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MULTILEG TANKER MOORING SYSTEM AND UNLOADING FACILITY: SYSTEM MODEL AND RELIABILITY ANALYSIS

January 1976

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U.S. ARMY MOBILITY EQUIPMENT

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The delivery of fuel by sea to friendly forces engaged with a hostile force has been subjected to a detailed inquiry using operations research methodology. A mathematical model has been formulated which represents both the supply and demand elements of the problem. The fuel delivery portion of the model accommodates: weather conditions, distance from shore to water of adequate depth for safe tanker operation, properties of the conduit through which fuel will flow, reliability of the mooring and unloading sys-

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tem, and the volume of fuel storage containers available. The fuel demand portion of the model consists of daily consumption plus a contribution to the fuel reserve. The fuel reserve itself may be varied to reflect differing philosophies toward fuel reserve accumulation. The model was employed to investigate how well one specific system – the Multileg Tanker Mooring System – would perform in a hypothetical 90-day-long hostility patterned after the U.S. Army Training and Doctrine Command's two Mideast Scenarios. It was established that as tankers moored farther offshore a mooring and unloading system would have to embody increasingly higher mission reliability values if the same level of performance was to be maintained, all other things being equal. Actual specified values (SV) and minimum acceptable values (MAV) were established for the Multileg Tanker Mooring System; the SV and MAV are reliability values with very specific meanings. The study effort also unearthed a number of qualitative conclusions which define areas where future studies and future research would be expected to provide the greatest marginal return.

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MULTILEG TANKER MOORING SYSTEM AND UNLOADING FACILITY: SYSTEM MODEL AND RELIABILITY ANALYSIS

I. EXECUTIVE SUMMARY

1. **Executive Summary.** The delivery of fuel by sea to friendly forces engaged with a hostile force has been subjected to a detailed inquiry using operations research methodology. A hybrid scenario has been formulated which modifies the Training and Doctrine Command (TRADOC), Fort Monroe, Virginia, mideast scenarios, superimposing certain demanding elements drawn from the Multileg Tanker Mooring System requirements document. The result is a hypothetical conflict embodying the TRADOC scenario's fuel consumption requirements but complicated by loss of formal port facilities and by extension of the hostility from 60 to 90 days in duration. Fuel delivery means have been limited to the air-transportable mooring and unloading line developed as part of the overall Multileg Tanker Mooring System.

A mathematical model has been formulated which represents both the supply portion of the problem – the mooring and offshore pipeline – and the demand portion – the military force located inland and the fuel distribution, storage, decontamination, and dispensing equipment required to sustain that force throughout a 90-day hostility. The model incorporates a fuel reserve objective established by the friendly forces' commander; fuel levels nominally rise toward that reserve objective as the hostility progresses; actual levels respond to the difference between cumulative consumption and cumulative deliveries. Deliveries may be prevented by unfavorable climatic conditions and imperfect equipment while consumption is observed to vary with time, the result of arrivals and departures of military units and the changing tempo of operations.

The model by necessity is extremely detailed and as expected incorporates a number of assumptions and decision rules; the more significant are as follows:

a. All fuel deliveries after midnight of day 4 will be made by tankers which will moor and discharge fuel for 30 hours, then depart for 18 hours – a 48-hour cycle repeated until operations cease on day 90.

b. A fuel reserve is required, and sufficient moorings and unloading lines will be placed allowing that reserve objective to be met by midnight of day 29 barring system failures but allowing for unfavorable weather conditions which preclude the tanker from entering the mooring.

c. A study of worldwide coastal climatology led to the conclusion that elevated seastates could hamper fuel deliveries to a substantial degree. The model reflects that conclusion by limiting deliveries to 40 percent of the time during the first 30 days – a figure derived from the unfavorable weather incidence rate during the worst month of the year at 14 worldwide sites. Deliveries are permitted 70 percent of the time during the latter 60 days – an incidence rate representative of the annual average occurrence.

d. Hostile forces do not prevent friendly forces from using the mooring or unloading line nor do they destroy the facility or any fuel.

e. Fuel storage containers are available in advance of the time they are required to receive the fuel.

f. Fuel will not be accepted once the fuel reserve objective has been reached. Fuel deliveries will be aborted and the tanker unmoored *before* the reserve objective is reached. Once a delivery is aborted, the tanker may not return until its next scheduled delivery.

g. If a delivery is aborted by a failure, the tanker will be released and not permitted to return until the next scheduled delivery. This will always prevail even though repairs may be completed within 4 hours, and the tanker may, consequently, be idled for as many as 43 hours after the repair has been made.

h. Each mooring and unloading line is associated with its own dedicated onshore storage containers *and* its own dedicated fraction of the friendly force which continues to draw fuel from those containers until no more remains. If one mooring is inoperative, the fuel on hand will continually diminish through consumption even though fuel storage containers in adjacent facilities might be filled to capacity.

i. No variations in the 48-hour fuel delivery cycle are permissible. This is true even if fuel reserves become dangerously low. In an actual situation, operating personnel would be expected to revise the delivery schedules; however, the model does not incorporate such flexibility.

j. The explosively embedded anchor projectiles are considered functional only when embedded 6 feet or more below the ocean bottom. It is further assumed that the anchors penetrate only 12 feet into the bottom, which is the smallest actual penetration observed.

Approaching the problem in this manner admittedly casts the system in a less favorable light than if the system's intrinsic physical and environmental characteristics could be described in precise detail. This is not possible, however, since uncertainty pervades this problem as it does virtually any meaningful attempt to describe and quantify the behavior of complex systems; the systems analyst must accept some alternative approach if such systems are to be studied at all. A consistent conservative bias – quite evident after reviewing the study assumptions – has been employed in this case to channel the uncertainty. The outcome of the study is admittedly sensitive to the assumptions made; if the assumptions are changed or if the model's rigid structure is relaxed, the study findings will also change. The set of all feasible solutions may be thought of as being situated between two boundaries: one representing consistent use of the most liberal assumptions which would produce upward biased predictions of system performance, and the other representing consistent use of the most conservative assumptions which would produce performance predictions biased in the opposite direction. The latter approach has been chosen in every case since, when this is done, the resulting predictions of system performance would be expected to equal or approximate the lower boundary. Performance predicted in such a manner would then gain credibility as a "good" estimator even though it would be one with a downward bias. Actual performance would be better than the predicted performance, but it is not possible to state by what amount.

The model described was employed to simulate approximately 32,000 90-day hostilities during which pipeline length, reserve objective, and mission reliability were systematically varied. Specified values (SV) and minimum acceptable values (MAV) were subsequently defined for cases where the theoretical minimum number of systems was placed and for a second case where the minimum number of systems was supplemented by one additional system.

A series of 36 SV's and 36 MAV's was derived; the 36 values of each result directly from the number of variables examined with the simulation model, i.e., six pipeline lengths varying from 1,000 to 5,000 feet, three reserve objectives varying from 10 to 30 days, and two different numbers of deployed systems. The numerical findings were subjected to statistical analysis from which it was extablished that the reserve objective had no statistically significant influence on the SV's and MAV's. However, a strong relationship was found to exist between the derived SV's, the MAV's, and the pipeline length. The data were fitted to two linear equations; the equations and their multiple R^2 – a statistical quantity which in this instance represents the proportion of the variability in the SV's and MAV's accounted for by the equations – are as follows:

$$SV = 0.18095 + 0.00014\ X;\ R^2 = 0.9401, \text{ and} \qquad (1)$$

$$MAV = 0.12143 + 0.00013\ X;\ R^2 = 0.8882, \qquad (2)$$

where X is the pipeline length in feet. The strength of the relationships is very much in evidence, accounting for 94 percent of the SV variation and 89 percent of the MAV variation. If the equations are solved for the 2,500- and 5,000-foot-long pipeline cases, one obtains the values given in Table 1.

Table 1. Relationship Between SV, MAV, and Pipeline Length

Pipeline Length (ft)	SV	MAV
2,500	0.53	0.45
5,000	0.88	0.77

The primary objective of this study was the establishment of SV's and MAV's which have as their basis a rigorous analytical foundation; formulation of a generalized mathematical model and the subsequent application of that model to a hybrid scenario constitute such a foundation. Accommodation of the primary objective – derivation of SV's and MAV's – automatically rendered explicit many factors peculiar to tanker mooring and unloading facilities as a generic class; thus, a number of qualitative generalizations was spawned as a direct byproduct of deriving the SV's and MAV's. Many of those generalizations warrant quantitative treatment – an effort which is deferred at this time but which promises to yield information of value in defining fertile areas for R&D; the information obtained also would be beneficial to those charged with operating the system described herein. The more substantive findings are summarized in the paragraphs which follow; however, the reader is urged to not stop there but, rather, to seek out those portions of the study where each topic is treated in depth; treatment of the admittedly complex subject within the brief space allotted for a summary may, unfortunately, tend to obscure an otherwise lucid exposition. With that caution, a synopsis of the qualitative findings follows:

a. Accumulation of a fuel reserve is absolutely essential if numerous weather-induced fuel interruptions are to be avoided.

b. A greater number of tankers, moorings, and unloading lines is required during the first 30 days of a hostility than during the post-day 30 period. This occurs since the fuel consumption plus a contribution to the fuel reserve must be accommodated during the first 30 days, while only consumption must be accommodated afterward.

c. The unloading line is expected to constitute the limiting bottleneck in virtually any mooring and unloading facility used by the military. While it generally will never be feasible to discharge fuel at a rate even approaching the volumetric capacity of a tanker's pumps, the problem could be ameliorated somewhat by: (1) use of multiple unloading lines with each mooring; (2) reducing pipeline friction by application of an internal coating to the unloading line or use of friction reducing fuel additives, thereby decreasing the roughness coefficient and increasing the flow rate; and (3) use of offshore pumping stations to increase flow rate.

d. Weather will periodically prevent a tanker from initially mooring or from remaining in a mooring; weather factors, therefore, influence the volume of fuel which may be actually discharged. The degree of influence will vary both from site-to-site and as a function of the month during which operations take place. While this problem may not be totally overcome in any reasonable manner, development of a second-generation mooring system capable of restraining tankers in seastates beyond the seastate 2 limitation of the current system would at least diminish the problem.

e. The current system may only service tankers moored within 5000 feet of the shore. This implies that the smallest tankers within the Military Sealift Command (MSC) fleet may be safely moored only 66 percent of the time off coastlines which are otherwise suitable. Attention should be given to developing a second generation unloading line which may be placed further offshore than the current line.

f. Since the 25,000-DWT-size tanker is the smallest within the MSC fleet – it is also the largest which the current system may handle – attention should be given to developing a second-generation mooring capable of safely accommodating tankers larger than the 25,000-DWT size.

g. The explosive embedment anchor development effort consisted largely of innovation rather than of deliberate application of theoretical research findings. While the anchor was subsequently proven to be a useful device, further improvement must await the theoretical findings which a basic and exploratory research effort would be expected to unearth. This problem is further exacerbated by ignorance of the mooring load/time history which the anchors must resist.

h. System performance has been differentiated from mission reliability for the purposes of this study. Performance is measured by the number of fuel interruptions experienced by the friendly force, while mission reliability is measured by the success with which the system moors and discharges a tanker during a 30-hour mission. System performance has been found to be a function of mission reliability and pipeline length; mission reliability has been found to be a function of the hardware design and the physical properties of the soil in which the anchors are embedded. Thus, a system would be expected to exhibit a higher mission reliability – and a superior level of performance – if the anchors were embedded in sand, clay, or coral than if the anchors were embedded in mud or silt. The effect of the other variable – pipeline length – may be examined in a similar manner. A system would experience the same number of mission failures if it has a short pipeline or a long pipeline; however, a system with a short pipeline would experience fewer fuel interruptions (i.e., it would exhibit a superior level of performance) than would a system which differed only by the inclusion of a pipeline of greater length. The term "identical" in this second example implies that both systems had anchors embedded in identical soil and were subject to identical weather conditions.

II. INTRODUCTION

2. **Objectives.** The work that follows is directed toward the establishment of minimum MAV's and SV's for the Multileg Tanker Mooring System. The uniqueness of the item and the resulting lack of long-term performance data preclude the use of parametric analysis and extrapolation techniques as commonly employed. The lack of a comprehensive scientific theory also precludes model formulation in the normal sense. The problem thus reduces to an examination of the mooring system's role in a broader context, i.e., what levels of MAV and SV are required if the mooring system is to perform its intended function? Once those values are actually quantified, the decision maker may compare them with the comparable values derived from Development Test II (DT II) data. Thus, the approach which follows is acknowledged from the very beginning as an attempt to develop a yardstick against which actual performance may be measured and not as a comparison of promised performance against actual—an intellectually appealing check but one which has little relevance to the adequacy of a fielded system.

A secondary but equally important objective is the study of offshore moorings and unloading lines as a generic class. The methodology employed to establish the MAV and SV gives visibility to a number of factors which impact on the operation of such an offshore system; the methodology also allows a systematic investigation of the mutual interaction of those factors.

3. **Methodology.** The study objectives will be fulfilled through use of a hybrid scenario formulated through combination of the background and specific performance characteristics contained in the Mooring System Requirements Document and in two scenarios prepared by TRADOC.[1] [2] The requirements document quantifies many specific system capabilities, while the scenarios present the fuel requirements by type and as a function of time. Where a direct conflict or ambiguity exists, the more demanding case has been integrated into the hybrid scenario.

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[1] Letter, U.S. Army Combat Developments Command, Subject: *Revised Department of the Army Approved Qualitative Materiel Requirement (QMR) for Multileg Tanker Mooring System*, 1 November 1972.

[2] R. C. Lybarger and J. H. Taylor, "Scores," *Army Logistician*, March-April 1975, pp. 30-32.

The military force addressed herein requires a multiplicity of mooring and unloading systems for its support; the actual number is dependent upon the magnitude of the reserve fuel supply objective established to insure continuity of operations. The effect of weather conditions is also examined, and the probability of weather allowing or precluding the delivery of fuel is addressed through the study of weather conditions present off numerous worldwide coastlines.

Once the performance requirements are established for an individual mooring and unloading facility, a mathematical model will be formulated which relates deliveries to consumption; the model also will count each instance when the fuel reserve reduces to zero – a measurement of system performance.

The model will be run on a computer and the fuel demand objectives, the probability of mission success, and the fuel flow rate all will be varied systematically, thereby enabling us to gain a detailed profile of system performance. The results of the simulations will be segregated into feasible, infeasible, acceptable, and unacceptable zones of performance from which the SV's and MAV's will be derived.

III. FUEL CONSUMPTION AND DELIVERY PATTERNS

4. **Corps Compositions.** The demands placed on a mooring and unloading facility are primarily and logically a function of the size and type of military force which the facility supports logistically. Certainly, a corps would be expected to consume far more fuel than would a single division; in a similar fashion, an Armor Division would consume far more fuel than would an Airborne Division. Identification of one or more baseline forces is then essential if the study is to draw meaningful quantitative conclusions; the two scenarios developed by TRADOC serve this purpose.

One scenario involves the deployment of a light corps; the other scenario involves a heavy corps. The composition of each is as reflected in the following:

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.

5. **Daily Consumption.** Knowledge of the force composition is essential, but it constitutes only part of the information required for a comprehensive investigation. From a pragmatic point of view, the military force cannot arrive instantaneously; instead, it must arrive piecemeal as limited transportation resources deliver groups and equipment according to some prespecified order of priority. The TRADOC scenarios detail the sequence quite explicitly, from which values for daily fuel consumption may be established. Such values are available from day 1 through day 60, the day on which the scenario terminates operations. The hybrid scenario actually employed in this study adjusts the TRADOC fuel consumption data, as actually imposed on the mooring and unloading facility, by assuming fuel supply during the first 4 days to be provided by unspecified means. The mooring and unloading facility is assumed to arrive during day 1, and its emplacement is assumed to begin at midnight of that day; the facility would then be available at midnight of day 4, its emplacement requiring 3 days given the favorable weather which is assumed. This variation is consistent with the basic scenarios since it simply differentiates between the source of fuel; it does diverge in its fundamental assumption that the conflict takes place in a region either without commercial ports or without existing and available means to secure and unload tankers. Even should such means be available, Army Doctrine suggests that "POL facilities should be dispersed and sited away from other port facilities."[3]

The fuel consumption data obtained from the TRADOC scenario has been adapted in a second way for the purposes of this study; the conflict duration has been extended from 60 to 90 days to bring the model into coincidence with the service life specified in the system requirements document. This change simply extends the hypothetical deployment of the system, thereby increasing the opportunity for chance, catastrophic, sequential failures to occur. The system reliability requirements derived from this study will be, therefore, somewhat more demanding for the 90-day case than for the 60-day case.

The daily fuel consumption for the light corps is listed in Appendix A (Table A-1) and is illustrated as a function of time in Figure 1. The incremental progression of fuel consumption is very much in evidence. The progression originates in the number of personnel and the level of military activities. The fuel consumption is observed to stabilize after day 44; the level of the last 46 days has been held constant for the period from day 60 to day 90. Comparable data for the heavy corps are also listed in Appendix A (Table A-2).

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[3] Department of the Army Field Manual FM 5-1, *Engineer Troop Organizations and Operations*, July 1971.

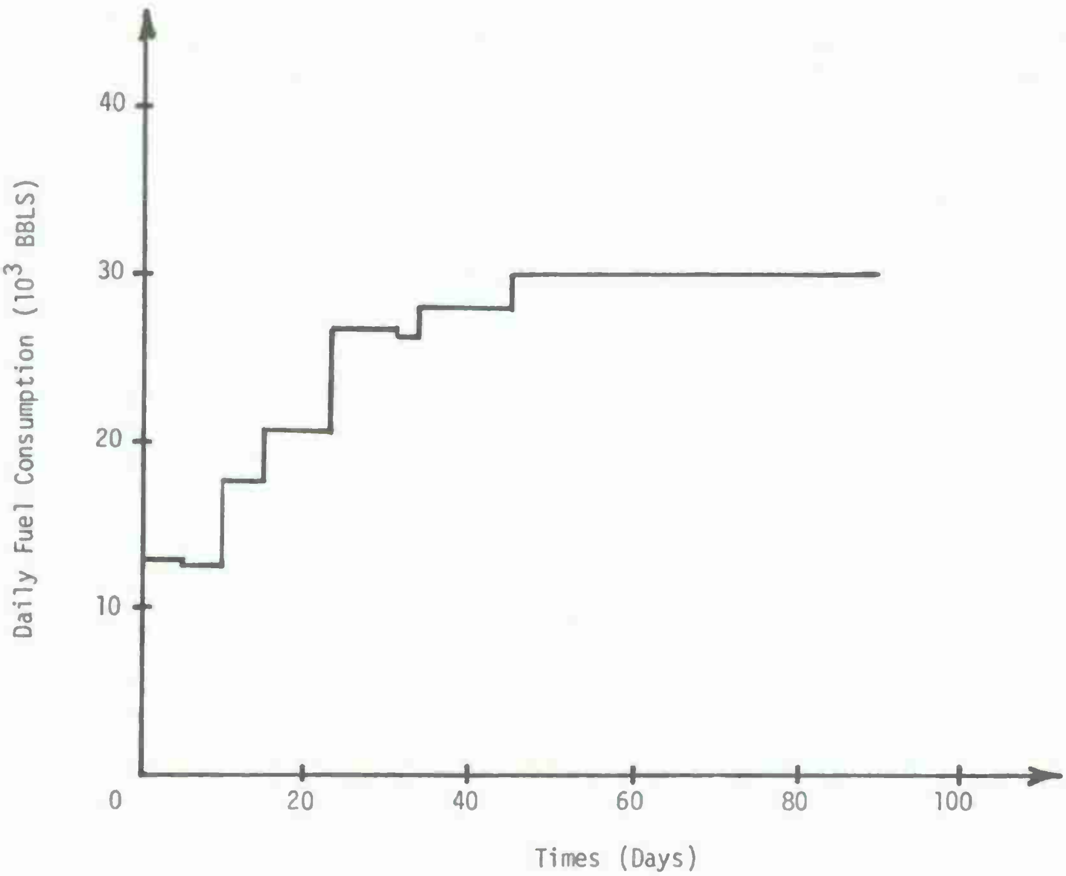

Figure 1. Daily fuel consumption for a light corps.

6. **Fuel Reserve.** The daily fuel consumption constitutes a demand that must be met on a continuous and instantaneous basis. This may be satisfied by: (1) 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 (2) 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 countervailing disadvantages which warrant further investigation. The first case requires that one tanker be dedicated to each unloading line 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 theoretical maximum flow rate possible through one unloading line would permit an exact determination of how many systems are required to support a corps size force; 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, would typically 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 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. The first of the two issues will receive extensive attention in the pages which follow, while the second issue will be dispatched after a brief investigation into the ramifications of various accumulation rates.

If the fuel reserve is to be accumulated at all, additional systems will be required over and above the number required to meet daily consumption exclusively. The number of additional systems required will increase directly as the desired accumulation rate is increased. Once the fuel reserve objective is reached, those additional systems could be idled since their primary utility is limited to the conveyance of reserve fuel stocks. One final factor weighing against an unduly rapid accumulation is the inevitable time lag which occurs between when the need for fuel storage containers is first realized and when 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 number of systems required but at the expense of increasing the uncertainty about availability of fuel supplies – the very purpose of developing a fuel reserve is a reduction of such uncertainties. The short duration of the hostility already described 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 an excessive number of additional systems nor should it require an unreasonable rate of fuel storage container placement. The precise effects of this choice will become increasingly clear in subsequent portions of the overall effort.

The mooring, pumping, and mooring cycle would be repeated until the 90-day duration of hostilities ceased. In this case, the tanker also would be a target but only intermittently. The occurrence of unfavorable weather would also result in the tanker leaving; however, presence of a reserve fuel cache onshore would permit military operations to continue in this case, unlike the preceding case. Thus, the greater the fuel reserve, the longer a military force could operate in the absence of the tanker, raising the question: How large a reserve is best? The short duration of the conflict and the desire to procure and deploy only some reasonable number of systems suggest examining three discrete cases which involve fuel reserves (i.e., 10-, 20-, and 30-day fuel reserves) giving only passing attention to the degenerate zero-reserve case which virtually assures periods during which fuel *will not* be available.

7. **Fuel Delivery Model.** Now that the nature of the overall fuel demand and the utility derived from a fuel reserve have been examined, it is appropriate to investigate the opposite side of the issue – fuel delivery. If a military force is to function effectively, the cumulative fuel delivered must be greater than or equal to the cumulative fuel consumed. The volume of fuel physically on hand is the fuel reserve; its absolute size will vary constantly, sometimes increasing and sometimes decreasing in response to fuel deliveries and to the tempo of military operations. The fuel reserve cannot sustain a deficit since the volume of fuel on hand must be nonnegative – positive or zero; negative values of the fuel reserve have no physical meaning in this case.

The delivery sequence used throughout this effort evolves from the 30-hour mission duration mandated in the system requirements document. For the purpose sought here, the 30-hour mission is interpreted as the actual time during which fuel is being pumped ashore; thus, each delivery sequence will result in the tanker remaining within 5,000 feet of shore (corresponding to the maximum pipeline length) between 31 and 32 hours. The additional time is consumed in the mooring, unmooring, and connection and disconnection of the cargo hose which joins the tanker to the pipeline. 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 loiters offshore; the delivery then forms a 48-hour cycle. Figure 2 illustrates the cumulative volume delivered during the first 10 days following deployment of troops into the objective area; the figure also illustrates the corresponding fuel reserve. The post-day 29 period has been deliberately ignored at this time since the actual delivery sequence utilized is better appreciated if left for development during discussion of the system simulation model.

8. **Fuel Demand Models.** The actual variation of fuel consumption with time as depicted previously in Figure 1 is somewhat cumbersome to deal with, so an idealized fuel demand model will be formulated for each of the three levels of fuel reserve to be given serious consideration. The demand models will treat the period starting midnight of day 4, thus ignoring the fuel demand which is met by other means until the appropriate number of mooring and unloading facilities is operative. The models will embody two demand rates: an initial rate extending from midnight of day 4 to midnight of day 29, hereinafter referred to as the initial period; and a subsequent rate extending from midnight of day 29 to midnight of day 90, hereinafter referred to as the subsequent period. These two distinct periods coincide closely with the fuel consumption patterns observed for the light and heavy corps; actual differences between the scenario rates and the model rates are minor as will be seen during derivation of the models.

