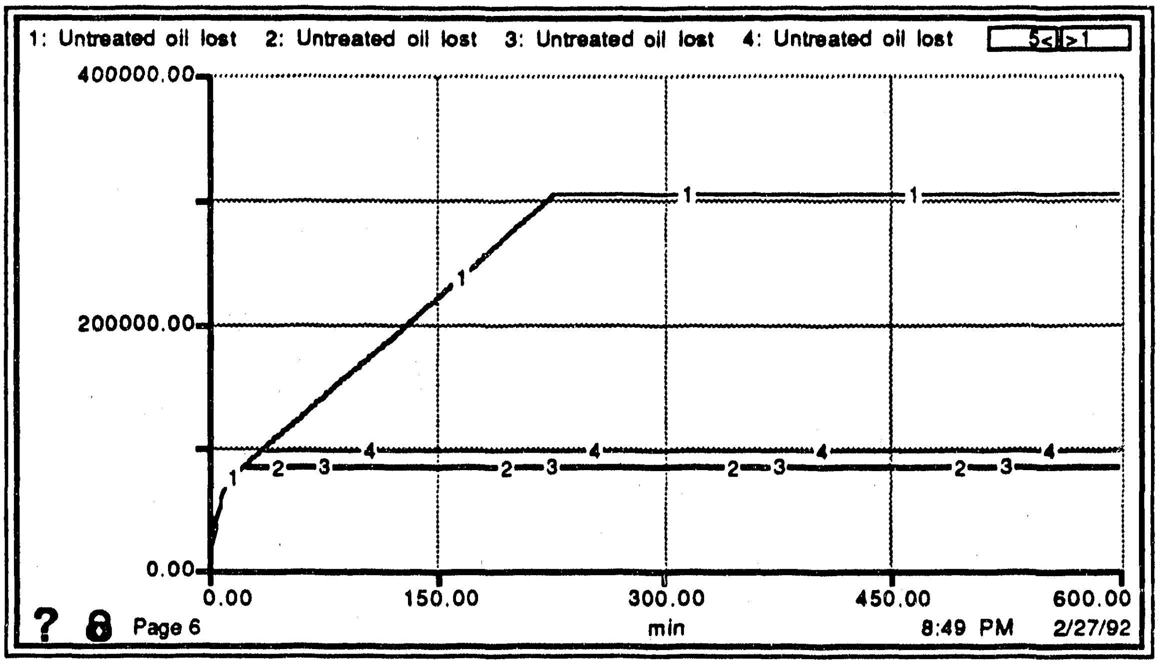
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 1182 |
| 2 | 12.0 | 6.00 | 1182 |
| 3 | 12.0 | 6.00 | 1182 |
| 4 | 12.0 | 6.00 | 1182 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 8.20 | 0.4 | 1.10 |
| 2 | 8.20 | 0.4 | 0.00 |
| 3 | 13.4 | 0.66 | 0.00 |
| 4 | 13.4 | 7.80 | 0.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 1.60 | 1.00 | 70.7 |
| 2 | 1.60 | 1.00 | 70.7 |
| 3 | 3.60 | 0.75 | 36.1 |
| 4 | 1.60 | 1.00 | 32.5 |

| Run # | Start t nom | Spray Duration |
|---|---|---|
| 1 | 10000 | 360 |
| 2 | 25.0 | 360 |
| 3 | 25.0 | 360 |
| 4 | 25.0 | 360 |




Setup #7 2/27/92 8:48 PM

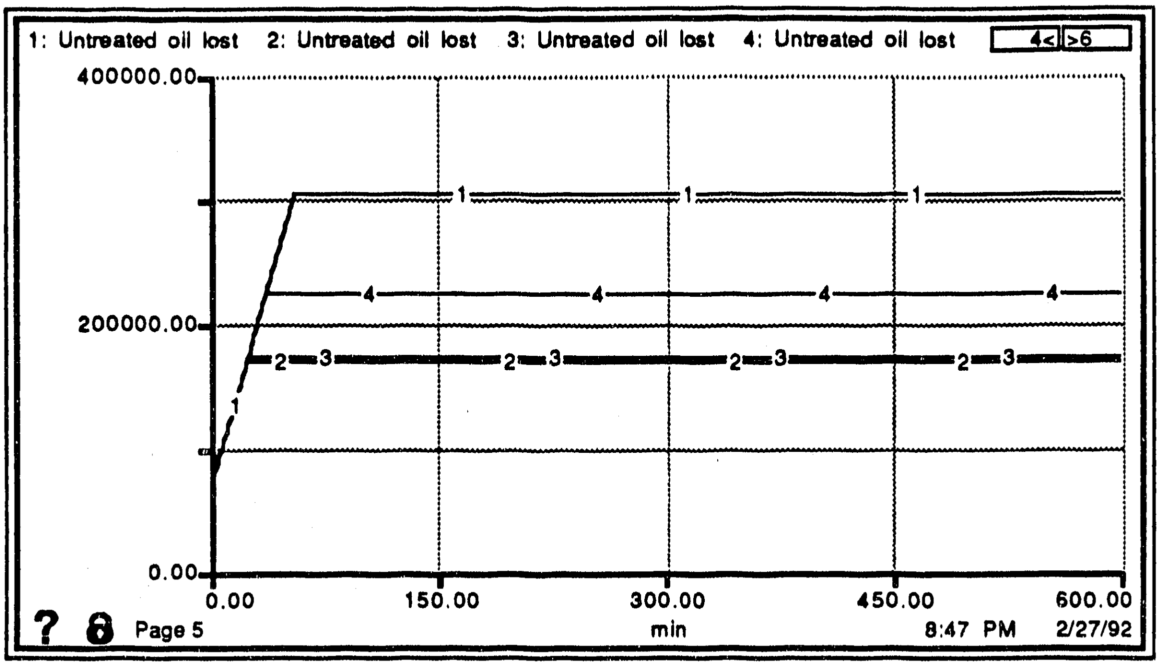
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 2.00 | 1.00 | 2713 |
| 2 | 2.00 | 1.00 | 2713 |
| 3 | 2.00 | 1.00 | 2713 |
| 4 | 2.00 | 1.00 | 2713 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 2.30 | 1.00 | 83.7 |
| 2 | 2.30 | 1.00 | 83.7 |
| 3 | 9.80 | 1.00 | 52.0 |
| 4 | 14.8 | 0.75 | 37.9 |

| Run # | Start t nom | Spray Duration |
|---|---|---|
| 1 | 10000 | 360 |
| 2 | 25.0 | 360 |
| 3 | 25.0 | 360 |
| 4 | 25.0 | 360 |




Setup #6 2/27/92 8:45 PM

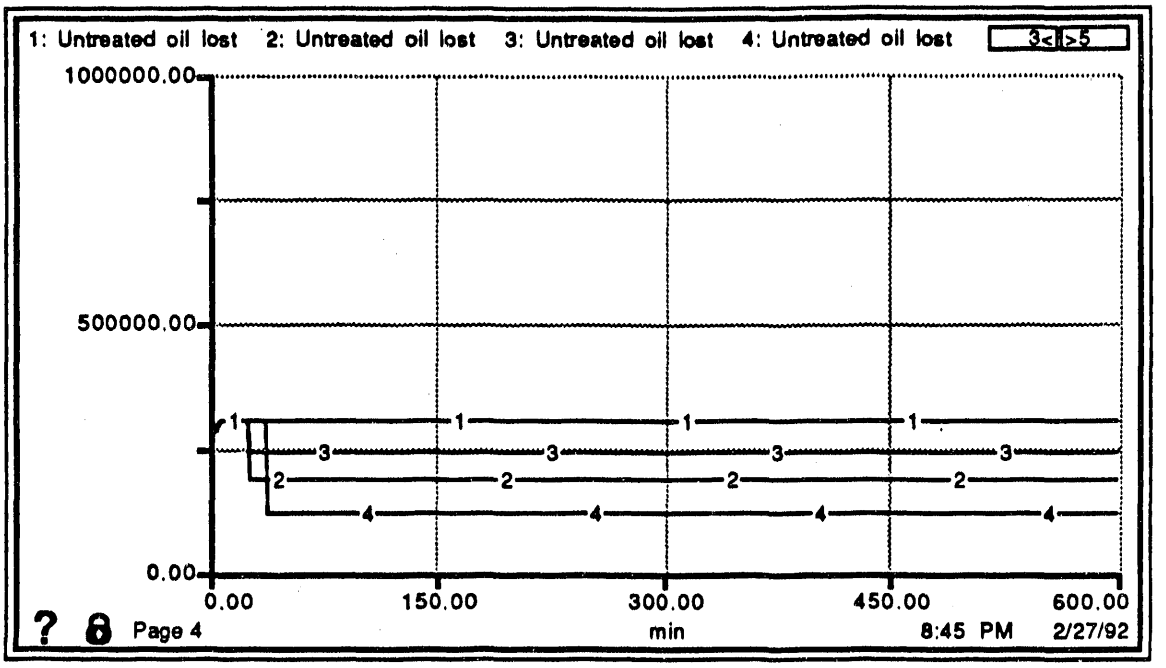
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 4.90 | 2.45 | 2713 |
| 2 | 4.90 | 2.45 | 2713 |
| 3 | 4.90 | 2.45 | 2713 |
| 4 | 4.90 | 2.45 | 2713 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 2.30 | 1.00 | 83.7 |
| 2 | 2.30 | 1.00 | 83.7 |
| 3 | 9.80 | 1.00 | 52.0 |
| 4 | 14.8 | 0.75 | 37.9 |

| Run # | Start t nom | Spray Duration |
|---|---|---|
| 1 | 10000 | 360 |
| 2 | 25.0 | 360 |
| 3 | 25.0 | 360 |
| 4 | 25.0 | 360 |




Setup #5 2/27/92 8:42 PM

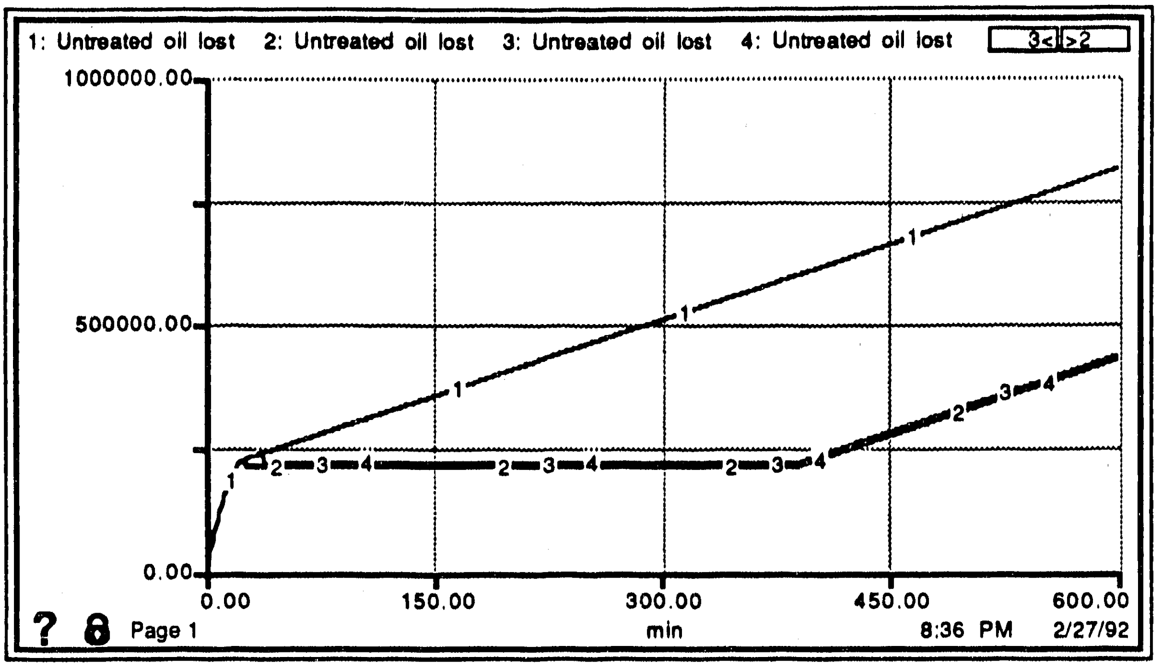
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 2713 |
| 2 | 12.0 | 6.00 | 2713 |
| 3 | 12.0 | 6.00 | 2713 |
| 4 | 12.0 | 6.00 | 2713 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 2.30 | 1.00 | 83.7 |
| 2 | 2.30 | 1.00 | 83.7 |
| 3 | 9.80 | 1.00 | 52.0 |
| 4 | 14.8 | 0.75 | 37.9 |

| Run # | Start t nom | Spray Duration |
|---|---|---|
| 1 | 10000 | 360 |
| 2 | 25.0 | 360 |
| 3 | 25.0 | 360 |
| 4 | 25.0 | 360 |




Setup #2 2/27/92 8:34 PM

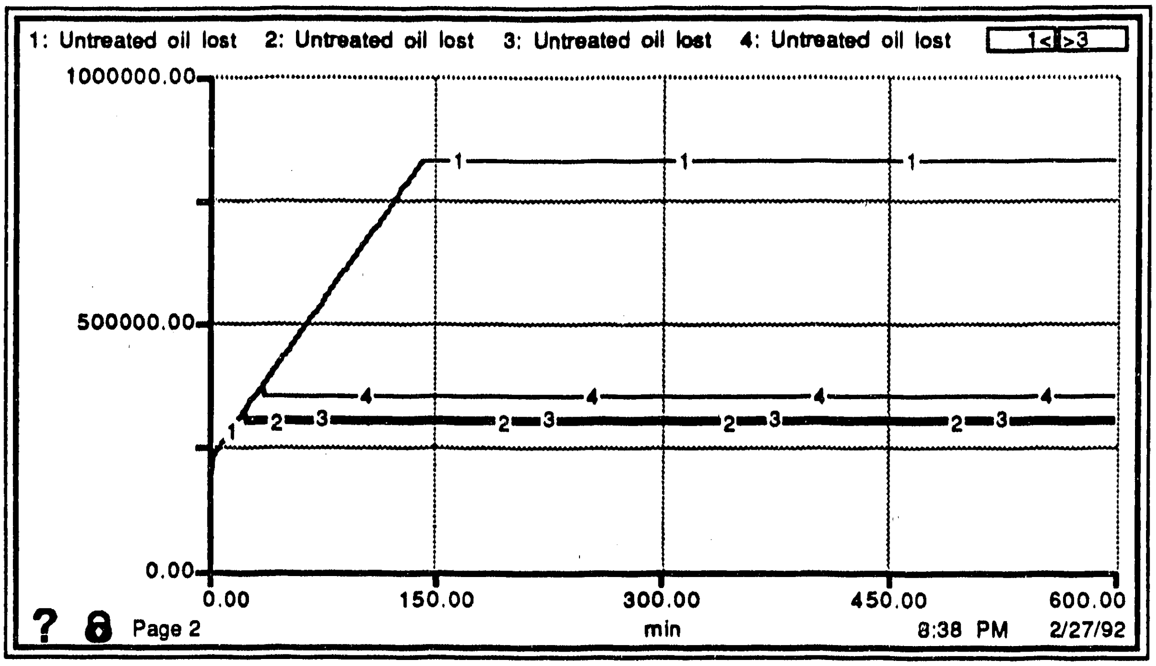
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 2.00 | 1.00 | 34000 |
| 2 | 2.00 | 1.00 | 34000 |
| 3 | 2.00 | 1.00 | 34000 |
| 4 | 2.00 | 1.00 | 34000 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 2.30 | 1.00 | 83.7 |
| 2 | 2.30 | 1.00 | 83.7 |
| 3 | 9.80 | 1.00 | 52.0 |
| 4 | 14.8 | 0.75 | 37.9 |

| Run # | Start t nom | Spray Duration |
|---|---|---|
| 1 | 10000 | 360 |
| 2 | 25.0 | 360 |
| 3 | 25.0 | 360 |
| 4 | 25.0 | 360 |




Setup #3 2/27/92 8:36 PM

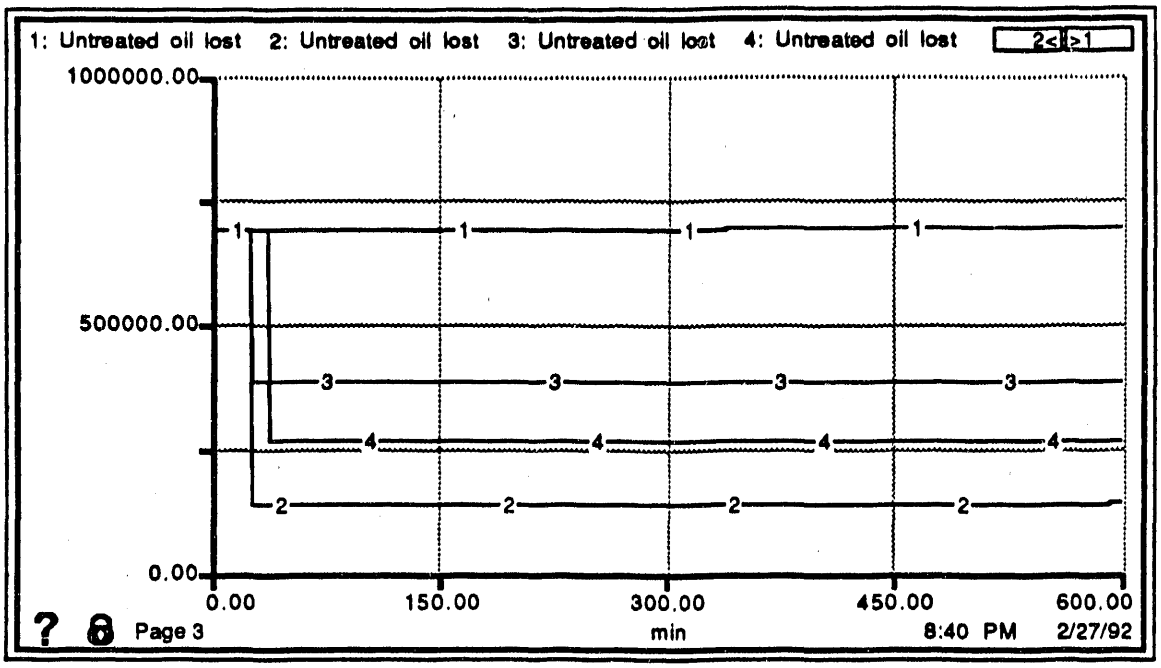
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 4.90 | 2.45 | 34000 |
| 2 | 4.90 | 2.45 | 34000 |
| 3 | 4.90 | 2.45 | 34000 |
| 4 | 4.90 | 2.45 | 34000 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 2.30 | 1.00 | 83.7 |
| 2 | 2.30 | 1.00 | 83.7 |
| 3 | 9.80 | 1.00 | 52.0 |
| 4 | 14.8 | 0.75 | 37.9 |

| Run # | Start t nom | Spray Duration |
|---|---|---|
| 1 | 10000 | 360 |
| 2 | 25.0 | 360 |
| 3 | 25.0 | 360 |
| 4 | 25.0 | 360 |




