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OFFSHORE FUEL-UNLOADING SYSTEM: A PILOT STUDY.(U)

JAN 78 O R PANNELL, F M CEVASCO

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OFFSHORE FUEL-UNLOADING SYSTEM:

A PILOT STUDY

by

O. R. Pannell

and

F. M. Cevalco

January 1978

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The study examines various operational significant variables (e.g., nearshore gradient, weather, and fuel demand); it also examines the forces which a conduit must be capable of withstanding. The findings of the initial analyses were subsequently applied to the identification of several solutions which appeared to offer substantial advantages when compared with the present standard system. One technically feasible alternative was examined in depth in an effort intended to highlight the numerous factors which must be made explicit and weighed before an intelligent decision can be reached. The single candidate system examined was judged technically feasible, but a final evaluation of optimality was deferred until such time as formal concept formulation activities can be completed.

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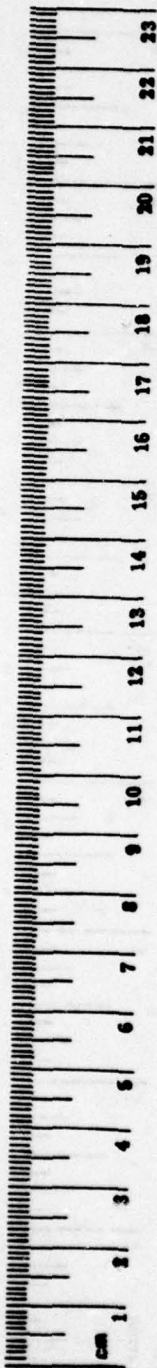
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
AREA				
in ²	square inches	6.5	square centimeters	cm ²
ft ²	square feet	0.09	square meters	m ²
yd ²	square yards	0.8	square meters	m ²
mi ²	square miles	2.6	square kilometers	km ²
	acres	0.4	hectares	ha
MASS (weight)				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	metric tons	t
VOLUME				
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	L
pt	pints	0.47	liters	L
qt	quarts	0.95	liters	L
gal	gallons	3.8	liters	L
ft ³	cubic feet	0.03	cubic meters	m ³
yd ³	cubic yards	0.76	cubic meters	m ³
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* 1 in = 2.54 cm (exactly).





Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
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LENGTH

mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi

AREA

cm ²	square centimeters	0.16	square inches	in ²
m ²	square meters	1.2	square yards	yd ²
km ²	square kilometers	0.4	square miles	mi ²
ha	hectares (10 000 m ²)	2.5	acres	

MASS (weight)

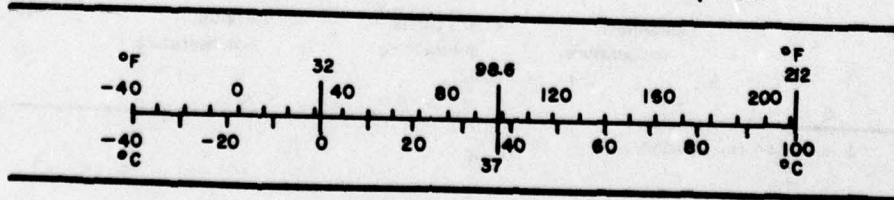
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	metric tons (1000 kg)	1.1	short tons	

VOLUME

ml	milliliters	0.03	fluid ounces	fl oz
L	liters	2.1	pints	pt
L	liters	1.06	quarts	qt
L	liters	0.26	gallons	gal
m ³	cubic meters	35	cubic feet	ft ³
m ³	cubic meters	1.3	cubic yards	yd ³

TEMPERATURE (exact)

°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F
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OFFSHORE FUEL—UNLOADING SYSTEM: A PILOT STUDY

I. SUMMARY

1. **Summary.** Large volumes of fuel are consumed daily by Military forces engaged on the battlefield. That fuel must be transported in bulk form by Military Sealift Command chartered tanker to the combat theater to be discharged through conduits to waiting storage containers located some distance inland. The fuel is then moved forward to the combat elements by use of pipelines, hoses, or tank trucks or a combination of the three. All of this is contingent upon first moving fuel across the sea-land interface; this short distance is perhaps the most difficult obstacle to be spanned and is the obstacle addressed in this investigation. As the investigation progressed, a number of conclusions were drawn; however, the reader is cautioned that while the generalizations possess validity in an absolute sense, any conclusions associated with individual components and hypothetical systems are intended in a purely exploratory way. The final system selection decision must be deferred until formal concept formulation activities – Trade-Off Determination, Trade-Off Analysis, Best Technical Approach, and Cost and Operational Effectiveness Analysis. The conclusions are as follows:

- a. The current Army standard tanker-discharge system falls far short of universality; i.e., it is usable offshore from a limited number of worldwide landing beaches.
- b. The current standard discharge system must be placed in relatively large numbers if a corps-size force is to be deployed.
- c. A number of alternative state-of-the-art discharge systems may be identified, all of which promise increased universality and discharge capability concurrent with a minor relaxation of constraints.
- d. At least one of the advanced discharge systems identified is eminently feasible given any reasonable set of objective evaluation criteria.

II. INTRODUCTION

2. **Background.** Contemporary Military forces rely upon sophisticated weapons systems, aircraft, and ground vehicles. Collectively, these systems and equipment consume large quantities of fuel, which, because of its sheer magnitude, is generally received and distributed in bulk (i.e., not packaged) form. The source of fuel typically will be distant from the theater of operations, making it necessary to transport large

volumes of fuel over substantial distances. Cargo aircraft and LSTs may be employed toward that end during the early stages of the hostility; however, the limited volume which may be conveyed by such means favors the early provision of a more efficient method. Another concern is that limited numbers of cargo aircraft and LST-type vessels will be available to the tactical commander. The dedication of some aircraft and vessel assets therefore could be assumed to be in direct conflict with the desire to apply all available assets in the roles which place greater pressure against the hostile force. While the provision of fuel is a prerequisite to modern combat, aircraft and LSTs dedicated to fuel delivery missions do so at the expense of reducing the number of troops, ammunition, and other combat material delivered. The solution to this dilemma is movement of bulk fuel from its distant source using Military Sealift Command tankers which discharge their cargo to combat forces ashore. The discharge operation typically requires a mooring of some type to secure the tanker safely and a conduit through which the fuel is moved from the ship to storage containers located some distance inland. A typical marine terminal complex is illustrated in Figure 1.

From the tactical commander's view, the mooring-and-discharge system which would be most favorable is one which is transported easily and rapidly, requires the fewest resources for installation and operation, may be installed rapidly, and has the greatest degree of universality (i.e., the percentage of worldwide landing beach offshore from which it may be used). A mooring-and-discharge system has been developed and type classified (received Army approval for issue). This system incorporates to a degree many of the desirable features outlined. Some of the more notable features are:

- a. Transportable by C-130 aircraft.
- b. May be installed by elements of a port construction company within 72 working hours without the benefit of onsite assets.
- c. Capable of mooring a 25,000-DWT tanker in Seastate 2 and a current velocity of 1 knot.
- d. Incorporates a 6-inch-diameter discharge line which may reach up to 5,000 feet offshore.

The system described will be referred to hereafter as the baseline system against which alternative advanced generation systems will be compared. The baseline system incorporates an adaptation of a Navy-developed 6-inch-diameter bottom-laid pipeline system. The amalgamation of an unconventional mooring system and an existing system was predicated on a desire to field a system in the fastest way and upon knowledge that the Navy equipment had proven itself through several years of use. Admittedly, the unorthodox requirement for installation without benefit of onsite

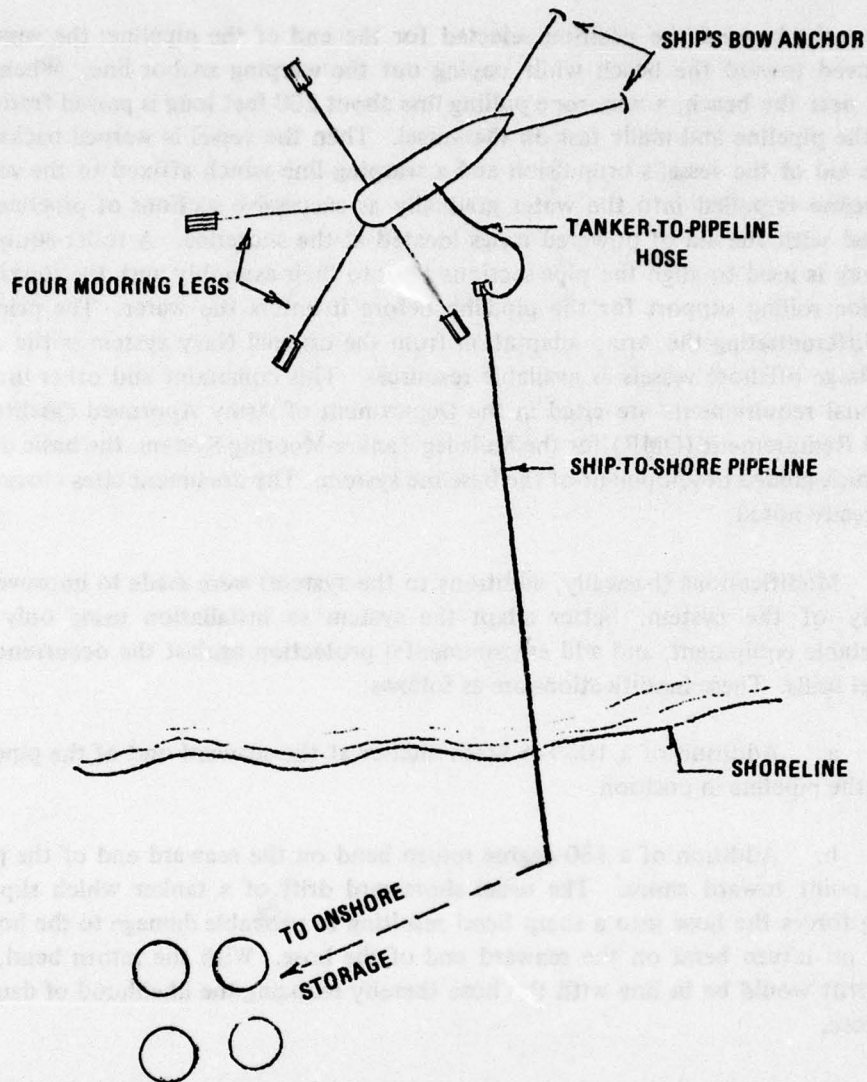


Figure 1. Marine terminal complex.

vessels made it necessary to introduce a number of modifications to the Navy equipment. It was also necessary to develop a special installation technique which allowed the pipeline to be placed rapidly using only equipment which is transportable within the limited confines of a C-130 aircraft.

The Navy usually installs the pipeline using a warping tug or LCU. In operation, either vessel deploys its warping anchor (an anchor deployed from the rear of the vessel which is used to assist the vessel to return to its starting point offshore along a

straight path) beyond the position selected for the end of the pipeline; the vessel is then moved toward the beach while paying out the warping anchor line. When the vessel is near the beach, a wire-rope pulling line about 200 feet long is passed from the end of the pipeline and made fast on the vessel. Then the vessel is warped backward with the aid of the vessel's propulsion and a warping line winch affixed to the vessel. The pipeline is pulled into the water gradually as successive sections of pipeline are assembled with the aid of powered tongs located at the shoreline. A roller-equipped launchway is used to align the pipe sections prior to their assembly with the tongs and to provide rolling support for the pipeline before it enters the water. The primary factor differentiating the Army adaptation from the original Navy system is the deletion of large offshore vessels as available resources. This constraint and other unique operational requirements are cited in the Department of Army Approved Qualitative Materiel Requirement (QMR) for the Multileg Tanker-Mooring System, the basic document which guided development of the baseline system. The document cites characteristics already noted.

Modifications (basically, additions to the system) were made to improve the reliability of the system, better adapt the system to installation using only air-transportable equipment, and add environmental protection against the occurrence of large fuel spills. These modifications are as follows:

- a. Addition of a 1000-lb Stato anchor at the seaward end of the pipeline to hold the pipeline in position.
- b. Addition of a 180-degree return bend on the seaward end of the pipeline to point toward shore. The usual shoreward drift of a tanker which slips its mooring forces the hose into a sharp bend resulting in probable damage to the hose if there is no return bend on the seaward end of the hose. With the return bend, the tanker drift would be in line with the hose thereby reducing the likelihood of damage to the hose.
- c. Addition of a check valve to preclude a large fuel spill from shore in the event the hose between the tanker and pipeline is broken or damaged.
- d. Replacement of the single soft-wall hose used by the Navy with dual hard-wall hoses which are more durable and less susceptible to damage. Since the tanker discharges into the system through a single hose, the second hose provides a standby should one hose be damaged or broken.
- e. Addition of a valving arrangement to permit rapid isolation of a damaged or broken hose.

f. Addition of a sled to the sea end of the pipeline to support the pipe end assembly and the 1000-lb Stato anchor during the pipeline launching.

g. Addition of a tow frame and foam-filled drum buoys to neutralize the weight of the pipe end assembly and the 1000-lb Stato anchor in the water and to prevent the end assembly from overturning in the water.

Figure 2 shows the pipeline end assembly which evolved through the incorporation of these modifications. The line used by the vessel to tow the pipeline offshore is attached to the center of the tow frame. When in position, the launching line is released from the tow frame by a quick-release hook which transfers the launching force to the anchor. Continued winching separates the anchor from the sled and strings out the wire-rope line between the anchor shank and the pipe end assembly. After the anchor is in position, a quick-release hook between the anchor crown and launching line is tripped to free the launching line.

The hose shown in Figure 2 is standard 150-lb/in² working pressure oil suction-and-discharge hose. Instead of longer lengths, 25-foot sections are used to facilitate shipment by C-130 cargo aircraft. The hose sections are joined by standard bolted flange connections.

Figure 3 shows the powered tongs and part of the launching platform which are standard Navy equipment. The unit is operated by a Military standard air compressor which drives the hydraulic power system integral with the unit. The tong head is the same as that used commercially for assembly of oil-well casing but is mounted on powered longitudinal and transverse tracks to provide alignment and to force thread contact between the pipe and coupling during joint makeup. The tong jaws are reversible so that the device can be used for both making up and unscrewing the pipe joints.

Launching of the pipeline is accomplished by winching through a floating offshore sheave (Figure 4). The floating sheave platform is a modification of a device (mooring-leg-deployment device) which was developed to deploy an explosive embedment anchor rapidly and then function as a mooring point in a tanker mooring. The unit is outfitted with machinery for lowering the embedment anchor to the ocean floor where it embeds automatically upon contact with the bottom.

Deployment of the modified unit is accomplished by a 25-foot US Coast Guard motor surf boat. The motor surf boat may be launched over a beach devoid of piers using an off-the-beach launch-and-recovery equipment set which is a shore-based winch see-sawing a wire rope line through a block anchored beyond the surf zone.



Figure 2. Pipe end assembly of present tactical ship-to-shore pipeline facility.



Figure 3. Powered tongs for assembly of present tactical pipeline facility.

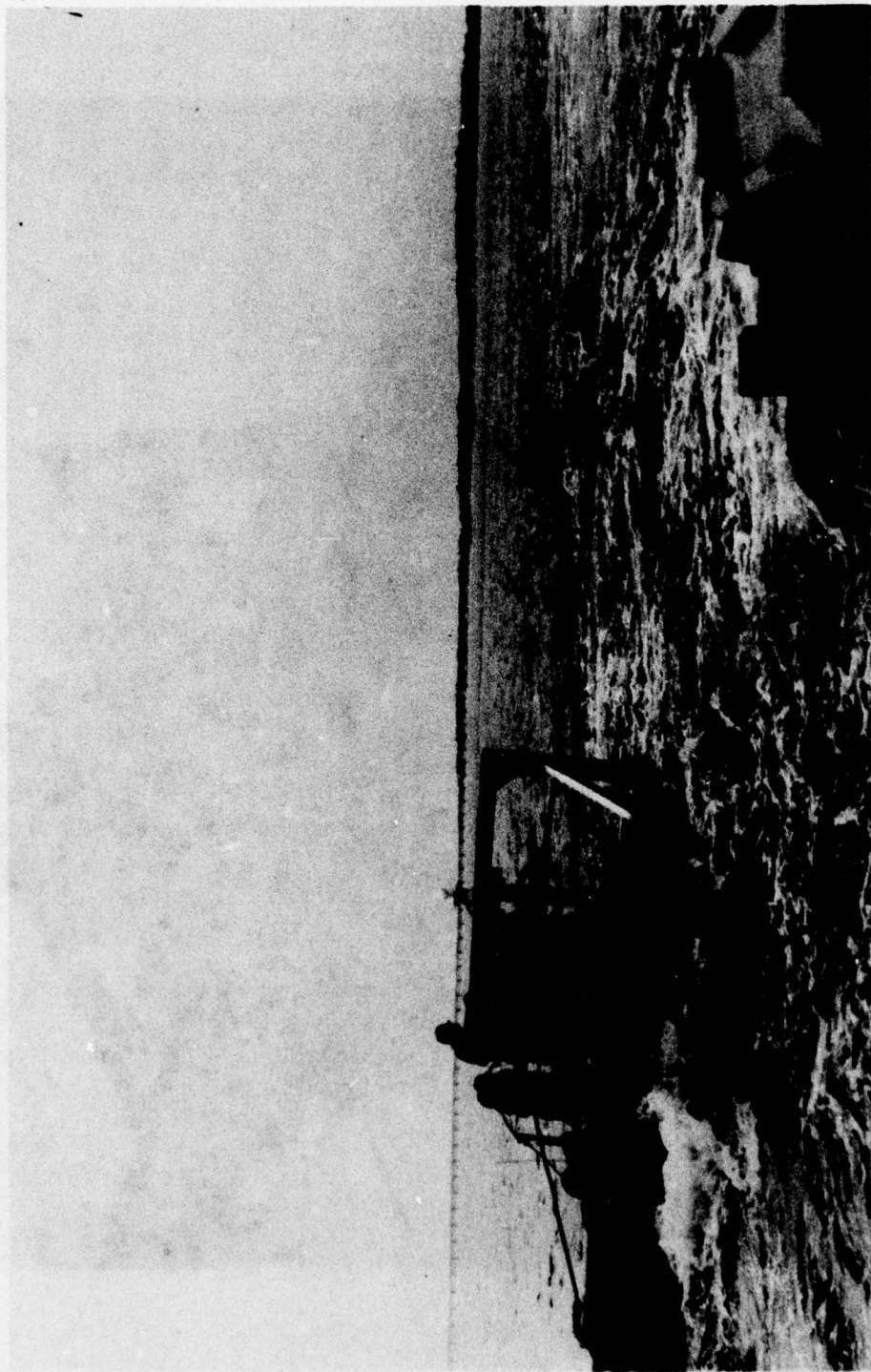


Figure 4. Modified mooring-leg-deployment device for launching present tactical pipeline.

The wire rope line for launching the pipeline is deployed from the shore winch around the floating sheave and back to the end of the pipeline by first deploying a 1¼-inch-diameter, floating, nylon-covered polypropylene rope by two motor surf boats and then catheading this rope to pull the wire rope from shore, around the sheave, and back to shore. Foam-filled drum buoys are used to float the wire rope so it will not drag on the sea bottom; thereby, a minimum force is exerted on the floating sheave during the launching of the pipeline. Figure 5 shows the pipeline being launched.

3. **Scope.** This investigation is focused on the various parameters which affect the design and utility of a tanker-to-shore discharge system. While the baseline system provides the Tactical Commander with a degree of flexibility well beyond that available in the past, it is severely lacking in terms of throughput capacity and universality. An advanced system embodying state-of-the-art technology could improve throughput and universality. The objective of this investigation is to identify alternative solutions to the problem of conveying fuel ashore. One of the alternatives identified will be singled out for a more detailed investigation of installation methodology, thereby demonstrating technical feasibility. This report is a pilot study only; it will not attempt to present an optimal solution to the problem, nor will it address the subject of an advanced mooring the operating characteristics of which would mirror those of the discharge system. The following problem analysis is intended to convince the reader that development of an advanced discharge system of some as-yet-unspecified configuration is a worthwhile endeavor in terms of the increased combat effectiveness it would provide. This investigation is intended as a prelude to the formal concept formulation activities which are undertaken jointly by the combat and materiel developers and which must be completed before an effort proceeds into the full-scale development phase.

III. INVESTIGATION

4. **Basis of Fuel Requirement.** The following pages, which discuss fuel requirements, reflect a detailed system model and reliability analysis developed for the present tactical multileg tanker-mooring-and-off-loading pipeline facility.¹ While the analysis is based on the 6-inch pipeline system, the fuel requirements are applicable to any pipeline system.

¹ F. M. Cevasco, *Multileg Tanker-Mooring System and Unloading Facility: System Model and Reliability Analysis*, Report 2163, U.S. Army Mobility Equipment Research and Development Command, Fort Belvoir, VA (January 1976).