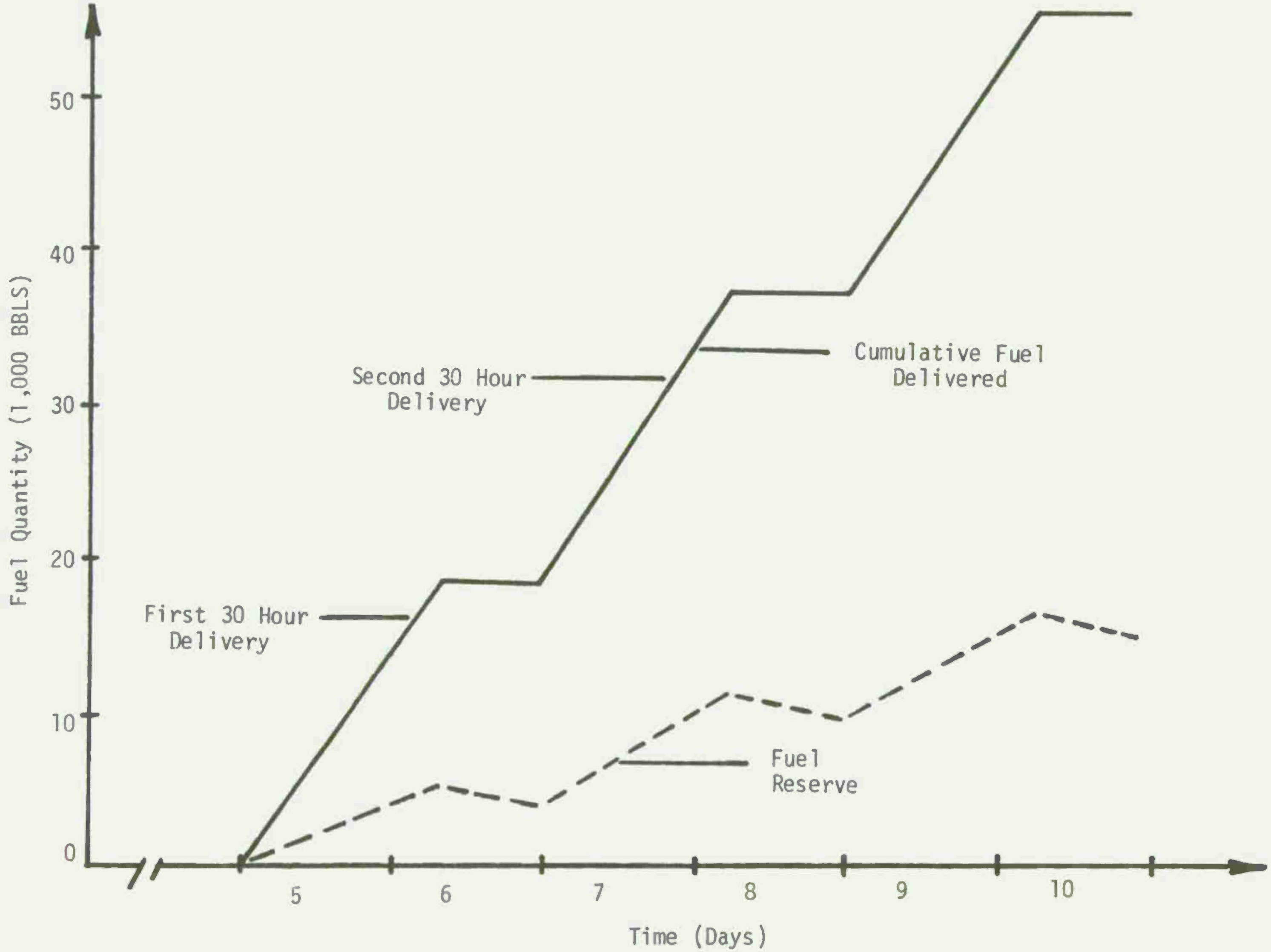

Figure 2. Fuel delivery model.

a. **Ten-Day-Reserve Case.** The cumulative post-day 4 fuel consumption has been computed from the more fundamental consumption data already presented. The cumulative figures for the light and heavy corps are located in Tables A-3 and A-4, respectively, of Appendix A. Those same two tables also incorporate a listing of the daily cumulative contribution to the fuel reserve which must be accommodated if the specified reserve is to be realized by midnight, day 29, the end of the initial period. Accumulation of a fuel reserve implies that the mooring and unloading facility would have to transmit a quantity of fuel equal to the summation of daily consumption and contribution to the reserve – a far more taxing requirement than providing a volume equal to daily consumption alone. This sum is hereinafter referred to as cumulative demand, which is distinguished from consumption. In the case of the light corps, cumulative consumption during the 86-day-long, post-day 4 period is equal to 2,288,290 barrels. The average consumption during the period is then 26,608 bbl/d; thus, a 10-day reserve consists of 266,080 barrels. If that reserve is accumulated during the initial period – from day 5 to day 29, a span of 25 days – the mooring and unloading facility must convey 10,643 more bbl/d than would be conveyed in the absence of a fuel reserve commitment; the comparable volume for a heavy corps is an additional 11,441 bbl/d. Adding a fuel reserve surcharge to the daily consumption data and then transforming the sum into cumulative form yield the two smooth and very similar curves illustrated in Figure 3 for the light and heavy corps. Closer examination of the cumulative demand curve for the light corps shows it to be steeper in the initial period than in the subsequent period – the result of the reserve contribution surcharge; the opposite is in evidence for the heavy corps. The figure also illustrates the proposed demand model which embodies a constant demand rate over the entire period for both size corps – an approach which closely approximates the two demand curves.

b. **Twenty-Day-Reserve Case.** The demand model for this second case is derived in a matter analogous to that used for the 10-day-reserve case. The cumulative consumption, cumulative reserve, and cumulative demand quantities for the light and heavy corps are listed in Tables A-5 and A-6, respectively, of Appendix A. The cumulative reserve objective for both corps simply becomes double the size reserve found for the smaller 10-day-reserve objective, thus steepening the demand curve in the region corresponding to the initial period. While not illustrated, the resulting curves are virtually identical up to day 29 wherefrom they diverge; both curves are essentially linear throughout. The demand model in this case consists of a single demand curve for both corps in the pre-day 30 region and a separate curve for each size of corps thereafter. The cumulative demand value which the model assigns to midnight, day 29, is the average of the values for the light and heavy corps:

Initial Period
Cumulative Demand = ½ (1,036,067 barrels + 988,716 barrels) = 1,012,392 barrels.

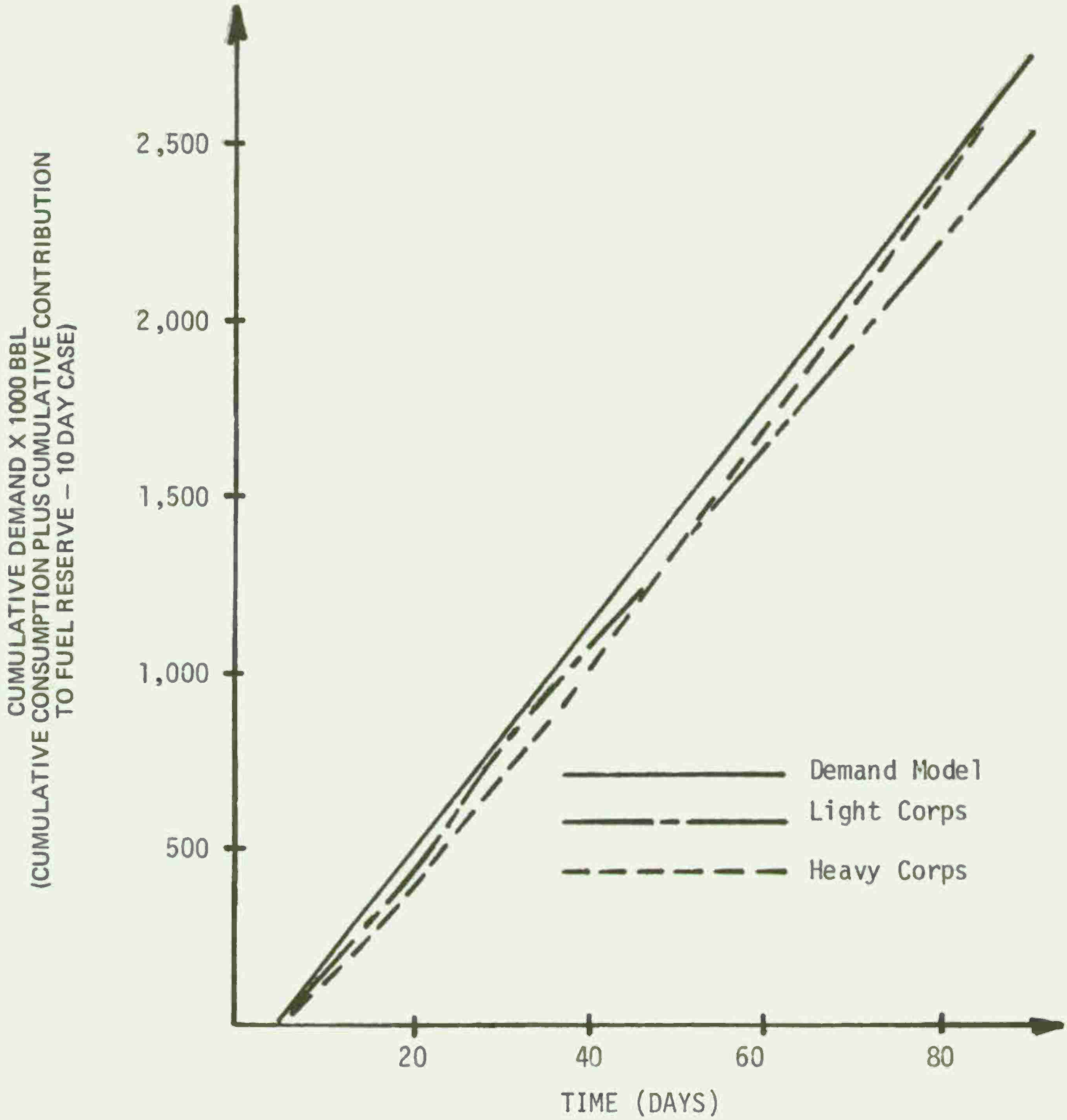

Figure 3. Cumulative demand for 10-day case as a function of time.

The subsequent period cumulative demand models are now easily defined using the starting point of 1,012,392 barrels and the end points corresponding to the cumulative demand on day 90 – values found at the bottom of Tables A-5 and A-6.

c. **Thirty-Day-Reserve Case.** The demand model for this third case takes a form analogous to that of the previous case. A single cumulative demand is used for both size corps during the initial period, and two distinct linear functions are used to describe cumulative consumption during the subsequent period. The cumulative consumption, cumulative reserve, and cumulative demand quantities for the light and heavy corps are listed in Tables A-7 and A-8, respectively. The cumulative demand value which the model assigns to midnight, day 29, is the average of the values for the light and heavy corps:

Initial Period
Cumulative Demand = ½ (1,302,147 barrels + 1,274,738 barrels) = 1,288,443 barrels.

d. **Summary.** The demand models may be used to establish average daily fuel demand for the initial and subsequent periods, given four different levels of fuel reserve objectives. The findings and the method of computation are contained in Table 2 and in the explanatory notes accompanying the table. Average daily demand during the initial period is observed to increase monotonically with increasing reserve fuel objectives. Thus, while larger fuel reserves are intuitively associated with an increased probability of possessing adequate fuel to support combat operations, this same action results in each mooring and unloading facility being tasked to convey increasing volumes of fuel given the same number of potential pumping hours per system. The increased throughput volume required would require the use of additional systems to accommodate the temporarily high demand rate. It is also apparent that no consistent trend exists for the average daily demand during the subsequent period – an understandable occurrence since the difference results from substitution of artificial linear models for the discrete values obtained from the TRADOC scenarios. Lastly, the flow rates presented for the initial period deliveries cite 384 hours as the potential number of hours during which the tanker may pump fuel ashore during the initial period. The 384 hours of pumping is derived by taking the sum of twelve 30-hour missions plus one 24-hour mission. The latter time period is that portion of a mission which occurs during day 29 – the day defined as the end of the initial period. Thus, in the absence of exogenous influences, it would be possible to pump fuel ashore for a theoretical 384 hours. Factors which mitigate this theoretical allotment will be given an in-depth examination elsewhere in this study.

Table 2. Summary of Daily Demand

Type of Corps	Average Daily Demand Initial Period[a] (bbl/d)	Flow Rate Corresponding to Initial Period[b] (bbl/h)	Average Daily Demand Subsequent Period[c] (bbl/d)
		No Reserve[d]	
Light	26,747	1,115	29,880
Heavy	23,252	969	35,098
		10-Day Reserve	
Light	31,928	2,079	31,928
Heavy	31,928	2,079	31,928
		20-Day Reserve	
Light	40,496	2,636	29,640
Heavy	40,496	2,636	33,106
		30-Day Reserve	
Light	51,538	3,355	29,477
Heavy	51,538	3,355	33,269

(a) Cumulative demand for initial period divided by 25 days, i.e., length of initial period.

(b) Cumulative demand for initial period divided by 384 hours, i.e., potential number of hours during which the tanker may pump fuel ashore during the initial period.

(c) Cumulative demand for subsequent period divided by 61 days, i.e., length of subsequent period.

(d) Peak values given for zero-reserve case; the flow rate is based on pumping 24 hours a day.

IV. SYSTEM REQUIREMENTS

9. **Background.** The preceding portion of this study consists of a detailed inquiry into the needs of a supported military force over time. A number of separate variations of those needs has been examined preparatory to a detailed analysis of the performance of a multileg tanker mooring and unloading facility (referred to as the System) as a function of a number of variables. Thus far, the fuel demands over time have been defined explicitly without concern for how that fuel would be physically conveyed. Some finite number of moorings and unloading lines is obviously required to accommodate that demand. The precise number is dependent on how far offshore the tanker is moored (the actual distance identically establishes the pipeline length and, consequently, the flow rate), on the nature of the fuel actually pumped, and on the availability of the mooring and unloading facility in the sense that climatic conditions outside the System's design envelope may preclude its use. Once these factors have received appropriate attention, it will be possible to establish the number of systems

required and, therefore, the expected fuel throughput required of each individual system as well. The performance of one such system – of N homogeneous systems – then may be investigated using the simulation model derived in section V. At this time, it is appropriate to present the assumptions which underlie the first parts of this section; each assumption subsequently will be reexamined and relaxed as the analysis evolves. The assumptions initially employed are: (1) that the mooring and unloading facility will have a composite reliability of unity; (2) that the environmental conditions, e.g., wind and waves, will remain within the ranges specified in the system requirements document; (3) that hostile forces neither prevent friendly forces from using the mooring or unloading facility nor destroy the facility or any fuel stores; and (4) that fuel storage containers are available in advance of the time they are required to receive the fuel reserve.

Given the preceding assumptions and the earlier observation that the mooring and unloading facility is placed under the highest operational stress during the initial period, it is evident that an equal or larger number of systems is required during the initial vis-a-vis the subsequent period. Thus, the number of systems required may be uniquely determined from the demands to be accommodated during the initial period. One last increment of knowledge is required before the number of systems may be established, and that is the nature of the fuel being transported. Actually, a series of fuels is involved, each with a different flow rate from the others, ceteris paribus. Since each unloading facility deployed will be used in a multiproduct mode, the actual throughput will vary as the type of fuel being pumped varies. This issue is best treated by discussing flow rates for a "composite fuel" macrovariable found by taking a weighted average of the flow rates for each fuel. The weighting factors used correspond to the percentage of each type of fuel consumed during the hypothetical conflicts reflected in the TRADOC scenarios. The composite fuel referred to hereinafter consists of 50 percent JP-4, 27 percent diesel, and 23 percent gasoline. Any variation of the fuel mixture would naturally result in a corresponding variation of the newly defined composite fuel flow rate. Despite this obvious possibility, the macro approach employed is regarded as quite representative even given the theoretically infinite number of composite fuels which could be defined. The actual flow rate used is skewed toward the higher density fuels, yielding conservatively low flow rates. The relative insensitivity of flow rate to actual mixture composition may be illustrated by considering the flow rates for aviation gasoline – the least dense conventional fuel – and diesel – the most dense – in the case of a 1000-foot-long pipeline of the type used here and at a head loss of 90 lbf/in^2. The aviation gasoline would flow at the rate of 1,808 gal/min, while the heavier diesel would flow at 1,661 gal/min, 92 percent of the aviation gasoline rate. Since the maximum possible variation of flow rates is limited to approximately 8 percent, any plausible composite fuel would certainly exhibit a much smaller deviation. In this particular instance, the possible deviation is further reduced since the light aviation gasoline is not used.

10. **Flow Rates – Unconstrained.** The fuel which is to be transported has been defined, so a determination of theoretical, or unconstrained, flow rate may be made after first commenting on: the pipe through which the fuel will flow; the pipeline lengths envisioned; and the tankship pumping capability. The pipe used has an inside diameter of 6.0 inches and an outside diameter of 6.625 inches; it is grade J-55, National Diamond "B" buttress-threaded oil field casing and is furnished in lengths of approximately 30 feet.[4] The actual length of pipeline emplaced offshore normally will be as short as possible since that will minimize the effort required for its placement and simultaneously maximize the fuel delivery rate. The incremental nature of the pipeline (167 lengths of pipe are shipped) makes it desirable to examine a broad range of feasible lengths at this time rather than to limit the discussion to the 2,500- and 5,000-foot lengths specified in the system requirements document. A number of discrete lengths varying from 1,000 to 5,000 feet will be examined, thus effectively encompassing the range of lengths and corresponding flow rates likely to be of practical concern; attention subsequently will be directed exclusively to the two specified lengths, not because of their intrinsic significance but rather because they illustrate the system's performance. The third issue of concern is the tankship which transports the fuel to the objective area. The tankships involved would be provided by the Military Sealift Command (MSC). The smallest size would be 25,000 DWT, would require approximately 42 feet of water depth for safe operation, and would be capable of delivering approximately 225,000 barrels of fuel each trip. In the absence of an extensive and available fuel-storage facility in the military objective area, it would be virtually impossible to physically accept such a monumental volume at the very start, thus making necessary the earlier assumption that fuel storage volume would become available at a rate equivalent to the growth in theoretical fuel on hand. The alternative to the preceding assumption would be an ability to create fuel-storage capacity instantaneously and discontinuously in advance of scheduled tanker arrivals – a highly improbable feat.

Since the supporting information has been presented, it is now appropriate to quantify the rates at which the hypothetical composite fuel would flow through varying lengths of pipe. Two series of flow tests have been run, and those results will be used here instead of depending purely on theoretical flow curves for steel pipe derived after assuming some internal roughness factor. The first series of flow tests was conducted by the Naval Civil Engineering Laboratory and was accomplished by pumping saltwater through a 4,000-foot-long pipeline.[5] The second series of tests was conducted at the U.S. Army Mobility Equipment Research and Development Center

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[4] 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, p. 17.

[5] 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, p. 56.

and involved pumping gasoline through approximately 90 feet of pipe. The test data recorded by each are summarized in Table 3.

Table 3. Flow Test Data

Navy Series[a]		Army Series[b]	
Head Loss (lbf/in^2)	Flow Rate (gal/min)	Head Loss (lbf/in^2)	Flow Rate (gal/min)
32	440	0.29	388
39	460	0.69	544
44	500	0.88	624
47	540	1.22	718
50	540	1.52	810
55	580	1.81	886
60	590	2.20	958
65	620	1.71	870
70	620	1.27	746
75	660	0.88	624
80	680	0.49	470

(a) Conducted with saltwater pumped through a 4,000-foot-long pipeline.

(b) Conducted with gasoline pumped through an 88.7-foot-long pipeline.

Roughness coefficient estimators were computed for each of the two sets of test data. The Navy data yielded a value of 0.0242, while the Army data yielded a lower figure, 0.0204. If those coefficients are then substituted into equation (3), the predicted flow rates obtained using the Army roughness estimator are found to be consistently 9 percent higher than the comparable rates obtained using the Navy roughness estimator. The relationship for determining flow rate for this particular pipe is given by the following:

$$Q = \left(\frac{577{,}763 \cdot h}{SG \cdot L \cdot f} \right)^{1/2}, \qquad (3)$$

where:

- Q is flow rate (gal/min),
- h is head loss (lbf/in^2),
- SG is specific gravity (dimensionless),
- L is pipeline length (feet), and
- f is friction factor (dimensionless).

The differences in computed roughness are most probably attributable to inaccuracy of the flow meters used; however, the condition of the pipe interior also may have played a role. The pipe used in the Army tests was thoroughly cleaned using internal scrapers before the flow tests were run; the pipe used in the Navy tests may not have received such advance preparation, thus leading to an increased roughness originating in interior scale and corrosion products. Table 4 contains the flow rates predicted by substituting the two roughness estimators into equation (3) along with a constant head loss of 90 lbf/in^2, a specific gravity of 0.7825 corresponding to the composite fuel, and a varying pipeline length; a third set of flow rates, the average of the Army and Navy predictions, is also included in the table. This third set of flow rates will be used throughout the remainder of this effort. The average is considered as being more representative than either constituent element, a conclusion drawn from the hypothesis previously proposed to explain the differences. The rates listed have been rounded to the nearest 10 units, an approach consistent with the quality of the original data.

Table 4. Predicted Flow Rates (Composite Fuel)

Pipeline Length	Army Predictions		Navy Predictions		Average Predictions*	
(ft)	(gal/min)	(bbl/h)	(gal/min)	(bbl/h)	(gal/min)	(bbl/h)
1,000	1,810	2,580	1,660	2,370	1,730	2,470
1,500	1,470	2,110	1,350	1,930	1,410	2,020
2,000	1,280	1,820	1,170	1,670	1,220	1,750
2,500	1,140	1,630	1,050	1,500	1,100	1,560
3,000	1,040	1,490	960	1,370	1,000	1,430
3,500	970	1,380	890	1,270	930	1,320
4,000	900	1,290	830	1,180	870	1,240
4,500	850	1,220	780	1,120	820	1,170
5,000	810	1,150	740	1,060	770	1,110

* Rounded after first taking averages of unrounded data.

11. Environmental Considerations. Each mooring is designed to resist the forces generated by a given size ship acted on by a given combination of environmental parameters. The ship size addressed would normally correspond to the largest size ship expected to use the mooring. 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 of remaining operable some prespecified fraction of the time. This latter approach is better suited to moorings intended for worldwide application, rather than for one specific site. The latter approach also would be expected to simultaneously minimize weight, cube, cost, emplacement time, and other related variables which are 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.

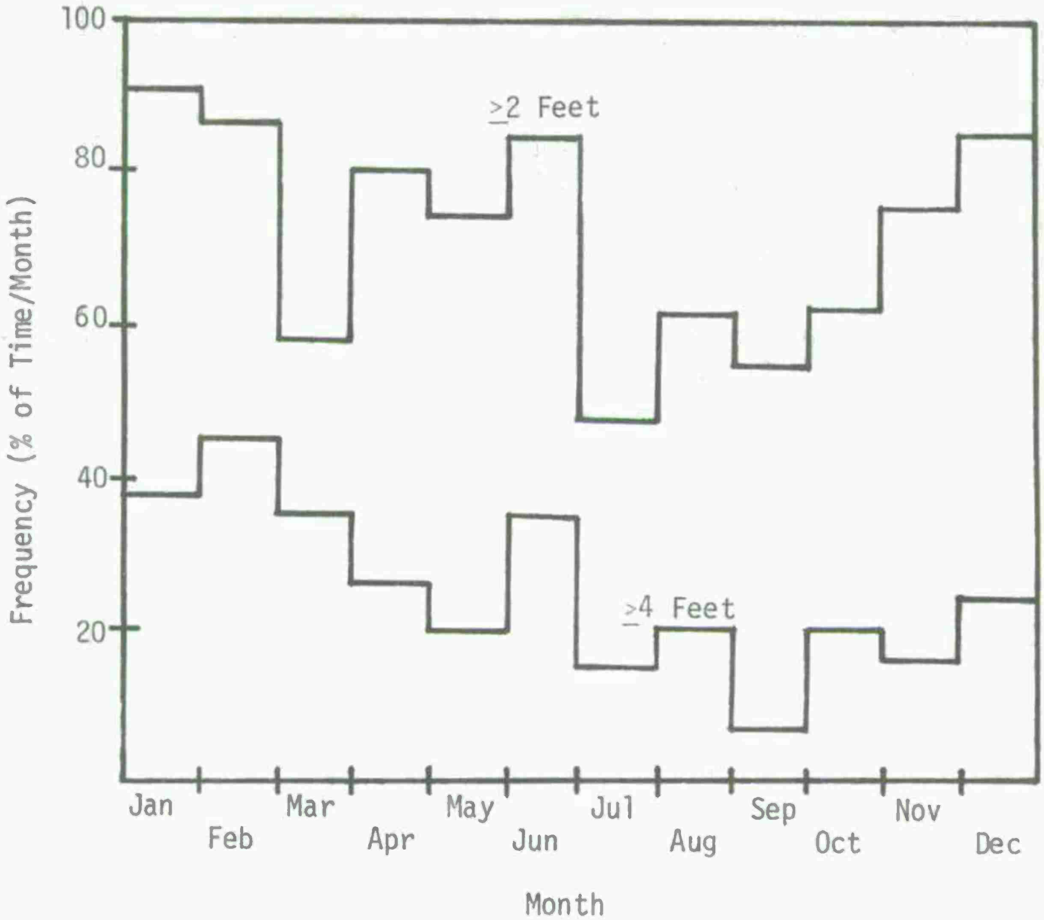

Figure 4. Seastate at SEACON I construction site (percentage of time per month that swells are greater than or equal to 2 or 4 feet).