**Setup #4** 2/27/92 8:38 PM

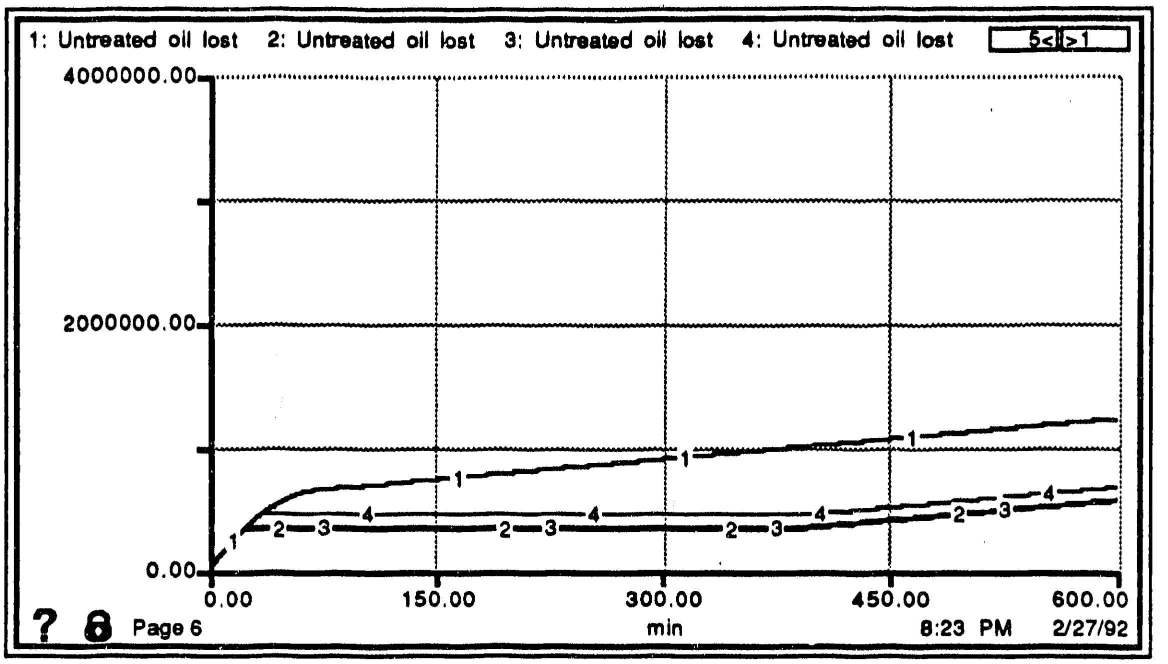
### Input Variables

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 34000 |
| 2 | 12.0 | 6.00 | 34000 |
| 3 | 12.0 | 6.00 | 34000 |
| 4 | 12.0 | 6.00 | 34000 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 2.30 | 1.00 | 83.7 |
| 2 | 2.30 | 1.00 | 83.7 |
| 3 | 9.80 | 1.00 | 52.0 |
| 4 | 14.8 | 0.75 | 37.9 |

| Run # | Start t nom | Spray Duration |
|---|---|---|
| 1 | 10000 | 360 |
| 2 | 25.0 | 360 |
| 3 | 25.0 | 360 |
| 4 | 25.0 | 360 |




Setup #7 2/27/92 8:21 PM

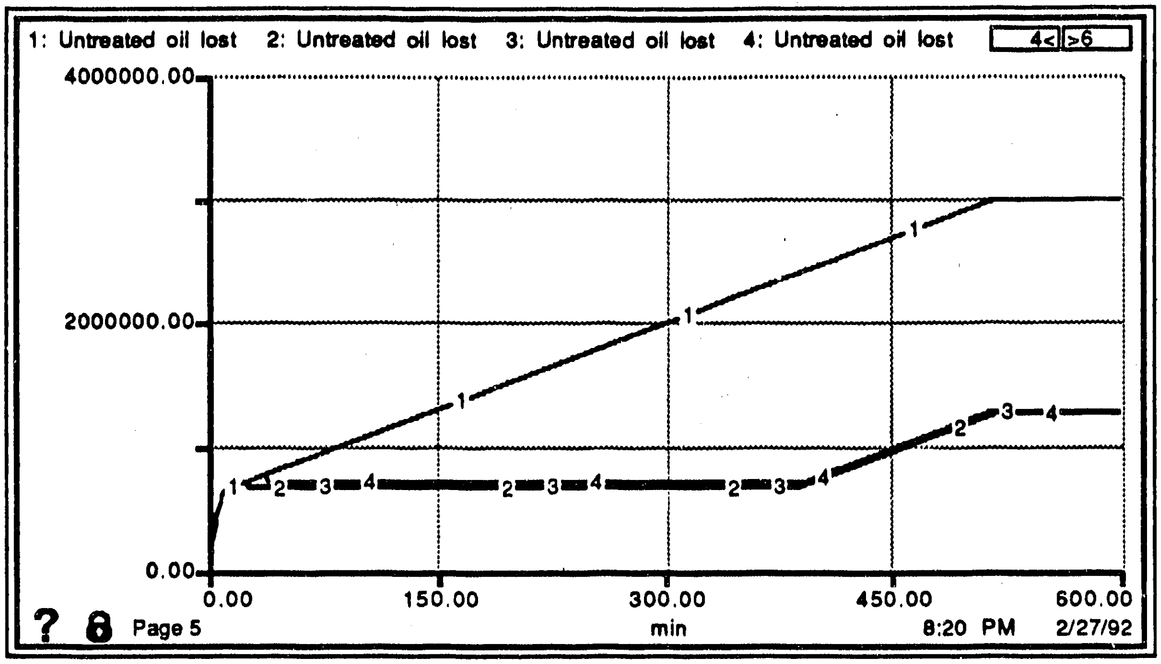
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 2.00 | 1.00 | 89700 |
| 2 | 2.00 | 1.00 | 89700 |
| 3 | 2.00 | 1.00 | 89700 |
| 4 | 2.00 | 1.00 | 89700 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 2.30 | 1.00 | 83.7 |
| 2 | 2.30 | 1.00 | 83.7 |
| 3 | 9.80 | 1.00 | 52.0 |
| 4 | 14.8 | 0.75 | 37.9 |

| Run # | Start t nom | Spray Duration |
|---|---|---|
| 1 | 10000 | 360 |
| 2 | 25.0 | 360 |
| 3 | 25.0 | 360 |
| 4 | 25.0 | 360 |




Setup #6 2/27/92 8:19 PM

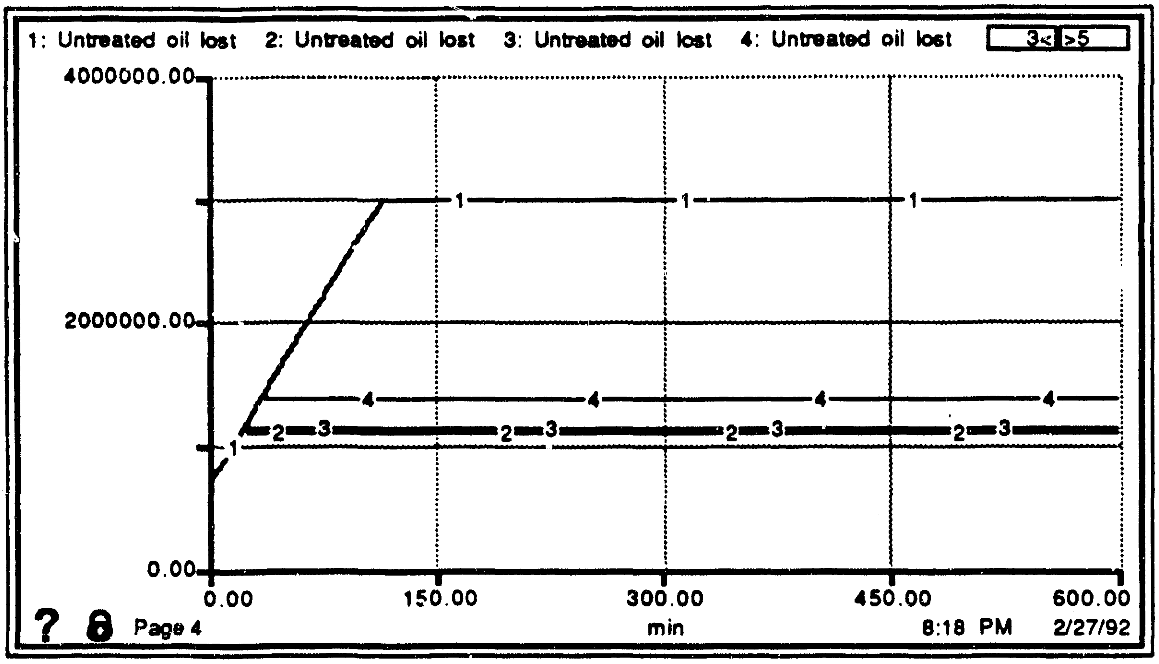
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 4.90 | 2.45 | 89700 |
| 2 | 4.90 | 2.45 | 89700 |
| 3 | 4.90 | 2.45 | 89700 |
| 4 | 4.90 | 2.45 | 89700 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 2.30 | 1.00 | 83.7 |
| 2 | 2.30 | 1.00 | 83.7 |
| 3 | 9.80 | 1.00 | 52.0 |
| 4 | 14.8 | 0.75 | 37.9 |

| Run # | Start t nom | Spray Duration |
|---|---|---|
| 1 | 10000 | 360 |
| 2 | 25.0 | 360 |
| 3 | 25.0 | 360 |
| 4 | 25.0 | 360 |




Setup #5 2/27/92 8:15 PM

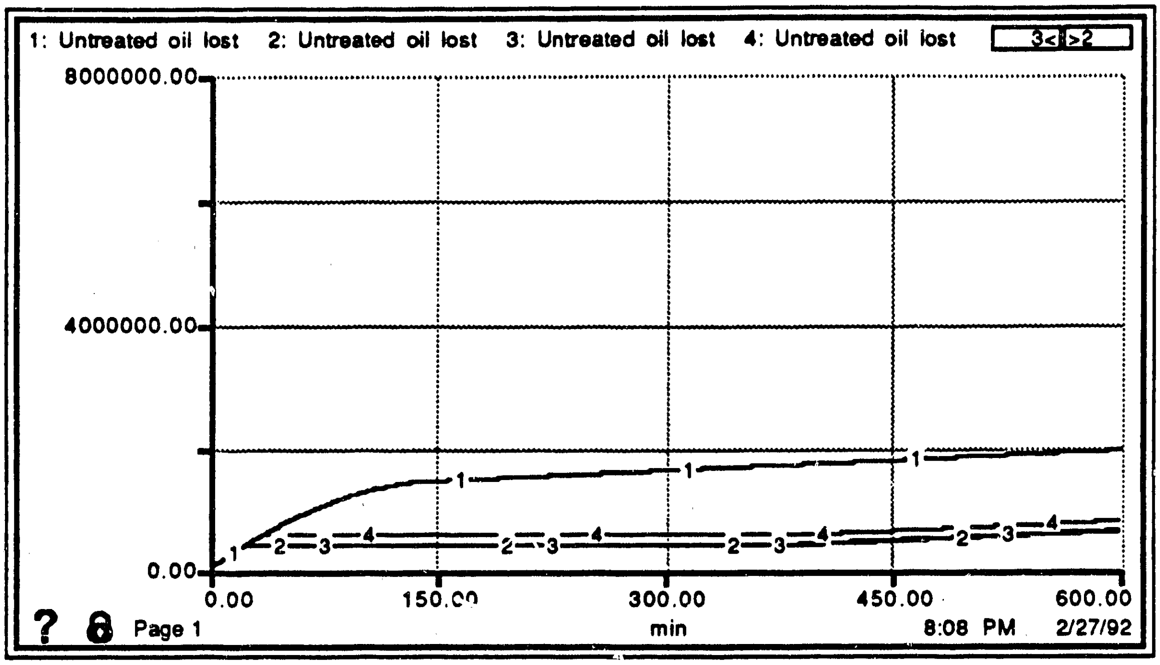
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 89700 |
| 2 | 12.0 | 6.00 | 89700 |
| 3 | 12.0 | 6.00 | 89700 |
| 4 | 12.0 | 6.00 | 89700 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 2.30 | 1.00 | 83.7 |
| 2 | 2.30 | 1.00 | 83.7 |
| 3 | 9.80 | 1.00 | 52.0 |
| 4 | 14.8 | 0.75 | 37.9 |

| Run # | Start t nom | Spray Duration |
|---|---|---|
| 1 | 10000 | 360 |
| 2 | 25.0 | 360 |
| 3 | 25.0 | 360 |
| 4 | 25.0 | 360 |




Setup #2 2/27/92 8:07 PM

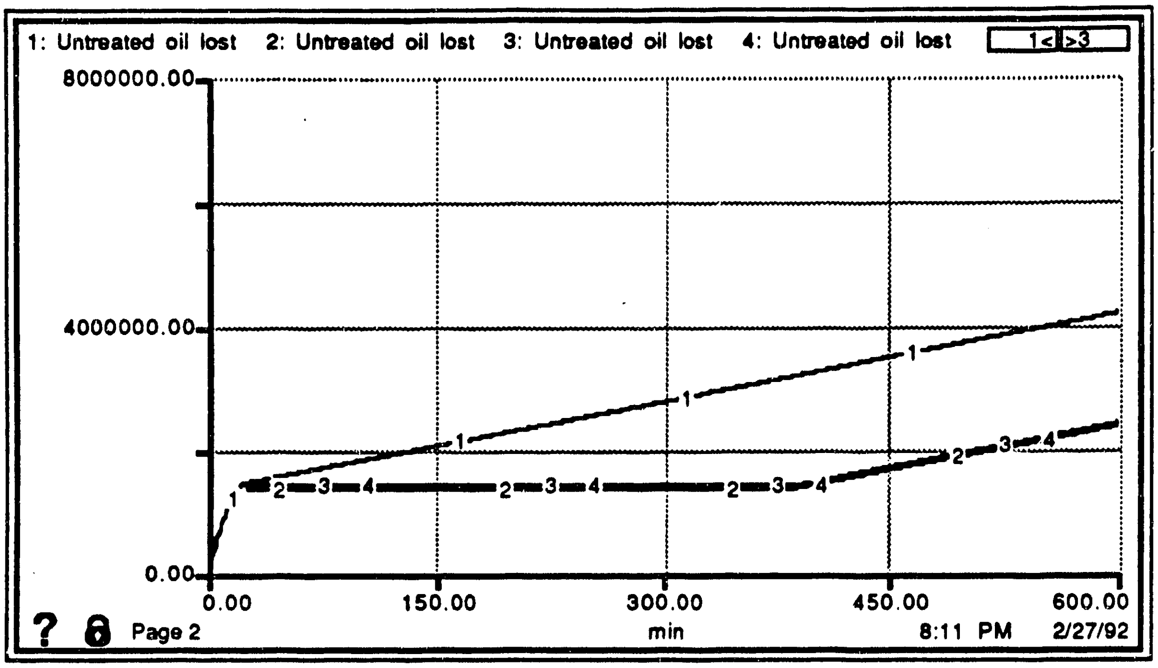
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 2.00 | 1.00 | 262000 |
| 2 | 2.00 | 1.00 | 262000 |
| 3 | 2.00 | 1.00 | 262000 |
| 4 | 2.00 | 1.00 | 262000 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 2.30 | 1.00 | 83.7 |
| 2 | 2.30 | 1.00 | 83.7 |
| 3 | 9.80 | 1.00 | 52.0 |
| 4 | 14.8 | 0.75 | 37.9 |

| Run # | Start t nom | Spray Duration |
|---|---|---|
| 1 | 10000 | 360 |
| 2 | 25.0 | 360 |
| 3 | 25.0 | 360 |
| 4 | 25.0 | 360 |




