CHAPTER 150

SPECIAL CONSIDERATION ON THE DESIGN OF AN LNG HARBOR

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SUMMARY

One of the primary considerations in the design of an LNG harbor is safety, requiring berths to be separated by large distance and well-protected from the outside wave agitation. Therefore, LNG harbors require expensive structures established as close as possible to the liquefaction plant (while crude tankers may be served by relatively much cheaper, single point mooring servers in deeper water). The cost of waiting time for the very expensive LNG ships has to be weighted against the cost of the additional berths and structures. (A 125,000 m^3 LNG ships costs $2000/hour.) The present paper describes the results of a study in which the optimum solution has been obtained by comparing these costs.

The number of options is characterized by the number of berths. The cost to be added to the cost of construction of the berths includes an additional length of breakwater and additional dredging, plus the costs of financing during construction and the cost of maintenance.

The waiting time for the LNG ship is generally determined, based on the classical Erlang formula for queing theory. It is recalled that this formula is developed for an open loop. A closed loop theory has been specially developed for the present problem (since LNG ships will most probably operate between two well-defined harbors). The waiting times are 15 to 20% smaller than given by the closed loop theory. A comparison between single berth and double berth is examined. The effect of the rate of filling which is a function of the cryogenic pump capacity (or size of ship depending upon the dominating controlling factor) is analyzed. Finally, the sensitivity of the recommended solution as a function of the interest rates--examined in view of current economic uncertainties--is also investigated.

The final recommendation for the design of the harbor, based on the prevailing factors, is the optimum economic solution.

1. INTRODUCTION

A very early and major problem in harbor planning is establishing the number of berths to be provided. A minimum number must be provided for loading the daily output. A larger number will reduce the average waiting time for ships to tie up at the berth and be connected to the loading equipment. Because of the very high cost of construction and operating LNG tankers, every hour of time saved is worth thousands of dollars. However, the capital cost of additional berths is also very high. Therefore, a detailed analysis is necessary to determine whether ship-time savings could be realized that would be of greater value than the additional capital cost necessary to achieve them.

The objective of this study is to determine the optimum number of berths required to handle a given volume of LNG to be shipped from a harbor.

In general, the calculation of the number of service berths is based on the following criteria:

1) The efficiency of loading berths defined by the rate of occupancy. It is expected that the occupancy of berths for LNG tankers is 20-30%.

2) The calculated mean waiting time, taking into account the irregular nature of traffic caused by all kinds of variations which may arise during trips between harbors.

3) The economic calculation of the loss due to average waiting time, versus the cost of the harbor and facilities.

In view of the fact that future fleets of LNG tankers is going to be quite uniform in size and properties,* the waiting time study should not be completely dependent on random parameters. This is not a general queuing problem of a harbor with completely random inter-arrival times and service times, where ships broadly vary in size, properties, and cargo. The formulation of the probabilistic part of the waiting time problem is based on a Markovian process which is fundamental to most of the queuing calculation. The statistics represented by this process seem to be close in nature to the semi-regulated traffic problem under study.

2. THE SHIPPING CYCLE

As a tanker arrives in the loading harbor and is maneuvered to a berth, the deballasting phase starts. The ballast in an LNG tanker is approximately 40% of its capacity, and deballasting requires about six hours. At the same time, the connection of the loading pipes takes place, thus preparing the ship for the filling operation, to start as soon as the deballasting phase is completed.

In order to guarantee a safe loading operation, loading facilities for LNG are commonly set-up to handle the loading of one tanker at a time for each pier. In other words, there is one loading set-up per two docking spaces. This would mean that while one ship is being loaded, a second tanker can be docking at the other side of the pier either being ready to be loaded, or in preparation for loading.

* A fleet of LNG carriers intended for the American market is presently under construction and consists of tankers whose characteristics and volume are virtually identical (125,000 m^3). The capacity of future ships may be increased to 200,000 m^3. The LNG carrier fleet intended to serve the European market is less homogenous and will range from 35,000 to 125,000 m^3 with an average ship size of 75,000 m^3.

