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JOINT INDUSTRY PROJECT

FEASIBILITY AND COSTS OF EXPLORATION AND PRODUCTION SYSTEMS IN OCS LEASE SALE 87, DIAPIR FIELD, ALASKA

VOLUME 1 (OF 2)
FINAL REPORT

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AOGA PROJECT NO. 233

BRIAN WATT ASSOCIATES, INC.
SEAFLO SYSTEMS
BEN C. GERWICK, INC.

211/BWA

ABSTRACT

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This joint industry study assessed the feasibility and costs of exploration and production systems in OCS Lease Sale 87 area in the Diapir Field, Alaska. It was conducted on behalf of twenty companies, and is listed by the Alaska Oil and Gas Association as Project No. 233. The lead role for the study was taken by Brian Watt Associates, Inc. (BWA) of Houston, Texas, working in conjunction with Ben C. Gerwick, Inc. (BCG) of San Francisco and Seaflo Systems, Inc. of Houston.

The study examined a number of different concepts, from bottom founded gravity structures with integrated drilling facilities, to artificial islands, floating drilling units, and subsea systems. The concepts were investigated in water depths between 60-ft and 300-ft, under ice and soil conditions typical to the Diapir Field.

Appropriate design criteria for the investigation were developed with reference to both proprietary and public information. Each concept was then studied to assess its technical feasibility. A trade off study was performed to investigate the cost sensitivity to changes in design parameters.

Tow routes and installation methods were examined. A risk analysis was carried out to quantify the probabilities of success in towing deep draft gravity structures to different locations in the sale area. A separate risk analysis was also performed to assess the probabilities of success in drilling from floating rigs at various locations.

Cost estimates were made for typical scenarios using each concept. Unit rates obtained from discussions with potential contractors and other consultants were used, together with BWA's own direct experience with Arctic projects. Estimates were also made for the construction schedules for each concept.

The study established the technical viability of the systems considered, and also identified the limitations to the application of each system. The scenarios considered enabled estimates to be made of the capital costs for each concept, together with their sensitivity to changes in the design parameters.

EXECUTIVE SUMMARY

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1.0 INTRODUCTION

This report presents the results of a joint industry study to assess the feasibility and costs of exploration and production systems in OCS Lease Sale 87 area in the Diapir Field, Alaska. It has been conducted on behalf of twenty companies in the oil and gas industry, and is listed by the Alaska Oil and Gas Association as Project No. 233. The lead role for the study was taken by Brian Watt Associates, Inc. (BWA) of Houston, Texas, working in conjunction with Ben C. Gerwick, Inc. (BCG) of San Francisco, and Seaflo Systems, Inc. of Houston.

2.0 THE LEASE SALE AREA

The lease sale area comprizes about 24,000 square miles of offshore territory, approximately 400 miles along the Alaskan Beaufort Sea Coast and bounded by the 300 ft isobath approximately 60 miles offshore (see Figure 1 attached with this Executive Summary). Of this, about 63 percent is in the 100-200 ft water depth range, with 16 percent below 100 ft and 21 percent over 300 ft. The area is characterized by severe ice conditions and is one of the most hostile that has ever been offered for lease to date.

3.0 STUDY OBJECTIVE

The objective of this study is to identify suitable exploration and production structures that will be feasible for operation in this area and estimate their capital costs to assist in lease sale planning exercises.

4.0 CONCEPTS INVESTIGATED

The following types of structures have been investigated for feasibility and cost:

<u>Exploration:</u> Cones resting on seabed (Figure 2),
Cones on sub-bases or gravel berms (Figure 3),
Caissons with or without sub-bases or berms (Figure 4),
Caisson Retained Islands (Figure 5),

Turret Moored Drillship (Figure 6),
Purpose built floating drilling unit (Figure 7).

Production: Cones with or without sub-bases or berms,
Caissons with or without sub-bases or berms,
Caisson Retained Islands,
Production/Loading Atoll (Figure 8),
Subsea systems (Figure 9).

5.0 APPROACH FOR DETERMINING FEASIBILITY

Appropriate design criteria for the investigation were developed with reference to both proprietary and public information. Each concept was then studied to assess its technical feasibility. Emphasis was placed on global behavior, rather than detailed analyses of the systems. The feasibility was assessed on the basis of resistance to environmental loads, and construction and installation considerations. A trade off study was performed to investigate the impact of change in the design parameters on the behavior, and ultimately cost, of the concepts.

Tow routes and installation methods were examined. A risk analysis was carried out to quantify the probabilities of success in towing deep draft gravity structures to different locations in the sale area. A separate risk analysis was also performed to assess the probabilities of success in drilling from floating rigs at various locations. These analyses were based on presently available data bases in the public domain.

Subsea systems were investigated to determine their application in the arctic environment.

From the above work the study was able to establish the technical viability of the systems considered, and also identify the limitations to the application of each system.

6.0 APPROACH FOR COST ESTIMATES

With their feasibility established, a typical scenario for each concept was broken down into its component construction phases and a cost build up exercise performed for each phase. Unit rates obtained from discussions with potential contractors and other consultants were used. BWA's own direct experience with Arctic projects was also applied. Using these component costs typical scenario costs were calculated, enabling estimates to be made of the capital costs for each concept, together with their sensitivity to changes in the design parameters. Estimates were also made for the construction schedules for each scenario. Drilling and operating costs, supply logistics, maintenance costs, and transportation costs were outside the scope of this study and have not been addressed.

7.0 CONCLUSIONS

The overall conclusions for the study are summarised as follows. The costs given are based on the construction of the structures being carried out on the west coast of North America. If Far East construction is employed, the costs are likely to be lower by about 15 - 20 percent than those given in this report. The costs are for the concepts under basic ice loads; for cost sensitivity to ice load refer to Section 5.5. The costs include construction, transportation, installation, and topsides associated with each concept.

EXPLORATION SYSTEMS

The following cost figures are for concepts on clay (c_u = 0.6 ksf) foundation material. For exploration cost sensitivity to soil conditions refer to Section 5.5.

All Water Depths

1) Monolithic caissons are generally cheaper than cones, but:

- are more sensitive to ice overload.

- rely on strength gain in the foundation when founded on clay soils.

2) The cone is the most reliable concept under ice overload, and is feasible on all stipulated soil conditions without allowances for strength gain.

3) Floating drilling units are significantly cheaper than gravity based structures, but have a much lower probability of successfully completing a well in any one year.

Shallow Water (60 - 130-ft)

1) The estimated cost for a cone to operate in this water depth range is $375MM.

2) The estimated cost for a monolithic caisson (for 75 - 130-ft) is $380MM.

3) In water depths up to approximately 100-ft the caisson retained island is the cheapest concept, but is primarily for single use only. The estimated cost of an island in 75-ft water depth is $165MM.

4) Floating drilling units are only applicable in water depths in excess of 100-ft. Their estimated cost is $150MM, independant of water depth. This cost does not include the cost of ice breaker support, supply logistics, etc.

Intermediate Water Depth (100 - 200-ft)

1) The estimated cost for a cone in this water depth range is $500MM.

2) The estimated cost of a monolithic caisson is $425MM.

3) The caisson retained island becomes more costly than other concepts due to high berm construction costs. ($845MM in 200-ft water depth)

4) Deep berms are not an economic alternative to independant sub-bases for large extensions in working depths.

5) Shallow berms (up to 50-ft) may be useful in providing a small extension to the operating depth of a structure.

Deep Water (200 - 300-ft)

1) The estimated cost for a cone based system is $790MM.

2) The estimated cost for a monolithic caisson is $550MM (for 100 - 300-ft).

3) The use of berms is not realistic in deep water, due to high cost and short construction season.

PRODUCTION SYSTEMS

All Water Depths

1) Monolithic Caissons are generally cheaper than cones, but:

- are more sensitive to ice overload.

- rely on strength gain in the foundation when founded on clay soils.

2) The cone is the most reliable concept under ice overload, and is feasible on all stipulated soil conditions without allowances for strength gain.

3) Subsea systems installation is feasible in the arctic environment and can be cost effective. Example costs are:

   1) To drill, complete and connect back to a permanent production facility a 10,000-ft deep satellite well, 2.5 miles from the facility, in 200-ft water depth will cost approximately $68MM.

   2) To install a 4-well template in 300-ft water depth, drill and complete the wells (15000-ft deep), and connect the template to a production facility 4 miles away will cost approximately $283MM.

   3) To dredge a glory hole and install an 8-well template in 200-ft water depth, drill and complete the wells (5000-ft deep) and connect back to a production facility 3 miles away will cost approximately $354MM.

Shallow Water (75 - 100-ft)

1) The estimated cost for a 200,000 BOPD production cone in 100-ft water depth varies from $720MM to $840MM, depending on the soil conditions.

2) The corresponding cost for a 200,000 BOPD production monolithic caisson in 100-ft water depth varies from $640MM to $765MM.

3) The caisson retained island is more expensive than the monolithic structures, costing $860MM in 75-ft water depth, due to high arctic hook-up costs.

4) Production and loading atolls are three to four times more expensive than other concepts, costing $2720MM in 80-ft water depth.

Intermediate Water Depth (200-ft)

1) The estimated cost for a 200,000 BOPD production cone in 200-ft water depth varies from $790MM to $950MM, depending on the soil conditions.

2) The corresponding cost for a 200,000 BOPD production monolithic caisson in 200-ft water depth varies from $715MM to $840MM.

3) A monolithic structure founded on the seabed is always cheaper than a shallower structure founded on a berm.

Deep Water (300-ft)

1) The estimated cost for a 200,000 BOPD production cone in 300-ft water depths varies from $915MM to $1090MM, depending on the soil conditions.

2) The corresponding cost for a 200,000 BOPD production monolithic caisson in 300-ft water depth varies from $800MM to $925MM.

General Conclusions

1) On strong soils, the overall size of a cone is governed by floating stability. In all other cases size is governed by geotechnical behavior.

2) On clay soils the monolithic caisson requires artifical strength gain techniques for realistic structural sizes to work.

3) For caissons, the use of artificial drains to improve geotechnical behavior is more effective in reducing structural size than the use of spud piles.

4) Ice loads on vertical sided structures are significantly larger than on cones and are sensitive to waterline diameter. It is our opinion that the deterministic method used overestimates ice loads on caissons. A method using a probabilistic approach, currently being developed, is considered to yield more realistic results.

5) For gravity structures, the overall size is more sensitive to soil conditions than to ice conditions.

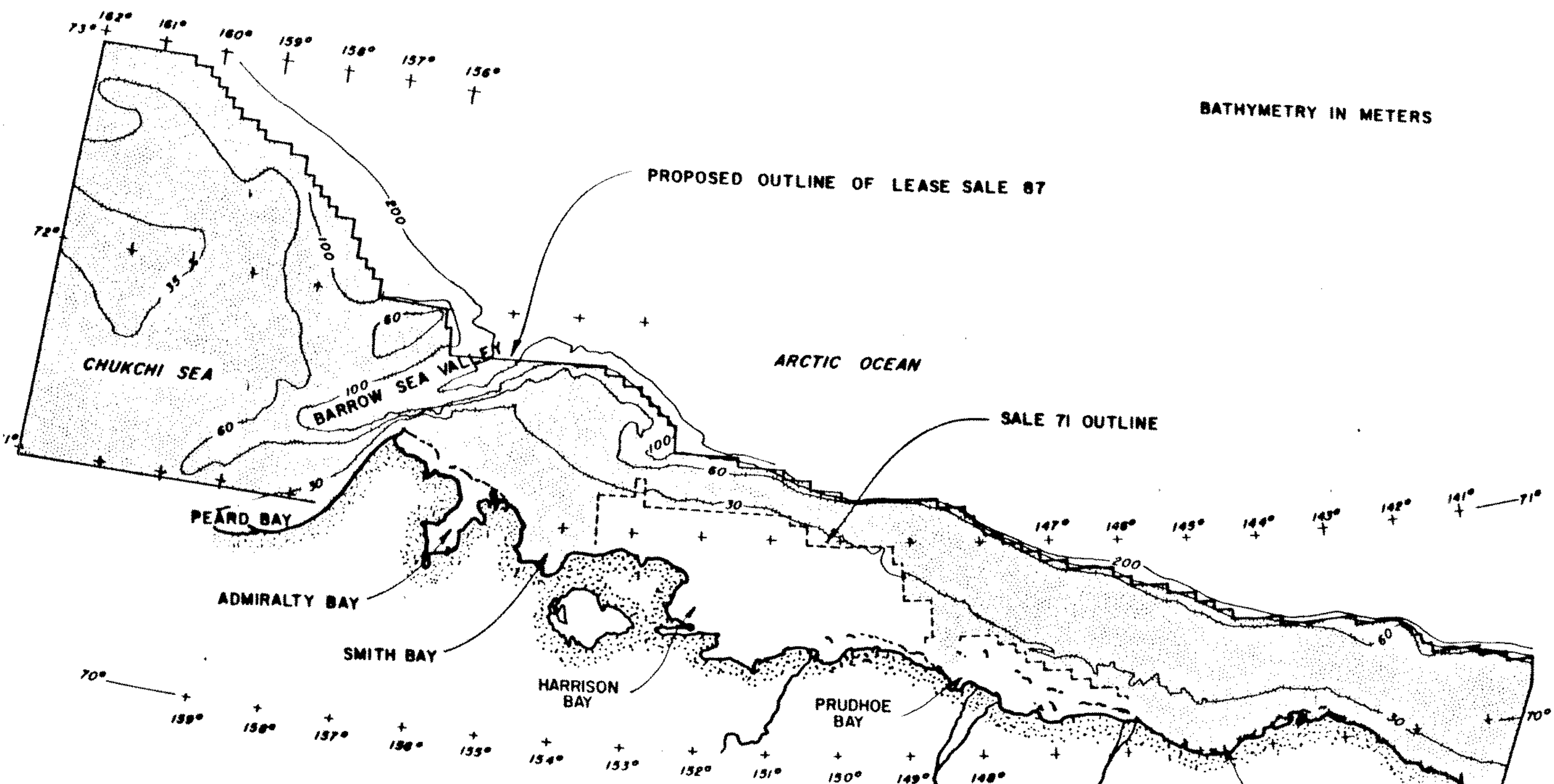
6) The probability of successfully installing a gravity structure is high, provided departure from Icy Cape takes place early in the open water season.

7) Increasing the towing draft requirement for gravity structures from 65-ft to 130-ft had little effect on the probability of successfully installing the structures, generally from 1 to 4 percent.

8) For caisson retained islands on weak soils, excavation and replacement of seabed material is necessary.

9) Floating units can be operated in the arctic in water depths in excess of 100-ft, but they only have a limited environmental window in which this is possible, and may not be able to complete a well in one season.

10) There is scope for technology improvements in the fields of drilling, protecting, and maintaining subsea installations.



	SQ. MILES	%
<30m =	4,000	16
30 - 60m =	15,296	63
60 - 100m =	3,303	14
>100m =	1,719	7
	24,318	100

FIGURE 1 PROPOSED OCS LEASE SALE

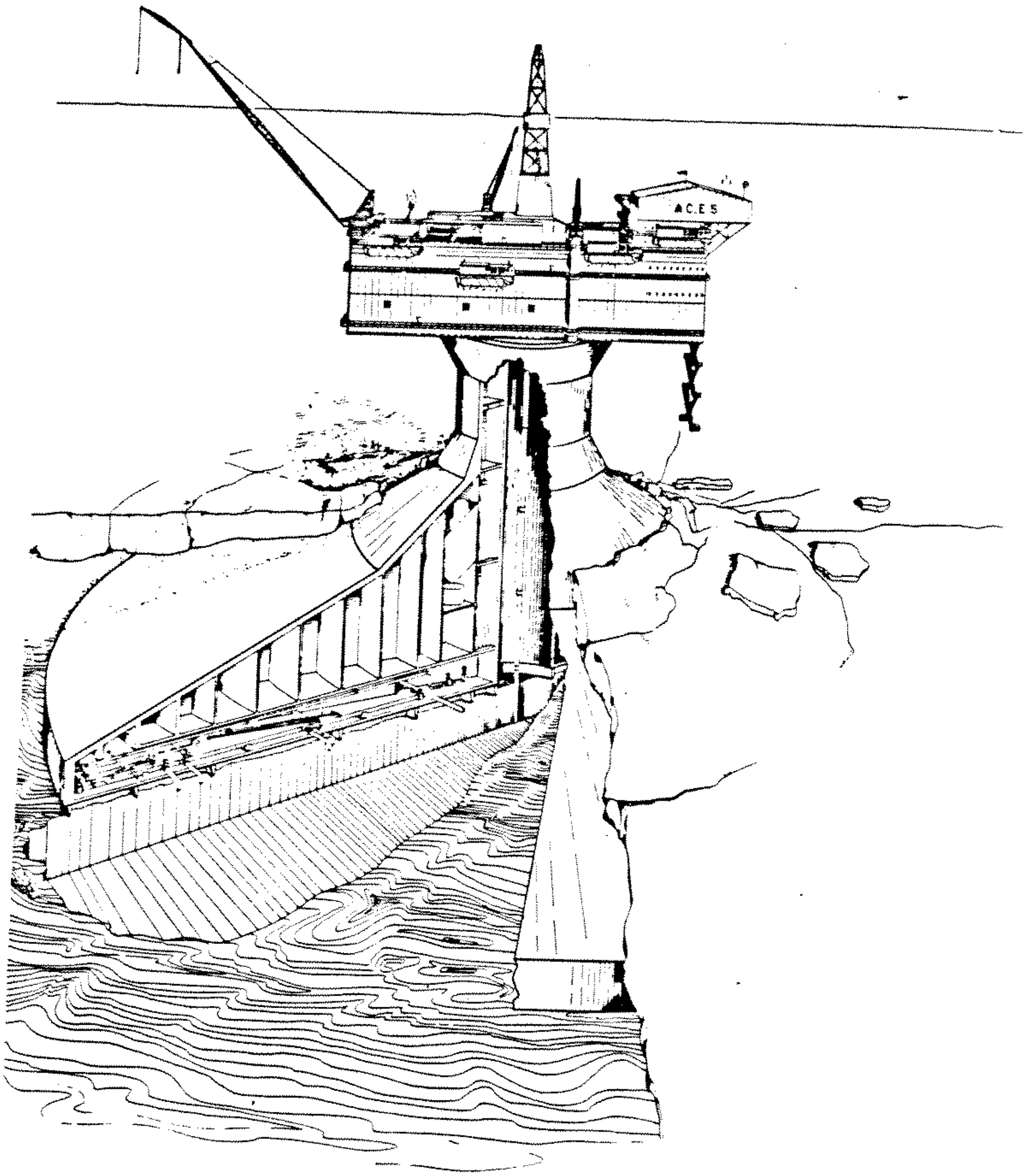
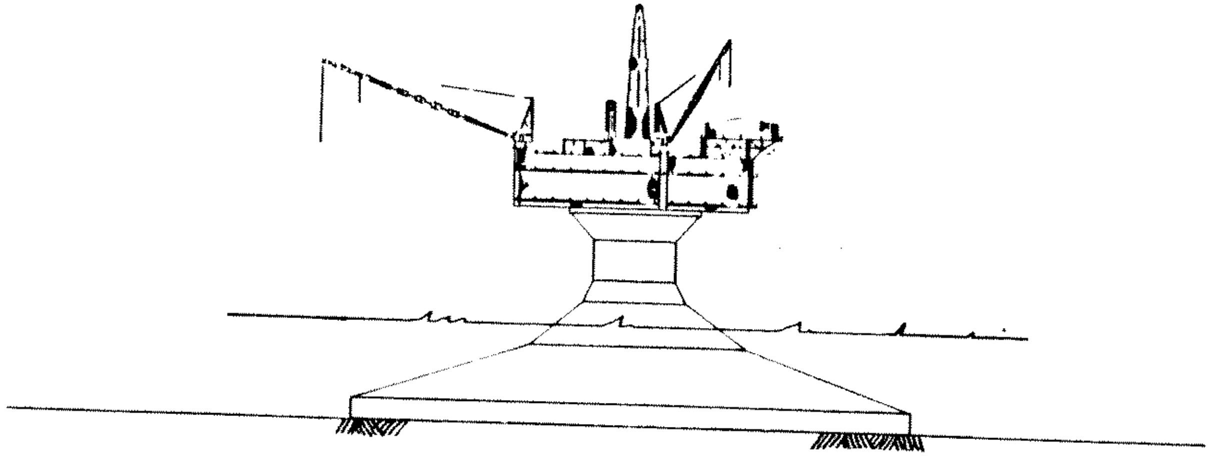
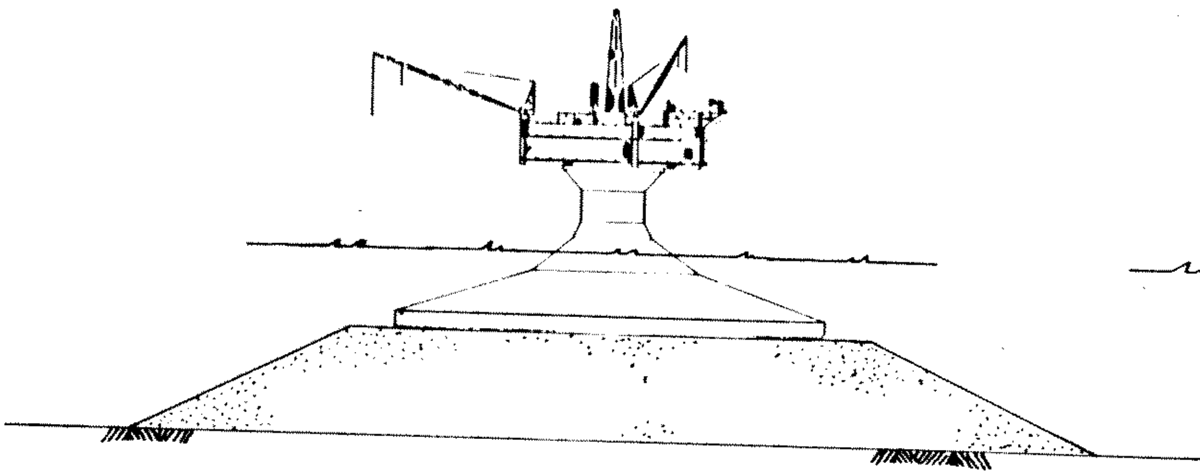