Setup #3 2/27/92 8:09 PM

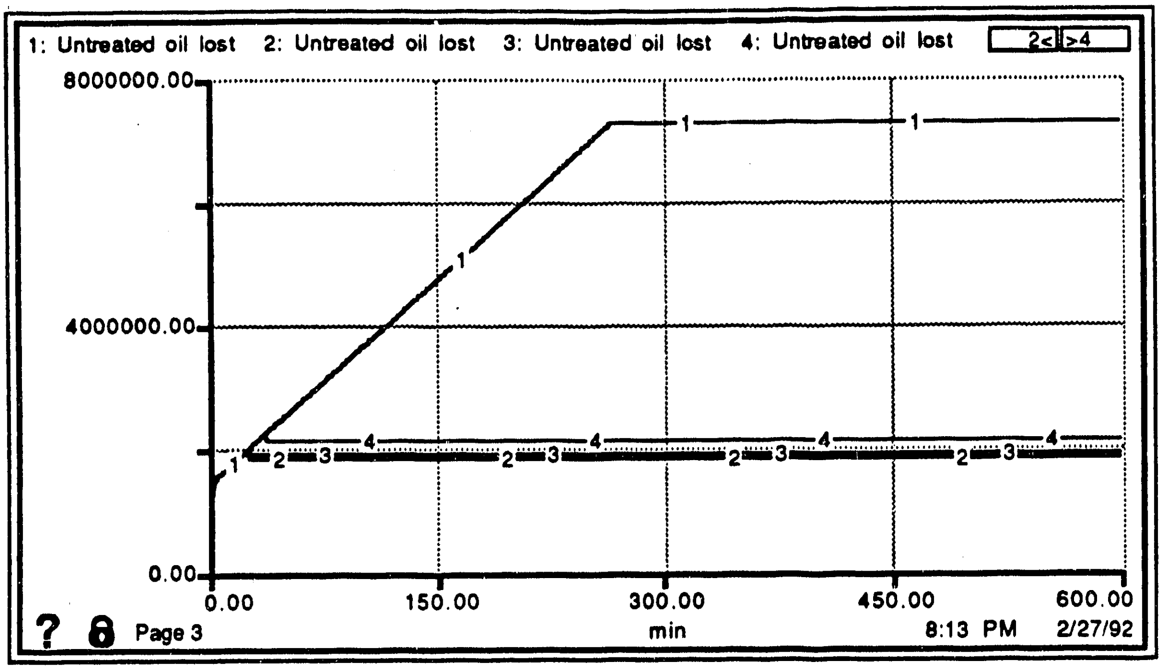
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 4.90 | 2.45 | 262000 |
| 2 | 4.90 | 2.45 | 262000 |
| 3 | 4.90 | 2.45 | 262000 |
| 4 | 4.90 | 2.45 | 262000 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 2.30 | 1.00 | 83.7 |
| 2 | 2.30 | 1.00 | 83.7 |
| 3 | 9.80 | 1.00 | 52.0 |
| 4 | 14.8 | 0.75 | 37.9 |

| Run # | Start t nom | Spray Duration |
|---|---|---|
| 1 | 10000 | 360 |
| 2 | 25.0 | 360 |
| 3 | 25.0 | 360 |
| 4 | 25.0 | 360 |




Setup #4 2/27/92 8:11 PM

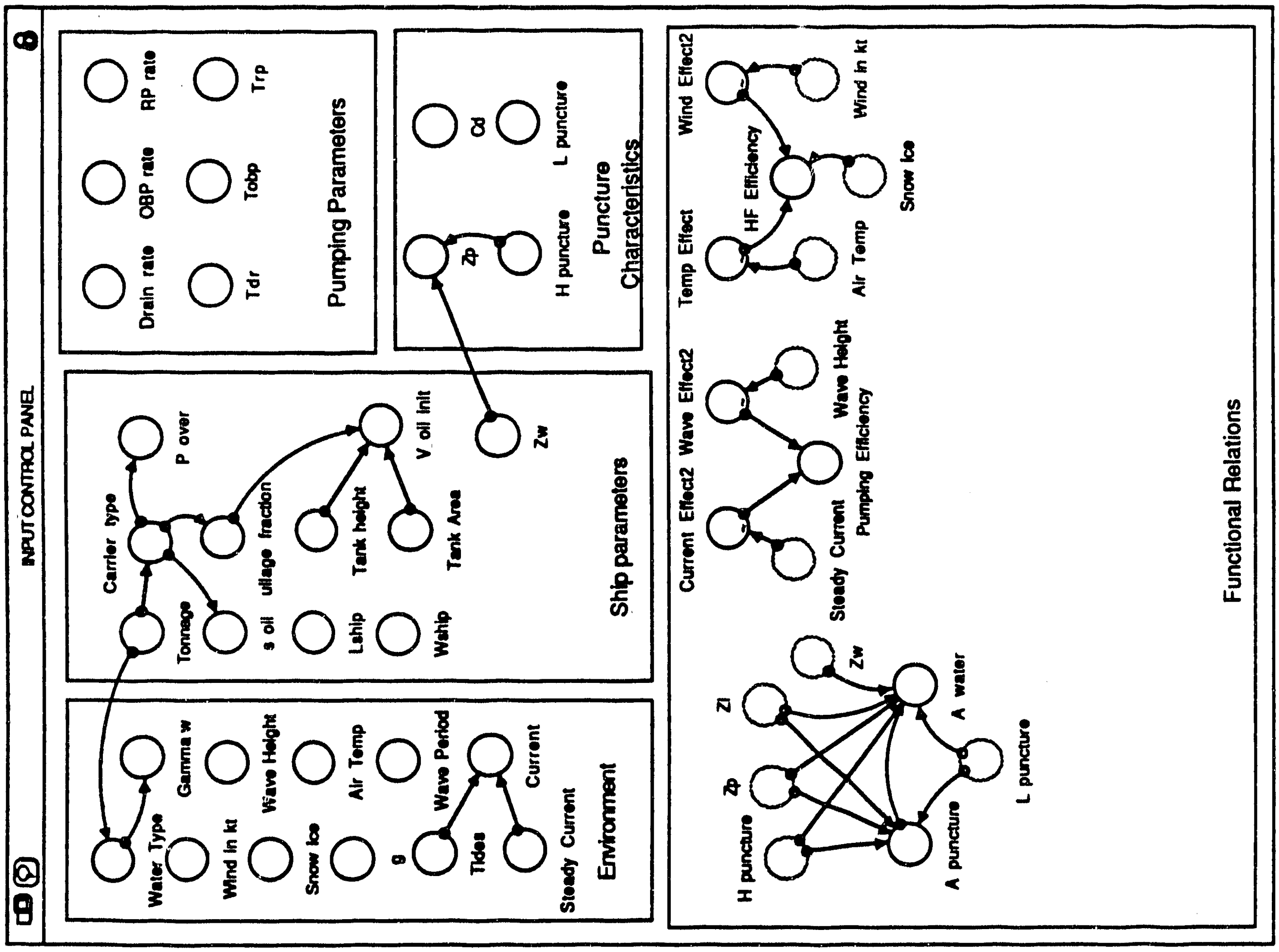
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 262000 |
| 2 | 12.0 | 6.00 | 262000 |
| 3 | 12.0 | 6.00 | 262000 |
| 4 | 12.0 | 6.00 | 262000 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

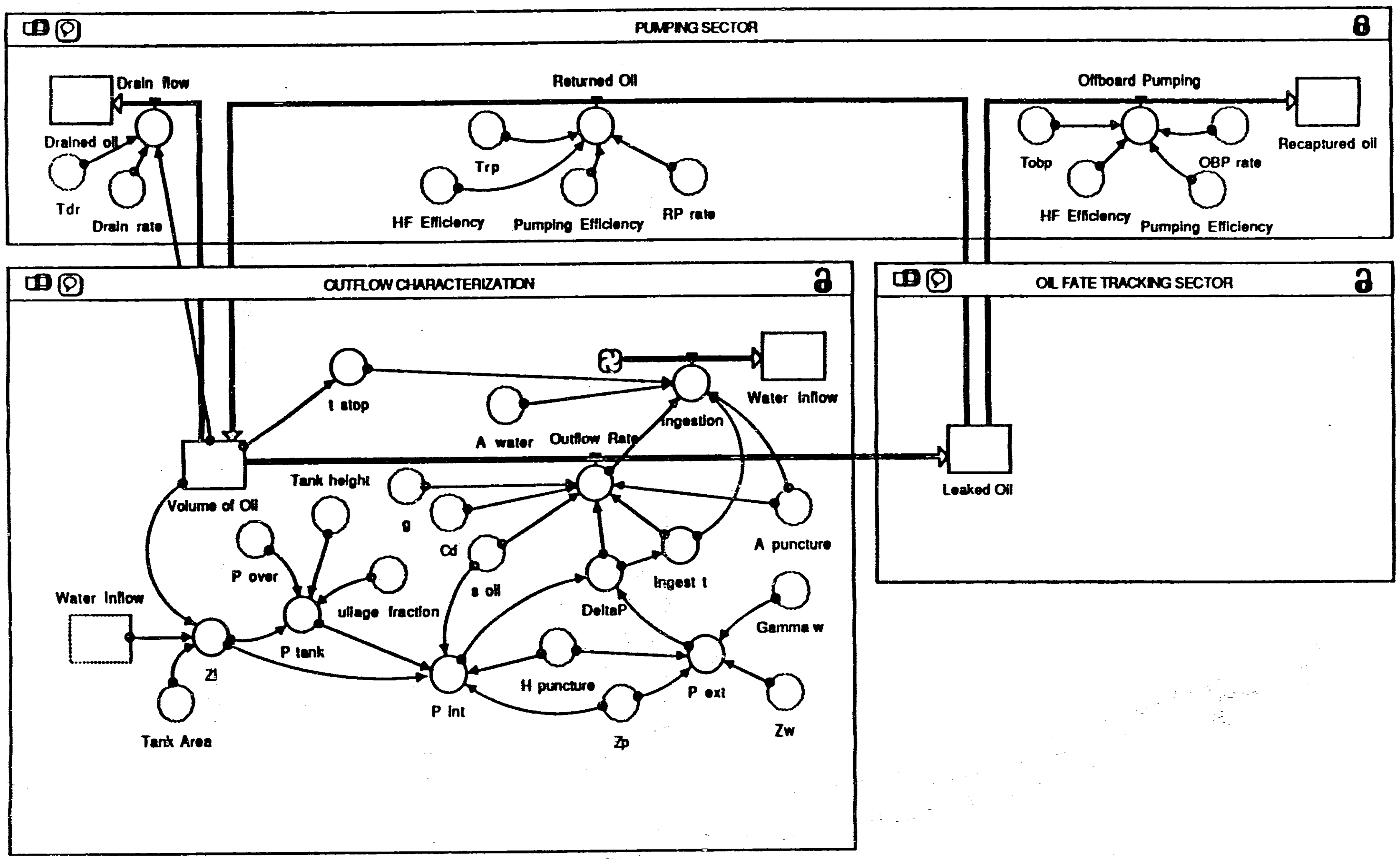
| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 2.30 | 1.00 | 83.7 |
| 2 | 2.30 | 1.00 | 83.7 |
| 3 | 9.80 | 1.00 | 52.0 |
| 4 | 14.8 | 0.75 | 37.9 |

| Run # | Start t nom | Spray Duration |
|---|---|---|
| 1 | 10000 | 360 |
| 2 | 25.0 | 360 |
| 3 | 25.0 | 360 |
| 4 | 25.0 | 360 |



INPUT CONTROL PANEL
Water Type
Gamma w
Wind in kt
Wave Height
Snow Ice
Air Temp
g
Wave Period
Tides
Current
Steady Current
Environment
Tonnage
Carrier type
P over
s oil
ullage fraction
V oil init
Lship
Tank height
Wship
Tank Area
Zw
Ship parameters
Drain rate
OBP rate
RP rate
Tdr
Tobp
Trp
Pumping Parameters
Zp
Cd
H puncture
L puncture
Puncture Characteristics
H puncture
Zp
Zl
Zw
A water
A puncture
L puncture
Current Effect2
Steady Current
Pumping Efficiency
Wave Effect2
Wave Height
Temp Effect
Air Temp
HF Efficiency
Snow Ice
Wind Effect2
Wind in kt
Functional Relations


- 2 -


PUMPING SECTOR
Drain flow
Drained oil
Tdr
Drain rate
Returned Oil
Trp
HF Efficiency
Pumping Efficiency
RP rate
Offboard Pumping
Recaptured oil
Tobp
OBP rate
HF Efficiency
Pumping Efficiency
OUTFLOW CHARACTERIZATION
t stop
Water Inflow
Ingestion
A water
Outflow Rate
Volume of Oil
Tank height
g
Cd
s oil
A puncture
Ingest t
P over
ullage fraction
DeltaP
Gamma w
Water Inflow
P tank
Zl
P int
H puncture
P ext
Tank Area
Zp
Zw
OIL FATE TRACKING SECTOR
Leaked Oil

- 1 -

**INPUT CONTROL PANEL**

DOCUMENT:

Collects all input variables for the model

- ○ Air_Temp = 70.7 {air temp. deg F}
- ○ A_puncture = IF (Zl > Zp) THEN (L_puncture*H_puncture) ELSE (MAX (0.01,((Zl - Zp + H_puncture)*L_puncture))) {Reference fluid flow area, sf. }
- ○ A_water = MAX (A_puncture/2, (Zw - Zl -(Zp-H_puncture)/2)*L_puncture) {Effective area of water backflow, sf}
- ○ Carrier_type = IF (Tonnage ≥ 34000) THEN 1 ELSE 0 {0 means carrier is a barge; 1 means carrier is a tanker}
- ○ Cd = .61 {Oil discharge coefficient}
- ○ Current = Steady_Current + Tides {Current in fps}
- ○ Drain_rate = 600{GPM}
- ○ g = 32.2 { acceleration of gravity, fps}
- ○ Gamma_w = IF (Water_Type = 1) THEN 64 ELSE 62.4 { Establishes the weight density of the water of operation, pcf.}
- ○ HF_Efficiency = Temp_Effect*Wind_Effect2*Snow_Ice{Combined degradation effect of both temperature and wind on human performance on deck}
- ○ H_puncture = 12 {Height of puncture, ft.}
- ○ Lship = 195 {length overall of ship, ft.}
- ○ L_puncture = 6 {Length of puncture, ft.}
- ○ OBP_rate = 600 {GPM}
- ○ Pumping_Efficiency = Current_Effect2*Wave_Effect2{overall efficiency factor in the presence of current and waves}
- ○ P_over = IF (Carrier_type = 1) THEN 2 ELSE 0{Initial ullage overpressure, psi; set at 2 psig. for tankers and 0 psig. for barges}
- ○ RP_rate = 600{GPM}
- ○ Snow_Ice = 1{Set expression to degradation factor (suggest .75) if snow or ice is present, otherwise set to 1}
- ○ Steady_Current = .4 {Current speed in kts}
- ○ s_oil = IF( Carrier_type = 1) THEN .86 ELSE .92 {specific gravity of cargo oil; =.86 for tankers (crude), or .92 for barges (diesel)}
- ○ Tank_Area = 1809.08 {Cross sectional area of cargo tank, sf.}
- ○ Tank_height = 10.5 {Height of tank, ft.}
- ○ Tdr = 60{Drain pumping nominal start time, min.}
- ○ Tides = 0 {Max. tidal current, fps}
- ○ Tobp = 25 {Spill-to-offboard pumping nominal start time; min.}
- ○ Tonnage = 628 {DWT for tankers or GT for barges}
- ○ Trp = 25 {Spill-back-to-tank pumping nominal start time; min.}
- ○ ullage_fraction = IF (Carrier_type = 1) THEN .02 ELSE .05 {Fraction of tank height which is left as void above cargo; for barges = 5%, for tankers =2%}

- ○ V_oil_init = 7.48*(1-ullage_fraction)*Tank_height*Tank_Area {Initial volume of cargo in tank, gal}
- ○ Water_Type = IF (Tonnage ≥ 2713) THEN 1 ELSE 0{1 means carrier operates in seawater; 0 in fresh water }
- ○ Wave_Height = 1.6 {significant wave height in ft.}
- ○ Wave_Period = 3 {Period in sec. of significant wave }
- ○ Wind_in_kt = 8.2 {Wind speed in kts.}
- ○ Wship = 36.5 {width of ship at midsection, ft.}
- ○ Zp = Zw -.4 + H_puncture/2 {Height of top of puncture above bottom of tank in ft. (center of puncture set equal to the height of the water -0.4 ft. for worst-case side puncture analysis)}
- ○ Zw = 9.6 {Height of the waterline above the tank bottom, ft.}

Current_Effect2 = GRAPH(Steady_Current)
(0.00, 0.99), (0.5, 0.95), (1.00, 0.835), (1.50, 0.62), (2.00, 0.285), (2.50, 0.14), (3.00, 0.065), (3.50, 0.015), (4.00, 0.00)

Temp_Effect = GRAPH( Air_Temp{ Place right hand side of equation here... })
(-40.0, 0.2), (-32.0, 0.215), (-24.0, 0.24), (-16.0, 0.28), (-8.00, 0.33), (0.00, 0.42), (8.00, 0.53), (16.0, 0.665), (24.0, 0.825), (32.0, 0.955), (40.0, 1.00), (48.0, 1.00), (56.0, 1.00), (64.0, 1.00), (72.0, 1.00), (80.0, 1.00), (88.0, 1.00), (96.0, 0.93), (104, 0.82), (112, 0.7), (120, 0.53)

Wave_Effect2 = GRAPH(Wave_Height)
(0.00, 1.00), (1.00, 0.93), (2.00, 0.765), (3.00, 0.445), (4.00, 0.245), (5.00, 0.135), (6.00, 0.065), (7.00, 0.03), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00)

Wind_Effect2 = GRAPH( Wind_In_kt{ Place right hand side of equation here... })
(0.00, 1.00), (1.00, 1.00), (2.00, 1.00), (3.00, 1.00), (4.00, 1.00), (5.00, 1.00), (6.00, 1.00), (7.00, 1.00), (8.00, 1.00), (9.00, 1.00), (10.0, 1.00), (11.0, 1.00), (12.0, 1.00), (13.0, 1.00), (14.0, 1.00), (15.0, 1.00), (16.0, 1.00), (17.0, 1.00), (18.0, 1.00), (19.0, 1.00), (20.0, 1.00), (21.0, 0.99), (22.0, 0.975), (23.0, 0.95), (24.0, 0.92), (25.0, 0.875), (26.0, 0.825), (27.0, 0.75), (28.0, 0.65), (29.0, 0.5), (30.0, 0.3)

**PUMPING SECTOR**
DOCUMENT:
Collects all pumping activities; "Drain" pumping from the damaged hold either into another vacant on-board space or off-board. "Returned" oil pumped up from the spilled oil pool, and back into the damaged hold, and "Offboard " pumping which moves oil from the spilled oil pool to some offboard holding area.