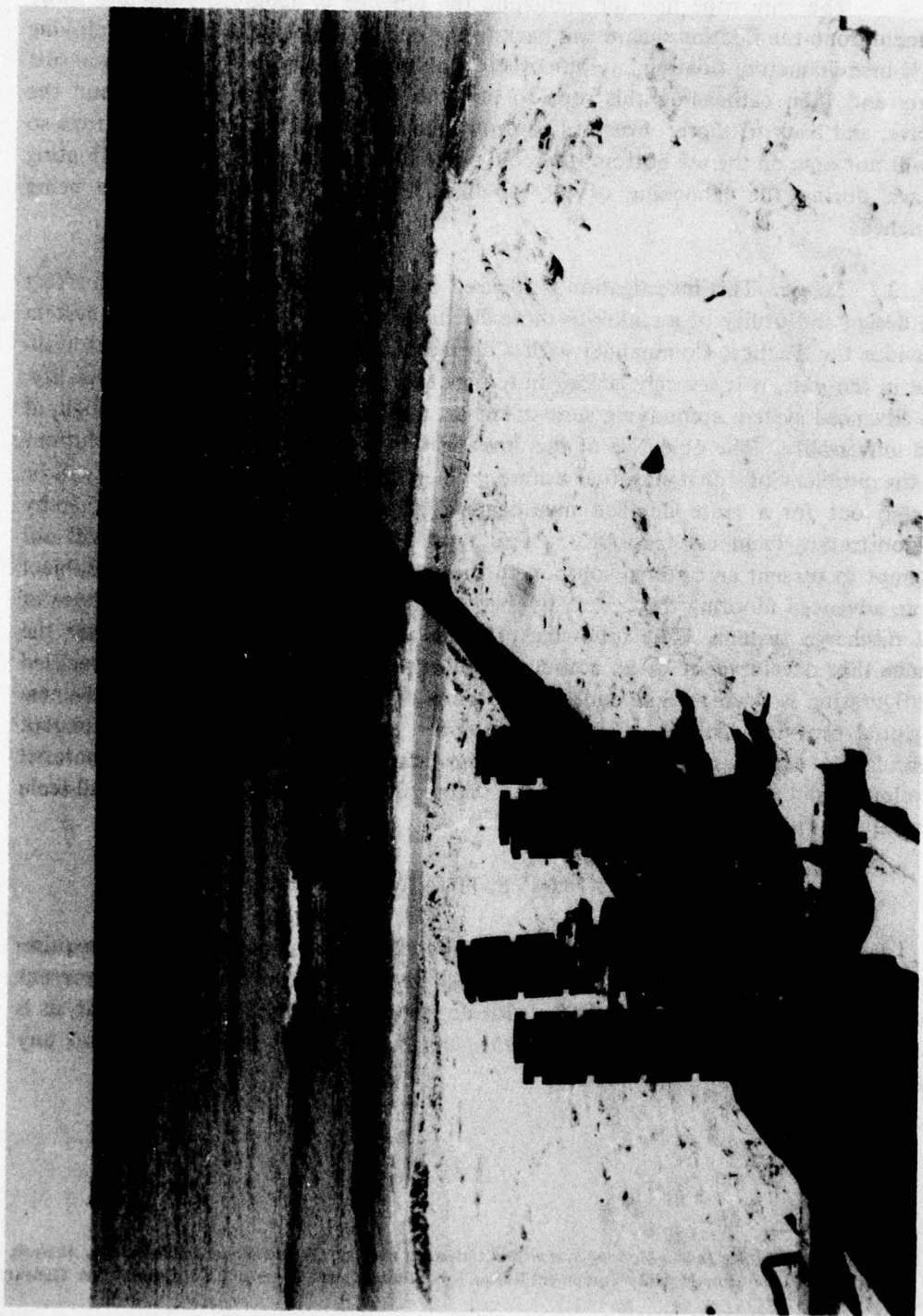


Figure 5. Present 6-inch tactical pipeline being launched.

As baseline forces, the analysis used two scenarios – one involves the deployment of a light corps; the second involves the deployment of a heavy corps. Table 1 gives the composition of each.

Table 1. Corps Composition*

Light Corps	Heavy Corps
Airborne Division	Cavalry Division
Airmobile Division	Armor Division
Cavalry Division including ACCB	Separate Brigade
COSCOM	Mechanized Division
Port	COSCOM
Airfield	Airfield

* The corps includes actual combat elements and supporting elements; Air Force requirements are also included.

The scenarios cover operations and requirements from day 1 through day 60, at which time the scenarios terminate operations. The scenarios detail the sequence of arrival and operations explicitly, from which values for daily fuel consumption may be established. Figure 6 shows the daily fuel consumption. In the conduct of the analysis, it was assumed that fuel would be supplied by unspecified means the first 4 days; the time span during which the appropriate number of tactical multileg moorings and offloading pipelines were delivered and installed. The scenarios were extended from a 60-day duration to a 90-day duration so they would be in accordance with the developmental requirements document for the existing tactical mooring and offloading pipeline facility.

5. **Fuel Reserve.** The daily fuel consumption constitutes a demand that must be met on a continuous and instantaneous basis. This may be satisfied by: mooring a tanker offshore permanently with its pumps operating 24 hours a day but at an output pressure which will produce a flow rate which coincides exactly with the instantaneous fuel consumption; or using fuel storage tanks to hold fuel delivered in excess of demand, allowing the tanker to come and go. Both cases offer both advantages and disadvantages. The first case requires that one tanker be stationed constantly at each unloading facility where it presents a continuing target, incurs substantial demurrage costs, and causes an interruption in fuel delivery each time unfavorable weather makes it necessary for the tanker to depart the mooring for the relative security of the open ocean. Knowledge of the probability of experiencing unfavorable weather would permit a Commander to estimate how frequently his force would be denied fuel.

The second case, which involves a deliberate policy of reserve fuel accumulation, typically would require the tanker to moor for a period of time, pump fuel ashore, and then leave. Each fuel delivery would include sufficient fuel to supply

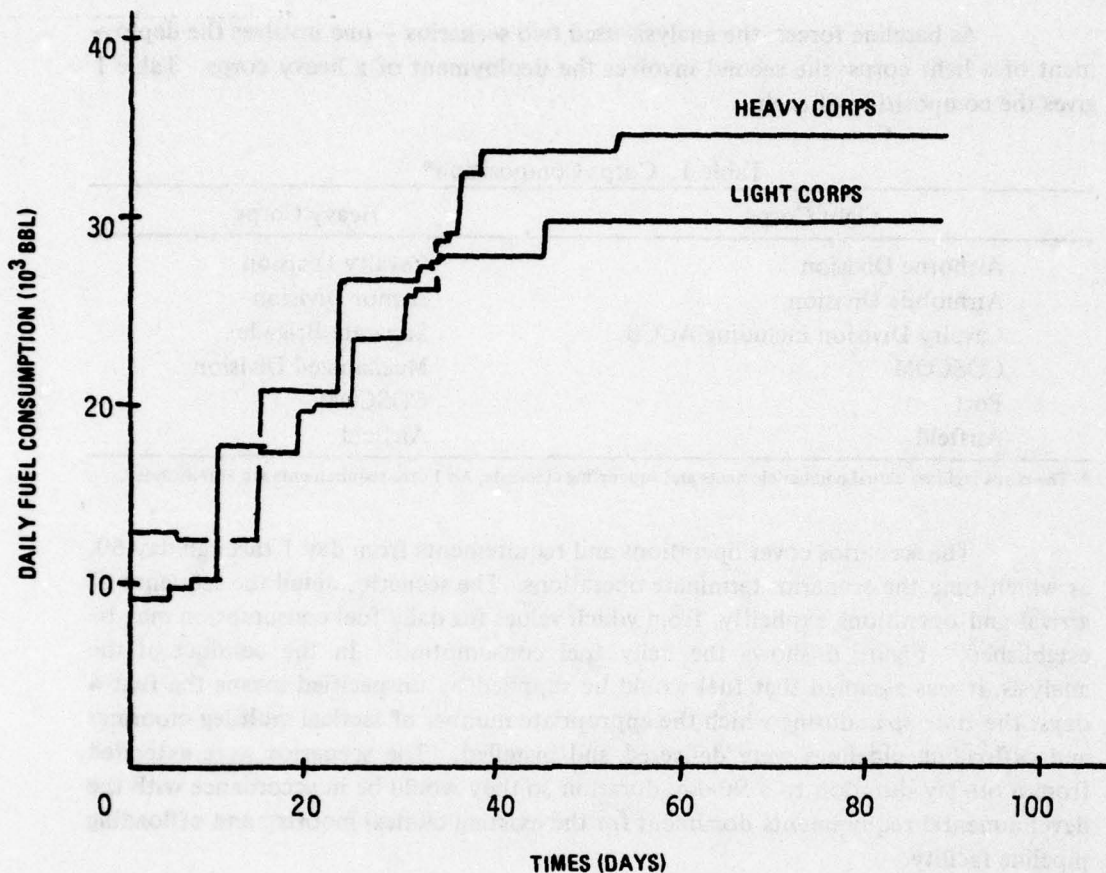


Figure 6. Daily Fuel Consumption.

friendly forces during the period between deliveries, plus some additional fuel which would constitute a portion of the fuel reserve. The percentage of the fuel delivered which is intended for the fuel reserve depends upon how large a fuel reserve is desired and how rapidly the fuel reserve must achieve the desired level.

If the fuel reserve is to be accumulated, additional system capability will be required over and above that required to meet daily consumption exclusively. Once the fuel reserve objective is reached, any additional system capability which was provided for the conveyance of reserve fuel stocks could be idled or could function as standby. One final factor weighing against an unduly rapid accumulation is the inevitable time lag which occurs between the time the need for fuel storage containers is first realized and the time those containers are actually available; thus, a planned rate of fuel accumulation which exceeds the rate at which the available engineer resources may place storage containers is destined to failure from its inception.

Accumulating the fuel reserve at a slow pace minimizes the system capacity required but at the expense of increasing the uncertainty about availability of fuel supplies. The purpose of developing a fuel reserve is reduction of such uncertainties. The short duration of the hostility further mitigates against a too gradual accumulation policy.

Given the 90-day duration hostility, a reasonable objective appears to be realization of the specified fuel reserve by midnight of day 29, an approach which should result in adequate fuel stocks during the early days of the conflict when the force's ability to survive is most tenuous. The accumulation rate implied by the day 29 objective should not require deployment of excessive system capacity, nor should it require an unreasonable rate of fuel storage container placement.

The mooring, pumping, and unmooring cycle would be repeated until the hostilities ceased. In this case, the tanker would also be a target, but only intermittently. The occurrence of unfavorable weather would also result in the departure of the tanker; however, presence of a reserve fuel cache would permit military operations to continue, unlike the preceding case. Thus, the greater the fuel reserve, the longer a military force could operate in the absence of the tanker. This raises the question: How large a reserve is best? Considering the short duration of the conflicts addressed herein, and the desire to procure and deploy only some finite storage capacity, prudence would indicate that a 10 day fuel reserve is adequate.

The delivery cycle used for the post day 4 through midnight day 29 period is 30 hours of pumping, followed by 18 hours during which the tanker remains offshore; the delivery sequence then forms a 48-hour cycle. Figure 7 illustrates the cumulative volume delivered during the first 10 days following deployment of troops into the objective area; the figure also illustrates the corresponding growth in reserve fuel levels. It should be pointed out that the delivery cycle of 30 hours of pumping for every 48-hour cycle is approximately equivalent to pumping 15 hours of each 24-hour day. Given the approximate relationship, the analysis developed throughout this investigation may be transformed and used to reflect upon the whole range of possible delivery cycles, at least in a qualitative manner. For example, a limitation of 12 hours pumping during each 24-hour cycle would require a higher pipeline throughput rate than would the delivery cycle actually used in the analysis.

6. Availability. Availability as used throughout this study is defined as that portion of the time that the system is operational during favorable weather conditions. Perfect, or 1.00, availability assumes no system malfunctions or hostile action which may cause an interruption of operations. The minimum acceptable availability is that value of availability below which the required quantity of fuel cannot be delivered by the deployed systems. The availability of a system is determined by dividing the total

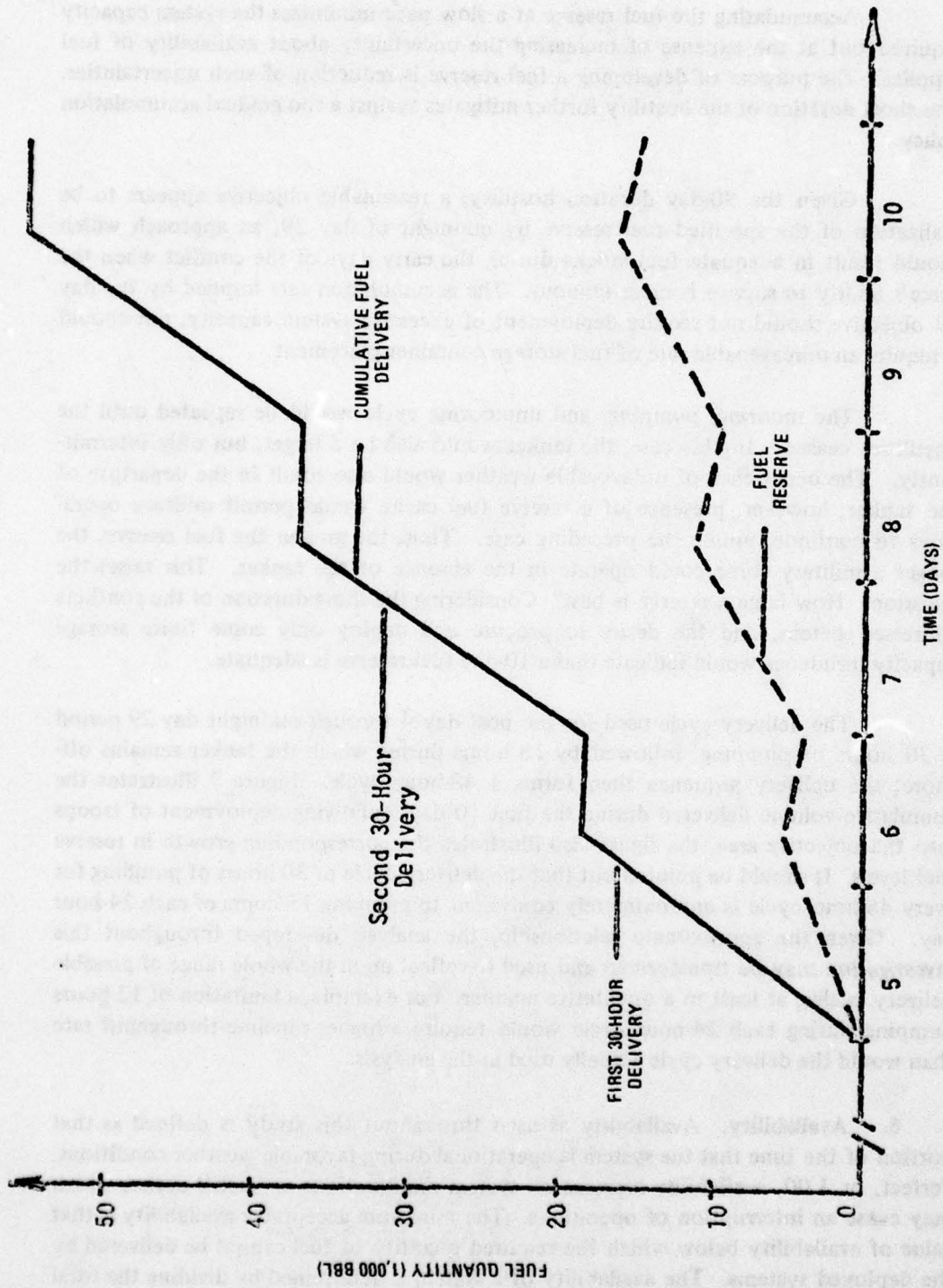


Figure 7. Fuel delivery model.

cumulative demand by the weather-constrained cumulative throughput capacity of all deployed systems. Thus, availability is a function of the reliability of the system and the extent of hostile action which may damage some part of the offloading facilities or prevent a tanker from entering the mooring.

An evaluation of availability must consider three separate conditions: the percent of the time that all systems are operational, the percent of the time that no systems are operational, and the number of systems deployed. The percent of the time all systems, or no systems, are operational progressively decreases as the number of systems is increased, as illustrated by Table 2.

Table 2. Effect of the Number of Deployed Systems on the Percentages of the Time that all Systems are Operable (Pa) and that all Systems are Inoperative (Po)

Number of Systems Deployed	0.75 Availability		0.60 Availability	
	Pa (%)	Po (%)	Pa (%)	Po (%)
1	75	25	60	40
2	56	6.3	36	16
3	42	1.6	22	6.4
4	32	0.4	13	2.6
5	24	0.1	7.8	1.0
6	18	0.02	4.7	0.4

Assuming n systems with identical availabilities, the percent of the time that all systems may be expected to be operational is given by:

$$Pa = A^n \times 100. \quad (1)$$

Where Pa is the percent of the time that all systems may be expected to be operational.

n is the number of independent systems deployed.

A is the availability.

The percent of the time that no systems would be operable, Po, is given by:

$$P_o = (1 - A)^n \times 100 \text{ (see footnote 2)} \quad (2)$$

For illustration, Table 2 gives the Pa's and Po's for 1 through 6 deployed systems with availabilities of 0.75 and 0.60.

Table 2 illustrates the following points:

- a. A multisystem installation can render the time at which no fuel can be delivered to an inconsequential portion if relatively high availability is provided and a sufficient number of systems are deployed.
- b. The portion of the time that all systems are operative reduces significantly as more systems are deployed.
- c. A relatively high availability dramatically increases the portion of the time that all systems are operative if a multi-system facility is deployed.

It should be pointed out at this point that a tanker would have to be on station for each deployed system since the specific periods that all systems will be operable can not be predicted.

The availability of a single or group of systems can be upgraded by adding redundant or standby systems. The percent of the time that the basic number of systems can be expected to be operational if one redundant system is deployed is given by:

$$P_1 = P_a + (100 - P_a) A_r \quad (3)$$

Where P_1 is the percent of time that the basic number of systems can be expected to be operable.

P_a is from equation (1).

A_r is the availability of the redundant system.

The percent of the time P_2 that the basic number of systems can be expected to be operational if two redundant systems are deployed is given by:

$$P_2 = P_1 + (100 - P_1) A_r \quad (4)$$

² With a facility comprised of systems with different availability factors, equation (1) becomes $P_a = (A_1)(A_2)(A_3) \dots (A_N) \times 100$, and equation (2) becomes $P_o = (1 - A_1)(1 - A_2)(1 - A_3) \dots (1 - A_N) \times 100$ where $A_1, A_2, A_3,$ and A_N are the different availability factors.

Where P_1 is from equation (3).

The same procedure can be followed to determine the effect of any number of redundant systems.

Table 3 conveys the effect of redundant systems on the percentage of the time that the basic number of systems can be expected to be available for use.

Table 3. Effect of Deploying Redundant Systems on Availability

Basic No. of Systems Required	75% Availability			60% Availability		
	Note 1	Note 2	Note 3	Note 1	Note 2	Note 3
1	75	93.8	98.5	60	84	93.6
2	56	88.0	97.0	36	74.4	89.8
3	42	85.5	96.4	22	68.8	87.5
4	32	83	95.7	13	65.1	86.0
5	24	80	95.0	7.8	64.1	85.6
6	18	79.3	94.8	4.7	61.8	84.7

NOTES:

1. The percentage of the time that all systems will be operational with no redundancy or standby systems. Presented previously in Table 2.
2. The percentage of the time that the basic number of systems will be operational with a single redundant system.
3. The percentage of the time that the basic number of systems will be operational with two redundant systems.

Table 3 indicates that redundant off-loading systems would have a significant impact on the number of tankers which must be dedicated to the operation and is a proper consideration for a trade-off determination and analysis. This fact is aptly illustrated by a 3-system 75-percent-available facility which provides for all three systems to be operational 42 percent of the time when no redundancy is provided and provides for three basic systems to be operable 85.5 percent of the time with a single redundant system. This in effect doubles the time at which three tankers can be pumping fuel simultaneously, thereby reducing tanker turn-around time by about ½—assuming that a negligible amount of time would be consumed in disconnecting from an inoperative facility and connecting to an operative one.

7. **Fuel Demand and Baseline System Performance.** The preceding sections address the background of the problem and the general methodology used to establish the fuel demand. The fuel demand (consumption plus contribution to a 10-day reserve) thus established from midnight of day D + 4 to midnight of day D + 29 is 703,693 bbl. The corresponding average daily demand during this period is 31,928 bbl/day.

The unconstrained capacity of the 6-inch baseline system, 5000 feet long, is 1110 bbl/hr of composite fuel. The constrained flow rate is 444 bbl/hr based on a weather constraint factor of 0.4 corresponding to a seastate 2 mooring limitation.³ The deployment of six systems (Figure 8) would provide a total capacity of 1,022,976 bbl during the time period from midnight of day D + 4 to midnight of day D + 29, based on pumping fuel for 30 hours of each 48-hour period. The required availability of the six baseline systems would be $702,693 \div 1,022,976$ or 0.69, based on a seastate 2 mooring limitation.

