A Systems Engineering Solution to Open-Sea Oil Spills

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A systems engineering approach was used to design an open-sea oil spill containment system. The major problem was to provide surface following characteristics in the presence of waves and currents. The critical parameter in solving the problem is the tension developed in the oil barrier. Orders of magnitude reduction in barrier tension was achieved by the Texas A&M Low Tension Barrier. The system is composed of an oil retention barrier connected at frequent intervals by elastic bridle lines to a main tension cable. The barrier responds rapidly in three dimensions without absorbing wave energy. The nature of the oil spill problem was identified, the hydrodynamic characteristic of oil interacting with a barrier on the surface of water under wind and current was determined, the barrier dynamics were predicted, and studies were made of packaging requirements, air delivery, and deployment. Although the barrier can be used for temporary containment, it is recommended that the barrier be used as a pump inlet for an active system to pump the oil into storage vessels as it builds up in depth against the barrier.

Problem Definition

Although pollution of the ocean and contamination of the shorelines from petroleum has been a problem due to natural seepage even before European trading vessels reached the shores of the North American Continent, the Torrey Canyon disaster and the Santa Barbara oil well blowout produced a public reaction calling for control of massive oil spills in the ocean. As a result, the United States Government has charged the United States Coast Guard with responsibility for controlling oil spills in the ocean as rapidly as possible in order to minimize the effects of such pollution.

The Coast Guard recognized that the total problem could be divided into distinct system requirements. Based on the observation that oil tankers rarely break up completely when they first become disabled, the first system was to provide a means of rapidly off-loading tankers that were disabled. The second requirement was to provide a containment system to hold spilled oil on the ocean in a local area until the oil could be removed. The third requirement was to develop a system for removing the oil from the surface of the ocean. The first system, that of unloading tankers, is being accomplished by the air deployed system called ADAPTS or Air Delivered Anti-Pollution Transfer Systems.

The containment problem requires a definition of the environment in which the system must operate. The environmental characteristics associated with the problem will be divided into physical, technical, business/political, economic and social.

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Environment

Physical

The physical constraints on the solution for removing oil from the ocean have two sets of characteristics. One set is the nature of the petroleum product being spilled and the volume and rate at which the spill will occur. The second set are those that limit the operations of the system being used to control the spill. The characteristics of the crude oil have been identified[1] as oil which will have a viscosity ranging between 1.4 and 1300 centipoise. The specific gravities will range from 0.729–0.982. The average crude oil will have a specific gravity of 0.87 and a viscosity of 84 centipoise. The oil viscosities and gravities will change due to temperature and exposure to wind, wave action and mixing with salt water. The largest changes are expected in viscosity which will increase two–ten times in a six-week period.

There are two distinct sources of oil spills; oil well blowouts and tanker mishaps. The maximum rate for an oil well blowout is approximately 10,000 barrels of oil per day but a most probable spill would not exceed 1000 barrels per day. The total volume depends upon the length of time that the well is out of control. The principle United States offshore oil producing areas are Alaska, California, and the Gulf Coast of Texas and Louisiana.

The volume of oil resulting from a tanker mishap will be a maximum of 110,000 barrels of oil, but a probable spill will average 50,000 barrels of oil. The rate is quite variable depending upon the total number of tanks ruptured and the manner in which the rupture occurs.

The environmental conditions related to atmospheric and ocean conditions can be fairly well determined for conditions under which a spill would occur and could be contained. Under certain climatic conditions the oil will not remain on the surface of the ocean. For example, a driving rain storm will mix the oil and water and disperse it through the ocean. Similarly, breaking waves will drive the oil into the water column. These limitations will provide the upper limit in which a containment removal system would be required to operate. An examination of the weather conditions for those areas in which an oil spill is most likely to occur results in the following averages: winds, 18 knots, surface temperature of the water will range from 40°F–83°F with an average of 65°F, and currents will range between 0.34 and 2.0 knots.

The Coast Guard requested that the oil containment barrier perform effectively in 5-ft significant seas combined with 20 mph winds and 2 knot currents. They also requested that the physical integrity of the barrier be retained in 10-ft significant seas with winds of 38 mph.

Technical

The time factor was established by the Coast Guard, who requested that the oil containment system be deployed within 4 hr after notification of a potential spill. Such a response time is feasible because of the current state of air delivery technology and the availability of Coast Guard and contract vessels in emergencies. Aircraft are available to transport 25,000 lb and air drop them with a high degree of accuracy. Coast Guard vessels are available approximately every 60 miles along the United States continental coastline. They can be dispatched within 10 min with the capability of staying on station for periods up to 12 hr. Oil company workboats, tugs, transport vessels, and other commercial vessels are generally available for emergency requirements in offshore oil producing areas and tanker lanes. These vessels have a speed capability exceeding 10 knots. Within 3 hr they could reach locations 30 miles from their initial dispatch point. Workboats and sea-going tugs have a capability of remaining on station for periods of time up to several weeks, however, the Coast Guard vessels cannot exceed 12–24 hr without a major loss in operational efficiency.

Business/political

The National Oil and Hazardous Materials Pollution Contingency Plan of June 1970 required that there be established at major ports, to be designated by the President, emergency task forces of trained personnel, adequate oil pollution control equipment and material, and a detailed oil pollution prevention and removal plan. The United States Coast Guard must furnish the on-scene commander and will direct the operation of any government owned specialized pollution clean-up equipment. In addition, the government is currently planning that penalties be placed on those who contribute to oil spills. The blow outs of oil wells both on the California coast and Gulf coast resulted in a temporary halt to drilling because there was no adequate means of controlling oil spills. The Union Oil Company in the Santa Barbara spill suffered a major expense in cleaning up the pollution created by the blow out of their well as did the Chevron Oil Company in attempting to control the oil flowing from their well in the Gulf coast off New Oreleans. Consequently, the development of an adequate system to control oil spills in the ocean is necessary to continue normal oil production and transport. This is even more important as the shortage of energy requires the additional drilling and production of petroleum products.