Drained_oil(t) = Drained_oil(t - dt) + (Drain_flow) * dt
INIT Drained_oil = 0 {gal}
INFLOWS:
Drain_flow = IF (Volume_of_Oil > 0) AND (TIME ≥ Tdr) THEN Drain_rate ELSE 0{GPM}

Recaptured_oil(t) = Recaptured_oil(t - dt) + (Offboard_Pumping) * dt
INIT Recaptured_oil = 0{initial value...}
INFLOWS:
Offboard_Pumping = IF (TIME ≥ Tobp/HF_Efficiency) THEN (OBP_rate*Pumping_Efficiency) ELSE 0 {Starts pump and discounts basic pumping capacity by the effects of the wave heights and current speed, GPM}

Drain_flow = IF (Volume_of_Oil > 0) AND (TIME ≥ Tdr) THEN Drain_rate ELSE 0{GPM}
OUTFLOW FROM: Volume_of_Oil (IN SECTOR: OUTFLOW CHARACTERIZATION)
INFLOW TO:

Returned_Oil = IF (TIME ≥ Trp/HF_Efficiency) THEN (RP_rate*Pumping_Efficiency) ELSE 0 {GPM}
OUTFLOW FROM: Leaked_Oil (IN SECTOR: OIL FATE TRACKING SECTOR)
INFLOW TO: Volume_of_Oil (IN SECTOR: OUTFLOW CHARACTERIZATION)

**OIL FATE TRACKING SECTOR**
DOCUMENT:
Provides total amounts (in gal.) of treated and untreated oil lost for each scenario.

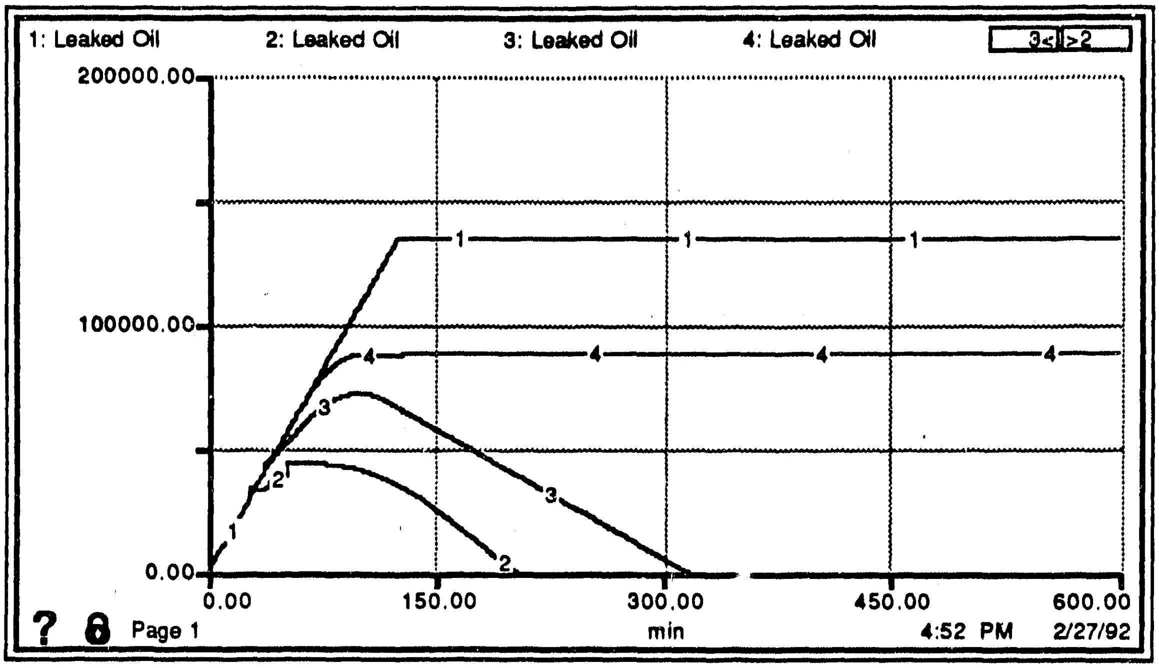
Leaked_Oil(t) = Leaked_Oil(t - dt) + (Outflow_Rate - Returned_Oil - Offboard_Pumping) * dt
INIT Leaked_Oil = 0{Cubic feet}
INFLOWS:
Outflow_Rate (IN SECTOR: OUTFLOW CHARACTERIZATION)
OUTFLOWS:

Returned_Oil (IN SECTOR: PUMPING SECTOR)
Offboard_Pumping (IN SECTOR: PUMPING SECTOR)

**OUTFLOW CHARACTERIZATION**

DOCUMENT:
Describes the actual time history of the oil outflow for the selected carrier, casualty and environmental scenario.

```
☐ Volume_of_Oil(t) = Volume_of_Oil(t - dt) + (Returned_Oil - Outflow_Rate - Drain_flow) * dt
    INIT Volume_of_Oil = V_oil_init{gal.}
    INFLOWS:
      Returned_Oil (IN SECTOR: PUMPING SECTOR)
    OUTFLOWS:
      Outflow_Rate = IF (Ingest_t = 1) THEN (60*7.48*Cd*(A_puncture/2)*s_oil*SQRT((2*g*DeltaP/(s_oil*62.4)))) ELSE
        (60*7.48*Cd*A_puncture*SQRT(2*g*DeltaP/(s_oil*62.4)))    {GPM}
      Drain_flow (IN SECTOR: PUMPING SECTOR)
☐ Water_inflow(t) = Water_inflow(t - dt) + (Ingestion) * dt
    INIT Water_inflow = 0{Amount of water ingested back into tank, gal}
    INFLOWS:
      Ingestion = IF (Ingest_t = 1) AND (t_stop ≠ 1) THEN (A_water*Outflow_Rate/(A_puncture/2)) ELSE 0 {Flow rate of water back into tank, GPM}
○ DeltaP = IF ((P_int - P_ext) ≥ (.01*14.7*144)) THEN (P_int - P_ext) ELSE (.01*14.7*144)  {Sets driving pressure difference, psf.}
○ Ingest_t = IF (DeltaP ≤ .01*14.7*144) THEN 1 ELSE 0{Captures start of water ingestion back into ruptured tank}
○ P_ext = 14.7*144 + Gamma_w*(Zw - Zp + (H_puncture/2)){External pressure of water acting on puncture, psf (absolute)}
○ P_int = P_tank + 62.4*s_oil*(Zl - Zp + (H_puncture/2)) {Internal pressure of the oil acting on the puncture, psf (absolute)}
○ P_tank = MAX( 14.7*144, (144*((P_over + 14.7)*(ullage_fraction)/(1 - (Zl/Tank_height))))) {Over pressure as a function of ullage, psf. (absolute)}
○ t_stop = IF (Volume_of_Oil ≥ 0) THEN 0 ELSE 1{Captures time at which all oil has flowed from the tank}
○ Zl = ((Volume_of_Oil + Water_inflow)/7.48)/Tank_Area {Height of oil above bottom, ft., including effect of backflowing water}
  Outflow_Rate = IF (Ingest_t = 1) THEN (60*7.48*Cd*(A_puncture/2)*s_oil*SQRT((2*g*DeltaP/(s_oil*62.4)))) ELSE
    (60*7.48*Cd*A_puncture*SQRT(2*g*DeltaP/(s_oil*62.4)))    {GPM}
    OUTFLOW FROM:
    INFLOW TO: Leaked_Oil (IN SECTOR: OIL FATE TRACKING SECTOR)
```




Setup #3 2/27/92 4:50 PM

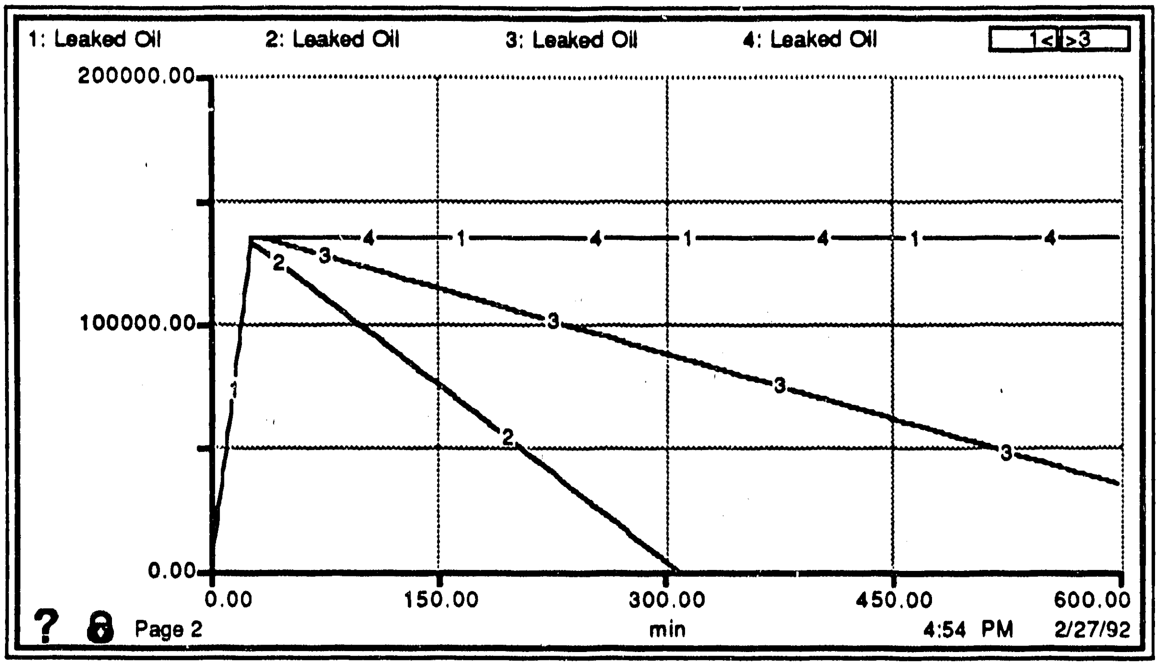
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 2.00 | 1.00 | 628 |
| 2 | 2.00 | 1.00 | 628 |
| 3 | 2.00 | 1.00 | 628 |
| 4 | 2.00 | 1.00 | 628 |

| Run # | BP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 600 | 600 | 600 |
| 3 | 600 | 600 | 600 |
| 4 | 600 | 600 | 600 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 8.20 | 0.4 | 0.00 |
| 2 | 8.20 | 0.4 | 0.00 |
| 3 | 13.4 | 0.66 | 0.00 |
| 4 | 13.4 | 7.80 | 0.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 1.60 | 1.00 | 70.7 |
| 2 | 1.60 | 1.00 | 70.7 |
| 3 | 3.60 | 0.75 | 36.1 |
| 4 | 1.60 | 1.00 | 32.5 |




Setup #4 2/27/92 4:52 PM

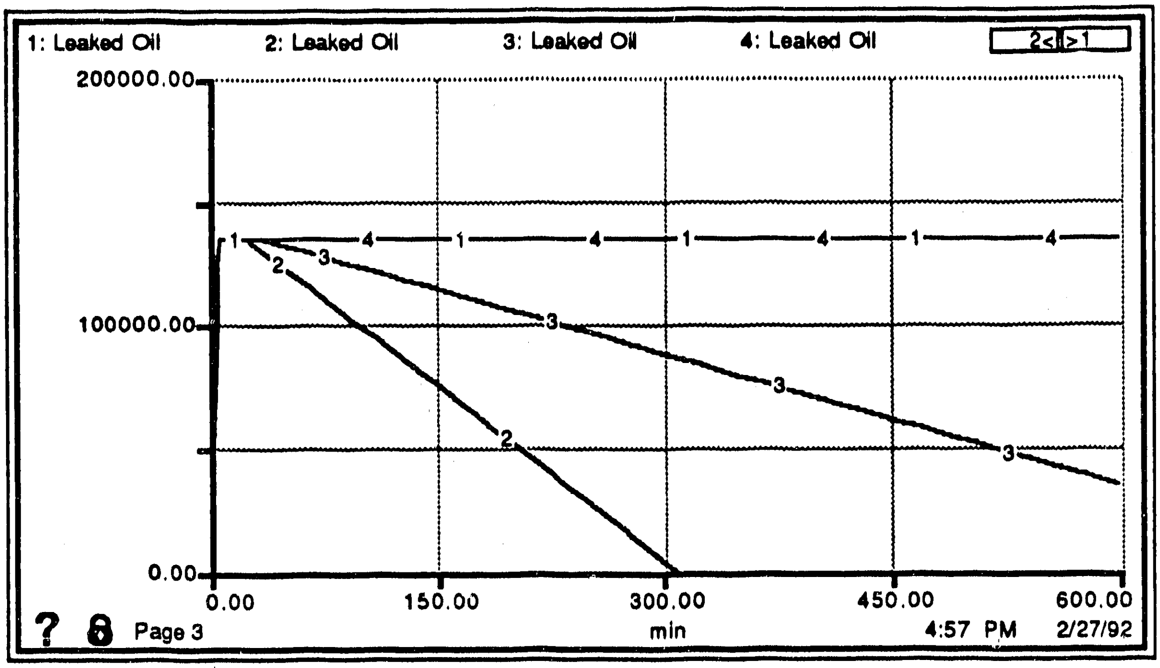
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 4.90 | 2.45 | 628 |
| 2 | 4.90 | 2.45 | 628 |
| 3 | 4.90 | 2.45 | 628 |
| 4 | 4.90 | 2.45 | 628 |

| Run # | RP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 600 | 600 | 600 |
| 3 | 600 | 600 | 600 |
| 4 | 600 | 600 | 600 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 8.20 | 0.4 | 0.00 |
| 2 | 8.20 | 0.4 | 0.00 |
| 3 | 13.4 | 0.66 | 0.00 |
| 4 | 13.4 | 7.80 | 0.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 1.60 | 1.00 | 70.7 |
| 2 | 1.60 | 1.00 | 70.7 |
| 3 | 3.60 | 0.75 | 36.1 |
| 4 | 1.60 | 1.00 | 32.5 |




Setup #5 2/27/92 4:56 PM

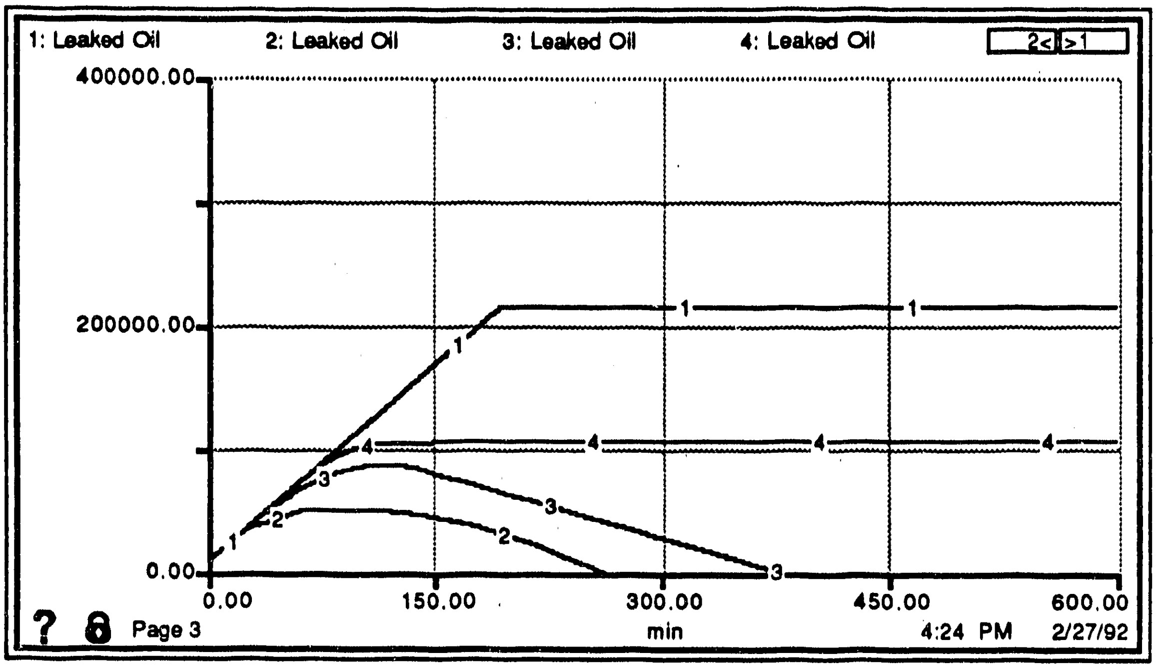
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 628 |
| 2 | 12.0 | 6.00 | 628 |
| 3 | 12.0 | 6.00 | 628 |
| 4 | 12.0 | 6.00 | 628 |

| Run # | BP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 600 | 600 | 600 |
| 3 | 600 | 600 | 600 |
| 4 | 600 | 600 | 600 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 8.20 | 0.4 | 0.00 |
| 2 | 8.20 | 0.4 | 0.00 |
| 3 | 13.4 | 0.66 | 0.00 |
| 4 | 13.4 | 7.80 | 0.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 1.60 | 1.00 | 70.7 |
| 2 | 1.60 | 1.00 | 70.7 |
| 3 | 3.60 | 0.75 | 36.1 |
| 4 | 1.60 | 1.00 | 32.5 |