8. **Environmental Considerations.** Weather constraints are a two-part consideration; i.e., the maximum seastate at which a tanker can remain in a mooring to discharge fuel, and the maximum seastate at which an installed pipeline facility can survive. The maximum seastate at which the mooring is capable of restraining the tanker and holding the vessel on position affects the delivery rates required to meet the daily demand, since the tanker must leave the mooring as the seastate approaches this limit. The maximum seastate at which the pipeline is required to survive impacts on the physical design of the pipeline system.

The values assigned to the environmental parameters may be established on the basis of the maximum event recorded for a particular site or on the desire to remain operable some specified fraction of the time. This latter approach would also be expected to simultaneously minimize weight, cube, cost emplacement time, and other related variables of major interest for military operations but which might not be given major attention by a marine engineering firm designing a mooring for commercial use.

Wind and wave height data are available for many areas of the world. However, since the values of such parameters are not uniform throughout the year, it may be misleading to simply use the single statistic – arithmetic mean – to represent such information. The lack of uniformity may be better appreciated after examining a typical distribution of wave heights as recorded by the Navy during 1968–1969 at a site in the Pacific Ocean off the southern California coast (Figure 9).⁴ The plotted distributions are observed to be multimodal rather than uniform as use of the mean implies. This variability is of particular significance for military operations, since current guidance indicates that the duration of such operations would be skewed toward the short (i.e., 60 or 90 days) end of the time continuum. Should a short-lived deployment coincide with a period of high percentage occurrence of wave heights

³ Composite fuel is defined as a hypothetical fuel whose specific gravity is computed as a weighted average of the average of the three fuels consumed in the TRADOC running scenario; i.e., 50 percent JP-4, 27 percent diesel, and 23 percent gasoline. Paragraphs 8 and 9 discuss weather constraints and constrained flow rates corresponding to seastate 2, 3, and 4.

⁴ S.T.R. Kretschmer et al, *Seafloor Construction Experiment*, SEACON I, Technical Report R-817, Civil Engineering Laboratory, Naval Construction Battalion Center, Port Hueneme, California (February 1975) p. 16.

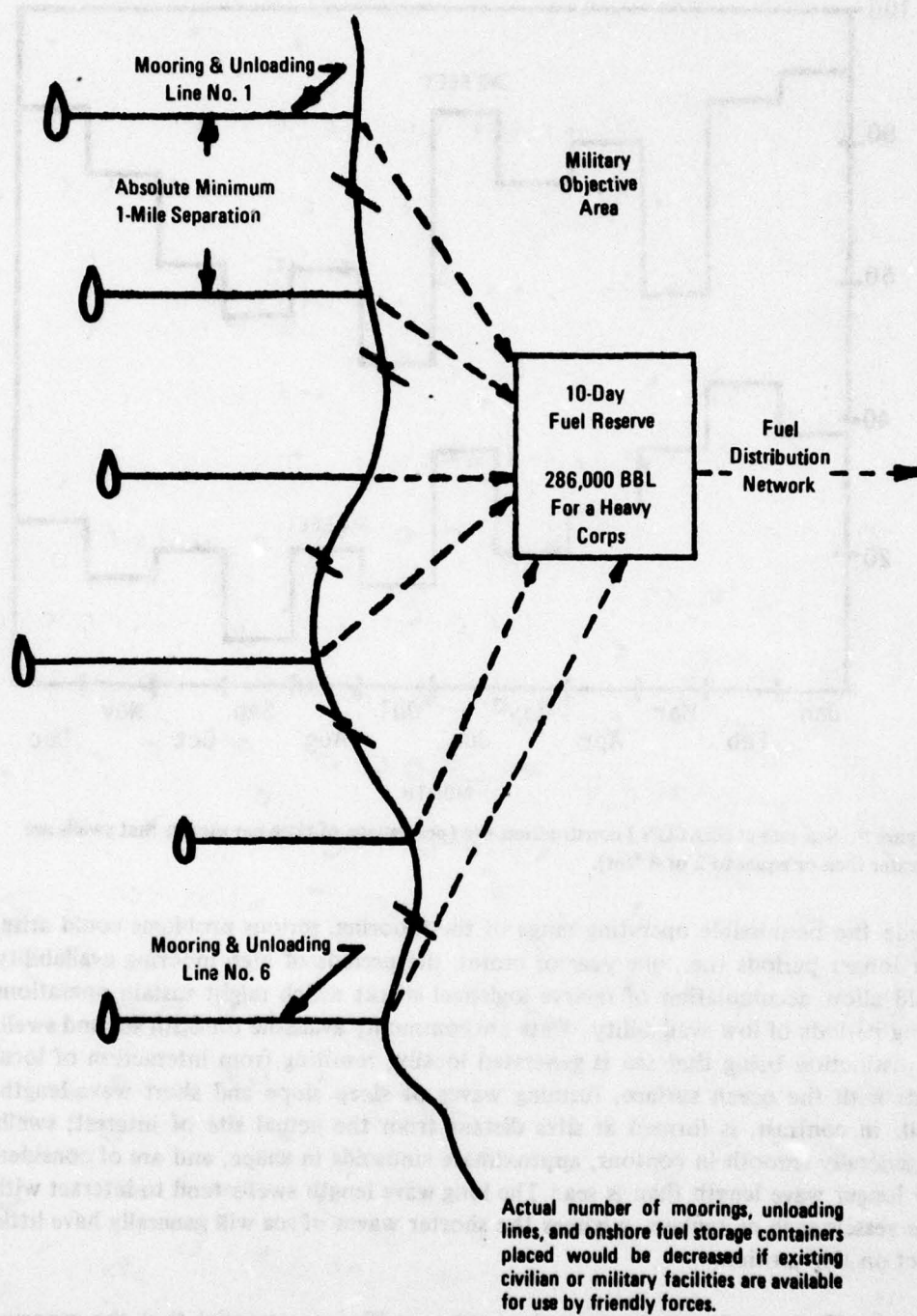


Figure 8. Deployment of baseline tanker offloading system.

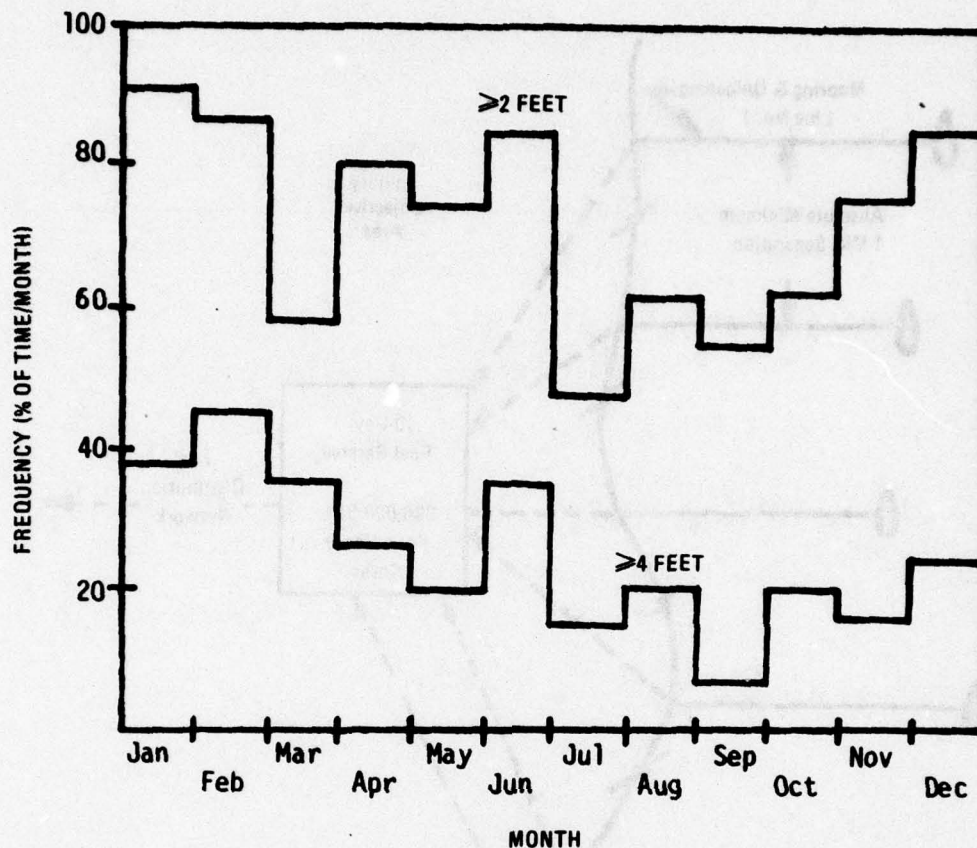


Figure 9. Seastate at SEACON I construction site (percentage of time per month that swells are greater than or equal to 2 or 4 feet).

outside the permissible operating range of the mooring, serious problems could arise. Over longer periods (i.e., one year or more), the periods of high mooring availability would allow accumulation of reserve logistical stocks which might sustain operations during periods of low availability. Data are commonly available for both sea and swell, the distinction being that sea is generated locally, resulting from interaction of local winds with the ocean surface, forming waves of steep slope and short wave length. Swell, in contrast, is formed at sites distant from the actual site of interest; swells are generally smooth in contour, approximate sinusoids in shape, and are of considerably longer wave length than is sea. The long wave length swells tend to interact with large vessels such as tankers, whereas the shorter waves of sea will generally have little effect on ship motion.

The mooring system requirements specified as essential that the mooring function in a seastate 2 and desirable that it function in a seastate 3. The term "seastate" represents the range of significant wave heights which exist at a specified

location on the ocean's surface. Table 4 conveys the characteristics associated with various seastates.

Table 4. Seastate Characteristics

Characteristic	Seastate					
	1	2	3	4	5	6
Wind Velocity (kn)	7	10	16	18	23	30
Wave Height (ft)	1	2-3	3-6	4-8	6-13	11.3-23
Wave Period (s)	3	1.0-6.0	2.0-8.8	2.5-10.0	3.4-12.2	4.7-16.7

It should also be pointed out that the wave height range specified for each seastate is the "significant wave height" – a statistical term. Use of such a specialized term is appropriate since actual wave heights for a given seastate will vary from zero to some multiple of the maximum presented in the table, thus making the use of a more familiar term, such as average, misleading. This paradox exists since individual waves may travel at different speeds, causing some to momentarily cancel or diminish one another, and causing others to become larger through superposition. For example, a seastate 2 nominally includes a range of 2 to 3 feet significant waves, but may include individual waves as high as 4.8 feet; i.e., 1.6 times the wave height constituting the upper bound.⁵ The significant wave height is found by positioning an observer at a fixed point offshore to list the heights of each wave that passes. The wave heights are then arranged in order of decreasing magnitude; the significant wave height, as used here, is then the average of the one-third highest wave.⁶ As a further example, if 999 waves are observed and arranged in order of decreasing height, the significant wave height would be the average of the 333 highest. Use of the term focuses attention on the larger waves which possess the greatest energy and, therefore, are of primary interest in an engineering sense.

The preceding discussion now makes it feasible to examine the subject of environmental parameters as they impact upon operation of a mooring. The contents of two sources of relevant data have been distilled into the following paragraphs.

The first was a study sponsored by the Naval Civil Engineering Laboratory in 1969 which examined coastal climatology at 11 locations around the world selected as being typical of those regions in which the U.S. might deploy a military force.⁷ The

⁵ R. L. Wiegel, *Oceanographical Engineering*, Prentice-Hall, Englewood Cliffs, New Jersey (1964) p. 208.

⁶ Significant wave height is sometimes defined as the average of the highest tenth, or some other fraction, vis-a-vis the highest third used exclusively throughout this study.

⁷ *Environmental as Analysis Relative to Portable Port Operations*, Ocean Science and Engineering, Inc. (21 November 1969).

average incidence of various seastates for the 11 sites has been computed on the basis of total number of days for which a given seastate or range of seastates is reported, divided by the total number of observations: i.e., 4015 possible days (11 sites times 365 days of observation at each site). In a number of cases the study gives wave height data in terms of the direction of wave origin, as would be of interest on different sides of an island, or for a harbor which is naturally shielded from waves originating from certain directions. When this situation was encountered, the exposure yielding the highest incident rate was used, thus yielding the most conservative values; the percentages do not sum exactly to 100 for this reason. Table 5 summarizes the results for the 11 sites.

Table 5. Average Occurrence of Seastate for 11 Sites

Seastate	Number of Occurrences	Percent* Occurrence	Number of Sites Observed
1-3	3426	85.3	11
4	426	10.6	11
5	124	3.1	10
6	13	0.3	4

* Number of occurrences divided by 4015 x 100.

While the data presented do not distinguish individual seastates lower than 3, the general nonlinear trending evident in the data makes it reasonable to estimate the percent occurrence of seastates less than or equal to 2 at between 50 and 65 percent, given the decreasing probability of increasingly severe seastates; a phenomenon consistent with extreme event prediction. It is also appropriate to caution that the data displayed are averages for an entire year, thus a high rate of elevated seastate recorded during a single month would be diffused into lower incident rates recorded during the remaining 11 months, biasing the perceived severity of the problem downward.

A more recent study⁸ sought to minimize the downward bias included through use of annual averages and instead introduce a bias favoring higher seastates. This second effort presents percent occurrence data which correspond with the worst month (the month with the highest occurrence of a given seastate or seastate range) for 14 worldwide locations. The data consists exclusively of percent occurrence of various height range sea and swell; thus for the reasons given earlier, the sea data have been neglected and swell data are used as the basis of establishing equivalent seastate. As expected, the frequency of occurrence reflected in Table 6 differs from that presented in the previous table. Table 6 is of greater relevance since the military conflicts which

⁸ *Systems for Mobile Piers and Causeways for Expeditionary Facilities*, Fredrick R. Harris, Inc., and Pre Systems Sciences Co. (June 1973).

are of interest here are of short duration and, therefore, must necessarily be considered in the content of the month or months of maximum wave activity.

Table 6. Maximum Percent Monthly Seastate Occurrence for 14 Sites

Seastate	Percent Occurrence	Range (%)
1-3	55.1	11-100
> 4	36.9	8-66
> 6	13.9	0-61

According to Table 6, a mooring such as the Multileg tanker mooring would be usable less than an average of 45 percent of the time during the most favorable month — the month in which lower seastates occur most frequently. The actual occurrences of seastates 1 through 3 is observed to vary from as seldom as 11 percent at one site, to as frequently as 100 percent during favored months at another. The latter site, which is predictably favorable during the month of October, becomes an undesirable site during other parts of the year, experiencing seastate 4 or worse 66 percent of the time during July. Conversely, seastate 4 or worse occurs as seldom as 8 percent and as frequently as 66 percent of the time during the least favorable month. In each instance, the macro level data of Table 5, which represent annual averages, are markedly different from the micro level data of Table 6. The monthly information is considered far more relevant to short duration military operations of the type addressed herein than is the corresponding yearly information.

The general nature of seastate designations (i.e., seastate 6 covers a range of wave heights from 11.3 to 23 feet) is not a useful basis for the selection of design parameters concerned with the survivability of a pipeline. Of more applicability are the occurrences of specific wave heights. The available data stipulate occurrences of waves with heights greater than 12 feet. This is near the bottom of the range of wave heights covered by seastate 6. Oceanographic charts covering the North Atlantic Ocean show that waves with heights greater than 20 feet occur about one-half as frequently as waves of greater than 12-foot height. It is assumed here that this approximation would apply to worldwide conditions in general. Figure 10 is a graphical presentation of the occurrences of wave heights, compiled from the data discussed and extended to cover 20-foot waves. In both the survivability of a pipeline and the weather constraints, the more stringent conditions occur during the initial period. Therefore, for this study emphasis is placed on the initial period.

9. **Constrained Flow Rates.** The QMR for the baseline system required that it be capable of mooring a 25,000-dwt tanker in a seastate 2 condition. The ability of the baseline system to perform under these conditions has been confirmed by tests. However, it is anticipated that any future generation mooring would be capable of

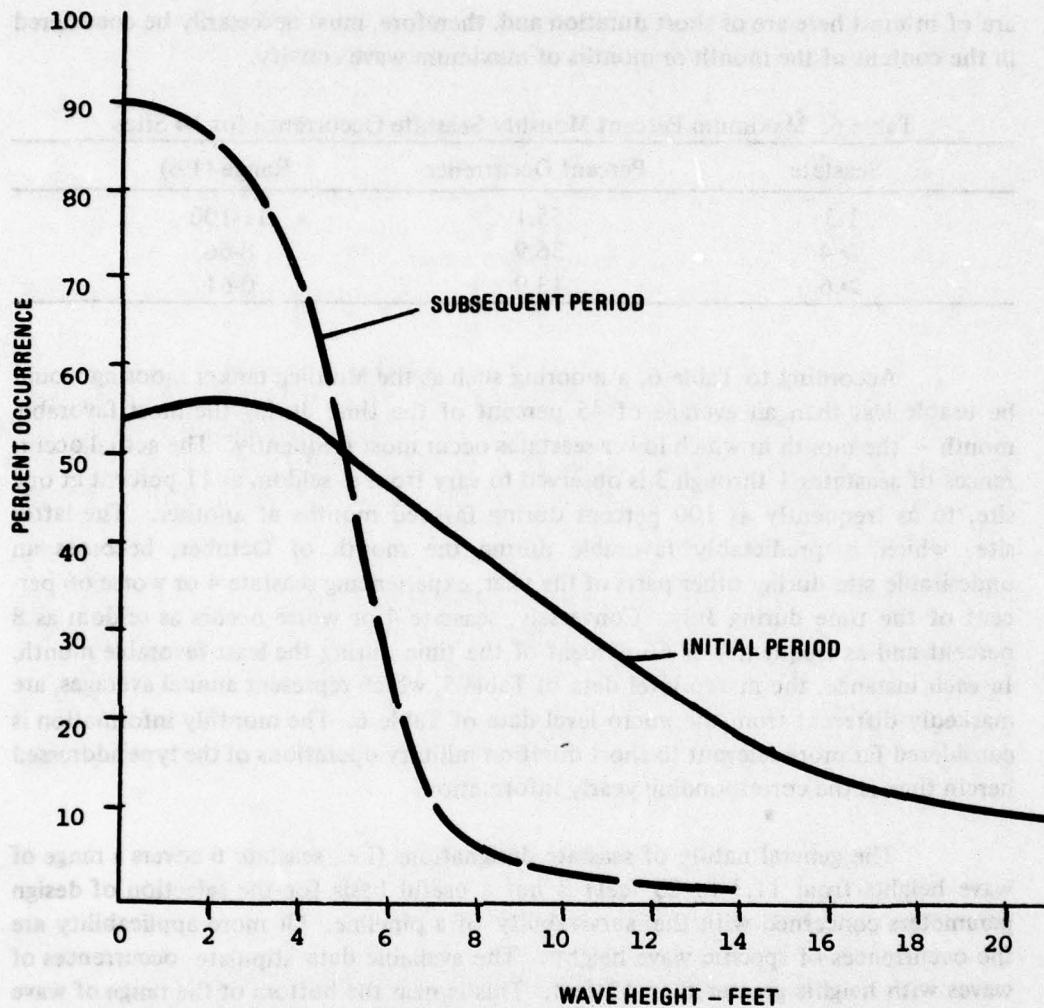


Figure 10. Percent occurrence of wave heights during initial and subsequent periods.

restraining a tanker in seastates higher than seastate 2. Therefore, the advantages of being able to operate in more elevated seastates are considered.

Since seastate 4 or greater occurs an average 36.6 percent of the time during the months that it is maximized, it may be inferred that average occurrence rates for seastates 1 through 3 would occur on average 63.4 percent of the time and seastate 2 or lower somewhat less than 63.4 percent of the time.

A figure of 40 percent appears to be a conservative estimate of the time that seastate 2 or calmer conditions will exist during the least favorable month. It becomes

less probable that equally unfavorable conditions would exist for two or three consecutive months. Therefore, the approach decided upon is to use 70 percent, the annual average of the occurrence of seastate 2 or calmer conditions for the subsequent period after the first month.

An improved system suitable for operation under seastate 3 conditions would be capable of operation 63.4 percent of the time during the initial period and 85.3 percent of the time during the subsequent period. Given a seastate 4 capability, the system would be capable of operation 79 percent of the time during the initial period and 89.4 percent of the time during the subsequent period.

The QMR for the baseline system stipulated a 30-hour mission. This was interpreted as the actual pumping time, with the tanker remaining off-shore for the remaining 18 hours of a 48-hour cycle. Thus, during the initial period, it is possible to pump 384 hours if the seastate never exceeds the maximum seastate that the system can tolerate.

With these percentages and the upper limit on pumping time imposed by the 48-hour delivery cycle, the rates at which fuel must be delivered to meet the demand imposed by a Heavy Corps during the initial period given 1.00 availability are: 4,575 bbl/hr if operations are limited to seastate 2 or less, 2,886 bbl/hr if operations are limited to seastate 3 or less, and 2,316 if the limitation is seastate 4 or less. During the subsequent period the required delivery rates are reduced from the preceding. This occurs since in the subsequent period demand is a function of consumption, while during the initial period, demand is a function of consumption *plus* a contribution to the fuel reserve. Thus, requirements during the initial periods are more demanding than requirements during the subsequent period.