Economic

In order to establish the value of an oil spill containment device, it is well to review the economic considerations related to offshore oil production. At the present time less than one percent of the outer continental shelf, some 9375 square miles, is under lease and has yielded 4.4 billion dollars to the United States Government. The Santa Barbara leases totaled $603,000,000.[2] The United States had also received 1.3 million dollars in royalties from the Santa Barbara area before the spill. The Santa Barbara spill was estimated at approximately 100,000 barrels of oil.[3] During the shutdown of Santa Barbara, it was estimated that more than $100,000 a day was lost to the production companies. Humble estimated their loss during the Santa Barbara shutdown at more than 1.75 million dollars in drilling operations during the shutdown.[4] This reduces not only income to the state and federal government but also reduces potential oil reserves.

An additional problem that faces the oil producing companies is the potential losses resulting from lawsuits. As a result of the Chevron spill more than 101.5 million dollars in lawsuits were filed against the oil company.[5] More than 2 billion dollars in lawsuits were filed as a result of the Santa Barbara spill. In addition to the direct immediate costs that can be established, there is also the problem relating to energy reserves for the nation. At the present time the United States is consuming approximately 4.7 billion barrels of oil[2] and in 1968 had a estimated 30.7 billion barrels in reserve. It is necessary that offshore reserves continue to be developed if the nation is going to adequately supply the energy required for the 1980's. Consequently, the spending of several million dollars for the development and operation of oil containment systems on the open ocean would seem adequately justified for both the United States Government and the producing oil companies.

Social

The potential danger of oil spills with the resultant damage to beaches, pleasure boating, valuable marine fisheries and damage to wildlife is a major concern of the nation today. The prevention of pollution of our natural resources has resulted in the strong measures that have been taken recently by federal and state authorities. Oil on the ocean is a particularly objectionable problem due to the visibility and long time presence of the weathered oil. The only solution that is acceptable to the public is one which contains and removes the oil from the surface of the ocean without dispersion through the water column.

System Design Requirements

Response Time

The time for deployment of an oil containment system is related to the rate at which the oil is being spilled, the weather, wind, waves and currents and the speed at which the oil spreads over the surface. The magnitude of this problem is illustrated in Fig. 1. This example indicates that in four hours a large oil spill can have very large geometric characteristics. Consequently, the time constraints of 3–4 hr would be the most reasonable constraints that could be placed on the systems design.

Deployment

The system must be packaged in such a manner that it can be loaded onto Coast Guard Aircraft and airdropped at the scene of an oil spill. The package should be towable to allow its being positioned in a proper place by either boats or helicopters. It would be desirable to deploy and move the barrier in position using only helicopter-type vehicles, but this is impractical because of the loads that are encountered in the deployment operation. This is illustrated in Fig. 2 which indicates the loads that would be encountered in attempting to position a 3000-ft-long barrier in the presence of ocean currents. Since currents are quite common, it is not reasonable to design a system for helicopter deployment that would be restricted to locations where only small currents exist. It is essential that deployment can be accomplished by relatively inexperienced crews with a minimum amount of instruction either in the form of written instructions on the package or instructions that can be relayed by radio from an on-scene commander. The system should be designed so that available boats, such as 44-ft Coast Guard Cutters, could tow the barrier into position and maintain it on station for 12–18 hr until ocean-going tugs could be dispatched to the scene to provide the longer station keeping capability.

Operational Requirements

The barrier must be able to be positioned in such a manner as to intercept the motion or movement of the oil spill. Since

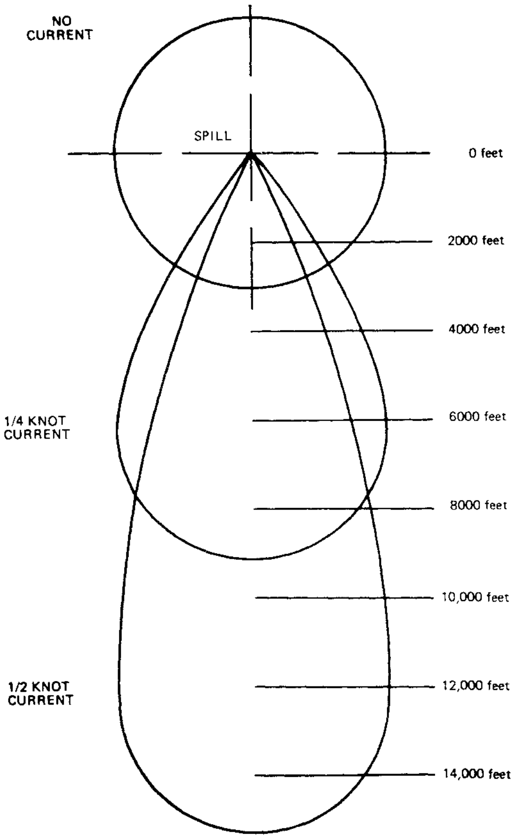

Fig. 1 Expected shape of a 50,000 barrel per day oil spill four hr after occurrence.

the oil spill's motion is subject to changing winds and current with time, the barrier must either totally surround the spill or be capable of being moved to accommodate the changes in direction. The primary characteristics of the barrier is that it be able to follow the surface of the ocean. Since oil floats on top of water, the barrier must not be pulled under or be pulled out of the ocean due to wave and current interaction. Because the sea-keeping capability of a floating flexible barrier is a function of the tension in the barrier it is essential that the tension be maintained at a relatively low level. A maximum recommended value for tension in the oil retention skirt is 20 lb. Because the wave motion is orbital in nature, the barrier must move back and forth with the waves to minimize the relative velocity. This criteria established a recommended minimum velocity increase of the barrier with respect to the ocean of 1 knot in a 6-ft-wave.