Setup #5 2/27/92 4:23 PM

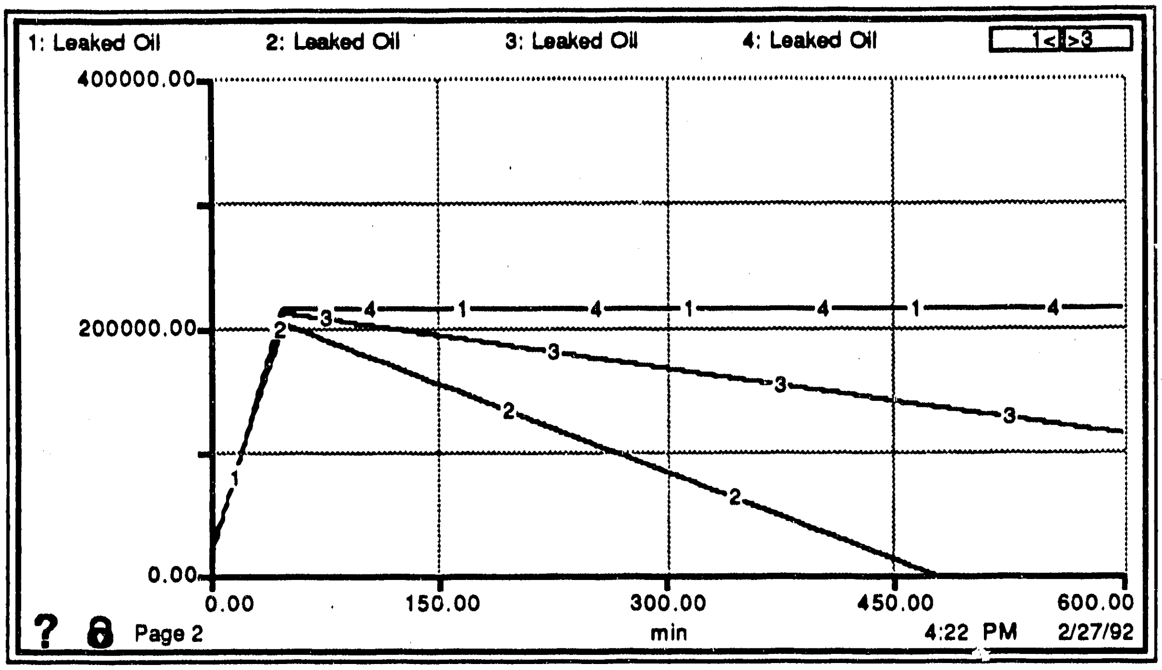
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 2.00 | 1.00 | 1182 |
| 2 | 2.00 | 1.00 | 1182 |
| 3 | 2.00 | 1.00 | 1182 |
| 4 | 2.00 | 1.00 | 1182 |

| Run # | RP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 600 | 600 | 600 |
| 3 | 600 | 600 | 600 |
| 4 | 600 | 600 | 600 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 8.20 | 0.4 | 0.00 |
| 2 | 8.20 | 0.4 | 0.00 |
| 3 | 13.4 | 0.66 | 0.00 |
| 4 | 13.4 | 7.80 | 0.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 1.60 | 1.00 | 70.7 |
| 2 | 1.60 | 1.00 | 70.7 |
| 3 | 3.60 | 0.75 | 36.1 |
| 4 | 1.60 | 1.00 | 32.5 |




Setup #4 2/27/92 4:21 PM

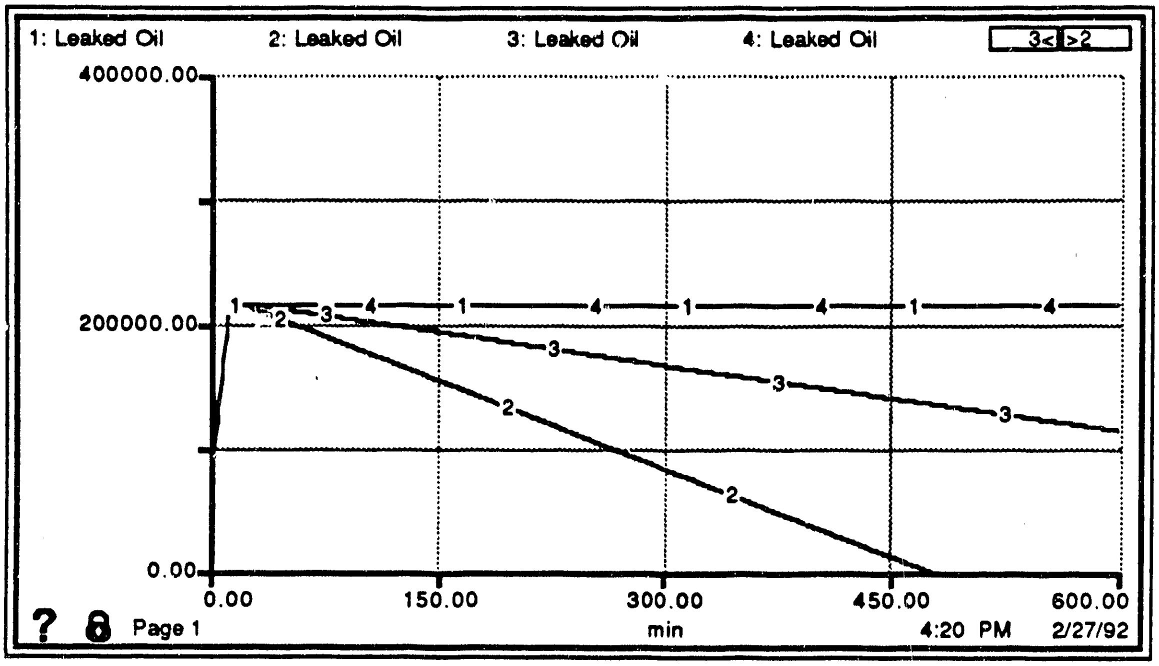
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 4.90 | 2.45 | 1182 |
| 2 | 4.90 | 2.45 | 1182 |
| 3 | 4.90 | 2.45 | 1182 |
| 4 | 4.90 | 2.45 | 1182 |

| Run # | RP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 600 | 600 | 600 |
| 3 | 600 | 600 | 600 |
| 4 | 600 | 600 | 600 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 8.20 | 0.4 | 0.00 |
| 2 | 8.20 | 0.4 | 0.00 |
| 3 | 13.4 | 0.66 | 0.00 |
| 4 | 13.4 | 7.80 | 0.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 1.60 | 1.00 | 70.7 |
| 2 | 1.60 | 1.00 | 70.7 |
| 3 | 3.60 | 0.75 | 36.1 |
| 4 | 1.60 | 1.00 | 32.5 |




Setup #3 2/27/92 4:19 PM

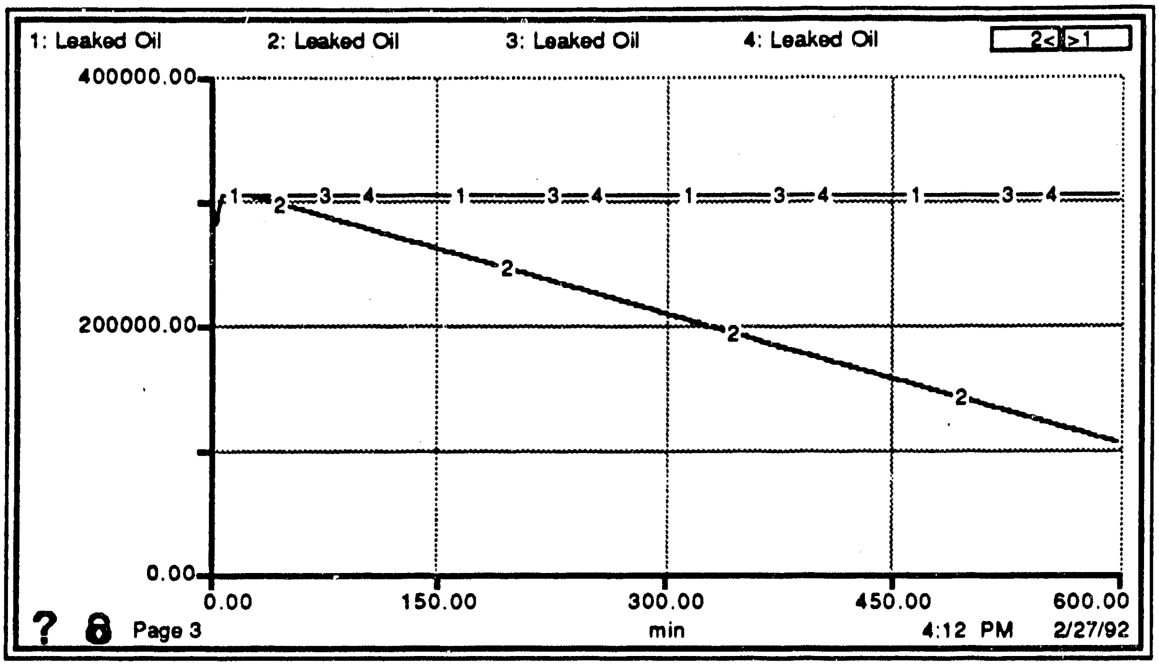
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 1182 |
| 2 | 12.0 | 6.00 | 1182 |
| 3 | 12.0 | 6.00 | 1182 |
| 4 | 12.0 | 6.00 | 1182 |

| Run # | BP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 600 | 600 | 600 |
| 3 | 600 | 600 | 600 |
| 4 | 600 | 600 | 600 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 8.20 | 0.4 | 0.00 |
| 2 | 8.20 | 0.4 | 0.00 |
| 3 | 13.4 | 0.66 | 0.00 |
| 4 | 13.4 | 7.80 | 0.00 |

| Run # | Wave Height | Snow Ice | Air Temp |
|---|---|---|---|
| 1 | 1.60 | 1.00 | 70.7 |
| 2 | 1.60 | 1.00 | 70.7 |
| 3 | 3.60 | 0.75 | 36.1 |
| 4 | 1.60 | 1.00 | 32.5 |




Setup #5 2/27/92 4:10 PM

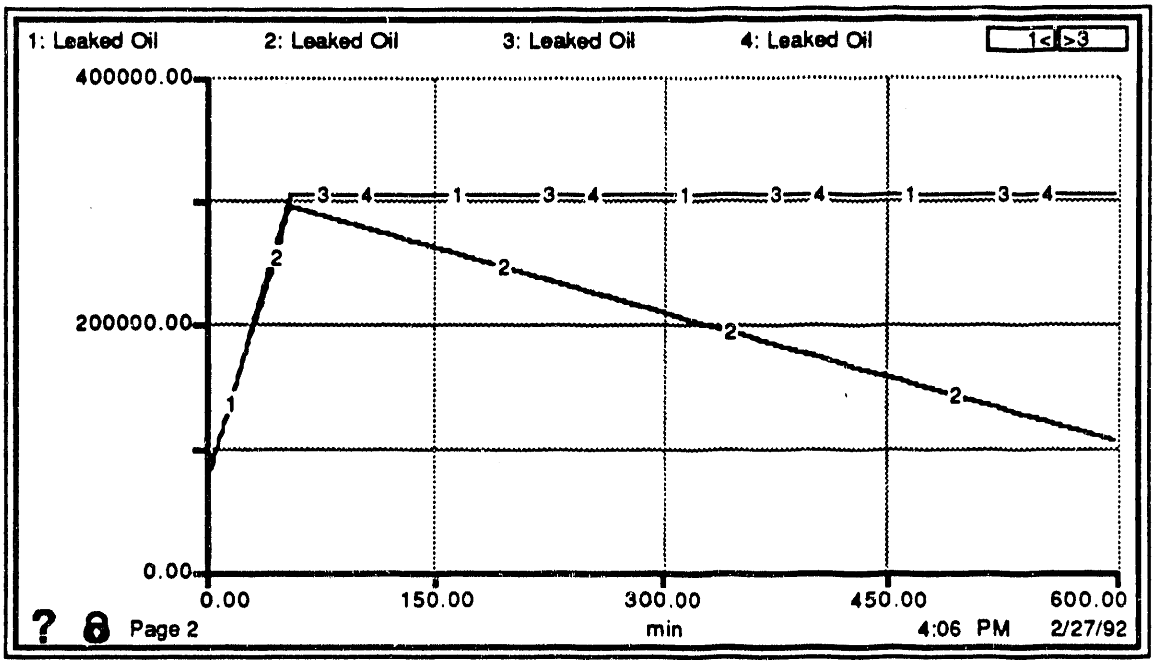
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 2713 |
| 2 | 12.0 | 6.00 | 2713 |
| 3 | 12.0 | 6.00 | 2713 |
| 4 | 12.0 | 6.00 | 2713 |

| Run # | RP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 600 | 600 | 600 |
| 3 | 600 | 600 | 600 |
| 4 | 600 | 600 | 600 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice |
|---|---|---|
| 1 | 2.30 | 1.00 |
| 2 | 2.30 | 1.00 |
| 3 | 9.80 | 1.00 |
| 4 | 14.8 | 0.75 |




Setup #3 2/27/92 4:08 PM

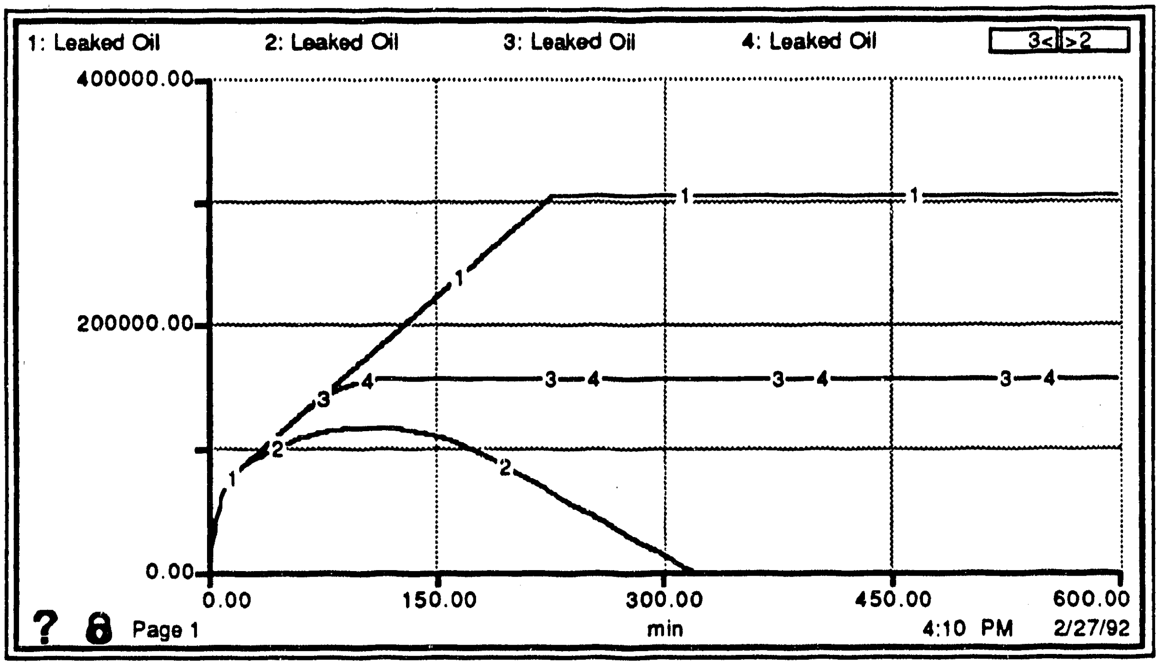
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 4.90 | 2.45 | 2713 |
| 2 | 4.90 | 2.45 | 2713 |
| 3 | 4.90 | 2.45 | 2713 |
| 4 | 4.90 | 2.45 | 2713 |

| Run # | RP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 600 | 600 | 600 |
| 3 | 600 | 600 | 600 |
| 4 | 600 | 600 | 600 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice |
|---|---|---|
| 1 | 2.30 | 1.00 |
| 2 | 2.30 | 1.00 |
| 3 | 9.80 | 1.00 |
| 4 | 14.8 | 0.75 |