The average service time of a tanker can be defined in two ways. The first way is based on the number of loading facilities, where the loading time of the ship is counted as the service time. This is based on the assumption that the loading pumps can be used continuously with a double berth. The second approach is based on the number of berths in the harbor. In this case, service time is the total time elapsing from ship arrival to departure, including waiting time away from a berth. It is evident that the loading system should be so designed that effectively the two waiting times will be close. The loading facilities should have the capacity of filling-up a tanker in 10 to 15 hours independently of its size.

A set of statistics for the filling rate of oil tankers as a function of their size exists. Such statistics do not exist, to our knowledge, for LNG ships. For the sake of the calculations, we have adopted the following typical values:

- 20 hours for 200,000 m^3 ships, determined by a pumping capacity of 10,000 cubic meters per hour.
- $12\frac{1}{2}$ hours filling time for a 125,000 m^3 ship.
- 10 hours for a 75,000 m^3 ship, determined by the size of the connecting system to fill said ship.

The filling rate will take account of the following. The volume coming from the LNG container is about 99% of the ship's capacity. The loss of gas during filling operations is estimated at about 1%. The volume of LNG actually loaded onto the ship is therefore 98% of the ship's capacity.

The loss from boil-off during travel is 0. 2 to 0. 3% per day; therefore, assuming, for instance, a 7-day trip covering a distance of 3360 miles, the corresponding loss will be 1. 75%. Also, 3% of the load is held back for the return trip, so that only 93. 25% of the LNG ship's capacity is actually delivered.

The shipping cycle involves also the maneuvering time of a ship in and out of the harbor. The average time of 6 hours is reasonable for this part of the shipping cycle. As mentioned before, it takes about 6 hours to deballast a ship and connect it to the loading facility.

In some cases, the queuing model will address itself to a complete shipping cycle involving loading, unloading, maneuvering operations at two harbors and the shipping round-trip. A complete cycle type problem involving a single loading harbor and several destination harbors will result in several queuing problems coupled together. Since waiting times are expected to be very small with respect to the cycle times, the queuing problem at each individual harbor can be isolated. In the present study, it was assumed that the loading process is identical to the unloading process, thus leading to a symmetric model. This assumption is perfectly acceptable, even though tankers are loaded by harbor facilities while they are unloaded by means of shipborne pumps.

Between harbors, it is expected that the LNG tankers will be cruising at a speed of 20 knots. For example, an LNG tanker will cover the distance between Arzew, Algeria, and Savannah, Georgia, a total of 3800 nautical miles, within 190 hours.

As in the harbor operations, it is expected that the ships' activity will be somewhat reduced due to weather and sea conditions as it cruises between harbors. For this reason, a 7% overall reduction in efficiency has been taken into account. Also, the harbor entrance may be closed because of wind, sea states, or fog.

The formulation of the waiting time problem is probabilistic and is closely related to the standard queuing theory. Let p the fraction of the total cycle time T, finding a single ship being in a server, the first case is loading or unloading and in the second case being in the harbor. Correspondingly, 1-p is the fraction of T for a ship being away from a server. To meet the annual shipment of Q m^3 of LNG will require using M ships:

$$M = \frac{QT}{330 \times 24\, a B D}$$

where

D = Volume of an average ship
a = Fullness of the ship ≈ 0.98
B = Weather and sea conditions factor ≈ 0.93

assuming that the ships operate 330 days a year.

Let the number of severs in the harbor be L and let the number of ships at any time at the harbor be K. In the event $K < L$, it will mean that all the ships at the harbor are served. If $K > L$, L ships are served while K - L ships are in queue waiting to be served. The fraction of time finding K ships at the harbor, of the total number of M ships dedicated to the operation, at any time t is $P^{K}_{M}(t)$, with K greater or smaller than L but less or equal to M.

On using a Markovian approach, we can now formulate the time fraction relationships representing the ship traffic through the harbor.