The barrier should be capable of operating in any sea that is not a breaking sea. Because oil on the surface of water affects the wave breaking characteristics, it may be possible that higher waves could occur than those that normally begin breaking due to the action of wind. The barrier should act as an effective containing device up to currents of 0.9 knots and should act as an effective barrier to increase the thickness of the oil at the barrier at currents up to 3 knots. The barrier should be designed so that it can be coupled with a pumping system to provide an active barrier for currents above 1 knot.

Retrieval

The barrier should be designed so that upon completion of clean up operations the barrier can be retrieved using Coast Guard 180 ft buoy-tenders.

Systems Synthesis

System Description

The Texas A&M Low Tension Barrier System is a barrier packaged in a container that can be parachuted from C-130 type aircraft into the ocean at the location of a potential oil spill and rapidly deployed into position to intercept the oil spill by any two available ocean-going vessels without special equipment. The barrier is composed of an oil retention skirt that has three feet extending below the surface of the water and one foot of free board to prevent waves from splashing over the barrier. The oil retention skirt is attached at two foot intervals by 25-ft-long elastic bridle lines to a main tension cable that is held by the boats as shown in Fig. 3.

The system is designed to be deployed and moved about by two vessels rather than providing a buoy-anchor system.

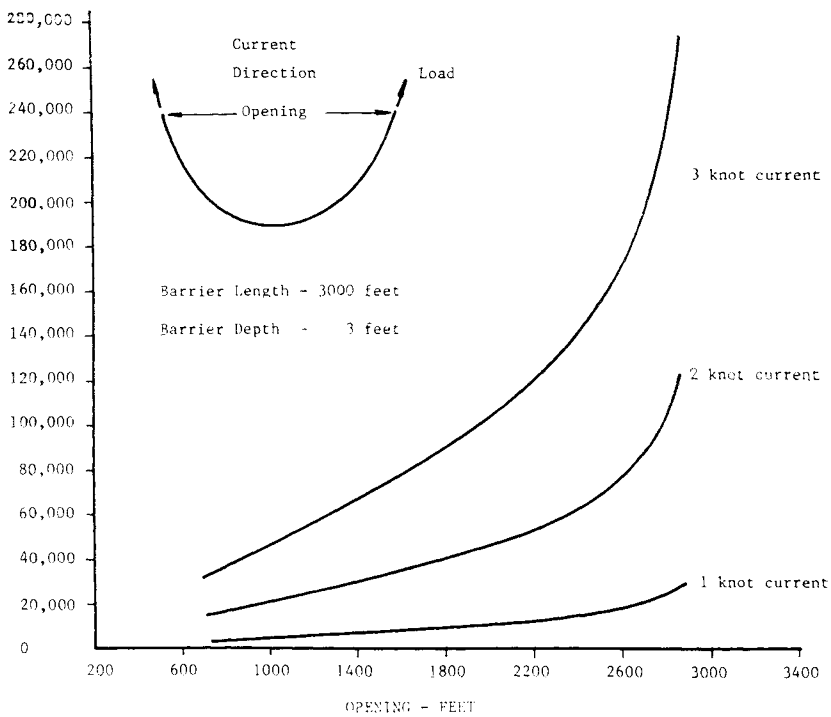

Fig. 2 Loads required to hold a 3-ft-deep, 3000-ft long barrier in the presence of currents.

This will provide the capability of positioning the barrier to respond to the changes of wind and current direction. Where conditions would allow mooring, then the anchors for the boats can be used to provide a mooring capability. To include airdroppable mooring system apart from boats would place an exceedingly difficult constraint on the air deployment capability. It was initially considered that a barrier would be placed in a manner to totally surround the spill but this is difficult to accomplish because of the necessity in every case to provide operational access of work vessels to the spill in the effort to bring it under control; whether it is a tanker, an oil well blow out, or an oil pipeline rupture. In addition, the deployment with boats allows the use of the system as a towed skimmer system to clean up large areas.

Design details

The essential features of Texas A&M Low Tension Barrier are detailed in Fig. 4. Referring to the numbers, the main elements are: 1) main float—sized to react the downward vertical component of the force in the elastic bridle lines; 2) main stiffener—48 in. in height; 3) horizontal stiffeners which prevent sag in freeboard; 4) intermediate vertical stiffeners; 5) weight housed in main stiffener to counteract upward forces when main tension cable is at a higher level than the skirt; 6) weight in bottom of intermediate stiffener to provide stability; 7) elastic bridle lines which allow the skirt to move horizontally in response to the waves; 8) main tension line (braided nylon), polypropylene end sections equipped with load limiting fuses; 9) stabilizer lines; 10) lower reinforcement; and 11) horizontal reinforcing tapes.