Setup #4 2/27/92 4:08 PM

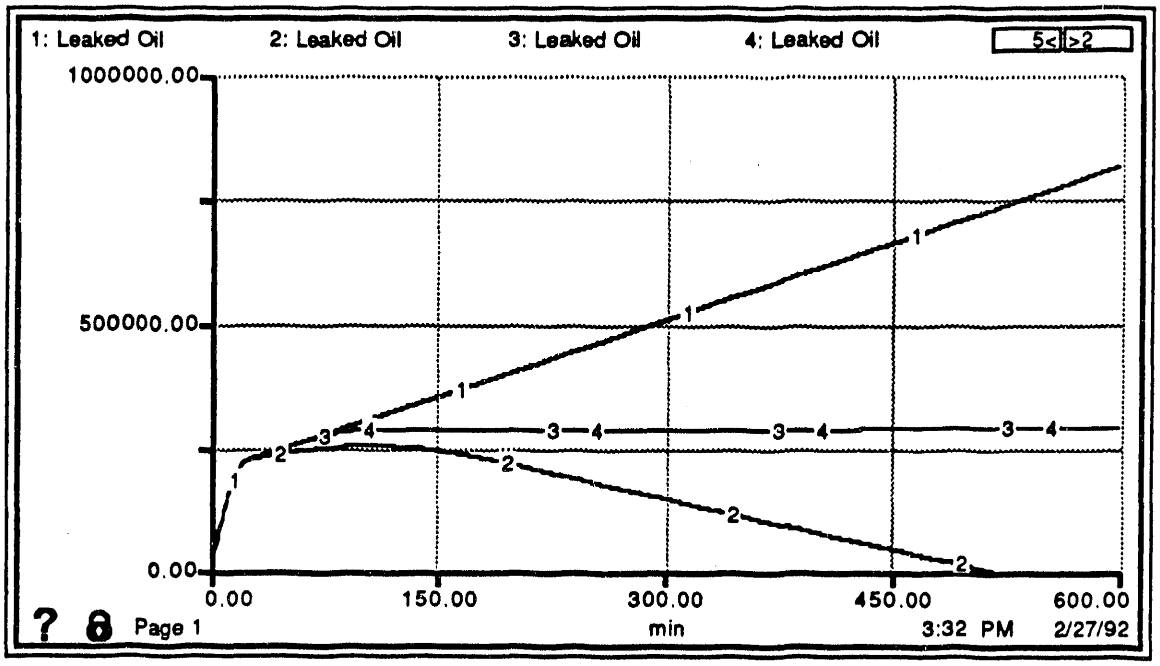
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 2.00 | 1.00 | 2713 |
| 2 | 2.00 | 1.00 | 2713 |
| 3 | 2.00 | 1.00 | 2713 |
| 4 | 2.00 | 1.00 | 2713 |

| Run # | RP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 600 | 600 | 600 |
| 3 | 600 | 600 | 600 |
| 4 | 600 | 600 | 600 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice |
|---|---|---|
| 1 | 2.30 | 1.00 |
| 2 | 2.30 | 1.00 |
| 3 | 9.80 | 1.00 |
| 4 | 14.8 | 0.75 |




Setup #3 2/27/92 3:31 PM

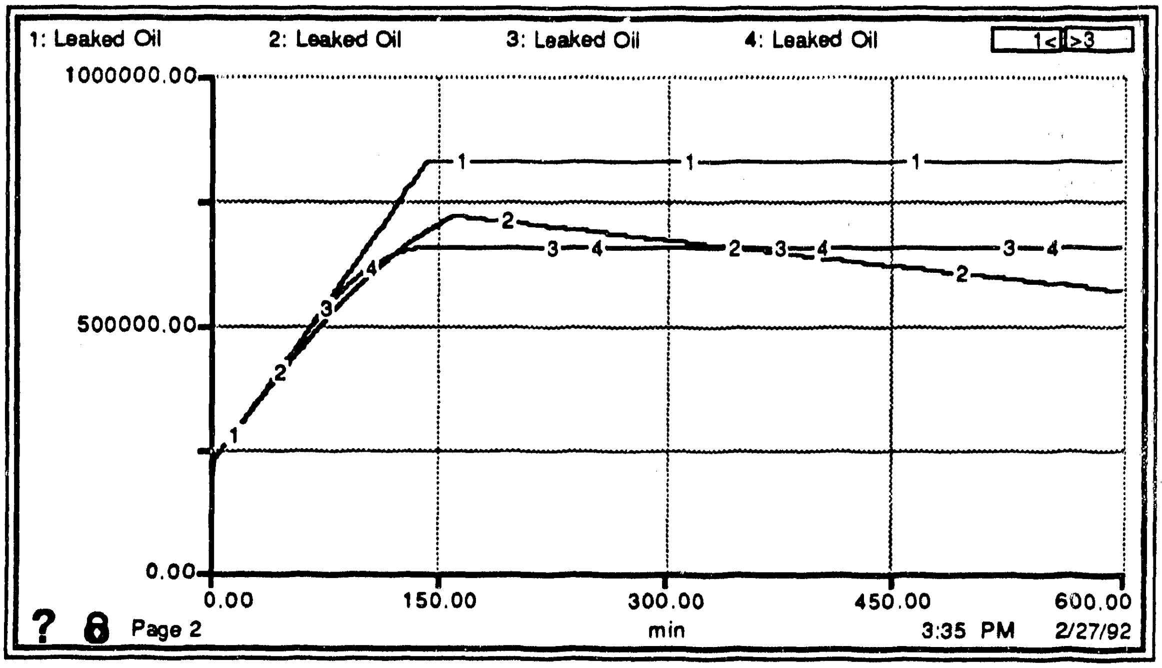
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 2.00 | 1.00 | 34000 |
| 2 | 2.00 | 1.00 | 34000 |
| 3 | 2.00 | 1.00 | 34000 |
| 4 | 2.00 | 1.00 | 34000 |

| Run # | RP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 600 | 600 | 600 |
| 3 | 600 | 600 | 600 |
| 4 | 600 | 600 | 600 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice |
|---|---|---|
| 1 | 2.30 | 1.00 |
| 2 | 2.30 | 1.00 |
| 3 | 9.80 | 1.00 |
| 4 | 14.8 | 0.75 |




Setup #4 2/27/92 3:33 PM

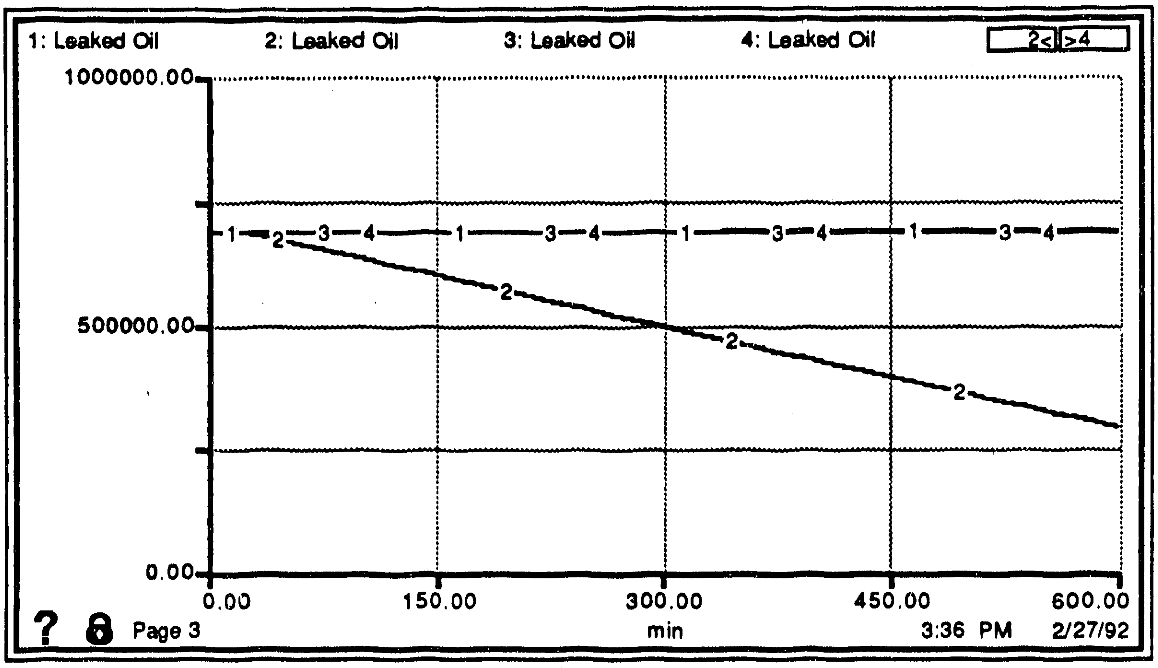
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 4.90 | 2.45 | 34000 |
| 2 | 4.90 | 2.45 | 34000 |
| 3 | 4.90 | 2.45 | 34000 |
| 4 | 4.90 | 2.45 | 34000 |

| Run # | RP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 600 | 600 | 600 |
| 3 | 600 | 600 | 600 |
| 4 | 600 | 600 | 600 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice |
|---|---|---|
| 1 | 2.30 | 1.00 |
| 2 | 2.30 | 1.00 |
| 3 | 9.80 | 1.00 |
| 4 | 14.8 | 0.75 |




Setup #5 2/27/92 3:35 PM

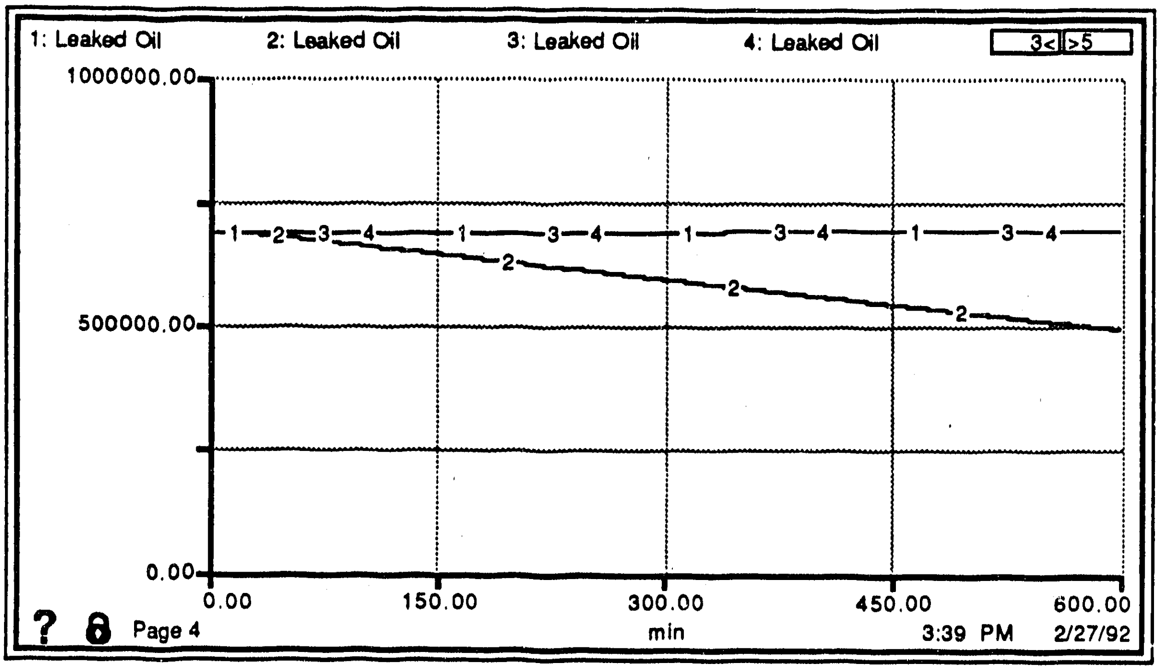
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 34000 |
| 2 | 12.0 | 6.00 | 34000 |
| 3 | 12.0 | 6.00 | 34000 |
| 4 | 12.0 | 6.00 | 34000 |

| Run # | RP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 600 | 600 | 600 |
| 3 | 600 | 600 | 600 |
| 4 | 600 | 600 | 600 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice |
|---|---|---|
| 1 | 2.30 | 1.00 |
| 2 | 2.30 | 1.00 |
| 3 | 9.80 | 1.00 |
| 4 | 14.8 | 0.75 |




Setup #6 2/27/92 3:38 PM

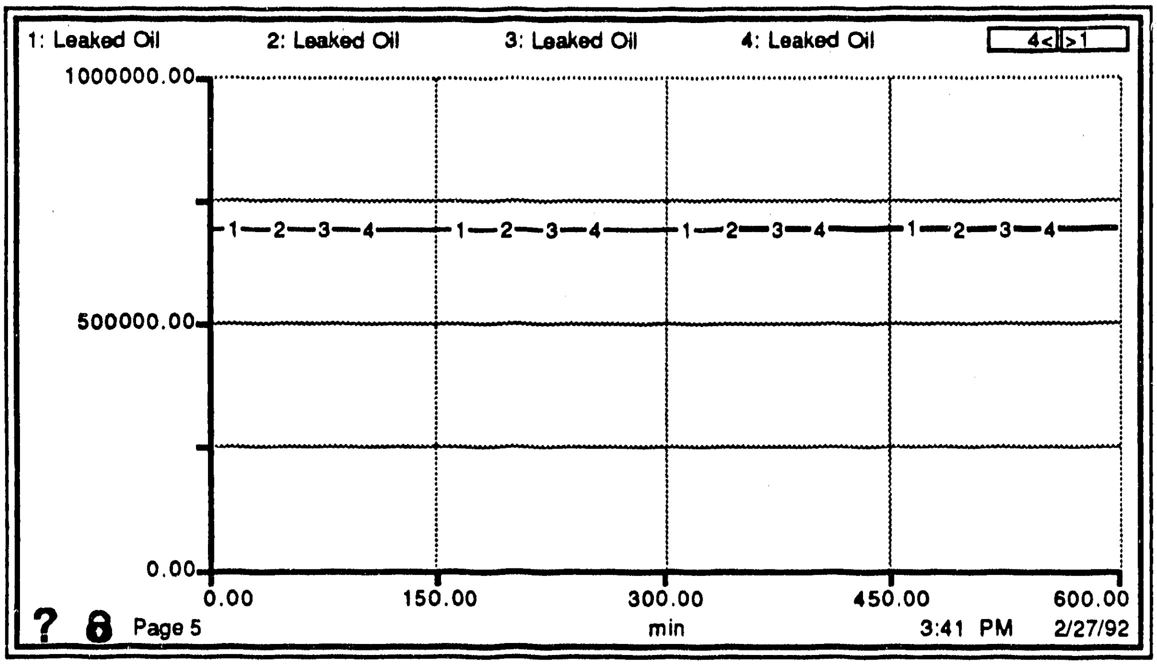
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 34000 |
| 2 | 12.0 | 6.00 | 34000 |
| 3 | 12.0 | 6.00 | 34000 |
| 4 | 12.0 | 6.00 | 34000 |

| Run # | RP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 0.00 | 600 | 0.00 |
| 3 | 0.00 | 600 | 0.00 |
| 4 | 0.00 | 600 | 0.00 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice |
|---|---|---|
| 1 | 2.30 | 1.00 |
| 2 | 2.30 | 1.00 |
| 3 | 9.80 | 1.00 |
| 4 | 14.8 | 0.75 |




Setup #7 2/27/92 3:40 PM

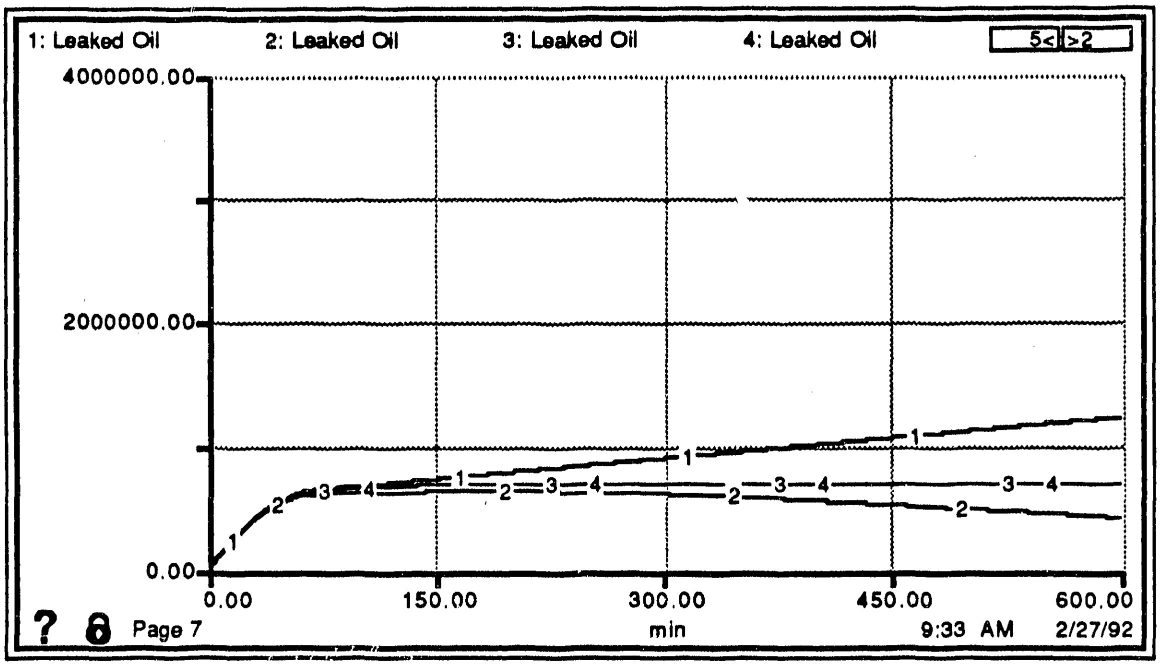
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 34000 |
| 2 | 12.0 | 6.00 | 34000 |
| 3 | 12.0 | 6.00 | 34000 |
| 4 | 12.0 | 6.00 | 34000 |

| Run # | BP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 0.00 | 0.00 | 600 |
| 3 | 0.00 | 0.00 | 600 |
| 4 | 0.00 | 0.00 | 600 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice |
|---|---|---|
| 1 | 2.30 | 1.00 |
| 2 | 2.30 | 1.00 |
| 3 | 9.80 | 1.00 |
| 4 | 14.8 | 0.75 |