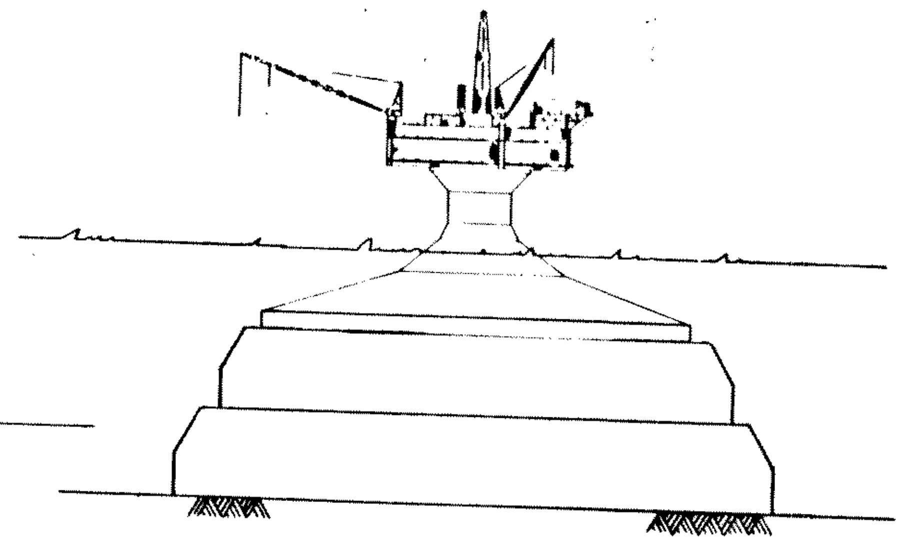
FIGURE 2 CONE CONCEPT



1. FOUNDED ON SEABED



2. FOUNDED ON GRAVEL BERM



3. FOUNDED ON SUBBASE SEGMENTS

FIGURE 3 APPLICATIONS OF CONE CONCEPT

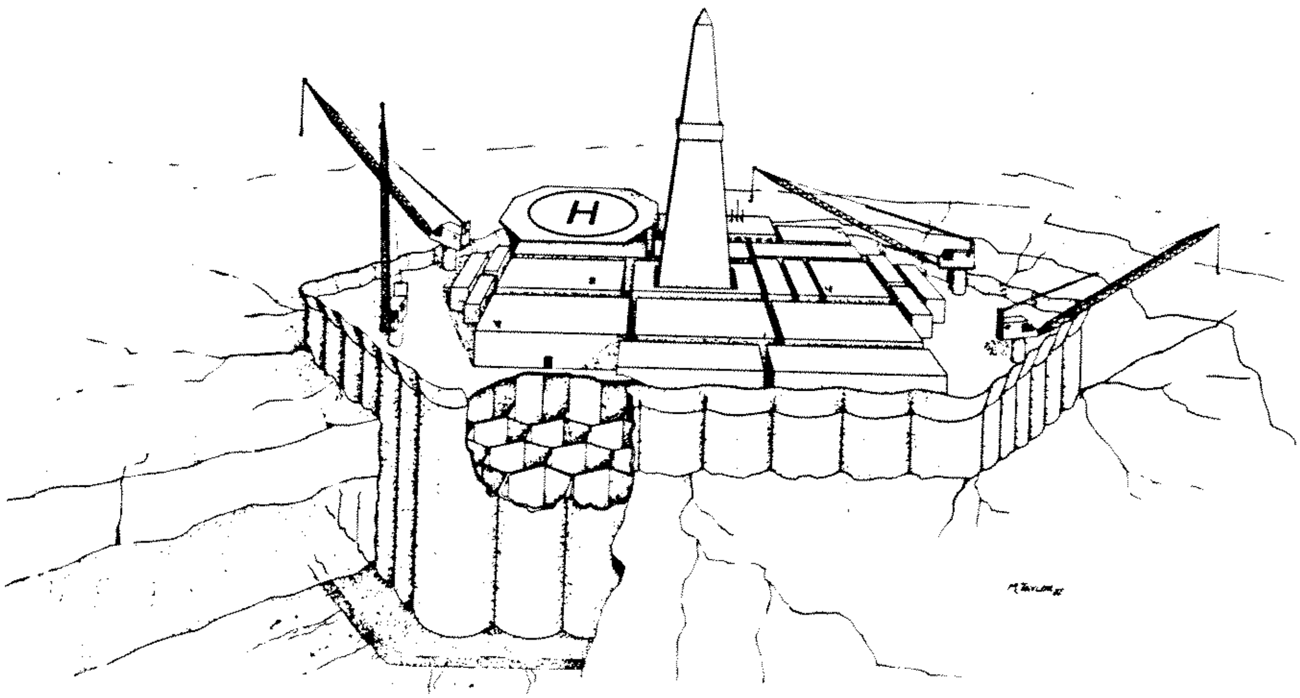


FIGURE 4 MONOLITHIC CAISSON CONCEPT

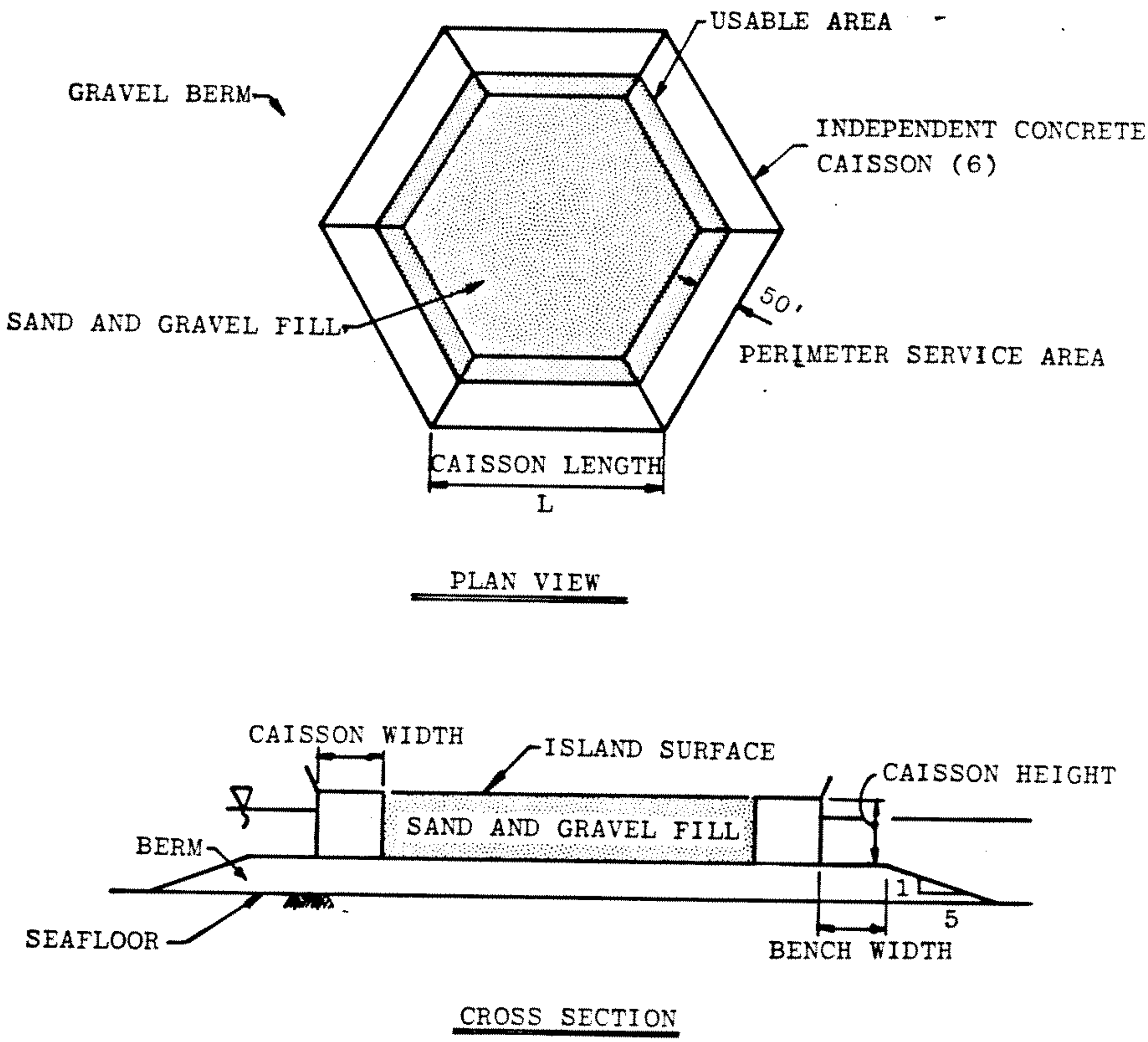


FIGURE 5 CAISSON-RETAINED ISLAND CONCEPT

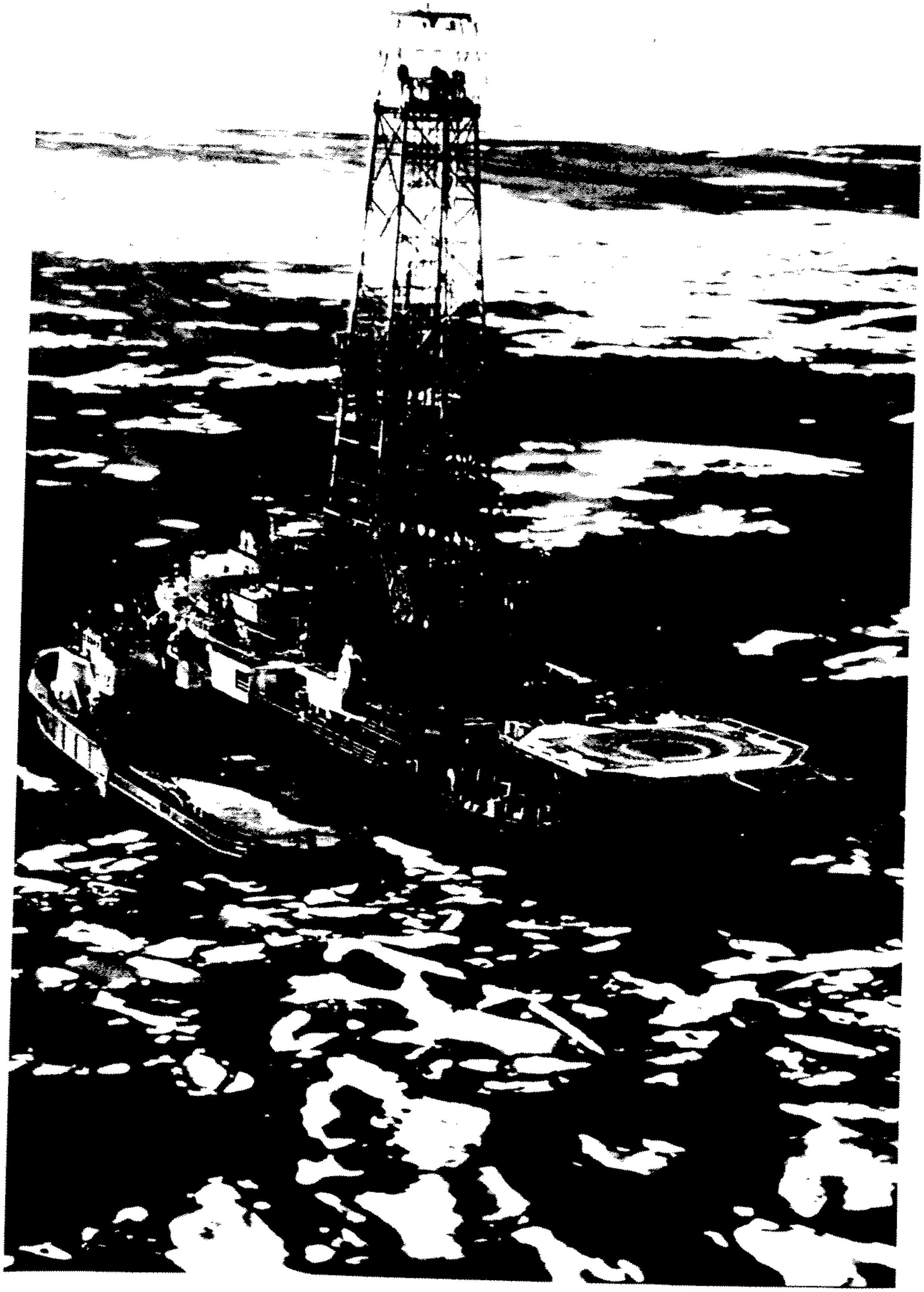


FIGURE 6 <u>TURRET MOORED DRILLSHIP</u>

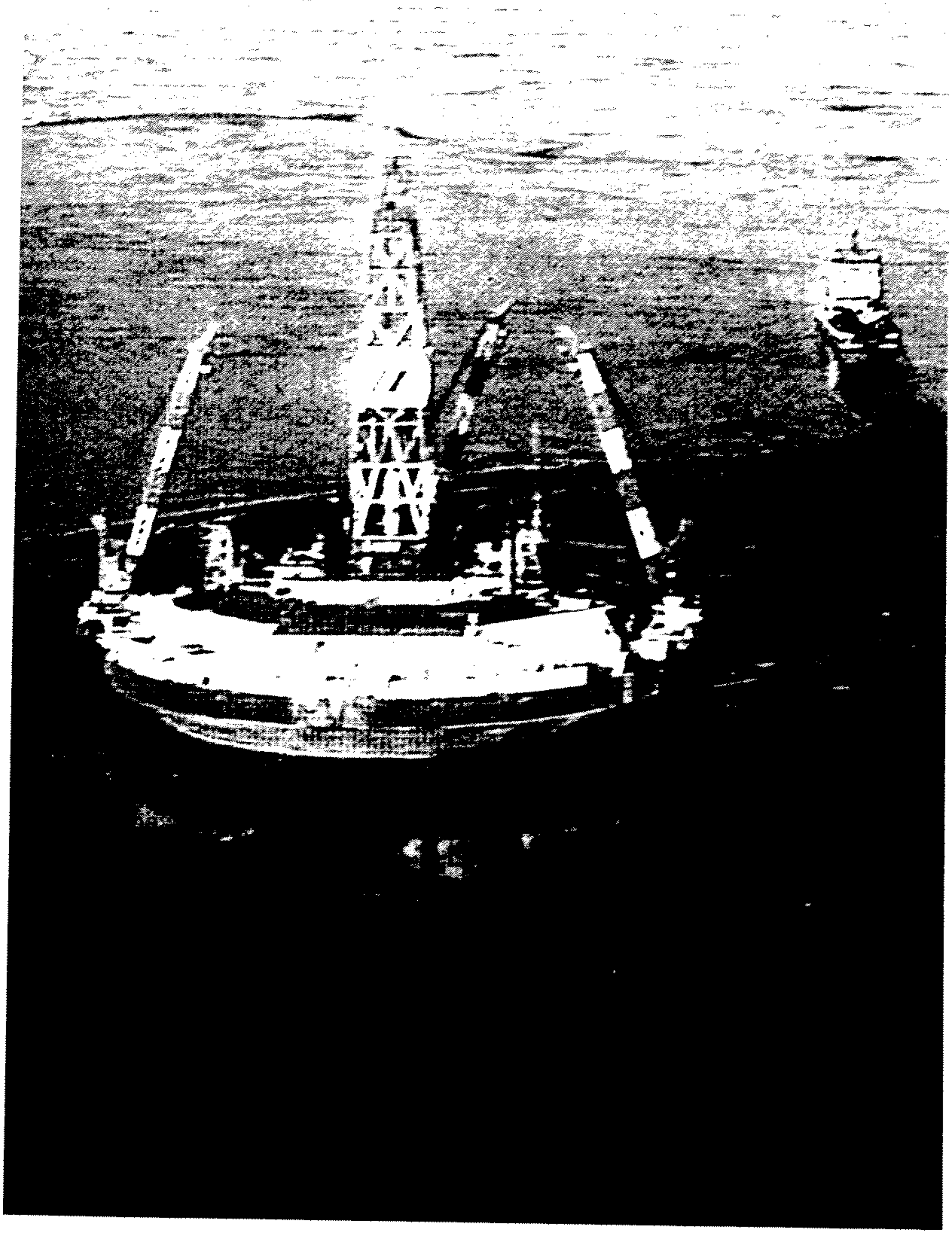


FIGURE 7 PURPOSE BUILT FLOATING DRILLING UNIT

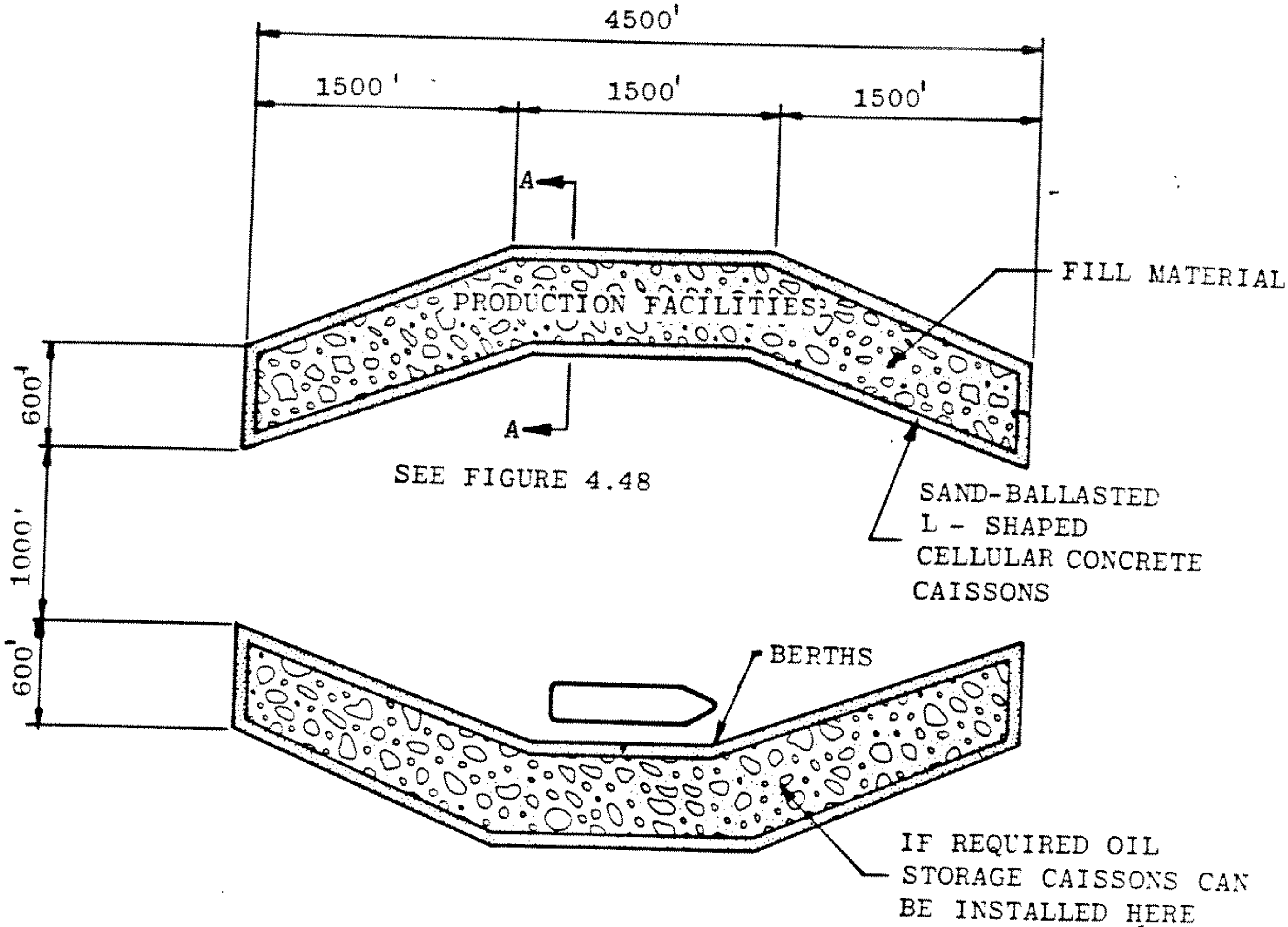


FIGURE 8 PRODUCTION AND LOADING ATOLL (SCHEME 1)

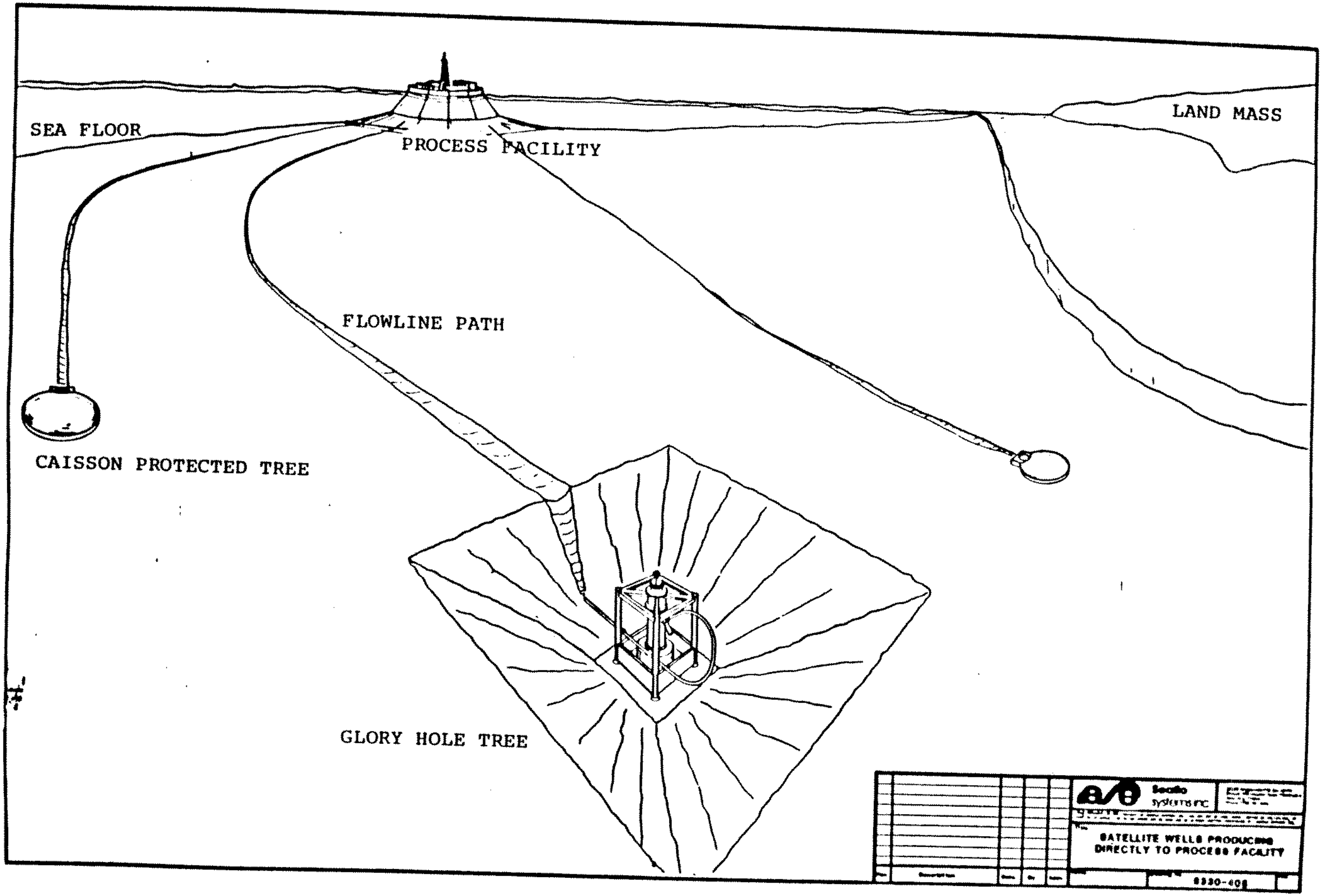


FIGURE 9 SATELLITE WELLS PRODUCING DIRECTLY TO PROCESS FACILITY

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for the case of circular foundation. The average bearing pressure at failure can be described with an approximate equation suggested by Meyerhof and Chaplin (7) as:

$$P_{ult} = c_u N_{ce}$$
$$N_{ce} = 5.05 + 0.33 \, B/H$$

where

N_{ce} = Equivalent bearing capacity factor
B = Foundation Diameter
H = Compressible soil layer thickness
c_u = Undrained shear strength of soil

ii) In Sand Sites

Bearing capacity of granular materials can be computed directly from the Buisman Terzaghi equation (8) modified to account for foundation shape, as follows:

$$P_{ult} = \tfrac{1}{2} \gamma' B N_\gamma \zeta_\gamma$$

where

γ' = Effective unit weight of the sand
B = Foundation width
N_γ = Bearing capacity factor
ζ_γ = Shape factor

The factor of safety for bearing capacity is calculated as:

$$F.S. = P_{ult}/P$$
$$P = \text{Structure effective weight/Base area.}$$

b) Stability Under Ice Loads

i) In Cohesive Soil Sites

Sliding at the skirt tip: Figure 4.6 illustrates this mode of failure. The sliding resistance is computed simply as the base area times the undrained shear strength at the mudline. The safety factor is taken as the ratio of the sliding resistance to the total horizontal load; the vertical component of the applied load does not affect the stability in this mode of failure.

Rotational stability: A limit equilibrium analysis method assuming a slip circle failure surface was used for stability prediction as shown in Figure 4.7. This investigation is necessary since this mode of failure may be generated by weak soil which could exist at some depth beneath the structure. We performed the stability analysis using our program, ROTATE. The procedure sets a grid pattern for the centers of the slip circles which are assumed to pass through one toe of the structure. For each circle, the moments about the center due to the forces and the soil resistance are computed. The safety factor is computed as the ratio of the moment due to applied forces and that due to the soil resistance. The critical slip circle is that which results in the minimum safety factor.

ii) <u>In Sand Sites</u>

Our study included a stability analysis corresponding to horizontal sliding. The sliding resistance was computed as the total effective vertical force times tan ϕ, where ϕ is the angle of internal friction of the sand. The safety factor is the ratio of the sliding resistance to the total applied horizontal load.

4.2.1.5 Geotechnical Considerations for Structures Resting on Berms

Submerged berms constructed of granular material can be used to extend the operating depth of an exploration unit as illustrated in Figure 4.8. Our stability analyses, and cost estimates were performed for berms having a top diameter equal to the structure diameter plus 100 feet (apron = 50 feet), a slope of 1:5, and height varying with water depth.

This section deals with the stability of structure-berm systems subject to gravity and ice loads for both cohesive and granular seabed soils.

a) **On Cohesive Seabed Soils**

The stability of the structure-berm system on cohesive seabed soils was studied using an approximate method, illustrated in Figures 4.9 and 4.10. This approach approximates the structure as a square of the same plan area, and assumes that failure takes place in such a way that the deformations are planar. The failure blocks is divided into several smaller blocks, and the equilibrium of forces on each individual block as well as of the whole mass, is studied. In this way it is possible to determine the maximum force necessary to cause failure. In order to account for three- dimensional effects, the shear forces acting on the two vertical side surfaces are also included in the analysis.

The safety factors of several surfaces of different sizes and penetration depths within the clay layer are determined, and the critical surface defined. The analyses was carried out using our in-house computer program, BERMSTAB.

b) **In Sand Sites**

Stability of the structure-berm system in sand sites was studied assuming that the berm and the foundation soil are a homogeneous material with the same ϕ angle. Stability under these conditions is not a governing criteria.

4.2.1.6 Naval Architecture

In general, conical structures have worsening stability characteristics as the draft increases. This is due to the smaller waterplane area and large displaced volume. For small diameter structures the floating stability can be inadequate even at their lightship draft. The floating behavior of the cone systems was therefore of great importance and, in some instances, dictated the global dimensions of the structures. In most other cases the geotechnical stability tended to govern the structure size.

The assumptions used in examining the stability is best illustrated by an example. Figures 4.11 and 4.12 show the installation procedure for a shallow water cone with one sub-base, operating in 200 ft water depth. Figure 4.13

shows the GM curve for this example. The combined structure has a very high GM at its lightship draft, which then decreases rapidly as the structure lowers into the water. The structure is lowered by first placing water ballast in the sub-base until it has a net buoyancy of 50,000 short tons. Subsequent ballasting then takes place in the cone. The reason for this is to maintain a compressive force at all times at the interface between the cone and the sub-base. By not allowing any tension at this interface the connection detail, which will be discussed further in the following section, is kept much simpler than if tension were allowed. In the stability calculations, a correction for free surface effects from the ballast water in both the cone and the sub-base has been allowed for.

When the GM has decreased to approximately 2-3 ft, further ballasting on an even keel would result in instability of the unit. To prevent this, it is necessary to differentially ballast the structure, as shown in Figure 4.12, until one edge rests on the seabed. Further ballasting, while maintaining this edge contact, will bring the structure to rest evenly on the seabed. Additional ballast can then be placed in both cone and sub-base to achieve the desired base pressure. A maximum tilting angle of 10^{o} was used in this study. If a particular configuration required a greater tilting angle then the structure dimensions were altered and rechecked.

The above procedure, in general, was also applied to exploration cones either on their own, or with two sub-bases. The governing principle being that a system should be capable of being ballasted on an even keel to its operating depth, or have tilting angle, as described above, of not greater than 10^{o} for floating stability to be acceptable.

4.2.1.7 Construction and Installation

a) Construction

The construction procedure follows that typically used for offshore gravity structures in the North Sea. The base section of the cone or sub-base would be constructed in a purpose built graving dock to a height such that it can be floated out with adequate under keel clearance above the dock gate sill. It would then be floated out and completed whilst moored in a sheltered offshore location. It is envisaged that, in the case of a cone and a sub-base being required, they would be constructed simultaneously in independant graving yards, not necessarily at the same location, in order to have the shortest possible construction schedule.

b) **Deck Mating**

Once the cone was complete, it would be towed to a sheltered deepwater location for the deck mating operation. This is illustrated in Figure 4.14. The deck would be built at a separate facility on two barges and transported to the mating site. With the aid of stability columns, the cone would be ballasted down to allow the deck to be floated over on the support barges. Deck mating would then be achieved by deballasting the cone as shown.

c) **Mating Cone and Sub-base**

To illustrate this operation it is again worthwhile to consider the general case of a cone and one sub-base. After completion of the two structures, they would be towed to a deep water location close to one of the construction sites. Figures 4.15 and 4.16 show the sequence of events for mating the two structures. Buoyancy tanks would be attached to the sub-base, located as shown to allow room for the cone to be maneuvered above the sub-base. The sub-base would then be ballasted to below the floating draft of the cone, and the cone towed in and positioned over the sub-base. Finally the sub-base would be deballasted, raising the combined system to its lightship draft.

Figure 4.17 shows a typical detail of the interface connection between the cone and the sub-base. The general principle is that the cone skirts will fit into recesses in the top of the sub-base, with a layer of compressed sand transferring the loads. Resistance to global horizontal loads will be provided by friction in the sand layer and reactions in the skirt recesses. The method used to achieve this detail is illustrated in Figure 4.17. The vertical load from the partially ballasted cone is initially taken by extended hydraulic jacks or flat jacks, placed in the bottom of the skirt recesses. The space between the underside of the cone and the top of the sub-base is filled with sand. The jacks are then depressurised while the sub-base is deballasted further, thereby compressing the sand layer. Sand undergrouting for tunnels, flood barriers, etc., has been carried out over a number of years now and a similar system will be used to sand undergrout the cone. It can be seen that this detail is not designed to carry tensile loads across the interface, which is the reason for the necessity to follow the ballasting procedure outlined in Section 4.2.1.5. In practice, however, it is likely that a limited amount of post tensioning tendons or drillpipe would be used to induce a nominal stress across the interface. These would be solely to provide a back-up system in the event of tension occuring due to unforseen causes, the primary behavior of the connection still being as described above.

With all mating operations complete, the entire system would be towed to the arctic and installed following the procedure discussed in Section 4.2.1.5. Tow routes and probabilities associated with successfully installing a gravity structure in the Lease Sale area are discussed in Section 4.5

4.2.1.8 Results

Figures 4.18 to 4.20 show examples of exploration cone systems, and Tables 4.1 and 4.2 give structural diameters, weights, and drafts of all the systems examined, and also berm volumes for comparison of the use of berms or sub-bases in deep water. There are two main points to be noted from these results.

The first is that the cone concept is feasible under all the environmental conditions considered, without any allowances being made for strength gain in the seabed soils due to consolidation effects.

The second is the sensitivity of the global dimensions of the structures to changes in the environmental conditions. Referring to Table 4.2 it can be seen by comparing the case of basic ice load and weak clay (c_u = 0.6 ksf) with that of high ice load and stiffer clay (c_u = 1.0 ksf), that the structural size is more sensitive to changes in soil conditions than ice conditions.

It is also worth noting that, on the stiffer clay (c_u = 1.0 ksf), the single cone is capable of operating from 100-200 ft, but on the weak clay (c_u = 0.6 ksf) this range is restricted to 120-200 ft. This is because up to 120 ft water depth the ice load is applied near the toe of the structure, resulting in a large moment acting on the cone which causes rotational failure on weak soil conditions. This last point should be qualified by noting that further investigation, considering the effects of consolidation, is likely to show that the operating range on the weak soil may be larger than shown.

To summarize the results, it can be seen from Tables 4.1 and 4.2 that exploration cone systems can be developed in water depths from 60 ft to 300 ft. The structural weight of these systems varies from approximately 350,000 short tons in shallow water (60-130 ft) to approximately 900,000 short tons in 300 ft water depth. The corresponding range of structural drafts is approximately 66 ft to 113 ft.

4.2.2 Monolithic Caissons

4.2.2.1 Structural Arrangement

Figure 4.21 shows a typical structural arrangement for a monolithic caisson. The caisson is hexagonal in plan and is composed of hexagonally shaped cells. This structural framework provides for highly efficient distribution of horizontal loads through the structure, thereby resulting in a low weight to volume ratio. The outer shell, which is designed to withstand both local and global ice loads, comprises a series of curved panels. With this system, a large proportion of the load on each panel is taken in compression, thereby making maximum use of the compressive strength of concrete. The base slab and skirts are designed to withstand the same loading conditions as for the cone, the latter being described in Section 4.2.1.1. The facilities for the caisson will be carried on the deck and the top slab is therefore designed to support a uniform load from the facilities modules. As for the cone, we have relied on our previous experience with caisson structures to establish member thicknesses.

There are two points regarding the overall geometry which should be noted:

1) Since the ice loads on a caisson are dependant on the structural diameter at the waterline, it is advantageous to utilize a stepped structure, in which the diameter at the seabed is larger than the waterline diameter. This enables a higher foundation resistance to be achieved for the same horizontal ice load. Where stepped structures have been used, a maximum aspect ration of 2:1 has been assumed for the stepped section of the structure to provide adequate rigidity on the projecting cantilever.

2) For the same reason as above, it is desirable to minimize the waterline diameter. It has therefore been assumed that the facilities modules would be stacked on two levels, thereby reducing the area requirement for the top deck. The area requirements used are shown in Table 4.3

4.2.2.2 Environmental Criteria

The variation in ice load with structural diameter for caissons is shown in Figure 4.22. The basis for these loads and the methodology behind their determination are given in Section 2.2 and Appendix A, respectively. By comparing Figure 4.22 with Figure 4.5 it can be seen that the ice loads on caissons are significantly greater than on cones. The effect of this on the behavior of the two concepts will be discussed in Sections 4.2.2.3 and 7.0. The soil condition used for examining the caisson feasibility is the same that is used for the cone systems (Section 4.2.1.3).

Since the caisson structure has a low weight to volume ratio, and is also vertically sided, it tends to have a shallow draft. Also, by increasing the height of the structure, it is capable of having a large operating depth range. Caisson systems were therefore examined with differing operating depth ranges, to cover the extent of water depths in the Lease Sale area, rather than using sub-bases. The operating depth ranges examined were 75-130 ft, 100-200 ft, and 100-300 ft.

For the sensitivity study, the ice loads assumed are shown in Figure 4.22. The reasoning behind these values is given in Section 2.3 of Appendix A. The soil conditions used for the sensitivity study are those used for cones (see Section 4.2.1.3).

4.2.2.3. Geotechnical Considerations for Caissons

The size of caisson structures is primarily governed by geotechnical considerations, since floating stability is not critical for vertical sided structures. Caisson structures in cohesive soil sites were initially dimensioned for undrained soil conditions. However, due to the large ice loads, the base areas required were extremely large, resulting in long construction schedules and high costs. In order to make these structures economically feasible two alternative foundation inprovement techniques have been investigated in this study:

1) Allowing for strength gain in the foundation soil with time.

2) Using spud piles to improve horizontal sliding resistance.

The strength gain in the soil can be accelerated with the aid of drains installed under the structure. Foundation drains or "wick" drains, as they are sometimes called, have been used to accelerate the consolidation of embankments on land for many decades. They comprise a 4 inch wide plastic core surrounded by a filter medium which is inserted into the soil with the use of a mandrel from a track mounted vehicle. The wick drains under the caisson structure will be installed using similar equipment from the deck.

Wick drains have been used in the foundation design of both exploration and production caisson structures, whereas the use of spud piles was limited to the design of production caissons only. This section will cover the geotechnical considerations for exploration caissons with and without wick drains.

The methods of analysis of the caisson structure sitting either directly on a cohesive soil or on a gravel berm are the same as those for the design of cones, and have been described in Section 4.2.1.4.