The barrier will be packaged in a sealed container that maintains an inert gas (dry nitrogen, for example) atmosphere to prevent deterioration of the rubber shock cords and other polymeric materials from which the barrier is made. Several ideas were presented by potential subcontractors on the design of the airdroppable package. A final design was not selected. However, the package would have outside dimensions compatible with that of the cargo hold of the C-130 type

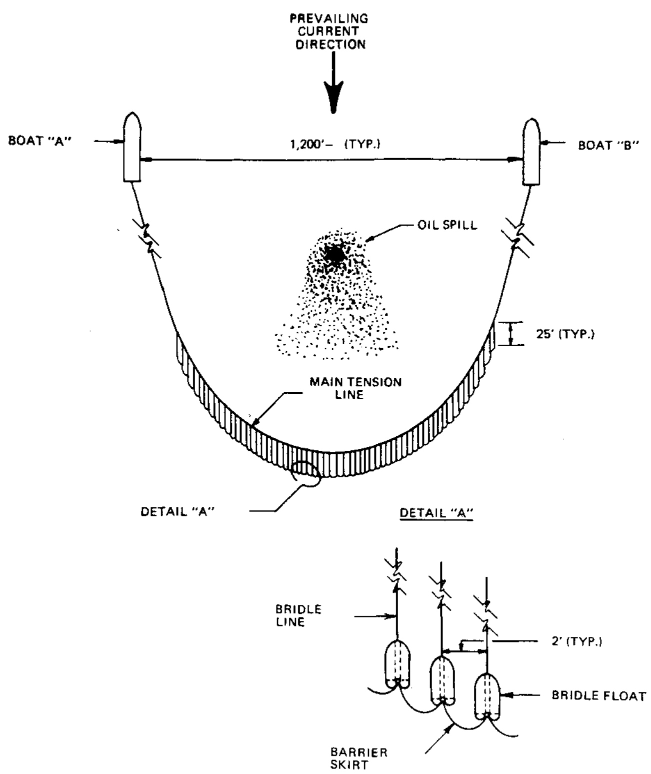

Fig. 3 Plan view of the low-tension barrier system.

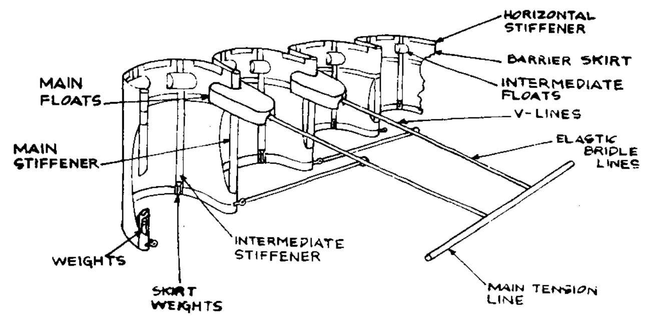

Fig. 4 Details of the low-tension oil containment barrier.

aircraft. The barrier length is limited by the weight that can be airdropped. Multiple barriers can be deployed to intercept any width or control any size oil spill.

The design was developed through a number of trade-off studies to optimize the various parameters. For example, the depth of the skirt was varied from 1–6 ft and the bridle line separations were varied from 2–30 ft with skirt sag opening ratios of $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$. The flotation study disclosed that both floats and weights were required to resist the vertical load components in the bridle lines. This problem is illustrated in Fig. 5. The numbers are typical for a 2-ft-deep skirt with 30-ft-long bridle lines attached to the skirt. The difference in force at the top of the wave and the bottom of the wave is due to the increase in current because of the relative motion of the wave adding to the current at the top and subtracting from the current at the bottom. The illustration shows that because the main tension cable is relatively stationary in the water, when the barrier is in a trough there is an upward force acting to pull the barrier out of the water. This force must be counteracted with sufficient weight of the system to maintain the barrier in the water. Conversely, when it is at the top of a wave, there is not only a greater downward force due to the tension in the bridle line resulting from the higher current but the added weights increase the flotation required to maintain the barrier at the ocean surface. The geometry and attachments to the bridles resulted from considerations of providing a best response of the barrier to the rapid motions of choppy waves and also prevent entanglement of the bridle lines during deployment. The bridle lines were designed to minimize the absorption of wave energy. If the barrier system is considered as a wall and cannot move back and forth with the waves, obviously the momentum of the waves would have to be reacted by the wall and would result in considerable splash at the wall as the momentum is exchanged between horizontal and vertical surface velocities. However, if the barrier is free to move with the waves then the relative velocity of the water with respect to the skirt is reduced and the splash is also lessened. Some typical design data is shown in Table 1. For the 25-ft-long bridle lines when the spring constant is increased from 10 lb per ft–30 lb per ft, the maximum bridle force is increased from 170 lb–225 lb. Also the maximum relative velocity is increased from 4.8 knots–5.9 knots due to the higher stiffness bridle lines. The bridle stiffness must be kept very low in order to reduce the force on

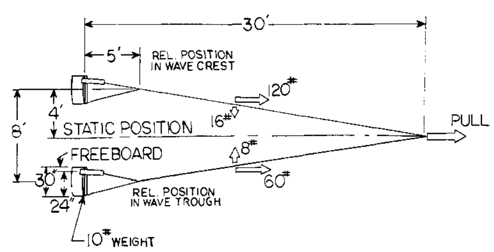

Fig. 5 Force diagram of bridle lines at the high and low positions due to waves.