10. Survivability. The ocean environment imparts physical loads to a pipeline through three independent mechanisms: current, wave, and surf action. A discussion of the effect which wave and surf action have on pipeline survivability would seem to follow the previous discussion naturally; however, it will be deferred until a subsequent section of this investigation since some principles relative to the effect of ocean tidal currents on a pipeline have application to the effect of water particle motion as generated by wave and sea action on a pipeline. The tidal current effect is more fundamental than the effects of wave and sea action; therefore, the current effects will be presented first in their entirety, with the effects of wave and surf action on the pipeline to follow.

a. **Tidal Current.** There is a scarcity of published data concerning worldwide near-shore tidal currents. What exists is limited to general or prevailing currents. The currents for a specific locale where an offshore tanker-mooring-and-off-loading

facility might be installed may be greater or less than those indicated on the generalized oceanographic charts, and may be in a direction opposite to that indicated on such charts. From the single study that purports to address the overall subject it has been determined that on a worldwide basis, localized currents of 2 knots or less occur an average of 88 percent of the time, and currents of 1 knot or less occur an average of 56 percent of the time.⁹ The data further indicated that there is wide variation between regions, with the incidence of occurrence of currents of 2 knots or less varying from about 60 percent to 97 percent of the time in some regions, and the incidence of occurrence of current flows of 1 knot or less varying between about 10 percent to 69 percent of the time in other regions. From this meager data, it is apparent that the deployment and use of a pipeline facility which can be used only under a maximum current flow of 1 knot would be extremely limited. On the other hand, if the facility could be deployed and used in 2-knot currents, it would be usable in most military operations. However, because of local conditions (i.e., bays, estuaries, shoreline features) which may cause higher currents, a current flow of 3 knots is used throughout this study.

A steady current imparts a drag force against a submerged pipeline on the ocean floor or suspended above the ocean floor and imparts a lift force on a pipeline lying on the ocean floor. The following formula quantifies these forces:

$$f = \frac{CDWV^2}{2g} \cos^2 \phi \quad .^{10} \quad (5)$$

where:

f = f_d (unit drag force), or f_l (unit lift force) applied to pipeline, pounds per foot.

C = C_d (coefficient of drag), or C_l (coefficient of lift).

W = weight of seawater, 64 pounds per cubic foot.

V = current velocity (or water particle velocity) feet per second.

ϕ = angle that current direction makes with a horizontal line perpendicular to the pipeline.

g = gravitational constant, 32.2 feet per sec².

The drag and lift coefficients, C_d and C_l vary with a dimensionless quantity known as the Reynolds Number, which is defined as:

⁹ S. P. Scott, *Statistical Properties of Assault Landing Beaches*, Report CZ89Z, Naval Ship Research and Development Laboratory, Panama City, Florida (January 1969).

¹⁰ There has been some experimental work on the effect of orientation of the direction of wave travel to the pipeline, but fully consistent results have not been obtained. This study rationalizes this effect by the cosine function which is in general agreement with the empirical data.

$$R = \frac{WDV}{gu} \quad (6)$$

where:

- D = pipe outside diameter, feet.
- V = current velocity, feet per second
- u = dynamic viscosity of seawater 2.28×10^{-5} lb sec per ft².

Below a Reynolds Number of about 2×10^5 laminar flow conditions exist, while turbulent conditions exist above a Reynolds Number of about 5.0×10^5 . The latter condition is associated with a nearly constant C which is much lower than the laminar range C. A transition zone between laminar and turbulent flow lies between these Reynolds Numbers. Figure 11 lists the Reynolds Numbers for different current velocities and sizes of pipe.

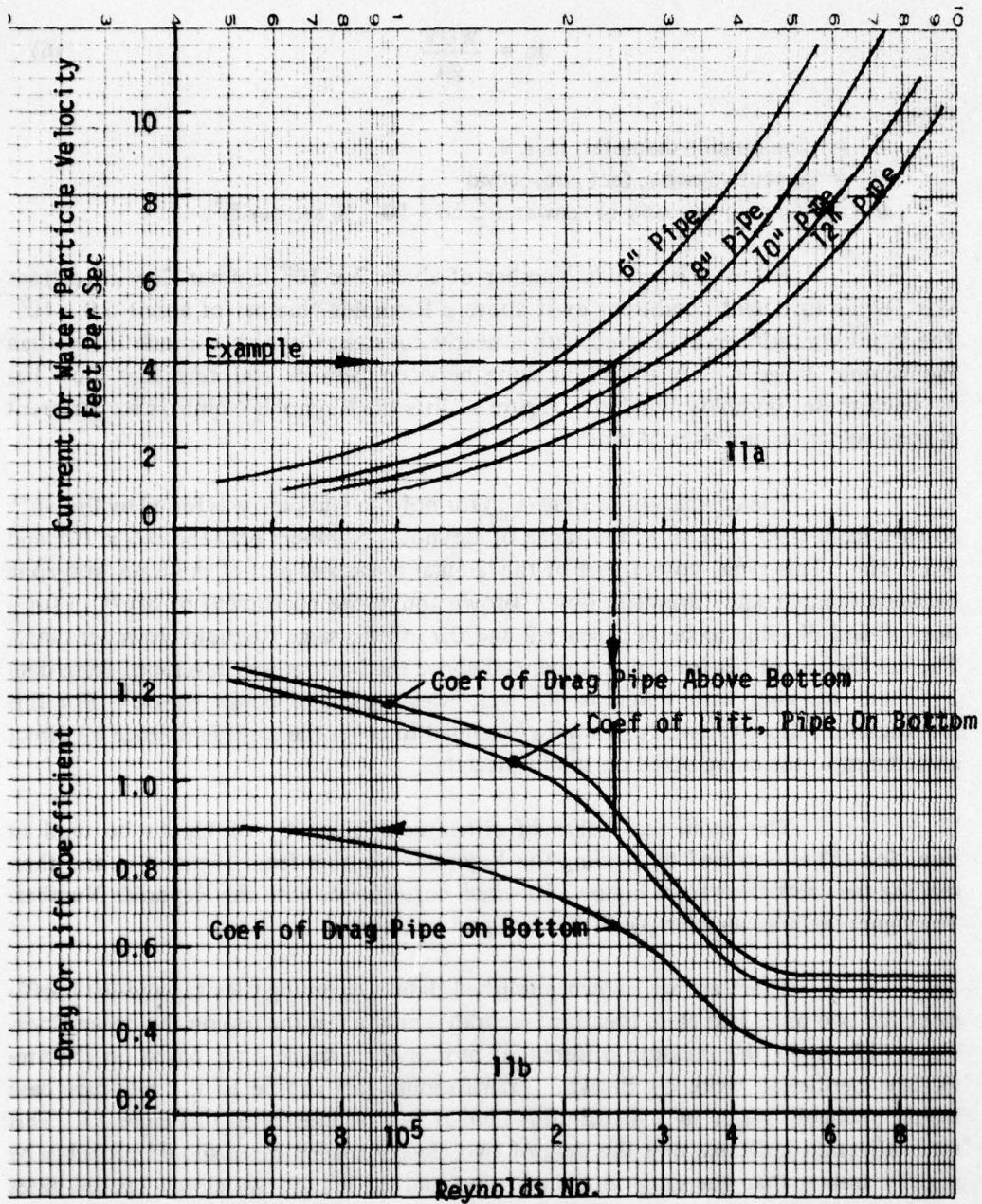
The coefficient of drag (C_d) for bottom-laid pipe was found by Brown¹¹ to vary from 0.90 to 0.55 in the range of Reynolds Numbers between 0.6×10^5 and 3.0×10^5 . This range covers part of the laminar range and part of the transition zone between laminar and turbulent flow. Brown found the coefficient of lift (C_l) for a bottom-laid pipeline to be between 1.2 and 0.75 in the same Reynolds Number range. The coefficient of lift for a pipe suspended above the bottom was developed from data by Evans working with water particle velocities typical of ocean waves.¹² For this investigation, Brown's two curves were extended to cover the turbulent range by direct correlation to the curve based on the Evans data.

The numerical value of either coefficient C_d or C_l to be used in Equation (5) is obtained by reading the Reynolds Number from Figure 11a and then reading the coefficient from Figure 11b which corresponds with the Reynolds Number. The figure includes an example of the two-part procedure.

There are no known published data concerning the drag-and-lift coefficient for two pipes laid close together (separated only a few inches) on the ocean floor. Figure 12 shows the pressure differential profile for a single pipe, based on the previously mentioned work by Brown. Transforming this profile to the two-pipe case would probably result in a distribution similar to that illustrated in Figure 13. This rationalization indicates that the drag of two closely spaced pipes should probably be slightly greater than the drag on a single pipe, and the lift for two closely spaced pipes would be significantly more than the lift of a single pipe. It is assumed for the

¹¹ R. J. Brown, *Drag and Lift Forces on a Submarine Pipeline Subjected to a Transverse Horizontal Current*, Bechtel Corporation (January 1966).

¹² D. J. Evans, *Analysis of Wave Force Data*, Shell Development Company (1969).



Example illustrates the determination of the coefficient of lift for an 8-inch-diameter pipe in a current or water particle velocity of 4 feet per sec.

Figure 11. Water current and water particle velocity versus drag and lift coefficient for single pipe.

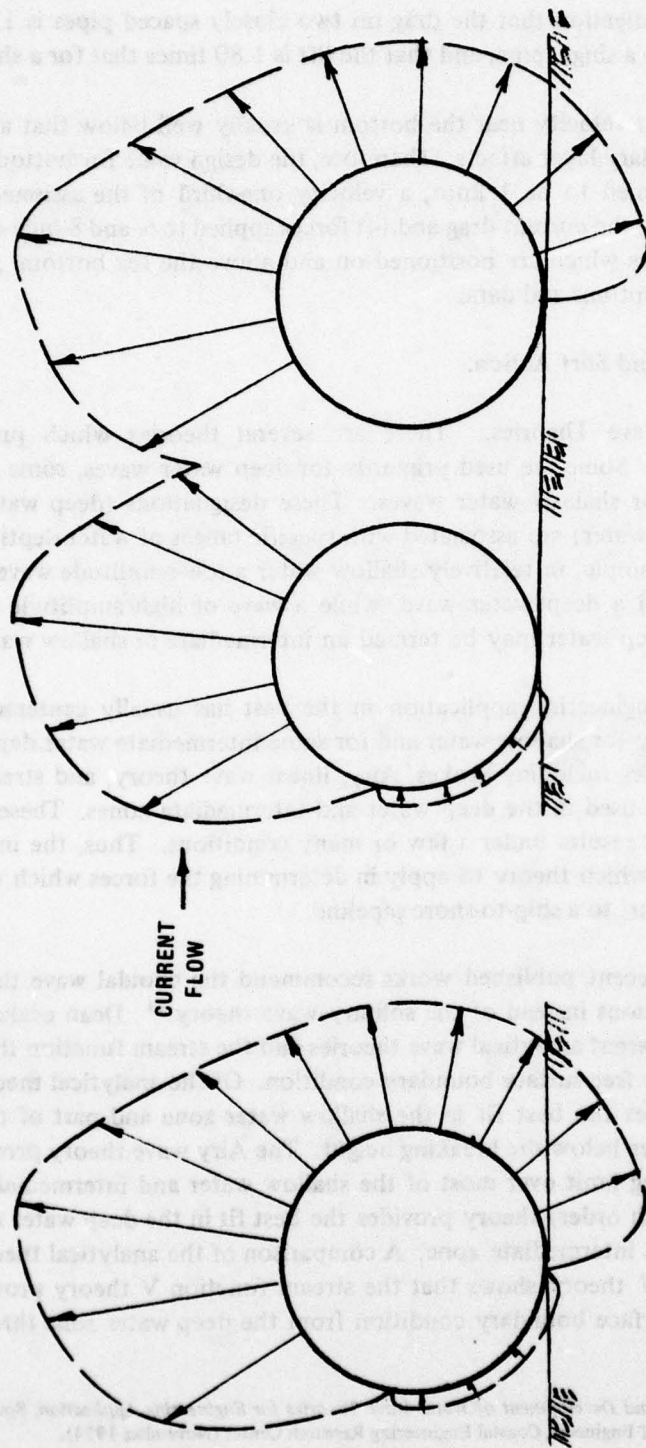


Figure 13. Development of pressure profile for current flow over two pipes closely spaced.

Figure 12. Pressure profile-current flow over single pipe (from Betchel Corp.).

purposes of this investigation that the drag on two closely spaced pipes is 1.25 times the unit drag force on a single pipe, and that the lift is 1.80 times that for a single pipe.

Current velocity near the bottom is usually well below that at the surface because of boundary layer effects. Therefore, the design value for bottom current is conservatively assumed to be 1 knot, a velocity one-third of the assumed surface velocity. Table 7 gives the current drag and lift forces applied to 6- and 8-inch-diameter, single and double pipes which are positioned on and above the sea bottom, given the previously cited assumptions and data.

b. Wave and Surf Action.

(1) **Wave Theories.** There are several theories which purport to describe ocean waves. Some are used primarily for deep water waves, some for intermediate, and some for shallow water waves. These designations (deep water, intermediate, and shallow water) are associated with specific ranges of water depth to wave length ratios. For example, in relatively shallow water a low-amplitude wave of short length may be termed a deep water wave, while a wave of high amplitude and long length in relatively deep water may be termed an intermediate or shallow water wave.

Engineering application in the past has usually centered on the "solitary" wave theory for shallow water and for some intermediate water depth applications. Other theories including Stokes, Airy, linear wave theory, and stream function theory have been used in the deep water and intermediate zones. These theories may all give different results under a few or many conditions. Thus, the immediate problem is to choose which theory to apply in determining the forces which wave and surf action would impart to a ship-to-shore pipeline.

Recent published works recommend the cnoidal wave theory for shallow water applications instead of the solitary wave theory.¹³ Dean evaluated the validity of several different analytical wave theories and the stream function theory for best fit to the dynamic free surface boundary condition. Of the analytical theories, the cnoidal theory provides the best fit in the shallow water zone and part of the intermediate zone for waves below the breaking height. The Airy wave theory provides the best fit at the breaking limit over most of the shallow water and intermediate zones, and the Stokes V (fifth order) theory provides the best fit in the deep water zone and the deeper part of the intermediate zone. A comparison of the analytical theories and the stream function V theory shows that the stream function V theory provides the best fit to the free surface boundary condition from the deep water zone through the

¹³ R. G. Dean, *Evaluation and Development of Water Wave Theories for Engineering Application*, Special Report No. 1, U.S. Army Corps of Engineers, Coastal Engineering Research Center (November 1974).

Table 7. Unit Lift-and-Drag Forces Imparted by Water Velocity
(Current-Flow and Wave-Generated Water Particle Velocities)

Water Velocity (knots)	Bottom Drag ^a		Bottom Lift ^b		Suspended Drag ^c		Bottom Drag ^a		Bottom Lift ^b		Suspended Drag ^c	
	Single Pipe	Double Pipe	Single Pipe	Double Pipe	Single Pipe	Double Pipe	Single Pipe	Double Pipe	Single Pipe	Double Pipe	Single Pipe	Double Pipe
	6-Inch Pipe						8-Inch Pipe					
1	1.4	1.8	1.9	3.3	2.1	2.6	1.7	2.1	2.2	3.9	2.4	3.0
2	5.0	6.3	6.6	11.6	6.9	8.6	5.3	6.6	7.8	13.7	8.4	10.5
3	9.0	11.3	12.1	21.2	12.9	16.1	9.4	11.8	12.3	21.5	13.4	16.8
4	13.3	16.6	16.8	29.4	18.4	23.0	12.0	15.0	17.2	30.1	18.6	23.3
5	14.8	18.5	20.7	36.2	22.7	28.4	17.2	21.5	24.4	42.7	26.4	33.0
6	19.1	23.9	27.0	47.3	29.0	36.3	24.9	31.1	35.2	61.6	38.1	47.6
	10-Inch Pipe						12-Inch Pipe					
1	2.0	2.5	2.8	5.0	2.9	3.6	2.3	2.9	3.2	5.8	3.3	4.1
2	6.7	8.4	8.8	15.8	9.7	12.1	6.6	8.3	8.5	15.3	9.1	11.4
3	10.3	12.9	13.7	24.7	14.8	18.5	9.7	12.1	13.8	24.8	14.9	18.6
4	14.1	17.6	21.3	38.3	22.2	27.8	16.8	21.0	24.0	43.2	25.5	31.9
5	21.6	27.0	30.9	55.6	32.7	40.9	25.7	32.1	36.7	66.1	38.9	48.6
6	31.2	39.0	44.6	80.3	47.3	59.1	37.2	46.5	53.0	95.4	56.2	70.3

^a Unit horizontal drag with pipe on sea bottom (pounds per foot).

^b Unit vertical lift with pipe on sea bottom (pounds per foot).

^c Unit horizontal drag with pipe suspended above bottom or floating on the sea surface (pounds per foot).

intermediate zone, and well into the shallow water zone. The cnoidal and the Airy wave theories are applicable in a much smaller range when the stream function is considered, than when only the analytical theories are considered.

The same work by Dean included a comparison of the total drag force that a wave would impart according to the different theories. The cnoidal theory predicts a total drag force of about twice that predicted by the Airy wave theory. The calculations were based on a wave with a height of 15.42 feet, a period of 20 seconds, a still water depth of 20 feet, and a ratio of wave height to breaker height of 0.99. This particular wave falls in the intermediate area of the transition between where the cnoidal, Airy, and stream function V theories provide the best fit to the free surface boundary condition. This indicates that there is little if any relationship between the quality of fit to the free surface boundary conditions and the force imparted to a submerged pipeline as predicted using any specific wave theory. The use of the cnoidal theory for the shallow water and intermediate zones where the sea action is most pronounced is the conservative approach. Figures 14 and 15 illustrate the solitary wave, sinusoidal wave, and the cnoidal wave.

There have been several experimental determinations of drag and acceleration (the latter is sometimes referred to as added mass or inertial) coefficients for use in calculating the wave-induced forces on a submerged body. The data from these efforts are scattered, which probably resulted from the difficulty in obtaining accurate data and the use of different wave theories to calculate the coefficients. Some

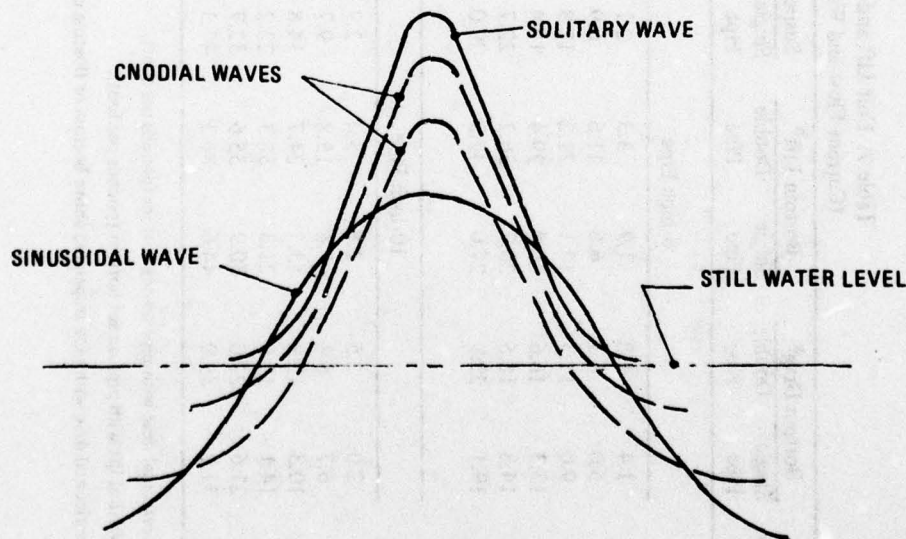
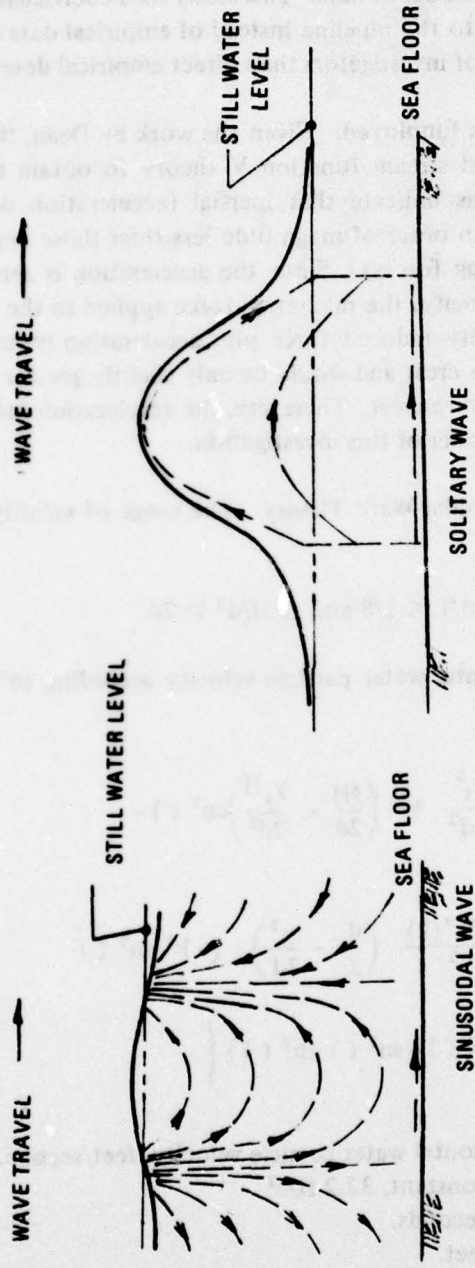


Figure 14. Comparison of wave profiles.