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 well 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 4).[6] The plotted distributions are observed to be multimodal (i.e., possess more than one local maximum) 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 end of the time spectrum, i.e., 60 or 90

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[6] 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.

days. Should a short-lived deployment coincide with a period of high-percentage occurrence of wave heights outside the permissible operating range of the mooring, serious problems could arise. Over longer periods, e.g., 1 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 the interaction of local winds with the ocean surface, which forms waves of steep slope and short wavelength. Swell, in contrast, is formed at sites quite distant from the actual site of interest; swells are generally smooth in contour, approximate sinusoids in shape, and are of considerably longer wavelength than is sea. The long-wavelength 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 document specifies that it is 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 5 conveys the characteristics associated with various seastates.

Table 5. Seastate Characteristics

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

It also should 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 because 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 significant waves of 2 to 3 feet but may include waves as high as 4.8 feet, i.e., 1.6 times the wave height constituting the upper bound.[7] The significant wave height is found by positioning an observer at a fixed point offshore to list the height of each wave that passes. The wave heights are then arranged in order of decreasing magnitude; the significant wave height, as used here, is

[7] R. L. Wiegel, *Oceanographic Engineering*, Prentice-Hall, Englewood Cliffs, New Jersey, 1964, p. 202.

then the average of the highest one-third of the waves.[8] 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 the operation of a mooring. Two sources of relevant data have been studied and their contents have been distilled into the following paragraphs.

The first source 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.[9] The *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., 4,015 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 6 summarizes the results for the 11 sites.

Table 6. Average Occurrence of Seastate for 11 Sites

Seastate	Number of Occurrences	Percent Occurrence*	No. of Sites At Which Observed
1-3	3,426	85.3	11
4	426	10.6	11
5	124	3.1	10
> 5	13	0.3	4

* Number of occurrences divided by 4,015 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

8 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.

9 *Environmental Analysis Relative to Portable Port Operations,* Ocean Science and Engineering, Inc., 21 November 1969, p. II-44.

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 study – also sponsored by the Navy – sought to minimize the downward bias induced through the use of annual averages and instead sought to introduce a bias favoring higher seastates.[10] This second effort presents percent-occurrence data which correspond with the worst month – i.e., the month with the highest occurrence of a given seastate or seastate range – for 14 worldwide locations. The data consists exclusively of the percent occurrence of various height range sea and swell; thus, for the identical reasons given earlier, the sea data has been neglected and the swell data has been used as the basis of establishing equivalent seastates. As expected, the frequency of occurrence reflected in Table 7 differs from that presented in the previous table; this second table is of greater relevance since the military conflicts which are of interest here are of short duration and, therefore, must necessarily be considered in the context of the month or months of maximum wave activity.

Table 7. Maximum Monthly Seastate Occurrence for 14 Sites (Percent)

Seastate	Occurrence (Pct)	Range (Pct)
1-3	55.1	11-100
⩽4	36.6	8-66
⩽6	13.9	0-61

According to Table 7, a mooring such as the Multileg Tanker Mooring System would be usable less than an average of 55 percent of the time during the most favorable month, i.e., the month in which lower seastates occur most frequently. The actual occurrences of seastates 1 through 3 are observed to vary from as seldom as 11 percent at one site to as frequently as 100 percent of the time 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. When the problem is examined from the opposite direction, 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 6, which represents annual averages, is markedly different than the micro-level data of Table 7. The monthly information is considered far more

10 *Systems for Mobile Piers and Causeways for Expeditionary Logistic Facilities*, Fredrick R. Harris, Inc., and PRC Systems Sciences Co., June 1973, pp. 3-8.

relevant to short-duration military operations of the type addressed herein than is the corresponding annual information.

12. Flow Rates – Constrained. The existence of a fuel reserve is clearly necessary with the present mooring and would be necessary even with an advanced mooring capable of operating under more severe conditions than permissible here. Given a mooring with a hypothetical capability to operate in seastate 3, fuel could be moved only 55 percent of the time during the most favorable month with a potential for as seldom as 34 percent of the time if operations took place in the Timor Sea during the month of July. Seastate 4 or greater is expected 66 percent of the time at that particular site.

Since seastate 4 or greater occurs an average 37 percent of the time during the months that it is maximized, it may be inferred that average occurrence rates for seastates 1 through 3 are minimized during those same months; the lower seastates would occur an average 63 percent of the time. Naturally, seastate 2 or less (the normal operating range for the Multileg Tanker Mooring System) would occur at an even lower incidence rate than 63 percent. If the wide range of seastate 4 or greater occurrence rates is now examined and if a conservative orientation is followed, a figure of 40 percent appears representative of maximum mooring availability during the least favorable month; thus, the actual volume of fuel delivered is observed to be a function of the exogenous variable – weather.

The reader is cautioned that 40 percent is an average and as such is subject to all the shortcomings associated with the use of averages to represent other than uniformly distributed phenomena. The actual occurrence of seastates 1 and 2 would range from somewhat less than 34 percent to somewhat less than 92 percent of the time for the 14 sites reflected in Table 7. The 34- and 92-percent figures are associated with seastates 1 through 3; thus, the more exclusive seastates 1 and 2 case would occur less frequently.

The significance of the weather-constraint value actually employed may be better appreciated after considering that those sites experiencing "good" weather greater than 40 percent of the time during the worst month could be serviced with fewer systems than is indicated by the numbers reflected in this study; conversely, sites experiencing "good" weather less than 40 percent of the time would require more systems than the numbers indicated herein. While this study will establish performance for only the 40-percent availability case, the analytical methodology developed here could be applied directly to any other numerical value, an exercise deferred at this time.

It becomes less probable that equally unfavorable conditions would exist for 2 or 3 consecutive months, so a seastate model embodying decreasing seastates is required. The approach decided upon is the use of 40 percent for the initial period followed by 70 percent availability for the subsequent period. The 40-percent value is derived from the month having the lowest likelihood of favorable (i.e., seastate 1 or 2) conditions, while the 70-percent figure coincides with the average annual likelihood of such conditions.

The reduced availability factors now may be used to transform the potential flow rates to weather-constrained flow rates; such rates are found in Table 8.

Table 8. Weather-Constrained Flow Rates

Pipeline Length (ft)	Unconstrained Flow Rate (bbl/h)	Constrained Flow Rate[a] (bbl/h) Initial Period[b]	Constrained Flow Rate[a] (bbl/h) Subsequent Period[c]
1,000	2,470	990	1,730
1,500	2,020	810	1,410
2,000	1,750	700	1,230
2,500	1,560	620	1,090
3,000	1,430	570	1,000
3,500	1,320	530	920
4,000	1,240	500	870
4,500	1,170	470	820
5,000	1,110	440	780

(a) Rounded to nearest 10 bbl/h
(b) 40 percent of unconstrained rate
(c) 70 percent of unconstrained rate

13. **Individual System Loading.** At this juncture, the fuel demand has been rigorously defined, and delivery rates have been adjusted for unfavorable weather conditions. It is now possible to respond to the question: How many mooring systems and unloading facilities are required to support the light and heavy corps of the TRADOC scenarios? This question will be answered for only two pipeline lengths – the 2,500- and 5,000-foot lengths specified in the system requirements document – so that the results will remain intelligible and yet also illuminate the problem to the maximum extent. The response will be made on the basis of the initial period since the number of moorings and unloading facilities required is greater for the initial period than for the subsequent period. This position is supported by the earlier observation that the average daily demand during the initial period is equal to or greater than the same figure associated with the subsequent period; the 60-percent downward adjustment in the initial period flow rate vis-a-vis a lesser 30-percent reduction during the subsequent period also supports the proposed approach. It is now possible to establish how much fuel a single mooring and unloading facility is capable of conveying during

the initial period. Table 9 presents the cumulative throughput given: (1) the unconstrained flow rates from the previous table; (2) the 384 hours of pumping time theoretically available during the initial period; and (3) the 40-percent factor which reduces the actual pumping time to a lesser number reflecting the impact of unfavorable weather conditions.

Table 9. Constrained Cumulative Throughput and Equivalent Delivery Rates for One Mooring and Unloading Facility During the Initial Period[a]

Pipeline Length (ft)	Constrained Cumulative Throughput[b] (bbl)	Equivalent Daily Delivery Rate[c] (bbl)
2,500	239,616	9,585
5,000	170,496	6,820

(a) Actually represents the delivery rates for each unloading facility deployed since a single mooring could theoretically accommodate two pipelines of the type discussed here.

(b) Unconstrained flow rate (Table 8) x 0.4 (weather factor) x 384 hours (theoretical pumping time during initial period).

(c) Unconstrained flow rate (Table 8) x 0.4 (weather factor) x 15.36 hour/d (average daily delivery time during the initial period, i.e., 384 hours/25 days).

Knowledge of the capabilities of a single system under conditions of perfect reliability and no damage by hostile action allows the determination of the number of systems required to support a light or heavy corps demand. Table 10 summarizes the results along with the actual delivery rates required of each deployed system under a combination of reserve fuel objectives and pipeline lengths; for a 10-day fuel reserve objective and the more demanding, and more physically meaningful, 5,000-foot pipeline length, it is observed that five systems would be adequate if a system availability of 0.94 could be assured. Another way of looking at this result is that five systems would be adequate if the system nonavailability resulting from hardware failures and hostile activity could be kept to 6 percent of the period during which the system was scheduled to function and during which environmental factors allowed operation. The effect which hardware reliability has on system availability and performance will be thoroughly investigated in the following section of this study; the impact of hostile activity will be left to the reader for speculation. At this point, it may be further observed that for the range of availabilities investigated the daily delivery rate for each system deployed is in the range of 5,000 to 8,000 bbl/d.

Table 10. Unit Delivery Rates and Required System Availabilities[a]

Pipeline Length (ft)	No. of Systems Deployed	Required Daily Delivery Rate Per System[b] (bbl/d)	Minimum Acceptable Availability[c]
		10-Day Reserve	
2,500	4	7,982	0.83
	5	6,386	0.67
5,000	5	6,386	0.94
	6	5,321	0.78
		20-Day Reserve	
2,500	5	8,099	0.85
	6	6,749	0.70
5,000	6	6,749	0.99
	7	5,785	0.85
	8	5,062	0.74
		30-Day Reserve	
2,500	6	8,590	0.90
	7	7,363	0.77
5,000	8	6,442	0.95
	9	5,726	0.84
	10	5,154	0.76

(a) Based on consumption and reserve contribution during initial period.

(b) Average daily demand during the initial period (from demand models) divided by the number of systems deployed.

(c) Total cumulative demand during the initial period (from demand models) divided by the constrained cumulative throughput of all the deployed systems (constrained cumulative throughput for one system (Table 9) times the number of systems).

V. ANALYSIS

14. **System Simulation Model.** The actual system of interest is configured much the same as the schematic representation reflected in Figure 5. A mooring consisting of the tanker's two bow anchors and two or four explosively anchored buoys restrains the tanker in a fixed orientation with respect to the shoreline. The configuration embodying four explosive anchors is the more demanding for reasons which will become obvious as the discussion proceeds, and for that reason the analysis is predicated on such a mooring. A 6-inch-diameter pipeline is linked to the tanker via a flexible cargo hose; the pipeline receives fuel from the tanker and conveys the fuel ashore where it is pumped into storage containers for eventual distribution. The offshore elements have been assumed to be perfectly reliable, an assumption which must eventually be relaxed on pragmatic grounds. A close examination of the system

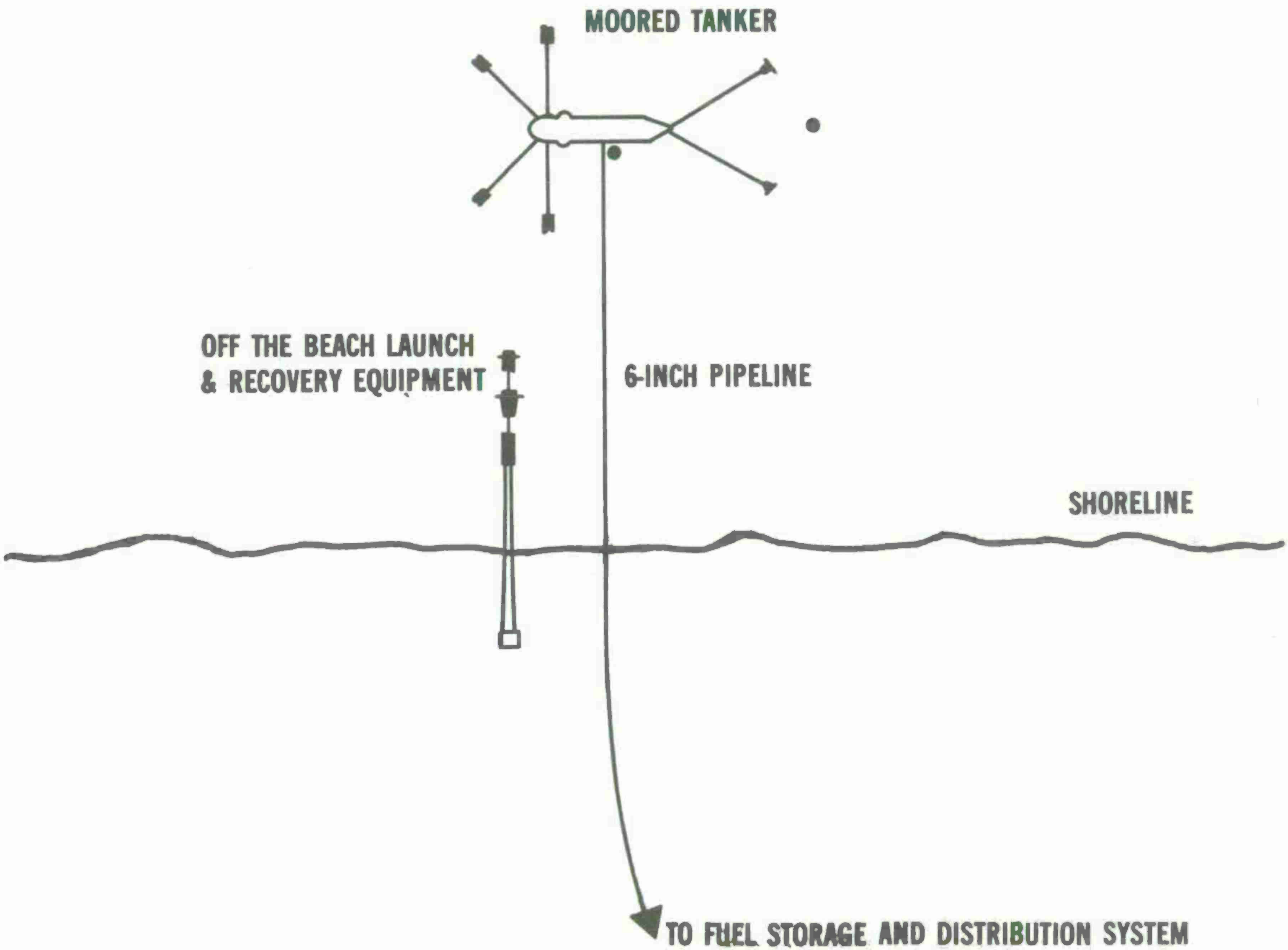

Figure 5. Mooring and unloading system.

identifies numerous potential areas where failures might occur; however, the brief period of exposure, i.e., 90 days, mitigates against the occurrence of most such failures. The single area in this system which warrants the closest examination is the anchoring device used to actually restrain the tanker. As is the case for *all* anchoring devices except deadweight anchors, which develop resistance through friction with the ocean bottom, the performance of explosively embedded plates, or projectiles, which develop the actual resistance attributed to explosive embedment anchor devices, is poorly understood. Even the performance of the universally accepted drag-type anchors is based almost exclusively on empirical data rather than on a theoretically based understanding of the anchor-soil interaction mechanism; similarly, the complex soil-projectile interactions, associated with explosive embedment anchors as a generic class, have received serious investigation during only the past 10 years. A number of theoretical and empirically derived models has been postulated; however, no one model begins to satisfactorily address long term, short term, static, *and* dynamic performance of plates with varying geometries, embedded in differing soil media. Limited empirical data have been gathered by the U.S. Army Mobility Equipment Research and Development Command on the short term performance of two distinct projectile types under static loading conditions. Figure 6 summarizes that data for one of the two types – the XM-50 anchor – in terms of soil type and stage of projectile design. The pre-1974 configuration embodied a weakness which effectively limited extraction force to a maximum of approximately 70,000 pounds; design changes incorporated into the post-1974 configuration have raised the ceiling to approximately 100,000 pounds. A still more recent design change has been incorporated to correct a problem encountered during tests off Eglin AFB, Florida, where an excellent sand bottom sustained only substandard extraction forces. The cause has since been traced to a design deficiency which prevented the embedded anchor projectile from rotating into position perpendicular to the axis of the applied load. The elevated extraction forces developed by the Clay III vis-à-vis the Clay II results bear witness to the effectiveness of the final design change.

Perhaps the most comprehensive investigation into the subject involved scale model anchor projectiles which were acted on by static and cyclic loads. This investigation, hereinafter referred to as the Bemben study, addressed the differences in extraction forces which develop under static and cyclic loading conditions.[11] The observed differences were found to be significant, raising doubts about the direct relevance of the fullscale test data as reflected in Figure 6 (which shows static extraction force data) to the problem of mooring a tanker, which imparts loading of a dynamic but aperiodic nature. At the risk of oversimplifying the findings of the investigation, it may be stated that a plate embedded in a soil mass will creep under load and that the

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[11] S. M. Bemben, M. Kupferman, and E. H. Kalajian, *Vertical Holding Capacity of Marine Anchors in Sand and Clay Subjected to Static and Cyclic Loading*, November 1971.

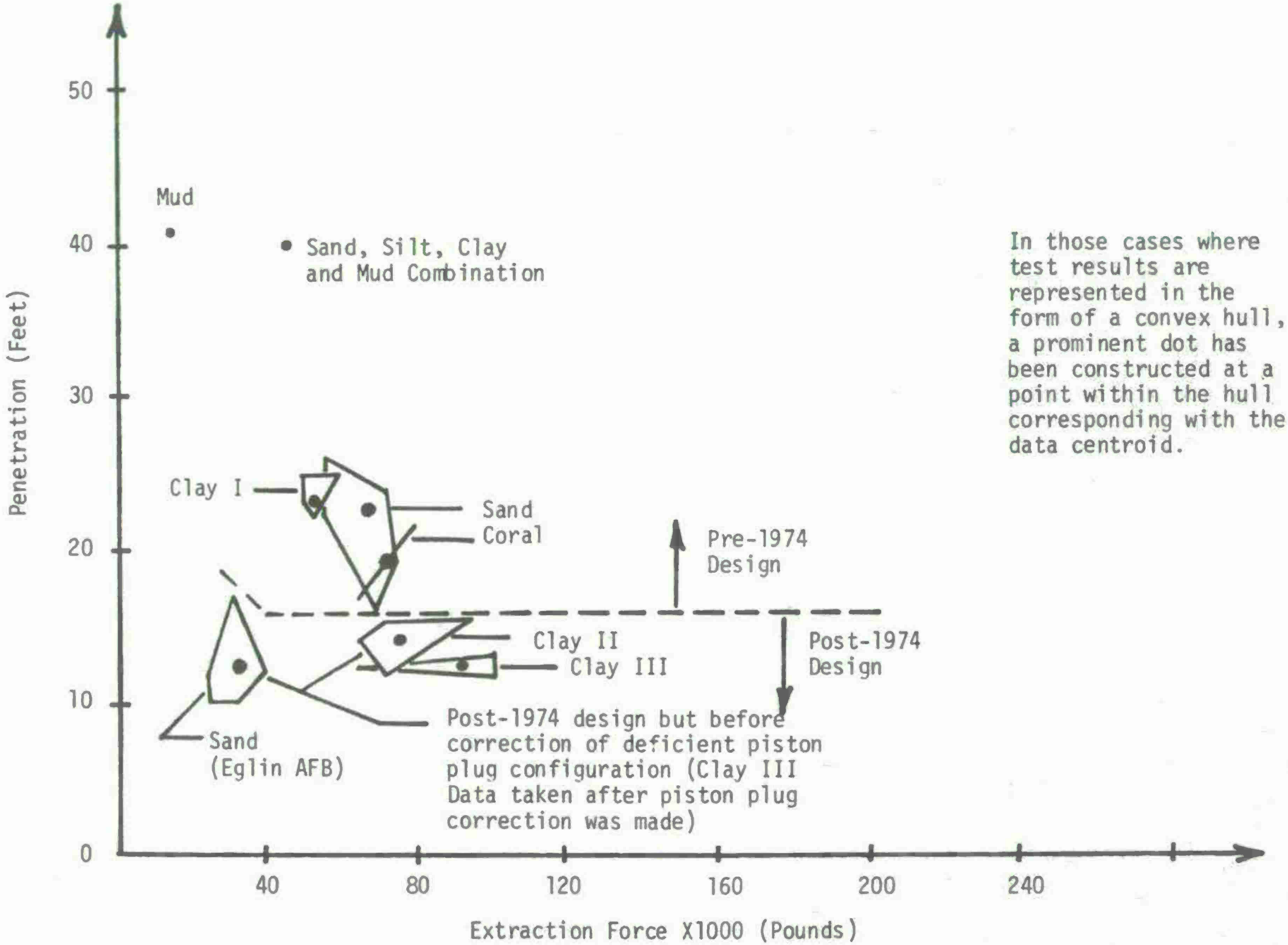

Figure 6. XM-50 Explosive Embedment Anchor.

rate of creep in a given material varies directly, but nonlinearly, with the magnitude of the applied load; the observation most significant to this immediate effort is that the creep rate is more rapid for a dynamic load of maximum value F than for a static load of the same value. Thus, if a single installation of anchoring devices is to perform over the life of a mooring, the creep rate must be limited to a value sufficiently low such that the projectile remains safely embedded in the ocean bottom from the time of its initial embedment to the time the mooring is abandoned at the completion of hostilities. Knowledge of the expected number of hours during which the anchors will be subject to mooring loads then may be combined with knowledge of the creep mechanism to establish a failure model for the embedded anchor projectiles. For the purposes of this study, total time in the mooring will be assumed as equivalent to the pumping time. Since a number of different fuel reserve objectives and pipeline length options has been established, a choice also must be made at this time: Which combinations of those possible variations previously identified warrant attention? The choices which appear most appropriate are those that place the system under stress for the longest periods; therefore, the smallest number of systems which satisfy demand for each of the three fuel reserve objectives and which do so at the reduced flow rates associated with the 5,000-foot pipeline length has been chosen. The exact number of systems is then established by reference to Table 10. Given the preceding, it is now possible to compute the total number of hours, a process rendered explicit in Table 11.

Table 11. Pumping Times

Number of Systems(a)	Fuel Delivered During Initial Period (bbl)(b)	Fuel Delivered During Subsequent Period (bbl)(c)	Per System Delivery–Subsequent Period (bbl)(d)	Pumping Time Subsequent Period (hours)(e)	Total Pumping Time (hours)(f)
		10-Day Reserve			
5	852,480	1,893,335	378,667	485.5	639
		20-Day Reserve			
6	1,022,976	2,019,446	336,574	431.5	585
		30-Day Reserve			
8	1,363,968	1,953,892	244,237	313.1	467

(a) Number of systems established from Table 10 using guidance from paragraph 14.

(b) Found by multiplying 170,496 barrels (from Table 9) by number of systems from first column.

(c) Cumulative demand for heavy corps as of day 90 less preceding column; corresponds to fuel volume which remains to be delivered during subsequent period.

(d) Equal to value from third column divided by number of systems taken from first column.

(e) Equal to value from fourth column divided by the constrained flow rate for a 5000-foot-long pipeline during the subsequent period, i.e., divided by 780 bbl/h (Table 8).

(f) Equal to the pumping time from the fifth column plus 153.6 hours of pumping which occurs during the initial period (384 hours multiplied by 0.4 (weather adjustment factor)).