In the cases where wick drains were used, the structures were first dimensioned to yield a safety factor of 2.0 against soil failure under gravity loads. Strength gain due to consolidation under the structure weight was determined using a simplified method assuming two-dimensional consolidation. The horizontal and vertical coefficients of consolidation were assumed to be equal and constant with depth and the drains were spaced at 12 ft centers. The boundary between the clay and the sand was considered impermeable. Consolidation depends on the stress history of the clay; the maximum past pressure was approximately determined at several depths using the method presented by Ladd and Edgers (5). The method uses the initial undrained shear strength of the soil, as explained in Figure 4.23

Consolidation causes changes in the strength profile and influences the critical failure modes. For example, the rapid consolidation near the mudline makes sliding at the structure base unlikely even though the shear strength near the mudline may initially have been low. The failure mode may be one of shallow rotational slip initiated by a weaker soil layer at depth. The use of wick drains does, however, produce a considerable improvement in resistance to horizontal ice loads.

The gain in soil strength with time is shown typically in Figure 4.24. The initial shear strength near the mudline was taken as 1.0 ksf; the shear strengths resulting after 4 months with and without wick drains are presesnted, as well as the strength after one year without drains, included for comparison. These curves correspond to a surcharge of 3 ksf, which is a typical value for the caisson structures. The beneficial effect of the wick drains can thus be seen.

4.2.2.4 Construction and Installation

The general method of construction of the caisson structures follows that for the cones (Section 4.2.1.7). The only significant difference being that the topsides and facilities modules would be lifted onto the caisson deck by crane barges, rather than using the deck mating operation used for the cone.

For installation, caisson structures are always stable, and can therefore be ballasted down on an even keel all the way to the seabed. However, before the structure can be set down, the wick drains required for foundation stability must be installed. It is envisaged that the drains would be installed from the deck through sleeves cast into the structure along two of the hexagon's sides. The caisson would be ballasted down close to the seabed and a row of drains installed through the sleeves. Further rows of drains would be installed by moving the caisson progressively across the site. When a sufficient area of the seabed has been covered, the caisson would be set down and ballasted to achieve the desired effective base pressure. It should be noted that the installation of the drains is likely to take several days. However, an accurate estimation of the time, equipment spread, and cost for this operation is a subject which requires further investigation.

4.2.2.5 Results

Figures 4.25 and 4.26 show examples of exploration caissons with different operating depth ranges. Table 4.4 gives a summary of structural diameters, weights, drafts, number of wick drains required, and berm volumes where applicable, for the varying environmental conditions considered. The most significant conclusion to be drawn from these investigations is the sensitivity of the caisson concept to changes in the environmental conditions. Referring to Table 4.4 it can be seen that under the combination of the high ice load and weak clay (c_u = 0.6 ksf), it is not possible to develop a caisson with an adequate factor of safety, even with the use of wick drains to accelerate consolidation. Furthermore, with the high ice load and stiffer clay (c_u = 1.0 ksf), it is still not possible to develope a caisson to work in shallow water. This is because in shallow water there is not enough depth to be able to step the structural diameter out the amount required without exceeding the assumed limiting aspect ratio for the stepped section of the structure.

To summarize the results, it was found that, provided foundation improvement techniques were used, caissons could be developed under the basic ice loads in water depths from 75 ft to 300 ft. Their structural weights range from approximately 325,000 short tons in shallow water (75-130 ft) to 510,000 short tons in 300 ft water depth. The corresponding range of structural drafts is approximately 44 ft to 65 ft. Between 1750 and 2400 artificial drains will be required to improve foundation behavior. Under the upper bound ice loads the caisson was generally found to be an infeasible concept.

4.2.3 Caisson Retained Islands

4.2.3.1 Design Procedure

Design of the caissons requires three major design considerations:

- The outer skin and bulkheads,
- The caisson cross-section,
- The caisson length.

The thicknesses of the outer skin and bulkheads was based on previous experience. The caisson cross-section was determined from:

- Wave run-up,
- Height of active wave zone,
- Active earth forces,
- Slurry forces,
- Caisson sliding resistance,
- Floating stability.

Ice loads were also considered in the design of the caisson cross-section, however, they have little impact on the final design cross-section. The lengths of the caissons were determined from:

Facilities area,
Island sliding stability.

Numerous other design considerations enter into the design process. However, only those factors significantly effecting the size of the caisson retained island were considered.

4.2.3.2 Design Conditions and Assumptions

The two water depths examined were 75-ft and 200-ft. The soil strength profiles were the same as those used for exploration cone structures, described in Section 4.2.1.3.

Even after shear strength gains were considered, the weak soil profile used showed that excavation of soil to a depth of about 20 feet would be needed. Therefore, the designs given here include excavation of soil to 20-ft depth.

We have examined the shear strength gains for both island designs. It was assumed that the island berms would be placed one year before installation of the caisson and backfilling. The shear strength gains given in Table 4.5 assume that preloading has taken place for one year. No artificial drains were used in determining the strength gains.

The ice loads used for evaluating island stability are identical to those given in the design criteria for caisson structures having vertical walls.

Unit weight of backfill material was assumed as 129 pcf and that for foundation soil as 120 pcf.

4.2.3.3 Analysis and Design

Previous experience shows that caissons having heights between 50 and 140 feet require concrete quantities of about 14% to 20% of the enclosed volume. For this study, we used 16%.

The height of the caisson is controlled mainly by the wave height. The freeboard height is determined from the height of run-up. On vertical walls run-up is typically taken to be twice the wave height. In order to reduce the amount of concrete used in caissons, a wave deflector was used to attain added freeboard. The caisson height below the waterline is a function of the significant wave height. Typically, 1.5 times the significant wave height defines the active wave zone below the water line. The significant wave height was taken as 16 feet. The resulting caisson height required below the waterline is 25-ft. The total caisson height was thus then taken as 70 feet excluding deflectors so that the gravel berm is well below the active wave zone.

Caisson width is based mainly on the ability to withstand horizontal loads such as slurry loads during backfilling, active earth pressures during operations, or ice loads. However, naval architecture considerations dictate that the aspect ratio, or base width divided by caisson height, is greater than or equal to 1.0. The passive pressure behind the caissons was considered adequate to resist the ice load, the caisson width being primarily controlled by active loads pushing the caisson outward. Although slurry loads will always be greater than active loads during operations, the safety factor can generally be lower during construction than the value of 1.5 used for operating loads. The slurry condition was taken to act over the top 30 feet of the caisson with active loads over the remainder of the caisson depth. Since the resulting load under this slurry condition was only slightly higher than the load in the fully active condition, the higher safety margins required for operating conditions governed the design.

The generalized load condition for the fully active earth pressure case is shown in Figure 4.27. Soil shearing occurs at the weakest zone in the foundation soil. Therefore, a failure zone occurs at 20-ft depth rather than at the base of the structure, as shown in Figure 4.28. The weaker the soil at the failure plane, the more likely the failure plane will pass through the toe of the berm. The lower the berm height, the more likely that failure plane is likely to pass near the toe or edge of the caisson.

Failure conditions for a 25-ft high berm usually occur with the passive wedge at the edge of the caisson. For a 150-ft berm, the failure zone usually passes at or near the toe of the berm.

Selection of caisson width based on the fully active load is illustrated in Figure 4.29 for an exploration island. A safety factor of 1.5 was considered for the design case. For 75 and 200-ft water depths, caisson widths should be about 85 and 120-ft, respectively. Figure 4.29 also shows that if the safety factor used for design is lowered slightly the caisson width can be reduced significantly.

The caisson length is determined by the island size needed to meet both area requirements for drilling equipment, quarters, storage, etc. and to satisfy the necessary resistance to ice load. The net area required for exploration islands is 125,000 sq. ft. However, we assumed that a 50-ft wide access or service perimeter would be needed for all islands. Therefore, a gross area of 196,000 sq. ft. was used. The failure modes under ice load are illustrated in the sketch in Figure 4.30.

As stated earlier, the passive resistance behind the structure is more than adequate to resist ice loads. Therefore, the critical sliding condition is through the weaker soil at 20-ft depth. A failure plane will pass through the berm or toe of the berm, depending on the height of the berm and the shear strength of the foundation soil.

The island sliding resistance is given in Figure 4.31 for an exploration island in 75-ft water depth. The area needed for resistance or equipment area is expressed as caisson side length which is the length along one side of the hexagon. Also shown are the net and gross surface areas needed for drilling operations.

Rotation of caissons due to eccentric loads on the end of the caisson was also studied. It was found that eccentric loads are unlikely to pose any threat to rotational movement.

4.2.3.4 Results

Results of the design caisson cross-sections and lengths, as well concrete and fill quantities are shown in Table 4.5. The caisson length for both water depths is 278-ft since area requirements exceed the size of island needed for sliding resistance. Since the foundation berms are below the active wave zone, no slope protection was included in island quantities. However, scour protection would be required at the toe of the caissons.

Additional design items which were not included in the scope of this study, but would be required for a final design, are listed below:

- Settlement
- Bottom unevenness
- Pile capacity for production modules
- Module transfer method
- Caisson connections
- Connection-structure interaction
- Soil-structure interaction
- Downdrag on inner caisson wall
- Permafrost degradation
- Floating/towing stability
- Sand grouting needs
- Wave deflectors
- Berm slope protection

It appears possible to design caisson retained island in 75-ft and 200-ft water depths for the given design assumptions. However, because of the large material quantities involved in deep water, it probably will not be feasible to construct an island in a reasonable amount of time particularly in deeper waters.

From the study of caisson retained islands, we can also conclude that the design is most sensitive to (1) water depth, (2) berm height, (3) soil shear strength, and (4) safety factor used.

4.2.4 Floating Units

The investigation into the capabilities of floating units to drill in ice infested waters centered on two types of vessels; a turret moored drill ship, and a conical drilling uint. The drill ship used for this study has a length of 534 feet. The conical drilling unit has a water plane diameter of 200 feet, a draft of 32 feet, and an angle with the horizontal of 21.3 degrees.

Both the drill ship and the conical drilling unit employed conventional catenary mooring systems. The drill ship's mooring system was composed of eight lines while the conical drilling unit system consisted of twelve lines. In anticipation of the large environmental loads, all mooring lines were taken as 6 inch diameter, Oil Rig Quality, (Arctic Class) stud link chain.

The overall objective of the investigation was to check that the drilling units could continue normal drilling operations in broken ice up to four feet thick, while subjected to a wind of 75 knots and a current of 2 knots. It was assumed throughout the study that sufficient ice breakers (Arctic Class 4) were available to ensure that the ice was indeed broken.

The term "normal drilling operations" deserves some explanation. The API suggests three definitions of modes of drilling operations. These modes are based on the angle (from the vertical) of the riser pipe at the lower ball joint. Normal drilling operations may continue up to a riser angle of 2 degrees. From 2 degrees to 4 degrees, drilling activities decrease. At 4 degrees the state of "limited drilling" exists. Only those drilling activities which can be quickly curtailed may continue. From 4 degrees to 9 degrees, drilling activities cease. At 9 degrees the "suspended" state exists. At this point preparations to shut in the well and abandon the site are underway.

The mooring system of the drilling units must be capable of keeping the riser angle less than 2 degrees. Therefore, the mooring system parameters were adjusted to achieve the maximum possible restoring force at the 2 degree angle. A vessel draft (30 ft) and the height of the BOP stack (40 ft) were considered in the calculations. The parameters which enabled this tuning are total length of line and line pretension.

The mooring lines can be considered long enough when the vertical force at the anchor is zero at the maximum anticipated vessel excursion. This implies that there is "some" length of chain lying on the seafloor. Finally, the pretension in the lines is adjusted until the system restoring force at the 2 degree angle is maximized. Figures 4.32 and 4.33 show the results of the mooring analysis for the 200-ft water depth. These figures show that at least one line of the optimized systems will reach its catalog breaking strength before the 9 degree angle is reached. However, at the operating angle, the restoring forces developed by the mooring systems are 600 kips and 900 kips, for the drill ship and conical drilling unit respectively. These figures also show the sensitivity of the mooring systems to line pretension.

The magnitude of the total environmental force the drilling unit would experience was estimated for comparison with the mooring system restoring force. The estimation of the environmental force included wind, current, and broken ice. The results of this exercise are shown in Figures 4.34 and 4.35. It was assumed that the drillship would always position itself head-on into the oncoming broken ice. These figures show that the magnitude of the anticipated environmental force is much less than the restoring capabilities of the mooring system.

For safety reasons, the floating drilling unit must incorporate a rapid riser disconnect system and a rapid rig anchor release system. These systems will enable the drilling unit to quickly release all bottom connections and abandon the site in an emergency.

In summary of the capabilities of floating systems, estimates of the environmental loads on the drilling units are much lower than the capabilities of the mooring systems, assuming broken ice. However, due to unforseen events, the drilling units should incorporate rapid disconnect equipment which will enable the expedient retreat from the site.

4.3 Production Systems

4.3.1 Cones

4.3.1.1 Structural Arrangement

The global ice loads on production structures are larger than on exploration structures. However, the extreme local pressures experienced under the two conditions are likely to be very similar. Since it is the local pressure which governs the structural member sizing, the structural assumptions made for exploration cones can be used for production cones as well. These are described in Section 4.2.1.1.

As production structures will be designed for specific locations, there is no requirement for an independant sub-base in deep water and the structures can therefore be designed as monolithic. For structural and construction purposes, however, a deep water production cone can still be considered as a cone and a sub-base, but with a rigid structural connection between the two. The loading, and therefore the structural arrangement, of the sub-base portion of the structure is the same as for the independant exploration sub-bases, described in Section 4.2.1.2.

The sub-structure can be designed to carry sufficient supplies for an eight month drilling season. This is assumed to require supplies for five 16,000-ft TVD wells for the 50,000 BOPD case, and for ten 16,000-ft TVD wells for the 200,000 BOPD case. The assumed dry weight of the deck and facilities was 20,000 s.tons for the 50,000 BOPD case and 25,000 s.tons for the 200,000 BOPD case. The corresponding operating weights were taken to be 30,000 s.tons and 50,000 s.tons respectively.

Order of magnitude estimates of the oil storage capacities of the production cones range from 1MM barrels to 7MM barrels, depending on the water depth, ice and soil conditions.

4.3.1.2 Environmental Criteria and Design Approach

Since production structures will be designed for specific locations, the water depth, ice criteria, and soil conditions will be known. The structure can therefore be optimized, in terms of it's size and geometry, to suit those conditions. This is an important distinction from exploration systems, in which the structures were sized for the worst criteria and therefore conservative for any other condition.

In order to fully investigate the range of conditions that are likely to be encountered in the Lease Sale area, a general approach was taken which combined optimization with sensitivity to environmental changes. The range of environmental conditions considered was as follows:

Water Depth	:	75, 180, 300-ft
Soil Conditions	:	Clay, c_u = 0.6 ksf at the mudline (lower bound) Clay, c_u = 1.5 ksf at the mudline (nominal value) Sand, ϕ = 35° (upper bound)
Ice Conditions	:	Basic Loads Sensitivity Loads (Nominal 30% increase on basic loads to give upper bound loads)

For ice loads, refer to Figures 4.36 for load values, and Section 2.2 and Appendix A for their determination. The method employed for structure optimization is illustrated in Figure 4.37. For each water depth, three structures of differing diameters were analysed for geotechnical stability. The failure modes and the methods of analysis are the same as those described in Section 4.2.1.4 for exploration cones. Each structure was analysed for the six combinations of ice and soil conditions. From the results of these analyses, graphs could be drawn, for each water depth, of minimum safety factor against sliding against structural diameter. Sliding along the mudline or shallow rotational failure was always the critical failure mode for these structures. From these graphs, using a critical factor of safety for these types of failure of 1.5, the optimum structural diameters for each combination of ice and soil condition were obtained, as indicated in Figure 4.37.

By this method, each of the production cones developed has the minimum allowable factor of safety against failure, provided all other considerations are satisfied. Also, the range of structures developed gives the effect of the environmental conditions on the size, and therefore cost, of the cone.

The other variable for production structures is the production rate. In the case of cones the major effect of differing production rates will be on the topsides facilities required. There will also be a requirement to increase the size of the moonpool. Neither of these have a significant effect on the overall size of the structure, and hence the same substructure has been assumed for all production rates.

4.3.1.3 Other Considerations

As described for exploration cones, naval architecture considerations can govern the global dimensions of cone systems rather than geotechnical stability. Therefore each of the optimized structures obtained by the method described in the previous section had to be checked for floating stability. The criteria by which the floating stability was assessed are as described for exploration cones. However, there is a significant difference in the ballasting procedure employed. Since the production structures have a rigid structural connection between the "cone" and "sub-base", all of the ballast may be placed in the "sub-base". This leads to a more stable structure, as the center of gravity is kept low by the ballast water. Figure 4.38 shows the installation procedure for the cone for high ice load and stiff clay soil (c_u = 1.5 ksf) in 300-ft water depth, and Figure 4.39 shows the corresponding GM curve for this example. It can be seen that, for this case, the cone is stable for it's full operating depth. As the cone diameter decreases, however, the structures become unstable and floating stability was found to govern.

One other consideration in the optimization process is the structure draft. Deep water cones on strong soils were found to have large drafts, up to a maximum of 130-ft. There was initially some scepticism about the feasibility of towing and installing structures of these drafts. However, the risk analysis discussed in Section 4.5 indicated that this would be possible without significant penalty.

Finally, the construction procedure for production cones follows that outlined for exploration cones in Section 4.2.1.6.

4.3.1.4 Results

Figures 4.40 and 4.41 show examples of optimized structures in 180-ft water depth. Table 4.6 gives a summary of the structural properties, and berm volumes where applicable, for the structures developed. The cone in Figure 4.40 is for the most favorable environmental conditions, while the cone in Figure 4.41 is for the least favorable. These two examples therefore indicate the range of structures which could be developed for the same water depth, depending on the environmental criteria. It should be noted that the cone in Figure 4.40 is applicable for both basic and sensitivity ice loads. This is an example of floating stability governing the overall size of a cone rather than geotechnical stability, when it is designed for strong soil conditions. Generally the results show that cone type structures are feasible under all the conditions considered, although there can be a large variation in structural size for a given water depth.

4.3.2 Monolithic Caissons

4.3.2.1 Design Approach and Environmental Criteria

The structural arrangement for production caissons was assumed to be the same as that for exploration caissons. The reasoning behind this is the same as that discussed in Section 4.3.1.1 for production and exploration cones. Similarly, the same principle of optimizing production structures to suit known environmental conditions also applies to production caissons. The behavior of caissons, however, is very different to that of cones and therefore the method of approach used to optimize these structures was also different.

The range of environmental conditions considered was as follows:

Water Depth	:	75, 200, 300-ft
Soil Conditions	:	Clay, c_u = 0.6 ksf at the mudline (lower bound) Clay, c_u = 1.5 ksf at the mudline (nominal value) Sand, ϕ = 35° (upper bound)
Ice Conditions	:	Basic and Sensitivity Loads as shown in Figure 4.42

For the determination of the ice loads refer to Section 2.2 and Appendix A. For a given combination of environmental criteria, the approach used was to first size a caisson to work on the stipulated soil conditions. On clay soils, the size of structure required to achieve a satisfactory factor of safety was generally very large. Therefore, in order to reduce the structural size, two alternative foundation designs were considered:

- allowing for strength gain during consolidation, with the aid of wick drains;

- using spud piles.

The methods of geotechnical analysis used for the initial sizing and after allowing for strength gain were the same as employed for all bottom founded structures described earlier in this study. The effect on strength gain of using wick drains is described in Section 4.2.2.3. When wick drains have been used, the structures have been sized to achieve an adequate safety factor after a period of 1 year. The assumptions and methodology used to analyse the cases with spud piles is described briefly in the next section, and in more detail in Appendix B.

With this approach, each combination of environmental conditions requires an independant, iterative, analysis procedure to arrive at an optimized structure. Therefore, it was not possible to adopt the more general approach used for cones, and a more limited study of the possible combinations of ice criteria, soil conditions, and water depth had to be carried out. The principle water depth examined was 200-ft, at which all possible combinations of ice criteria and soil conditions were investigated. Example cases were then examined in 75-ft and 300-ft water depths.

Unlike cones, the production rate can have a significant effect on the size of caisson required. This is because the area requirement, and therefore the size of the structure at the waterline varies with production rate. In some circumstances this may also effect the ice load on the structure. The study concentrated on a production rate of 200,000 BOPD, however, example cases were examined in 200-ft water depth with a production rate of 50,000 BOPD. In establishing the area requirements, stacking of facilities modules up to three levels was assumed. (see Table 4.3)

As for the cone, the sub-structure of the monolithic caisson can be designed to carry sufficient supplies for an eight month drilling season. The assumptions made for the cone regarding consumables on board also apply to the caisson concept (see Section 4.3.1.1). Similarly, the oil storage capacities of the production caissons also range from approximately 1MM barrels to 7MM barrels, depending on the water depth, ice and soil conditions.

It is worth commenting on the type of ballast used for caisson structures. In general, using a heavier ballast, such as sand, will provide added weight both to resist environmental loads and to accelerate consolidation effects. This was indeed found to be beneficial for the case of sand foundation soils. On clay soils, however, the maximum effective base pressure is limited by that which will cause bearing capacity failure on initial set down. In all cases, this pressure could be exceeded with the use of water ballast, and there was therefore no advantge in using sand ballast in these conditions.

4.3.2.2 Use of Spud Piles

a) Introduction

The use of spud piles is another method of improving the lateral capacity of monolithic caissons by keying them into the foundation. However, the large ice forces involved make it infeasible for the entire lateral load to be supported by piles, and so a design method was adopted to take advantage of the natural sliding resistance of the base in combination with the lateral resistance of a number of piles driven through the caisson into the subsoil.

b) Caisson Layout

In the design of the piled bases it was initially assumed that the caisson would be vertically sided, and that it would be large enough to allow space for the required topsides area. In addition, room for a single ring of piles skirting the perimeter of the topsides area would be provided as shown in Figure 4.43-(a). In all cases this proved infeasible due to impracticably close pile spacings required.

If the size of structure thus produced was insufficient for soil stability, an increased base diameter at foundation level, while maintaining the same waterline diameter, and hence ice loading was used. This would enable a second ring of piles to be driven through the base at foundation level from the working surface on the deck.

In some cases even this was not feasible, and so the next step was to increase the foundation area still further, thus increasing the surface sliding resistance, whilst maintaining the two "rings" of piles (Figure 4.43-(b)).

c) Design Method

The design method is described in detail in Appendix B. It sets out six design criteria as follows and describes the methods employed to satisfy the criteria:

1) $F \geq 2$ for bearing failure
2) $F \geq 2$ for overturning about the toe
3) $F \geq 1.5$ for lateral failure by sliding as a block
4) $F \geq 1.5$ for combined pile/sliding failure
5) Underbase shear stress at design load $\leq 0.66\,\tau_u$
6) Maximum steel stress in pile at design load $\leq 0.66\,\sigma_y$

where F = Factor of safety
τ_u = undrained shear strength of soil at skirt tip level
σ_y = yield stress of steel pile

The design was generally governed by criteria 5 and 6, which ensure that neither the piles nor the shear soil at the skirt tip is overstressed at the design load. The method employed to check this takes into account the varying lateral stiffnesses of these two components - underbase soil stress and pile resistance, which affects the way in which the total load is distributed between piles and soil.

d) **Construction and Installation**

When spud piles are used, they would be installed through sleeves built into the caisson, using a vibratory pile driver. The methods for constructing and installing the caisson itself follow those described in preceding sections for all monolithic structures.

4.3.2.3 Results

Figures 4.44 and 4.45 show examples of optimized structures in 200-ft water depth. Tables 4.7 to 4.9 give summaries of structural properties for the three design cases. The caisson in Figure 4.44 is for the most favorable environmental conditions and it can be seen that, provided sand ballast is used, a straight sided caisson will work without allowing for any strength gain in the foundation material. In this case it is the facilities area requirement which governs the overall size of the structure. Figure 4.45 illustrates a case in less favorable conditions, for which both a stepped structure and an allowance for stength gain with the aid of wick drains is required. The results in Tables 4.7 to 4.9 show the following main conclusions:

- monolithic caissons will work on sand soils without any allowance for strength gain.

- on clay soils the use of either wick drains to accelerate consolidation effects, or spud piles to improve horizontal resistance is necessary to achieve realistically sized structures.

- the use of wick drains results in smaller structures than the use of spud piles.

- whichever design method is used, the caisson is very sensitive to changes in environmental conditions and, in severe ice and weak soil conditions, becomes an infeasible structure.

4.3.3 Caisson Retained Islands

4.3.3.1 Design Procedure

The design procedure for production islands was the same as that described earlier for exploration islands. (Section 4.2.3)

4.3.3.2 Design Conditions and Assumptions

The two water depths chosen to examine the feasibility of caisson retained islands for production were the same as for exploration islands, i.e., 75-ft and 200-ft. The soil strength profile corresponded to the soil profile having a seafloor shear strength of 1.5 ksf. This profile was selected in order to obtain a comparable design with cones and caissons. In addition, a production rate of 200,000 BOPD was assumed.

The shear strength gains were determined for a period of one year after berm placement. The resulting shear strength at 20-ft depth is given in Table 4.5. The remaining soil properties were the same as those used for exploration islands.

4.3.3.3 Analysis and Design

The procedures for analyzing and designing production islands was the same as for exploration islands.

For production islands, the significant wave height was 26-ft, giving an active wave zone of about 40-ft below the waterline. Thus the total caisson height was taken to be 80-ft, 30-ft above sea level and 50-ft below sea level, excluding the deflector.

The caisson width was determined using the analysis described earlier for exploration islands. The resulting widths were 140-ft and 80-ft for 75-ft and 200-ft water depths, respectively, as shown in Table 4.5.

The net area required for facilities on production islands is 360,000-ft for a 200,000 BOPD production rate and assuming one floor level. The gross area required, including the 50-ft access perimeter, is 480,000-ft.

4.3.3.4 Results

For islands in 75-ft water depth, the island area is governed by sliding resistance. The resulting caisson length is 447-ft as indicated in Table 4.5. In 200-ft water depth, the area required for facilities gives a caisson length of 430-ft. The remaining caisson dimensions and island quantities are given in Table 4.5.

Although production islands are feasible in both water depths, the deeper waters pose a problem due to the large fill quantities involved.

4.3.4 Production and Loading Atolls

This section describes the feasibility of production and loading atolls which permit operations on a year round basis. This type of facility cannot be compared directly with those described earlier since it is used as a loading terminal, as well as a production island. It is included merely to show the relative quantities involved.

Two basic schemes were considered in this study, as shown in Figures 4.46, 4.47 and 4.48. Both schemes are modifications of concrete caisson retained islands and provide a protective enclosure for the tankers and production facilities.

4.3.4.1 Principal Characteristics

The principal dimensions and characteristics of the atolls are:

	Scheme I	Scheme 2
Water Depth (ft)	80	80
Maximum Tanker Draft (ft)	70	70
Atoll Length (ft)	4500	3300
Total Height (ft)	110	110
Free Board (ft)	30	30
Caisson Height (ft)	100	100
Caisson Width (ft)	60 & 120	60 & 120
Fill Volume ($x10^6$ cu.yd) (including ballast)	21	13.5
Concrete Volume ($x10^3$cu.yd) (16% of caisson volume)	950	700

The shape and length of the atolls were selected to ensure that the tankers were protected from ice floe impacts and that sufficient room was available for maneuvering the tankers.

The atolls are designed to withstand an ice load of 600 kips/ft. The soil strength is assumed to be 1.5 ksf.

The L-shaped cellular concrete caissons are sand ballasted and the reinforced concrete volume is 16% of the caisson volume. This is based on our previous experience with concrete structures such as BWACS (BWA Caisson System).

Except for the overall shape, the atoll schemes shown in Figures 4.46, 4.47 and 4.48 are similar. However, this difference will have a significant impact on cost, construction schedule and reliability of each scheme.

Though the fill and concrete volumes of Scheme 1 are greater than those of Scheme 2 (by 35.7% and 26.3%, respectively), Scheme 1 offers greater reliability in the event that one of the entrance/exits is blocked by ice floes or rubble piles.

It is imperative that good ice management techniques be used to ensure that the entrances to the loading facilities are clear of ice. Such techniques could include:

- bubbler systems
- waste heat injection
- ice clearing

The investigation of these schemes was outside the scope of this study.

4.4 Subsea Systems

4.4.1 Subsea Systems Definition

The term "subsea systems" includes the various equipment and methods that have been used in the last few years to produce hydrocarbons with seafloor installations. These installations are implemented with completely remote techniques from the water surface, thus the term subsea systems.

The subsea systems that can be used in the Diapir 87 lease area may consist of a well, drilled through a guidebase resting on the seafloor (see Figure 4.49). The drilling will be carried out with a floating drilling vessel through a subsea wellhead. The christmas tree will be installed on the subsea wellhead and will be equipped for completely remote operation of its functions. The hydrocarbon production from the subsea christmas tree will be carried through a subsea flowline to a permanent production treatment facility. The well, with its subsea christmas tree, will be controlled from the permanent facility through a control umbilical installed on the seafloor together with the subsea flowline.

Another version of a subsea system is a cluster of subsea wells drilled through and supported by a template (see Figure 4.50). In this case, the template replaces the guidebase. The cluster of wells is frequently accompanied by a subsea manifold that comingles the production from all wells before it is directed to the permanent facility. This subsea system will normally use remotely controlled subsea chokes.

Maintenance of subsea wells is similar to maintenance of surface wells. The difference is that floating drilling techniques or through-flowline (TFL) tools must be used. The subsea equipment, however, is maintained either subsea with divers or remote tools, or by pulling the equipment to the surface.

4.4.2 Need for Subsea Systems Production in Diapir 87 Field

The present feasibility study may require the use of subsea systems for field development. There are a number of reasons for using subsea systems in the Diapir 87 Field or in any field in general. The major reasons are:

- To produce small neighboring reservoirs back to the main production structure. Thus, small pockets of hydrocarbons can be accessed without excessive investment costs.

- To produce a reservoir in deep water back to a production structure located in shallow water. In numerous occasions, the producing formation is located in deep water, but shallow water depths are in the near vicinity. In that event, it makes good economic sense to use subsea systems in the deep water and locate the more expensive production structure in shallow water.

- To complete and produce exploration wells. Exploration wells in general are plugged and abandoned. Considering that in the Diapir 87 area these wells will be very expensive, subsea systems will provide an economical method for completing a good exploration well.