The details of this theory have been developed at Tetra Tech and presented by Fersht (1974). Only the results are presented herewith.

3. LNG BERTHS - ALTERNATIVE SOLUTIONS

In view of the fact that filling and maneuvering times decrease less rapidly than tanker size, without calculating the waiting time, and simply on the basis of the time necessary to ship a given volume of LNG, it is immediately apparent that the number of mooring berths required increases when the size of tankers decreases.

Consequently, in all probability and assuming an equal distribution of LNG between the two markets, it will require an extra berth to satisfy the European market with ships of 75 - 85,000 m^3 average capacity than it will to satisfy the American market with ships of 125,000 m^3 capacity or more. This is emphasized by the fact that since the distance to American destination harbors is greater, the relative waiting time and consequently, the financial losses derived therefrom are of the same order of magnitude for both markets.

As a result, the appropriate option is to be chosen from a number of alternatives, defined by the number of berths, such as:

	Number of Berths	
	American Market	European Market
Option I	2	3
II	3	4
III	4	5

Waiting time and corresponding costs are determined for these three solutions. It is immediately apparent that in passing from one solution to the other, there results, in both cases, an increase in cost corresponding to:

1) One double berth;
2) An increase in the length of the main breakwater equal to the projection perpendicular to the shore of the distance between two berths (i. e. , approximately 320 meters);
3) A supplementary dredging area 320 m long, extending parallel to the shore.

In passing from Option I to Option III, the corresponding cost is doubled. The appropriate solution, therefore, should be evident.

A comparison of the results obtained with the Fersht closed loop mathematical model and Erlang open loop formula shows that the Erlang formula is more conservative. It is also to be noted that the methods of calculation based on the Erlang formula are independent of the market, destination harbor, cruising speed, and other effects. The only factor considered is the frequency of arrival of ships at the harbor, the capacity of said tankers, and their filling and maneuvering times.

In the Fersht model, account must be taken of the complete shipping cycle.

The results of the calculations are set forth in Table 1 for the American market, and presents the results of the two theories. The figures in parentheses are the results of the closed loop theory developed by Fersht (1974). The other figures give the results obtained from the Erlang formula for an open queue.

A similar Table has been established for the European market. The cruising time in a round-trip for the American market without losses due to weather and sea conditions is 380 hours. The corresponding average cruising time for the European market is 70 hours. For the American market, two types of LNG tankers have been considered which are the 125,000 m^3 tanker currently under construction and the future tanker of 200,000 m^3. In the European case, an average tanker size of 75,000 m^3 has been considered. As mentioned before, where pumping is regarded as determining the waiting time, calculations are carried out for 1, 2, and 3 servers. In the event the criterion for service is based on time in the harbor, the number of berths is regarded as the number of servers. Therefore, in the second case, one should use 2, 4, and 6 as the number of servers. The time values, using the loading criterion for the American market are (a is the service time of a ship in hours, b the total cruising time of a ship in a cycle).

For	D = 125,000 m^3	a = 12.5 hrs.	b = 405 hrs.
For	D = 200,000 m^3	a = 20 hrs.	b = 410 hrs.

The corresponding values for the berths criterion are:

For	D = 125,000 m^3	a = 25 hrs.	b = 380 hrs.
For	D = 200,000 m^3	a = 35 hrs.	b = 380 hrs.

In a similar fashion for the European market using a tanker size of D = 75,000 m^3, the times used are:

Loading case:	a = 10 hrs.	b = 94 hrs.
Berth case:	a = 24 hrs.	b = 70 hrs.