The results dramatically reflect the differences in cumulative stress experienced under varying reserve objective decisions. In all cases, each system deployed would be operated for the same number of hours, i.e., 153.6 hours, during the initial period. Since the fuel demand rate is greater during the initial period than during the subsequent period, the number of systems which must be deployed is an exclusive function of the fuel reserve objectives; the larger the fuel reserve objective, the greater the number of systems which must be deployed initially. Once the subsequent period has been entered, the number of hours which each system must operate declines if all the systems originally deployed remain in service, a situation which reduces the cumulative stress experienced by each deployed system as a direct function of increasing reserve objective. An alternative approach is use of a reduced number of systems during the subsequent period; the unused systems reasonably could be left in position until the termination of hostilities, thus functioning as spares. The use of fewer moorings after the 29th day would also allow the military force to be supported by fewer tankers. If the 30-hours-pumping-per-48-hour-cycle objective followed during the initial period is continued throughout the subsequent period – a policy consistent with the improbability that sufficient storage capacity ever would be available to accommodate the entire 225,000-barrel cargo of a fully loaded tanker – the tanker would remain in the general vicinity repeating this 48-hour cycle of activity until its cargo had been exhausted. This approach yields a theoretical 906 hours of pumping during the subsequent period, that is, 30 missions of 30 hours each plus 6 hours during day 30. The latter represents the last 6 hours of a 30-hour mission started on day 29 of the initial period. The expected duration of actual pumping would be only 70 percent of 906 hours (634.2 hours) after introduction of the weather adjustment factor. Recall the earlier discussion leading to a conclusion that the mooring would be available only 70 percent of the time during the subsequent period, a conclusion which resulted in creation of the variable "constrained flow rate." This information now may be combined with the information outlined in the preceding table to obtain revised pumping times (Table 12) associated with each of the three fuel-reserve-objective cases.

Table 12. Pumping Time – Revised (5,000-Foot Pipeline)

Reserve Objective (days)	Fuel Delivered During Subsequent Period (bbl)[a]	Required Pumping Time–Subsequent Period (hours)[b]	Required Systems–Subsequent Period[c]	Total Pumping Time (hours)
10	1,893,335	1,706	3	722
20	2,019,446	1,819	3	760
30	1,953,892	1,760	3	740

(a) From Table 11.

(b) Equal to the preceding column divided by unconstrained flow rate of 1,110 bbl/h from Table 8, 5,000-foot-long pipeline case; corresponds with the *actual* number of hours that a tanker would have to pump, *not* the total number of scheduled delivery hours required to accumulate the indicated number of pumping hours.

(c) Equal to the preceding column divided by adjusted number of pumping hours available per system during subsequent period, i.e., 634.2 hours, rounded to next higher integer.

The revised total pumping times now become approximately equal and will be represented hereinafter as the largest value, 760 hours.

This derived information now may be combined with projectile penetration data displayed in Figure 6 and with the observations of the investigation of embedded plate behavior already noted. Figure 6 reflects a diversity of projectile penetration depths; this results from differences both in soil and in anchor configuration. For these reasons, a penetration of 12 feet, the minimum recorded and, therefore, the most conservative value, will be used for the purposes of this study as representative of the XM-50 anchors which restrain the tanker. Before proceeding, it also must be mentioned that projectile extraction occurs through a deep and shallow soil-failure mechanism, with creep occurring at more rapid rates when the projectile creeps toward the surface past a depth equal to four times its minimum dimension. This transition depth is the point where the soil-failure mechanism changes from deep to shallow; for the XM-50 anchor, the transition depth is 6 feet. A further conservative assumption now will be invoked whereby embedment of less than 6 feet will be equated with an unacceptably high creep rate; thus, a projectile's useful life, as considered here, is limited to the time it lies beneath 6 feet such that the creep rate is controlled by the deep failure mechanism. The total distance available for creep is then equal to the 12-foot initial embedment less the 6-foot upper limit, or 6 feet. The Bemben study cites a *maximum* allowable design cyclic creep rate of 0.01 ft/min for sand and a rate of 0.04 in./h for clay. Given 760 hours of loading on each embedded projectile, these rates would result in 456 feet of creep in sand and 2.53 feet in clay. Smaller creep rates are, therefore, essential for projectiles embedded in sand if total creep is limited to a maximum of 6 feet during 760 hours of loading; such a combination limits the creep rate to 0.0079 ft/h (0.0016 in./min).

The actual failure process is admittedly far more complex than presented here and imperfectly understood. What is known is that it requires less force to dislodge an embedded projectile which lies close to the surface than is required for one that is deeply embedded, ceteris paribus. This knowledge supports use of the assumption that the usable life of an embedded projectile is limited to the time it is embedded greater than 6 feet within a soil mass. A second increment of knowledge is that creep in sandy materials is more severe than creep in clays. Lastly, the Bemben study produced a consistent series of curves which relates creep rate in sandy material to the ratio of applied cyclic load, to static failure load (a quantity assumed equivalent to the full-scale extraction forces reflected in Figure 6), and to depth of embedment. Those curves associate a ratio of 0.45 with the allowable creep rate of 0.0016 in./min at an embedment depth equivalent to 6 feet. Thus, if the average extraction force of 90,000 pounds associated with the clay III region of Figure 6 (which corresponds to the current XM-50 anchor configuration) is considered representative of the static failure load, an appropriate working load for an embedded XM-50 projectile would be 40,000 pounds.

Knowledge regarding the complementary issue of mooring-load magnitude is no less well defined than is knowledge of the mechanism by which a plate embedded in a soil mass develops resistance to applied loads which vary with time. Curves are available in a number of reference works which purport to estimate the individual load contributions originating in wind, current, and wave action; however, the maximum mooring loads computed vary substantially as a function of which reference is used.[12] [13] Perhaps the most useful information on the subject of mooring loads is the data collected in June 1974, when an instrumented Multileg Tanker Mooring System held a 25,000-DWT tanker for a period of 30 hours.[14] The forces recorded in individual mooring lines during the test varied from zero to an unsustained high of 9,143 pounds, which was recorded during a single 10-minute period; more typical were values in the 2,000- to 4,000-pound range. Thus, the designer is faced with uncertainty on both sides of the problem: the mooring loads generated by a tanker of a given size subject to given environmental conditions and the resisting ability of plates embedded in a soil mass and acted upon by mooring loads of an aperiodic nature.

If the problem is now examined in its totality, it is apparent that the maximum mooring loads recorded under environmental conditions less than the maximum environmental conditions specified in the Mooring System Requirements Document are, admittedly, far less than the 40,000-pound, cyclic load which an embedded XM-50 could conservatively sustain for the duration of a 90-day hostility. However, any serious investigation of what level of performance could be expected must make explicit allowance for the inevitable lack of perfection associated with manmade devices and for the previously articulated lack of certainty regarding projectile behavior and the magnitude of tanker-induced forces. A reasonable failure model then must be proposed which embodies the available information.

If one refers to Figure 5, which depicts a complete operating system, and objectively examines the three constituent elements, it becomes readily apparent, for reasons already discussed, that the mooring is the most likely element to experience failures. The mooring itself consists of four explosively embedded anchors, each tethered to a passive surface buoy. Thus, the embedded anchor projectiles must be examined once again. Consider the case where a complete system has been emplaced and a tanker arrives and is secured in the mooring. At that point, the projectiles are embedded at their maximum depth within the ocean bottom soil mass. Once acted on by the tanker-generated mooring loads, the embedded anchors would begin to creep

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12 NAVFAC DM-26, *Design Manual: Harbor and Coastal Facilities*, Naval Facilities Engineering Command, July 1968.

13 Department of the Army Technical Manual TM 5-302, *Army Facilities Components Systems—Designs*, September 1973, Drawing 12-21.

14 G. Jastrab, *Development Test II (Engineering Phase) of Multileg Tanker Mooring System: Final Report*, Aberdeen Proving Ground, Maryland, August 1975.

along a line perpendicular to the axis of the applied load. In this case, the wire rope line, which emanates from the anchor, would be gradually drawn into the soil as it attempts to line up with the force which the surface buoy conveys between the tanker and the ocean bottom.

Given the depth of anchor embedment, it is improbable that the projectile would be extracted during the first 30-hour mission since this would mandate a creep rate greater than or equal to 0.4 ft/h, a rate which would require a force approximating static failure (90,000 pounds) and one unlikely to be generated by tankers of 25,000 DWT under any conditions comparable to those specified in the Mooring System Requirements Document. Of course, a failure resulting from some latent production defect could occur; however, tests conducted prior to initial acceptance could be reasonably expected to prevent this. Thus, failure during the first 30-hour mission is considered an impossible event for the purposes of this analysis. Failure during later missions is both possible and allowed on the grounds that creep may occur at more rapid rates than those predicted using Bemben's findings. The incomplete body of knowledge almost certainly assures the presence of heretofore unknown factors which may cause unexpected results. Since: (1) each mooring consists of four embedded projectiles; (2) each projectile resists mooring forces as determined by its position in the mooring array; and (3) the wind, current, and wave direction and intensity vary with time throughout each 30-hour mission, each projectile will creep at its own rate which varies instantaneously in response to each of the preceding factors. Thus, cumulative creep will vary from one projectile to another. If the hypothesized probability of failure for each anchor is plotted over time as in Figure 7, the probability of failure for each anchor is represented as a symmetrical function with each of the four functions offset from one another in appreciation of the consistently greater loads resisted by some of the projectiles. Of course, the delineation of individual days in the figure time axis is purely for purposes of illustration; for reasons already presented, this *does not* imply an actual quantified failure distribution for individual embedded projectiles. This difference originates in the patterns of prevailing winds and in the fixed relationship between the tanker axis and prevailing current. The four anchors shown are the original four; an endless series of individual curves should be visualized since as each projectile is pulled from the ocean bottom it would be replaced and the replacement would experience a similar probability of failure over time. If the individual probabilities are summed vertically and if the sum is plotted on the same axis, the result may be approximated by a horizontal line which initially rises only slightly faster than does the probability of anchor number 1 failing; the horizontal line has been extended to the left, where it terminates at midnight of day 6. The area under the line and to the left of anchor number 1 curve is an additional instance of the conservative assumptions contained herein; this is the case since the horizontal line signifies a failure rate considerably greater than that expected on the basis of the hypothesized failure mechanism.

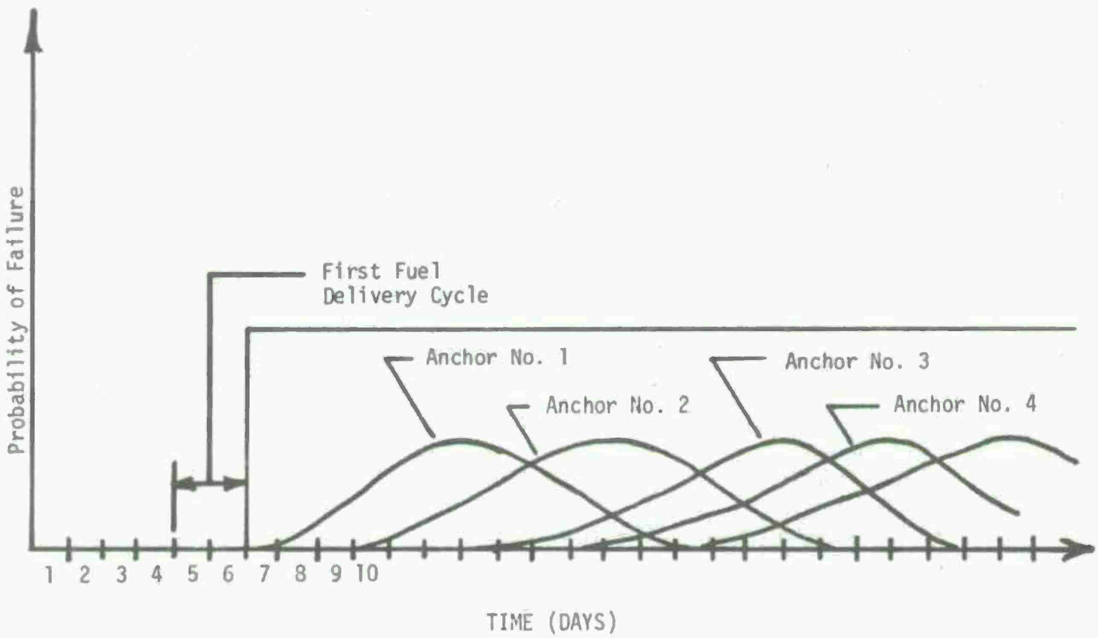

Figure 7. Hypothesized failure model.

In summary, the horizontal line of Figure 7 represents a constant failure rate, a characteristic of the exponential distribution; for reasons noted earlier, it permits failures only after midnight of day 6. It is now possible to discuss the impact which each projectile failure would have on the delivery cycle.

It already has been explicitly stated that each delivery begins at midnight and terminates at 0600 hours on the following day. The tanker will, therefore, moor during the hours of darkness and quite likely depart under the same conditions. This mode of operation is found wanting on pragmatic grounds; however, the value of the proposed model is not actually diminished. This position gains credibility if the reader views a variation of the problem which embodies the precise structure of the proposed model but which involves a linear time transformation whereby all events begin 8 hours later. Thus, while the proposed model incorporates deliveries beginning at midnight of day 4, its merits are not negated in any real manner if the actual delivery sequence begins 8 hours later, i.e., at 0800 hours, and ends 8 hours later, i.e., at 1400 hours the following day. A decision rule now may be introduced to further simplify the model while maintaining the level of conservatism already embodied in the analysis.

The beginning of each delivery period is rigidly scheduled as midnight of even numbered days, with departure rigidly scheduled at 0600 hours the following even numbered day, given that no failure occurred during the programed 30-hour mission. Should a failure occur, the tanker would depart immediately, terminating the mission prematurely. Approaching the problem in this manner casts the system in a less favorable light than if the model performed tanker scheduling on a more flexible basis; however, the consistent incorporation of a conservative bias is viewed here as a desirable approach. The final outcome of the study obviously will be sensitive to the assumptions made, and the use of explicit assumptions is unavoidable because uncertainty pervades the overall effort. If the assumptions are changed, the study findings will also change, varying between two boundary values: one representing consistent use of the most liberal assumptions and the second representing consistent use of the most conservative assumptions. The latter have been chosen in every case since they cause the predicted system performance to equal or closely approximate an absolute minimum value. The predicted performance, therefore, would gain credibility as a "good" estimator of actual performance, which would be expected to equal or exceed the predicted value.

This reasoning process leads to a series of 30 possible failure variations. In each instance, the model establishes if the mooring is operative during each hour of the planned 30-hour mission; if the answer is yes throughout, the delivery sequence would continue and the cumulative fuel delivery over time would coincide with that depicted in Figure 2. Should the model establish that a failure occurs during the second or a subsequent delivery cycle, pumping would terminate immediately, the tanker would depart, the failed anchor would be replaced, and the system would remain idle until the next scheduled delivery. The period from the time of the tanker's departure until its next scheduled arrival will vary from a maximum of 47 hours if failure occurs at the end of the 1st hour of pumping to a minimum of 18 hours if failure occurs at the end of the 30th hour of pumping. Since the actual replacement task may be easily completed within 4 hours, the mooring is assured of being operative well in advance of the next delivery. Figure 8 represents cumulative fuel delivered in the case where a failure occurs after 15 hours of pumping during the second delivery mission. The cumulative fuel volume actually delivered is observed to be less than the volume which would have been transferred under theoretically perfect conditions. The volume not conveyed as a direct result of the failure is found by measuring the vertical distance between the two curves. It should be noted that given the inflexible delivery schedule the gap will never decrease but will remain constant and then widen as subsequent failures occur.

One final issue requires attention before proceeding further. In the absence of failures, and hostile activity to the contrary, the three reserve objectives, i.e., 10, 20 and 30 days, could be reached on or about day 20, that is, well in advance of the previously espoused target date of midnight day 29. This occurs since only integer values of systems may be deployed, making it necessary to deploy more whole systems than the minimum number calculated arithmetically. The maximum fuel storage capability is identically equal to the day 29 cumulative contribution to reserve; three

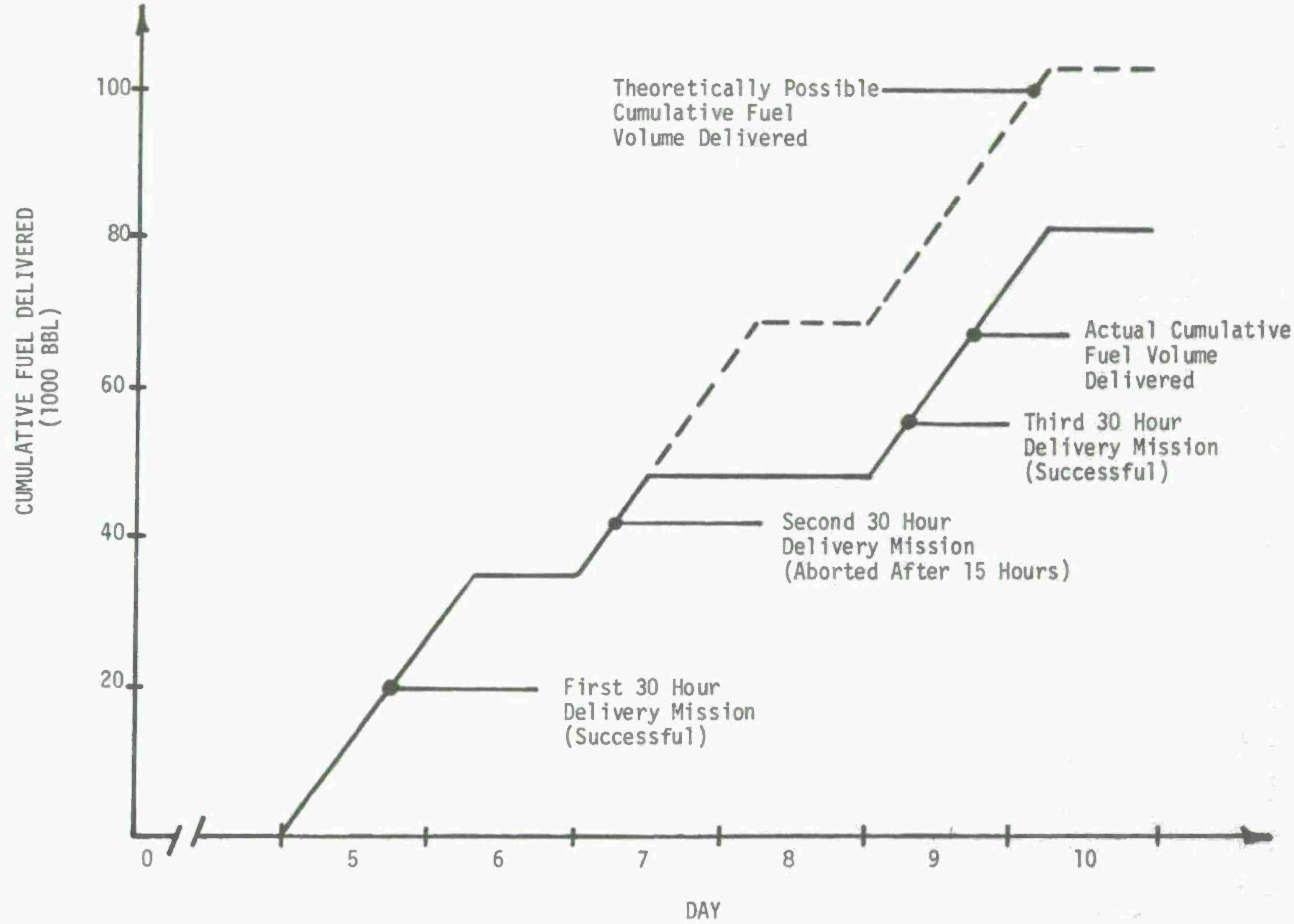

Figure 8. Delivery model with failure.

such values exist for the purposes here, i.e., the heavy corps, day 29 cumulative contribution to reserve for each of the three reserve objectives.

For example, the heavy corps, 10-day fuel reserve requirement is 286,022 barrels. Since storage capacity generally would be expected to be a limiting factor, the proposed model must continually monitor the magnitude of the fuel reserve, i.e., cumulative deliveries less cumulative consumption, and abort the fuel delivery mission *before* the fuel reserve exceeds the present reserve requirement, which is 286,022 barrels for the 10-day reserve objective case. Delivery is allowed to continue up to the point where the reserve would exceed its limit if pumping were to continue for one more hour. What remains is the problem of defining the demand which each system must accommodate.

Given that each system is nominally identical in every respect, that the operational mode and delivery capability of a system are accurately known, and that each system deployed is deployed along a sufficiently short length of coastline such that each is subject to the same environmental conditions, it becomes possible to allocate some fixed fraction of corps demand against each deployed system. Thus, if one assumes further that the number of systems actually deployed will coincide with the number required to satisfy the most demanding case, i.e., the 5000-foot-long pipeline, then the burden which each system must sustain is uniquely defined for the purpose of this study as are related parameters such as maximum fuel reserve which may be accumulated in the storage containers serviced by the mooring.

While it certainly would be naive to believe that each system will mimic every other system in minute detail, the belief that the composite of N systems will *on the average* behave similarly to N independent systems is not an unreasonable one. In like manner, the analysis also specifies the association of one pipeline with the specific storage containers which it services exclusively. The decision to examine one representative system rather than all deployed systems simplifies the analysis and introduces further conservative bias.

The first of the two consequences of the arithmetic allocation requires each system to function independently; whereas, in an actual hostility fuel delivered by adjacent pipelines would undoubtedly be interconnected. Such an arrangement would continue to supply the whole corps with fuel; whereas, this model would theoretically abort fuel delivery to those fractional corps which experienced failures while simultaneously fueling the remainder. The model is obviously less flexible than would be an actual series of systems operated by rational beings who would certainly revise prior decisions in response to changing conditions, a capability not bestowed on this model. The allocation of dedicated storage containers falls into this same category. A fuel reserve limitation will result in aborting fuel deliveries when the fractional reserve limit has been reached, even though adjacent fractional reserves may be well below their ceiling.

The parameters for the actual system under study now may be summarized explicitly and are found in Table 13. The table includes two different numbers for the initial period. The first coincides with the minimum number cited in Table 10 for a 5,000-foot-long pipeline, while the second is one more than the minimum. Both values are presented since the required availability rates for the minimum number of systems range from a low of 0.94 to a high of 0.99. Such elevated availability requirements may well be associated with physically unattainable system reliabilities, thus making it prudent to investigate both the minimum number *and* a slightly greater number of systems.

Table 13. Parameters for a Single System

No. of Systems		Daily Demand Per System (bbl/d)[b]		Maximum Allowable Fuel
Initial Period	Subsequent Period[a]	Initial Period	Subsequent Period	Reserve Per System (bbl)[c]
		10-Day Reserve		
5	4	6,386	7,982	57,204
6	4	5,321	7,982	47,670
		20-Day Reserve		
6	4	6,749	8,277	95,341
7	4	5,785	8,277	81,721
		30-Day Reserve		
8	4	6,442	8,317	107,258
9	4	5,726	8,317	95,341

(a) Four systems are reflected for the subsequent period instead of the three reflected in Table 12. This had been done because, even given perfect reliability, the theoretical delivery capability of three systems is only 3 percent greater than the cumulative consumption between day 30 and day 90. Thus, if any deliveries were aborted because of reaching the maximum allowable reserve, the actual fuel deliveries would fall below cumulative consumption.

(b) Demand is for the heavy corps (corps daily demand data from Table 2).

(c) Number of systems used in this context is the initial number of systems deployed; the reserve objective used is for the heavy corps (from Appendix A).

The essence of the proposed model now has been presented. The basic model combines the more demanding elements of the TRADOC scenarios with the scenario implied in the Mooring System Requirements Document. Once the use of a fuel reserve was cited, the fuel demand model follows directly from the TRADOC scenarios and reflects the changes in that demand over time as additional military units arrive in the objective area.

The fuel delivery model initially presented was subsequently adjusted to compensate for weather outside of the environmental envelope specified in the requirements document; the weather adjustment was administered in the form of monthly factors since a paucity of data prevents treatment of the day-to-day occurrence of favorable weather in a formal probabilistic sense. Lastly, the internal structure of the proposed model has been presented as have a number of decision rules which directs the model to depart from its fundamental, 48-hour cycle when certain events are sensed; the other decision rule precludes accumulation of a fuel reserve in excess of some prescribed volume. At this point, it is possible to proceed to the next issue, which is: How may the model be applied toward satisfaction of the previously articulated study objectives?

15. Analytical Methodology. The topic for discussion now moves to examination of the methodology selected for achievement of the study objectives; the simulation technique constitutes that methodology since it permits a relatively direct application of the system model toward satisfaction of those objectives.[15] [16] A computer program (Appendix B) has been formulated which embodies the problem structure as presented thus far; the formulation permits the researcher to assign values to key variables, thus allowing a systematic investigation of the nature and magnitude of the effects which operational changes and variations in physical factors would have on system performance.

Reliability is one key variable and already has been the subject of a rather detailed analysis. At that time, the conclusion was reached that mission failures would follow an exponential distribution. With that knowledge, we may use the simulation technique to investigate a theoretical system's performance as that performance is influenced by mission failures which occur at a rate corresponding to the prescribed failure distribution.

It is worthy of note at this time that the exponential distribution associates some small but finite probability to the undesirable event whereby failures occur during the first few hours of two or more sequential mooring missions. Should that happen, actual fuel delivery would be limited to only a few hours over a 4-, 6- or 8-day period; friendly forces would then draw their fuel almost exclusively from the fuel reserve stores during such a period since consumption would continue unabated (consumption being independent of delivery rate). In an analogous but antithetical manner, a given simulated, 90-day hostility may include few failures; such a simulation

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[15] F. Hiller and G. Lieberman, *Introduction to Operation Research*, Holden-Day, Inc., San Francisco, California, 1967, pp. 439-471.