ARROWS INDICATE WATER PARTICLE TRAJECTORIES

Figure 15. Illustration of sinusoidal wave and solitary wave—limiting cases of cnoidal wave.

work to empirically determine the maximum force which a wave imparts to an under-water body has been accomplished, but the data are meager and subject to the inherent inaccuracies in obtaining such ocean data. This study uses coefficients for the calculation of the forces imparted to the pipeline instead of empirical data since this method has received more attention of investigators than direct empirical determinations.

(2) **Theories Employed.** Given the work by Dean, this study employs the cnoidal wave theory and stream function V theory to obtain the water particle velocities. Trial calculations indicate that inertial (acceleration dependent) forces applied to the pipeline are an order of magnitude less than those dependent upon the water particle velocities (drag forces). Since the acceleration is zero at the point of maximum water particle velocity, the maximum force applied to the pipeline (summation of water particle velocity induced force plus acceleration induced force) would occur very close to the wave crest and would be only slightly greater than the velocity induced force alone at the wave crest. Therefore, the acceleration induced forces have been neglected for the remainder of this investigation.

(a) **Cnoidal Wave Theory.** The range of validity for the cnoidal wave theory is

$$d/L < 1/8 \text{ and } L^2 H/d^3 > 26.$$

The equation for the horizontal water particle velocity according to the cnoidal wave theory is as follows:

$$\sqrt{\frac{u}{gd}} = \left\{ -5/4 + \frac{3y_t}{2d} - \frac{y_t^2}{4d^2} + \left(\frac{3H}{2d} - \frac{y_t H}{2d^2} \right) \text{cn}^2(\cdot) - \right. \quad (7)$$

$$\left. \frac{H^2}{4d^2} \text{cn}^4(\cdot) - \frac{8HK^2(k)}{L^2} \left(\frac{d}{3} - \frac{y_t^2}{2d} \right) (-k^2 \text{sn}^2(\cdot) \right.$$

$$\left. \text{cn}^2(\cdot) + \text{cn}^2(\cdot) \text{dn}^2(\cdot) - \text{sn}^2(\cdot) \text{dn}^2(\cdot) \right\}$$

where:

- u = the local horizontal water particle velocity, feet/second.
 - g = gravitational constant, 32.2 ft/s².
 - T = wave period, seconds.
 - L = wave length, feet.
 - d = still water depth.
 - y_t = distance from bottom to wave trough x feet.
- cn, dn, and sn are Jacobian elliptic functions.

- H** = wave height, feet.
y_c = distance from bottom.
y = distance from bottom to point of consideration, feet.
y = 0 at bottom.
sn () = sn {2K(k) (X/L)} for a stationary coordinate system

The wave length of a cnoidal wave is given by:

$$L/d = \sqrt{3} K(k) (2\bar{L} + 1 - y_t/d)^{-0.5}$$

where K(k) is the complete elliptic integral of the first kind of modulus K.

$$k^2 = \frac{y_c/d - y_t/d}{2\bar{L} + 1 - y_t/d}$$

and

$$2\bar{L} + \frac{-y_t}{d} E(k) = \left(2\bar{L} + 2 \frac{-y_c}{d} - \frac{y_t}{d} \right) K(k)$$

where E(k) is the complete elliptic integral of the second kind of modulus (k)

Practical application of the cnoidal wave theory requires a computer with a large memory or the use of graphical aids. Graphical solutions were used for this study, which require that the wave period, T; wave height, H; and the still water depth, d, be specified.

In any wave theory $L = CT$, where C is the celerity or wave velocity. Of these characteristics, only T may be considered constant as the wave train travels from deep to shallow water.

(b) Stream Function. The stream function is a solution of the Laplace differential equation. The horizontal water particle velocity variable is given by:

$$u(\theta, S) = \sum_{n=1}^{n=N} X(n) \frac{\{2\pi n\}}{L} \cosh \frac{\{2\pi n S\}}{L} \cos n\theta \quad (8)$$

where:

N is the order of the stream function.

X is the stream function coefficient.

n is index used in the summation.

θ is the phase angle $\frac{(2\pi x)}{L}$

S is the vertical coordinate referenced to the bottom, positive upward.

Other terms are as previously given.

Solution of the higher order stream function equations requires either a sophisticated computer or extensive tables. This study uses tables which express the variables in dimensionless forms. For example, the dimensionless form of the horizontal water particle function is $\frac{u}{H/T}$. Use of tables requires that the wave period, T; wave height, H; and the still water depth, d, be specified.

(3) **Shoaling waves.** Ocean waves, as they near the beach, change their form. If they are heading directly toward the beach from deep water, their heights often increase; the magnitude of the height depends on the bottom gradient and other factors. If the direction of travel is not perpendicular to the beach, the waves refract toward the beach and reduce in height. The magnitude of the reduction depends on the direction of wave travel relative to the shore line, bottom gradient, and other factors.

Obviously, a total accommodation of the above would require consideration of the local conditions at the specific beach where a system is to be installed. For a universal pipeline system, the conservative approach would be to consider the wave travel as directly toward the beach, thereby causing an increase in wave height; but such a direction of wave travel would be in general alignment with the pipeline axis thereby imparting only a fraction of the force which would be imparted if the direction of wave travel were broadside to the pipeline. Because of the reduction in the heights of refracting waves, the force imparted by waves generally parallel to the shore line would be dramatically reduced as they enter shallow water and start to refract. Therefore, it is conservatively assumed that the direction of wave travel is toward the shore and skewed to the pipeline.

The assumed increase in wave heights as they approach the beach are given in Table 8. The shoreline factors were obtained from data compiled by the U.S. Army Coastal Engineering Research Center. The table assumes a linear increase in wave height from the deep water wave height at a ratio of wave height to still water

depth of 0.1 to the full shoaling height at the breaking depth – a ratio of breaker height to still water depth of 0.78.

(4) **Wave Period.** Table 2 defines the range of periods associated with different seastates. Table 8 gives the wave periods used in this particular study. These wave periods were selected on the basis of curves published by the U.S. Navy Hydrographic Office which indicated that the occurrence of greater periods are relatively rare.¹⁴

Table 8. Design Wave Characteristics

Deep Water Wave Height H (feet)	Period T (sec)	Deep Water Wave Length (feet)	Shoaling Height Factor	Hb/d=.78	.7	.6	.5	.4	.3	.2	.1
23	11.2	642	1.215	27.9	27.4	26.6	25.9	25.1	24.4	23.7	23
20	10.5	562	1.215	24.3	23.8	23.2	22.5	21.9	21.3	20.7	20
16	9.7	474	1.220	19.5	19.1	18.6	18.1	17.6	17.0	16.5	16
12	8.9	403	1.330	16.0	15.4	14.9	14.2	13.8	13.2	12.6	12
8	7.2	265	1.330	10.4	10.3	9.9	9.2	9.6	8.8	8.4	8
4	5.6	160	1.394	5.6	5.4	5.2	4.9	4.7	4.5	4.2	4

Figure 16 gives water particle velocities for various wave heights up to and including a deep water wave height of 23 feet.

To prevent lateral movement of the pipeline and ensure survivability, the following condition must be satisfied:

$$B_N = f_1 + C_f f_d$$

where B_N is the negative buoyancy required, lb/ft.

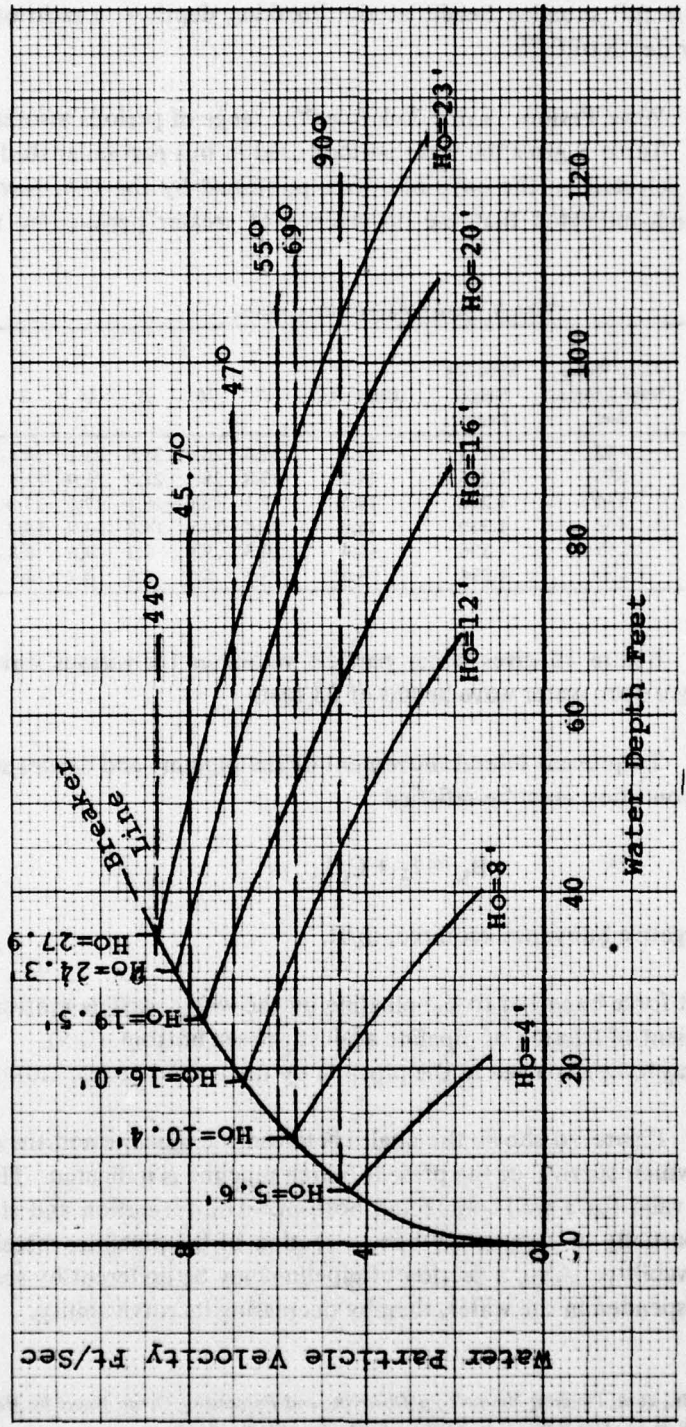
f_1 = unit lift force imparted to the pipeline by the water particle motion lb/ft.

C_f = Coefficient of friction of pipeline against the sea bottom, (0.5).

f_d = Unit drag force imparted to the pipeline by the water particle motion, lb/ft.

Figure 16 shows the angles between the pipeline and the direction of wave trains at which survival of the present 6-inch pipeline is indicated. The indication is considered valid for a well-compacted bottom. The formation and shifting of sand domes may partially or completely bury a section of the pipeline, thereby vastly increasing its survivability. Also, a section of pipeline may be undercut by scouring so that it would be suspended in the water, thereby decreasing its survivability.

¹⁴ William J. Pierson, Jr., et al, *Practical Methods for Observing and Forecasting Ocean Waves by Means of Wave Spectra and Statistics*, H. O., Pub 20603 U.S. Navy Hydrographic Office (1955).



Note: The degree numbers indicate the angle between the direction of pipeline and the direction of wave travel at which survival of the present 6-inch tactical pipeline is indicated when filled with diesel fuel.
 Ho = Deep Water Depth.

Figure 16. Maximum horizontal water particle velocities relative to water depth and wave height.

11. Distance From Shore to Operational Depths. The minimum distance from the shore to the tanker mooring (end of the ship-to-shore pipeline) should be about 1250 feet seaward of the minimum depth at which the tanker can maneuver. The minimum depth is taken as the draft of the loaded tanker, plus $\frac{1}{2}$ the tidal range, plus 6 feet.

At the present time military fuels are carried in tankers in the 25,000 to 38,000-dwt range which have drafts of approximately 35 feet when fully loaded. Tankers of the 70,000-dwt class and larger are used exclusively for the transportation of crude oil; except in unusual situations they may be chartered for transporting refined product. The Military Sealift Command (MSC) chartered two 70,000-dwt tankers to transport refined product during the Vietnam conflict, but at the present time the 38,000-dwt tanker is the largest chartered. The draft of the 70,000-dwt tanker is comparable to that of the smaller tankers. Therefore, a mean water depth of 45 feet is satisfactory as the limit of the maneuvering space for the tankers currently chartered as well as for the 70,000-dwt tankers which might be chartered in support of an extended future conflict.

The National Intelligence Survey identifies beaches which are potentially suitable for amphibious operations along a majority of the world's coastlines. A more recent and ongoing effort derives its data from a series of documents generated by and in cooperation with the DIA (i.e., Amphibious Objective Studies (AOS), Special Amphibious Studies (SAS), and Amphibious Area Studies (AAS)). Figure 17 is a graphical representation of these data.

The relationship between conduit length and the percent of landing beaches which may be serviced is reflected in Table 9. The values reflect the average of two mutually exclusive studies as reported by Cevasco.¹⁵ The values are adjusted to compensate for the 1,250 feet of maneuvering space required by a tanker (i.e., the 45-foot water depth would have to be within 3,750 feet of shore if a 5,000-foot conduit were the maximum available length).

From the table it is apparent that increasing the length at the greater distances from shore provides additional utility but at a decreasing rate. A reasonable cut-off point would intuitively fall around the 10,000-foot point. A longer pipeline would serve only a small number of additional beaches, and the delivery capacity of a pipeline decreases dramatically as the length is increased. A final determination of the maximum practical length must weigh the desirability of a longer pipeline against the resultant decrease in flow rate and the capability of troops to install the system.

¹⁵ F. M. Cevasco. "Coastal Characteristics and Their Affect on Tanker Discharge Operation," Report 2203, U.S. Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia (January 1977).

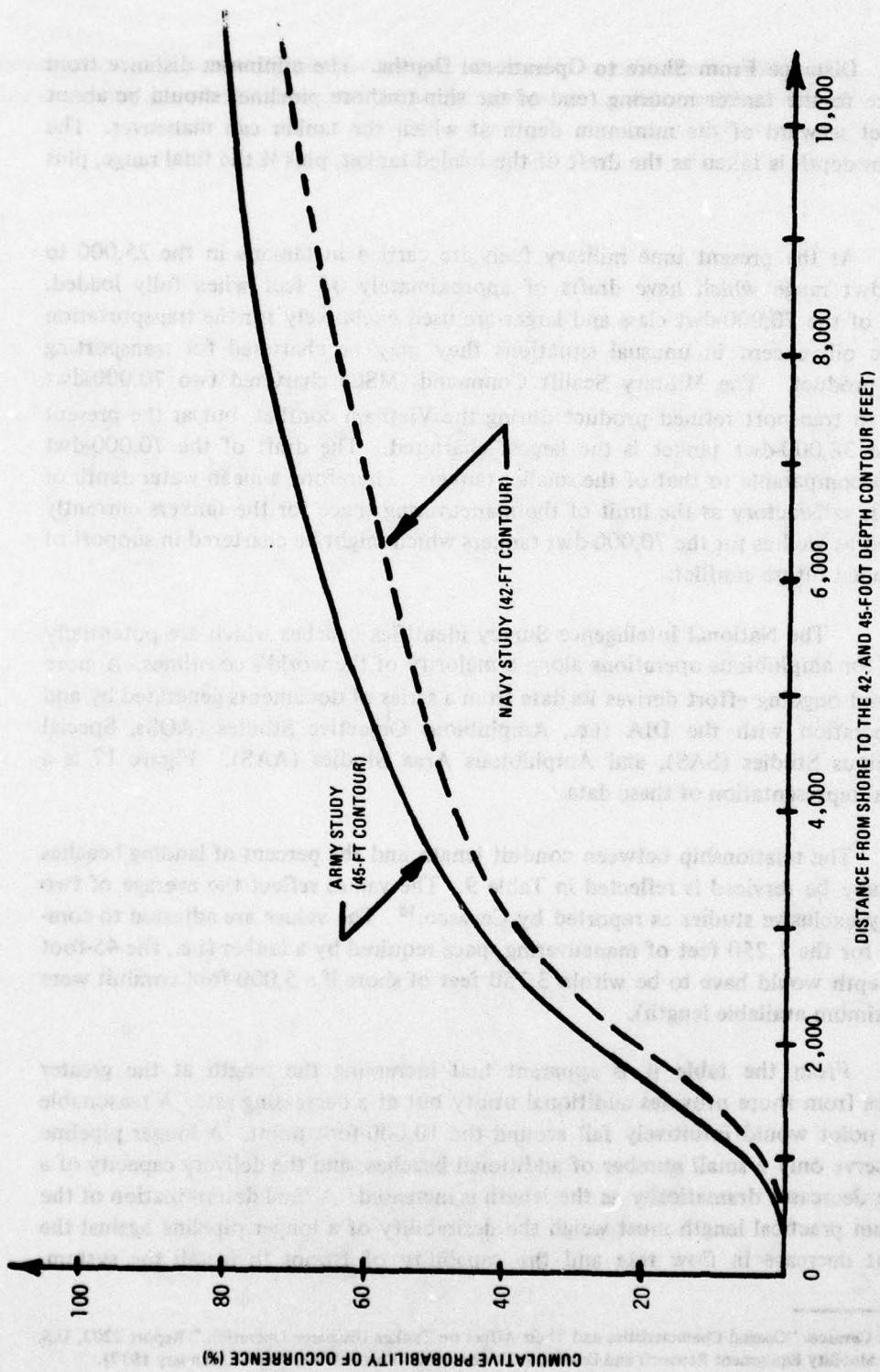


Figure 17. Accumulated percentage occurrence of 45-foot water depth related to distance from shore.

Table 9. Relationship Between Conduit Length and Cumulative Frequency

Conduit Length (ft)	Cumulative Frequency (%)
2,500	13
5,000	47
7,500	63
10,000	71
12,500	76

Installation, which is addressed in depth in a subsequent section, will become increasingly difficult as pipeline length and diameter are increased. The problem is, therefore, quite complex and the analytical treatment given within this pilot study must be considered as tentative pending detailed analysis of this and other critical issues identified herein.

12. **Pipeline Flow Rates.** The following parameters are used in determining the flow rated through different sized pipelines:

Specific gravity of composite fuel: 0.7825.¹⁶

Kinematic viscosity at 60°F: 1.11 centistokes.

Allowable head loss (90 lb/in²): 266 feet.

The Darcy-Weisback equation is used for all fuel flow computations in accordance with the procedures given in TM5-343.¹⁷

The Darcy-Weisback equation is as follows:

$$H_f = \frac{fLV^2}{2gD} \quad (9)$$

where:

H_f = head loss due to friction, feet.

f = dimensionless friction factor.

L = length of pipe, feet.

V = velocity of fluid flow, feet per second.

g = gravitational constant, 32.2 feet/second².

D = Inside diameter of pipe, feet.

¹⁶ Based on consumption of 50 percent JP-4, 27 percent diesel, and 23 percent gasoline; proportions derived from TRADOC planning scenarios.

¹⁷ TM 5-343, *Military Petroleum Pipeline Systems*, Department of the Army (February 1969).

Substituting 266 feet for 90 lb/in² and using appropriate conversion factors, the equation becomes:

$$Q = 110.72 \frac{(d^5)}{(fL)} \quad (10)$$

where:

Q is the fuel flow in bbl/hour.¹⁸

d is the inside diameter of the pipe in inches.

Other items are as given above.

The friction factor, f, is dependent on the pipe roughness and the Reynolds number.

The Reynolds number is given by:

$$R = \frac{2212Q}{dk} \quad (11)$$

where:

R is the Reynolds number.

Q is the fuel flow in bbl/hour.