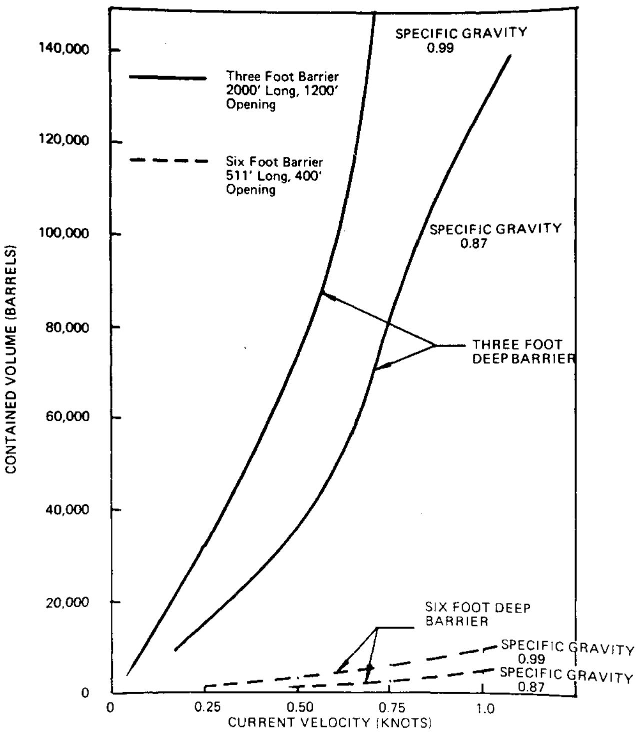

Fig. 6 The containment capacity of equal weight barriers three and six ft deep.

Table 1 Design data for a 3-ft-deep barrier in a 2 knot current[a]

Description			
Spring constant #/ft	10	20	30
Mass in slugs	0.52	0.52	0.52
Volume in cu ft	0.79	0.79	0.79
Float depth in ft	0.33	0.33	0.33
Maximum length at bridle under load forward side of wave	41.99	35.63	33.45
Minimum length of bridle under load back side of wave	33.62	27.50	25.71
Maximum bridle force	170.134	213.43	255.40
Minimum bridle force	86.275	50.19	22.32
Freeboard maximum	1.120	1.137	1.144
Freeboard minimum	0.9715	0.9276	0.8877
Relative velocity	4.878	5.441	5.921
Maximum vertical motion	4.701	4.652	4.608
Minimum vertical motion	−3.491	−3.484	−3.489
Bridle length at valley	37.19	30.427	27.99
Bridle length at crest	38.45	32.549	30.97
Maximum force for vertical component (float)	137.35	157.59	189.54
Minimum force for vertical component (weight)	123.60	112.517	96.49
Freeboard at wave crest	0.9734	0.9371	0.9013
Freeboard at wave valley	1.118	1.127	1.12
No load length	25.0	25.0	25.0
Float position	1.17	1.17	1.17
Barrier depth	4.0	4.0	4.0

[a] With waves 8 ft high, 146 ft long and a 5.36 sec period.

the barrier and the accompanying deleterious effects. The main tension line was designed with breakable fuse links near the boats in order to insure that if the line fails it would not fail in an area where oil was being contained.

Another interesting study was a comparison of equal weight barriers, one 3 ft deep and the other 6 ft deep. Approximately 2000 ft of a 3-ft-barrier could be packaged for airdrop. The same weight 6-ft-deep barrier would be 511 ft long. The oil containment characteristics of these two systems are shown in Fig. 6. The results were only carried out to one knot because entrainment occurs at this velocity. What is surprising is the greater capacity of the 3 ft barrier.

Systems Analysis

The analysis is divided into three separate areas. One was the development of the necessary equations to predict the interaction of the barrier and oil floating on the water under the effect of wind and current. The second area was to determine the amount of oil that could be contained in various geometries and current conditions. And the third was the development of the barrier dynamics.

Oil Setup

Oil setup due to wind

A two-dimensional equation for the setup of floating oil due to the wind generated surface stress was developed and

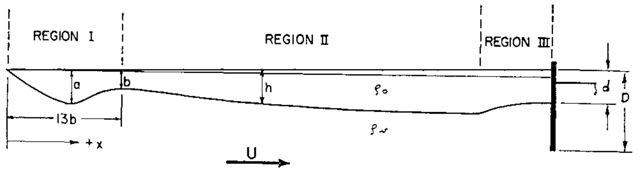

Fig. 7 The cross-sectional view of an oil spill interacting with a barrier as a result of ocean currents.

reduced to the following equation

$$d_0/L = [2C\ \rho_w/\rho_0]^{1/2}(U/g'L) \tag{1}$$

where d_0 is the depth of the oil at the barrier, L is the fetch length, ρ_w is the density of water, ρ_0 is the density of oil, U is the wind velocity, $g' = g(1 - \rho_0/\rho_w)$ where g is the acceleration of gravity, C is a drag coefficient for the shear at the air-oil interface and will be determined from laboratory tests. Equation (1) indicates that the dimensionless set up, d_0/L, is a function of the densiometric Froude number, $U/g'L$, and was substantiated experimentally. The experimental tests were run in a 2-ft-wide, 3-ft-deep × 120-ft-long wind-wave flume. Tests were run for 20 mph and 40 mph winds.