[16] H. Wagner, *Principles of Management Science: With Applications to Executive Decisions*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1970, pp. 497-527.

would report numerous deliveries aborted because the maximum reserve limit was reached repeatedly.

In this context, system performance—or system effectiveness, terms used interchangeably here—is measured by the success with which fuel is provided to friendly forces. Thus, as long as a nonzero reserve exists, system performance is flawless for the purposes of this study. The actual magnitude of the fuel reserve at any instant is not considered relevant since the ability of friendly forces to carry on operations is primarily a function of the existence—not the size—of a fuel reserve; success or failure to deliver fuel during any single 30-hour delivery mission has only an indirect effect on operations. Since the presence of a fuel reserve serves to insulate the military commander from the vagaries of offshore climatology, one would intuitively associate increasing fuel reserve with an increase in system performance. This belief may be tested directly by using the computer to simulate a series of system deployments and for each simulation to count both the number of times the system *does not* perform as desired and the number of times the system performs so well that deliveries are aborted because the maximum fuel reserve level has been reached.

If system performance is exemplified by the uninterrupted availability of fuel, knowledge of its antithesis – fuel interruption – allows the researcher to measure the degree of its absence. Consider, for example, the case where: (1) a 10-day fuel reserve objective has been specified by the Commander; (2) five systems are deployed and utilized during the initial period; (3) only four of the five are used during the subsequent period; and (4) the researcher may freely vary the pipeline length – and, therefore, the flow rates – as well as the system reliability. A two-dimensional matrix may be constructed for use in recording the number of times when fuel on hand decreases to zero – hereinafter referred to as a fuel interruption and not to be confused with an aborted fuel delivery mission – for each discrete site within the matrix; the matrix worksheet employed to record the findings of such an effort is illustrated in Figure 9. The six system configurations selected for investigation and the demands and limitations associated with the six are among those listed in Table 10. Two cases – A and B – are included for each of the three reserve objectives. In each instance, case A corresponds with the minimum number of systems required to support a heavy corps during the initial period if fuel is conveyed through a 5,000-foot-long offshore pipeline. Case B corresponds with the use of one more system than the minimum during the initial period; this second case is of interest because of the extremely high minimum availability values associated with use of the minimum number of systems. Table 10 lists minimum availability values varying between 0.94 and 0.99 for case A and values for the minimum number varying between 0.78 and 0.85 for case B. In both instances, the number of systems left operative during the subsequent period is four because of reasons already discussed.

Pipeline Length (ft)	Initial Flow Rate (bbl/h)	Subsequent Flow Rate (bbl/h)	Average Number of Times (and Range of Times) Fuel Reserve Falls to Zero at Reliability R during a90-Day Operation								
			R=0.3	R=0.4	R=0.5	R=0.6	R=0.7	R=0.8	R=0.85	R=0.9	R=0.95
1,000	990	1,730									
2,000	700	1,230									
2,500	620	1,090									
3,000	570	1,000									
4,000	500	870									
5,000	440	780									

1. Reserve Objective = __________ Days.

2. Number of Systems Deployed During Initial Period = _______, During Subsequent Period = ________ .

3. Failures May Not Occur During Day 5 and Day 6; They May Occur Starting With The Beginning of the Second 30-Hour Mooring Mission, i.e., After Midnight of Day 6.

4. All Mooring Missions Will Consist of a Theoretically Possible 30 Hours of Pumping Time Followed by 18 Hours of Drawdown.

5. Initial Period Daily Demand = ________ bbl/d; Subsequent Period Daily Demand = ________ bbl/d.

6. Cutoff Limit For Fuel Reserve = ____________ bbl.

Figure 9. Matrix worksheet.

While destruction of fuel stores and interruption of scheduled deliveries as a direct result of hostile acts have been left to the reader's speculation thus far, that speculation is now invoked to consider the implications associated with minimum acceptable availabilities numerically close to unity. Recall the manner in which those availabilities were computed, i.e., the cumulative system demand divided by the cumulative system delivery capability. The values found then may be viewed as the fraction of the scheduled hours of delivery during which it is absolutely essential that delivery must actually occur if the initial period fuel demand is to be accommodated. For example, an availability of 0.98 indicates the necessity to deliver fuel for 88.2 hours of every 90 hours during which fuel delivery is scheduled. The difference, 1.8 hours in the example, is defined here as "slack"; the presence of slack allows hostile activity to interrupt fuel deliveries for a maximum of 1.8 hours in this hypothetical situation without influencing the System's ability to satisfy the fuel demand objectives. It must be remembered that anchor failures also must be absorbed within the slack if deliveries are to equal or exceed demand.

For the problem addressed in this study, use of four systems during the subsequent period acquires respectability if the reader notes the unreasonably small slack, i.e., 3 percent of the number of delivery hours scheduled during the subsequent period, which is associated with the three-system case. Similarly, the threat of hostile activity directed at the fuel reserve combined with the System's acknowledged physical imperfections also makes it intuitively questionable to endorse using the lesser number of systems associated with case A, even given the obvious desirability of procuring and operating fewer systems.

When the actual simulation for each specific combination of parametric constants investigated is run, the number of fuel interruptions is observed to vary considerably from one 90-day simulated hostility to the next. This result originates in the use of a probability distribution to describe failures rather than the use of a more direct approach of using only the failure distribution's mean to compute the expected number of interruptions. A series of 100 simulations, each series corresponding to a specific combination of the two system parameters, flow rate and reliability, has been employed throughout so that a comprehensive picture of overall effectiveness may be obtained. The 100 outcomes for each series offer ample opportunity for a broad range of numerical values to occur and for the mean to stabilize; the validity of this contention is supported by the near equivalency of separate runs of 100 simulations each which embody the same parametric constants.

16. Simulation Results. The raw output corresponding to the six system configurations delineated in Table 13 may be found in Appendix C, Tables C-1 through C-6. The tables list the average number of times the fuel reserve fell to zero during a 90-day period given the assigned values of parameters listed in each table; the tables also list the lowest and highest number of fuel interruptions which occurred for each specific case.

The average number of fuel interruptions for each series of 100 simulations was computed by summing the total number of times fuel reserve falls to zero and by dividing that sum by 100. For example, Table C-6 cites an average of 0.15 for the situation where a 5,000-foot-long pipeline is actually placed, given a system reliability of 0.95. In that particular instance, an examination of the actual simulation output established that the reserve: fell to zero one time in each of nine 90-day hostilities; fell to zero two times in each of three hostilities; and fell to zero in none of 88 hostilities. On the average, a fuel interruption would be expected to occur extremely infrequently even under the rigid conditions and circumstances adhered to throughout this analysis. The range of fuel interruptions cited in Appendix C was found through an examination of the simulation output corresponding to each series of 100 simulations. Figure 10 is representative of the output produced by the program.

The effort expended up until this point has been concentrated on: (1) development of a generic model, (2) application of that model to the system under examination, and (3) generation of a substantial mass of system effectiveness indicators obtained by simulating approximately 32,000 90-day hostilities. With this, the preliminary work is complete, its sole product being the six tables of simulation results found in Appendix C. Attention must now be directed toward the primary study objectives, the secondary objectives having been indirectly addressed during model formulation. The following section will present the methodology whereby the simulation output may be transformed into SV's and MAV's for the Multileg Tanker Mooring System.

17. **Establishment of SV's and MAV's.** The transformation of system effectiveness data into SV's and MAV's will depend upon first insuring that the meaning of the two terms in the context of this particular problem is the same to everyone reviewing this effort. It is then appropriate to first examine the formal definition of each term and the reasoning process by which each of the two formal definitions may be applied here.

> The specified value is defined as that value of good performance which will have a high probability of acceptance for development or operational test. The specified value will be determined considering operational requirements, technical capability, cost to develop and produce, and logistic requirements.[17]

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[17] U.S. Army Regulation AR 702-3, *Army Materiel Reliability, Availability, and Maintainability (RAM)*, 22 March 1973.

RESULTS OF MULTI-LEG MOORING SYSTEM SIMULATION

RELIABILITY IS .95 SAMPLING INTERVAL IS 1.00

NUMBER OF SIMULATIONS IS 100

PROBABILITY PER UNIT TIME FOR SYSTEM FAILURE .0017

PROBABILITY OF FAILURE DURING TIME INTERVAL DT .0017

THE DELIVERY RATE IS 440. 780.
THE DRAWDOWNS IN REDUCD DELIVERY CYCLE ARE 16 18
A FAILURE CANNOT OCCUR WITHIN THE FIRST 30. HOURS
THE MAXIMUM FUEL ON HAND IS 95341.0
THE CONSUMPTION RATE FOR FIRST 29 DAYS IS 5726.
THE CONSUMPTION RATE AFTER 29 DAYS IS 8317.

TOTALS PER SIMULATION

NUMBER OF FAILURES	NUMBER BELOW ZERO	NUMBER OF OVERFLOWS
2.00	0.00	19
2.00	0.00	20
2.00	0.00	20
1.00	0.00	21
0.00	0.00	21
1.00	0.00	19
1.00	0.00	17
3.00	0.00	17
4.00	0.00	12
2.00	0.00	16
5.00	0.00	15
3.00	0.00	15
2.00	0.00	17
3.00	0.00	18
3.00	0.00	19
1.00	0.00	19
2.00	0.00	16
1.00	0.00	20
3.00	0.00	16
4.00	0.00	16
1.00	0.00	19
1.00	0.00	21
3.00	0.00	17
2.00	0.00	17
3.00	0.00	17
3.00	1.00	14
4.00	1.00	18
2.00	0.00	18
1.00	0.00	20
4.00	0.00	15
4.00	0.00	16
2.00	1.00	19
1.00	0.00	21
1.00	0.00	21
0.00	0.00	21
1.00	0.00	19
5.00	1.00	16
2.00	1.00	19
2.00	0.00	18
1.00	0.00	20
2.00	0.00	19
1.00	0.00	20
3.00	0.00	13

Figure 10. Typical simulation output.

1.00	0.00	20
2.00	2.00	19
3.00	0.00	18
2.00	0.00	16
4.00	1.00	12
4.00	0.00	14
0.00	0.00	21
3.00	0.00	17
2.00	0.00	18
5.00	0.00	13
2.00	0.00	15
2.00	0.00	16
0.00	0.00	21
2.00	0.00	18
1.00	0.00	19
5.00	0.00	15
2.00	0.00	18
2.00	1.00	19
0.00	0.00	21
0.00	0.00	21
3.00	0.00	15
1.00	0.00	18
1.00	0.00	21
1.00	0.00	20
2.00	2.00	19
2.00	0.00	20
2.00	0.00	18
2.00	0.00	17
1.00	0.00	20
1.00	0.00	18
1.00	0.00	20
2.00	0.00	17
5.00	0.00	12
2.00	0.00	16
2.00	0.00	17
1.00	0.00	18
2.00	2.00	16
7.00	1.00	9
2.00	0.00	19
0.00	0.00	21
1.00	0.00	21
6.00	0.00	12
0.00	0.00	21
4.00	0.00	17
1.00	0.00	17
1.00	0.00	21
1.00	0.00	21
2.00	0.00	20
0.00	0.00	21
2.00	0.00	19
0.00	0.00	21
2.00	0.00	15
0.00	0.00	21
4.00	1.00	17
0.00	0.00	21
1.00	0.00	21
1.00	0.00	20

MEAN	2.02	.15
SD	1.46	.44

Figure 10. Typical simulation output (cont'd).

The system addressed in this study already exists and has been the subject of a lengthy and exhausting DT II/Operational Test II (DT II/OT II). The system requirements document[18] specifically mandates the use of explosive embedment anchors as the means to secure a tanker; other constraints, most notably the rapid installation rate and transportability requirements, effectively limit attention to the smaller of two sizes of embedment anchors. In effect, the specificity of the requirements document closely defines the ultimate system configuration and the identity of its component elements. In the absence of further R&D at the basic and exploratory research level, the system's performance is essentially as high as it may go.

From the very beginning, this study has equated operational requirements with an ability to satisfy the Commander's thirst for fuel; the ability to moor individual tankers for a 30-hour mission was purposely subordinated to the reliable fueling of friendly forces. Naturally, success of one is ultimately dependent on success of the other. Numerous uncontrollable factors have been presented and examined as this effort has progressed; the attendant uncertainty which is inherently linked to uncontrollable factors guarantees an occasional fuel interruption even if the system hardware exhibits near perfect reliability, an improbable situation.

The specified value is to be determined " . . . considering operational requirements, technical capability, cost to develop and produce, and logistical requirements."[19] Three of these factors have historical standing only, therefore forcing this effort to focus on the one remaining factor – operational requirements. The simulation produced predictions of how well one system of N homogeneous systems would meet the fuel requirements of a friendly force under specified conditions. In the sense that the SV must represent something close to a performance ceiling, this may be given operational meaning through its association with some small but acceptable number of fuel interruptions during a 90-day use. Since the value chosen also must be verifiable by some economically feasible test, the number of fuel interruptions, and, therefore, the number of anchor failures, generally must be nonzero.

The proposed criterion differentiates between pragmatically infeasible and feasible values by loosely defining an indicated 1.00 or fewer fuel interruptions as the boundary between feasible and infeasible. From the Appendix C tables, it is found that two fuel interruption values adjoin the boundary; the smaller of the two – which will always be less than or equal to 1 – is hereby defined as the lower feasible limit for fuel interruptions. Asking the question, "How effective should the system be?" is certain to solicit the reply, "As good as possible." Unfortunately, such a reply is

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[18] Letter, U.S. Army Combat Developments Command, Subject: *Revised Department of the Army Approved Qualitative Materiel Requirement (QMR) for Multileg Tanker Mooring System*, 1 November 1972.

[19] U.S. Army Regulation AR 702-3, *Army Materiel Reliability, Availability, and Maintainability (RAM)*, 22 March 1973.

observed to possess little operational meaning. The proposed criterion accepts the virtual inevitability of an occasional failure to meet performance expectations but seeks to limit the occurrence to fewer than one failure during a 90-day hostility. It must be further recognized that: (1) the model consistently opted for conservative assumptions when a choice was necessary; (2) the model is exceptionally rigid in a number of instances; (3) at the higher levels of reliability, i.e., 0.9 or more, the expected number of fuel interruptions is invariably less than the limiting value of 1, with a substantial number being less than 0.2; and (4) in an actual operation, adjacent individual systems would not be separated by an impenetrable boundary as exists here but would be physically interconnected by pipe or hose or would at the least possess the ability to transfer fuel laterally between adjacent systems using tank trucks or helicopter transported drums. Thus, for the reasons articulated, it becomes readily apparent that the *actual* number of fuel interruptions during a single hostility would be less than the number of interruptions predicted by the model. It may, therefore, be implied that a fuel interruption would be expected only every second, third, or fourth 90-day hostility, given reliability values at least equal to the SV's defined in accordance with the proposed criterion.

Each of the six tables in Appendix C includes a solid line which divides the economically/pragmatically feasible values – those to the lower left of the line – from the infeasible values – those to the upper right. The largest reliability adjoining the feasible/infeasible boundary for each pipeline length (the value immediately to the right of the solid line) is the SV. The results obtained in this manner are summarized in Table 14.

Table 14. Specified Values

Pipeline Length (ft)	Case A Fuel Reserve Objective[a]			Case B Fuel Reserve Objective[b]		
	10-Day	20-Day	30-Day	10-Day	20-Day	30-Day
1,000	0.3	0.3	0.3	0.3	0.3	0.3
2,000	0.5	0.6	0.5	0.4	0.5	0.4
2,500	0.6	0.7	0.7	0.5	0.6	0.6
3,000	0.7	0.8	0.8	0.6	0.6	0.6
4,000	0.8	0.9	0.8	0.7	0.8	0.8
5,000	0.95	0.95	0.95	0.8	0.85	0.85

(a) The absolute minimum number of systems required to service a heavy corps during the initial period through a 5,000-foot-pipeline with four systems used during the subsequent period in all cases; e.g., for the 10-day reserve case, five systems are used during the initial period and four during the subsequent period (see Table 13).

(b) Reflects use of one more system during the initial period than in the preceding case and four systems during the subsequent period in all cases.

The MAV, which represents a performance floor, must be examined, and a process must be established to derive numerical values.[20]

> Minimum acceptable value is defined as that value which represents the least operational capability the user can tolerate. It represents a level of marginal performance, below which the item is unacceptable, and will have a small probability of acceptance during test.[21]

Establishment of MAV's, then, hinges on differentiating between acceptable and unacceptable levels of system performance. While admittedly judgmental, the boundary between acceptable and unacceptable is defined here as 3.00 fuel interruptions during each 90-day hostility. This criterion implies that, on the average, a marginal but acceptable system could experience a maximum of 1 fuel interruption during each month of operation. For the reasons cited during the discussion relating to SV's, the numerical quantity 3.00 must not be construed as a precise numerical prediction of fuel interruptions but only as a pessimistic (high) estimate of interruptions, given the conservative assumptions and inflexible operating rules embodied in the model which produced the interruption data.

Each of the six tables in Appendix C includes a dashed line which divides the marginal but acceptable values – those to the upper right of the line – from the unacceptable values – those to the lower left. The largest reliability value adjoining the dashed-line boundary for each pipeline length – the value immediately to the right of the dashed line – is the MAV. The results obtained through application of these criteria are summarized in Table 15.

The proposed acceptability criteria were derived through an admittedly heuristic process, but this does not diminish their utility. Selection of an average number of fuel interruptions equal to 1 is judged both responsive to a Commander's desire for absolute assurance of fuel supplies and to an awareness that reasonable men could never promise an absolute assurance of fuel given an operational environment of the type described herein, nor for any actual one for that matter. In like manner, while a larger number than three fuel interruptions could be proposed and supported with much the same argument, one forecast fuel interruption each month appears to constitute a middle ground fully in keeping with the spirit of the Army Materiel Command (AMC), Alexandria, Virginia, and TRADOC policy governing the establishment of RAM requirements.

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20 Memorandum of Agreement between U.S. Army Materiel Command and U.S. Army Training and Doctrine Command, dated 16 May 1974, on the subject of establishing and assessing reliability, availability, and maintainability (RAM) requirements.

21 U.S. Army Regulation AR 702-3, *Army Materiel Reliability, Availability, and Maintainability (RAM)*, 22 March 1973.

Table 15. Minimum Acceptable Values

Pipeline Length (ft)	Case A Fuel Reserve Objective[a] 10-Day	20-Day	30-Day	Case B Fuel Reserve Objective[b] 10-Day	20-Day	30-Day
1,000	0.3	0.3	0.3	0.3	0.3	0.3
2,000	0.4	0.4	0.4	0.3	0.3	0.3
2,500	0.5	0.5	0.5	0.4	0.4	0.4
3,000	0.5	0.6	0.6	0.6	0.5	0.5
4,000	0.7	0.7	0.7	0.7	0.6	0.6
5,000	0.8	0.85	0.8	0.85	0.7	0.7

(a) The absolute minimum number of systems required to service a heavy corps during the initial period through a 5,000-foot pipeline with four systems used during the subsequent period in all cases; e.g., for the 10-day reserve case, five systems are used during the initial period and four during the subsequent period (see Table 13).

(b) Reflects use of one more system during the initial period than in the preceding case and four systems during the subsequent period in all cases.

Once again, it should be noted that the number of fuel interruptions forecast by the simulation model is numerically larger than the *actual* number which would occur – but by some unknown factor. Thus, an actual system, with a mission reliability equal to a derived MAV, would physically outperform the model's forecast. For this same reason, an actual system would meet the permissible three-fuel-interruption criterion even though such a system possessed a reliability numerically lower than the MAV which the system model associates with the three-interruption case.

This acceptance of less-than-perfect performance is the direct consequence of the numerous factors identified as being relevant to this problem. Most of the factors have been accommodated deterministically – a procedure which admittedly lacks purity when dealing with factors which may take on many values – as the study has evolved, and one – reliability – has been treated probabilistically. Nonetheless, much latitude has been present while dealing with virtually every variable, and that latitude must logically lead to uncertainty in the numerical results. That uncertainty has been bounded in this study by consistently choosing conservatism throughout.

The numerical values reflected in Tables 14 and 15 now may be examined and interpreted in light of the earlier discussion. Both the SV's and the MAV's are clearly observed to increase with increasing pipeline length; however, the relationship between the SV and the reserve objective and between the MAV and reserve objective appears weak at best. A multiple linear regression analysis was performed for the four groups of data consisting of the SV's and MAV's for cases A and B in an attempt to further examine the nature and strength of the various relationships.

A stepwise regression routine was employed which systematically identifies the strongest relationship present in the data.[22] The routine also provides coefficients for a linear equation of the form:

$$y = \alpha_0 + \alpha_1 x_1 + \alpha_2 x_2, \qquad (4)$$

where:
- y is the SV or MAV,
- x_1 is the reserve objective in days,
- x_2 is the pipeline length in feet,
- α_0 is a constant, and
- α_1, α_2 are linear regression coefficients.

If the y-variable correlates strongly with one x-variable and weakly with the other, equation 4 may be rewritten in simplified form.

$$y = \alpha_0 + \alpha_i x_i; i = 1,2. \qquad (5)$$

In such an event, equation 5 would account for the observed variations in the y-term equally as well as the more complex equation 4. The strength of the relationship may be computed mathematically and is generally referred to as the multiple R^2, values of which are listed in Table 16. The multiple R^2 represents the proportion of the variation in y which is accounted for by the expression on the right side of equations 4 or 5.

Table 16. Relative Strength of Reserve Objective and Pipeline Length as Potential Predictors of SV's and MAV's

Dependent Variable (y)	Explanatory Variables (x_1 & x_2)*	Multiple R^2	Increase In Multiple R^2
SV–Case A	Length	0.9043	0.9043
	Length & Res Obj	0.9083	0.0040
SV–Case B	Length	0.9401	0.9401
	Length & Res Obj	0.9485	0.0084
MAV–Case A	Length	0.9796	0.9796
	Length & Res Obj	0.9812	0.0015
MAV–Case B	Length	0.8882	0.8882
	Length & Res Obj	0.9072	0.0189

* The explanatory variables are listed in decreasing order of their utility in accounting for variations in the dependent variable y.

[22] W. Dixon, ed., *BMD: Biomedical Computer Programs*, University of California Press, Berkely, California, 1973, pp. 305-330.

It is readily observable from Table 16 that the x_2 variable, i.e., pipeline length, has been consistently selected as the first variable to be examined, a reflection of its strength in accounting for variations in SV's and MAV's. It may be further observed that when both x-variables are used the increased proportion of the y-variation accounted for as a result of its use is quite small, actually varying from a low of 0.0015 to a meager high of 0.0189. Before proceeding, it is interesting to note that the increased R^2 obtained through introduction of the reserve objective variable is considerably higher for the case B's than for the corresponding case A's, an observation which cannot be explained at this time. It is now appropriate to present the four regression equations derived from the data of Tables 14 and 15:

SV–Case A: $$y_1 = 0.18333 + \underset{(0.00206)}{0.00167\, x_1} + \underset{(0.00001)}{0.00016\, x_2} \quad (6)$$

SV–Case B: $$y_2 = 0.13929 + \underset{(0.00133)}{0.00208\, x_1} + \underset{(0.00001)}{0.00014\, x_2} \quad (7)$$

MAV–Case A: $$y_3 = 0.14286 + \underset{(0.00076)}{0.00083\, x_1} + \underset{(0.00000)}{0.00013\, x_2} \quad (8)$$

MAV–Case B: $$y_4 = 0.17976 - \underset{(0.00167)}{0.00292\, x_1} + \underset{(0.00001)}{0.00013\, x_2} \quad (9)$$

Below each α_1 and α_2 regression coefficient will be found a number in parenthesis; that number is the standard error for the corresponding coefficient. It may be observed that in all four equations the standard error is numerically close to the α_1 coefficient – reserve; whereas, the standard errors associated with the α_2 coefficients are consistently different by an order of magnitude. This leads to the conclusion that the α_1 coefficients do not significantly differ from zero; thus, equations 6 through 9 should be rewritten in terms of two rather than three variables. The four new equations, which have revised coefficients computed exclusively from the y and x_2 data, plus their corresponding multiple R^2 values are as follows:

SV–Case A: $$y_1 = 0.21667 + \underset{(0.00001)}{0.00016\, x_2}\,;\; R^2 = 0.9043 \quad (10)$$

SV–Case B: $$y_2 = 0.18095 + \underset{(0.00001)}{0.00014\, x_2}\,;\; R^2 = 0.9401 \quad (11)$$

MAV–Case A: $$y_3 = 0.15952 + \underset{(0.00000)}{0.00013\, x_2}\,;\; R^2 = 0.9796 \quad (12)$$

MAV–Case B: $$y_4 = 0.12143 + \underset{(0.00001)}{0.00013\, x_2}\,;\; R^2 = 0.8882 \quad (13)$$

Equations 10 through 13 may be used to estimate the SV's and MAV's appropriate for an offshore pipeline of any length within the 1,000- to 5,000-foot range, given any fuel reserve objective within the 10- to 30-day range employed in the model. The reader is cautioned against yielding to the temptation of using the equations to predict SV's and MAV's outside the range of pipeline lengths and reserve objectives actually investigated in this study. The results obtained under such conditions will probably depart from reality to a substantial degree; this is a risk associated with extrapolating potentially nonlinear functions using a linear approximation. Though the four regression equations account for 89 to 98 percent[23] of the variations in y, this excellent predictive ability is almost certain to fade quickly as one extrapolates farther and farther outside the range of variables actually investigated. A number of other relationships now may be investigated in anticipation of obtaining a fuller comprehension of the factors which influence the operation of the mooring and unloading line.