- Early production. Offshore field development in general, and arctic areas in particular, require large investment. Subsea methods can provide early cash flow while the main production structure is in its fabrication and installation stages.

- Injection wells. Injection wells in general need to reach the periphery of a reservoir. If the reservoir is of substantial dimensions and area, it is not practical to reach it from the main production platform. In such a case, a subsea injection well is ideal for providing this function.

- Delineation and development of shallow reservoir. A shallow reservoir of sizable dimensions may not be reached from the surface production facility. Subsea systems are well suited for such a reservoir, not only in deep water, but also in shallow water.

4.4.3 Alternate Subsea Systems

4.4.3.1 General

Depending on water depth, reservoir size, recoverable reserves, hydrocarbon properties, ice conditions, days in the drilling season, etc., a number of alternate subsea systems developments can be visualized. The systems presented are not intended to be an exhaustive list of all subsea alternative systems, but rather those most applicable to the particular problems posed by the design conditions of this feasibility study. The description of the three systems most suitable for the development of the Diapir 87 Field are presented below.

4.4.3.2 Satellite Wells Producing to Permanent Facility

This subsea system consists entirely of satellite wells with individual flowlines connected to the main production facility. Figure 4.49 presents a pictorial view of three satellite wells connected to the process facility. The system provides the greatest flexibility as to how far wells can be placed and the delineation of a large reservoir.

a) System Advantages

The independent satellite system makes it possible to drill and complete one well in one drilling season and, with proper planning and coordination, to lay a flowline and begin production during the winter months.

Because of the independent spacing of the wells, a large shallow reservoir can be produced without the directional drilling restrictions imposed on wells drilled from a template or a platform. In the event of an ice feature scouring the area, the monetary loss due to damage of one tree is minimized.

The subsea system composed of satellite trees allows for the most simple subsea components and does not require the use of subsea chokes. One of the most important features is that the tree controls can be a simple straight hydraulic system for distances up to 5 or 6 miles away from the main production facility.

Another advantage is that the common risk of drilling wells through a template while producing the already completed wells does not exist. Thus, satellite wells that are completed can be freely produced while other satellite wells are being drilled.

b) <u>Disadvantages</u>

The biggest disadvantage of this method is the flowline cost. In the arctic environment where the flowlines have to be buried below iceberg scour depth, the cost is amplified disproportionately to the other components of the system.

The other disadvantage of the system is that due to the large area occupied by trees and flowlines, the risk of one well or one flowline being damaged by ice features is increased. The solution is to position all equipment well below scour depth.

4.4.3.3 Template Well System Producing to a Permanent Facility

This subsea system is shown pictorially on Figure 4.50. The system consists of a template installed in a glory hole and a flowline carrying the comingled hydrocarbons back to the production facility. The template can contain as many wells as necessary. It will employ a subsea manifold with chokes and a complex subsea control system. The system shown in Figure 4.50 also employs protective covers to prevent seabed soils fouling the template area.

a) **Advantages**

Compared to the all-satellite subsea system, the template system minimizes the flowline costs. Further, because of the small seafloor area occupied by the template and the flowline, the system has minimal risk of ice damage.

b) **Disadvantages**

The major disadvantage of the system is that it cannot be used in conjuction with shallow reserviors, since a large reservior cannot be easily reached from one location with directional drilling. Further, during the drilling months, the already completed wells will be producing while drilling activity is continuing on adjacent wellbays. The drilling operation increases the risk of dropping an object on a producing tree with potentially disastrous results.

Because of the large numbers of trees and manifold functions required, the control system is complex. In general, and depending on the number of trees employed, an electrohydraulic control system will be used with the template subsea system. The complexity of the control system is a disadvantage that will introduce unwanted subsea maintenance.

The last disadvantage of the system is that, in the event of an ice feature scouring the template area, potentially all template equipment would be destroyed. It should be mentioned, however, that this probability is very small.

4.4.3.4 Satellite Wells Connected to a Manifold Base Producing to a Permanent Facility

The system consists of a manifold on a template base connected with a flowline to a production facility. As shown in Figure 4.51, several satellite wells with individual flowlines are connected to the manifold base.

The system attempts to combine the flexibility of the all-satellite well system with the minimum cost of the template system. However, it also combines a number of the disadvantages of both systems.

a) **Advantages**

The major advantages of the concept are that a shallow reservior can be produced with moderate flowline cost compared to the all-satellite subsea system. Further, producing while drilling is a minimum risk operation, since the production and drilling operations are physically separated from each other.

b) **Disadvantages**

The disadvantage of major loss in the event of an ice feature scouring the bottom is still present because if the manifold is damaged, the entire field production will be shut down. In addition, because of the large area covered by the satellite wells and their flowlines, the chances of damage are increased. It should be mentioned that compared to the all-satellite well system, this probability of damage is small. The disadvantages of subsea chokes and complex control systems associated with the template wells still exists with this system also. The control problem is further complicated by the fact that the control umbilical path is from the permanent facility to the manifold base and then branches out to each of the satellite trees. It should be mentioned, however, that these problems have been solved in the past.

4.4.3.5 Recommended System

Within the limits of the present feasibility study and the existing reservoir information, it is not possible to firmly recommend one of the above candidate subsea systems. Therefore, since the objective of this study is to provide cost estimates for field development analysis, the cost information has been provided in such a form that the cost of any type of subsea system can be reconstructed from the basic information furnished.

4.4.4 Technology Development Status

Installation of subsea systems in the Diapir 87 lease area have three principle problems to overcome. The first problem is protection of the seafloor installations against scouring by ice features; the second is drilling of the subsea wells in a timely cost-effective fashion; and the third is maintenance of the subsea wells.

The most effective way of resolving the ice scouring problem is burial or glory hole installation of all the subsea equipment below the scouring depth.

Glory hole dredging at the water depths occupied by the lease area is within available equipment capabilities and present technology.

Trenching of channels for flowline burial is outside the capabilities of presently available equipment. Presently, pipelines and flowlines are buried to 6 feet below the ocean floor, while the ice scouring depth in this area requires pipelines to be buried up to 20 feet below the ocean floor. Presently available trenching equipment can be used to make several passes to reach the desired channel depth. However, the cost will proportionately increase. Therefore, new trenching equipment is required for a cost-effective burial of flowlines to arctic requirements.

Drilling the subsea wells is a time-consuming operation beacause of the short ice-free season. Traditionally, subsea wells are drilled from floating drilling rigs. However, a floating drilling rig, even with ice strengthening, can operate for only a brief period in the Diapir 87 area, and some years it cannot operate at all.

To take advantage of the potential benefits of a subsea installation, methods of drilling subsea wells from fixed exploration units developed for the arctic should be investigated. Then, year-round drilling of subsea well clusters could make subsea installations very attractive.

Subsea well maintenance methods are well developed. However, they can be carried out from a floating drilling rig positioned directly above the subsea installation, or with TFL techniques. The TFL capability has been included in all the subsea systems presented for the Diapir 87 lease area. However, TFL maintenance capabilities are limited to certain specific tasks.

Complete well maintenance can be done only with a drilling rig during the ice-free season. However, with a careful program of well-designed and operated wells and by carrying out maintenance ahead of time when feasible, the production downtime due to well maintenance can be minimized. A discussion on well maintenance systems can be found in Appendix C.

The overall conclusion from the technology status review is that subsea systems installation in the arctic is feasible with the present technology. The subsea installations can also be cost effective compared to the fixed structure alternatives, if a few improvements are brought about in the methods of drilling, protecting and maintaining these installations.

4.5 Risk Analysis

4.5.1 Introduction

From the foregoing, it can be seen that several types of structures and systems are potentially feasible for carrying out exploration and production operations in the Diapir 87 lease area. What has not been demonstrated so far is whether the resulting deep draft structures can be towed to their various destinations through the ice environment, or whether there is a reasonable chance a floating drilling unit will be able to complete a well in a given season.

We have used risk analysis methods to attempt to answer these questions. We have analyzed the data bases available to obtain statistics of ice features, combined this analysis with the limitations of the structural systems, and derived levels of risks associated with selected scenarios. This analysis is not exhaustive by any means and further work is warranted to improve the understanding of this subject, eventually relating risks to costs.

4.5.2 Approach Used

Risk analysis can be used to evaluate the probability of successfully completing an operation. If several methods are available to achieve an objective (e.g., the drilling of wells), the success probabilities for each method can be used to advantage in comparing the different methods or in developing contingency plans. In this study, the risk analysis procedure used to estimate the success probabilities relies on Monte Carlo simulation techniques.

Monte Carlo simulation is a procedure which estimates the statistical solution of a problem by repeatedly evaluating the results. This procedure requires a mathematical model of the problem together with statistical descriptions of parameters affecting the problem. These descriptions are usually in the form of probability distributions based on historical data. The results of the simulation is in the form of a probability distribution of values which the solution may hold, or probabilities for each of the possible outcomes of the problem.

The risks associated with floating drilling programs and with towing and installing gravity structures were evaluated using this approach. A sensitivity study was performed for each of these operations in order to identify the important factors affecting the modelled operations. Only the influences of the ice environment on the success of the operations were considered in evaluating risks. Other factors, such as waves, wind, visibility, temperatures, etc., were not used.

4.5.3 Floating Drilling

The risk associated with a floating drilling program (i.e., its probability of success) is related to the amount of drilling time provided by the drilling unit and its icebreaker support fleet and to the time required to complete the well. The length of time provided by the drilling fleet is dependent on the ice conditions at the drill site and the ability of the drilling fleet to withstand these ice conditions. However, ice conditions can be quite variable from year to year and therefore, the time available for drilling will also vary.

The particular ice "events" influencing the success of a floating drilling program include the ice deterioration in late spring, the pack ice invasions during the summer, and the growth of new ice in the fall. From year to year, these events will generally occur at a different time and with a different intensity (i.e., rate, frequency, severity or persistence). Because of their large variability, these ice conditions can only be reasonably described in statistical terms. The statistical parameters are obtained by analyzing the historical data, and are generally in the form of a probability distribution function for one of the characteristics of an ice event (e.g., the persistence of a summer pack ice invasion).

Historical data in the public domain on ice conditions in the lease sale area are available from a joint industry study, AOGA 35 (9), and a National Weather Service report, NWS AR-34 (10). A model of a floating drilling program was developed for the data from each of these reports since they cover different regions of the lease sale area and their data are presented in significantly different formats. The risk of the drilling program was evaluated by both methods at a common site so a comparison between the two models could be made. Each model, its required inputs, and its output are described separately below.

4.5.3.1 AOGA 35 Data Risk Model

The flow chart of the model using the AOGA 35 data to estimate the probability distribution of the length of time available for a floating drilling operation is shown in Figure 4.52. In general, the available drilling time is estimated by determining the amount of time lost in a year due to pack ice invasions and subtracting this time from the amount of drilling time available if no pack invasions had occurred.

For one simulated year, the length of the potential drilling time is determined by selecting the data at which the drilling fleet can move to the drill site and the date at which it will be forced to return to its winter mooring site. The number of pack ice invasions occurring that summer is selected. For each invasion, its duration is selected and subtracted from the potential drilling time. In addition, for each ice invasion, a certain amount of downtime is subtracted to account for the time required to reconnect the mooring system and to re-enter the well. The drilling period before the invasion is selected, so that the potential drilling time can be adjusted for invasions that last through the stop date. The total time remaining after all adjustments have been made is the available drilling time for that year.

The above procedure is repeated numerous times with the values of the start and stop dates, the number and duration of invasions, and drilling periods between invasions chosen according to their respective distributions. This results in a series of available drilling times of varying length from which the distribution of available drilling time is determined. If the drilling time requirement is constant (i.e., deterministic), the available drilling time distribution can be converted to give the probability of the available time being greater than the required time. These probabilities are identical to the success probability for a given drilling time requirement.

This model is used to evaluate the risk associated with a floating drilling program to be carried out in 300 ft of water in the Beaufort Sea, although drilling has been carried out in waters much shallower than this. Two possible drill sites are considered, one is located north of Camden Bay and the other is located north of Cape Halkett. The drilling unit is accompanied by a sufficient number of icebreakers that allow drilling to be performed when the ice concentration is less than 50 percent. If this level is exceeded, an invasion occurs and the drilling unit will be disconnected from the well and mooring system. After the invasion has passed, the mooring system will be reconnected and the well is re-entered. These operations are assumed to take three days.

Based on the above limitations of the drilling program, analyses of the AOGA 35 data (9) for the two drill sites provided the ice condition distributions shown in Tables 4.10 and 4.11. In addition to the four distributions given in the tables, the simulator requires the distribution of the date when the drilling fleet is forced to return to its winter mooring site (i.e., the stop date). If this date is given by the day when the new ice reaches a specified thickness, ice growth curves can be used to determine the stop date distribution. Table 4.12 lists normal distributions fitted to ice growth data (11) at Barter Island. If the same rate of ice growth occurrs at the drill sites, then these distributions are identical to the stop date distributions.

The AOGA 35 data also indicated that the ice concentration did not always fall below 50 percent every year. For the Camden Bay site, this occurred in 5 of 23 years, which implies a 22 percent chance of not being able to drill in any one year. The corresponding probability for the Cape Halkett site is 26 percent.

The distributions of available drilling time are presented in Figures 4.53 and 4.54 for the two drill sites and for a range of new ice thicknesses used to specify the stop date. These distributions are based on ten thousand simulated years. The convergence of the curves is due to the above probabilities of not being able to drill in a given year.

4.5.3.2 NWS Data Risk Model

The National Weather Service report (10) contains semi-monthly ice concentration maps which show probability contours of the 50 percent ice boundry being located south of a location. This information is much coarser than that provided in AOGA 35 and cannot provide the detailed ice condition distributions needed for the above risk analysis model. Figure 4.55 shows a flowchart for a risk model of a floating drilling program that can use the NWS data. The principal behind this model is the same as that for the previous model; namely, estimating the amount of available drilling time by accounting for ice invasions.

For one simulated year, the drilling fleet is assumed to be prepared to move to the drill site after 15 June once the ice cover falls below 50 percent. The date at which the drilling fleet is forced to return to its winter mooring site is selected. For each time period, the ice cover is selected, it being either less than or greater than 50 percent. If there is a change in ice cover, the date of the change in the ice cover is selected uniformly between the two time periods and the number of days with less than 50 percent ice cover is added to the cumulated number of available drilling time (A.D.T.). If there is no change in ice conditions between periods and drilling is possible, fifteen days are added to the available drilling time. These steps are repeated for each time period until the stop date is reached. Repeating the above procedure numerous times provides an estimate of the distribution of the available drilling time.

This model is used for two drill sites; one located in the Chukchi Sea and the other off Cape Halkett. The latter site is the same as was used for the previous model. Table 4.13 gives the ice cover probabilities determined from the NWS ice maps (10) for the two sites. Table 4.14 lists the stop date distributions for the Chukchi Sea site and Table 4.12 lists these distributions for the Cape Halkett site. Figure 4.56 and 4.57 present the available drilling time distributions obtained from 10,000 simulated years.

4.5.3.3 Discussion

A sensitivity study was performed to identify factors affecting the risk associated with floating drilling operations. The factors investigated include:

a) the risk analysis model;
b) the location of the drill site;
c) the maximum new ice thickness; and
d) the time requirement to drill the well.

Two well depths were considered; the first was a 5,000 foot well requiring between 55 and 80 days to complete, and the second a 15,000 foot well requiring 80 to 150 days. The success probabilities for these two examples used in the sensitivity study are presented in Tables 4.15 and 4.16. These probabilities are for drill sites in 300 ft of water. If the drill sites were located in shallower water, the probability of success would increase.

a) Risk Analysis Model

Comparing the results from the two models (i.e., AOGA 35 and NWS data based models) for the Cape Halkett site and the 5000-ft well (Table 4.15), it can be seen that the two models give similar results with the AOGA 35 data model giving consistantly higher probabilities of success. However, for longer drilling times (Table 4.16), the difference between the results from the two models begin to diverge.

b) **Drill Site Location**

Using the AOGA 35 data model as a base, the highest chances of successfully drilling a well are at the Camden Bay site. The Cape Halkett and Chukchi Sea sites are nearly identical, varying by about 5 percent, with the Cape Halkett site having a higher chance of success.

c) **Maximum New Ice Thickness**

For a particular site, Tables 4.15 and 4.16 show the success probabilities for a range of the maximum new ice thickness at which drilling operations are halted for the winter. Being able to continue drilling until the new ice becomes 2 feet thick, greatly increases the chance of success of the operation than if drilling is halted when freeze-up occurs (0-ft). However, doubling this maximum thickness to 4 feet does not increase chances of success as much, generally less than 25 percent.

d) **Required Drilling Time**

The time required to drill a well has the greatest influence on the probability of success of the floating drilling program. For a particular case (site and ice thickness), the probability of success can be quite good (i.e., greater than 50%) for the shallow well, while the deeper well has a very small chance of being completed.

4.5.4 Towing and Installation of Gravity Structures

4.5.4.1 Risk Model

The risk associated with towing and installing a gravity structure is affected by the towing draft, water depth where the structure will be installed, the time requirements for these two operations, and the time at which one is prepared to start these operations. The draft and installation water depth influence the severity of the ice conditions in which these operations will be carried out. The time requirements affect the amount of exposure to the severe ice conditons. Finally, the starting date affects the time available to attempt the operations. The effects that these factors have on the probability of successfully towing and installing a gravity structure have been evaluated in a sensitivity study.

The risks of the towing operation and the installation operation arise from different circumstances. A towing operation can be considered to be a short-term operation which is affected by ice conditions over a long distance, whereas the installation operation is affected by ice conditions at a specific location over a period of time. In view of these differences, separate models for these operations are developed and then combined in order to estimate the risk associated with the entire operation.

Historical data on the ice conditions along the Alaskan Coast (10) indicate that there are several locations where the ice cover is heavier than in adjacent areas (e.g., Point Barrow). These locations can be represented as "gates" along the tow route. Towing can only proceed past these points when the gates are open. The times at which the gates are open depend on the ice conditions in which towing can be performed. A successful towing operation would be one in which each gate along the tow route is successfully negotiated, in turn, before freeze-up occurs.

The installation operation is similar to a floating drilling operation, however, a simpler model can be used, because of the shorter time required. After the structure has been successfully towed to the drill site, if the time remaining before freeze-up is greater than the installation time, the structure can be considered to be successfully installed.

Figure 4.58 shows a simplified flowchart of the combined towing and installation model with multiple gates along the tow route. The start date is the earliest day on which the towing operation can begin and is treated deterministically. The stop date is the day on which freeze-up occurs and is a random variable. Other inputs into the model are the probabilities of the gates being open at semi-monthly intervals during the summer and also a description of ice conditions at the drill site. The results from this model will be in the form of the probability that the structure will be successfully installed at the site, as well as the probabilities that it will be stopped for the winter at intermediate points along the tow route.

4.5.4.2 Sensitivity Study

For the sensitivity study, the tow routes shown in Figure 4.59 were used to evaluate the risk of towing and installation operations. Since the bathymetry shown on this chart is in meters, this unit will be used for describing this section. The tow route starts at Icy Cape, are for two draft requirements, 20 and 40 meters, and terminates at one of four possible drill sites. These sites correspond to water depths of 60 and 100 meters off Cape Halkett and Camden Bay. In addition, two towing velocities are considered; namely, one and two knot average velocities. The starting dates are also varied from 15 June to 1 September. Ninety-six towing and installation operations were modelled.

The tow routes were divided into two or three legs with a gate at the end of each leg. These gates represent Point Barrow, Cape Halkett, and the drill site. Data on the ice conditions at each of these points are available from ice concentration maps compiled by the National Weather Service (10). If the structure can only be towed when the ice concentration is less than 50 percent, the open gate probabilities for the various gates and drill sites are given in Table 4.17. Since the tow route is the same until after Point Barrow, only one set of open gate probabilities need to be specified.

The time of freeze-up (i.e., the stop date) is determined from the ice growth data from Barter Island (11), which showed that freeze-up occurs between 10 September and 20 October (Table 4.12). A normal distribution was fitted to these two dates. Finally, the installation of this structure was assumed to take seven days with the ice concentration always being less than 50 percent.

The probability of successfully installing the structure at the drill site in one summer season was estimated by simulating 10,000 towing operations for each modelled operation. The results of the simulation are presented in Figures 4.60 and 4.61, and give the probability of success as a function of the starting date. Figure 4.60 is for the Cape Halkett sites, while Figure

4.61 is for the Camden Bay sites. A discussion of the various factors affecting the tow are given below:

a) **Starting Date**

The factor with the most significant effect on the probability of success is the starting date. If the operation can be started before 15 August, the chance of success is always better than 75 percent. However, the chance of success drops to less than 10 percent one month later.

b) **Towing Velocity**

By doubling the towing velocity from one to two knots, increases the probability of success between 3 and 25 percent. The increase is a function of the start date and increases as the start date moves later into the year.

c) **Towing Draft**

The tow route draft had little effect on the probability of success, generally from 1 to 4 percent. However, the draft becomes more important for the slower towing velocity.

d) **Site Location**

The location of the drill site had a significant influence on the probability of success. Structures intended to be installed north of Camden Bay had a higher chance of success than those off Cape Halkett. The severer ice conditions off Cape Halkett caused this to occur, eventhough the tow route was shorter. The difference was generally, 5 to 7 percent.

The water depth at the drill site had negligible effect on the probability of success.

5.0 COSTS

5.1 Introduction

Capital cost estimates have been made for all the concepts studied. It was not the intention of this study to address operating costs, consummables, maintenance, supply logistics, etc. The capital costs of systems include construction, transportation, installation, and topsides. Costs for pipelines to shore and subsea systems have been treated separately. The costs for floating exploration systems is again the capital cost of the systems only. Ice breakers and logistic support for drilling operations are not included.

This section describes the methodology behind the capital cost estimates for each of the concepts, together with a discussion of the cost results.

5.2 Cones and Caissons

5.2.1 Methodology

The approach was to identify and provide unit costs for each of the key components in a typical scenario. These components included such items as: construction of the structure; marine operations at construction site, during towing, and at the installation site; topsides; mechanical and electrical systems; and berm construction. Total costs for a wide range of scenarios were then built up, using these unit costs. The scenarios considered were sufficient to be able to identify cost trends with variables such as environmental conditions, water depth, production rate, or the use of a berm or sub-base.

The unit costs have been built up using BWA's own experience in dealing with potential construction firms, marine operators, suppliers and other similar sources. We have been involved in several arctic engineering projects over the past six years involving a variety of systems, including concrete and steel structures, gravel islands, floating units, marine operations, etc. We have tracked the costs of these systems closely over the years, both in the U.S. and abroad and believe that the cost estimates presented in this report are realistic for lease sale planning purposes.

The cost data is presented in such a form that additional scenario costs may be put together, by individual companies if desired, again using the unit costs developed. Tables 5.1 and 5.2 show the proformas used to build up a scenario cost. Table 5.1 summarises the environmental and concept data. Table 5.2 lists each of the components in a typical scenario, with a reference to the unit cost table or figure to be used to determine each cost item. The last sheet of this table summarises the total scenario cost. Examples illustrating the use of this proforma are given in Appendix D. The build up of each of the unit costs is described in the following sections.

5.2.2 Construction Costs

5.2.2.1 Construction Facility

The cone and caisson structures were assumed to be built in a purpose built graving yard which, for cost purposes, was further assumed to be on the West Coast of North America. Figure 5.1 shows a plan of a typical graving yard. Using this plan as a guideline, the cost of constructing this type of facility was developed. In general, the cost included items such as site acquisition, site clearance, excavation, paving of storage areas, buildings, utilities, and essential site services. The size of the structures developed in this study varies considerably, and therefore, the size and cost of the construction facility required will also vary. Figure 5.2 shows the cost variation with the diameter of the structure to be constructed. The full line shows the range of diameters actually computed. The broken lines are extrapolations.

5.2.2.2 Construction of the Structure

The cost of the actual construction of the structure was developed in two parts:

1) The cost of the materials; the operational costs for the construction facility; labor, overhead, and profit.

2) The capital cost of the site plant, with an allowance for resale value on major items.

For the first part, the unit rates assumed for concrete, reinforcing steel, post-tensioning tendons, and formwork are given in Table 5.3. These are again based on the West Coast of North America. If construction were to take place in the Far East, the unit rates for reinforcing steel and formwork would most likely be lower than those used.

Table 5.4 illustrates an example of how these unit rates were used to build up a unit rate for each component of the structure. The example given is for the base wall of a cone structure. The same procedure was carried out for each of the structural components in both cones and caissons, and a summary of the unit rates developed is given in Table 5.5. It should be noted that different thicknesses are given for each component and that the unit rate increases with reducing thickness. Different thicknesses apply to different water depths and to the cone or caisson structure. The variation in unit rate with thickness is primarily due to higher formwork costs per cubic yard for thinner members.

To calculate the total materials and operational cost for a given structure, the relevant unit rate for each structural component was applied to the known concrete volume for that component, and the resulting costs summed.

The plant costs were divided into the onshore construction phase and the offshore construction phase. Typical equipment spreads were identified and cost estimates developed. For major items of plant, such as tower cranes, mobile cranes, batching plant, the cost was estimated as 40% depreciation per annum on the capital cost of the items.

The total cost of the construction of the monolithic structures was then obtained by adding the plant costs to the materials and operational cost, and adding a further 8% for engineering and management.

Figures 5.3 to 5.7 summarize the concrete construction costs for cones and caissons and are referenced in the proforma (Table 5.2). They are presented as cost variation with water depth for exploration and production structures, under basic and sensitivity ice loads. The influence of soil condition is also shown on each figure. These figures may be used to determine the concrete construction cost for either a cone based system or a monolithic caisson, under a variety of environmental conditions.

5.2.3 Topsides, Mechanical and Electrical and Marine Operations Costs

5.2.3.1 Topsides Costs

a) Production Cones and Caissons

Topsides costs constitute a large proportion of total costs and need to be estimated with reasonable accuracy. We have first made an estimate of the weight of topside facilities for the two production rates, as shown in Table 5.6. This amounts to a total of 32,500 s.tons and 55,000 s.tons for the 50,000 BOPD and 200,000 BOPD cases, respectively. Table 5.7 shows the maximum facilities weights carried on some of the North Sea Condeep structures for comparison.

The cost breakdown for the two cases is shown in Table 5.8 and is based on our experience with similar structures in the arctic. It allows for the somewhat lower cost of fabricated steelwork which is currently available in the market.

Although it is the intention to completely outfit these gravity structures before being towed out to location, historical evidence indicates that this is seldom achieved and some offshore hook-up work is almost always required. The costs shown in Table 5.8 makes allowance for this fact.

The total costs of facilities amount to \$285MM and \$434MM for the 50,000 and 200,000 BOPD cases respectively, including an allowance for engineering and management.

Figure 5.8 indicates corresponding cost estimates made by the National Petroleum Council (NPC) (12) in December 1981. Typical costs of topsides facilities on some of the North Sea offshore platforms are also shown on this figure for comparison.

Figure 5.9 shows the total topsides costs for different production rates, broken down into the various components. The discontinuity at 100,000 BOPD is meant to reflect the use of two drilling rigs for larger production rates. The NPC cost estimate in 1981 U.S. dollars is also superimposed for comparison.

b) Exploration Cones and Caissons

Table 5.9 shows the topside facilities cost for exploration structures . This is again based on our previous experience with similar structures. The cost of the facilities is approximately $42MM with a further $15MM for the steel deck structure. The total cost including engineering and management is likely to be $61.5MM.

5.2.3.2 Mechanical/Electrical Systems inside the Hull for Cones and Caissons

The cost of these systems should not be underestimated. This work requires careful scheduling to fit in with the remainder of the structure construction. Very often the mechanical and electrical installation is on a critical path, particularly in confined spaces, and unless properly addressed could lead to expensive cost overruns.

The cost breakdowns shown in Figures 5.10 and 5.11 are based, again, on our previous experience. They are plotted against the base diameter on the abcissa since the ballast and undergrouting systems are governed mainly by the plan area at the base. Tubular handling costs are high since tubulars for two complete wells may be stored vertically in hull compartments and a transporting system will be required to bring them up to the pipe racks on deck. Other items stored inside the hull are bulk material, drill water and fuel. Adequate HVAC, electrical and instrumentation systems have to be provided for servicing these items. Total installed costs of all hull systems run from $25MM to $34MM.

Not all the mechanical and electrical systems required for the cones or caissons are needed for the sub-bases. Costs are correspondingly lower, i.e. $10MM to $25MM as shown on Figure 5.11.

5.2.3.3 Marine Operations for Cones and Caissons

Marine operations are sub-divided into three main phases as follows:

a) Marine Operations at Construction Site

Each task involved in the operation has been considered separately as shown in Table 5.10. The likely duration of each operation is first assessed and an equipment/labor spread estimated. Currently available day rates have then been used to arrive at approximate costs for each task. The level of detail used in the costing of marine operations in general is illustrated in Figure 5.12, which shows a sample worksheet. Engineering and management is also included. The costs shown in Table 5.10 have not been totalled since each concept uses a different make-up. The proforma sheets (see Table 5.2) should be referred to for establishing the individual cost components for a given scenario.

b) Marine Operations during Tow

The major cost item here is the tow itself. An allowance of $2.7MM has been made for preparing a holding site just outside the arctic where the convoy can wait for sea ice to clear (see Table 5.11). This site may also serve as a winterizing site for the structure in case ice conditions do not permit the arctic leg of the tow to commence. Work will mainly involve bathymetric and geotechnical surveys to select a suitable location where the structure can be set down if the need arises. An estimate of $3.7MM has also been made for the cost of each winterizing site at selected points along the arctic tow route. This is in case the structure is not able to reach its designated location after having entered the lease sale area, and needs to be set down on bottom in a suitable arctic location.