Setup #3 2/27/92 9:35 AM

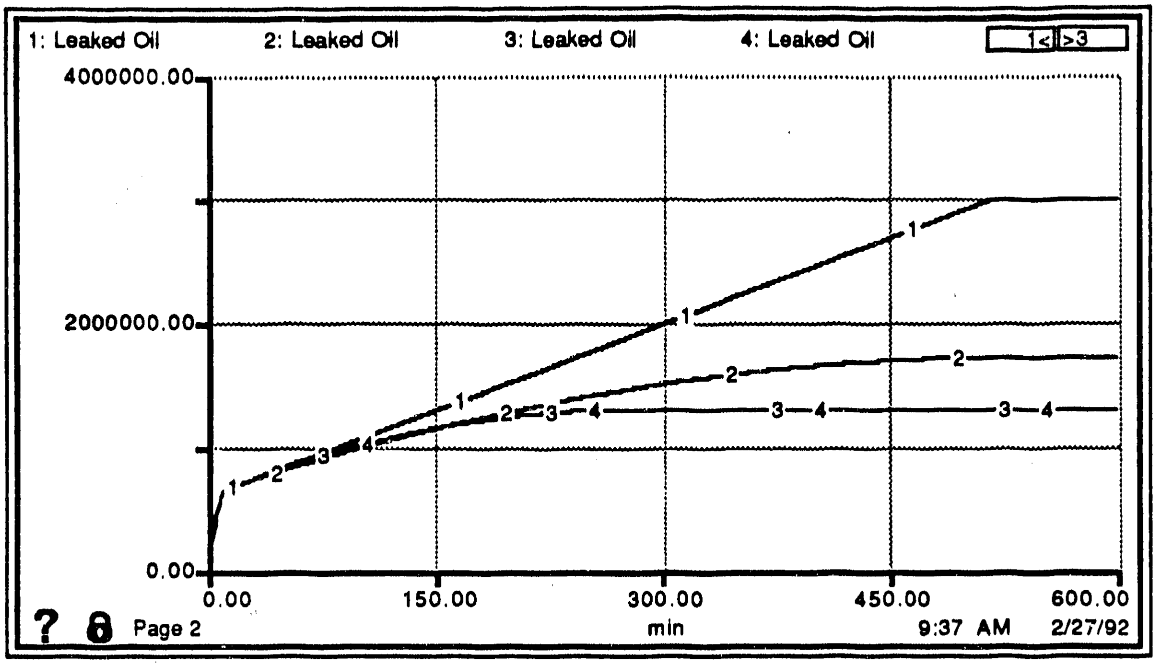
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 2.00 | 1.00 | 89700 |
| 2 | 2.00 | 1.00 | 89700 |
| 3 | 2.00 | 1.00 | 89700 |
| 4 | 2.00 | 1.00 | 89700 |

| Run # | RP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 600 | 600 | 600 |
| 3 | 600 | 600 | 600 |
| 4 | 600 | 600 | 600 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice |
|---|---|---|
| 1 | 2.30 | 1.00 |
| 2 | 2.30 | 1.00 |
| 3 | 9.80 | 1.00 |
| 4 | 14.8 | 0.75 |




Setup #4 2/27/92 9:36 AM

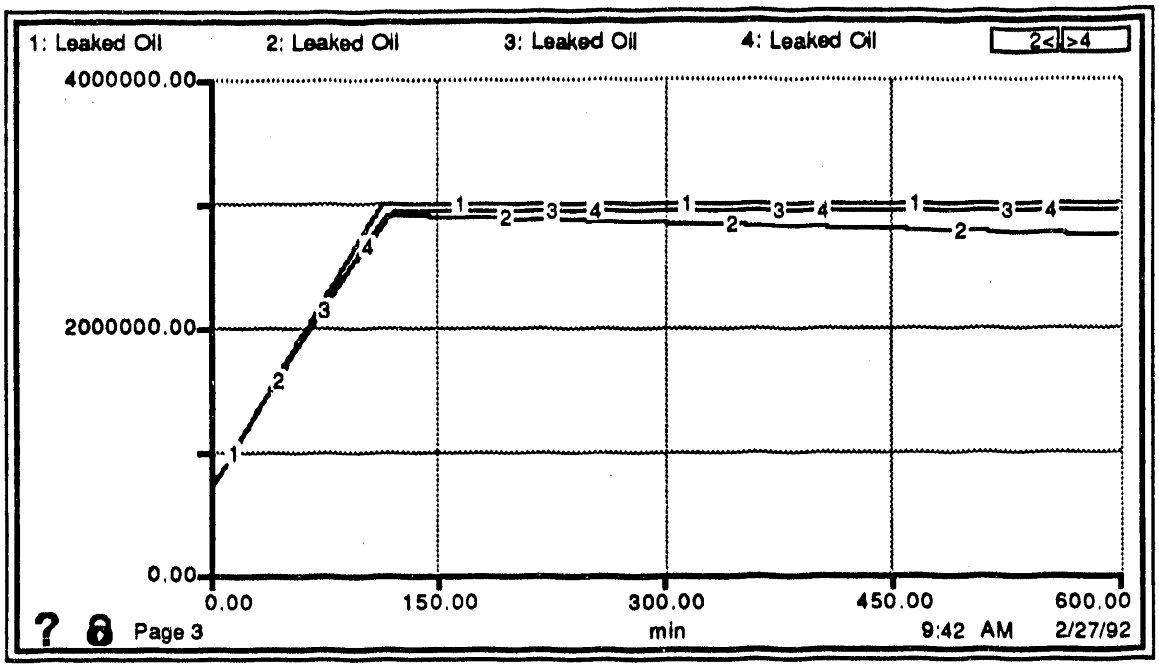
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 4.90 | 2.45 | 89700 |
| 2 | 4.90 | 2.45 | 89700 |
| 3 | 4.90 | 2.45 | 89700 |
| 4 | 4.90 | 2.45 | 89700 |

| Run # | BP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 600 | 600 | 600 |
| 3 | 600 | 600 | 600 |
| 4 | 600 | 600 | 600 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice |
|---|---|---|
| 1 | 2.30 | 1.00 |
| 2 | 2.30 | 1.00 |
| 3 | 9.80 | 1.00 |
| 4 | 14.8 | 0.75 |




Setup #5 2/27/92 9:40 AM

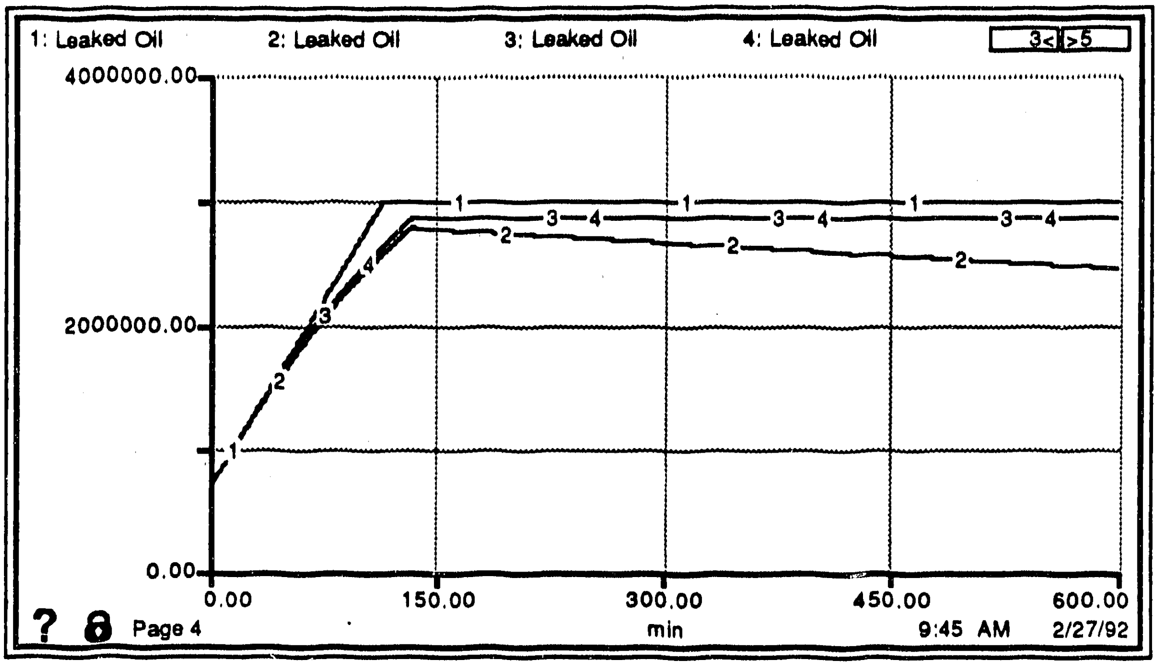
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 89700 |
| 2 | 12.0 | 6.00 | 89700 |
| 3 | 12.0 | 6.00 | 89700 |
| 4 | 12.0 | 6.00 | 89700 |

| Run # | RP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 600 | 600 | 600 |
| 3 | 600 | 600 | 600 |
| 4 | 600 | 600 | 600 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice |
|---|---|---|
| 1 | 2.30 | 1.00 |
| 2 | 2.30 | 1.00 |
| 3 | 9.80 | 1.00 |
| 4 | 14.8 | 0.75 |




Setup #6 2/27/92 9:43 AM

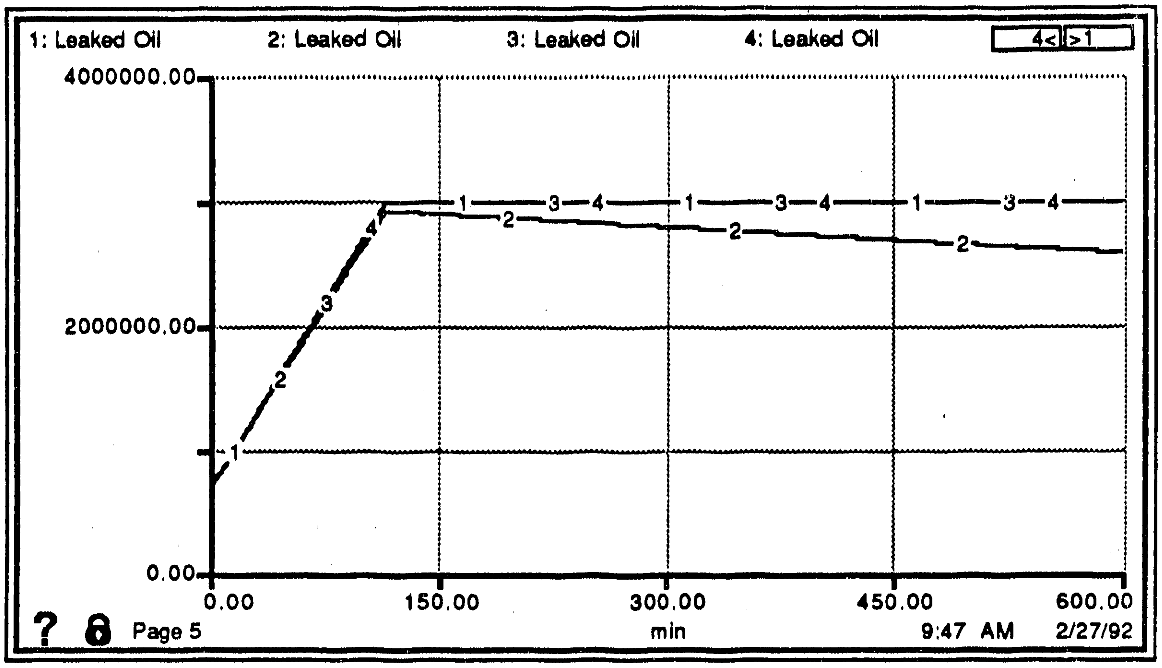
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 89700 |
| 2 | 12.0 | 6.00 | 89700 |
| 3 | 12.0 | 6.00 | 89700 |
| 4 | 12.0 | 6.00 | 89700 |

| Run # | BP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 0.00 | 600 | 600 |
| 3 | 0.00 | 600 | 600 |
| 4 | 0.00 | 600 | 600 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice |
|---|---|---|
| 1 | 2.30 | 1.00 |
| 2 | 2.30 | 1.00 |
| 3 | 9.80 | 1.00 |
| 4 | 14.8 | 0.75 |




Setup #7 2/27/92 9:46 AM

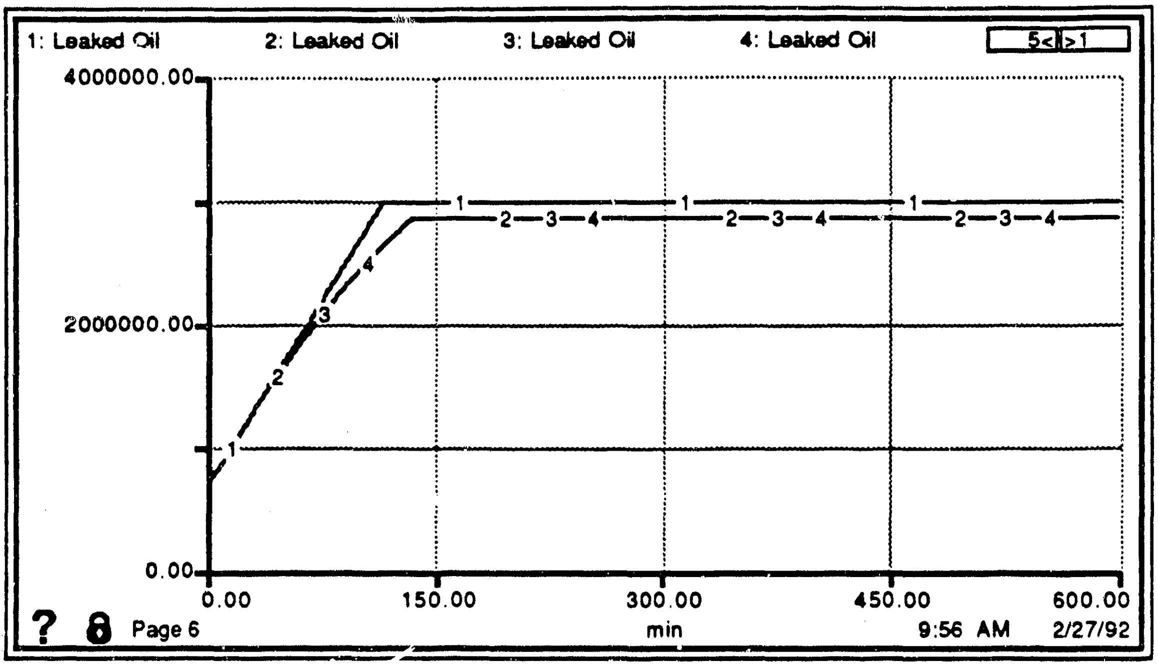
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 89700 |
| 2 | 12.0 | 6.00 | 89700 |
| 3 | 12.0 | 6.00 | 89700 |
| 4 | 12.0 | 6.00 | 89700 |

| Run # | RP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 0.00 | 1200 | 0.00 |
| 3 | 0.00 | 1200 | 0.00 |
| 4 | 0.00 | 1200 | 0.00 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice |
|---|---|---|
| 1 | 2.30 | 1.00 |
| 2 | 2.30 | 1.00 |
| 3 | 9.80 | 1.00 |
| 4 | 14.8 | 0.75 |




Setup #8 2/27/92 9:54 AM

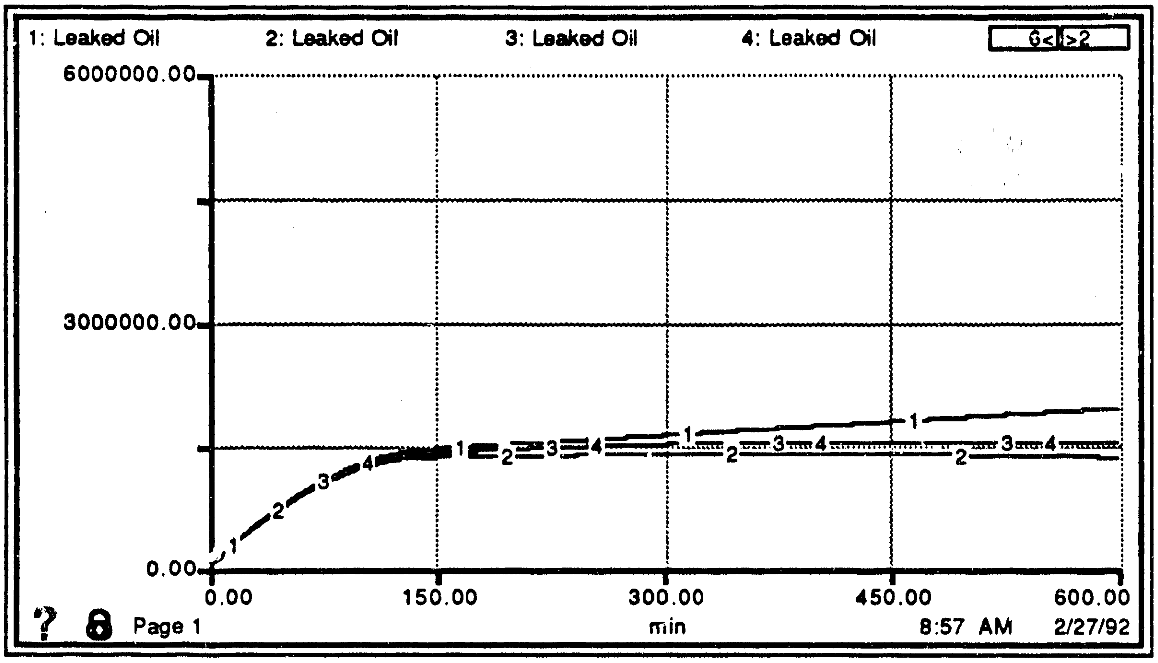
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 89700 |
| 2 | 12.0 | 6.00 | 89700 |
| 3 | 12.0 | 6.00 | 89700 |
| 4 | 12.0 | 6.00 | 89700 |

| Run # | BP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 0.00 | 0.00 | 1200 |
| 3 | 0.00 | 0.00 | 1200 |
| 4 | 0.00 | 0.00 | 1200 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice |
|---|---|---|
| 1 | 2.30 | 1.00 |
| 2 | 2.30 | 1.00 |
| 3 | 9.80 | 1.00 |
| 4 | 14.8 | 0.75 |