TABLE I

Daily Production: 108,000 m^3
Annual Production: 36,000,000 m^3

Ship Capacity		Present		125,000 m^3
Number of loads per year				290.9
Time interval between ships' arrivals				27.36
Waiting time based on times in hours		Loading 12.5	In Service 22.5	Total at Port 30
Solution 1:	2 berths	(9.45)	Not valid	10.26
	1 pumping station	10.51	Not valid	12.89
Solution 2:	3 berths	Not valid	(4.29)	(1.69)
	2 pumping stations	Not valid	4.58	1.79
Solution 3:	4 berths	(0.71)	Not valid	(0.28)
	2 pumping stations	0.72	Not valid	0.28

All these cases were examined numerically for the service times specified. In addition, the service time has been varied to demonstrate the dependence of the waiting time on the time length of the ships' service. An example of the obtained results is presented in Figure 1.

The results obtained clearly indicate that the loading criterion results in longer waiting times. This does not come as a surprise, by the fact that the loading criterion does not differentiate between waiting outside the harbor and waiting at one side of the pier while a second tanker is loaded at the same pier or its other side. A better comparison between waiting times for the two criterions will require a much more elaborate mathematical model for the time fraction study. The two criteria used here are sufficient to provide waiting time data for an economic study of an LNG harbor.

Typical values for Erlang's waiting time formula, which is related to an open cycle can be found in Torse (1961). Since the queue in the open cycle can be infinitely long, the waiting times are somewhat longer. For the American market where M is fairly large, Erlang's formula provides answers which are 10-20% larger than those obtained by the Tetra Tech method.

We would like to point out here that using Erlang's formula for the European market will result in unrealistically large waiting times.

TABLE 2

Annual Waiting Time &
Time Savings by Each Option (Hours)

	American Market		European Market	
Option	Total Waiting Time	Time Saved	Total Waiting Time	Time Saved
1	3750	----	5819	----
2	1332	2418	499	5320
3	209	1123	199	300

It is also important to bear in mind the fact that one ship may be immobilized at the mooring pier for a certain number of days for maintenance. The waiting time must, therefore, be calculated for the actual number of berths minus one. Since this occurs rarely, the problem is more operational than it is economical.

It is also important to note that the harbor may not be accessible say 30 days per year due to adverse weather and sea conditions. In this case, a queue will form at the harbor entrance, since one ship arrives for filling either every 27-36 hours (American market), or every 16-33 hours (European market), creating a transient. If a storm lasts three days, for instance, at least another three days will be required to fill all the ships which have been queuing to enter the harbor. Option 1 would require more than twice that waiting time.