Figures 5.13 and 5.14 indicate the relationship of the towing resistance with the submerged and exposed characteristics of cones and caisson structures. Based on these, the range of tug horsepower required varies from about 25,000HP in 75-ft water depth to over 70,000HP in 300-ft water depth for either cones or caissons. This is based on towing at 2 kn in a 7-ft significant sea. We have used a minimum of five tugs for the smaller water depth and seven tugs for the larger water depth structures. Tug sizes would vary from 11,000 IHP to 22,000 IHP each. Our assumptions are probably on the conservative side and we believe this to be realistic in view of the uncertanties associated with tug availability, spare capacity required, maneuvering capacity, etc. The tugs are assumed to mob/demob at Seattle. We have assumed an average towing speed of 3 kn from Seattle to Icy Cape. This journey is expected to take about 52 days. Five class 4 ice breaking vessels will accompany the tow from Icy Cape to location. These vessels are assumed to mob/demob from the Prudhoe Bay area. A 2 kn speed is assumed from Icy Cape to arctic location. Journey times from Icy Cape will probably range from 2 days to 10 days at this average speed. Figure 5.15 gives an indication of typical total towing costs for cones and caissons at different locations in the lease area and water depths. This chart has been used in establishing costs for different scenarios. The costs are likely to range from about $10MM to $20MM.

c) **Marine Operations at Installation Site**

Table 5.12 indicates the items considered for this operation. The berm construction costs are covered separately under Section 5.2.4. The actual installation of the structure is assumed to take approximately one week after the structure arrives at location. The tug and ice breaker fleet is assumed to stand by during that time. Also, a crane barge and ancillary support mobilized from Prudhoe Bay has been allowed in the costs shown. The ballasting operation cost is insensitive to water depth and a chart is not considered necessary.

The sand undergrouting costs is based on discussions with potential contractors and allows an appropriate spread of barges and support craft to enable the sand or cement grout to be pumped under the structure at the arctic location.

Figure 5.16 shows the cost of spud piles if used . It is based on $1200/s.ton for pile fabrication and $50,000 for transporting and installing each 7-ft diameter, 100-ft long spud pile from the structure.

Some structures may require additional ballast in the form of sand, instead of water which is normally used (see Table 4.7). The sand will be placed using a dredge and barge spread mobilized in the Prudhoe Bay area. Other costs shown in Table 5.12, i.e., scour protection, wick drains, pipeline connections, etc. are considered reasonable estimates for the purposes of this study.

5.2.4 Berm Construction and Costs

5.2.4.1 Construction Scenarios

The berm construction costs are highly sensitive to the location of the gravel borrow source. This has a significant effect on the equipment spread and the time required for construction. Cost estimates have therefore been developed for the following three different construction scenarios, dependant on the borrow source location:

1) Borrow source at site.
2) Offshore borrow source, remote from site.
3) Onshore borrow source.

For scenarios 2) and 3), which involve gravel haulage, the effect of haul distances on construction cost has also been investigated. It was necessary to develop a total of four separate equipment spreads for these scenarios. These will subsequently be referred to as Equipment Spreads A, B, C, and D; the purpose of each spread is listed in Table 5.13.

5.2.4.2 Equipment Spreads and Daily Rates

a) Equipment Spread A: (Dredge local to site)

The equipment, labor, materials and supplies required for dredging local to the site are listed in Tables 5.14 to 5.16. This equipment spread comprises the basic equipment for berm construction: dredging and pipeline handling equipment, crew facilities, and supply barges. The production rate assumed for this equipment spread is 33,000 cu. yd/day. For large berm volumes this rate may not be adequate for the desired construction period. In these cases multiple equipment spreads would be required, but the total cost would remain unaltered. This is a conservative approach, as not all of the equipment would be required to be duplicated for each additional spread.

The cost of the equipment was calculated on a day rate basis, using the following assumptions:

- The capital cost of the equipment was amortized at 10% annual return over a period of 4 years. (The annual capital cost factor is thus 31.5 percent of the purchase cost of the new equipment).
- Mobilization charges for a 120 day round trip from Seattle were included, distributed over 4 years. These charges were only applied for marine based equipment, as much of the land equipment already exists on the North Slope.
- The annual equipment and mobilization costs were divided by the length of the construction season to obtain the daily rate.
- Labor costs were assumed to be $450/day for marine labor, and $550/day for land based labor. The latter rate is higher as additional camp facilities are required for land based labor.

Table 5.17 shows the daily rate cost calculation for Equipment Spread A, for a 60 day construction season. This type of calculation was typical for each of the equipment spreads and differing construction seasons. Figure 5.17 shows the variation of daily rate with construction season for Equipment Spread A. It can be seen that the daily rate, and ultimately the total cost, is very sensitive to the length of the permissable construction season. The implication of this is that in deep water, where the construction season will be short, berm costs are likely to be high.

b) **Equipment Spread B:** (Dredge and haul from offshore source)
The equipment, labor, material and supplies required for dredging and hauling from a remote offshore source are listed in Tables 5.18 to 5.20. This

equipment spread is very similar to Spread A, but with the addition of hopper barges and line haul tugs for haulage operations. The variation of the daily rate with construction season is shown in Figure 5.18.

c) **Equipment Spread C:**
(Excavation and haul from land source to dock facility.)
The construction of a berm from an onshore borrow source is a two stage operation. The gravel must first be excavated and transported to a dock facility on the coast, and subsequently hauled to the installation site. Equipment Spread C was developed for the first stage of this operation. The equipment, labor, material and supplies are listed in Tables 5.21 to 5.23. It was assumed that land based operations would take place during the winter season. This would enable a stockpile of material to be built up at the dock facility, ready for offshore haulage at the start of the open water season. Equipment necesesary to construct and maintain a snow road from the borrow pit to the dock facility has been included. The daily rate variation with construction season is shown in Figure 5.19. It should be noted that the length of season considered is longer than for the other equipment spreads, due to winter construction.

d) **Equipment Spread D:** (Haul from dock facility to site.)
This equipment spread is for the second stage of construction from an onshore source; that of hauling from a dock facility to the installation site. It was assumed that the gravel would be loaded directly into hopper barges from the dockside. Equipment necessary for this operation has been included in the equipment spread, in addition to the marine equipment. Tables 5.24 to 5.26 list the equipment, labor, material and supplies, while Figure 5.20 shows the daily rate variation with construction season.

5.2.4.3 Construction Cost Calculation

The calculations for the total costs for berm construction were carried out in three stages:

- fill construction costs.

- total costs, including fill construction, fixed costs, overhead, profit, and contingency.

- effect of varying haul distances, where applicable, on total costs.

a) <u>Fill Construction Costs</u>

To determine the fill construction cost, the fill volume is first calculated as the berm design volume plus an allowance for lost material. For offshore dredging and filling this allowance was 30%; for onshore excavation it was 15%. The appropriate production rate was then applied to the fill volume to determine the fill construction time. A downtime factor of 1.25 was then applied to the fill constuction time to obtain the total construction time. Finally, the fill construction costs was calculated by applying the day rate for the relevant equipment spread to the total construction time.

b) <u>Total Costs</u>

The total cost for berm construction comprises the fill construction cost, fixed costs, overhead, profit, and contingency. The fixed costs are for shorebase facilities, dock facilities, and snow road construction. The allowances for these were as follows:

For offshore borrow sources an allowance of $2,000,000 was made for a limited shorebased camp. For onshore borrow sources it was assumed that a purpose built dock facility would be required. The cost of such a facility is dependant on the length of causeway required from the shoreline to achieve adequate draft for the hopper barges. This will be very dependant on the location of the facility. From comparison of the costs for existing and proposed facilities in the arctic region, an estimated cost of $15,000,000 was used. The cost for snow road construction was assumed to be $60,000 per mile.

The total cost was therefore calculated by adding the relevant fixed costs to the fill construction cost, and then applying overhead (25%), profit (15%), and contingency (10%) to the cumulative totals. Overhead includes engineering, construction management, and contractor's insurance.

For offshore operations, the fixed costs are low in comparison to the total costs. It can therefore be assumed that the total cost is proportional to the daily rate. Therefore, if the total cost for a particular construction season is calculated, the cost for a different construction season can be obtained by multiplying the total cost by the ratio of the daily rates for the two seasons. This approach has been taken for Equipment Spreads A, B, and D, and costs are presented for one construction season, with factors provided for different seasons. The assumption is not applicable, however, for land operations (Equipment Spread C), because the dock facility cost is a significant proportion of the total cost. For this operation a winter construction season of 135 days has been used, allowing for time to build the snow road. The variation of total cost with design berm volume for on site dredging (Equipment Spread A) is shown in Figure 5.21.

The length of summer construction season was assumed to be the number of days on which there is three octas or less ice coverage. This can be related to water depth, as the ice coverage is more severe in deeper waters further from the shore. The lengths of season assumed were as follows:

WATER DEPTH (FT)	LENGTH OF SEASON (DAYS)
50	60
100	40
200	30
300	20

c) **Effect of Varying Haul Distances on Total Costs**

There are two possible approaches to investigating the cost variation with haul distance:

- Maintain a constant equipment spread, using a decreasing production rate with haul distance.

- Maintain a constant production rate by increasing the equipment spread as the haul distance increases.

The second approach is more efficient as it makes maximum use of the dredging or excavating equipment, and was therefore the one adopted. With this method, the daily cost increases each time the equipment spread is increased. Figure 5.22 shows this effect for Equipment Spread B. The assumptions regarding production rates, haulage times, and equipment spread increments for Equipment Spreads B, C, and D are given in Tables 5.27, 5.28 and 5.29, respectively. On Figure 5.22, the flat portion of the graph indicates redundancy in haulage equipment. For haul distances in this portion, the costs could be reduced by omitting some of this equipment.

To determine the total cost variation with haul distance, the same calculation procedure that has been outlined in the preceding sections was carried out for varying haul distances. For each haul distance, however, the revised daily rate was used. The resulting costs are shown in Figures 5.23, 5.24, and 5.25 for Equipment Spreads B, C, and D, respectively. These figures also give the effect on total cost of berm volume and length of construction season.

5.3 Caisson Retained Islands and Loading Atolls

The cost estimates for caisson retained islands and loading atolls followed the same approach as that for cones and caissons. However, due to basic differences between the two types of concept, some of the component costs were different.

5.3.1 Construction Costs

Although the overall size of the islands is comparable to that of the gravity structures, the individual caissons are small enough to be built in existing dry docks. There is therefore no requirement for a purpose built graving yard, and the plant requirements will differ from those for gravity structures. In calculating the costs for the caisson construction facilities, allowances were made for dry dock leasing, and new equipment spreads were developed. The costs for the equipment spreads were built up using the same assumptions as for gravity structures.

The weights for the individual caissons were calculated on a percent by volume basis (refer Section 4.2.3.3). The materials and operational costs were therefore estimated by applying an average unit rate for the whole structure to the total concrete volume. The rate used was the average rate from all the monolithic caisson cost estimates, as the structural frameworks of the two structures are very similar. The total construction cost was obtained by adding 8% for engineering and management.

5.3.2 Topsides

The topsides costs assumed for exploration and production caisson retained islands are given in Tables 5.30 and 5.31. The essential difference between these costs and those for integrated deck structures is the increased offshore hook up cost. This is due to the hook up operation being carried out in the Arctic instead of in the lower 48.

The topsides costs of the production facilities for the loading atoll were assumed to be the same as those for the production caisson retained island. An additional topside cost for this concept, however, is that of the loading facilities. An allowance of $275MM was made for these facilities, which includes costs for ballast water treatment, vapor recovery system, power generation, oil handling pumps, and general utilities. As mentioned in 4.3.4., the production loading atoll serves the storage and loading function as well and cannot be compared with the other concepts. The cost estimate is for information only.

5.3.3 Scenario Costs

The remainder of the scenario component costs were built up using the same unit rates as for cones and caissons, but only applying those which were relevant to these concepts. For example, the only mechanical and engineering system cost allowed for in the individual caissons was that for a ballast system. Also, many of the marine operations are not applicable to island construction.

5.4 Floating Units

5.4.1 Purpose Built Floaters

The published capital cost of Beaudrill's "Kulluk" drilling unit was approximately $128MM (US) from a Japanese ship yard in April 1983 (13). This includes approximately $48MM (US) of owner furnished drilling equipment. Mobilizing the unit to its arctic location from Japan is likely to cost approximately $10MM, including laying anchors, etc. The total cost including engineering and management is thus likely to be about $150MM.

It should be noted, of course, that capital cost is not the only criterion for comparing alternative concepts. Some of the factors that must be included in comparing floaters with bottom supported units, in addition to capital costs are:

- Time to construct and deploy units.
- Risk of not being able to complete a well in any given time because of environmental conditions.
- Cost of providing havens when not being able to operate the unit.
- Cost of being forced to abandon station and standing by due to environmental reasons.
- Cost of drilling the well including ice-breaker and other support necessary.

- Cost of re-supply operations.

- Risk associated with failure.

The above factors will enable a realistic assessment to be made of the cost and time required to be able to complete a well from different types of units.

It was not the object of this study to make an economic comparison involving drilling costs using different units. However, to be meaningful, such a comparison must be made and a follow up project is recommended to address this issue.

5.4.2 Drillship

The capital cost of building a conventional drillship at the present time runs between $110MM and $120MM, including the drilling equipment. With some ice strengthening the cost may go up to between $120M and $130MM. These are very similar to the cost of the "Kulluk", and for the purpose of this study the same comments relating to costs apply to both types of floating units.

5.5. Cost Results

5.5.1 Example Scenarios for Cones and Caissons

Figures 5.26 to 5.29 show the total costs for a range of possible scenarios for exploration and production cones and caissons. The scenarios shown illustrate the cost trends with changing environmental conditions and the extremes of cost which could be encountered.

Figure 5.26 shows scenario costs for exploration cones. In 200-ft water depth all combinations of basic and sensitivity ice loads and weak and stronger soil conditions are shown. From these the general trend of increasing cost with increasingly severe environmental conditions can be seen. Also shown is the cost comparison of using a berm or a sub-base, and the effect of the different berm construction scenarios. It can be seen that a berm constructed from dredging local to the site is marginally cheaper than using a sub-base.

When haulage operations are involved, however, the berm costs increase, making the sub-base option cheaper. Even though a berm with on-site dredging may be cheaper than a sub-base, it is worth noting that a sub-base is a reusable system, whereas a berm is a sacrificial concept.

In 75-ft and 300-ft water depths, only the upper and lower bound costs are shown. The high cost of berm construction in 300-ft water depth shows the effect that water depth, and therefore construction season, has on berm costs.

Figure 5.27 shows the same scenarios as above for exploration caissons. The same cost trends with increasingly severe environmental conditions and berm construction scenarios are evident. For caissons, however, even a berm constructed from dredging local to site is more expensive than the monolithic structure. This is due to the lighter caisson structure in comparison with the cone. Also evident from this figure is the sensitivity of the caisson structure under high ice loads.

Figures 5.28 and 5.29 show the corresponding scenarios for production cones and caissons, for the 200,000 BOPD case. The same general trends are again evident, but with higher costs due to the production facilities. It is worth noting that the berm option is more expensive than the monolithic structure in all cases. This is because, for production structures, the monolithic structure has been optimised for each water depth.

From these results it can be concluded that a berm is not an economic alternative to a sub-base for operating in deep water. The cost summaries for monolithic structures given in the next section are therefore for structures founded on the seabed, with concrete sub-bases where necessary. Figures 5.26 to 5.29 should be referred to for scenario costs using berms.

5.5.2 <u>Cost Summary</u>

Figures 5.30 to 5.34 summarize the total installed costs for exploration and production concepts. The figures show the variations of total cost with water depth for differing ice and soil conditions. The following is a discussion on the capital cost aspect of the various concepts, a more general discussion, considering feasibility, sensitivity, risk, and time as well as cost is given in Section 7.0.

5.5.2.1 Exploration Systems

Figure 5.30 shows the cost variation with water depth for exploration cones under basic ice loads. The costs for both a shallow cone, with the option of one, or two sub-bases, and a deep cone, with the option of one sub-base are given. The costs for the shallow cone system on weak clay range from approximately $375MM in 60 - 130-ft water depth to $810MM in 230 - 300-ft water depth. Comparison of the two systems indicates that, if the water depth range of principal interest is 100 - 200-ft, then the deep cone is the more economical system, yielding a cost of $500MM compared with $550MM. The figure also shows the significant effect on cost of the soil conditions. A reduction in cost of between 10% and 14% was found when the strength of the clay soil profile used was increased from 0.6 ksf at the surface to 1.0 ksf at the surface.

Figure 5.31 gives the corresponding costs, under basic ice loads, for exploration caissons, caisson retained islands, and floating units. In 75 - 130-ft water depth range, the caisson cost is very similar to that of the cone. However, in deeper water, the benefical effects of the caisson's lower weight to volume ratio make the caisson the cheaper structure. The cost for caisson structures varies between $380MM for 75 - 130-ft water depth to $550MM for 100 - 300-ft depth range. As on the previous figure, the effect of soil conditions on cost is also shown.

The caisson retained island has a relatively low cost in 75-ft of water ($165MM), but it's cost rises very quickly as the water depth increases, reaching $845MM in 200-ft of water. The main reason for this is the large berm volume required, combined with a shortening construction season as the water depth increases.

Floating units can be seen to have a much lower cost in deep water than gravity structures, costing \$150MM for a unit to operate between 200-ft and 300-ft. However, they only have a limited application in this severe environment. As stated earlier, the costs of ice breaking vessels, re-supply logistics, and cost of not being able to complete a well on time will have to be considered with a floating system to make a comparison with fixed structures meaningful.

Figure 5.32 shows the costs for cones and caissons under sensitivity ice loads. A cost is only given for a caisson on the stronger clay soil as it was found to be infeasible on the weak clay under these loads. The costs for the deep cone system are shown, and can be seen to be generally about 10% higher than those for the basic ice loads. The sensitivity ice loads for cones are about 30% higher than the basic ice loads.

5.5.2.2 Production Systems

The variation of installed cost with water depth for production concepts (200,000 BOPD) under basic ice loads is shown in Figure 5.33. The costs shown indicate a band of costs for cones and caissons, dependant on the soil conditions. For example, the total cost for a production cone, including topsides, may vary between \$705MM and \$810MM in 75-ft of water and between \$915MM and \$1090MM in 300-ft of water. Correspondingly, the cost for a caisson ranges from \$640MM to \$765MM in 100-ft water depth (the caisson will not work in 75-ft water depth on weak clay), and from \$800MM to \$925MM in 300-ft of water. The above costs indicate that caissons are generally less expensive than cones.

Production caisson retained islands were found to be more expensive than gravity structures in all water depths. This is due to the high arctic hook up costs and also, high berm costs in deeper water. The loading atoll was three to four times more expensive than any of the other concepts. This is due to the extremely large quantities of both fill and concrete required to construct an atoll. As mentioned earlier, the atoll cannot be directly compared with other structures because of its different function.

The costs for production cones and caissons (200,000 BOPD) under sensitivity ice loads are shown on Figure 5.34. The same trends are evident as under basic ice loads, except that the cassion is infeasible on the weak clay profile. Comparison of Figures 5.33 and 5.34 shows the effect on the cost of changes in the ice loads. It is worth noting that these changes have no effect for either cones or caissons when the structures are founded on the sand soil profile.

5.6 Pipeline Costs

The cost data given below is based on estimates made by the National Petroleum Council (12). It must be emphasized that no detailed engineering of pipelines or pipeline construction methods has been conducted as part of this study. The costs are presented only to allow a more complete estimate to be made of the production system. Also, since pipeline costs may be borne by several users, their costs are not combined with overall production system capital costs. Study participants are expected to use these costs to suit their own particular situations. All cost data are presented in constant January 1981 dollars and do not take into account subsequent inflation.

5.6.1 Land Pipelines

The adequacy of the current state of technology for land pipeline construction and operation has been well demonstrated by TAPS. Any new lines would follow this same technological pattern.

For a crude oil pipeline, direct burial of uninsulated pipe would be used to the maximum extent possible, limited by the presence of thaw unstable soils. In those areas where heat from the buried line could cause thawing and line subsidence, above-ground construction techniques would be used, with either refrigerated or conventional piles for line support as local conditions require.

The cost of a 42-inch land pipeline to handle 1 million barrels of oil per day is estimated to be about $12 million per mile, including new haul roads where necessary and pump stations. The cost is dependent upon the terrian. Fifty percent of the pipeline is assumed to be above ground and 50 percent buried.

Construction schedules of three or four years are projected for the land pipeline projects; if a haul road must be constructed first, a minimum of four years will be necessary. These completion times assume that all permits have been obtained and no subsequent permitting delays are encountered.

5.6.2 Marine Pipelines

No major marine pipeline systems exist in the arctic. It is considered technically feasible to construct long large-diameter marine pipeline systems in Arctic waters off Alaska. The task of installing and protecting these pipelines, particularly for the northernmost Beaufort and Chukchi Basins, would involve direct extensions of current technology. One major need would be to protect these pipelines from ice scour, probably by lowering the line into the sea floor in trenches.

The major portion of the marine pipelines would be uninsulated. Shore approaches where shallow permafrost could be present would be protected with appropriate insulation. The on-bottom stability of the pipelines before burial would determine either the pipe thickness requirement or, alternatively, the thickness of the concrete weight coating requried. A number of combinations of pipe diameter, pipe wall thickness, and concrete coating thickness would be satisfactory.

Trenching by specially made subsea plows and pipeline installation by the bottom-tow method are construction methods considered feasible for the Beaufort, Chuckchi and Hope basins.

Order-of-magnitude cost estimates show that installation of a 36-inch diameter pipeline to produce 1 million barrels or oil a day would cost approximately $10 million per mile (January, 1981) allowing for weather and regulatory delays.

5.7 Subsea Cost Estimates

Estimates of subsea development costs were made for both satellite and template wells. The estimates include the cost of dredging a glory hole, transporting and installing guidance structures and templates, drilling and completing the wells, and finally installing, burying, and connecting the required flowlines. All wells are drilled with a ship-shape, ice-strengthened floating drilling vessel assumed capable of working an average season of 80-days. As stated earlier, subsea system costs should be treated separately since they include costs for drilling as well as capital costs and also since risks of completing a well in a given time are excluded.

A modular approach was followed throughout the estimating, to provide flexibility in rearranging total costs, if the assumptions used do not suit individual participant requirements following the completion of this project.

The major assumptions made are that all drilling and installation equipment is mobilized from a West Coast port with a 30-day transit time to the lease area. All floating vessels are always accompanied by at least one ice-breaking vessel while in transit or while working. the drilling rig and its support vessels when they are not in transit or working are paid a winter standby dayrate. The breakdown of the floating drilling rig dayrate is shown in Figure 5.35.

Satellite well cost sensitivity to total drilling depth and production flow was investigated. From Figure 5.36, it is evident that costs are practically insensitive to flow, but very sensitive to well depth. Figure 5.37 shows the total cost of satellite wells for varying well depths. It is evident that the bulk of the cost is associated with the floating drilling rig, whether it is working, in transit, or on standby.

In the cost section of the Subsea Systems, Appendix C, detailed documentation is furnished on the drilling and completion costs, the number of days used in arriving at the drilling costs, and in general, all the assumptions and unit costs employed to construct the total subsea systems cost.

The cost of four representative cases is presented in the form of examples. The first three examples are subsea installations drilled with a floating drilling unit. The fourth example is comparable to Example 2, with the difference that the drilling is carried out using a bottom-supported conical exploration unit (see Figure 5.38). The total cost of each example is presented in Tables 5.32 thru 5.35. Each table entry has a reference table or figure to assist the reader in reconstructing the cost, if he is interested.

The four cost accumulation examples follow below:

Example 1

Drill , complete and connect back to a permanent production facility a 10,000-ft deep satellite well, at a distance of 2.5 miles from the facility, in 200-ft water depth. Accumulate the total cost required to place the well in production.

From Figures 5.36 and 5.37, it is obvious that the cost is relatively insensitive to production rate. From Figure 5.37, read the total drilling and completion cost for a 10,000-ft well as $55.4MM.

From Table 5.43 , the cost per mile of flowline is $3.028MM, and the fixed mobilization charges for the pipelaying equipment are $8.1MM. Therefore, the total cost for installing and connectionn 1.5 miles of flowline is $12.6MM.

The total cost to make the satellite well operational is shown in Table 5.32 as $68.04MM.

Example 2

Install a 4-well template in 300-ft water depth, drill and complete the wells and connect the template to a production facility 4 miles away. The wells will be drilled to a 15,000-ft depth. Accumulate the costs associated with the system and estimate the total time required to achieve full production.

The template does not require installation within a glory hole because it is in water depths greater than the scouring depth of icebergs. The template, manifold and control equipment costs are found in Tables 5.39 and 5.42, respectively. Installation and piling cost is from Table 5.41.

Drilling and completion costs and time lengths are obtained from Tables 5.36, 5.37, and 5.38. Finally, flowline material and installation costs are obtained from Table 5.43.

The costs for this case are summarized on Table 5.33. It should be noted that five drilling seasons are necessary to complete all work and place the subsea facility into full production. An average drilling season of 80-days has abeen assumed. If the drilling season is longer, then the total cost will be substantially higher.

Example 3

Dredge a glory hole and install an 8-well template in 200-ft water depth. The wells are drilled to 5000 feet, completed subsea, and the production is directed through a flowline to a production treatment facility 3 miles away from the template.

The total costs of this installation is accumulated in similar method to Example 2 and is presented in Table 5.34.

Example 4

Drill, complete and connect back to a permanent production facility four 15,000-ft deep wells drilled from a conical exploration unit in 200 feet of water depth (shown in Figure 5.38). The wells are drilled through a template and at a distance of 4 miles from the production facility. Accumulate the total costs associated with the subsea system.

Completing to production the wells of this example is directly comparable to completing the wells of Example 2. The difference is that the wells are drilled from a drilling unit that can operate year-round, although at a very high dayrate ($500,000 per day). Even with this dayrate, the total system cost shown in Table 5.35 is more than $40 million less than the cost shown in Table 5.33. Therefore, it is concluded that such a year-round drilling system has merit and should be further investigated, insofar as the subsea systems are concerned.

6.0 CONSTRUCTION SCHEDULES

The construction and installation schedules will have a significant impact on the return on investment. It is therefore important to identify the differing schedules associated with each concept. However, it is also important to note that the schedules will vary significantly within each concept, depending on the water depth, ice criteria, and soil conditions. This section summarises the typical range of schedules likely to be encountered. All time periods are from placing of the order to completion of installation and hook-up.

In evaluating the schedules, several assumptions were made regarding the time required for each phase of a given scenario. For concrete construction, an average production rate of 1500 cu.yd./week was assumed from placing of the order to completion of the structure. This rate of production is based on the recent performance in constructing North Sea platforms, particularly the Statfjord series structures. It assumes round the clock working.

The towing times for gravity structures were assumed to be approximately 50 days from Seattle to Icy Cape, and 10 days from Icy Cape to the installation site. Installation was assumed to take 7 days. Hook-up times after installation were assumed to take only a few days for exploration concepts with integrated facilities, and approximately 1 month for exploration artificial islands. The corresponding times for production concepts were 2 months and 6 months, respectively. The latter times are based on the assumption that it would not be necessary to hook-up the full capacity of the rig for the start of drilling operations.

To optimise the schedule it is important to sequence the work such that the towing and installation operations, which must take place in the short open water season, are able to follow directly after completion of construction of the structure.

A summary of the schedules for the different concepts is given in Table 6.1. From this it can be seen that an exploration shallow water gravity structure will require between 2½ and 3 years from placing of the order to completion of installation and hook-up. In deep water, 3½ to 4½ years are required for cone based systems, and 2½ to 3 years for caisson structures. This latter difference is due to the lighter caisson structure, which becomes significant as the overall structural size increases with water depth.

Deep water structures have been assumed to be constructed simultaneously in two sections at independant locations. This explains why, in some instances, the schedules do not appear to vary with water depth. The range of schedules for each concept is due to the variation in structural size resulting from different environmental conditions. In the concept feasibility and sensitivity section (Section 4.0) this variation was seen to be very significant in some cases, and this is reflected in the construction schedules. The range indicated is larger for production gravity structures than for exploration. For example, a production cone in either 75-ft or 300-ft may take from 2½ years to 4 years. This large variation is due to the wider range of environmental conditions considered for production structures.

A caisson retained island in shallow water (75-ft) can be constructed in 2 to 2½ years if the phasing of berm and caisson construction is timed correctly. The berm must be completed in the first open water season after placing the order, and the caisson construction, which can be completed in 1 year, must be carried out simultaneously. The caisson installation and island backfilling can then be completed in the second open water season. In deep water, however, the berm volumes are very large (18 x 10^6cu.yd.), and construction periods will depend on how much equipment can be mobilised in the area at the same time. This also applies to loading atolls, which require very large volumes of both fill and concrete for their construction.

Purpose built floating units are estimated to take approximately 2 years from placing of the order to completion of construction.

7.0 GENERAL DISCUSSION

This section provides a general discussion on the results for each of the concepts studied. All of the factors examined are considered, namely feasibility, sensitivity, risk, time, and cost. For a more detailed discussion on each of these factors, the relevant section (from Section 4.0 to 6.0) should be referred to.

7.1 Cone

In general the cone was found to be the most widely applicable to the lease sale area from all of the concepts. It was found to be feasible under all environmental conditions considered without any allowances being made for strength gain in the seabed soils due to consolidation effects. This applies to both exploration and production structures. The overall size of the cones was generally governed by geotechnical stability, however, due to the cone geometry, floating stability became more critical when the structure was founded on strong soils. In general, the structural size was found to be more sensitive to changes in soil conditions than ice loads.

The risk analysis performed indicated that, if departure from Icy Cape took place before August 1st, then the probability of successfully installing a structure would be between 75% and 98%. It also showed that these probabilities were only decreased by between 1% and 3% when the draft requirement was increased from 65-ft to 130-ft.

The construction schedules for the exploration cone are from 2½ to 3 years in shallow water, and from 3½ to 4½ years in deep water depending on the ice and soil conditions. For production structures the schedules vary from 2½ to 4 years in all water depths. The times are from placing of the order to completion of installation and hook-up operations, and assume simultaneous construction of cone and sub-base in deep water.

The costs for exploration cones, under basic ice loads on weak clay soils, range from $375MM in 60 - 130-ft water depth to $810MM in 230 - 300-ft. If the predominant range of 100 - 200-ft is considered (i.e. 63% of the whole lease sale area) the probable cost of an exploration cone will be approximately \$500MM to \$550MM including installation and hook-up. The costs for 200,000 BOPD production cones, under basic ice loads, range from \$705MM to \$810MM in 75-ft water depth, \$790MM to \$950MM in 200-ft water depth and \$915MM to \$1090MM in 300-ft water depth.