Setup #3 2/27/92 8:56 AM

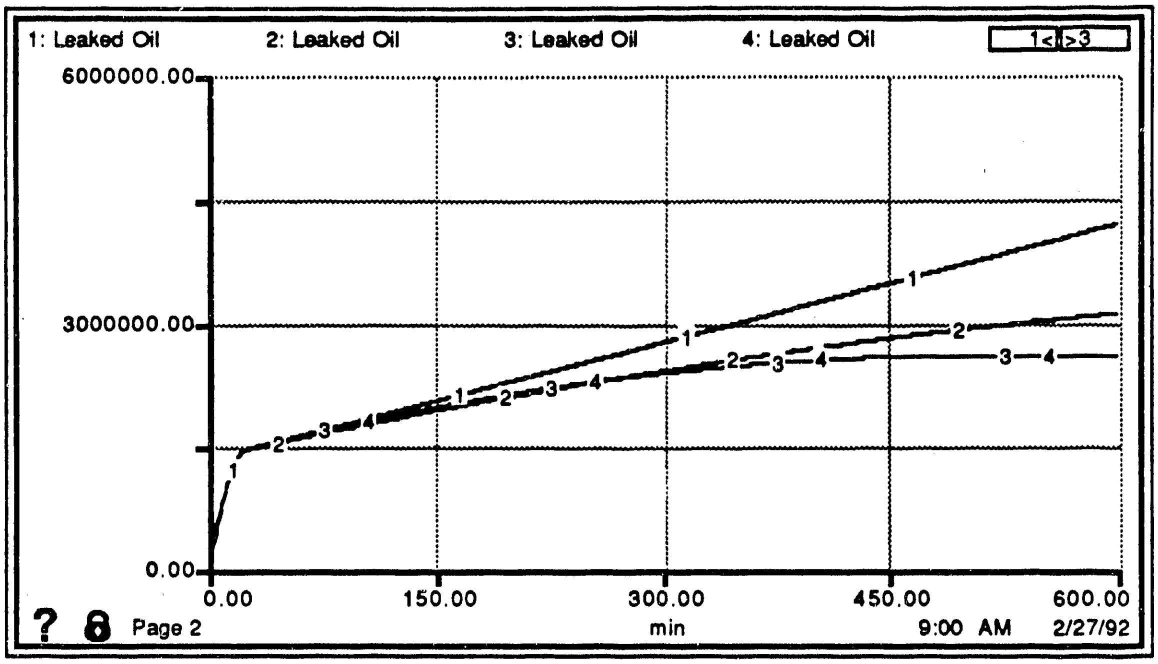
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 2.00 | 1.00 | 262000 |
| 2 | 2.00 | 1.00 | 262000 |
| 3 | 2.00 | 1.00 | 262000 |
| 4 | 2.00 | 1.00 | 262000 |

| Run # | RP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 600 | 600 | 600 |
| 3 | 600 | 600 | 600 |
| 4 | 600 | 600 | 600 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice |
|---|---|---|
| 1 | 2.30 | 1.00 |
| 2 | 2.30 | 1.00 |
| 3 | 9.80 | 1.00 |
| 4 | 14.8 | 0.75 |




Setup #4 2/27/92 8:58 AM

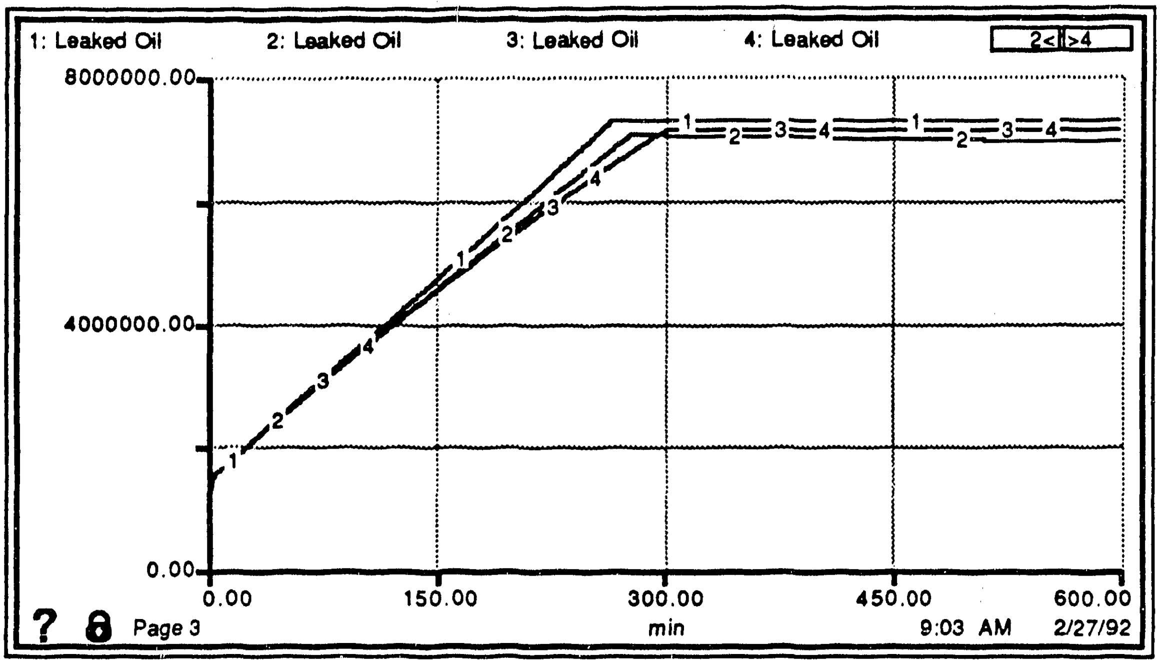
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 4.90 | 2.45 | 262000 |
| 2 | 4.90 | 2.45 | 262000 |
| 3 | 4.90 | 2.45 | 262000 |
| 4 | 4.90 | 2.45 | 262000 |

| Run # | RP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 600 | 600 | 600 |
| 3 | 600 | 600 | 600 |
| 4 | 600 | 600 | 600 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice |
|---|---|---|
| 1 | 2.30 | 1.00 |
| 2 | 2.30 | 1.00 |
| 3 | 9.80 | 1.00 |
| 4 | 14.8 | 0.75 |




Setup #5 2/27/92 9:00 AM

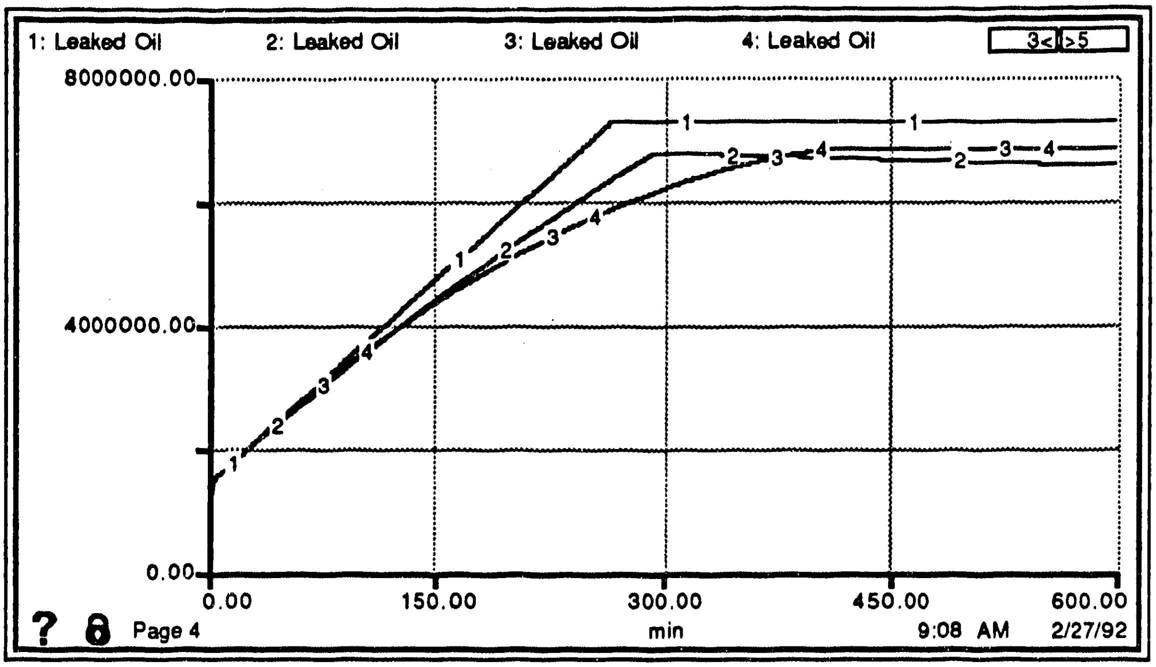
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 262000 |
| 2 | 12.0 | 6.00 | 262000 |
| 3 | 12.0 | 6.00 | 262000 |
| 4 | 12.0 | 6.00 | 262000 |

| Run # | BP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 600 | 600 | 600 |
| 3 | 600 | 600 | 600 |
| 4 | 600 | 600 | 600 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice |
|---|---|---|
| 1 | 2.30 | 1.00 |
| 2 | 2.30 | 1.00 |
| 3 | 9.80 | 1.00 |
| 4 | 14.8 | 0.75 |




Setup #6 2/27/92 9:06 AM

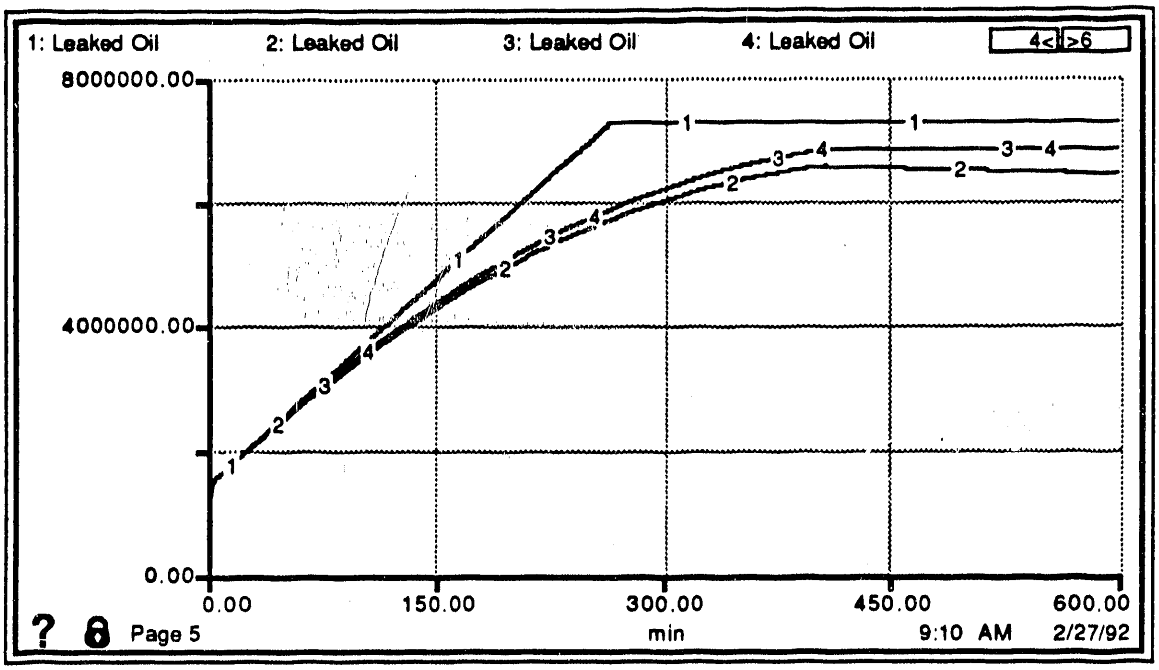
**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 262000 |
| 2 | 12.0 | 6.00 | 262000 |
| 3 | 12.0 | 6.00 | 262000 |
| 4 | 12.0 | 6.00 | 262000 |

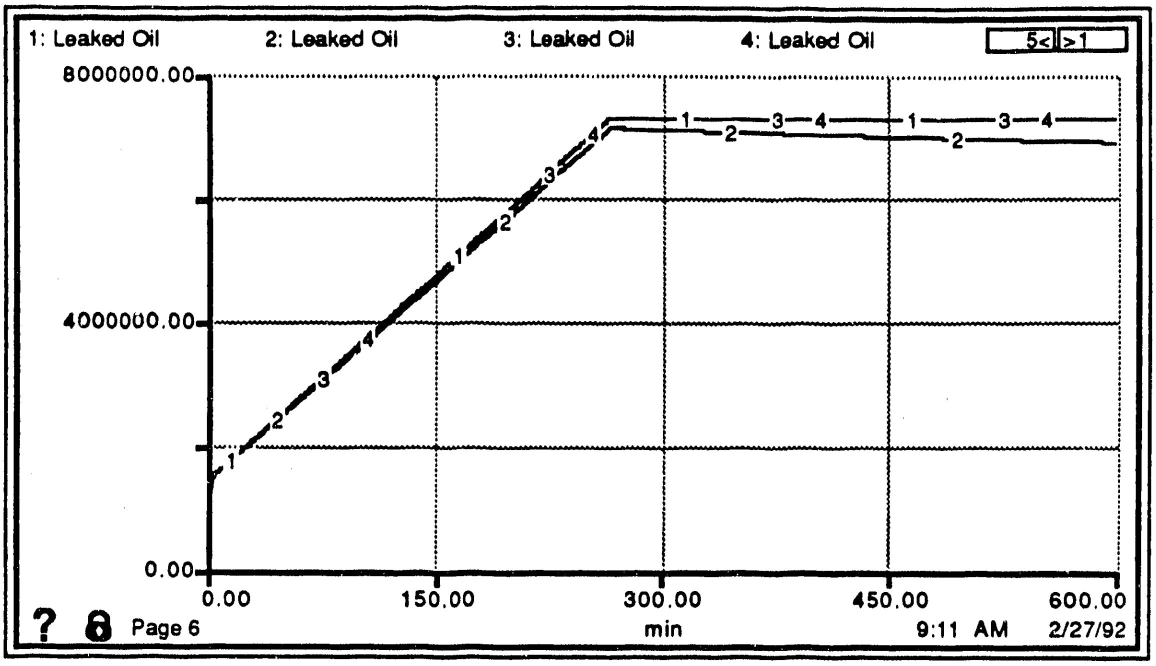
| Run # | RP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 1200 | 1200 | 1200 |
| 3 | 1200 | 1200 | 1200 |
| 4 | 1200 | 1200 | 1200 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice |
|---|---|---|
| 1 | 2.30 | 1.00 |
| 2 | 2.30 | 1.00 |
| 3 | 9.80 | 1.00 |
| 4 | 14.8 | 0.75 |




| Setup #7 | | | 2/27/92 9:08 AM |
|---|---|---|---|
| | **Input** | **Variables** | |
| Run # | H puncture | L puncture | Tonnage |
| 1 | 12.0 | 6.00 | 262000 |
| 2 | 12.0 | 6.00 | 262000 |
| 3 | 12.0 | 6.00 | 262000 |
| 4 | 12.0 | 6.00 | 262000 |
| Run # | RP rate | OBP rate | Drain rate |
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 0.00 | 1200 | 1200 |
| 3 | 0.00 | 1200 | 1200 |
| 4 | 0.00 | 1200 | 1200 |
| Run # | Wind in kt | Steady Current | Tides |
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |
| Run # | Wave Height | Snow Ice | |
| 1 | 2.30 | 1.00 | |
| 2 | 2.30 | 1.00 | |
| 3 | 9.80 | 1.00 | |
| 4 | 14.8 | 0.75 | |




Setup #8 — 2/27/92 9:10 AM

**Input Variables**

| Run # | H puncture | L puncture | Tonnage |
|---|---|---|---|
| 1 | 12.0 | 6.00 | 262000 |
| 2 | 12.0 | 6.00 | 262000 |
| 3 | 12.0 | 6.00 | 262000 |
| 4 | 12.0 | 6.00 | 262000 |

| Run # | BP rate | OBP rate | Drain rate |
|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 |
| 2 | 0.00 | 1200 | 0.00 |
| 3 | 0.00 | 1200 | 0.00 |
| 4 | 0.00 | 1200 | 0.00 |

| Run # | Wind in kt | Steady Current | Tides |
|---|---|---|---|
| 1 | 10.0 | 0.85 | 1.10 |
| 2 | 10.0 | 0.85 | 1.10 |
| 3 | 17.5 | 2.00 | 2.70 |
| 4 | 27.0 | 0.00 | 1.00 |

| Run # | Wave Height | Snow Ice |
|---|---|---|
| 1 | 2.30 | 1.00 |
| 2 | 2.30 | 1.00 |
| 3 | 9.80 | 1.00 |
| 4 | 14.8 | 0.75 |

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