Oil Setup by Current

Experiments were conducted to study the geometry and behavior of an oil layer floating on a flowing stream of water interacting with a barrier. The geometry of the oil setup behind a barrier, as a result of current, can be divided into three distinct regions as shown in Fig. 7. Region I is considered the head wave region. It was found to have a characteristic shape. The neck of the head wave occurs at a distance equal to $13b$ where b is given by the equation

$$b = U^2/3.5g(1 - \rho_0/\rho_w) \tag{2}$$

Three failure mechanisms, which allowed oil to pass the barrier, were identified in the testing program. At low water velocities, up to 1 fps, the failure mechanism is primarily due to the oil building up to a thickness exceeding the depth of the barrier and a continuous flow of oil past the barrier occurs. It was found that the failures could be related to the densiometric Froude number

$$F_{cr} = U_\infty^2/g(1 - \rho_0/\rho_w)(D - d) \tag{3}$$

The critical Froude number for the low velocity failure is about 5. As the water velocity is increased, interfacial wave action against the barrier occurs in region II and the interfacial wave action causes intermittent failures at lower Froude numbers. In the velocity range from 1.0 fps–1.6

Table 2 Containment volumes and bollard pulls for a 3-ft-deep, 2000-ft-long barrier[a]

Opening ft	Current knots	Bollard pull lb	Contained volume-barrels Specific gravity 0.80	0.87	0.94
600	0.5	3,880	31,822	36,884	47,998
600	1.0	7,750	79,570	92,164	24,490
900	0.5	5,950	42,176	48,801	63,501
900	1.0	11,900	71,670	122,119	38,294
1,200	0.5	8,250	46,346	53,639	69,816
1,200	1.0	16,500	116,805	134,975	54,513
1,500	0.5	11,300	42,398	49,093	63,936
1,500	1.0	22,600	107,876	125,036	75,816

[a] In 20 mph wind and 4 ft waves.

fps, intermittent failure occurred at a critical Froude number at about 2.5. At water velocities above $1\frac{1}{2}$ fps failure by entrainment became significant. All along the oil-water interface breaking waves occurred and a continuous formation of liquid particles having a core of water surrounded by a layer of oil were created at the interface. The particles have a density very near that of water and most of them flow under the barrier. Those which are retained behind the barrier are persistent and form an oil-water froth behind the barrier. The entrainment phenomena occurred with very different oils with the only difference being in the size of particles. Using SAE 10 motor oil the particles ranged from about $\frac{3}{8}$ in. in diam–$\frac{3}{4}$ in. in diam. Using diesel fuel, the range was $\frac{1}{8}$ in.–$\sim\frac{3}{8}$ in. in diam.

Region II is the region in which the majority of the oil is located when a barrier is used as a containment device. Flow in this region is dependent not only on gravitational forces but also on the viscous forces caused by the shear stress at the oil-water interface. The shearing action tends to pull the oil near the oil-water interface in the direction of the current. However in order to maintain a steady-state setup, continuity considerations require that the oil velocity oppose the direction of the current near the air-oil interface so that the net flow across any cross section vanishes. The thickness of the oil in region II can be calculated by Eq. (4) where ν_w is the kinematic viscosity of the water, τ_s is the shear stress of the surface, C_i and n are parameters that must be determined experimentally.

$$h = \left(\frac{U^2(x - 13b)}{g(\rho_0/\rho_w)(1 - \rho_0/\rho_w)}\left\{C_i\Big/\left[\frac{U(x - 13)}{\nu_w}\right]^{1/n} + \tau_s\Big/\tfrac{1}{2}\rho_w U^2\right\} + b^2\right)^{1/2} \quad (4)$$

The results of the experiments indicated that n was fairly constant at a value of 5. C_i was not constant but had a value of approximately 0.1 at 1 fps and 0.2 at 1.5 fps. Above this value the interfacial waves break and the equation is no longer valid. For lower current values, C_i would approach the smooth flat plate value of 0.058. The values were determined experimentally by running tests under the condition where the shear stress at the free surface τ_s is equal to zero because of an absence of wind velocity. These equations and limitations allow evaluation of the barrier for flow conditions up to approximately one knot.

Oil Retention Characteristics

It is interesting to examine the capability of the Low Tension Barrier for the containment of oil up to velocities of one knot. Using the equations developed previously, the containment characteristics of various geometry barriers can be determined. A typical example is shown in Fig. 8. It is possible to contain up to 100,000 barrels of oil with a barrier 3 ft deep, 2000 ft long with a 1200 ft opening under 4-ft waves and a 20 mph wind. However, Fig. 8 also illustrates the criticality of various parameters. For example, waves cause a relative velocity at the barrier high enough to reduce the critical Froude number for the high density oils. Entrainment was not considered a function of relative velocity, only the current velocity. When the current drops below 0.25 knots there is a rapid decrease in containment capability which is not plotted. However, there is a high degree of probability of having conditions in which the current ranges from 0.25-0.75 knots and the barrier would be very useful for containing oil until storage capacity could be deployed to the scene.

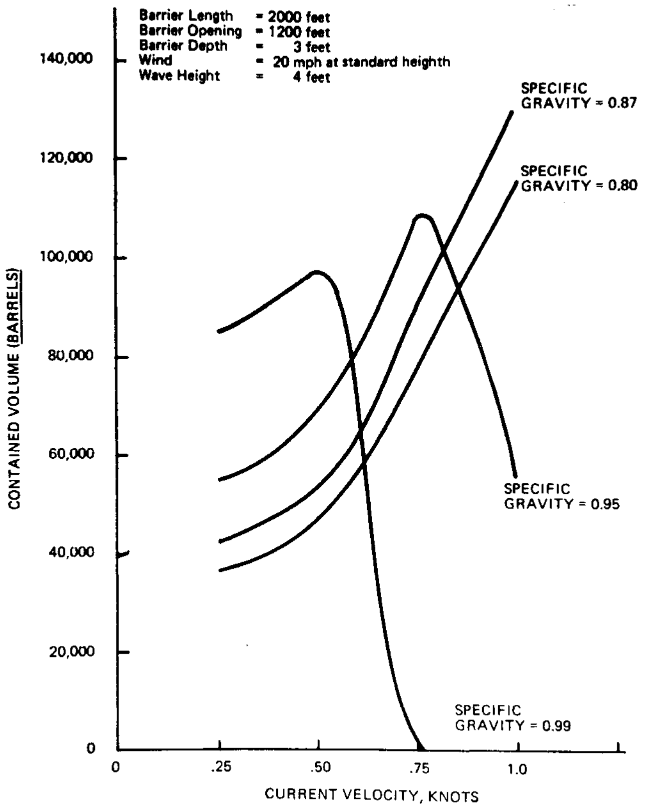

Fig. 8 The containment capacity of a low-tension barrier in the presence of wind, waves and current.