The use of independant sub-bases to extend the operating depth of a structure was found to be generally more economical than the use of berms. Sub-bases also have the advantage of multiple use. However, berms may be applicable for small increments in water depth, up to approximately 50-ft.

7.2 Monolithic Caisson

The monolithic caisson is structurally lighter than the cone. However, the ice loads on the caisson are significantly larger and are also sensitive to waterline diameter. Caissons were found to be feasible, without any allowances for strength gain, on strong sandy sites. On clay soils, however, in order to make structures of realistic overall size work, some form of foundation improvement was required. Two techniques were examined: the use of wick drains to accelerate consolidation effects, and the use of spud piles to improve horizontal sliding resistance. Of these techniques, the use of wick drains proved to be the more effective in reducing structural size. The caisson was also found to be very sensitive to changes in environmental conditions and, under the sensitivity ice loads considered, has only limited application on clay soils.

The risk analysis results given above for cones also apply to caissons, except that, at a given location, a caisson would have a slightly lower probability of success due to the increased installation time required to install the wick drains. The construction schedules for exploration caissons are between 2½ and 3 years in all water depths. The schedules for production caissons range form 2-2½ years in 75-ft water depth and from 3-3½ years in 300-ft water depth.

The costs for exploration caissons, under basic ice loads and on weak clay soils, range from $380MM in 75 - 130-ft water depth to $550MM in 100 - 300-ft. The costs for 200,000 BOPD production caissons, under basic ice loads, range from $640MM to $765MM in 100-ft water depth, $715MM to $840MM in 200-ft water depth and $800MM to $925MM in 300-ft water depth.

7.3 Caisson Retained Island

The caisson retained island was found to be feasible but with limitations to it's application. On weak clay soils, excavation of the seabed material to a depth of approximately 20-ft was necessary, and on all clay soils, shear strength gain due to consolidation effects from the berm had to be considered. In 75-ft water depth an exploration island could be constructed in approximately two years with a cost of $165MM. However, as the water depth increases, the berm volume required increases rapidly and the construction season available decreases. Therefore, the cost for an island also increases rapidly, reaching $845MM in 200-ft water depth. For production islands, the high cost of carrying out offshore hook-up operations in the arctic causes the cost of an island, even in 75-ft water depth, to be high ($860MM). It should also be noted that, although it will be possible to re-use the caissons, the berm construction and island fill costs would be written off for each island location.

7.4 Production and Loading Atoll

The production and loading atoll, while being a feasible concept, is required to be extremely large in size. The resulting quantities of both fill (21.6 x 10^6cu.yd.) and concrete (940 x 10^3cu.yd.) make the logistics of constructing such an island very complex. The time required will depend on the amount of equipment that could be mobilised in the area at the same time. The cost for an atoll in 80-ft water depth is $2720MM; three to four times the cost of the other concepts.

7.5 Floating Drilling Unit

Floating drilling units only have a limited environmental window in which they can operate. This is governed by the thickness of broken ice that can be tolerated, and the assumption that there is always sufficient ice breaker support to ensure that the ice is broken. The operational water depth will depend upon the drilling vessel configuration and the environmental forces imposed. Floating drilling operations have been carried out in water depth as low as 80-ft in the Canadian arctic, using a BOP stack placed in a glory hole.

The risk analysis indicated that, if broken ice thicknesses up to 2-ft can be tolerated, then the probability of drilling a 5000-ft well in one season lies between 50% and 75%, and that for a 15,000-ft well between 20% and 65%, depending on the location in the lease sale area. It is estimated that the chances of success may improve by about 10 to 15 percent if drilling is carried out closer to shore in say 100-ft of water. However, further work will be needed to justify this. The corresponding probability ranges, if broken ice thickness up to 4-ft can be tolerated, are 75 - 78% and 58 - 78%, respectively. The probabilities tend to be higher in the eastern Beaufort than in the western Beaufort.

A purpose built drilling unit could be constructed in approximately 2 years from placing the order, at a cost of $150MM. To this must be added the cost of ice breakers, supply logistics, etc. Further work is needed to quantify this.

7.6 Subsea Systems

The study found that the installation of subsea systems in the arctic was feasible with current technology. However, it identified three areas where improvements could be made which would benefit arctic usage.

The first of these is in the field of protection from ice scour, particularly for flowline burial. Current equipment is capable of burying pipelines to a depth of 6-ft. However, ice scour protection would require this depth to be increased to 20-ft.

The second concerns the drilling of the wells. Subsea wells are generally drilled from floating drilling rigs, which in the arctic are subject to the limitations discussed in the previous section. It is therefore worthwhile investigating the technical feasibility of drilling and completing subsea wells from gravity structures.

The third is in the field of well maintenance where, again, improvements in technology could reduce the reliance on floating units for complete well maintenance.

The cost of subsea systems will depend on the system used: single satellite wells, template wells, or satellite wells connecting to a manifold. The cost section (Section 5.7) should therefore be referred to for cost examples, however, in general it was found that subsea systems could be a cost effective option to be used in conjunction with fixed central production facilities.

8.0 CONCLUSIONS

The overall conclusions for the study are summarised in the following sections. The costs given are based on the construction of the structures being carried out on the west coast of North America. If Far East construction is employed, the costs are likely to be lower by about 15-20 percent than those given in this report. The costs are for the concepts under basic ice loads; for cost sensitivity to ice load refer to Section 5.5. The costs include construction, transportation, installation, and topsides associated with each concept.

8.1 Exploration Systems

The following cost figures are for concepts on clay (c_u = 0.6 ksf) foundation material. For exploration cost sensitivity to soil conditions refer to Section 5.5.

8.1.1 All Water Depths

1) Monolithic caissons are generally cheaper than cones, but:

   - are more sensitive to ice overload.

   - rely on strength gain in the foundation when founded on clay soils.

2) The cone is the most reliable concept under ice overload, and is feasible on all stipulated soil conditions without allowances for strength gain.

3) Floating drilling units are significantly cheaper than gravity based structures, but have a much lower probability of successfully completing a well in any one year.

8.1.2 Shallow Water (60 - 130-ft)

1) The estimated cost for a cone to operate in this water depth range is $375MM.

2) The estimated cost for a monolithic caisson (for 75 - 130-ft) is $380MM.

3) In water depths up to approximately 100-ft the caisson retained island is the cheapest concept, but is primarily for single use only. The estimated cost of an island in 75-ft water depth is $165MM.

4) Floating drilling units are only applicable in water depths in excess of 100-ft. Their estimated cost is $150MM, independant of water depth. This cost does not include the cost of ice breaker support, supply logistics, etc.

8.1.3 Intermediate Water Depth (100 - 200-ft)

1) The estimated cost for a cone in this water depth range is $500MM.

2) The estimated cost of a monolithic caisson is $425MM.

3) The caisson retained island becomes more costly than other concepts due to high berm construction costs. ($845MM in 200-ft water depth)

4) Deep berms are not an economic alternative to independant sub-bases for large extensions in working depths.

5) Shallow berms (up to 50-ft) may be useful in providing a small extension to the operating depth of a structure.

8.1.4 Deep Water (200 - 300-ft)

1) The estimated cost for a cone based system is $790MM.

2) The estimated cost for a monolithic caisson is $550MM (for 100 - 300-ft).

3) The use of berms is not realistic in deep water, due to high cost and short construction season.

8.2 Production Systems

8.2.1 All Water Depths

1) Monolithic Caissons are generally cheaper than cones, but:

   - are more sensitive to ice overload.

   - rely on strength gain in the foundation when founded on clay soils.

2) The cone is the most reliable concept under ice overload, and is feasible on all stipulated soil conditions without allowances for strength gain.

3) Subsea systems installation is feasible in the arctic environment and can be cost effective. Example costs are:

   1) To drill, complete and connect back to a permanent production facility a 10,000-ft deep satellite well, 2.5 miles from the facility, in 200-ft water depth will cost approximately $68MM.

   2) To install a 4-well template in 300-ft water depth, drill and complete the wells (15000-ft deep), and connect the template to a production facility 4 miles away will cost approximately $283MM.

   3) To dredge a glory hole and install an 8-well template in 200-ft water depth, drill and complete the wells (5000-ft deep) and connect back to a production facility 3 miles away will cost approximately $354MM.

8.2.2 Shallow Water (75 - 100-ft)

1) The estimated cost for a 200,000 BOPD production cone in 100-ft water depth varies from $720MM to $840MM, depending on the soil conditions.

2) The corresponding cost for a 200,000 BOPD production monolithic caisson in 100-ft water depth varies from $640MM to $765MM.

3) The caisson retained island is more expensive than the monolithic structures, costing $860MM in 75-ft water depth, due to high arctic hook-up costs.

4) Production and loading atolls are three to four times more expensive than other concepts, costing $2720MM in 80-ft water depth.

8.2.3 Intermediate Water Depth (200-ft)

1) The estimated cost for a 200,000 BOPD production cone in 200-ft water depth varies from $790MM to $950MM, depending on the soil conditions.

2) The corresponding cost for a 200,000 BOPD production monolithic caisson in 200-ft water depth varies from $715MM to $840MM.

3) A monolithic structure founded on the seabed is always cheaper than a shallower structure founded on a berm.

8.2.4 Deep Water (300-ft)

1) The estimated cost for a 200,000 BOPD production cone in 300-ft water depths varies from $915MM to $1090MM, depending on the soil conditions.

2) The corresponding cost for a 200,000 BOPD production monolithic caisson in 300-ft water depth varies from $800MM to $925MM.

8.3 General Conclusions

1) On strong soils, the overall size of a cone is governed by floating stability. In all other cases size is governed by geotechnical behavior.

2) On clay soils the monolithic caisson requires artifical strength gain techniques for realistic structural sizes to work.

3) For caissons, the use of artificial drains to improve geotechnical behavior is more effective in reducing structural size than the use of spud piles.

4) Ice loads on vertical sided structures are significantly larger than on cones and are sensitive to waterline diameter. It is our opinion that the deterministic method used overestimates ice loads on caissons. A method using a probabilistic approach, currently being developed, is considered to yield more realistic results.

5) For gravity structures, the overall size is more sensitive to soil conditions than to ice conditions.

6) The probability of successfully installing a gravity structure is high, provided departure from Icy Cape takes place early in the open water season.

7) Increasing the towing draft requirement for gravity structures from 65-ft to 130-ft had little effect on the probability of successfully installing the structures, generally from 1 to 4 percent.

8) For caisson retained islands on weak soils, excavation and replacement of seabed material is necessary.

9) Floating units can be operated in the arctic in water depths in excess of 100-ft, but they only have a limited environmental window in which this is possible, and may not be able to complete a well in one season.

10) There is scope for technology improvements in the fields of drilling, protecting, and maintaining subsea installations.

9.0 RECOMMENDATIONS FOR FURTHER STUDY

As a result of the study, certain research and development topics in specific areas have been identified. Many of these have already been proposed as extensions to the scope of this study. However, a list of the topics is given below.

1) Logistics support and operating risks evaluation for exploration, development, and production operations in lease sale 87 area. The present study has identified several concepts, both bottom founded and floating, as being technically viable for operations in the lease sale area, and their capital costs have been estimated. However, different concepts will have different support requirements and operating risks. One particular canidate is the floating drilling system, whose capital cost is low and is applicable in a wide range of water depths. In order to make overall concept comparisons, therefore, it is necessary to carry out an estimate of the operating and logistics support costs, in addition to their initial capital costs. It is also necessary to evaluate the effectiveness of the system to perform its function in a given time tegether with the associated risks.

2) Further work on risk analysis for towing and installation operations. A preliminary risk analysis has already been performed, however, further work will yield a clearer understanding of the risks associated with these operations. The work needs extension into the open water towing operations in the harsh Gulf of Alaska and Pacific Ocean waters.

3) Probabilistic load selection for caissons. The existing ice load design criteria for caisson structures were based on a deterministic approach. This approach yielded design load levels considerably higher than those selected for conical structures and which we believe to be very conservative. An evaluation of loads using probabilistic selection techniques will yield more reasonable design ice load criteria for caissons and reductions in costs.

4) Development and calibration of method to predict soil strength gain due to consolidation with and without artificial drains. This topic complements the recommended work on the installation of artificial drains (Topic No. 5). There is a need for a convenient method to reliably predict the soil strength improvement when artifical drains are used in order that cost effective structures can be designed. The method will require calibration with actual field measurements which are available at the present time..

5) Assessment of submarine installation of artificial drains for soil stabilisation. This study has shown that cost effective caisson structures can be developed, provided that the weak foundation soils can be stabilized by using artificial drains. Further work is necessary to fully investigate the problems associated with installing these drains, and the full potential for strength gain when they are used.

6) Use of subsea systems with bottom founded drilling units. The applications of subsea systems in arctic environments would be greatly enhanced if the systems can be installed in sub mudline silos from bottom founded units. Investigation is needed to identify the problems and solutions associated with this concept.

7) Effect of thaw subsidence on systems components. Thawing of the permafrost and the resulting subsidence could have a significant effect on the structural systems, wells, subsea equipment, pipelines, and production facilities. Therefore, a greater understanding of the extent, effect, and possible methods of reducing these is needed.

8) Tanker mooring/loading system for Production Cones. This involves the development of a cost effective system mounted on production cones which will enable tankers to be moored and loaded directly. Application could be for early production, prior to pipelines being installed, or as an alternative to pipelines in remote locations.

9) Further engineering work on sub-bases and connections. This study has addressed key items to demonstrate the overall feasibility of deepwater systems. However, further work is needed to develop workable solutions for aspects such as the structural design of sub-bases, mating hardware and operations, and the M & E systems required in sub-bases.

10) Development of trenching equipment for subsea flowline burial. Present equipment is only capable of excavating subsea trenches to a depth of 6-ft. To protect flowlines from ice scour they will need to be buried 20-ft below the mudline. There is therfore a need to develop new equipment with the capability for deeper excavation.

11) Further assessment of spud piles to increase sliding resistance. Several important design assumptions were made in the preliminary design of caisson structures with spud piles in this study. There is a need to examine each of these assumptions in greater depth, and investigate the sensitivity of the spud pile design to each of the assumptions.

REFERENCES

1. OCSEAP, Climatic Atlas of the Continental Shelf Waters and Coastal Regions of Alaska, Vol. III, Chukchi - Beaufort Sea, 1977.

2. USGS, Geologic Framework, Hydrocarbon Potential and Environmental Conditions for Exploration and Development of Proposed Oil and Gas Lease Sale 87 in the Beaufort and Northeast Chukchi Seas. Open File Report 82-482, 1982.

3. Slomski, S. and Vivatrat, V., "Selection of Design Ice Pressures and Application to Impact Load Predictions", Proceedings, Conference on Polar and Ocean Engineering under Arctic Conditions, Helsinki, Finland, April 1983.

4. Ralston, T. D., "Plastic Limit Analysis of Sheet Ice Loads on Conical Structures", International Union of Theoretical and Applied Mechanics Symposium of Physics and Mechanics of Ice, Copenhagen, 1979.

5. Ladd, C. C. and Edgers, L., "Consolidated Undrained Direct-Simple Shear Tests on Saturated Clays", Res. Report R72-82, No. 284, Dept. of Civil Engineering, Mass. Institute of Technology, Cambridge, 1972.

6. Vivatrat, V. and Watt, B. J., "Stability of Arctic Gravity Structures", ASCE Specialty Conference on Geotechnical Practice In Offshore Engineering Austin, Tx., April 1983.

7. Meyerhof, G. G., and Chaplin, T. K., "The Compression and Bearing Capacity of Cohesive Layers", British Journal of Applied Physics, 1953, Vol. 4, No. 20, pp. 20-26.

8. Vesić, A. S., "Bearing Capacity of Shallow Foundations", Foundation Engineering Handbook, Chapter 3, Van Nostrand Reinhold Co., New York, 1975, pp. 121-147.

9. Sea Ice Consultants, "Sea Ice Conditions Along the North Coast of Alaska, Cape Halkett to Camden Bay, June Through October, 1953 to 1975", AOGA Project 35, December, 1975.

10. Webster, B. D., "Empirical Probabilities of the Ice Limit and Fifty Percent Ice Concentration Boundry in the Chukchi and Beaufort Seas", National Weather Service, Alaska Ocean Services Unit, NOAA Technical Memorandum NWS AR-34, May, 1982.

11. Potocsky, G. J., "Alaskan Area 15- and 30-Day Ice Forecasting Guide", Naval Oceanographic Office Special Publication, AD-A010 527, February, 1975.

12. "U.S. Arctic Oil and Gas", Report prepared by the National Petroleum Council, December, 1981.

13. Gaida, K. P., Barnes, J. R. and Wright, B. D., "Kulluk - An Arctic Exploratory Drilling Unit", Proceedings, Offshore Technology Conference, OTC Paper No. 4481, Houston, Texas, May, 1983.

RETURN PERIOD (YEARS)	ZONE 1	ZONE 2	ZONE 3
10	75	70	70
100	100	90	90

TABLE 2.1 SUSTAIN WIND SPEED (1-MINUTE AVERAGE) IN KNOTS FOR LEASE SALE 87 ZONES

ETURN PERIOD (YEARS)	WATER DEPTH (FT) 60	120	≥180
10	2.0	1.7	1.3
100	3.0	2.5	2.0

TABLE 2.2 SEA SURFACE RISE DUE TO STORM SURGE AND BAROMETRIC EFFECTS (ALL ZONES)

	ZONE 1			ZONE 2			ZONE 3		
WATER DEPTH (FT):	**60**	**120**	**≥180**	**60**	**120**	**≥180**	**60**	**20**	**≥180**
RETURN INTERVAL (YEARS)	**MAX. WAVE HEIGHT (FT)**								
10	28	30	34	26	30	34	26	30	34
100	44	49	53	40	46	49	42	48	51
	SIG. WAVE HEIGHT (FT)								
10	15	16	18	14	16	18	14	16	18
100	24	27	29	22	25	27	23	26	28
	PEAK SPECTRAL PERIOD (SEC.)								
10	10	11	11	10	11	11	10	10	10
100	13	14	14	13	14	14	13	13	13

TABLE 2.3 **PROPOSED DESIGN WAVE CRITERIA FOR LEASE SALE 87 AREA, BY ZONE**

	ZONE					
	1		2		3	
WATER DEPTH (FT):	60	≥120	60	≥120	60	≥120
RETURN INTERVAL (YEARS)						
10	3.0	2.0	2.0	1.5	2.0	1.5
100	4.5	3.0	3.0	2.0	3.0	2.0

TABLE 2.4 DESIGN MID-DEPTH CURRENT (KNOTS)

Drilling Season	8 Months
Number of Wells	3
On-Board Supplies Capacity	For 8-Month Season
Well Depth (TVD)	16,000 Feet
Minimum Well Spacing	7 Feet - 6 Inches
Reservoir Pressure	5,000 psi

TABLE 2.5 EXPLORATION DRILLING REQUIREMENTS

DESCRIPTION		CASE 1	CASE 2
1.	PRODUCTION RATE:		
	Oil	50,000 BOPD	200,000 BOPD
2.	PRODUCED WATER:		
	Initial (15%)	7,500 BWPD	30,000 BWPD
	Depletion (80%)	40,000 BWPD	160,000 BWPD
3.	GAS:	GOR 1,000	GOR 1,000
4.	FLOWING CONDITION:		
	Pressure at 1st Stg. Sep.	500 PSIG	500 PSIG
	Temperature	150°F	150°F
	Oil Gravity	28.5° API	28.5° API
	Gas Gravity	0.7	0.7
5.	WELL FLOW RATE:	2,500 BOPD	2,500 BOPD
6.	NUMBER OF WELL SLOTS:	25	100
7.	PIPELINE PUMPS DESIGN @:	1,000 PSIG	1,000 PSIG
8.	COMPRESSOR FOR GÀS INJECTION	5,000 PSIG	5,000 PSIG

TABLE 2.6 BASIS FOR SIZING PRODUCTION FACILITIES (SH. 1)

DESCRIPTION		CASE 1	CASE 2
9.	**WATER FLOOD:**		
	Inject Pressure	3,000 PSIG	3,000 PSIG
	Rate	50,000 BPD	200,000 BPD
	Number of Wells for Injection	5	15
	Seawater Source	40' to 100' Deep	40' to 100' Deep
	Seawater Temperature	$-1^{o}C$ to $+5^{o}C$	$-1^{o}C$ to $+5^{o}C$
10.	**POWER SUPPLY:**	a. Gas Turbine Driven With 100% Standby b. Use Diesel for Emergency c. Use Separate Power Supply for Drilling	a. Gas Turbine Driven with 100% Standby b. Use Diesel for Emergency c. Use Separate Power Supply for Drilling
11.	**CREW QUARTERS:**	Production and Drilling 150 Men	Production and Drilling 280 Men
12.	**HELIPAD:**	Chinook	Chinook
13.	**NUMBER OF DRILLING RIGS:**	1	2
14.	**STORAGE FOR CONSUMABLE GOODS:**	8 Months Supply	8 Months Supply

TABLE 2.6 BASIS FOR SIZING PRODUCTION FACILITIES (SH. 2)

DESCRIPTION	CASE 1	CASE 2
15. STANDBY PHILOSOPHY:		
a. Production Trains	Single	1 or 2 Trains Depending on Space Limitation
b. Compression	Two 50% Units No Standby	Two 50% Units No Standby
c. Pipeline Pump	Turbine Driven Two On-Line; One Spare	Turbine Driven Two On Line; One Spare
d. Waterflood Pumps	Turbine Driven One 100% Unit No Spare	Turbine Drive Two 50% Units No Spare

TABLE 2.6 BASIS FOR SIZING PRODUCTION FACILITIES (SH. 3)

ICE CRITERIA			BASE CASE
SOIL CRITERIA			BASE CASE
STRUCTURE	WATER DEPTH (ft)	CODE	CLAY c_u = 0.6 KSF
Cone	60-130	1	525
		2	348
		3	66
Cone + Sub-Base	130-200*	1	525/525
		2	561
		3	90
Cone + Two Sub-Bases	230-300	1	525/525/525
		2	901
		3	119
Cone + Berm	200	1	525
		4	2.1

CODES:

1 = Cone Diameter/Base Diameter(s) (ft)

2 = Total Concrete Weight (x 10^3 short tons)

3 = Draft to U/S of Skirts (no air) (ft)

4 = Berm Volume (x 10^6 cu.yd.)

*For Water Depths from 200 - 230-ft use Cone + Sub-Base + Shallow Berm

TALBE 4.1 EXPLORATION CONES - STRUCTURAL SUMMARY SYSTEM 1 - SHALLOW CONE

ICE CRITERIA			BASE CASE		HIGH	
SOIL CRITERIA			BASE CASE	HIGH	BASE CASE	HIGH
STRUCTURE	WATER DEPTH (ft)	CODE	CLAY 0.6 KSF	CLAY 1.0 KSF	CLAY 0.6 KSF	CLAY 1.0 KSF
Cone	100-200	1	600*	525	650*	575
		2	548	433	632	507
		3	72	75	70	73
Cone + Sub-Base	200-300	1	600/600	550/550	650/650	575/575
		2	943	808	1061	871
		3	112	115	108	113
Cone + Berm	300	1	600	525	650	575
		4	4.4	3.9	4.8	4.2

CODES: 1 = Cone Diameter/Base Diameter (ft)

2 = Total Concrete Weight (x 10^3 short tons)

3 = Draft to U/S of Skirts (no air) (ft)

4 = Berm Volume (x 10^6cu.yd.)

*120' - 200' Water Depth Range Only (see text Section 4.2.1.7)

TABLE 4.2 EXPLORATION CONES - STRUCTURAL SUMMARY SYSTEM 2 - DEEP CONE

		PRODUCTION	
	EXPLORATION	**50,000 BOPD**	**200,000 BOPD**
Required Area (Ft^2) (Single Level)	125,000	180,000	360,000
Equivalent Diameter (Ft)	400	500	700

TABLE 4.3 <u>**FACILITIES REQUIREMENTS FOR EXPLORATION AND PRODUCTION CAISSONS**</u>

ICE CRITERIA			BASE CASE		HIGH	
SOIL CRITERIA			BASE CASE	HIGH	BASE CASE	HIGH
STRUCTURE	WATER DEPTH (ft)	CODE	CLAY 0.6 KSF	CLAY 1.0 KSF	CLAY 0.6 KSF	CLAY 1.0 KSF
Caisson	75-130	1	450/650	350/550	>1000	>1000
		2	323	228	-	-
		3	44	43	-	-
		5	2400	1750	-	-
Caisson	100-200	1	350/650	325/550	>1000	325/625
		2	383	294	-	320
		3	51	54	-	47
		5	2400	1750	-	2250
Caisson	100-300	1	450/650			
		2	511			
		3	65			
		5	2400			
Caisson + Berm	200	1	450/650	350/550	>1000	>1000
		4	2.6	2.2	-	-

CODES:

1 = Caisson Diameter at waterline/at mudline (max. dist. across corners) (ft)
2 = Total Concrete Weight (x 10^3 short tons)
3 = Draft to U/S of Skirts (no air) (ft)
4 = Berm Volume (x 10^6 cu.yd.)
5 = No. of Wick Drains

TABLE 4.4 EXPLORATION CAISSONS - STRUCTURAL SUMMARY

WATER DEPTH	75		200	
ISLAND TYPE	EXP.	PROD.	EXP.	PROD.
Soil Strength (K.S.F.)	.90	1.3	1.0	1.70
Caisson Length (FT)	278	447	278	430
Caisson Height (FT)	70	80	70	80
Caisson Width (FT)	85	140	120	80
Berm Height (FT)	25	25	150	150
Bench Width (FT)	80	80	80	80
Concrete Quantity, cu.yd.	48,000	146,000	6,200	87,000
Fill Quantity, cu.yd.	1,400,000	2,600,000	18,600,000	17,200,000
Excavation, cu.yd.	400,000	-	3,400,000	-

TABLE 4.5 CAISSON RETAINED ISLAND DESIGN PARAMETERS AND MATERIAL QUANTITIES

ICE CRITERIA			BASE CASE			HIGH		
SOIL CRITERIA			CLAY (ksf)		SAND	CLAY (ksf)		SAND
STRUCTURE	WATER DEPTH (ft)	CODE	0.6	1.5	$\phi = 35°$	0.6	1.5	$\phi = 35°$
Cone	75	1 2 3	650 438 60	500 271 70	500 271 70	710 516 58	525 295 67	500 271 70
Cone + Base	180	1 2 3	470/650 556 72	470 443 90	425 371 98	500/710 640 68	520 489 86	425 371 98
Cone + Base	300	1 2 3	475/660 836 91	445 562 130	445 562 130	505/720 950 88	415/500 608 111	445 562 130
Cone + Berm	180	1 4	650 5.2	500 4.0	500 4.0	710 5.7	525 4.2	500 4.0
Cone + Berm	300	1 4	470/650 6.8	470 5.2	425 4.9	500/710 7.4	520 5.6	425 4.9

CODES:

1 = Cone Diameter/Base Diameter (ft)
2 = Total Concrete Weight (x 10^3 short tons)
3 = Draft to U/S Skirts (no air) (ft)
4 = Berm Volume (x 10^6 cu.yd.)

TABLE 4.6 PRODUCTION CONES (50,000 & 200,000 BOPD) - STRUCTURAL SUMMARY

PRODUCTION RATE			50,000 BOPD		200,000 BOPD					
ICE CRITERIA			BASE	HIGH	BASE			HIGH		
SOIL CRITERIA			CLAY	CLAY	CLAY (ksf)		SAND	CLAY (ksf)		SAND
STRUCTURE	WATER DEPTH (ft)	CODE	1.5 ksf	1.5 ksf	0.6	1.5	$\phi = 35^\circ$	0.6	1.5	$\phi = 35^\circ$
Caisson	75	1				750/900			>1000	
		2				-			-	
		3				-			-	
	200	1	325/675	375/775	>1000	450/675	450*	>1000	450/850	450*
		2	327	425	-	391	261	-	-	261
		3	44	43	-	51	77	-	-	77
	300	1				450/675			450/850	
		2				536			-	
		3				67			-	

CODES: 1 = Caisson Diameter at waterline/at mudline (max. dist. across corners) (ft)
2 = Total Concrete Weight (x 10^3 short tons)
3 = Draft to U/S of Skirts (no air) (ft)

*Requires approximately 750,000 cu.yd. of sand ballast.