A substantial portion, i.e., 95 percent, of the total variation in the six SV's corresponding to the 5,000-foot pipeline length is accounted for in the relationship between the SV's and the required daily delivery rates per system during the initial period; the latter values are found in Table 10. While the consistency of the relationship was examined for only a small portion of the available observations, this relationship would be expected to prevail throughout, a position supported through visual examination. Another way of stating the preceding is that two linear expressions may be written which predict the SV: the first in terms of the pipeline length and the second in terms of the required daily delivery rate per system. In both cases, the predicted SV's would be excellent estimators of the SV's obtained from the simulation.

The presence of two parallel relationships is logically pleasing since the fuel demand allocated to each system is based on the number of systems required if a 5,000-foot-long pipeline is used. Thus, a system with a pipeline shorter than 5,000 feet faces the same demands as does a system with a 5,000-foot line; however, shorter lines possess a greater throughput capability than the comparable capability of a 5,000-foot line. This increased throughput capability permits systems with lines shorter than 5,000 feet to restore their fuel reserve levels much more quickly after a failure, or series of failures, than could a system with the longer, 5,000-foot, line.

A final examination of information previously acquired discloses that a correlation of + 0.9995 exists between the minimum acceptable availabilities (MAA) and the expected number of fuel interruptions given a 5,000-foot pipeline and the corresponding specified values. The actual numerical values for the two variables corresponding to the six system configurations examined are summarized in Table 17.

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[23] Percent is found by multiplying the multiple R^2 values by 100.

Table 17. Minimum Acceptable Availabilities and Expected Fuel Interruptions

Reserve Objective (days)	Minimum Acceptable Availability[a]			Expected Number of Fuel Interruptions[b]		
	Case A	Case B	Avg	Case A	Case B	Avg
10	0.94	0.78	0.86	0.42	0.67	0.55
20	0.99	0.85	0.92	0.68	0.88	0.78
30	0.95	0.84	0.90	0.58	0.83	0.71

(a) Availability as used throughout this study is defined as total cumulative demand during the initial period (from demand models) divided by the constrained cumulative throughput of all the deployed systems (constrained cumulative throughput for one system (Table 9) times the number of systems). These values were first presented in Table 10.

(b) From Appendix C, the number of fuel interruptions given a 5,000-foot-long pipeline *and* the SV's listed in Table 14.

With this, the investigative portions of the study have been completed. The conclusions which follow will address the system configurations which best service the various situations. The derived SV's and MAV's also will be presented and discussed in relation to the system requirements document. Lastly, generalizations distilled from this study of offshore moorings and unloading lines as a generic class of system will be outlined as will areas worthy of future study.

VI. SUMMARY AND CONCLUSIONS

18. **Summary and Conclusions.** The effort expended thus far has consisted of formulating a mathematical model for a logistical system comprising a mooring, unloading, and conveying means. The system is one intended to transport liquid products – fuel in this specific instance – from a point offshore to a point onshore. The model's structure permits the specification of demand rates and a number of variables which modify the supply rates; once an appropriate failure distribution has been identified, the model also accommodates the physical imperfections invariably associated with manmade systems.

The primary study objective articulated at the very beginning of this work was establishment of SV's and MAV's; the mathematical model was formulated expressly to fulfill that objective. Single-system capabilities were investigated as was the impact which various fuel reserve philosophies had on the number of systems required. It eventually became possible to establish how many systems were required to accommodate the fuel consumption needs of light and heavy corps whose deployment and operation are described in two TRADOC-approved senarios. Six separate cases, which embodied a suitable mixture of characteristics, were identified and investigated in detail using the model; the six are listed in Table 13. Fuel reserve objectives of 10, 20, and 30 days are reflected in the six cases, as are six pipelines ranging from 1,000 to

5,000 feet in length.

Through this mechanism, it was subsequently determined that the predicted number of fuel interruptions varied little, if any, regardless of whether a 10-, 20-, or 30-day fuel reserve objective was specified. This observation combined with the knowledge that implementation of a 30-day reserve objective would require three more systems than would implementation of the lesser 10-day objective clearly identified the preferable alternative. Attention is, therefore, focused on two of the original six candidate system designs selected for investigation. Choosing between the two remaining designs is also straightforward, with case B (six systems) favored over case A (five systems); the slight cost increase associated with the choice of case B is mitigated by the observed reduction in SV's and MAV's obtained through the use of one system more than the theoretical minimum. While representing a qualitative consideration, case B also merits attention if hostile forces are considered capable of posing a threat to friendly fuel reserves. Given the preceding and the residual uncertainty inherent in the basic problem, endorsement of the slightly more expensive case B design would appear prudent. The optimal fuel delivery system configuration appropriate for a heavy corps now has been firmly established on the basis of a rigorous analysis; that configuration is illustrated in Figure 11.

The numerical SV's and MAV's sought from the outset now may be computed from equations 11 and 13, respectively; the results of such computations are listed in Table 18.

Table 18. System SV's and MAV's

Pipeline Length (ft)	SV	MAV
1,000	0.32	0.25
2,000	0.46	0.38
2,500	0.53	0.45
3,000	0.60	0.51
4,000	0.74	0.64
5,000	0.88	0.77

The second objective articulated was the study of offshore moorings and unloading lines as a generic class; this objective was pursued in hope of identifying general characteristics of such systems. This parallel effort was possible and in fact complementary since the process of model formulation necessarily addresses and renders explicit many of the factors peculiar to such systems. A number of conclusions was reached, some of which have application to the current system; others merit attention because of their utility in focusing attention on variables which might otherwise be ignored. The observations reflected in the remainder of this section summarize obser-

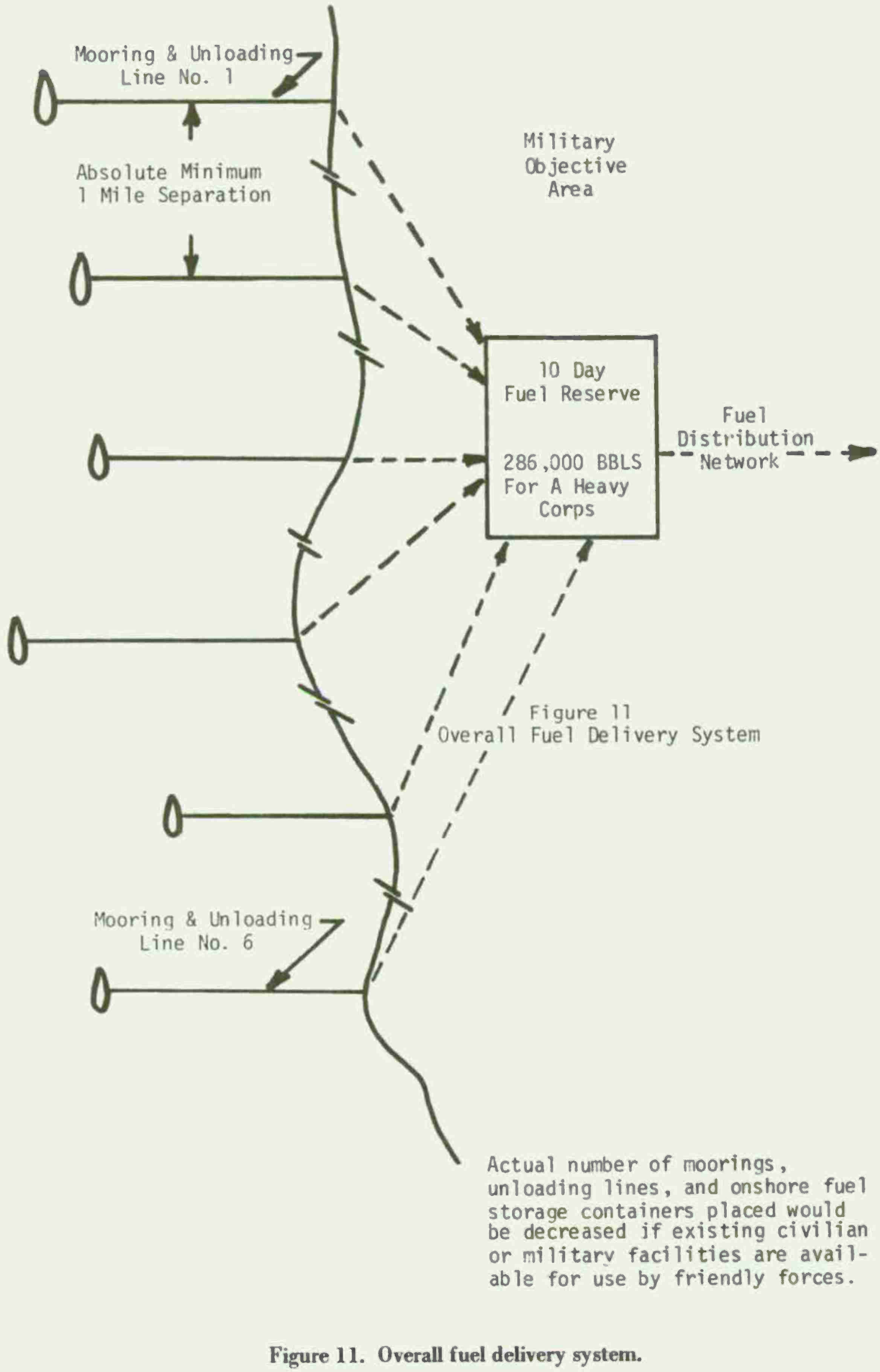

Figure 11. Overall fuel delivery system.

vations made as the study progressed; they generally follow the order in which the same or related topics originally appear.

One primary difference between the hybrid scenario developed and the two TRADOC scenarios is the imposition of the requirement that all fuel deliveries must be conveyed through Multileg Tanker Mooring Systems. Just as the TRADOC scenarios abstract the problem of conveying fuel from ship to shore by postulating the existence of suitable and available facilities which are not subject to unfavorable weather, the hybrid scenario excludes any such facilities. Actually, a given situation may involve both existing moorings and unloading lines *and* Multileg Tanker Mooring Systems, each with their respective strengths and weaknesses. Existing systems might be reasonably expected in the vicinity of commercial ports; such ports are generally sited in protected reaches of coastline where they automatically shield moored vessels from adverse weather. In such cases, average flow rates would be greater than comparable rates recorded at a facility off an undeveloped portion of coast; a vessel moored in the latter location generally would be afforded little protection from wind-, wave-, and current-induced mooring forces.

Very early in the analysis it was determined that if a fuel reserve was to be accumulated the deployed fuel delivery resources would be placed under greater stress during the initial period than during the subsequent period. This situation arises directly from the need to convey a volume of fuel during the initial period which is equivalent to the summation of fuel consumption plus a contribution to reserve; a volume equivalent to consumption alone must be conveyed during the subsequent period.

A further observation is that a larger number of tankers, i.e., six, would be required to fuel the heavy corps during the initial period, with four tankers required during the subsequent period. A change in composition of each system, i.e., association of one mooring with two unloading lines, would halve the required number of tankers. This is so since the unloading line throughput capacity is the "limiting bottleneck" in the system as it currently exists. The tanker's pumps are theoretically capable of discharging at a 24,000 bbl/h rate if suitable unloading lines are available. Therefore, it becomes readily apparent that the unloading line associated with virtually any military mooring will always limit the flow to a rate far below the theoretically possible rate; one possible means of increasing the fuel delivery throughput from each mooring placed would be the use of multiple pipelines of a size compatible with rapid movement and placement. Of course, it must be acknowledged that upgrading the present system from one to two unloading lines could not be accomplished summarily; such a major change in system configuration could be introduced only after an extensive modification, test, and evaluation effort.

A second modification of merit also presents itself, and that is reduction of the unloading line's internal friction factor by the application of an internal coating to the pipe at the time of its procurement. These two changes, while not feasible at this particular moment, would do much to reduce the fuel delivery bottleneck, thereby leading to a reduction in the number of tankers and systems otherwise required.

Weather was identified as a factor with a major role in establishing how many systems were required to support the postulated friendly force. It is pointed out that the conclusions drawn regarding the required number of systems are predicated on the mooring being available 40 percent of the time during the initial period and 70 percent during the subsequent period as far as weather is concerned; physical failures would naturally preclude use of the mooring from time to time regardless of weather. Should the hypothetical friendly force be deployed to a region where seastate 3 or greater occurs more than 60 percent of the time during the first month or more than 30 percent during the second and third months, it would be necessary to deploy greater numbers of mooring systems than the numbers presented herein; in both instances, performance is assumed to be maintained at equivalent levels. Conversely, if a region was subject to seastate 3 or greater less frequently than the occurrence rates used here, fewer systems would be required to sustain performance.

The number of systems required could be reduced if the mooring could accommodate a tanker in seastates up to 3 vis-à-vis the present seastate-2 capability. This would increase the mooring's actual availability – in terms of weather – from an estimated 40 percent to approximately 55 percent of the time during the worst month of the year; weather-derived availability on an annual average would be increased from between 50 and 65 percent of the time to 85 percent of the time as a result. The increased theoretical throughput would make it possible to deploy fewer systems with a commensurate savings in cost and engineer resources.

While not specifically addressed in this study, the physical characteristics of numerous landing beaches from throughout the world have been subjected to statistical analyses.[24] [25] Landing beaches are reaches of coastline identified as nominally suitable for amphibious operations; the physical characteristics which make a coastline amenable to amphibious operations, e.g., relative absence of offshore and onshore obstructions, suitable offshore gradient (not flat), and onshore trafficability, are closely coincident with the characteristics sought when selecting a site for a mooring and unloading system. This apparent digression becomes relevant when the question is asked: How often will a tanker be able to approach within 5,000 feet of shore as required if it is to unload its cargo given use of the Multileg Tanker Mooring System or the navy-developed buoyant hoselines and submarine pipelines?

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[24] D. P. Scott, *Statistical Properties of Assault Land Beaches,* Report C2892, Naval Ship Research and Development Laboratory, Panama City, Florida, January 1969, p. 281.

[25] F. Cevasco, *Landing Beach Study,* U.S. Army Mobility Equipment Research and Development Center, Fort Belvoir, Virginia, Unpublished Report.

If tankers of 25,000 DWT or larger are used to deliver fuel to friendly forces, water depths of approximately 42 feet will be required for safe operation. A pipeline 5,000 feet long would extend to water of the necessary depth only approximately 66 percent of the time. A capability to place pipelines further than 5,000 feet offshore would result in such a system being capable of servicing an increased percentage of sites which are suitable on the basis of all criteria other than gradient. However, it must be noted that each unit increase in length will return a smaller percent increase in landing beaches potentially serviceable than does the preceding unit increase – the diminishing-return phenomenon.

It should be further acknowledged that the 25,000-DWT tanker, while it is the maximum size which the Multileg Tanker Mooring System may safely accommodate, is also the smallest size tanker which the MSC will provide. The mooring could handle slightly larger tankers which are partially loaded; however, the preferable approach is development of a second generation mooring which trades off some of the transportability characteristics of the present system in exchange for an ability to moor tankers of larger size under more demanding sea conditions.

Further improvements in system effectiveness – a proxy variable for mission reliability and, in this case, also a proxy variable for explosive anchor performance – depend primarily on the acquisition of additional knowledge of explosive anchor performance and on the physical parameters which affect that performance. Additional research efforts would be expected to benefit both the current system and any future military system which employs explosive anchor technology.

Effectiveness of the Multileg Tanker Mooring System could be improved by substituting the larger XM-200 explosive anchor for the smaller XM-50 actually used. This occurs since the larger anchor's static failure load is at least twice the static failure load of the smaller XM-50. Given that we would have the same induced mooring loads and a doubled static failure load should the XM-200 anchor be used, the ratio of the mooring load to the static failure load, would be smaller in magnitude than would the comparable ratio for the XM-50. Using Bemben's findings, which relate that ratio to projectile creep rate, it is concluded that use of the XM-200 in this application would increase the mission reliability. In defense, it must be noted that such a possibility was seriously considered during the early phases of development and rejected because of the rigorous transportability requirements. A second reason for rejection was the minimal resources available to the military organization charged with responsibility to place the system; future development programs may permit such an approach.

System effectiveness depends on anchor performance, which in large part depends on soil type (see Figure 6). Thus, a system with a short pipeline may perform adequately if the anchors are in mud but only at the expense of replacing numerous anchors which fail. It would, therefore, be desirable to derive new expressions for SV's and MAV's which include two explanatory variables, i.e., pipeline length and a second variable representing soil property.

While knowledge of explosive anchors is poor for static loading conditions, present knowledge of performance under dynamic conditions is primitive at best. An expanded knowledge of dynamic behavior would do much to dispell the uncertainty which pervades any attempt such as this one to predict or plan the configuration of offshore systems responsive to rapidly changing military requirements; this same factor prevents widespread commercial application.

As also noted in the study, the accuracy with which the time history of mooring loads applied by tankers may be predicted also leaves much to be desired. The utility of obtaining mathematical models and actual data for multileg moorings is admittedly questionable; however, it would be appropriate to investigate the existence of models which describe advanced moorings of the single-leg type. This latter class of mooring would have to be chosen if tankers greater than 25,000 DWT are to be held reliably in a seastate 3.

While not given explicit attention, the onshore effort necessary to erect storage containers will be extremely demanding. The combination of offshore/onshore work dedicated to fuel delivery and storage will involve substantial sums as well as considerable engineer resources. Reduction of fuel reserve objectives to the lowest adequate levels would do much to ameliorate the high cost and extensive personnel requirements associated with the provision of such facilities. With this, the study is complete having answered the questions posed at its initiation. However, it must be noted that the study has also surfaced a number of related issues which warrant further investigation, a situation not uncommon when complex systems embodying numerous variables are studied.

APPENDIX A

FUEL CONSUMPTION AND FUEL DEMAND DATA

Table A-1. Daily Consumption–Light Corps

Day	Army Daily Consumption (gal/d)	Army Daily Consumption (bbl/d)	AF Daily Consumption (gal/d)	AF Daily Consumption (bbl/d)	Total Daily Consumption (gal/d)	Total Daily Consumption (bbl/d)
1	165,184	3,933	372,825	8,877	538,009	12,810
2	"	"	"	"	"	"
3	"	"	"	"	"	"
4	"	"	"	"	"	"
5	"	"	"	"	"	"
6	"	"	368,626	8,777	533,810	12,709
7	"	"	"	"	"	"
8	"	"	"	"	"	"
9	"	"	"	"	"	"
10	370,704	8,826	"	"	739,330	17,603
11	"	"	"	"	"	"
12	"	"	"	"	"	"
13	"	"	"	"	"	"
14	"	"	"	"	"	"
15	497,723	11,851	"	"	866,349	20,627
16	"	"	"	"	"	"
17	"	"	"	"	"	"
18	"	"	"	"	"	"
19	"	"	"	"	"	"
20	"	"	"	"	"	"
21	"	"	"	"	"	"
22	"	"	"	"	"	"
23	754,757	17,970	"	"	1,123,383	26,747
24	"	"	"	"	"	"
25	"	"	"	"	"	"
26	"	"	"	"	"	"
27	"	"	"	"	"	"
28	"	"	"	"	"	"
29	"	"	"	"	"	"
30	"	"	"	"	"	"
31	"	"	335,957	7,999	1,090,714	25,969
32	"	"	"	"	"	"
33	"	"	"	"	"	"
34 through 44	829,554	19,751	"	"	1,165,511	27,750
45 through 90	918,988	21,881	"	"	1,254,945	29,880

Table A-2. Daily Consumption—Heavy Corps

Day	Army Daily Consumption (gal/d)	Army Daily Consumption (bbl/d)	AF Daily Consumption (gal/d)	AF Daily Consumption (bbl/d)	Total Daily Consumption (gal/d)	Total Daily Consumption (bbl/d)
1	0	0	372,825	8,877	372,825	8,877
2	0	0	"	"	"	"
3	0	0	"	"	"	"
4	4,030	96	"	"	376,855	8,973
5	"	"	"	"	"	"
6	20,544	489	368,626	8,777	389,170	9,266
7	80,721	1,922	"	"	449,347	10,698
8	"	"	"	"	"	"
9	"	"	"	"	"	"
10	154,654	3,682	"	"	523,280	12,459
11	"	"	"	"	"	"
12	"	"	"	"	"	"
13	"	"	"	"	"	"
14	"	"	"	"	"	"
15	354,474	8,440	"	"	723,100	17,217
16	"	"	"	"	"	"
17	"	"	"	"	"	"
18	"	"	"	"	"	"
19	450,158	10,718	"	"	818,784	19,495
20	466,514	11,108	"	"	835,140	19,884
21	"	"	"	"	"	"
22	"	"	"	"	"	"
23	"	"	"	"	"	"
24	"	"	"	"	"	"
25	607,969	14,476	"	"	976,595	23,252
26	"	"	"	"	"	"
27	"	"	"	"	"	"
28	607,939	14,475	"	"	976,565	23,251
29	"	"	"	"	"	"
30	708,493	16,869	"	"	1,077,119	25,646
31	739,254	17,601	335,957	7,999	1,107,880	26,378
32	805,440	19,177	"	"	1,174,066	27,954
33	807,820	19,234	"	"	1,176,446	28,011
34	863,238	20,553	"	"	1,231,864	29,330
35	880,061	20,954	"	"	1,248,687	29,731
36	982,344	23,389	"	"	1,350,970	32,166
37	1,015,756	24,185	"	"	1,384,382	32,962
38	"	"	"	"	"	"
39 through 54	1,073,930	25,570	"	"	1,442,556	34,347
55 through 90	1,105,472	26,321	"	"	1,474,098	35,098

Table A-3. Cumulative Demand (10-Day-Reserve Case)–Light Corps

Day	Cumulative Consumption – Post-Day 4 (bbl)	Cumulative Contribution To 10-Day Reserve (bbl)	Total Cumulative Demand (bbl)
4	0	0	0
5	12,810	10,643	23,453
6	25,519	21,286	46,805
7	38,228	31,930	70,158
8	50,937	42,573	93,510
9	63,646	53,216	116,862
10	81,249	63,859	145,108
11	98,852	74,503	173,355
12	116,455	85,146	201,601
13	134,058	95,789	229,847
14	151,661	106,432	258,093
15	172,288	117,075	289,363
16	192,915	127,719	320,634
17	213,542	138,362	351,904
18	234,169	149,005	383,174
19	254,796	159,648	414,444
20	275,423	170,291	445,714
21	296,050	180,935	476,985
22	316,677	191,578	508,255
23	343,424	202,221	545,644
24	370,171	212,864	583,035
25	396,918	223,507	620,425
26	423,665	234,151	657,816
27	450,412	244,794	695,206
28	477,159	255,437	732,596
29	503,906	266,080	769,986
30	530,653	"	796,733
31	556,662	"	822,742
32	582,591	"	848,671
33	608,560	"	874,640
44	913,810	"	1,179,890
90	2,288,290	"	2,554,370

Table A-4. Cumulative Demand (10-Day-Reserve Case)—Heavy Corps

Day	Cumulative Consumption—Post-Day 4 (bbl)	Cumulative Contribution To 10-Day Reserve (bbl)	Total Cumulative Demand (bbl)
4	0	0	0
5	8,973	11,441	20,414
6	18,239	22,882	41,121
7	28,937	34,323	63,260
8	39,635	45,764	85,399
9	50,333	57,205	107,538
10	62,792	68,645	131,437
11	75,251	80,086	155,337
12	87,710	91,527	179,237
13	100,169	102,968	203,137
14	112,628	114,409	227,037
15	129,845	125,850	255,695
16	147,062	137,291	284,353
17	164,279	148,732	313,011
18	181,496	160,173	341,669
19	200,991	171,614	372,605
20	220,875	183,054	403,929
21	240,759	194,495	435,254
22	260,643	205,936	466,579
23	280,527	217,377	497,904
24	300,411	228,818	529,229
25	323,663	240,259	563,922
26	346,915	251,700	598,615
27	370,167	263,141	633,308
28	393,419	274,582	668,001
29	416,671	286,022	702,693
30	442,317	"	728,339
31	468,695	"	754,717
32	496,649	"	782,671
33	524,660	"	810,682
34	553,990	"	840,012
35	583,721	"	869,743
36	615,887	"	901,909
37	648,849	"	934,871
38	681,811	"	967,833
54	1,231,363	"	1,517,385
90	2,459,793	"	2,745,815