Table 2 provides some values for the contained volume and also the bollard pull required to maintain the 3-foot-deep barrier in various opening configurations. This allows the prediction of the volume that could be contained by boats with restricted bollard pull capabilities. It is assumed that a long wave essentially acts against the barrier with the same relative velocity occurring over the entire length of the barrier. Because this is not true, the numbers are conservative in that the bollard pulls would be somewhat less and the contained volume would be greater than that indicated by the table.

Barrier Dynamics

Several computer models were developed to analyze the dynamics of the barrier. An elastic model was found to be very accurate but involved such a large amount of computer time that it was not considered practical. Two rigid models were developed and were used for design and were substantiated by tests. The first was a two degree-of-freedom rigid model which analyzed the barrier system by considering a single stiffener having translatory motions in two directions and attached to a bridle line. The bridle line is represented as a spring and the model assumes each section to be independent of the other. This model was verified by using a two-dimensional model of the barrier in the wave tank and subjecting it to combined current and waves. The bridle line tension was measured and recorded. The measured and pre-

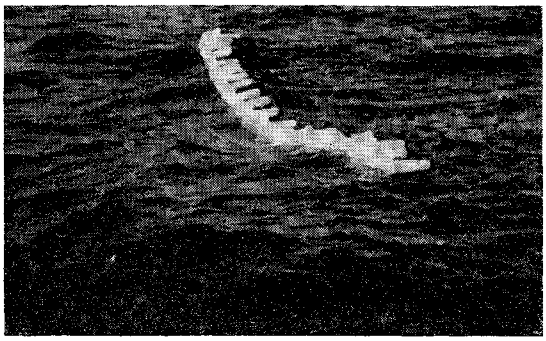

Fig. 9 Photograph of the low-tension barrier deployed in the Gulf of Mexico.

dicted bridle tensions were in excellent agreement as was the response of the computer model and the test barrier. This model was used to determine design curves for various barrier geometries.

A four degree-of-freedom rigid model was also developed which idealized each stiffener as a rigid body under the action of constant, velocity-dependent, time-dependent or displacement-dependent forces. Four degrees-of-freedom are assigned to each rigid stiffener: three principle translations of the stiffener and a rotation about the mass center. This type of representation neglects out of plane rotation but allows rigid body translations in three directions. By specifying this type of motion only the most significant rotation of the stiffener is retained, and as a result the numerical formulation of the equations of motion produced a completely uncoupled set of equations. This allows the solution of a large system in a realistic amount of computer time. Even though the equations of motion are written separately for each stiffener, the forces depend upon the displacements of adjacent stiffeners. In this manner the combined effect of all the stiffeners is incorporated into the system response. The response predicted by this model has compared favorably with observations made for the full scale tests of a 20 section barrier under actual sea conditions. However, no transducer measurements have been made for verification.

Compatibility

This system has been designed to be compatible with existing Coast Guard boats, equipment, personnel, C-130 aircraft and typical Air Force loading equipment. The use of boats as a mooring system for the barrier was chosen for flexibility in responding to the direction of movement of oil slicks. The system was designed so that it can be deployed using any two boats with nominal towing capabilities greater than 8000 lb. The only requirement for the boats is that they can take a line aboard and tow the barrier into the proper position. To maintain large openings (1200 ft) in currents of 2 knots requires boats with bollard pull capacities of 25,000–30,000 lb. Most Coast Guard motor lifeboats and buoy-tenders have this capacity but many commercial boats are also available. For example, standard 110 ft ocean-going tugs have bollard pulls of 56,250 lb. A typical offshore supply vessel 160 ft long has a bollard pull of 45,000 lb. Some ocean tow vessels 120 ft long with 4000 horsepower have bollard pulls of 120,000 lb. Therefore practically any ocean-going vessel normally used for oil supply work could be pressed into service for the oil spill containment and clean up.

Studies of aircraft capable of air delivering the Texas A&M Low Tension Oil Containment System were based on the capability of the Air Force C-130. Other aircraft that are considered suitable are the C-141 and C-5A aircraft because they also use the 463-L loading system. The main factor influencing the suitability of aircraft is their airdrop air speed, which is an indication of attainable airdrop accuracy. Of the aircraft examined, the C-130 had the lowest airdrop air speed at 120 knots. Another factor is the availability of aircraft on short notice. The United States Air Force, which is charged with emergency support of the United States Coast Guard, has large numbers of C-130 aircraft on emergency stand-by status. The cargo compartment capacity and weight limitations constrain the size of the airdrop system to approximately 25,000 lb. The compartment constraints dictated package dimensions of 24 ft long, 9 ft wide and a height of 8 ft. Range estimates of the C-130 with a 25,000-lb airdrop capacity were made for a total gross weight of 108,000 lb, a cruising altitude of 20,000 ft and a fuel load of 12,000 lb. The range of the C-130 is 8700 miles. This capability is sufficient to reach all continental coastal areas within two hours from Air Force bases having cargo aircraft with most oil producing areas being accessible within a 1 hr flight time.