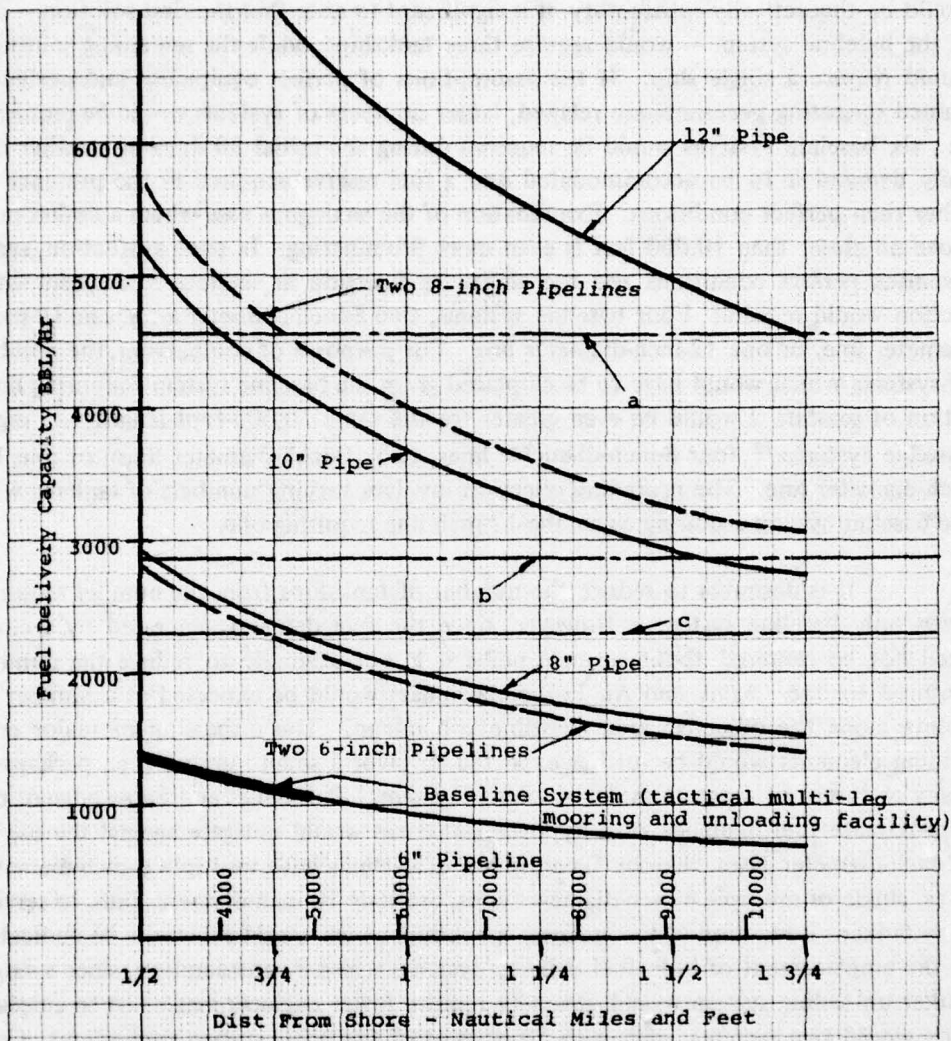
k is the kinematic viscosity in centistokes (1.11 centistokes for the composite fuel at 60° F).

Since Q appears in both of the above equations a solution must be accomplished by iteration.

Figure 18 shows the flow capacities of single 6-, 8-, 10-, and 12-inch and double 6- and 8-inch diameter uncoated steel pipeline versus the distance from shore as determined from the above equations. The friction factors, f, were obtained graphically from TM-5-343, *Military Petroleum Pipeline Systems*.

Figure 18 illustrates the disparity between the fuel delivery rate of a single baseline system and the fuel demand given an operational limitation of seastate 2. For this reason, a multiplicity of baseline systems must be emplaced even given perfect equipment, an assumption implicit in the figure. In contrast, if operations in seastate 3 were possible and if a tanker could be moored within 5000 feet of shore, theoretically it would be possible to meet the initial (through midnight of day 29) fuel demand of a hypothetical heavy corps with: three baseline systems, two 8-inch-diameter lines, one 10-inch-diameter line, or one 12-inch-diameter line. While each of the four solutions

¹⁸ Published data indicates that the capacities of lined or coated steel pipe, aluminum pipe, and plastic pipe are about 15 percent greater than that of uncoated steel pipe.



(Composite fuel at 90-psi friction loss)

- a. Adjusted initial demand given the capability of operating in Seastate 2 or less
- b. Adjusted initial demand given the capability of operating in Seastate 3 or less
- c. Adjusted initial demand given the capability of operating in Seastate 4 or less

Figure 18. Pipeline delivery capacity—distance from shore.

would be theoretically satisfactory, it is significant to note that the first solution – use of the baseline system – would require three tankships, while the remaining solutions would require a single ship. If the assumptions of perfect equipment and perfectly trained operating personnel are relaxed, larger numbers of systems would be required; i.e., six baseline systems would be required during the initial 30 days of conflict if a daily demand is to be accommodated *and* a fuel reserve acquired in the presence of other than perfect conditions. Examination of the analogous case where a tanker may move no closer than 10,000 feet is even more illuminating. In such a situation, again assuming perfect conditions and the ability to function in seastate 3, demand satisfaction would require: Four baseline systems, two 8-inch-diameter lines, one 10-inch-diameter line, or one 12-inch-diameter line. For purposes of comparison, the number of systems which would have to be emplaced given the baseline system's mooring limitation of seastate 2 would be even greater for the same 10,000-foot length; i.e., eight baseline systems,¹⁹ four 8-inch-diameter lines, two 10-inch-diameter lines, or one 12-inch-diameter line. The preceding selection involves varying numbers of tankers, with the baseline system requiring eight, the 12-inch line requiring one.

It is desirable to reduce the number of tankships from the number required given only baseline systems. However, since the fuel demand generated by a corps need not be centered about a single point it is not desirable to reduce the number required to one. Army and Air Force consumers would be expected at a number of points along the objective area coastline and inland. The dispersion of major consuming elements would be further expected to favor a small number (i.e., perhaps as many as three) of separate tanker discharge systems. This belief and knowledge of the approximate fuel demands of a hypothetical corps would mitigate against the use of 12-inch-diameter lines, thereby favoring use of systems with multiple 6-inch-diameter lines, single or multiple 8-inch-diameter lines, or single 10-inch-diameter lines to service each tanker. Reduction of the engineer manhours which would otherwise be dedicated to the emplacement of bulk fuel delivery systems is also a consideration, since a single tanker unloading system would generally require fewer engineer manhours to emplace than would two systems, each with 50 percent of the single system throughput. Conversely, multiple systems would require more operating personnel than would a single system. The total number of personnel and man-hours is expected to be approximately proportional to the number of operative systems. The problem involves a number of variables, some of which move in opposite directions. Therefore, as one variable is optimized, one or more are observed to diminish in utility. The task is then to identify a series of alternative solutions to the problem, now that the underlying physical constraints have been examined. It will then be possible to determine, in at

¹⁹ Assuming for purposes of the example that a baseline system is installed by some unspecified means. This assumption is needed since the baseline system has only been tested in lengths of 5000 feet and less.

least a qualitative manner, the degree to which each alternative maximizes the total utility.

13. **System Concepts.** There are three generic classes of relevant system concepts: surface systems, submerged buoyant systems, and bottom systems. Each of these have been used or proposed for use by the military at one time or another.

a. **Surface Systems.** A surface system could theoretically incorporate pipe which is inherently buoyant when filled with air or fuel, pipe which is equipped with auxiliary flotation units to insure buoyancy, hose which is inherently buoyant, or hose equipped with auxiliary flotation units. As a general observation, surface systems have been limited to hoses. The conduit used would be susceptible to fatigue failures caused by sea action which would constantly flex and work the system. This problem would be exacerbated with increasing length and the presence of tidal currents.

(1) **Navy 6-Inch Floating Assault Hose System.** A floating buoyant system of 6-inch collapsible hose has been used by the Navy for some time.²⁰ The system is installed from the deck of a warping tug, LCU or other suitable vessel equipped with a warping anchor. In operation, the vessel drops its anchor beyond the ultimate position for the offshore end of the hose and moves toward the beach while paying out the warping line. When near the beach, the end of the hose and tension line which are on separate reels, are passed to the beach and are anchored. The hose and tension line are payed-out as the vessel warps – winches itself back to the warping anchor – itself from the beach. Floats, a 100-pound anchor, and a tension line, are attached to the hose at 50-foot intervals. The tension line is slightly shorter than the hose sections so that no actual tension forces are applied to the hose. The system is relatively easy to install and is typically recovered after each use to prevent damage by water craft and by sea action. The system can be installed up to 5000 feet from shore.

(2) **Army Floating Hose System.** (Project terminated before acceptance.) In June 1970, the USAMERADCOM, then USAMERDC, essentially completed development of an 8-inch floating hose system for over-the-beach bulk fuel delivery in tactical or amphibious assault operations.²¹ The hose system was comprised of a hose-reeling unit anchored on the beach, up to 1000 feet of flexible 8-inch-diameter floating hose, tension cable for the hose, and hose purging equipment. Figure 19 shows a prototype hose-reeling unit.

²⁰ J. J. Traffalis, *600-GPM Ship-To-Shore Bulk Fuel Delivery Systems*, Technical Report R-202, U.S. Naval Civil Engineering Laboratory, Port Hueneme, California (29 June 1962).

²¹ Henry C. Mayo, *Eight-Inch Floating-Hose System for Ship-to-Shore Fuel Delivery*, Report 2009, U.S. Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia (June 1971).

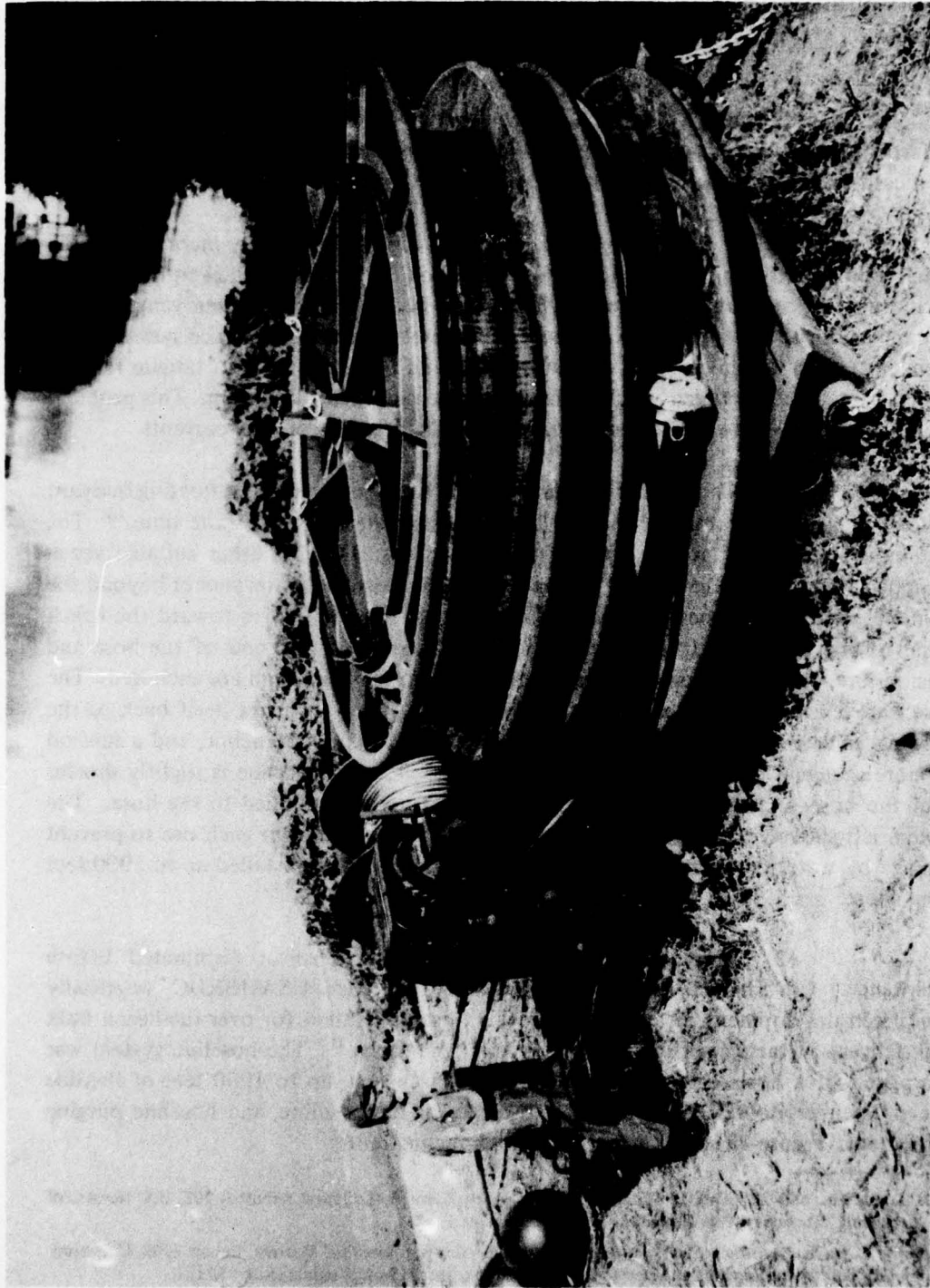


Figure 19. Prototype of Army 8-inch floating hose line system.

The Army system was intended for use in discharging fuel from fuel barges or lighters positioned up to 1000 feet from shore. The normal operational procedure was to tow the two-part tension cable with a work boat from the beach to the moored vessel, power the hoseline from the beach to the vessel with the tension line (which runs from the tension winch to the moored vessel, through blocks, and back to the hose on the reel), pump the fuel ashore, purge the hoseline, and recover the hose and tension line with the reeling unit.

Development of the system was completed before the work was terminated by the Combat Development Command's withdrawal of the requirement for the system. However, the surplus hose was used in Vietnam with good to excellent results.

The Army's 8-inch floating hoseline system gave every indication of being satisfactory for the purpose for which it was intended – the conveyance of fuel from barges or lighters to shore storage. The primary drawback of this system is obvious – an array of lighters or fuel barges, each with a pumping system is required for the delivery of bulk fuel from a tanker to onshore storage. Another drawback of the system was the high lateral forces which would be generated by high velocity along shore currents in some locations.

(3) West German Army Hoseline System. The West German Army has a hoseline system similar to the U.S. Army system described above. The primary difference in the two systems is that the West German hose wall is weighted by lead pellets so that the hose will float during deployment but will sink when filled with fuel. This system is, therefore, a hybrid of the surface and bottom categories previously defined for purposes of analysis herein.

b. Submerged Buoyant System. A submerged buoyant system is one which is held, usually only a few feet, above the ocean bottom by anchors attached at intervals. As in the case of the surface systems, hose or pipe may be used with or without auxiliary buoyancy units.

Figure 20 illustrates a submerged buoyant, 8-inch, fiberglass-reinforced plastic pipe system designed specifically for theater-of-operations use and which is incorporated into the Army Functional Components System.²² The pipe walls are 0.4 inch thick to resist the ocean environment – double the standard thickness. The system was designed to be installed within two days after arrival at the beach work site but at the expense of mobilizing a large array of floating equipment. Eighteen barges

²² *Army Functional Components System: Tactical Fiberglass Submarine Pipeline*, Van Houten Associates, New York, N.Y. (September 1974).

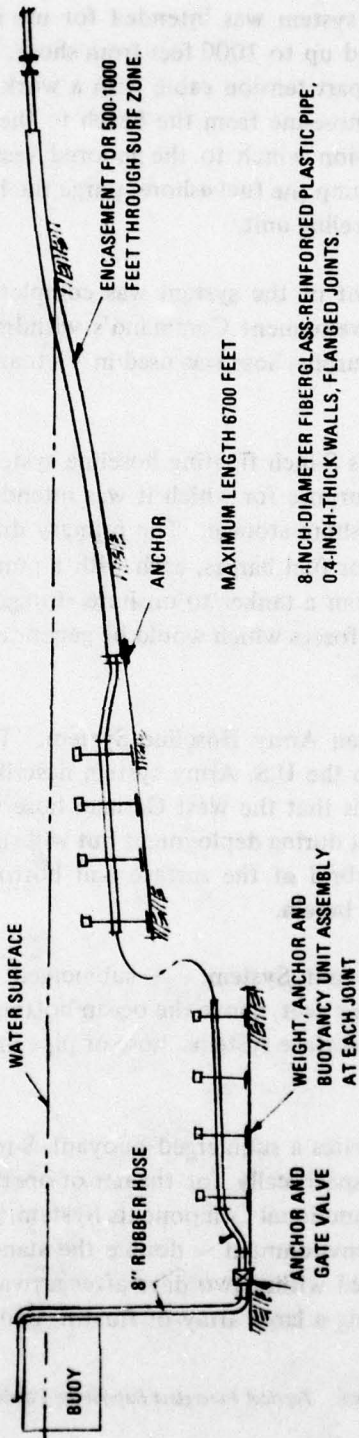


Figure 20. Tactical Fiberglass-Reinforced Plastic Pipeline System (Army Functional Components System).

are used simultaneously in the emplacement of the system after the pipeline is pre-assembled on shore into 400-foot sections. Cost of the system is estimated at \$374,000 for an 80-foot depth and \$404,000 for a 100-foot depth (exclusive of specialized floating plant). This particular design has not been subjected to any model or full-scale field testing.

The only known system of this generic type was designed for the Air Force and installed at Eniwetok Atoll in a protected area. Considerable difficulty was encountered during its installation. Heavy floating equipment and 13 Navy frogmen were required to finally complete the installation.

The advantages of a submerged buoyant system include reduced vulnerability to surface-craft-induced damage, reduced water particle velocities and acceleration vis-a-vis surface systems, and the ability to use a lightweight pipeline—aluminum, fiberglass-reinforced plastic, or, possibly, thin-walled steel pipe. This advantage would result in lower shipping and handling costs for the pipe than a bottom-laid system which requires heavy pipe or weight coating. The advantages are mitigated to some degree by the need for locally fabricated weights required to keep the line in place. While hose theoretically could be used in this mode, its characteristics have limited its use in the past to surface or bottom applications.

A submerged buoyant system of rigid pipe would be influenced by wave action which would tend to impart a circular or elliptical motion to the pipeline. Each section of the pipeline would be subjected to a different cycle of the motion, depending on the phase of the wave which is crossing the particular point of the pipeline. Beneath the crest, the motion imparted to the pipeline would be in the direction of wave travel, and between the wave trough and crest, the motion would be vertically upward or downward, depending on whether the trough or crest had just passed. Given the irregular nature of ocean waves and the fact that the mass of the pipeline will resist changes in the pipeline's state of motion, temporary resonant conditions could be expected to occur occasionally. With constant flexing of the pipeline about both axes and given occasional resonant conditions and the inherent requirement for low unit weight, elevated stress levels would be expected with the attendant problem of induced fatigue failures. These problems would be less should the same line be surface mounted, but far greater if the line was fixed to the ocean bottom.

c. **Bottom-laid System.** A bottom-laid system is one which is held in place on the ocean floor by its own weight or by a combination of its own weight and added weight or anchors. The bottom-laid system is generally acknowledged to be the choice of private industry; it is also the primary type of system now used by the Army and Navy when operations are to continue for more than a short period.

As described at the beginning of this report, the pipeline facility of the present tactical multileg mooring subsystem is an adaptation of the Navy bottom-laid assault system. The pipe sections are connected by threaded couplings assembled by powered tongs mounted on vertical and horizontal tracks to align the pipe sections and to force thread contact. The threads are national "buttruss" threads. The Navy conducted tests with standard tapered pipe threads which were found to be unsatisfactory for extended use in the surf zone. Navy tests also identified a number of other mechanical joint designs which could not withstand the rigor imposed by a sea environment.

In the early 60's, the Army type classified a system comprised of 8-inch- through 20-inch-diameter welded steel pipe. The 8-inch pipe has 0.322-inch-thick walls to provide sufficient in-place specific gravity when filled with air. All pipe larger than 8-inch diameter is weight-coated with heavy aggregate concrete to provide sufficient in-place specific gravity when filled with air. The development of this system was based on standard commercial practice which prevails to the present time.

Installation of the system requires a specially outfitted barge (Figure 21) and a large assortment of beach equipment (e.g., several crawler tractors equipped with side booms, about 20 special dollies which provide rolling support on the beach for the pipeline, welding equipment, and radiographic weld-inspection equipment). The requirement for such an extensive and costly equipment spread combined with the absolute dependence upon specially trained welders tends to discount use of this system in an assault role.

In a bottom-laid system, two or more pipelines could be installed as a single system so that multiple products can be discharged simultaneously. The means to discharge more than one product simultaneously is a desirable characteristic for a tanker discharge system, vis-a-vis the "batching" which has to be done with a single pipeline. Batching requires close coordination of operating personnel onboard the tanker, at the shoreline and at the storage facility; any errors will result in potentially large volumes of "slop" fuel (i.e., combinations of two or more fuels).