TABLE 4.7 PRODUCTION CAISSONS WITHOUT STRENGTH GAIN - STRUCTURAL SUMMARY

PRODUCTION RATE			50,000 BOPD		200,000 BOPD					
ICE CRITERIA			BASE	HIGH	BASE			HIGH		
SOIL CRITERIA			CLAY	CLAY	CLAY (ksf)		SAND	CLAY (ksf)		SAND
STRUCTURE	WATER DEPTH (ft)	CODE	1.5 ksf	1.5 ksf	0.6	1.5	$\phi = 35°$	0.6	1.5	$\phi = 35°$
Caisson	75	1				450/550			850/1000	
		2				182			-	
		3				40			-	
		5				1730			-	
	200	1	325/525	325/600	450/750	450/525	N/A*	>1000	450/675	N/A*
		2	232	276	441	295	N/A	-	391	N/A
		3	54	47	47	66	N/A	-	51	N/A
		5	1575	2050	3215	1575	N/A	-	2600	N/A
	300	1				450/525			450/650	
		2				403			517	
		3				84			70	
		5				1575			2420	

CODES:
1 = Caisson Diameter at waterline/at mudline (max. dist. across corners) (ft)
2 = Total Concrete Weight (x 10^3 short tons)
3 = Draft to U/S of Skirts (no air) (ft)
5 = No. of Wick Drains

*Wick Drains not required on Sand Soils

TABLE 4.8 PRODUCTION CAISSONS WITH WICK DRAINS - STRUCTURAL SUMMARY

PRODUCTION RATE			50,000 BOPD		200,000 BOPD					
ICE CRITERIA			BASE	HIGH	BASE			HIGH		
SOIL CRITERIA			CLAY	CLAY	CLAY (ksf)		SAND	CLAY (ksf)		SAND
STRUCTURE	WATER DEPTH (ft)	CODE	1.5 ksf	1.5 ksf	0.6	1.5	ø = 35°	0.6	1.5	ø = 35°
Caisson	75	1				500/550			N/F+	
		2				196			-	
		3				39			-	
		6				95/60			-	
	200	1	375/525	375/600	N/F+	500/550	N/A*	N/F+	500/700	N/A*
		2	266	307	-	345	N/A	-	432	N/A
		3	55	49	-	64	N/A	-	50	N/A
		6	130/70	166/100	-	95/60	N/A	-	220/100	N/A
	300	1				500/600			500/700	
		2				522			604	
		3				79			68	
		6				85/55			220/100	

CODES:

1 = Caisson Diameter at waterline/at mudline (max. dist. across corners) (ft)
2 = Total Concrete Weight (x 10^3 short tons)
3 = Draft to U/S of Skirts (no air) (ft)
6 = No./Penetration (ft) of Piles

*Piles not required on Sand Soils

+Piles required at less than 2 dia. cs. (not feasible)

TABLE 4.9 PRODUCTION CAISSONS WITH SPUD PILES - STRUCTURAL SUMMARY

START DATE:

Normal Distribution

Mean	=	8 Aug
Std. Deviation	=	20.1 Days
Minimum	=	10 Jul
Maximum	=	18 Sep

INVASION FREQUENCY:

Poisson Distribution

Mean	=	0.500 Invasions/Year

INVASION DURATION:

Exponential Distribution

Mean	=	16.51 Days

DRILLING PERIOD BETWEEN INVASIONS:

Exponential Distribution

Mean	=	16.716 Days
Minimum	=	3.759 Days

TABLE 4.10 ICE CONDITION DISTRIBUTIONS AT CAMDEN BAY

START DATE:

Normal Distribution		
Mean	=	14 Aug
Std. Deviation	=	17.9 Days
Minimum	=	15 Jul
Maximum	=	23 Sep

INVASION FREQUENCY:

Poisson Distribution		
Mean	=	0.657 Invasions/Year

INVASION DURATION:

Exponential Distribution		
Mean	=	16.99 Days

DRILLING PERIOD BETWEEN INVASIONS:

Exponential Distribution		
Mean	=	13.14 Days
Minimum	=	1.805 Days

TABLE 4.11 ICE CONDITION DISTRIBUTIONS AT CAPE HALKETT

NEW ICE THICKNESS (in)	EARLIEST	LATEST	MEAN	STANDARD DEVIATION (days)
0	10 Sep	20 Oct	1 Oct	6.7
6	26 Sep	5 Nov	16 Oct	6.7
12	11 Oct	19 Nov	1 Nov	6.5
24	12 Nov	19 Dec	1 Dec	6.2
36	13 Dec	19 Jan	1 Jan	6.2
48	15 Jan	4 Mar	9 Feb	8.4

TABLE 4.12 ICE GROWTH DISTRIBUTIONS AT BARTER ISLAND

TIME PERIOD	CHUKCHI SEA	CAPE HALKETT
1 Jul	0.0	1.8
15 Jul	2.8	0.5
1 Aug	9.8	16.0
15 Aug	14.3	23.0
1 Sep	42.0	46.5
15 Sep	63.0	66.0
1 Oct	39.0	48.0
15 Oct	25.0	30.5

TABLE 4.13 PROBABILITIES OF LESS THAN 50% ICE COVER AT DRILL SITES

THICKNESS (in)	EARLIEST	LATEST	MEAN	DEVIATION (days)
0	1 Sep	21 Oct	26 Sep	8.4
6	18 Sep	3 Nov	11 Oct	7.7
12	3 Oct	18 Nov	26 Oct	7.5
24	7 Nov	15 Dec	27 Nov	6.5
36	10 Dec	11 Jan	26 Dec	5.4
48	17 Jan	28 Feb	7 Feb	7.1

TABLE 4.14 ICE GROWTH DISTRIBUTIONS AT POINT BARROW

LOCATION	MAXIMUM NEW ICE THICKNESS (FT) FOR DRILLING				
	0	1	2	3	4
Camden Bay	2-25	32-63	66-75	76-78	78
Cape Halkett (AOGA 35)	0.3-14	20-51	55-69	69-72	73
Cape Halkett (NWS)	0.2-6	6-34	28-56	45-67	60-76*
Chukchi Sea	0.03-2	2-25	22-51	40-63	68-75

*NOTE: (60-76) = First number is for drilling time of 80 days, second is for 55 days.

TABLE 4.15 SUCCESS PROBABILITIES IN PERCENT FOR 5,000-FT WELL

LOCATION	MAXIMUM NEW ICE THICKNESS (FT) FOR DRILLING				
	0	1	2	3	4
Camden Bay	0-2	0-32	0.2-66	22-76	66-78
Cape Halkett (AOGA 35)	0-0.3	0-20	0-55	12-69	55-73
Cape Halkett (NWS)	0-0.2	0-6	0-28	0.9-45	10-60*
Chukchi Sea	0-0.03	0-2	0-22	0.2-40	8-68

NOTE: (10-60) = First number is for drilling time of 150 days, second is for 80 days.

TABLE 4.16 SUCCESS PROBABILITIES IN PERCENT FOR 15,000-FT WELL

DATE	POINT BARROW	CAPE HALKETT				CAMDEN BAY			
		20M	40M	60M	100M	20M	40M	60M	100M
1 Jul	10.5	4.5	3.5	2.5	0.0	15.5	8.3	4.5	3.3
15 Jul	21.0	2.5	1.0	0.4	0.2	37.5	22.5	16.0	13.5
1 Aug	36.0	34.0	26.0	22.0	16.0	79.0	29.0	21.0	19.5
15 Aug	53.5	47.0	36.5	28.0	23.0	81.0	49.0	36.5	31.0
1 Sep	73.0	60.0	52.5	48.5	46.5	78.0	64.0	51.0	47.0
15 Sep	82.0	78.5	74.5	70.0	66.0	94.5	85.0	73.0	70.0
1 Oct	54.5	54.5	52.5	50.0	48.0	77.0	69.5	63.0	59.5
15 Oct	40.0	36.0	34.0	32.5	30.5	35.0	31.0	27.5	26.5

TABLE 4.17 OPEN GATE PROBABILITIES IN PERCENT FOR SEMI-MONTHLY PERIODS (BASED ON ICE CONCENTRATION OF LESS THAN 50 PERCENT)

SCENARIO NO.

1. **PURPOSE OF PLATFORM**

Exploration:

Production:

2. **SITE INFORMATION:**

Location Coordinates:

Water Depth:

Ice Conditions:

Soil Conditions:

Distance from Icy Cape:

3. **STRUCTURE INFORMATION**

Cone - Base Dia:

Caisson - Base Dia:

Sub-Base 1 Dia:

Sub-Base 2 Dia:

Spud Piles: No/Penetration

Wick Drains: No/Spacing

4. **BERM INFORMATION**

Height:

Volume:

Onshore Haul Distance:

Haul from Shore to Location:

Offshore Haul to Location:

TABLE 5.1 SCENARIO COST PROFORMA - SHEET 1 OF 2

5. PIPELINE INFORMATION

Offshore	: No./Dia.
	: Total Distance
	: Burial Distance
Onshore	: No./Dia.
	: Distance

6. SUBSEA SYSTEMS

Satellite Wells	: No.
	: Depth
Template Wells	: No. in template
	: Depth
Flow Lines	: No./Dia.
	: Total Length
	: Buried Length

TABLE 5.1 **SCENARIO COST PROFORMA - SHEET 2 OF 2**

SCENARIO NO. ______

ITEM	COST ($1,000,000)	COST CHART REFERENCE
1. **Construction Facility**		Figure 5.2
1.1 For Upper Structure		
1.2 For Sub-Base 1		
1.3 For Sub-Base 2		
2. **Construction of Concrete Structure**		Figures 5.3 - 5.7
2.1 Upper Structure		
2.2 Sub-Base 1		
2.3 Sub-Base 2		
3. **Float-Out of Graving Yard**		Table 5.10
3.1 Upper Structure		
3.2 Sub-Base 1		
3.3 Sub-Base 2		
Total (p.1)		

TABLE 5.2 SCENARIO COST PROFORMA - SHEET 1 OF 6

ITEM	COST ($1,000,000)	COST CHART REFERENCE
4. Moorings during Construction Afloat		Table 5.10
4.1 Upper Structure		
4.2 Sub-Base 1		
4.3 Sub-Base 2		
5. Temporary Buoyancy Tanks (Incl. Installing)		Table 5.10
5.1 Upper Structure		
5.2 Sub-Base 1		
5.3 Sub-Base 2		
6. M & E Systems Inside Hull		Figures 5.10, 5.11
6.1 Upper Structure		
6.2 Sub-Base 1		
6.3 Sub-Base 2		
7. Topsides (Incl. Deck & Modules)		Table 5.9 Figure 5.9
Total (p.2)		

TABLE 5.2 SCENARIO COST PROFORMA - SHEET 2 OF 6

ITEM	COST ($1,000,000)	COST CHART REFERENCE
8. <u>Tow to Mating Site</u>		Table 5.10
8.1 Upper Structure		
8.2 Sub-Base 1		
8.3 Sub-Base 2		
8.4 Topsides (Incl. Deck & Modules)		
9. <u>Submergence Tests</u>		Table 5.10
9.1 Upper Structure		
9.2 Sub-Base 1		
9.3 Sub-Base 2		
10. <u>Mate Structures</u>		Table 5.10
10.1 Upper Structure to Sub-Base 1		
10.2 Upper Structure to Sub-Base 2		
11. <u>Mate Deck & Topsides to Sub-Structure</u>		Table 5.10
11.1 Submergence Test		
11.2 Deck Mating		
11.3 Lift on Modules		
Total (p.3)		

TABLE 5.2 SCENARIO COST PROFORMA - SHEET 3 OF 6

ITEM	COST ($1,000,000)	COST CHART REFERENCE
12. <u>Marine Ops. during Tow</u>		Table 5.11 Figure 5.15
12.1 Prepare Holding Site - Icy Cape		
12.2 Ocean Tow to Arctic		
12.3 Prepare Contingency Site & Plans (No.)		
13. <u>Berm Construction</u>		Figures 5.21, 5.23 - 5.25
13.1 Onshore Haul (m)		
13.2 Haul from Shore to Location (m)		
13.3 Offshore Haul to Location (m)		
14. <u>Marine Ops. at Installing Site</u>		Table 5.12 Figure 5.16
14.1 Site Investigation		
14.2 Ballast Down Structure		
14.3 Sand Undergrouting		
14.4 Spud Piles/Wick Drains		
14.5 Pipeline Connections		
Total (p.4)		

TABLE 5.2 SCENARIO COST PROFORMA - SHEET 4 OF 6

ITEM	COST ($1,000,000)	COST CHART REFERENCE
15. Pipelines		Refer to text, Section 5.6
15.1 Offshore Laying		
15.2 Offshore Burial		
15.3 Onshore Construction		
16. Subsea Systems		See Separate Cost Estimate
16.1 Satellite Wells		
16.2 Template Wells		
16.3 Flowlines		
(Total p.5)		

TABLE 5.2 SCENARIO COST PROFORMA - SHEET 5 OF 6

PAGE TOTALS:	($1,000,000)	
Page 1		
2		
3		
4		
5		
TOTAL	$	

TABLE 5.2 <u>SCENARIO COST PROFORMA - SHEET 6 OF 6</u>

ITEM	RATE	WORK INCLUDED IN UNIT RATE
Lightweight Concrete (f'_c = 7000 psi) (γ_c = 115 pcf)	\$160/cu.yd.	- Materials - Operational Cost of Mixing and Transportation - Placing - Labor, Overhead and Profit
Reinforcing Steel	\$1120/short.ton	- Materials, Cutting and Bending - Operational Costs of Transportation - Fixing, Labor, Overhead and Profit
Post-Tensioning Tendons	\$1.90/lb.	- Materials - Operational Costs of Transportation - Placing, Stressing and Grouting - Labor, Overhead and Profit
Formwork	\$7.90/ft^2	- Materials, Making, Fixing and Striking - Labor, Overheads and Profit

TABLE 5.3 **UNIT RATES ASSUMED FOR CONCRETE CONSTRUCTION COSTS**

CONE BASE WALL

ITEM	QUANTITY PER CU.YD.	UNIT RATE	COST PER CU.YD. ($/CU.YD.)
Concrete	0.947 cu.yd.	$160/cu.yd.	152
Rebar	0.311 short.tons	$1120/short.ton	348
P/S Tendons	200 lbs.	$1.90/lb.	380
Formwork	13.5 ft^2	$7.90/$ft^2$	106

Total Rate For Cone Base Wall = $986/cu.yd.

TABLE 5.4 **CALCULATION OF UNIT RATE FOR TYPICAL STRUCTURAL MEMBER**

ITEM	STRUCTURAL THICKNESS (FT)	TOTAL UNIT RATE ($/CU.YD.)
Skirts	Ave 1.0	1012
Base Slab	1.5	1026
	2.5	969
	3.5	948
	4.0	937
Base Wall	2.5	1004
	4.0	986
Cone Shell	2.5	1024
	3.25	984
	4.0	959
	6.0	926
Upper Wall	3.25	875
	4.0	850
Top Slab	1.0	992
	1.5	886
	2.0	779
Internal Walls	1.0	1157
	1.5	1014
	2.0	943
Internal Slabs	1.5	864

TABLE 5.5 <u>**SUMMARY OF UNIT RATES FOR STRUCTURAL MEMBERS**</u>

MAXIMUM TOPSIDES WEIGHT (S.TONS)

	BOPD	
	50,000	200,000
Production Equipment	7,000	11,000
Drilling Rig/s	2,500	6,000
Drilling Consumables	15,000	27,000
Enclosures and Model Steelwork	3,000	4,000
Deck Steelwork	4,000	7,000
TOTAL (s.tons)	32,500	55,000

TABLE 5.6 MAXIMUM TOPSIDES WEIGHT FOR PRODUCTION CONES AND CAISSONS

	BERYL A	BRENT B	BRENT D	FRIGG TCP 2	STAT A	STAT B	STAT C
M. BOPD	150	160	160	GAS	300	180	200
Slots	40	38	48	-	42	42	42
Towout Topsides (mt)	14,000	10,300	13,600	13,500	18,500	40,000	42,000
Deck Type	Pl. Gr.	Pl. Gr.	Pl. Gr.	Truss	Pl. Gr.	Truss	Truss
Deck (mt)	6,300	4,000	3,700	3,500	12,000	7,000	7,000
Max Deck WT (mt)	28,000	24,000	24,000	21,000	50,000	50,000	50,000

TABLE 5.7 **TOPSIDES INFORMATION ON NORTH SEA CONDEEPS**

	BOPD	
	50,000	**200,000**
Production Facilities	46	62
Drilling Facilities*	17	34
Quarters, Heli, Etc.	20	34
Enclosure Steelwork, Cladding, Firewalls, Etc. $4000/s.t.	12	16
Deck Steelwork $3000/s.t.	12	21
On-Shore Fab & Hook-Up	100	150
Offshore Hook-Up	55	80
Offshore Commissioning	2	5
Sub Total	264	402
Engineering/Management - 8%	21	32
Total - $MM	285	434

*Non Consummables

TABLE 5.8 TOPSIDES COST ($MM)

	$MM
Drilling Facilities*	17.0
Quarters, Helipad, Hanger, Fuel, etc.	20.0
Hook-Up and Commission	5.0
Deck and Modules 5000 s.ton @ $3000/s.ton	15.0
Sub-Total ($MM)	57.0
Engineering/Management - 8%	4.5
Total ($MM)	61.5

*Installed Cost

TABLE 5.9 TOPSIDES COSTS FOR EXPLORATION STRUCTURES

		$MM
1.	Float out from graving yard	1.6
2.	Moorings during construction afloat	3.2
3.	Install temporary buoyancy tanks on cone	5.4
4.	Install temporary buouancy tanks on sub-base	2.8
5.	Tow sub-base to mating site	0.8
6.	Tow cone-caisson to mating site	0.8
7.	Tow deck/topsides to mating site	0.4
8.	Submergence test of sub-base	1.1
9.	Submergence test for cone/caisson	1.1
10.	Mate cone/caisson to sub-base	8.4
11.	Mate deck to sub-structure (including submergence test)	3.8

TABLE 5.10 <u>MARINE OPERATIONS AT CONSTRUCTION SITE</u>

		($MM)
1.	Prepare Holding Site outside Arctic	2.7
2.	Ocean Tow to Arctic	(See Chart) (Figure 5.15)
3.	Prepare Contingency Sites and Plans in Arctic Tow Route	3.7

TABLE 5.11 **MARINE OPERATIONS DURING TOW**

		($MM)
1.	Topographical, Geophysical and Geotechnical Site Survey and Investigations	4.3
2.	Berm Construction (covered separately)	-
3.	Ballasting Down of Structure	3.4
4.	Sand Undergrouting	7.5
5.	Spud Piles (7' Ø x 100' long)	(See Chart)
6.	Pipeline Connections (1-36" Ø Pipe)	3.0
7.	Sand Ballasting	3.0
8.	Scour Protection	3.0
9.	Wick Drain Installation	5.0

TABLE 5.12 MARINE OPERATIONS AT INSTALLATION SITE

SPREAD	PURPOSE
A	DREDGE LOCAL TO SITE
B	DREDGE & HAUL FROM OFFSHORE SOURCE
C	EXCAVATION & HAUL FROM ONSHORE SOURCE TO DOCKING FACILITY
D	HAUL FROM DOCKING FACILITY TO SITE

TABLE 5.13 **EQUIPMENT SPREADS FOR BERM CONSTRUCTION**

ITEM	COST/UNIT ($)	UNITS	COST/ITEM ($)
1. Cutter or Plain Suction Dredge, 27-in.	8,000,000	1	8,000,000
2. Pipeline, Submerged & Self-Floating	850	7,000 Ft	5,950,000
3. Crane Barge	1,000,000	1	1,000,000
4. Pipeline Anchor Barges	275,000	4	1,100,000
5. Anchor Handling Barge	250,000	1	250,000
6. Tending & Supply Tugs, 1500-hp	2,000,000	2	4,000,000
7. Crane (for Item 3), 150-ton	1,000,000	1	1,000,000
8. End Barge	750,000	1	750,000
9. Survey Launch	200,000	1	200,000
10. Crew Boat, 50-passengers	1,000,000	1	1,000,000
11. Shop & Supply Warehouse	300,000	1	300,000
12. Fuel & Supply Barge	1,250,000	1	1,250,000
13. Floating Camp 80-persons & Fuel Storage Barge	2,000,000	1	$ 2,000,000
Equipment Sub-Total			$26,800,000

TABLE 5.14 **EQUIPMENT SPREAD A (DREDGE LOCAL TO SITE)**

ITEM	PERSONNEL @ $450/DAY	COST/ITEM ($/DAY)
1. Cutter or Plain Suction Dredge (1)	14	6,300
2. Pipeline (7,000-Ft)	4	1,800
3. Crane Barge (1)	6	2,700
4. Pipeline Anchor Barges (4)	-	-
5. Anchor Handling Barge (1)	-	-
6. Tending & Supply Tugs (2)	12	5,400
7. Crane (included in Item 3), (1)	-	-
8. End Barge (included in Items 3 & 1), (1)	-	-
9. Survey Launch (1)	4	1,800
10. Crew Boat (1)	5	2,250
11. Shop & Supply Warehouse (1)	8	3,600
12. Fuel & Supply Barge (1)	-	-
13. Floating Camp & Fuel Storage Barge (1)	7	3,150
Labor Sub-Total	60	$27,000/Day

TABLE 5.15 LABOR FOR EQUIPMENT SPREAD A (DREDGE LOCAL TO SITE)

ITEM	COST/DAY ($)	UNITS	COST/ITEM ($/DAY)
1. Cutter or Plain Suction Dredge	3,050	1	3,050
2. Pipeline (7,000-Ft)	3,150	1	3,150
3. Crane Barge	300	1	270
4. Pipeline Anchor Barges	175	4	700
5. Anchor Handling Barge	110	1	110
6. Tending & Supply Tugs	840	2	1,680
7. Crane (for Item 3)	175	1	175
8. End Barge	200	1	200
9. Survey Launch	185	1	185
10. Crew Boat	440	1	440
11. Shop & Supply Warehouse	245	1	245
12. Fuel & Supply Barge	170	1	170
13. Floating Camp & Fuel Storage Barge	175	1	175
Supplies Sub-Total			$10,550/Day

TABLE 5.16 SUPPLY AND MATERIAL FOR EQUIPMENT SPREAD A (DREDGE LOCAL TO SITE)

1.	EQUIPMENT, $26,800,000 Amortized at 10% over 4 years, using 60-day working season	$140,700/day
2.	MOBILIZATION, $3,216,000 120-day, mobilization and demobilization charges distributed over 4 construction seasons	13,400/day
3.	LABOR 60-persons @ $450/day	27,000/day
4.	SUPPLY AND MATERIAL	10,550/day
	Total Daily Cost	$191,650/day

TABLE 5.17 TOTAL DAILY COST-EQUIPMENT SPREAD A

ITEM	COST/UNIT ($)	UNITS	COST/ITEM ($)
1. Cutter/Plain Suction Dredges, 27-in.	8,000,000	2	16,000,000
2. Pipeline, Submerged & Self Floating	850/ft	1000 Ft	850,000
3. Hopper Barges, 2600 cu.yd.	2,000,000	10	20,000,000
4. Line Haul Tugs, 4500-hp	8,000,000	5	40,000,000
5. Crane Barge	1,000,000	1	1,000,000
6. Pipeline Anchor Barges	275,000	4	1,100,000
7. Anchor Handling Barge	250,000	1	250,000
8. Tending & Supply Tugs, 1500-hp	2,000,000	2	4,000,000
9. Crane, 150-ton	1,000,000	1	1,000,000
10. End Barge	750,000	1	750,000
11. Survey Launch	200,000	1	200,000
12. Crew Boat	1,000,000	1	1,000,000
13. Shop & Supply Warehouse	300,000	1	300,000
14. Fuel & Supply Barge	1,250,000	1	1,250,000
15. Floating Camp & Fuel Storage Barge	2,000,000	1	2,000,000
Equipment Total			$89,700,000

TABLE 5.18 EQUIPMENT SPREAD B
(DREDGE & HAUL FROM OFFSHORE SOURCE)

ITEM	PERSONNEL @ $450/DAY	COST/ITEM ($/DAY)
1. Cutter/Plain Suction Dredge, 27-in.	28	12,600
2. Pipeline, Submerged & Self Floating	3	1,350
3. Hopper Barges, 2600 cu.yd.	-	-
4. Line Haul Tugs, 4500-hp	50	22,500
5. Crane Barge	6	2,700
6. Pipeline Anchor Barges	-	-
7. Anchor Handling Barge	-	-
8. Tending & Supply Tugs, 1500-hp	12	5,400
9. Crane, 150-ton (included in Item 5)	-	-
10. End Barge (included in Item 1)	-	-
11. Survey Launch	4	1,800
12. Crew Boat	5	2,250
13. Shop & Supply Warehouse	8	3,600
14. Fuel & Supply Barge	-	-
15. Floating Camp & Fuel Storage Barge	7	3,150
Labor Total	123	$55,350/Day

TABLE 5.19 LABOR FOR EQUIPMENT SPREAD B (DREDGE & HAUL FROM OFFSHORE SOURCE)

ITEM	COST/DAY ($)	UNITS	COST/ITEM ($/DAY)
1. Cutter/Plain Suction Dredges, 27-in.	3,050	2	6,100
2. Pipeline, Submerged & Self Floating	3,150	1	3,150
3. Hopper Barges, 2600 cu.yd.	-	10	-
4. Line Haul Tugs, 4500-hp	2,470	5	12,350
5. Crane Barge	300	1	300
6. Pipeline Anchor Barges	175	4	700
7. Anchor Handling Barge	110	1	110
8. Tending & Supply Tugs, 1500-hp	840	2	1,680
9. Crane, 150-ton	175	1	175
10. End Barge	200	1	200
11. Survey Launch	185	1	185
12. Crew Boat	440	1	440
13. Shop & Supply Warehouse	245	1	245
14. Fuel & Supply Barge	170	1	170
15. Floating Camp & Fuel Storage Barge	175	1	175
Supplies Total			$25,980/Day

TABLE 5.20 SUPPLY AND MATERIAL FOR EQUIPMENT SPREAD B (DREDGE & HAUL FROM OFFSHORE SOURCE)

ITEM	COST/UNIT ($)	UNITS	COST/ITEM ($)
BORROW PIT			
1. Ripper Dozer, CAT D-8	450,000	4	1,800,000
2. Front End Loaders, CAT 988	375,000	4	1,500,000
3. Track Drills and Compressors	140,000	4	560,000
4. Light Plants, 6-kw	16,000	8	128,000
5. Snow Blower on CAT 966 FEL	340,000	1	340,000
6. Motor Grader, CAT 16G	325,000	1	325,000
SNOW ROAD MAINTENANCE			
7. Motor Graders, CAT 16G	325,000	2	650,000
8. Snow Blowers on CAT 966 FEL	340,000	2	680,000
GENERAL			
9. Tractor - Trailer Belly Dumps, 30CYD	175,000	25	4,375,000
10. Mechanics Trucks, 1-Ton	60,000	2	120,000
11. Fuel Trucks, 3500-Gal.	75,000	2	150,000
12. Gas Truck, 2500-Gal.	60,000	1	60,000
13. Tire Trucks	160,000	2	320,000
14. Repair Shop, Supply Warehouse	550,000	1	550,000
15. Lubrication Truck	75,000	1	75,000
16. Pickup Trucks	16,000	12	192,000
17. Buses	100,000	2	200,000
18. Lunch Shack	65,000	2	130,000
19. Generators, 30-kw	60,000	2	120,000
		Total	$12,275,000

TABLE 5.21 EQUIPMENT SPREAD C
(EXCAVATION AND HAUL FROM LAND SOURCE TO DOCK FACILITY)

ITEM	PERSONNEL @ $550/DAY*	COST/ITEM ($/DAY)
BORROW PIT		
1. Ripper Dozer, CAT D-8	13	7,150
2. Front End Loaders, CAT 988	8	4,400
3. Track Drills and Compressors	12	6,600
4. Light Plants, 6-kw	-	-
5. Snow Blower on CAT 966 FEL	2	1,100
6. Motor Grader, CAT 16G	2	1,100
SNOW ROAD MAINTENANCE		
7. Motor Graders, CAT 16G	4	2,200
8. Snow Blowers on CAT 966 FEL	4	2,200
GENERAL		
9. Tractor - Trailer Belly Dumps, 30CYD	50	27,500
10. Mechanics Trucks, 1-Ton	8	4,400
11. Fuel Trucks, 3500-Gal.	4	2,200
12. Gas Truck, 2500-Gal.	2	1,100
13. Tire Trucks	8	4,400
14. Repair Shop, Supply Warehouse	8	4,400
15. Lubrication Truck	2	1,100
16. Pickup Trucks	4	2,200
17. Buses	4	2,200
18. Lunch Shack	-	-
19. Generators, 30-kw	-	-
Totals	135	$74,250/Day

*Rate for Land Based Labor

TABLE 5.22 LABOR FOR EQUIPMENT SPREAD C (EXCAVATION AND HAUL FROM LAND SOURCE TO DOCK FACILITY)

ITEM	COST/DAY ($)	UNITS	COST/ITEM ($/DAY)
BORROW PIT			
1. Ripper Dozer, CAT D-8	175	4	700
2. Front End Loaders, CAT 988	215	4	860
3. Track Drills and Compressors	60	4	240
4. Light Plants, 6-kw	25	8	200
5. Snow Blower on CAT 966 FEL	120	1	120
6. Motor Grader, CAT 16G	145	1	145
SNOW ROAD MAINTENANCE			
7. Motor Graders, CAT 16G	145	2	290
8. Snow Blowers on CAT 966 FEL	120	2	240
GENERAL			
9. Tractor - Trailer Belly Dumps, 30CYD	175	25	4,375
10. Mechanics Trucks, 1-Ton	145	2	290
11. Fuel Trucks, 3500-Gal.	145	2	290
12. Gas Truck, 2500-Gal.	145	1	145
13. Tire Trucks	145	2	290
14. Repair Shop, Supply Warehouse	120	1	120
15. Lubrication Truck	145	1	145
16. Pickup Trucks	120	12	1,440
17. Buses	130	2	260
18. Lunch Shack	-	2	-
19. Generators, 30-kw	35	2	70
		Total	$10,220/Day

TABLE 5.23 SUPPLY AND MATERIAL FOR EQUIPMENT SPREAD C (EXCAVATION AND HAUL FROM LAND SOURCE TO DOCK FACILITY)

ITEM	COST/UNIT ($)	UNITS	COST/ITEM ($)
OFFSHORE			
1. Hopper Barges, 2600 CYD	2,000,000	8	16,000,000
2. Line Haul Tugs, 4500-hp	8,000,000	4	32,000,000
3. Crane Barge	1,000,000	1	1,000,000
4. Tending and Supply Tugs, 1500-hp	2,000,000	1	2,000,000
5. Crane, 150-ton	1,000,000	1	1,000,000
6. Survey Launch	200,000	1	200,000
7. Crew Boat	1,000,000	1	1,000,000
8. Shop & Supply Warehouse	300,000	1	300,000
9. Fuel & Supply Barge	1,250,000	1	1,250,000
10. Floating Camp & Fuel Storage Barge	2,000,000	1	2,000,000
ONSHORE (AT DOCK FACILITIES)			
11. Dozers/Pushers, CAT D-8	450,000	4	1,800,000
12. Lighting Plants, 6-kw	16,000	8	128,000
13. Dragline Cranes	825,000	2	1,650,000
14. Front End Loader, CAT 966	230,000	4	920,000
15. 30 CYD Dump Trucks	175,000	8	1,400,000
16. Conveyors	25,000	2	50,000
		Total	$62,698,000

TABLE 5.24 EQUIPMENT SPREAD D
(HAUL FROM DOCK FACILITY TO SITE)

ITEM	PERSONNEL @ $450/DAY	COST/ITEM ($/DAY)
OFFSHORE		
1. Hopper Barges, 2600 CYD	-	-
2. Line Haul Tugs, 4500-hp	40	18,000
3. Crane Barge	6	2,700
4. Tending and Supply Tugs, 1500-hp	6	2,700
5. Crane, 150-ton	-	-
6. Survey Launch	4	1,800
7. Crew Boat	5	2,250
8. Shop & Supply Warehouse	8	3,600
9. Fuel & Supply Barge	-	-
10. Floating Camp & Fuel Storage Barge	7	3,150
ONSHORE (AT DOCK FACILITIES)	**@$550/DAY**	
11. Dozers/Pushers, CAT D-8	12	6,600
12. Lighting Plants, 6-kw	-	-
13. Dragline Cranes	4	2,200
14. Front End Loader, CAT 966	8	4,400
15. 30 CYD Dump Trucks	16	8,800
16. Conveyors	2	1,100
Totals	118	$57,300/Day

TABLE 5.25 LABOR FOR EQUIPMENT SPREAD D (HAUL FROM DOCK FACILITY TO SITE)

ITEM	COST/DAY ($)	UNITS	COST/ITEM ($/DAY)
OFFSHORE			
1. Hopper Barges, 2600 CYD	-	8	-
2. Line Haul Tugs, 4500-hp	2,470	4	9,880
3. Crane Barge	300	1	300
4. Tending and Supply Tugs, 1500-hp	840	1	840
5. Crane, 150-ton	175	1	175
6. Survey Launch	185	1	185
7. Crew Boat	440	1	440
8. Shop & Supply Warehouse	245	1	245
9. Fuel & Supply Barge	170	1	170
10. Floating Camp & Fuel Storage Barge	175	1	175
ONSHORE (AT DOCK FACILITIES)			
11. Dozers/Pushers, CAT D-8	175	4	700
12. Lighting Plants, 6-kw	25	8	200
13. Dragline Cranes	220	2	440
14. Front End Loader, CAT 966	100	4	400
15. 30 CYD Dump Trucks	175	8	1,400
16. Conveyors	200	2	400
		Total	$15,950/Day

TABLE 5.26 SUPPLY AND MATERIAL FOR EQUIPMENT SPREAD D (HAUL FROM DOCK FACILITY TO SITE)

DREDGES (2 NO.):

- 33,000 cu.yd./day each

BARGES (2,600 CU.YD.):

- Towed in Pairs
- Ave. Speed = 8 knots
- Dump Time = 10 mins.