Table A-5. Cumulative Demand (20-Day-Reserve Case)—Light Corps

Day	Cumulative Consumption—Post-Day 4 (bbl)	Cumulative Contribution To 20-Day Reserve (bbl)	Total Cumulative Demand (bbl)
4	0	0	0
5	12,810	21,286	34,096
6	25,519	42,573	68,092
7	38,228	63,859	102,087
8	50,937	85,146	136,083
9	63,646	106,432	170,078
10	81,249	127,719	208,968
11	98,852	149,005	247,857
12	116,455	170,291	286,746
13	134,058	191,578	325,636
14	151,661	212,864	364,525
15	172,288	234,151	406,439
16	192,915	255,437	448,352
17	213,542	276,723	490,265
18	234,169	298,010	532,179
19	254,796	319,296	574,092
20	275,423	340,583	616,006
21	296,050	361,869	657,919
22	316,677	383,156	699,833
23	343,424	404,442	747,866
24	370,171	425,728	795,899
25	396,918	447,015	843,933
26	423,665	468,301	891,966
27	450,412	489,588	934,000
28	477,159	510,874	988,033
29	503,906	532,161	1,036,067
30	530,653	"	1,062,814
31	556,662	"	1,088,823
32	582,591	"	1,114,752
33	608,560	"	1,140,721
44	913,810	"	1,445,971
90	2,288,290	"	2,820,451

Table A-6. Cumulative Demand (20-Day-Reserve Case)—Heavy Corps

Day	Cumulative Consumption—Post-Day 4 (bbl)	Cumulative Contribution To 20-Day Reserve (bbl)	Total Cumulative Demand (bbl)
4	0	0	0
5	8,973	22,882	31,855
6	18,239	45,764	64,003
7	28,937	68,645	97,582
8	39,635	91,527	131,162
9	50,333	114,409	164,742
10	62,792	137,291	200,083
11	75,251	160,173	235,424
12	87,710	183,054	270,764
13	100,169	205,936	306,105
14	112,628	228,818	341,446
15	129,845	251,700	381,545
16	147,062	274,582	421,644
17	164,279	297,463	461,742
18	181,496	320,345	501,841
19	200,991	343,227	544,218
20	220,875	366,109	586,984
21	240,759	388,991	629,750
22	260,643	411,872	672,515
23	280,527	434,754	715,281
24	300,411	457,636	758,046
25	323,663	480,518	804,181
26	346,915	503,400	850,315
27	370,167	526,281	896,448
28	393,419	549,163	942,582
29	416,671	572,045	988,716
30	442,317	"	1,014,362
31	468,695	"	1,040,740
32	496,649	"	1,068,694
33	524,660	"	1,096,705
34	553,990	"	1,126,035
35	583,721	"	1,155,767
36	615,887	"	1,187,932
37	648,849	"	1,220,894
38	681,811	"	1,253,856
54	1,231,363	"	1,803,408
90	2,459,793	"	3,031,838

Table A-7. Cumulative Demand (30-Day-Reserve Case)–Light Corps

Day	Cumulative Consumption– Post-Day 4 (bbl)	Cumulative Contribution To 30-Day Reserve (bbl)	Total Cumulative Demand (bbl)
4	0	0	0
5	12,810	31,930	44,740
6	25,519	63,859	89,378
7	38,228	95,789	134,017
8	50,937	127,718	178,656
9	63,646	159,648	223,294
10	81,249	191,578	272,827
11	98,852	223,507	322,359
12	116,455	255,437	371,892
13	134,058	287,367	421,425
14	151,661	319,296	470,957
15	172,288	351,225	523,514
16	192,915	383,156	576,071
17	213,542	415,085	628,627
18	234,169	447,015	681,184
19	254,796	478,944	733,740
20	275,423	510,874	786,297
21	296,050	542,804	838,854
22	316,677	574,733	891,410
23	343,424	606,662	950,087
24	370,171	638,593	1,008,764
25	396,918	670,522	1,067,440
26	423,665	702,452	1,126,117
27	450,412	734,381	1,184,793
28	477,159	766,311	1,243,470
29	503,906	798,241	1,302,147
30	530,653	"	1,328,894
31	556,662	"	1,354,863
32	582,591	"	1,380,832
33	608,560	"	1,406,801
44	913,810	"	1,712,051
90	2,288,290	"	3,086,531

Table A-8. Cumulative Demand (30-Day-Reserve Case)—Heavy Corps

Day	Cumulative Consumption—Post-Day 4 (bbl)	Cumulative Contribution To 30-Day Reserve (bbl)	Total Cumulative Demand (bbl)
4	0	0	0
5	8,973	34,323	43,296
6	18,239	68,645	86,884
7	28,937	102,968	131,905
8	39,635	137,291	176,926
9	50,333	171,614	221,947
10	62,792	205,936	268,728
11	75,251	240,259	315,510
12	87,710	274,582	362,292
13	100,169	308,904	409,073
14	112,628	343,227	455,855
15	129,845	377,550	507,395
16	147,062	411,872	558,934
17	164,279	446,195	610,474
18	181,496	480,518	662,014
19	200,991	514,840	715,831
20	220,875	549,163	770,038
21	240,759	583,486	824,245
22	260,643	617,809	878,452
23	280,527	652,131	932,658
24	300,411	686,454	986,865
25	323,663	720,777	1,044,440
26	346,915	755,099	1,102,014
27	370,167	789,422	1,159,589
28	393,419	823,745	1,217,164
29	416,671	858,067	1,274,738
30	442,317	"	1,300,384
31	468,695	"	1,326,762
32	496,649	"	1,354,716
33	524,660	"	1,382,727
34	553,990	"	1,412,057
35	583,721	"	1,441,788
36	615,887	"	1,473,954
37	648,849	"	1,506,916
38	681,811	"	1,539,878
54	1,231,363	"	2,089,430
90	2,459,793	"	3,317,860

APPENDIX B

SIMULATION PROGRAM

```
      PROGRAM CEVASCO(INPUT,OUTPUT,TAPE2,TAPE1=INPUT,TAPE3=OUTPUT)
C
      COMMON DEL1,DEL2
      COMMON     NOS,IOVFLO(100),F,HUP,FULMAX
      COMMON    XUP(100),XDOWN(100),XUPPER(100),XD(100),TP(100),NO
      COMMON TIME1(100),TIME2(100),TIME11(100),TIME22(100),TTAP,TI
      COMMON XXM,XM,XNET,XNETY
      TYPE REAL NF(200),NZ(200),NMR(200)
      DIMENSION STAT1(8),STAT2(8),STAT3(8)
      IPOT=1
      READ(1,501) NVAR
  501 FORMAT(I3)
      DO 2000 MOOR=1,NVAR
      DO 10 I=1,100
10    IOVFLO(I)=0
C R IS THE RELIABILITY                                                   GJHB
C DT IS THE TIME INTERVAL                                                GJHB
C NS IS THE NUMBER OF SIMULATIONS                                        GJHB
C DEL IS THE DELIVERY RATE PER HOUR
C IDRDN1 IS THE DRAWDOWN TIME. ALTERNATES WITH IDRDN2.                   GJHB
C IDRDN2 IS THE DRAWDOWN TIME. ALTERNATES WITH IDRDN1.                   GJHB
C XNHBF IS THE NUMBER OF HOURS BEFORE A FAILURE CAN OCCUR.               GJHB
C FULMAX IS THE MAXIMUM FUEL ON HAND
      READ(1,500) R,DT,NS,DEL1,DEL2,IDRDN1,IDRDN2,XNHBF,FULMAX,CONS1,
     X  CONS2
  500 FORMAT( 2F10.0,I3, 2F7.0,2I5,F5.0,F10.0,2F7.0)
C XM IS CONSUMPTION RATE
      XM = CONS1/24.
      XXM = CONS2/24.
      N = 30/DT
      XNET = (DEL1*N)-(XM*N)
      XNETY = (DEL2*N)-(XXM*N)
      XLAMBDA=-ALOG(R)/30.
      PDT = 1.0 - EXP(-XLAMBDA*DT)
C N IS THE NUMBER OF RANDOM NUMBERS REQUIRED FOR A 30 HOUR MISSION
C XLAMBDA IS PROBABILITY PER UNIT TIME FOR SYSTEM FAILURE
C PDT IS PROBABILITY OF FAILURE DURING TIME INTERVAL DT
      WRITE(3,400)
  400 FORMAT(1H1,2X,*RESULTS OF MULTI-LEG MOORING SYSTEM SIMULATION*)
      WRITE(3,405) R,DT
  405 FORMAT(1H0,5X,*RELIABILITY IS*,F6.2,5X,*SAMPLING INTERVAL IS*,
     1 F6.2)
      WRITE(3,410) NS
  410 FORMAT(1H0,5X,*NUMBER OF SIMULATIONS IS*,I10)
      WRITE(3,415) XLAMBDA
  415 FORMAT(1H0,5X,*PROBABILITY PER UNIT TIME FOR SYSTEM FAILURE*,
     1 F10.4)
      IF(IPOT.NE.1) GO TO 102
      WRITE(3,420) PDT
  420 FORMAT(1H0,5X,*PROBABILITY OF FAILURE DURING TIME INTERVAL DT*,
     1 F10.4)
      WRITE(3,430) DEL1,DEL2,IDRDN1,IDRDN2,XNHBF
430   FORMAT(1H0,*THE DELIVERY RATE IS*,2F7.0,/,* THE DRAWDOWNS IN REDUCE
     XD DELIVERY CYCLE ARE*,2I5,/,* A FAILURE CANNOT OCCUR WITHIN THE FI
     XRST*,F7.0,* HOURS*)
      WRITE(3,2010) FULMAX
2010  FORMAT( * THE MAXIMUM FUEL ON HAND IS *,  F9.1 )
```

```
      WRITE(3,2020) CONS1,CONS2
 2020 FORMAT( * THE CONSUMPTION RATE FOR FIRST 29 DAYS IS *, F6.0,/,
     X * THE CONSUMPTION RATE AFTER 29 DAYS IS *, F6.0)
  102 DO 1000 NOS=1,NS
      NS=0
      NO = 1
      LOW = 0
      NZERO = 0
      BDOWN = 0.0
      TPA = 0.0
      TTA = 0.0
      TRA = 0.0
      TIMA = 0.0
      DOWN = 0.0
      LJ = XNHBF/DT                                                     GJHB
      JJ = 0
      K = 0
      NM1 = 0
      N2 = 0
      F = 0.0
      OLD=0                                                             GJHB
      ISWTCH=0                                                          GJHB
  510 J = 0
      J42 = 0
      IJJ = 0
      TTAP = TTA
      NJ=(2064.-TTA)/48.*30./DT
  520 RN = RANF(DUM)
      IF(J.GE.NJ) GO TO 990
      J = J+1
      IF(IPDT.NE.1) GO TO 100
  101 IF(RN.GT.PDT) GO TO 520
      IF(K.GT.0) GO TO 521
      IF(J.LT.LJ) GO TO 520
      IF(IPDT.NE.1) GO TO 103
  521 WRITE(2,600) RN
  600 FORMAT(1H-,5X,*RANDOM NUMBER IS*,F10.4)
      WRITE(2,605) NOS
  605 FORMAT(1H ,5X,*SIMULATION NUMBER*,I4)
      K = K+1
      WRITE(2,610) K,J
  610 FORMAT(1H ,5X,*SYSTEM FAILURE NUMBER*,I6,5X,*NUMBER OF RANDOM NUMB
     1ERS USED*,I10)
      NM = J/N
      XNM = FLOAT(J)/FLOAT(N)-NM
C K IS FAILURE COUNT
C NM IS NUMBER OF COMPLETE 30 HOUR MISSIONS
C XNM IS PORTION OF INCOMPLETE 30 HOUR MISSION
C PUMP TIME BETWEEN FAILURE K,K-1
      TP(K) = J*DT
C TIME INTO INTERRUPTED 30 HOUR MISSION AT FAILURE
      TI = XNM*DT*30.
C ACCUMULATED PUMPING TIME
      TPA = TPA + TP(K)
C ACCUMULATED TIME TO DATE-UP TO TIME OF FAILURE MISSION
      TTD = 18.*NM+TP(K)-TI
C ALTERNATES BETWEEN SHORT AND LONG FAILURES                            GJHB
```

```
C      N1 = N/2
C      M1 = N1-N2
C      N2 = N1
C ALL FAILURES WILL BE OF SHORT VARIETY                                 GJHB
C      M1=0                                                             GJHB
C ALL FAILURES WILL BE OF LONG VARIETY
       M1=0
C ACCUMULATED REPAIR TIME FOR K FAILURES
       TRA = TRA+24.+M1*48.
C      JM = 1
       JM=0
       IF (TI.LE.24.) JM=0
C DOWNTIME AFTER KTH FAILURE
       TIM = 48.*(M1+1)+JM*24.-TI
C ACCUMULATED DOWNTIME TO START OF NEXT PUMPING SEQUENCE AFTER KTH FAILURE
       TIMA = TIMA+18.*NM+TIM
C HYPOTHETICAL FUEL ON HAND AT TTA LESS PARTIAL MISSION
       FH = F+ DEL1*(TP(K)-TI)-CONS1*TTD/24.
       JOLD=JOLD+NM
       IF(TTA.LE.600.) GO TO 530
       IF(TTAP.GE.600.)FH=FH-CONS1*TTD/24.                              GJHB
       IF(TTAP.LT.600.)FH=FH-CONS1*(TTD-(600.-TTAP))/24.                GJHB
       GO TO 540
  100  N5=N5+1
       TF=N5*DT
       IF(TF.GT.30.) TF=0
       PUT=0/15.*TF*(1.-R)
       GO TO 101
  103  WRITE(2,420) PUT
       N5=0
       GO TO 521
  530  TTH = TTD+TTAP
       IF(TTH.LE.600.) GO TO 540
       TX = TTH-600.
       FH = FH-CONS1*TX/24.
540    IF(FH.LE. FULMAX .AND. ISWTCH.EQ.0) GO TO 535                    GJHB
C EXCESS FUEL DELIVERED
       IP=0
       J9=0                                                             GJHB
       J4=0                                                             GJHB
       IF(ISWTCH .EQ. 1) GO TO 810
       ISWTCH=1                                                         GJHB
       IP=JOLD-NM
       FX = FULMAX
       DO 805 JA=1,12
       J4=JA-1
       FX=FX-DEL1*30.+CONS1*2.
       IF(FX.LT.0.0) GO TO 810
805    CONTINUE                                                         GJHB
       DO 800 JA=1,31
       J9=JA
       FX=FX-DEL2*30.+CONS2*2
       IF(FX.LT.0.0) GO TO 810
800    CONTINUE                                                         GJHB
C IN = NUMBER OF TIME INTERVALS IN THE REDUCED FUEL DELIVERY SEQUENCE.  GJHB
810    IN=NM-J4-J9+IP
       IF(IN.GT.NM)IN=NM
```

```
      IF(IN.LE.0)IN=NM
      JIJ=IH
C NUMBER OF 66 HOUR DRAWDOWNS
      IJJ = JIJ/2
C NUMBER OF 42 HOUR DRAWDOWNS
      J42 = JIJ-IJJ
      TTA = TTD+(IDRDN1-18.)*J42+(IDRDN2-18.)*IJJ+TIM+TI+TTAP            GJHB
      LL = 0
      IF(JIJ.GE.1) LL=1
      GO TO 550
  535 TTA = TTD + TIM + TI + TTAP
      LL = 0
  550 MO = 1
      IF(LL.EQ.1) GO TO 560
      IF(TTAP.GE.600) GO TO 560
      IF(TTA.LE.600) GO TO 551
      TT2 = TTA-TIM
      TT3 = TT2-TI
      IF(TT3.GE.600) GO TO 560
      IF(TT2.GE.600) GO TO 552
      MO = 2
      GO TO 551
  552 MO = 3
  551 CALL UPFUNE(NM,XNM,TIM,TPA,TIMA,TTA,BDOWN,  LOW,NZERO,MO)
      GO TO 580
  560 CALL UPFUWO(NM,XNM,TIM,TPA,TIMA,TTA,D,BDOWN,LL,  J42,IJJ,LOW,
     1 NZERO,IDRDN1,IDRDN2)                                              GJHB
  580 IF(TTA.LT.2064.) GO TO 510
      NMR(NOS) = LOW
      NZ(NOS) = NZERO
      NF(NOS) = K-1
      WRITE(2,620) LOW
  620 FORMAT(1H ,5X,*NUMBER OF TIMES FUEL ON HAND DIPS BELOW MINIMUM RES
     1ERVE LINE*,I10)
      WRITE(2,625) NZERO
  625 FORMAT(1H ,5X,*NUMBER OF TIMES FUEL ON HAND DIPS BELOW ZERO*,I10)
      GO TO 1000
  990 WRITE(2,992)
  992 FORMAT(1H0,*HIT RANDOM NUMBER LIMIT-EXCESSIVE TIME*)
      GO TO 521
 1000 CONTINUE
      WRITE(3,1001)
 1001 FORMAT(1H0,2X,*TOTALS PER SIMULATION*)
      WRITE(3,1002)
 1002 FORMAT(1H0,T5,*NUMBER OF FAILURES*,T25,*NUMBER BELOW MIN RESERVE*,
     x T52,*NUMBER BELOW ZERO*,T71,*NUMBER OF OVERFLOWS*)
      WRITE(3,1003) (NF (NOS),NMR(NOS),NZ(NOS),IOVFLO(NOS),NOS=1,NS)
1003  FORMAT(9X,F6.2,20X,F6.2,18X,F6.2,14X,I3)
      CALL BDS(NF,NS,STAT1)
      CALL BDS(NMR,NS,STAT2)
      CALL BDS(NZ,NS,STAT3)
      WRITE(3,1004) STAT1(1),STAT2(1),STAT3(1)
      WRITE(3,1005) STAT1(6),STAT2(6),STAT3(6)
 1004 FORMAT(1H-,1X,*MEAN*,1X,F7.2,18X,F7.2,16X,F7.2)
 1005 FORMAT(1H-,1X,*SD*,3X,F7.2,18X,F7.2,16X,F7.2)
 2000 CONTINUE
      STOP
      End
```

```
      SUBROUTINE UPFUNE(NM,XNM,  TIM,TPA,TIMA,TTA,BDOWN,  LOW,NZERO,MO)
      COMMON DEL1,DEL2
      COMMON      NOS,IOVFLO(100),F,BUP,FULMAX
      COMMON     XUP(100),XDOWN(100),XUPPER(100),XD(100),TP(100),NO
      COMMON TIME1(100),TIME2(100),TIME11(100),TIME22(100),TTAP,T1
      COMMON XXM,XM,XNET,XNETY
C TTA IS LESS THAN OR EQUAL 600 HOURS OR 25 DAYS
      DOWN = F
      WRITE(2,200) TIM,TPA,TIMA,TTA
  200 FORMAT(1H ,5X,*TIM*,F10.2,5X,*TPA*,F10.2,5X,*TIMA*,F10.2,5X,
     1*TTA*,F10.2)
      WRITE(2,1) NM,XNM,BDOWN,F
    1 FORMAT(1H ,5X,*NM*,I4,5X,*XNM*,F8.4,5X,*BDOWN*,F10.2,5X,*F*,F10.2)
      T2 = TTAP
      IF(NM.LT.1) GO TO 24
      DO 10  IJ=1,NM
      UP = DOWN + XNET
      XUP(IJ) = UP
      T1 = T2+30.
      TIME1(IJ) = T1
      DOWN = UP - XM*18.
      XDOWN(IJ) = DOWN
      T2 = T1+18.
      TIME2(IJ) = T2
   10 CONTINUE
C
C UP IS THE NET DELIVERY AFTER EACH 30 HOUR MISSION AND DOWN IS FUEL ON
C HAND AFTER EACH 18 HOUR DRAWDOWN
C BUP CALCULATES NET DELIVERY FOR PARTIAL 30 HOUR MISSION AND BDOWN CALCULATES
C DRAWDOWN DURING FAILURE
C
   24 GO TO(13,22,23) MO
C CHANGE IN DRAWDOWN OCCURS DURING TIM
   22 BUP =     XNET*XNM+DOWN
      F = BUP-XM*(600.-T2-T1)-(TTA-600.)*XXM
      GO TO 26
C CHANGE IN DRAWDOWN OCCURS DURING PUMPING OF INTERRUPTED MISSION
   23 XNX = (600.-T2)/30.
      XNY = XNM-XNX
      BUP =     XNET*XNX+ XNETY*XNY+DOWN
      F = BUP-TIM*XXM
      GO TO 26
   13 BUP =     XNET*XNM+DOWN
      F = BUP-XM*TIM
   26 TIP = T2+T1
      TID = TIP+TIM
   17 IF(NM.LT.1) GO TO 29
      DO 18 IJ=1,NM                                                     GJHB
      IDRD=18                                                           GJHB
      IF(XUP(IJ).GT. FULMAX)CALL FULL1(XUP,IDRD,XDOWN,NM,IJ,TIME1(IJ))
18    WRITE(2,25) XUP(IJ),TIME1(IJ),IDRD,XDOWN(IJ),TIME2(IJ)            GJHB
   25 FORMAT(6X,*NET DELIVERY AFTER COMPLETE MISSION*,F10.2,5X,*TIME*,
     XF10.2,5X,I2,* HOUR DRAWDOWN*,F10.2,5X,*TIME*,F10.2)               GJHB
29    IF(BUP.GT.FULMAX )CALL FULL2(BUP,IDRD,F,TIP)
      WRITE(2,30) BUP,TIP,F,TID
   30 FORMAT(6X,*NET DELIVERY AFTER PARTIAL MISSION*,F10.2,5X,*TIME*,
     1F10.2,5X,*DOWNTIME DRAWDOWN*,F10.2,5X,*TIME*,F10.2)
```

```
C
C F IS FUEL ON HAND AT TIME TTA
C RF IS RESERVE FUEL LINE
C
      RF=FULMAX/3.
      IF(TTA.LE.1248.)
     XRF=FULMAX/3./2./624.*TTA
      IF (F.GE.RF) GO TO 19
      LOW = LOW+1
      WRITE(2,14) TTA
   14 FORMAT(1H ,2X,*FUEL ON HAND DIPS BELOW REQUIRED MINIMUM RESERVE AT
     1*,F10.2)
      IF (F.GE.0.0) GO TO 19
      B = F + XM*TTA
      XT = B/XM
      NZERO = NZERO+1
      WRITE(2,15) XT
   15 FORMAT(1H ,2X,*DRAWDOWN HITS ZERO AT HOUR*,F10.2)
      F = 0.0
19    WRITE(2,20) F,RF,TTA
   20 FORMAT (1H ,5X,*FUEL ON HAND*,F10.2,5X,*RESERVE FUEL REQUIRED*,
     1F10.2,5X,*TOTAL ACCUMULATED TIME*,F10.2)
      BDOWN = F
      RETURN
      END
```

```
      SUBROUTINE UPFUWO(NM,XNM,TIM,TPA,TIMA,TTA,D,BDOWN,LL,  J42,IJJ,
     1 LOW,NZERO,IDRDN1,IDRDN2)                                         GJHB
      COMMON DEL1,DEL2
      COMMON     NUS,IOVFLO(100),F,BUP,FULMAX
      COMMON    XUP(100),XDOWN(100),XUPPER(100),XD(100),TP(100),NO
      COMMON TIME1(100),TIME2(100),TIME11(100),TIME22(100),TTAP,TI
      COMMON XXM,XM,XNET,XNETY
C TTA IS MORE THAN 600 HOURS OR 25 DAYS
      T2 = TTAP
      K1 = NM-(J42+IJJ)
      WRITE(2,200) TIM,TPA,TIMA,TTA
  200 FORMAT(1H ,5X,*TIM*,F10.2,5X,*TPA*,F10.2,5X,*TIMA*,F10.2,5X,
     1*TTA*,F10.2)
      WRITE(2,210) NM,XNM,BDOWN,LL,F,J42,IJJ
  210 FORMAT(1H ,5X,*NM*,I4,5X,*XNM*,F8.4,5X,*BDOWN*,F10.2,5X,*LL*,I2,
     15X,*F*,F10.2,5X,*J42*,I5,5X,*IJJ*,I5)
      IF(NO.GE.2) GO TO 94
      NO = 2
      IF(TTAP.GE.600.) GO TO 94                                         GJHB
      D = BDOWN
      IF(K1.LT.1) GO TO 131
C CHANGE IN DRAWDOWN OCCURS BEFORE START OF PARTIAL MISSION
      TT1 = 600.-TTAP
      NM2 = TT1/48.
      TX = TT1-NM2*48.
      IF(NM2.LT.1) GO TO 92
      DO 90 IJK=1,NM2
      UPPER = D+XNET
      XUPPER(IJK) = UPPER
      T1 = T2+30.
      TIME11(IJK) = T1
      D = UPPER-XM*18.
      XD(IJK) =D
      T2 = T1+18.
      TIME22(IJK) = T2
   90 CONTINUE
   92 IJK = NM2+1
      IF(TX.GE.24.) GO TO 91
      UPPER = D+XNET
      D = UPPER-XM*18.
      GO TO 93
   91 ZNET = (XNET*.8)+(XNETY*.2)
      UPPER = D + ZNET
      D = UPPER-XXM*18.
   93 T1 = T2+30.
      TIME11(IJK) = T1
      T2 = T1+18.
      XUPPER(IJK) = UPPER
      XD(IJK) = D
      TIME22(IJK) = T2
      K0 = NM2+2
      GO TO 95
   94 K0 = 1
      D = F
      IF(NM.LT.1) GO TO 113
      GO TO 96
   95 IF(K0.GT.NM) GO TO 113
```

```
   96 IF(K1.LT.1) GO TO 131
      DO 100 IJK=K0,K1
      UPPER = D + XNETY
      XUPPER(IJK) = UPPER
      T1 = T2+30.
      TIME11(IJK) = T1
      D = UPPER - XXM*18.
      XD(IJK) = D
      T2 = T1+18.
      TIME22(IJK) = T2
  100 CONTINUE
      DO 101 IJK=1,K1                                                   GJHB
      IDRD=18                                                           GJHB
      IF(XUPPER(IJK).GT.FULMAX )CALL FULL1(XUPPER,IDRD,XD,K1,IJK,
     X TIME11(IJK))
  101 WRITE(2,130) XUPPER(IJK),TIME11(IJK),IDRD,XD(IJK),TIME22(IJK)     GJHB
  130 FORMAT(6X,*NET DELIVERY AFTER COMPLETE MISSION*,F10.2,5X,*TIME*,
     XF10.2,5X,I2,* HOUR DRAWDOWN*,F10.2,5X,*TIME*,F10.2)               GJHB
      T2=TIME22(K1)
      D=XD(K1)                                                          GJHB
  131 IF(LL.NE.1) GO TO 113
C CALCULATE IDRDN1 HOUR DRAWDOWN                                        GJHB
  111 T1=T2+30.
      T2 = T1+IDRDN1                                                    GJHB
      IF(T1.GE.624.)ALTUP=D+XNETY
      IF(T1.LE.600.)ALTUP=D+XNET
      IF(T1.GT.600..AND.T1.LT.624.)ALTUP=D+DEL1*24.+DEL2*6.-(T1-600.)*
     X XXM-(630.-T1)*XM
      IF(T2.GE.642.)ALTD=ALTUP-(FLOAT(IDRDN1)*XXM)
      IF(T2.LT.642.)ALTD=ALTUP-(T2-600.)*XXM-(642.-T2)*XM
      IF(T2.LE.600.)ALTD=ALTUP-(FLOAT(IDRDN1)*XM)
      J42 = J42-1
      IDRD=IDRDN1                                                       GJHB
      IF(ALTUP.GT.FULMAX )CALL FULL2(ALTUP,IDRD,ALTD,T1)
      WRITE(2,114)ALTUP,T1,IDRD,ALTD,T2                                 GJHB
  114 FORMAT(   6X,*NET DELIVERY*,F10.2,5X,*TIME*,F10.2,5X,I2,* HOUR DRAGJHB
     1WDOWN*,F10.2,5X,*TIME*,F10.2)
      D = ALTD
      IF(IJJ.LE.0) GO TO 113
C CALCULATE IDRDN2 HOUR DRAWDOWN                                        GJHB
      T1 = T2+30.
      T2 = T1+IDRDN2                                                    GJHB
      IF(T1.GE.624.)ALTUP=D+XNETY
      IF(T1.LE.600.)ALTUP=D+XNET
      IF(T1.GT.600..AND.T1.LT.624.)ALTUP=D+DEL1*24.+DEL2*6.-(T1-600.)*
     X XXM-(630.-T1)*XM
      IF(T2.GE.642.)ALTD=ALTUP-(FLOAT(IDRDN2)*XXM)
      IF(T2.LT.642.)ALTD=ALTUP-(T2-600.)*XXM-(642.-T2)*XM
      IF(T2.LE.600.)ALTD=ALTUP-(FLOAT(IDRDN2)*XM)
      IJJ = IJJ-1
      IDRD=IDRDN2                                                       GJHB
      IF(ALTUP.GT.FULMAX )CALL FULL2(ALTUP,IDRD,ALTD,T1)
      WRITE(2,114)ALTUP,T1,IDRD,ALTD,T2                                 GJHB
      D = ALTD
      IF(J42.LE.0) GO TO 113
      GO TO 111
  113 BUPPER = XNETY *XNM+D
```

```
      TIPA = T2+T1
      F  = BUPPER-XXM*TIM
      TIDA = TIPA+TIM
      IF(K1.LT.1) GO TO 133
      IF(NM.LT.1.OR.KU.GT.NM) 132,133
132   DO 134 IJK=1,K1                                                   GJHB
      IORD=IA                                                           GJHB
      IF(XUPPER(IJK).GT.FULMAX )CALL FULL1(XUPPER,IORD,XD,K1,IJK,
     X TIME11(IJK))
134   WRITE(2,130) XUPPER(IJK),TIME11(IJK),IORD,XD(IJK),TIME22(IJK)     GJHB
133   IF(BUPPER.GT. FULMAX)CALL FULL2(BUPPER,IORD,F,TIPA)
      WRITE(2,135)BUPPER,TIPA,F,TIDA
  135 FORMAT(6X,*NET DELIVERY AFTER PARTIAL MISSION*,F10.2,5X,*TIME*,
     1F10.2,5X,*DOWNTIME DRAWDOWN*,F10.2,5X,*TIME*,F10.2)
      RF=FULMAX/3.
      IF(TTA.LE.1248.)RF=FULMAX/3./2./624.*TTA
      IF (F.GE.RF) GO TO 120
      LOW = LOW+1
      WRITE(2,136) TTA
  136 FORMAT(1H ,2X,*FUEL ON HAND DIPS BELOW REQUIRED MINIMUM RESERVE AT
     1*,F10.2)
      IF (F.GE.0.0) GO TO 120
      H = F + XXM*TTA
      XT =  H/XXM
      NZERO = NZERO+1
      WRITE(2,115) XT
  115 FORMAT(1H ,2X,*DRAWDOWN HITS ZERO AT HOUR*,F10.2)
      F = 0.0
  120 WRITE(2,125) F,RF,TTA
  125 FORMAT (1H ,5X,*FUEL ON HAND*,F10.2,5X,*RESERVE FUEL REQUIRED*,
     1F10.2,5X,*TOTAL ACCUMULATED TIME*,F10.2)
      RETURN
      END
```

```
      SUBROUTINE FULL2(ALTUP,IDRD,ALTD,T)
      COMMON DEL1,DEL2
      COMMON      NOS,IOVFLO(100),F,BUP,FULMAX
      IOVFLO(NOS)=IOVFLO(NOS)+1
      DEL=DEL1
      IF(T.GT.600.)DEL=DEL2
      NHRS=(ALTUP- FULMAX)/DEL
      ALTUP=ALTUP-(NHRS*DEL)                                          GJHB
      IDRD=IDRD+NHRS                                                  GJHB
      ALTD=ALTD-(NHRS*DEL)                                            GJHB
      RETURN                                                          GJHB
      END                                                             GJHB
```

```
      SUBROUTINE FULL1(XUPPER,IDRD,XD,K1,IJK,T)
      COMMON DEL1,DEL2
      COMMON      NOS,IOVFLO(100),F,BUP,FULMAX
      DIMENSION XUPPER(1),XD(1)                                       GJHB
      IOVFLO(NOS)=IOVFLO(NOS)+1
      DEL=DEL1
      IF(T.GT.600.)DEL=DEL2
      NHR=(XUPPER(IJK)- FULMAX)/DEL
      IDRD=IDRD+NHR                                                   GJHB
      DO 10 I=IJK,K1                                                  GJHB
      XUPPER(I)=XUPPER(I)-(NHR*DEL)                                   GJHB
   10 XD(I)=XD(I)-(NHR*DEL)                                           GJHB
      BUP=BUP-NHR*DEL
      F=F-NHR*DEL
      RETURN                                                          GJHB
      END                                                             GJHB
```