Systems Tests

The barrier model test was conducted in the laboratory, in Lake Somerville and in the Gulf of Mexico.

Laboratory Model Tests

Tension effects tests

A test was designed to study the effect of tension in a flexible simulated barrier consisting of floats and weights attached to a tension line. An 8-ft nylon string with floats and weights evenly distributed was designed to provide good wave conformation for an 8-ft-long and 8-in.-high wave with a line tension of 2.5 lb. The model was tested by placing it in a wave tank and securing each end so that a constant tension could be held on the line under the effect of waves. The model was observed under zero tension and applied tension loads to 30 lb. Excellent conformity with the wave surface was achieved with zero tension on the model. As the tension was increased the line deviated more from the wave surface but good conformity was observed until the design tension of 2.5 lb was exceeded. The test with 30 lb of tension resulted in very little motion of the floats from the horizontal. The floats completely submerged appearing to move approximately 1 in. in the 8 in. waves.

Elastic bridle line tests

A test in the laboratory was made in the wave tank to examine the motion of a barrier attached by elastic lines and to validate the two-dimensional rigid computer model. The elastic bridle lines were instrumented to measure the forces in the bridle lines. Visual and photographic observations were made. One important observation was the lack of splash at the barrier when a wave passed. The measured forces in the bridle lines were predicted very accurately by the computer model.

Full-Scale Tests

Lake tests

A three section test model with a 2-ft deep skirt and 6-in. free board was tested in Lake Somerville. Each section was 3-ft long with a 2-ft opening. The bridle lines were braided nylon with a relatively high spring constant. The tests were qualitative in nature and provided information related to entanglement problems, the stability of the floats as a function of the connection to stiffeners and reinforcement requirements for the free board. Design changes resulted from these tests.

Gulf of Mexico tests

A 20 section barrier was constructed for tests in the Gulf of Mexico. The barrier skirt was 2-ft-deep with a 6-in. free board. The total length of the skirt was 60 ft but the bridle lines were connected at 2-ft intervals to result in a deployed barrier length of 40 ft. Floats were pinned to intermediate stiffeners and the lead weight necessary for good wave following was contained in the lower portion of the main stiffeners. A short length of chain was used to weight the center portion of the skirt. The total weight of the barrier was approximately 6 lb per ft. The bridle lines were manufactured from elastic cord designed for aircraft use with approximately 10 lb per ft spring constant. The main tension line was made of braided nylon.

The first test was performed by anchoring the boats and observing the response of the barrier to waves under conditions of a wind driven current of approximately 0.25 knots. The wind was approximately 10–12 mph, waves were approximately 2-ft-high in the sea with 4–5-ft wave heights created by the use of the third boat. Breaking waves were created both from the upcurrent and down current sides of the barrier to observe the response. The barrier conformed closely to the ocean swells and choppy surface and to the 4–5 ft-breaking waves generated by the third boat. Towing tests were made at various speeds. Low-speed tows were made to observe the response to wave action under currents and the structural integrity of the barrier was tested by towing at 5 knots. The barrier showed a good response to waves at currents up to 2 knots, some tendency to submerge was indicated at 3 knots and at 5 knots the barrier was almost totally submerged but it retained its structural integrity. The only problem observed was some splashing over the top of the barrier under the highest breaking waves. It is felt that extending the 6-in. freeboard to 9 or 12 in. would prevent such splash over. Incidentally, the tests were run approximately 10 miles offshore from Freeport, Texas and when the barrier was retrieved, oil stains were found on the barrier skirt. A photograph of the deployed barrier and the wave conditions is shown in Fig. 9.

Recommendations

Active Barrier

It is recommended that the Texas A&M Low-Tension Barrier be combined with a pumping and storage capability in order to prevent ecological damage resulting from oil spills in the open ocean. Although the barrier can be used as a containment device in a large number of oil spills for short periods of time, it can be a completely effective barrier by making it an active barrier using the low-tension skirt as a pump inlet.

Full Scale Oil Test

It is recommended that a barrier of 600-ft deployed length be tested in the Gulf of Mexico with a simulated oil spill, using a vegetable oil, to determine the interaction of the barrier with oil under actual operating conditions. The barrier could be towed to simulate various currents and could be tested for various wave heights by using a third boat to create waves.

Systems Studies

It is recommended that studies be initiated to determine the best strategy for barrier deployment and geometric configuration to control anticipated oil spills. The study performed for the United States Coast Guard considered only the possibility of airdropping the barrier but it would seem reasonable that the barrier and boats can be deployed from shore locations, from the oil well platforms or even from tankers as rapidly as it could be airdropped. The pumping capability could be supplied from a modified ADAPTS for immediate response and in most oil producing areas or tanker lanes, tankers or other oil storage tanks could be transported to the scene within a reasonable period of time after the barrier was deployed. Trade-off studies should be made to determine what is the most effective depth barrier. It would appear that a 2-ft or 3-ft depth would be satisfactory but the depth should be traded off with length of barrier to obtain the best geometric configuration for intercepting the potential spill. The determination of the best length or the deployment of multiple barriers should be examined to include the effective redundancy to insure that the oil spill does not escape the spill area. Since the U. S. Coast Guard has awarded a contract for the development of an air-deployed barrier it would seem reasonable that the Coast Guard or the oil industry, through such an organization as the American Petroleum Institute, should immediately institute a one year, $500,000 prototype development program to provide a back-up system with the accompanying systems study.

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