14. Survey of Competing Alternatives. The fuel delivery requirements for a corps-size operation can be met using pipeline of any diameter, providing a sufficient number are installed. As indicated earlier, six of the present 5000-foot-long, 6-inch-diameter pipeline systems are required to provide the required quantity of fuel for a Heavy Corps operation. The major disadvantages of this large number of systems are obvious: *the requirement for a separate mooring system and the complete dedication of a tanker for each pipeline facility.* Advantages of a larger number over a smaller number of systems would appear to be that in the event one system becomes inoperable, the remainder would be theoretically capable of supplying a large percentage of

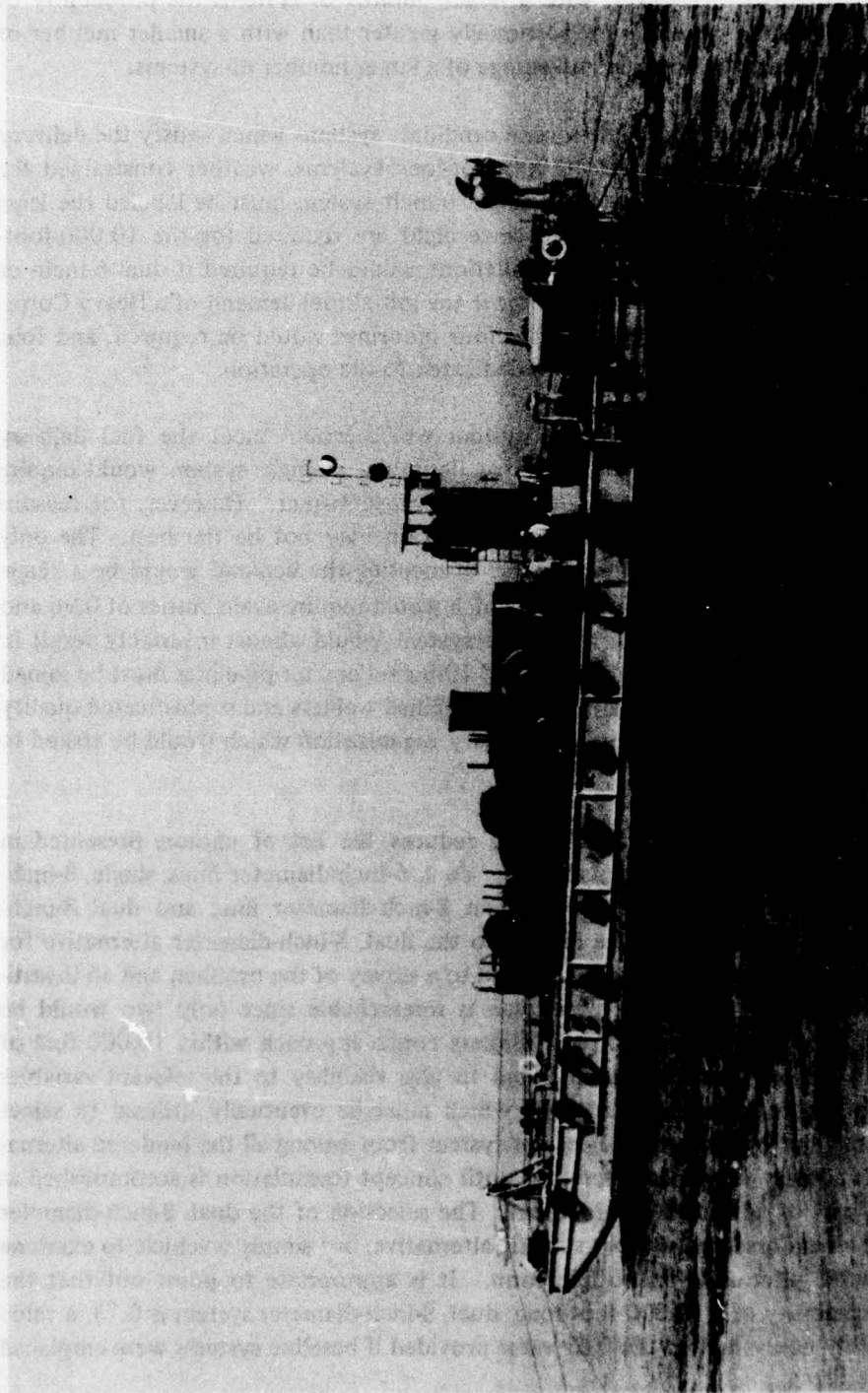


Figure 21. Pipeline pulling barge (112 feet long).

the fuel requirement. However, with a larger number of systems the probability of having an inoperative system is proportionally greater than with a smaller number of systems; this tempers the apparent advantage of a larger number of systems.

Tables 10 and 11 include several candidate systems which satisfy the delivery requirements for 5,000-foot- and 10,000-foot-long systems, weather constrained for seastate 2 or calmer conditions. The single 6-inch system must be labeled the least desirable of the alternatives presented since eight are required for the 10,000-foot-long pipeline case. Similarly, four installations would be required if dual 6-inch- or single 8-inch-diameter lines are used to meet the initial fuel demand of a Heavy Corps. This would not be desirable either since four moorings would be required, and four tankers would have to remain on station dedicated to the operation.

The installation of a single system which would meet the fuel delivery requirements *would appear* to be the most desirable; a single system would require only a single mooring and the dedication of a single tanker. However, for reasons previously noted, the intuitively appealing solution may not be the best. The only systems which would be singularly capable of meeting the demand would be a single 12-inch system or a dual 10-inch system which would require availabilities of 0.96 and 0.82, respectively. Any breakdown in the system would almost invariably result in suspension of operations. Also, 12-inch- and 10-inch-diameter pipelines must be joined by welding, a technique which requires highly skilled welders and sophisticated quality control, neither of which exists in the military organization which would be tasked to perform the installation.

The preceding line of reasoning reduces the list of choices presented in Tables 10 and 11 to systems consisting of: dual, 6-inch-diameter lines; single, 8-inch-diameter line; combination of a 6- and an 8-inch-diameter line; and dual, 8-inch-diameter lines. Attention will be limited to the dual, 8-inch-diameter alternative for the purposes of this report, which is limited to a survey of the problem and an investigation of feasibility. The example chosen is researchable since only two would be required to support a Heavy Corps if tankers could approach within 10,000 feet of shore. This limited treatment is intended to give visibility to the relevant variables and outline the analytical methodology which must be eventually utilized to select the most cost and operationally effective system from among all the tendered alternatives. Such activity is properly deferred until concept formulation is accomplished as an integral part of advanced development. The selection of the dual, 8-inch-diameter lines is *not an* endorsement of that specific alternative, but simply a vehicle to examine one reasonable alternative in outline form. It is appropriate to point out that the required availability of a 10,000-foot-long, dual, 8-inch-diameter system is 0.73, a value approximately equivalent to the 0.69 value provided if baseline systems were emplaced

Table 10. 5,000-Foot-Systems – Tabulation of Candidate Pipeline Systems

System	Unconstrained Flow Rate Per System (bbl/hr)	Weather Constrained Flow Rate Per System ^a (bbl/hr)	No. of Systems Required	Total Constrained Flow Capacity (bbl/hr)	Availability ^b Required
Single, 6-inch	1100	440	6	2640	.69
Dual, 6-inch	2200	880	3	2640	.69
Single, 8-inch	2250	900	3	2700	.68
Single, 8-inch plus single, 6-inch	3350	1340	2	2680	.68
Dual, 8-inch	4500	1800	2	3600	.51
Single, 10-inch	4150	1660	2	3320	.55
Dual, 10-inch	8300	3320	1	2230	.55
Single, 12-inch	6750	2700	1	2700	.68

^a Flow rates are adjusted by a factor of 0.4 which corresponds with the proportion of the time during which a tanker could be safely moored to discharge its cargo if the mooring was limited to seastate 2 or less and if the worldwide seastate distribution correlated with the local distribution.

^b Availability as used throughout this report is the ratio of cumulative demand to potential cumulative throughput. Ratios approaching 1.00 imply that an equipment failure is associated with an increasing probability of corps operations being hampered by lack of fuel.

Table 11. 10,000-Foot-Systems – Tabulation of Candidate Pipeline Systems

System	Unconstrained Flow Rate Per System (bbl/hr)	Weather Constrained Flow Rate Per System ^a (bbl/hr)	No. of Systems Required	Total Constrained Flow Capacity (bbl/hr)	Availability ^b Required
Single, 6-inch	750	300	8	2400	.76
Dual, 6-inch	1500	600	4	2400	.76
Single, 8-inch	1570	628	4	2512	.73
Single, 8-inch plus single, 6-inch	2320	928	3	2784	.66
Dual, 8-inch	3140	1256	2	2512	.73
Single, 10-inch	2850	1140	2	2280	.80
Dual, 10-inch	5600	2240	1	2240	.82
Single, 12-inch	4750	1900	1	1900	.96

^a Flow rates are adjusted by a factor of 0.4 which corresponds with the proportion of the time during which a tanker could be safely moored to discharge its cargo if the mooring was limited to seastate 2 or less and if the worldwide seastate distribution correlated with the local distribution.

^b Availability as used throughout this study is the ratio of cumulative demand to potential cumulative throughput. Ratios approaching 1.00 imply that an equipment failure is associated with an increasing probability of corps operations being hampered by lack of fuel.

to discharge tankers moored 5,000 feet offshore, given equal fuel demand in each instance.

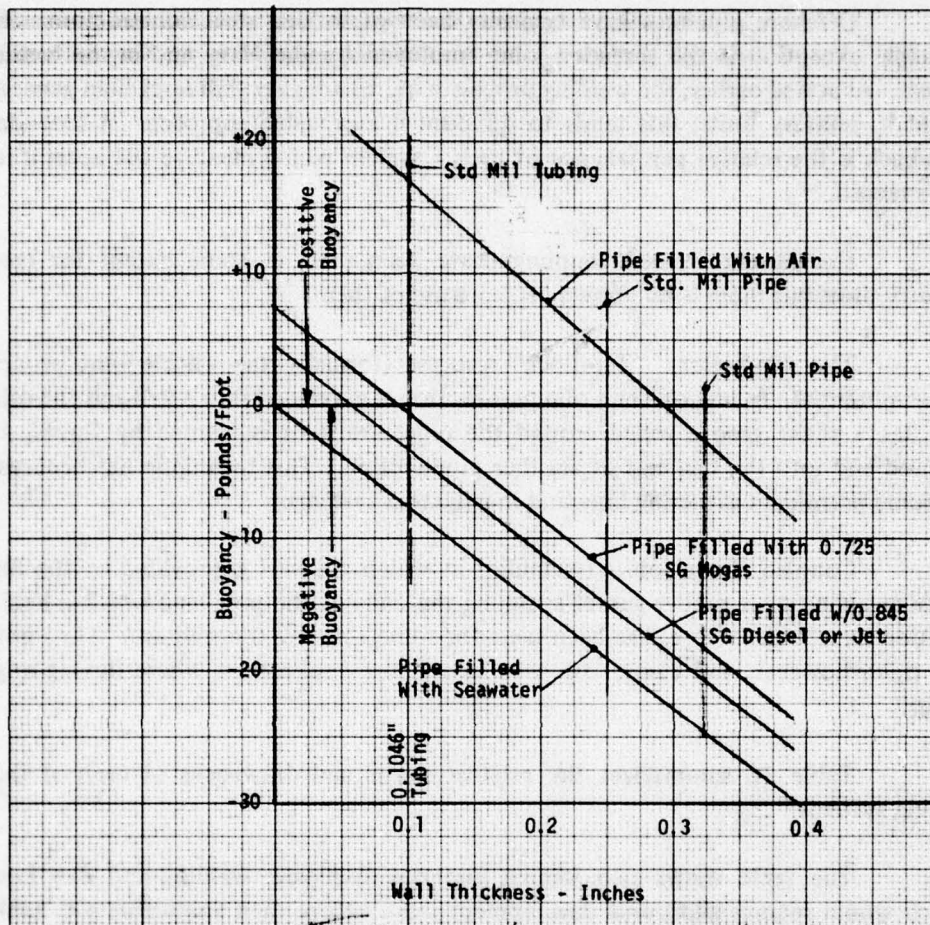
Moorings are not a subject of this study, but the mooring capability impacts on the pipeline system by either requiring less system capability or by providing lower availability requirements as the seastate keeping ability is elevated. The preceding discussion of required availability is predicated on a seastate 2 limitation of the mooring. The following paragraphs give an indication of the improvements which would be provided by a capability to operate in higher seastates.

Under seastate 3 conditions, two dual, 8-inch systems would provide an availability requirement of 0.32 at a 5,000-foot distance from shore, and a single installation of a dual, 8-inch system would provide an availability requirement of 0.64 and 0.92 at 5,000- and 10,000-foot lengths, respectively. The 0.92 availability requirement for the 10,000-foot distance is not acceptable. Internal coating of the pipe to reduce the friction factor would reduce the availability requirement from 0.92 to 0.80 at the 10,000-foot distance.

A mooring suitable for seastate 4 conditions would provide required availability factors of 0.51 and 0.74 for 5,000-foot and 10,000-foot systems, respectively, for a single installation of a dual, 8-inch pipeline system compared to 0.64 and 0.92 for a seastate 3 limitation.

Figure 22 shows the buoyancy characteristics of 8-inch steel pipe filled with air, mogas, diesel or jet, and seawater. The wall thicknesses tabulated in the table on Figure 22 are standard pipeline wall thicknesses used by the petroleum industry, except for the 0.1046-inch wall thickness which applies to the standard military light-weight tubing. The 0.322-inch wall thickness pipe is the pipe which is type classified as part of the deliberate tanker off-loading pipeline system. The survivability of this pipe is comparable to the present 6-inch tactical pipeline. Figure 22 indicates that a significant reduction in pipe weight cannot be made or the pipe will float when filled with air. An 8-inch pipe with a wall thickness of 0.293 inch is neutrally buoyant when filled with air — a reduction in the wall thickness of the standard pipe of only 0.029 inch. The conduit chosen must possess sufficient submerged weight and strength to resist the buoyant forces and the combined effects of lift and drag forces caused by hydro-dynamic processes; e.g., current, deep water waves, and breaking waves.

15. Joining Techniques. Numerous techniques have been developed to join lengths of conduit. Some are applicable to specific materials, some to a limited range of conduit diameters or range of wall thicknesses, while others are appropriate for specific applications.



Wall Thick	Unit Wt.	Wt/20' length
0.1046*	10.6 Lb/Ft	212 Lbs
0.188	16.94	339
0.219	19.66	393
0.250	22.36	447
0.277	24.70	494
0.312	27.70	554
0.322	28.55	571
0.344	30.42	608
0.375	33.04	660

Figure 22. Buoyancy characteristics of 8-inch steel pipe.

Offshore pipelines have typically been of welded steel construction. The principle exception is the threaded joint employed by the Navy and in the baseline system. As stated earlier, the welding process requires a higher skill level than generally found in military units; this tends to discount it as a viable approach. A secondary drawback is the relative permanence of such a system which must be cut apart if it is to be reused.

Explosively welded couplings have been used to some extent for cross-country pipe, but there is no known offshore use of them.

The proprietary "Zap-Lock" process (formally the buckle-joint process) shows potential. In use, one end of a pipe section is expanded into a bell and the other end has a slight groove rolled around the pipe; the joint is formed by forcing the grooved end into the bell end of another pipe section. This technique has been used for some petroleum gathering lines and in irrigation systems.

Coupled sleeve joints (victaulic) in which the seal is provided by the fluid pressure acting on a rubber gasket spanning the ends of the pipe, and which is held in position by a metal sleeve, has been used for some time by the military. The joint is not rigid, however, and cannot be used in offshore applications where flexing might occur.

Table 12 summarizes the relative merits and drawbacks of each of these joining systems.

The table shows two joining methods (explosive welding and Zap Lock) which would require additional development work before their applicability to tanker discharge systems may be established; the remainder have been generally proven through prior use. For example, adaptation of the threaded coupling joint would require only the design and fabrication of joining machinery in sizes larger than the current 6-inch-diameter equipment. However, such adaptation is considered to be a straight design problem, with virtually no technical risk.

The table indicates that pipe with bolted flange joints might be satisfactory for submarine pipeline applications since such pipe would require a minimum of training and is a proven method of joining pipe. However, as far as is known this method of joining pipeline has never been used for long submarine pipelines in the commercial sector, the reasons for which are probably twofold: The magnified shipping volume created by the flanges, and the difficulty of installation by the bottom-pull method since the flange projections would create high passive soil resistance while the pipeline was pulled into position; the flanges would also be prone to hang on underwater obstructions.

Table 12. Pipe-Joining Methods

Joint	Suitability for Use			Extent of Training Required	Adaptability ^a to Training	Indicated Dependability in Offshore Applications	State-of-Art	Reliability and Performance
	Suitability for Offshore in Military Applications	Suitability for Troop Use	Offshore					
Electric ^b Welded	Excellent	Poor	Extensive	Poor	Excellent	Advanced	Excellent	
Explosive ^c Weld	Good	Excellent	Intermediate	Poor	Good	Primarily in development	Unknown	
Threaded ^d Coupling	Good	Excellent	Intermediate	Excellent	Good	Advanced	Good	
Zap-Lock	Good	Good - Questionable	Intermediate	Poor	Good	In Use and development	Unknown	
Bolted Flange	Poor	Good	Minimum	Excellent	Good	Advanced	Good	
Coupled Sleeve (Victaulic)	Unsatisfactory	Excellent	Minimum	Excellent	Very Poor	Advanced	Unsatisfactory	
Other Mechanized Coupling	Unsatisfactory	Excellent	Minimum	Excellent	Poor	Advanced and development	Unsatisfactory	

^a All methods listed as poor require expenditure of materials and complete removal of joint area at completion of training and for retrieval of pipeline for reuse at another location.

^b Electric welded pipeline would require extensive training and practice to maintain proficiency. As such they are poorly adapted to training.

^c Explosively welded joints have been under development by industry for some time but have not found widespread use. Therefore, reliability and performance cannot be assessed accurately.

^d Threaded coupling joints are proven joints. In 4- and 6-inch sizes they have been demonstrated by the Army and Navy as being fully satisfactory for troop use and appear to be satisfactory in 8-inch size. Suitability of threaded couplings in sites greater than 8-inch diameters appear questionable because of the requirement for larger sizes, more powerful equipment, and handling problems.

Therefore, only three joining methods will be surveyed at this time: the explosively welded joint, the Zap Lock joint, and the threaded coupling joint. Of these, only the threaded coupling can be considered as fully proven in military applications. Further treatment of joining techniques will be deferred until concept formulation. The joint chosen here has been proven in somewhat less demanding application but theoretically could be extrapolated to larger sizes with little difficulty. Its choice here should not be construed as a total indorsement but simply as an acknowledgment of its probable adequacy in an advanced discharge system. It was selected to allow the authors to address feasibility of an advanced system which would embody a suitable, but at this point unknown, joining technology.

16. Installation. The choices of materials and joining technology limit this exploratory investigation to a series of alternative approaches applicable to the installation of a pipeline which once in place will remain on the ocean bottom by virtue of its own weight, or a combination of its weight supplemented by auxiliary weights. The installation techniques to be presented are variations of the bottom-pull approach, where the pipeline is assembled onshore and pulled to a position adjacent to a tanker mooring. The following paragraphs summarize the methods now in use and present a series of alternative methods which have potential applicability for any advanced system.

a. Present Methods of Bottom-Pull Installations of Submarine Pipeline.

(1) Winch-on-Shore. The baseline system uses a winch on shore pulling through a floating block anchored a short distance beyond the position for the end of the pipeline. Deployment of the buoyed, wire-rope launching line is accomplished by deploying floating nylon-covered polypropylene braided rope with motor surf boats and then using the floating rope with a cathead onshore to pull the wire-rope winch line from shore, around the sheave of the floating block, and back to shore. One mile appears to be the practical limit for this method because of the difficulty in running the nylon-covered polypropylene rope at greater distances and the necessity for a wide separation, probability 1500 to 2000 for a 2-mile pipeline, between the winch site and the pipe launching site to prevent the wire rope lines (winch to floating block and floating block to pipeline) from becoming entangled.

(2) Pulling-Barge Launching. A pipeline-pulling barge (Figure 21) was developed to install the welded pipelines which preceded the baseline system. In use, the barge is moved as close to the beach as practical for passing the wire-rope winch line from the barge to the beach. A tug is used to move the barge from the beach to its position beyond the end of the pipeline as the wire-rope launching line from the winch is payed out. A reeling machine and large steel storage reels are provided aboard the Army barge to install additional wire rope lengths on the winch

drums for payout as each drum becomes empty. When on location, lateral control anchors are deployed to hold the barge on position and 6,000-pound LWT (light-weight-type) anchors are deployed to provide the pulling power for launching the pipeline.

(3) **Navy Warping Vessel Launching.** The Navy uses a warping tug or barge to install the 6-inch bottom-laid assault system. Installation is accomplished as follows:

(a) The warping vessel drops its warping anchor a short distance beyond the position for the end of the pipeline and moves toward the beach while paying out its warping line.

(b) When the vessel is near the beach, a wire-rope line about 200 feet long is attached to the end of the pipeline and passed to the vessel and made fast.

(c) The pipeline is launched by warping the vessel backwards from the beach. The launching is stopped during the time that each joint is made up.

b. Launching a 10,000-Foot-Long Pipeline.

(1) **General.** The specially equipped pulling barge described above is satisfactory for installing an advanced discharge system, but its cost, relative immobility, and the need of an extremely well-trained team collectively mitigate against such a choice. As indicated above, the winch-on-shore method, as used with the baseline system, would be unsuitable for the installation of pipeline systems over 1 mile long. However, techniques and equipment worked out for the baseline system can be modified to install a pipeline system up to 10,000 feet long. This could be accomplished without the need to dedicate a large floating plant.

The Army is procuring the new class 1646 LCU. This vessel has a drive-through fore-to-aft deck which would be excellent for use as a submarine pipeline launching vessel. The anchor to develop the pulling force could be either a conventional drag anchor or a propellant-embedded anchor. Lateral control of the moored vessel could be provided by small lateral-control anchors and soft lines with a winch cathead for adjustment. All launching equipment could be designed as lift-on and lift-off equipment held in place on the vessel by cargo tiedowns. Only minor alteration of the vessel would be required. The following concepts for launching the pipeline are all based on using a 1646 class LCU.