APPENDIX C

SUMMARY OF SIMULATION OUTPUT

Table C-1.

Pipeline Length (ft)	Initial Flow Rate (bbl/h)	Subsequent Flow Rate (bbl/h)	Average Number of Times (and Range of Times) Fuel Reserve Falls to Zero at Reliability R During a 90-Day Operation								
			R=0.3	R=0.4	R=0.5	R=0.6	R=0.7	R=0.8	R=0.85	R=0.90	R=0.95
1,000	990	1,730	0.35 (0-5*)	0.14 (0-3*)	0.05 (0-3*)	0.02 (0-1*)	0	0	0	0	0
2,000	700	1,230	3.52 (0-14*)	1.81 (0-9*)	0.77 (0-6*)	0.31 (0-4*)	0.29 (0-3*)	0.03 (0-1*)	0.08 (0-2*)	0.03 (0-1*)	0
2,500	620	1,090	6.65 (0-17)	3.45 (0-9)	1.82 (0-9*)	0.96 (0-11*)	0.42 (0-4*)	0.28 (0-4*)	0.12 (0-3*)	0.03 (0-1*)	0.02 (0-1*)
3,000	570	1,000	9.45 (0-22)	4.93 (0-14*)	2.99 (0-9*)	1.59 (0-8*)	0.86 (0-7*)	0.48 (0-3*)	0.21 (0-2*)	0.14 (0-2*)	0.06 (0-2*)
4,000	500	870	14.03 (5-25)	9.15 (1-23)	5.72 (0-12)	3.61 (0-10*)	1.69 (0-8*)	0.89 (0-5*)	0.55 (0-4*)	0.41 (0-3*)	0.12 (0-2*)
5,000	440	780	19.35 (6-33)	13.10 (5-25)	9.06 (3-19)	5.92 (1-13)	4.24 (0-12*)	2.34 (0-6*)	1.55 (0-5*)	1.23 (0-5*)	0.42 (0-3*)

1. Reserve Objective = 10 Days.
2. Number of Systems Deployed During Initial Period = 5, During Subsequent Period = 4.
3. Failures May Not Occur During Day 5 and Day 6; They May Occur Starting with the Beginning of the Second 30-Hour Mooring Mission, i.e., After Midnight of Day 6.
4. All Mooring Missions will Consist of a Theoretically Possible 30 Hours of Pumping Time Followed by 18 Hours of Drawdown.
5. Initial Period Daily Demand = 6,386 bbl/d; Subsequent Period Daily Demand = 7,982 bbl/d.
6. Cutoff Limit for Fuel Reserve = 57,204 bbl.

* Indicates that for every simulated 90-day hostility in which the fuel on hand dropped to the minimum, i.e., zero, level one or more times, it *also* rose to the maximum cutoff level, causing truncation of one or more fuel deliveries.

NC indicates not computed.

NOTE: Solid line divides feasible (lower left) from infeasible (upper right) values. Dashed line divides unacceptable (lower left) from acceptable (upper right) values.

Table C-2.

Pipeline Length (ft)	Initial Flow Rate (bbl/h)	Subsequent Flow Rate (bbl/h)	Average Number of Times (and Range of Times) Fuel Reserve Falls to Zero at Reliability R During a 90-Day Operation								
			R=0.3	R=0.4	R=0.5	R=0.6	R=0.7	R=0.8	R=0.85	R=0.90	R=0.95
1,000	990	1,730	0.23 (0-5*)	0.04 (0-2*)	0.01 (0-1*)	0.02 (0-1*)	0	NC	NC	NC	0
2,000	700	1,230	1.85 (0-9*)	0.71 (0-6*)	0.38 (0-5*)	0.11 (0-3*)	0.03 (0-2*)	0.07 (0-1*)	0.02 (0-1*)	0.02 (0-1*)	0
2,500	620	1,090	4.19 (0-13)	1.60 (0-6*)	0.62 (0-6*)	0.28 (0-7*)	0.14 (0-3*)	0.08 (0-1*)	0.01 (0-1*)	0.03 (0-1*)	0
3,000	570	1,000	5.92 (0-18)	2.92 (0-14*)	1.54 (0-9*)	0.36 (0-5*)	0.13 (0-4*)	0.19 (0-3*)	0.05 (0-2*)	0.03 (0-1*)	0.01 (0-1*)
4,000	500	870	11.64 (0-25)	6.04 (0-18)	3.16 (0-14)	1.50 (0-11*)	0.69 (0-7*)	0.26 (0-3*)	0.14 (0-2*)	0.08 (0-2*)	0.03 (0-1*)
5,000	440	780	17.82 (8-27)	11.55 (0-25)	7.36 (0-17)	3.43 (0-14)	1.81 (0-10)	0.67 (0-5*)	0.52 (0-7*)	0.14 (0-2*)	0.08 (0-2*)

1. Reserve Objective = 10 Days.
2. Number of Systems Deployed During Initial Period = 6, During Subsequent Period = 4.
3. Failures May Not Occur During Day 5 and Day 6; They May Occur Starting with the Beginning of the Second 30-Hour Mooring Mission, i.e., After Midnight of Day 6.
4. All Mooring Missions will Consist of a Theoretically Possible 30 Hours of Pumping Time Followed by 18 Hours of Drawdown.
5. Initial Period Daily Demand = 5,321 bbl/d; Subsequent Period Daily Demand = 7,982 bbl/d.
6. Cutoff Limit for Fuel Reserve = 47,670 bbl.

* Indicates that for every simulated 90-day hostility in which the fuel on hand dropped to the minimum, i.e., zero, level one or more times, it *also* rose to the maximum cutoff level, causing truncation of one or more fuel deliveries.

NC indicates not computed.

NOTE: Solid line divides feasible (lower left) from infeasible (upper right) values. Dashed line divides unacceptable (lower left) from acceptable (upper right) values.

Table C-3.

Pipeline Length (ft)	Initial Flow Rate (bbl/h)	Subsequent Flow Rate (bbl/h)	Average Number of Times (and Range of Times) Fuel Reserve Falls to Zero at Reliability R During a 90-Day Operation								
			R=0.3	R=0.4	R=0.5	R=0.6	R=0.7	R=0.8	R=0.85	R=0.90	R=0.95
1,000	990	1,730	0.51 (0-6*)	0.19 (0-3*)	0.07 (0-3*)	0.04 (0-2*)	0.01 (0-1*)	0.01 (0-1*)	0.01 (0-1*)	0	NC
2,000	700	1,230	4.21 (0-13)	2.52 (0-10*)	1.29 (0-6*)	0.41 (0-5*)	0.17 (0-2*)	0.14 (0-2*)	0.03 (0-1*)	0.05 (0-1*)	0.02 (0-1*)
2,500	620	1,090	7.04 (1-18)	4.00 (0-12)	2.65 (0-12*)	1.55 (0-11*)	0.76 (0-5*)	0.20 (0-3*)	0.16 (0-3*)	0.13 (0-3*)	0.08 (0-2*)
3,000	570	1,000	10.18 (2-23)	6.11 (0-16)	3.91 (0-13)	2.55 (0-11*)	1.36 (0-8*)	0.70 (0-4*)	0.34 (0-4*)	0.18 (0-3*)	0.08 (0-3*)
4,000	500	870	15.93 (7-26)	10.66 (2-23)	7.23 (2-16)	4.46 (0-13)	2.96 (0-10)	1.38 (0-5*)	1.04 (0-4*)	0.54 (0-4*)	0.18 (0-2*)
5,000	440	780	20.78 (9-32)	14.85 (4-23)	10.22 (4-21)	6.33 (2-15)	4.19 (0-17)	3.06 (0-8)	2.06 (0-6)	1.46 (0-5*)	0.68 (0-3*)

1. Reserve Objective = 20 Days.
2. Number of Systems Deployed During Initial Period = 6, During Subsequent Period = 4.
3. Failures May Not Occur During Day 5 and Day 6; They May Occur Starting with the Beginning of the Second 30-Hour Mooring Mission, i.e., After Midnight of Day 6.
4. All Mooring MIssions will Consist of a Theoretically Possible 30 Hours of Pumping Time Followed by 18 Hours of Drawdown.
5. Initial Period Daily Demand = 6,749 bbl/d; Subsequent Period Daily Demand = 8,277 bbl/d.
6. Cutoff Limit for Fuel Reserve = 95,341 bbl.

* Indicates that for every simulated 90-day hostility in which the fuel on hand dropped to the minimum, i.e., zero, level one or more times, it *also* rose to the maximum cutoff level, causing truncation of one or more fuel deliveries.

NC indicates not computed.

NOTE: Solid Line divides feasible (lower left) from infeasible (upper right) values. Dashed line divides unacceptable (lower left) from acceptable (upper right) values.

Table C-4.

Pipeline Length (ft)	Initial Flow Rate (bbl/h)	Subsequent Flow Rate (bbl/h)	Average Number of Times (and Range of Times) Fuel Reserve Falls to Zero at Reliability R During a 90-Day Operation								
			R=0.3	R=0.4	R=0.5	R=0.6	R=0.7	R=0.8	R=0.85	R=0.90	R=0.95
1,000	990	1,730	0.17 (0-4*)	0.06 (0-3*)	0.03 (0-2*)	0.02 (0-1*)	0	0	0	NC	NC
2,000	700	1,230	2.20 (0-11)	1.04 (0-8*)	0.49 (0-5*)	0.18 (0-4*)	0.05 (0-1*)	0.01 (0-1*)	0.03 (0-1*)	0	NC
2,500	620	1,090	4.37 (0-15)	1.75 (0-11)	1.15 (0-11*)	0.48 (0-7*)	0.12 (0-2*)	0.08 (0-2*)	0.02 (0-1*)	0.04 (0-1*)	0
3,000	570	1,000	7.90 (0-21)	3.78 (0-14)	1.92 (0-11*)	0.90 (0-11*)	0.45 (0-5*)	0.21 (0-3*)	0.09 (0-2*)	0.04 (0-2*)	0.04 (0-1*)
4,000	500	870	14.35 (3-26)	8.47 (0-23*)	5.03 (0-15)	2.02 (0-11*)	1.25 (0-8*)	0.43 (0-4*)	0.26 (0-2*)	0.19 (0-3*)	0.02 (0-1*)
5,000	440	780	19.88 (7-30)	13.70 (2-25)	8.80 (1-20)	4.99 (0-15)	2.71 (0-14)	1.74 (0-7)	0.88 (0-6*)	0.62 (0-4*)	0.16 (0-2*)

1. Reserve Objective = 20 Days.
2. Number of Systems Deployed During Initial Period = 7, During Subsequent Period = 4.
3. Failures May Not Occur During Day 5 and Day 6; They May Occur Starting with the Beginning of the Second 30-Hour Mooring Mission, i.e., After Midnight of Day 6.
4. All Mooring Missions will Consist of a Theoretically Possible 30 Hours of Pumping Time Followed by 18 Hours of Drawdown.
5. Initial Period Daily Demand = 5,785 bbl/d; Subsequent Period Daily Demand = 8,277 bbl/d.
6. Cutoff Limit for Fuel Reserve = 81,721 bbl.

* Indicates that for every simulated 90-day hostility in which the fuel on hand dropped to the minimum, i.e., zero, level one or more times, it *also* rose to the maximum cutoff level, causing truncation of one or more fuel deliveries.

NC indicates not computed.

NOTE: Solid line divides feasible (lower left) from infeasible (upper right) values. Dashed line divides unacceptable (lower left) from acceptable (upper right) values.

Table C-5.

Pipeline Length (ft)	Initial Flow Rate (bbl/h)	Subsequent Flow Rate (bbl/h)	Average Number of Times (and Range of Times) Fuel Reserve Falls to Zero at Reliability R During a 90-Day Operation								
			R=0.3	R-0.4	R=0.5	R=0.6	R=0.7	R=0.8	R=0.85	R=0.90	R=0.95
1,000	990	1,730	0.36 (0-5*)	0.14 (0-3*)	0.05 (0-3*)	0.02 (0-1*)	0	0.01 (0-1*)	0.01 (0-1*)	NC	NC
2,000	700	1,230	3.14 (0-12)	2.05 (0-10*)	1.00 (0-6*)	0.27 (0-4*)	0.10 (0-1*)	0.05 (0-2*)	0.03 (0-1)	0.01 (0-1*)	NC
2,500	620	1,090	6.19 (0-17)	3.25 (0-12)	2.00 (0-11*)	1.03 (0-9*)	0.40 (0-5*)	0.16 (0-2*)	0.13 (0-4*)	0.06 (0-2*)	0.01 (0-1*)
3,000	570	1,000	9.63 (1-23)	5.31 (0-16)	3.28 (0-13)	1.90 (0-11)	1.02 (0-8*)	0.53 (0-4*)	0.24 (0-3*)	0.14 (0-2*)	0.05 (0-2*)
4,000	500	870	15.74 (7-28)	10.24 (2-23)	6.74 (1-15)	3.86 (0-12)	2.41 (0-10)	0.99 (0-4*)	0.71 (0-4*)	0.38 (0-4*)	0.10 (0-1*)
5,000	440	780	20.79 (9-31)	14.89 (5-26)	10.14 (4-22)	6.24 (2-15)	3.99 (0-17)	2.89 (0-7)	1.87 (0-6)	1.31 (0-5)	0.58 (0-3*)

1. Reserve Objective = 30 Days.
2. Number of Systems Deployed During Initial Period = 8, During Subsequent Period = 4.
3. Failures May Not Occur During Day 5 and Day 6; They May Occur Starting with the Beginning of the Second 30-Hour Mooring Mission, i.e., After Midnight of Day 6.
4. All Mooring Missions will Consist of a Theoretically Possible 30 Hours of Pumping Time Followed by 18 Hours of Drawdown.
5. Initial Period Daily Demand = 6,442 bbl/d; Subsequent Period Daily Demand = 8,317 bbl/d.
6. Cutoff Limit for Fuel Reserve = 107,258 bbl.

* Indicates that for every simulated 90-day hostility in which the fuel on hand dropped to the minimum, i.e., zero, level one or more times, it *also* rose to the maximum cutoff level, causing truncation of one or more fuel deliveries.

NC indicates not computed.

NOTE: Solid line divides feasible (lower left) from infeasible (upper right) values. Dashed line divides unacceptable (lower left) from acceptable (upper right) values.

Table C-6.

Pipeline Length (ft)	Initial Flow Rate (bbl/h)	Subsequent Flow Rate (bbl/h)	Average Number of Times (and Range of Times) Fuel Reserve Falls to Zero at Reliability R During a 90-Day Operation								
			R=0.3	R=0.4	R=0.5	R=0.6	R=0.7	R=0.8	R=0.85	R=0.90	R=0.95
1,000	990	1,730	0.16 (0-4*)	0.05 (0-3*)	0.03 (0-2*)	0.01 (0-1*)	0	0	0	NC	NC
2,000	700	1,230	2.03 (0-10)	0.93 (0-8*)	0.44 (0-5*)	0.15 (0-4*)	0.04 (0-1*)	0.01 (0-1*)	0.03 (0-1*)	0	NC
2,500	620	1,090	4.20 (0-15)	1.68 (0-11)	1.05 (0-10*)	0.50 (0-7*)	0.10 (0-2*)	0.07 (0-2*)	0.05 (0-2*)	0.03 (0-1*)	0
3,000	570	1,000	7.88 (0-20)	3.68 (0-14)	1.83 (0-10)	0.87 (0-11*)	0.44 (0-5*)	0.21 (0-3*)	0.09 (0-2*)	0.04 (0-2*)	0.04 (0-1*)
4,000	500	870	14.16 (3-25)	8.32 (0-23)	4.90 (0-15)	1.83 (0-11)	1.12 (0-7*)	0.37 (0-3*)	0.23 (0-3*)	0.18 (0-3*)	0.02 (0-1*)
5,000	440	780	19.96 (8-30)	13.84 (1-25)	8.85 (1-21)	4.86 (0-15)	2.59 (0-14)	1.61 (0-7)	0.83 (0-6)	0.58 (0-4*)	0.15 (0-2*)

1. Reserve Objective = 30 Days.
2. Number of Systems Deployed During Initial Period = 9, During Subsequent Period = 4.
3. Failures May Not Occur During Day 5 and Day 6; They May Occur Starting with the Beginning of the Second 30-Hour Mooring Mission, i.e., After Midnight of Day 6.
4. All Mooring Missions will Consist of a Theoretically Possible 30 Hours of Pumping Time Followed by 18 Hours of Drawdown.
5. Initial Period Daily Demand = 5,726 bbl/d; Subsequent Period Daily Demand = 8,317 bbl/d.
6. Cutoff Limit for Fuel Reserve = 95,341 bbl.

* Indicates that for every simulated 90-day hostility in which the fuel on hand dropped to the minimum, i.e., zero, level one or more times, it *also* rose to the maximum cutoff level, causing truncation of one or more fuel deliveries.

NC indicates not computed.

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