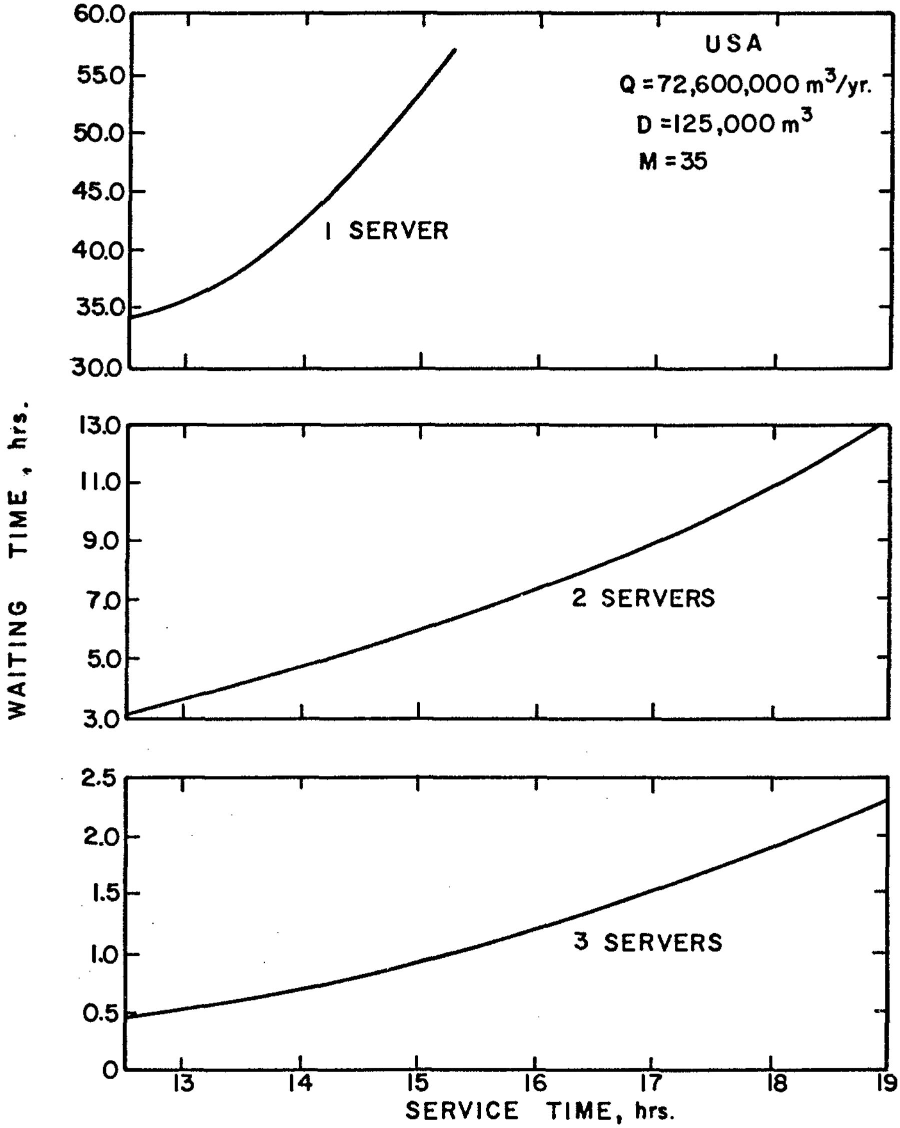
USA
Q = 72,600,000 m³/yr.
D = 125,000 m³
M = 35
1 SERVER
2 SERVERS
3 SERVERS
WAITING TIME, hrs.
SERVICE TIME, hrs.
60.0
55.0
50.0
45.0
40.0
35.0
30.0
13.0
11.0
9.0
7.0
5.0
3.0
2.5
2.0
1.5
1.0
0.5
0
13
14
15
16
17
18
19

FIGURE 1

4. COSTS OF THE OPTIONS VS LOSS OF WAITING TIME

The cost of Option 1 is not considered here, since this is the minimum size port that can handle the demand. The additional cost of Option 2 over Option 1 is as follows:

One pier with two berths	$10,000,000
* Breakwater 320 ($42,430/m)	13,600,000
Dredging (2,000,000 m^3, $7.0/$m^3$)	14,000,000
	$37,600,000

Option 3 would involve an equivalent additional construction beyond Option 2, and would costan additional $37,600,000. Total additional construction cost of Option 3 over Option 1 would be $75,200,000. In addition to the construction cost, provision would also be required for (1) financing costs during the construction period, and (2) maintenance costs during the life of the project.

* The deeper the breakwater, the less dredging. The shallower the breakwater, the more dredging. The numbers which are given are the results from a parallel study done concurrently on the optimization of cost of breakwater-dredging.

Construction would take place over three years and money for financing would be drawn down as used, and an interest obligation incurred. This interest obligation is generally capitalized and added to construction cost as part of the total financial package for long-term financing. With a 7% interest rate, the financing costs on $37,600,000 would be approximately $4,010,000.

Maintenance costs over the life of the project would be estimated from the following tabulation developed from analyses of harbors and dockyard facilities, and which have also been partly the results of a parallel optimization study.

Item	Annual Average Maintenance Cost as % of Construction Cost
Structures Not Exposed to Seawater	0.1
Structures Constantly Exposed to Seawater	0.25
Utilities	1.0
Machinery Infrequently Used	2.0
Machinery Frequently Used	3.0

In the present case, the rate for structures constantly exposed to seawater (0.25%) would apply. This might involve an overhaul every 10 years at 2.5% of the original construction cost.