(2) **Wire-Rope Winch Launching.** An adjustable fairlead would be required to insure proper spooling of the wire-rope line on the winch drums because of

the short fleet distance. Other fairleads would be required for the anchor line and for use of the catheads and reeling machine. Figure 23 is a preliminary layout of the equipment and allocation of space of a class 1646 LCU outfitted to launch pipeline with a winch and wire-rope launching line. A variation of the technique developed for the present tactical system of using nylon-covered polypropylene rope with a specific gravity of 1.02 which barely floats in sea water could be used for deployment of the long wire-rope launching line. With this technique, the offshore vessel or platform is anchored on position and the nylon-covered polypropylene rope deployed by pulling part of the line from the beach by a motor surf boat and paying part out from the boat. With the air transportable motor surf boats used with the present tactical system 4,500-foot lengths of rope are windrowed on the beach and 3,400 feet are faked out in the motor surf boat. To run each of the two lines (in-haul line and out-haul line), an end of the section windrowed on the beach and an end of a section in the motor surf boat are connected. The motor surf boat heads upcurrent and pulls all rope from the beach before paying out the rope faked in the boat. The run is made as quickly as practical so that connections can be made before the current takes up the slack rope.

A more practical approach for launching 10,000-foot-long pipeline would be to deploy $\frac{1}{2}$ of the rope from the moored vessel and the other half from the beach. This could be accomplished by providing a meeting station at about the midpoint of the distance between the beach and the moored vessel. This meeting station could be an anchored buoy or floating platform. The runs from the moored vessel to the meeting station would begin almost simultaneously with the first one to arrive at the meeting station connecting its rope. The second boat arriving would connect the two sections of rope and free the line, thereby completing the deployment of the nylon-covered polypropylene rope. The rope on the beach would be windrowed as is presently done with the tactical system. A long open-box container would be required for the rope which would be pulled from the launching vessel.

It would be advisable to sink the nylon-covered polypropylene rope to prevent damage by marine activity in the area. This could be accomplished by attaching 20-pound weights to the line, with sash cord starting at the vessel and running along the line, and attaching a weight at each point where the line surfaces. This was accomplished during the early phases of the baseline system development and was found to be effective and easy to accomplish. Using two small boats, a complete nylon-covered polypropylene line 10,000 feet in length can be sunk within 20 minutes.

The deployment of the wire rope launching line would be accomplished by catheading the wire rope from the launching vessel to shore. Figure 24 shows the catheading operation for deployment of the wire-rope launching line in the installation of the baseline systems. For this improved system, the catheading operation would be identical.

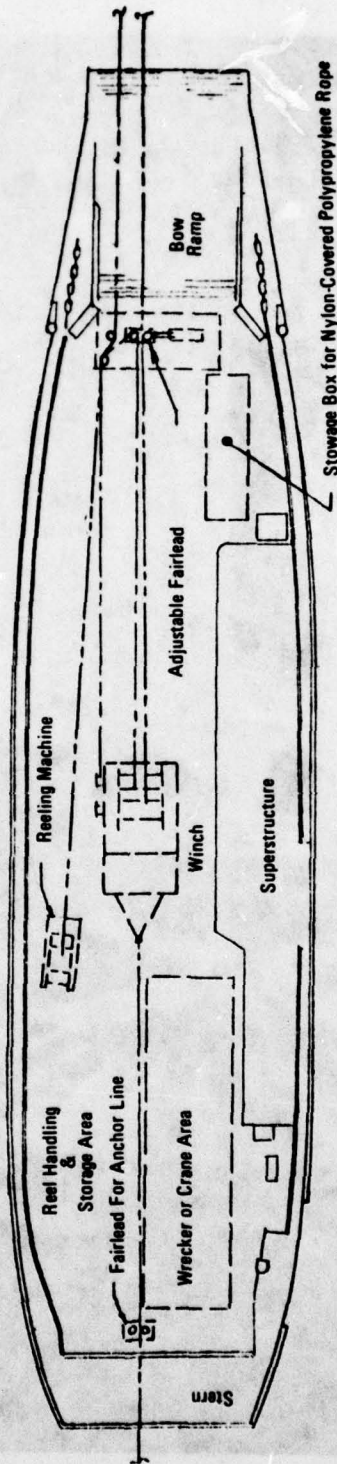


Figure 23. LCU, Class 1646, outfitted to launch submarine pipeline.

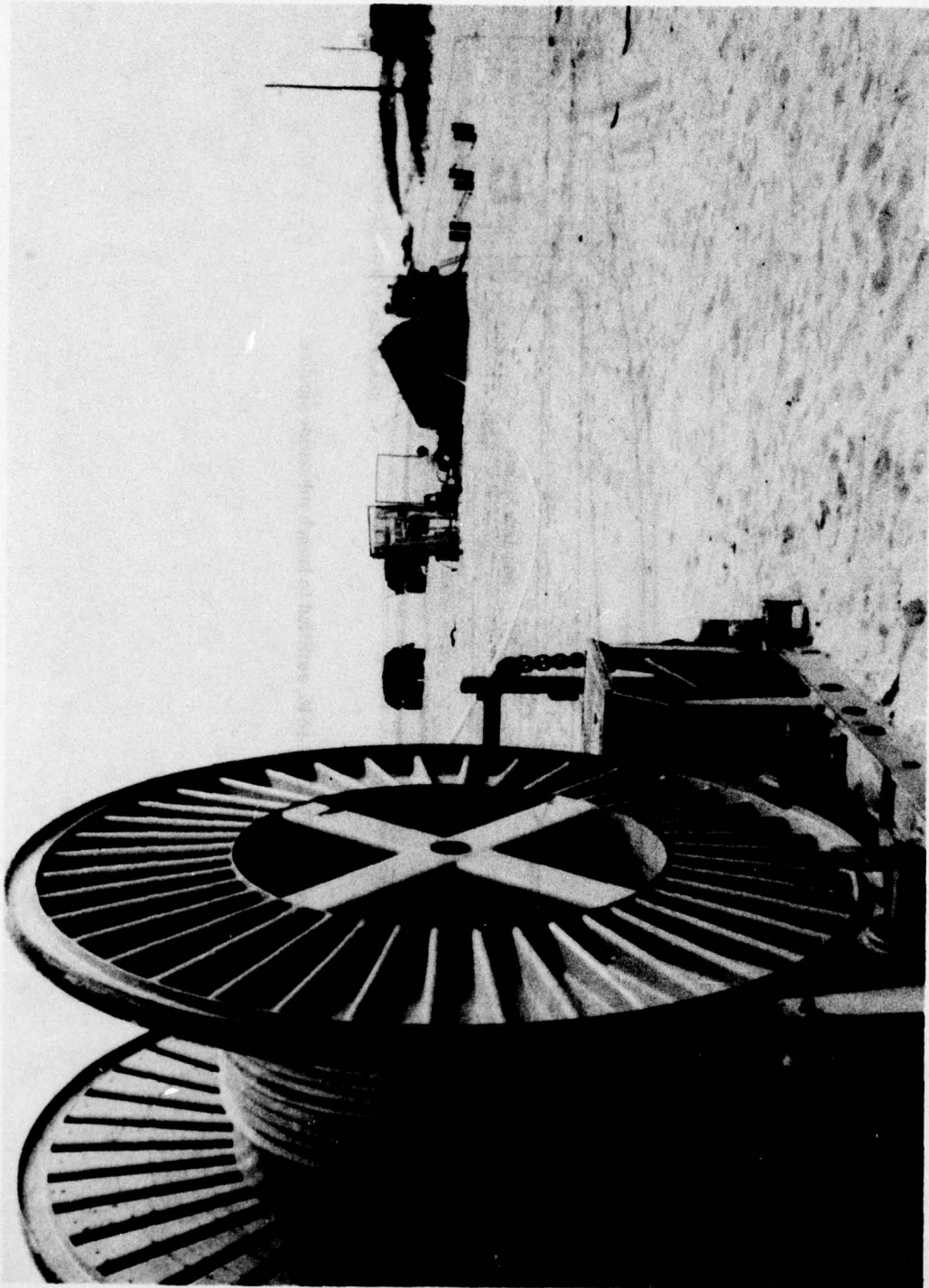


Figure 24. Cathedding nylon-covered polypropylene rope for deployment of wire-rope launching line.

The wire-rope line would be under winch control as it is payed out during the catheading of the nylon-covered polypropylene rope. If the winch drum capacity is insufficient for the length of wire rope required to reach to shore, successive sections of wire rope would be spooled onto the winch.

Experience with the baseline system indicates that the wire rope launching line must be buoyed for sandy bottom materials, since the wire rope often becomes embedded in the sand and becomes difficult and sometimes impossible to move without breaking. This not only overstresses the wire rope but may cause failure of the anchor providing the launching force reaction. It has been found that 55-gallon drums, filled with polyurethane foam to prevent imploding in the event of submergence, and spaced about 200 feet apart for $\frac{3}{4}$ -inch wire rope – greater spacing for smaller wire rope and closer spacing for larger wire rope – are satisfactory for floating the wire rope line. Also, 3-buoy clusters positioned at about 8 to 10 times the water depth from the end of the pipeline aid in launching the pipeline by lifting the end of the pipeline during unusually hard pulls.

Preassembly of the pipeline into long sections would facilitate a rapid installation. However, preassembly requires a deep beach which may not be available at many locations and additional beach equipment to handle the longer lengths of pipe. Therefore, time estimates for installation of the system are based on assembling individual pipe section as the pipeline is launched.

The present baseline system with its 5,000-foot-long discharge conduit and mooring is capable of installation within 72 hours after arrival at an undeveloped beach work site. There is no breakout of the individual times required for installation of the pipeline and the mooring. More assembly and launching time would be required to launch a dual pipeline 10,000 feet from shore than required for the present 5,000-foot tactical facility. Deployment of nylon-covered polypropylene rope and the wire rope for this improved system would require about the same time as the baseline system since about the same lengths of each are required. Working with the baseline system, experienced crews have deployed the nylon-covered polypropylene rope and the wire rope in 4 hours 12 minutes and launched pipeline at the rate of one 30-foot length every 3 minutes. The additional time to assemble a dual pipeline is estimated to be 1.5 minutes per 30-foot length of pipeline for a total of 4.5 minutes per 90-foot length. Therefore, on this basis it would require about 30 hours to deploy the rope lines and launch 10,000 feet of dual pipeline.

A single pipeline 10,000 feet long would require about 22 hours for deployment of the lines and launching of the pipeline. However, the installation of a dual pipeline system by sequential installation of two single pipelines would require about double the time required to install a single pipeline.

(3) Launching Pipeline with Double-Braided Nylon-Covered Polypropylene Rope. Deployment of nylon-covered polypropylene rope is covered in the previous section on wire-rope launching of pipeline. Launching the pipeline by using nylon-covered polypropylene rope would be accomplished by suitable pulling and line control devices aboard the launching vessel. The nylon-covered polypropylene rope has a significant stretch when under high tension. The stretch of this rope is much less than rope of conventional twisted strand construction, but in 10,000 feet the stretch can nevertheless amount to several hundred feet. The strain energy stored in this much elongation can be a safety hazard, and control of the rope line and pipeline is absolutely essential to prevent runaway of the pipeline.

A traction winch similar to those used aboard large ships for pulling long lengths of rope and by some construction companies for stringing power lines should be used to provide the launching force, since such a winch would provide better control of the line than a regular winch cathead. A traction winch is basically two grooved drums mounted a short distance apart and tilted so that the grooves align properly. A rope stop-and-holding device (Figure 25) would be required for stopping and holding the rope during the time that rope sections are separated and to prevent a runaway in the event control of the rope is lost.

Safety aboard the launch vessel would be of primary concern. The tremendous amount of energy which would be stored in the line would be particularly hazardous in the event control of the line is lost and it surges from the vessel into the sea. Because of the limited space aboard the vessel, barricades and protective screens would have to be provided to keep people out of hazardous areas and to protect personnel from flying rope in the event of a mishap.

Onshore control of the pipeline could easily be accomplished by the attachment of removable clamp devices to the pipeline or by a crawler tractor lowering its blade onto the pipeline.

(4) Launching Pipeline by Parallel-Yarn Rope. Parallel yarn rope is rope constructed with the yarns parallel with the axis of the rope. The rope is held together by a sheaf jacket. This rope has a significantly lower elongation than braided or twisted strand rope since only the stretch of the fibers contributes to the elongation of the rope — not compaction and straightening of the fibers as with the other constructions.

Parallel-yarn rope may be made from any of the common fibers. A new fiber, "Kevlar," an aramid fiber manufactured by the DuPont Company, has recently been formed into parallel yarn rope. Kevlar has a higher density than most other yarn material — a parallel yarn rope made from Kevlar with a polyester jacket has

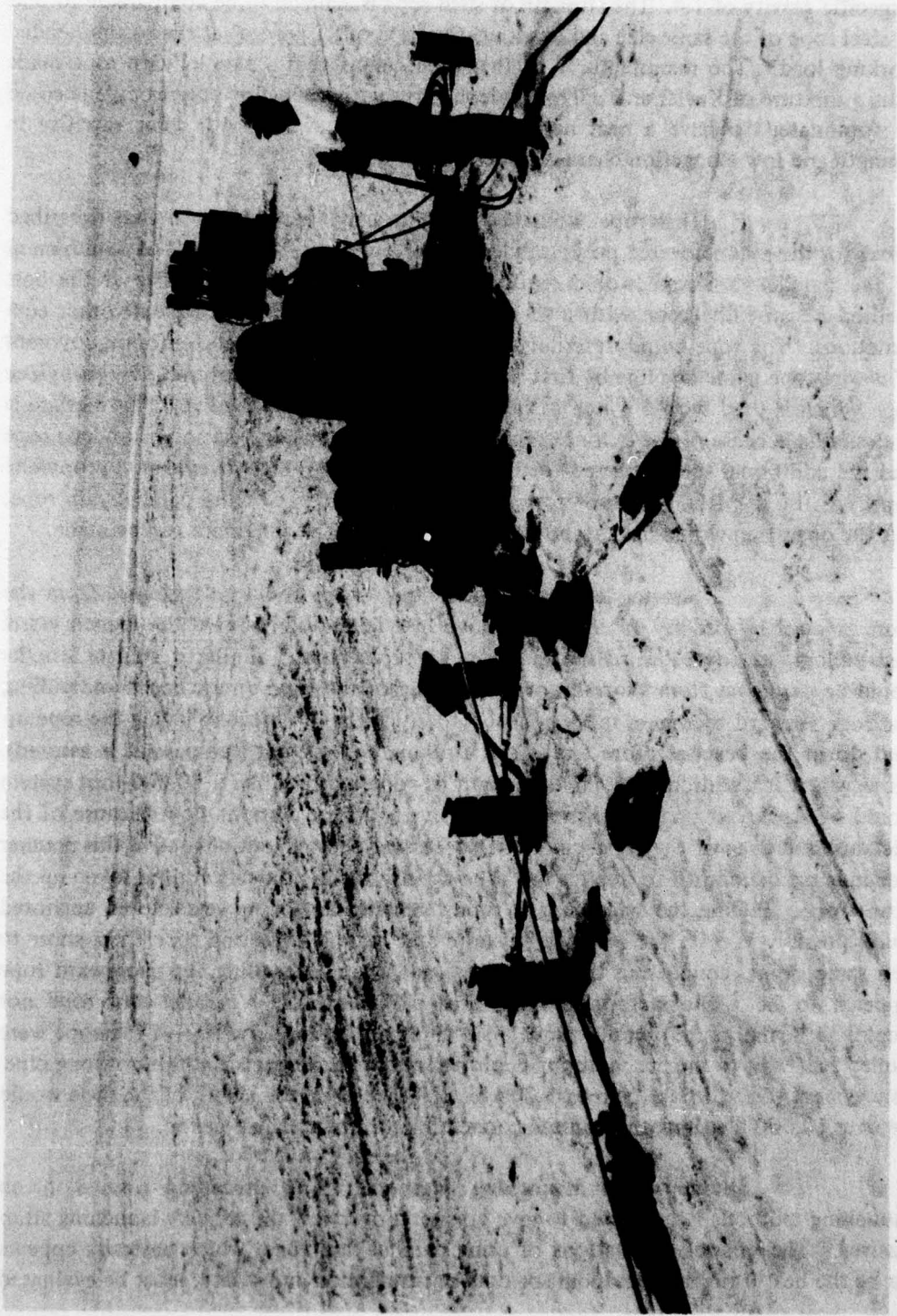


Figure 25. Rope stop-and-holding device.

a specific gravity of 1.4. The strength of such rope is claimed to be comparable to that of steel rope of the same size and its elongation is about 1 percent at the recommended working load. The manufacturer of this rope claims that a parallel-yarn rope made from a mixture of Kevlar and polypropylene yarns with a sheaf of polypropylene could be formulated to have a near neutral buoyancy in seawater with some sacrifice in strength and low elongation characteristics.

This rope would be used in a manner similar to that described above for the nylon-covered polypropylene rope. However, the method of deployment of the parallel-yarn rope would require some experimentation to arrive at the best method because the rope with a sheaf is significantly stiffer than rope of other constructions. The rope could definitely be deployed as described above for deployment of a wire-rope launching line by first deploying a floating nylon-covered polypropylene rope which is used with a winch cathead to deploy the launching line. This method is undesirable because of the extra expenditure for the nylon-covered polypropylene rope and the additional time required for deployment of the nylon-covered polypropylene rope. An LCM might be satisfactory for faking and payout of the parallel-yarn rope, but the operation would have to be tried before a definitive judgment can be made.

Shorter lengths of parallel-yarn rope could be deployed from the launch vessel by orderly faking of the rope in a faking box aboard the launch vessel and pulling the rope toward shore by one or more boats. Similarly, shorter lengths could be deployed from shore by orderly faking of the rope on the beach and pulling the rope seaward by one or more boats ("orderly faking" is actually laying the rope up and down the beach or fore and aft in a faking box so that free payout is assured). However, it is questionable that the length of rope required for a 10,000-foot system could be deployed in this manner during any significant current flow because of the distance and drag of the rope, since the success of deployment of rope in this manner depends on the ability to deploy the rope rapidly before the current has taken up the spare rope. Pulling the parallel-yarn rope from the launching vessel to an anchored buoy possibly $\frac{1}{2}$ or $\frac{3}{4}$ the distance to shore and pulling a floating rope from shore to the same point, connecting the two ropes, and then catheading the shoreward rope appears to be a satisfactory method of deployment. The parallel-yarn rope not deployed in the payout would provide slack for a running current - if the rope were pulled half-way to the beach during deployment for launching a 10,000-foot-long pipeline system, there would be over 5,000 feet of slack since the length of the rope would be over 10,000 feet long to facilitate connecting the end to the pipeline.

c. **Summary on Launching Method.** The preceding discussion on launching methods is presented to give a general overview on *possible* launching alternatives. The possible limitations of using parallel-yarn rope, which basically appears to be the best from the standpoint of time of installation and safety, must be evaluated

by actual experiment before the method could be adapted. The use of double-braided, nylon-covered polypropylene rope to launch the pipeline would be slightly quicker than using parallel-yarn rope, but there are unsettled safety considerations. Using wire rope to launch the pipeline would require more time than either of the other two but presents the least technical risk.

17. Transportation. With the exception of the LCU, all components of the alternative investigated would be transportable by ship, rail, truck, or aircraft of C-130 size or larger. However, the aircraft option, while available, is not expected to be a primary means because of the number of aircraft which would be required and the shortage of larger cargo aircraft with respect to the demand.

18. Economic Factors. Life-cycle costs are all costs associated with the acquisition and operation of a new system from its inception until the time it is replaced or there is no longer a need for it. Such costs include research, development, tests, acquisition, inventory management, training, deployment, and overhaul.

A primary consideration is whether or not the benefits obtained from a new system justifies the cost. This is especially true if a workable system exists; such is the case here. The advanced system examined here in basic terms would possess a higher degree of universality, equivalent deployment characteristics, and a higher performance level. In a complete economic analysis, all such factors would be quantified so that they could be evaluated objectively.

Such an economic analysis is an important part of the concept formulation process and is beyond the scope of this study which is limited to an investigation into the feasibility and engineering aspects of an advanced tanker discharge system. A complete economic analysis would cover all aspects of the problem in its quest to define a true optimum system. Towards that end, the optimum might be thought of as the system capable of delivering a specific quantity of fuel at the lowest overall cost while providing acceptable levels of universality, reliability, availability, and maintainability, subject to specified resource and transport constraints. The alternatives investigated would then be compared with the baseline system. This effort, as previously noted, is deferred for treatment as an integral part of formal concept formulation activities.

IV. CONCLUSIONS

19. Conclusions. An advanced-generation tanker-discharge system is indeed feasible from a technical point of view. One possible system was identified to include an examination of alternative installation techniques. This limited review, while hardly exhaustive in nature, illustrates vividly the operational constraints which the baseline system, the Navy systems, and the early (and ponderous) Army systems place on the

tactical Commander. An advanced system capable of reaching further offshore, of supporting elevated discharge rates, and of installation under more demanding environmental condition than the baseline system, appears eminently feasible and cost operationally effective given any reasonable set of objective evaluation criteria.

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