The present value of costs to be incurred in the future requires a discounting of the future costs. In this case, 10% is an appropriate discount rate. For the first 25 years of the life of these facilities, the present value for maintenance would equal $37,000,000 x 0.0025 x 9.0768 (25-year cumulative 10% discount factor), or $40,000.

The total additional cost of Option 2 would be:

Construction Cost	$37,000,000
Financing Cost During Construction	4,010,000
Present Value of Maintenance for 25 years	840,000
Total:	$41,850,000

The total additional cost of Option 2 is $41,850,000. Option 3 would cost twice this amount, or $83,700,000 more than Option 1.

The value per hour of waiting time saved must be computed separately for each market because of the difference in construction and operating costs of the tankers. The waiting time that would be saved each year will be discounted at 10% to develop the present value for future time saved. A project lifetime of 25 years will be assumed in the computation, though this is conservative.

The capital, financing, and operating costs for three sizes of LNG tankers over an entire 20-year life are estimated by the Economist Intelligence Unit, assuming 340 days of operation per year. Converting to an hourly basis, the cost for a 125,000 m^3 tanker is $2000. A capital cost of $67,000,000 is assumed. The current tankers on order for El Paso in the United States will cost approximately $90 million. Therefore, using this higher updated cost of $90 million instead of $67 million and making comparable changes in interest charges, an hourly cost of $2040 is derived. For a tanker of 75,000 m^3 capacity, the hourly cost is $1350.

Using these hourly values for the time saved in Option 2 and 3, the following values are derived for annual waiting time saved:

	American Market (125,000 m^3 Tanker)	European Market (75,000 m^3 Tanker)	Total
Option 2:	Savings Over Option 1:		
	$4,940,000	$7,230,000	$12,170,000
Option 3:	Additional Savings Over Option 2:		
	$2,294,000	$ 408,000	$ 2,702,000

The present value of time saved over 25 years of full operation is derived by discounting at 10%, giving a value of 0.9091 of the annual value for the first year, 0.8264 for the second year, and 0.0923 for the twenty-fifth year. The sum of these values is 9.0768. This factor times the annual value of time saved gives the present value of 25 years of time saved for each option.

Computation of Present Value of Time Saved

Period:	25 years
Discount Rate:	10%
Cumulative Discount Factor:	9.0768
Option 2: Annual Savings:	$ 12,100,000
Present Value /25 yr. savings:	$110,510,000
Option 3: Annual value of additional savings over Option 2:	$ 2,702,000
Present Value/25 yr savings:	$ 24,530,000

A comparison of the construction, financing during construction, and present value of 25-year maintenance costs for Options 2 and 3, with the present value of time saved for each option yields the following:

	Option 2	Option 3 in Excess of Option 2
Total cost (construction, finance during construction, & present value of 25-year maintenance costs)	$37,600,000	$37,600,000
Present value of time saved to tankers over 25 years	$110,510,000	$24,530,000

The value of time saved to ship operators enables ultimate purchasers to pay the seller that much more for an LNG F.O.B. port. Thus, the seller can expect to recoup the additional port costs of Option 2 in the sales prices negotiated for LNG.

It is clear that expenditure of the additional $37,600,000 for Option 2 over the basic minimum of Option 1 will yield an amount more than twice as large in present value of ship time saved - $110,510,000. This expenditure is therefore warranted.

The further expenditure of an additional $37,600,000 for Option 3 would yield an additional present value for ship time saved of only half as much--$24,530,000. This expenditure is marginal.

The sensitivity of this decision to a change in the discount rate was examined in view of the current uncertainties about interest rates and discount rates.

This analysis confirms that whatever the discount rate used, the present value of time savings under Option 2 will exceed the cost of Option 2, and the present value of additional time savings under Option 3 will fall marginally short of the additional cost of Option 3 over Option 2.

Therefore, it appears that Option 2 is the optimum solution. However, it is pointed out that due to transient effect (after a long storm, for example), or due to the possible immobilization of one berth by a ship under repair, an additional berth is recommended to Option 2 -- this is an operational, not an economic decision.

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