OPERATING EFFICIENCY:

- 100%

EQUIPMENT SPREAD INCREMENT:

- 2 No. Barges; 1 No. Line Haul Tug; plus associated Labor, Supply and Material

TABLE 5.27 **PRODUCTION RATE ASSUMPTIONS - EQUIPMENT SPREAD B**

ASSUMPTIONS:

- 30-cyd Dump Trucks
- 2-min. Loading Time
- 2-min. Dump Time
- 35-mph/50-mph Travel Speeds
- 15% Material Losses
- 85% Operating Efficiency

⇒ Production Rate = 15,600 cu.yd./day

EQUIPMENT SPREAD INCREMENT:

- 5 No. Dump Trucks, plus associated Labor, Supply and Material

TABLE 5.28 PRODUCTION RATE ASSUMPTIONS - EQUIPMENT SPREAD C

PRODUCTION RATE AT DOCK FACILITY:

- 40,000 cu.yd./day

BARGES:

- Towed in Pairs
- Ave. Speed = 8 knots
- Dump Time = 10 min.

OPERATING EFFICIENCY:

- 100%

EQUIPMENT SPREAD INCREMENT:

- 2 No. Barges; 1 No. Line Haul Tug; plus associated Labor, Supply and Material

TABLE 5.29 PRODUCTION RATE ASSUMPTIONS - EQUIPMENT SPREAD D

	$MM
Drilling Facilities (including fabrication)	12
Quarters, Utilities, etc.	10
Module Steel	8
Transportation	2
Offshore Installation & Hook-Up	10
Engineering & Management (8%)	3.4
Total	$45.4MM

TABLE 5.30 TOPSIDES COSTS FOR EXPLORATION CAISSON RETAINED ISLANDS

	$MM
Production Facilities	65
Drilling Facilities	45
Quarters, Utilities, etc.	30
Module Steel	15
Onshore Fabrication	130
Transportation	15
Offshore Installation & Hook-Up	250
Engineering & Management (8%)	45
Total	$595MM

TABLE 5.31 TOPSIDES COSTS FOR PRODUCTION CAISSON RETAINED ISLANDS (200,000 BOPD)

	REFERENCE	COST ($MM)
Mobilization/Demobilization	Figure 5.36	8.10
Winter Standby Charge	Figure 5.36	27.00
Glory Hole Dredging	Figure 5.36	2.80
Well Protective Structure	Figure 5.36	1.00
Well Drilling (10,000-ft)	Table 5.36	11.30
Well Completion	Table 5.37	5.20
Flowline Costs (1.5-mile)	Table 5.43	4.54
Flowline Mobilization/Demobilization	Table 5.43	8.10
	Total	68.04

TABLE 5.32 TOTAL COST - EXAMPLE 1
SATELLITE WELL TO PERMANENT FACILITY

	REFERENCE	COST ($MM)	TIME (Days)
Template Cost	Table 5.39	0.60	-
Manifold and Control Equipment Cost	Table 5.42	1.41	-
Template Installation and Piling	Table 5.41	1.71	9.5
Drill Four Wells @ 15,000-ft	Tables 5.36, 5.38	59.47	240.0
Complete Four Wells @ 15,000-ft	Tables 5.37, 5.38	23.82	104.0
Flowline Cost 4 -miles	Table 5.43	12.11	12.0
Flowline Installation Equip. - Mob./Demob.	Table 5.43	8.10	-
Sub-Total		107.22	365.5 (5 Seasons)
Drilling Rig Mob. - 5 x $8.1MM	Figure 5.36	40.50	
Rig Winter Standby - 5 x $27.00MM	Figure 5.36	135.00	
Sub-Total		175.50	
GRAND TOTAL		282.72	

TABLE 5.33 TOTAL COST - EXAMPLE 2
4-WELL TEMPLATE PRODUCING TO FIXED FACILITY

	REFERENCE	COST ($MM)	TIME (Days)
Template Cost	Table 5.39	1.20	-
Manifold and Control Equipment Cost	Table 5.42	3.47	-
Glory Hole Dredging	Table 5.40	3.29	7.0
Template Installation and Piling	Table 5.41	1.65	7.5
Mobilize Template Installation Equipment	Table 5.41	11.10	-
Drill Eight Wells @ 5,000-ft	Tables 5.36, 5.38	69.20	280.0
Complete Eight Wells @ 5,000-ft	Tables 5.37, 5.38	36.80	160.0
Flowline Cost 3-miles	Table 5.43	9.08	9.0
Flowline Installation Equip. - Mob./Demob.	Table 5.43	8.10	-
Sub-Total		143.89	463.5 (6 Seasons)
Drilling Rig Mob. - 6 x $8.1MM	Figure 5.36	48.60	
Rig Winter Standby - 6 x $27.00MM	Figure 5.36	162.00	
Sub-Total		210.60	
GRAND TOTAL		354.49	

TABLE 5.34 TOTAL COST - EXAMPLE 3
8-WELL TEMPLATE PRODUCING TO FIXED FACILITY

	REFERENCE	COST ($MM)	TIME (Days)
Template Cost	Table 5.39	0.6	-
Manifold and Control Equipment Cost	Table 5.42	1.4	-
Template Installation	Table 5.41	6.0	12
Drill Four Wells @ 15,000-ft	Tables 5.36, 5.38	141.1	240
Complete Four Wells @ 15,000-ft	Tables 5.37, 5.38	59.6	104
Flowline Cost 4-miles	Table 5.43	12.1	12
Flowline Installation Equip. - Mob./Demob.	Table 5.43	8.1	-
Sub-Total		228.9	368
Conical Unit Mobilization		10.0	
GRAND TOTAL		238.9	

NOTE: Conical Unit Dayrate - $500,000/Day

TABLE 5.35 TOTAL COST - EXAMPLE 4
4-WELL TEMPLATE DRILLED WITH CONICAL UNIT

	WELL DEPTH		
	5,000 ft (35 days)	10,000 ft (45 days)	15,000 ft (60 days)
Fuel and Lubricants	$ 180,250	$ 231,750	$ 309,000
Mud/Chemicals/Service	203,100	386,200	573,300
Cement/Service	125,500	185,750	246,000
Bits, Reamers	140,000	230,000	345,000
Fishing Tools	15,000	15,000	15,000
Casing and Accessories	527,800	811,800	845,000
Wellhead, Hangers	340,000	340,000	340,000
Well Logging	105,000	135,000	180,000
Mud Logging	35,000	45,000	60,000
Misc. Operating Supplies	80,000	100,000	150,000
Diving Equipment & Services	175,000	225,000	300,000
Transportation	1,122,000	1,430,000	1,906,000
SUBTOTAL	$3,048,650	$4,135,500	$5,269,300
Drilling Rig & Support ($160,000/day)	5,600,000	7,200,000	9,600,000
TOTAL	$8,648,650	$11,335,500	$14,869,300

TABLE 5.36 DRILLING COST

	WELL DEPTH		
	5,000 ft (20 days)	10,000 ft (23 days)	15,000 ft (26 days)
1. DOWNHOLE EQUIPMENT & SERVICES			
(a) 3-in tubing	353,550	483,550	613,550
(b) 4-in tubing	402,800	557,500	712,800
(c) 5-in tubing	477,050	632,050	787,050
2. SUBSEA TREE			
(a) 3-in tubing	920,000	920,000	920,000
(b) 4-in tubing	964,000	964,000	964,000
(c) 5-in tubing	1,008,000	1,008,000	1,008,000
3. DRILLING RIG			
Rig and Support Vessel	3,200,000	3,680,000	4,160,000
TOTAL COST			
(a) 3-in tubing	4,473,550	5,083,550	5,693,550
(b) 4-in tubing	4,566,800	5,201,500	5,836,800
(c) 5-in tubing	4,685,050	5,320,000	5,955,050

TABLE 5.37 WELL COMPLETION COST (USD)

	WELL DEPTH		
	5,000 ft	10,000 ft	15,000 ft
1. Glory Hole Dredging	5	5	5
2. Protective Structure Installation	5.5	5.5	5.5
3. Drilling	35	45	60
4. Completion	20	23	26
SUBTOTAL (days)	65.5	78.5	96.5
Mobilization	30	30	30
Demobilization	30	30	30
TOTAL (days)	125.5	138.5	156.5

TABLE 5.38 SATELLITE WELL COMPLETION TIME (DAYS)

Number of Wells	Structural Weight (tons)	Cost (USD 1,000)
4	200	600
6	300	900
8	400	1,200
10	500	1,500
12	600	1,800

TABLE 5.39 TEMPLATE STRUCTURE COST

Number Of Wells	Equipment Cost (USD 1000's)	Days Required	Type of Rig	Dayrate USD 1000's/day	Total Cost (USD 1000's)
4	2,000	6	Drilling	160	2,960
6	2,000	6	Drilling	160	2,960
8	2,000	7	Crane Barge	185	3,295
10	2,000	8	Crane Barge	185	3,480
12	2,000	9	Crane Barge	185	3,665

NOTE: Mobilization and demobilization costs not included.

TABLE 5.40 TEMPLATE GLORY HOLE DREDGING COST

Number Of Wells	Equipment Costs (USD 1000's)	Installation Rig	Dayrate USD 1000's/day	Days Required	Pile and Level Rig	Days Required	Total Cost (USD 1000's)
4	191	Drilling	160	4	Drilling	5.5	1711
6	191	Drilling	160	4	Drilling	5.5	1711
8	402	Crane Barge	185	2	Drilling	5.5	1652
10	402	Crane Barge	185	2	Drilling	5.5	1652
12	402	Crane Barge	185	2	Drilling	5.5	1652

NOTE: Mobilization and Demobilization costs not included.
Crane barge - $11.1 million.
Drilling rig - $8.1 million.

TABLE 5.41 TEMPLATE INSTALLATION COST

Number Of Wells	Manifold Cost (USD 1000's)	Control Equip. Cost (USD 1000's)	TFL Diverter Cost (USD 1000's)	Total Cost (USD 1000's)
4	1,076	280	60	1,415
6	1,614	420	60	2,094
8	2,152	1,200	120	3,472
10	2,690	1,500	120	4,310
12	3,228	1,800	120	5,148

NOTES:

1. Manifold costs estimated as $269,000 per well slot.
2. Control system for up to 6 wells is straight hydraulic. For 8 wells or more, the system was assumed to be electrohydraulic multiplex.

TABLE 5.42 MANIFOLD AND CONTROL EQUIPMENT COST

1.	MATERIALS		
	Pipe	92,000	
	Concrete	111,300	
	Control Hose or Cable	237,600	$ 440,900
2.	FLOWLINE BURIAL		1,600,000
3.	PIPELAYING COST		497,700
4.	FLOWLINE END CONNECTION		490,000
		TOTAL COST/MILE	$3,028,600

5. MOBILIZATION/DEMOBILIZATION (60 days)

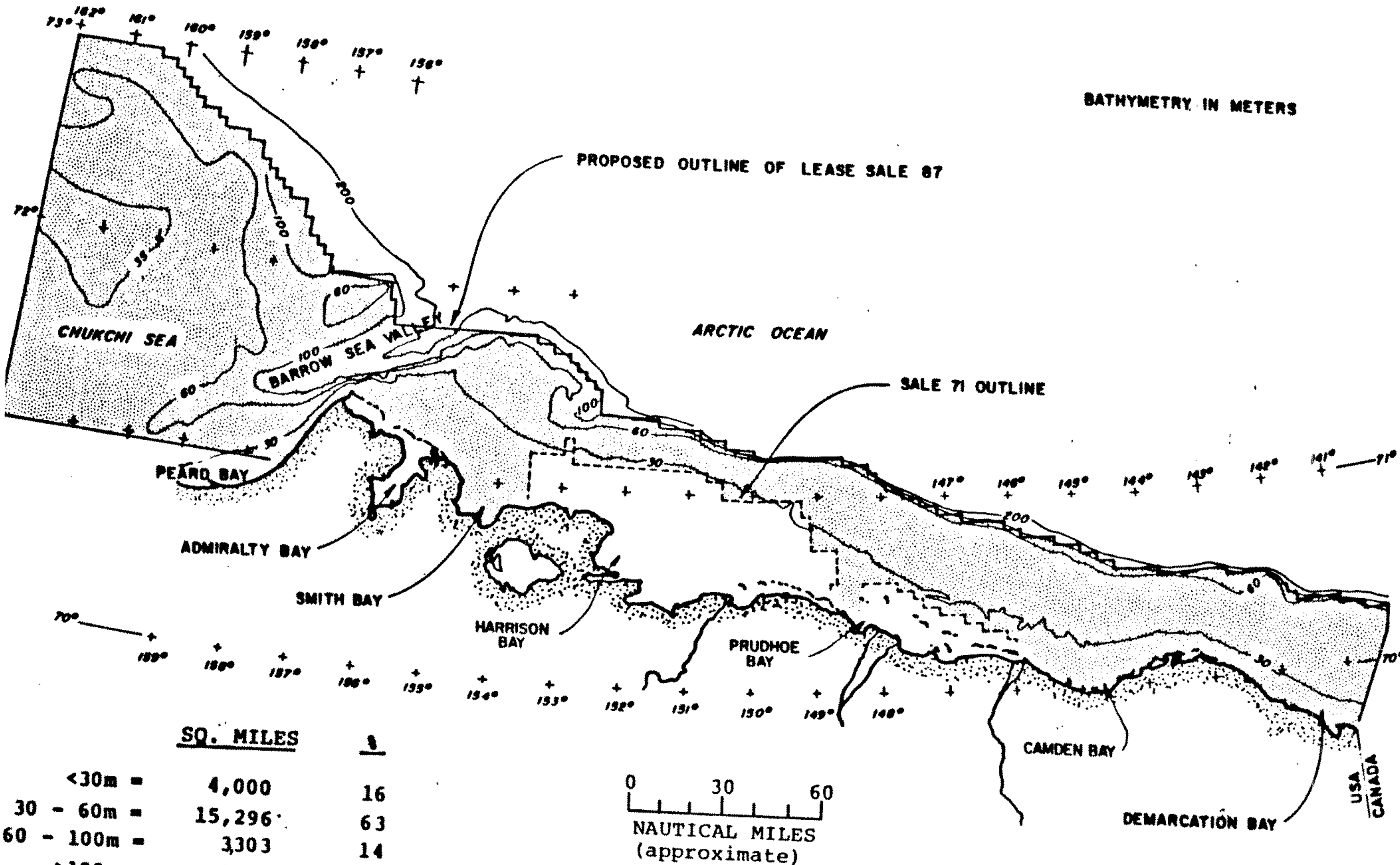
Pipelaying barge	100,000 x 60 =	$6,000,000
Towing tugboat	15,000 x 60 =	900,000
Icebreaking vessel	20,000 x 60 =	1,200,000
Total Cost		$8,100,000

TABLE 5.43 FLOWLINE INSTALLATION COST/MILE

CONCEPT		WATER DEPTH (FT)	CONSTRUCTION SCHEDULE (YRS.)*
Exploration Cone		60-130	2½-3
		200-300	3½-4½+
Production Cone		75	2½-4
		300	2½-4+
Exploration Caisson		75-130	2½-3
		100-300	2½-3+
Production Caisson		75	2-2½
		300	3-3½+
Caisson	Exploration	75	2
Retained	Production	75	2½
Island	Both	200	See Text (Section 6.0)
Loading Atoll		80	See Text (Section 6.0)
Floating Unit		200-300	2

*From placing of order to completion of installation and hook-up.
+Structures assumed to be constructed in two sections simultaneously.

TABLE 6.1 CONCEPT CONSTRUCTION SCHEDULES



	SQ. MILES	%
<30m =	4,000	16
30 - 60m =	15,296	63
60 - 100m =	3,303	14
>100m =	1,719	7
	24,318	100

FIGURE 1.1 PROPOSED OCS LEASE SALE

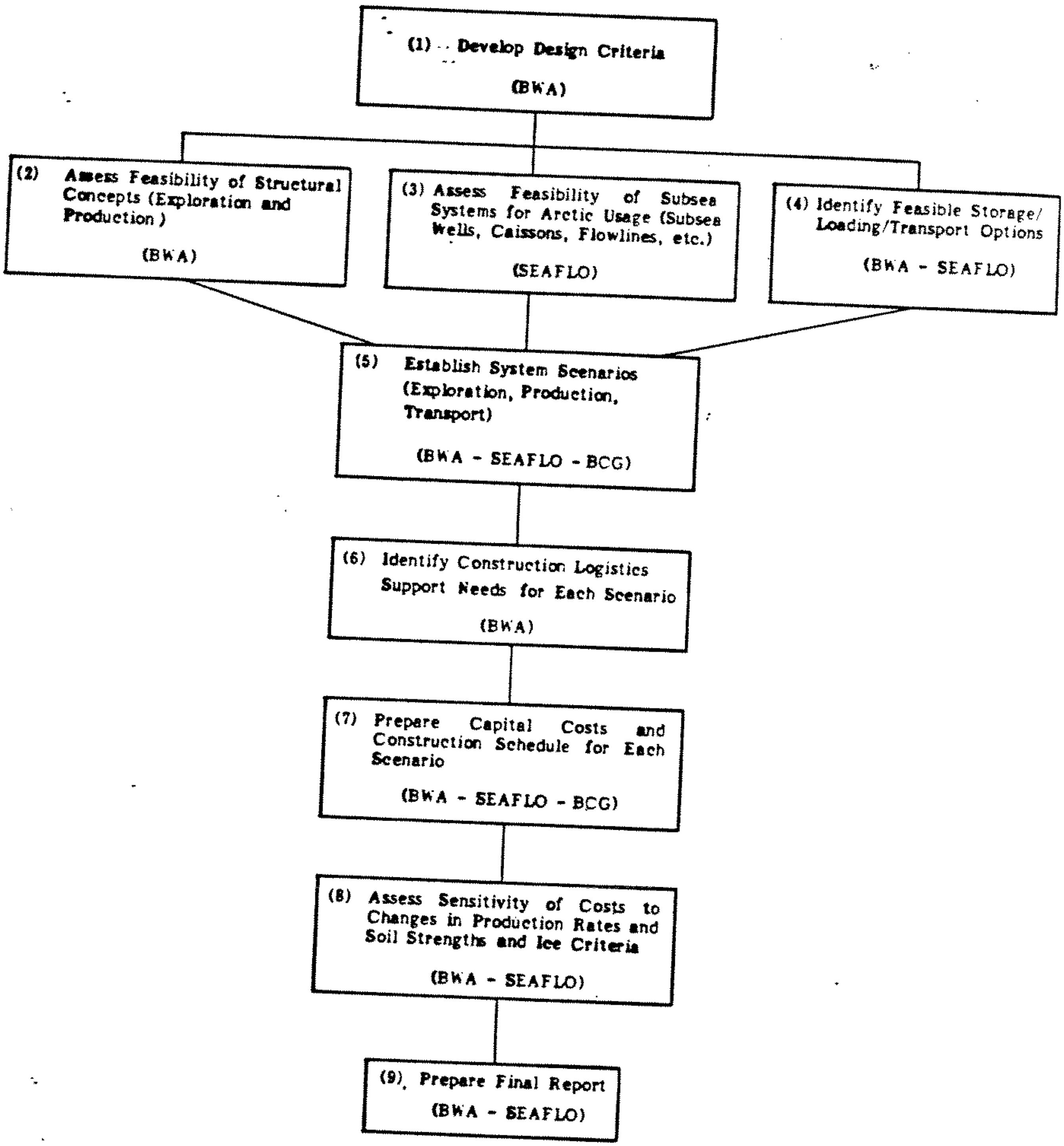
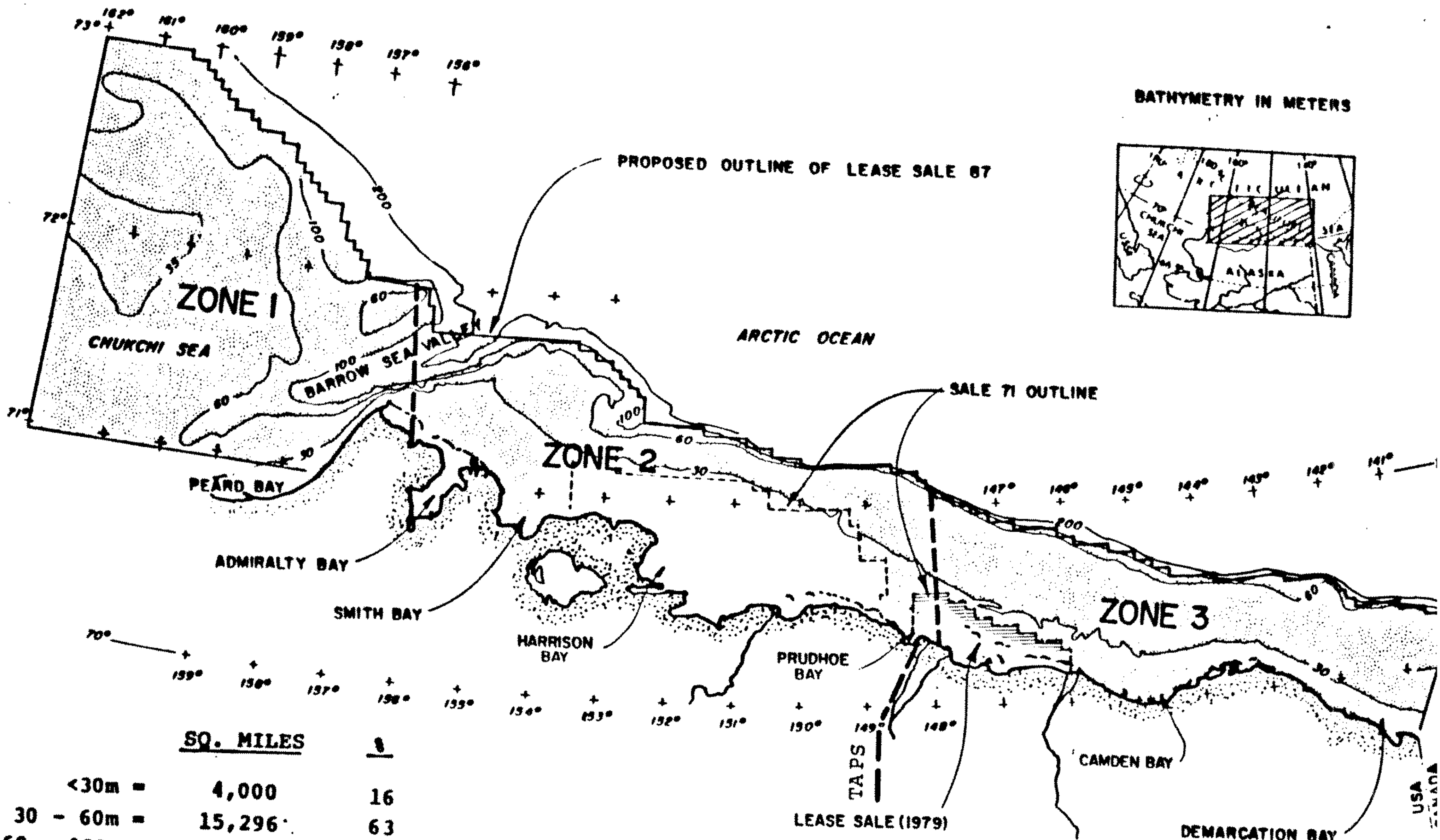


FIGURE 1.2 <u>DIAPIR-87 STUDY PLAN</u>



	SQ. MILES	%
<30m =	4,000	16
30 - 60m =	15,296	63
60 - 100m =	3,303	14
>100m =	1,719	7
	24,318	100

FIGURE 2.1 PROPOSED OCS LEASE SALE 87

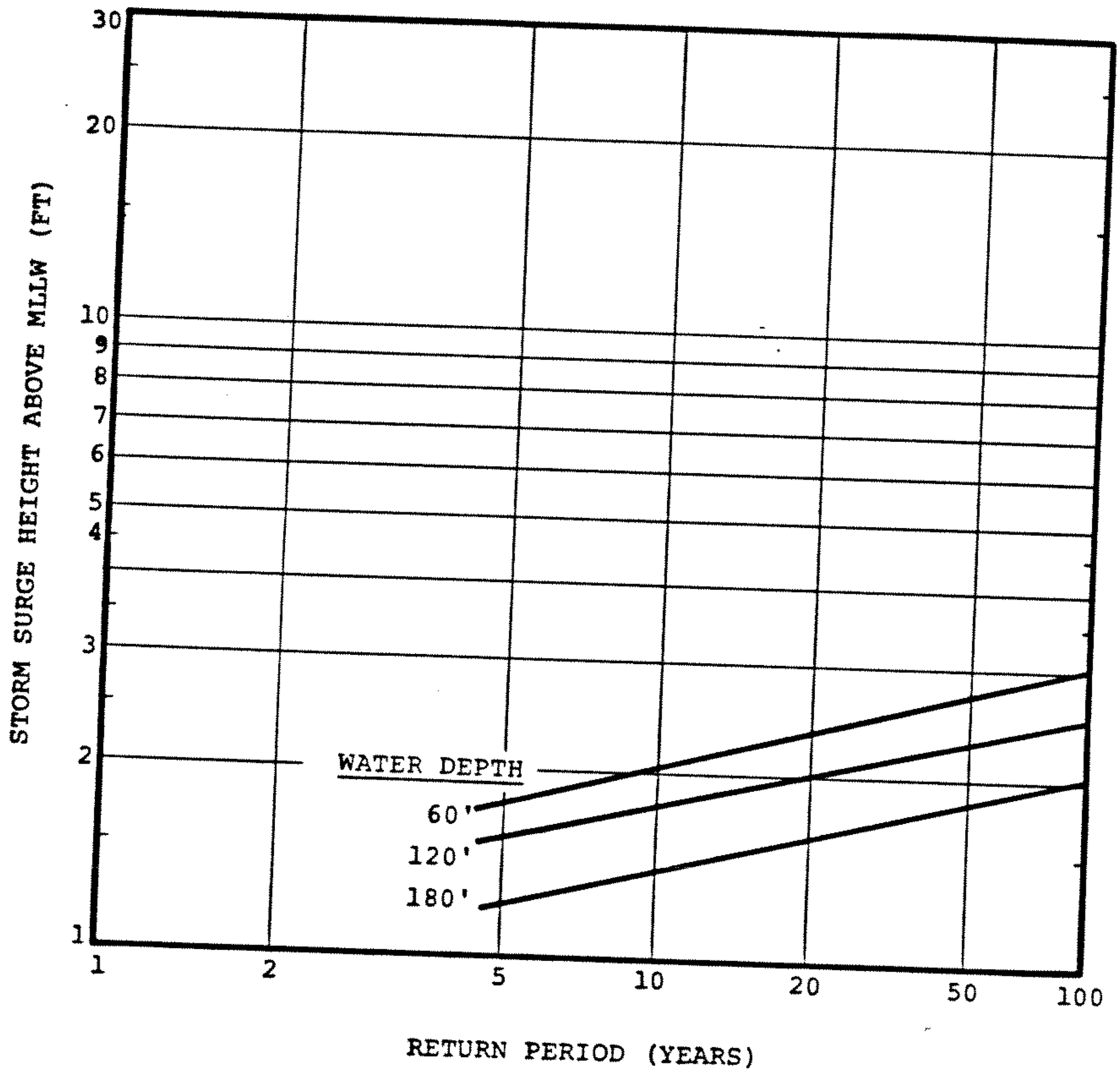


FIGURE 2.2 STORM SURGE HEIGHT ABOVE MLLW (FT) FOR LEASE SALE 87 (ALL ZONES)

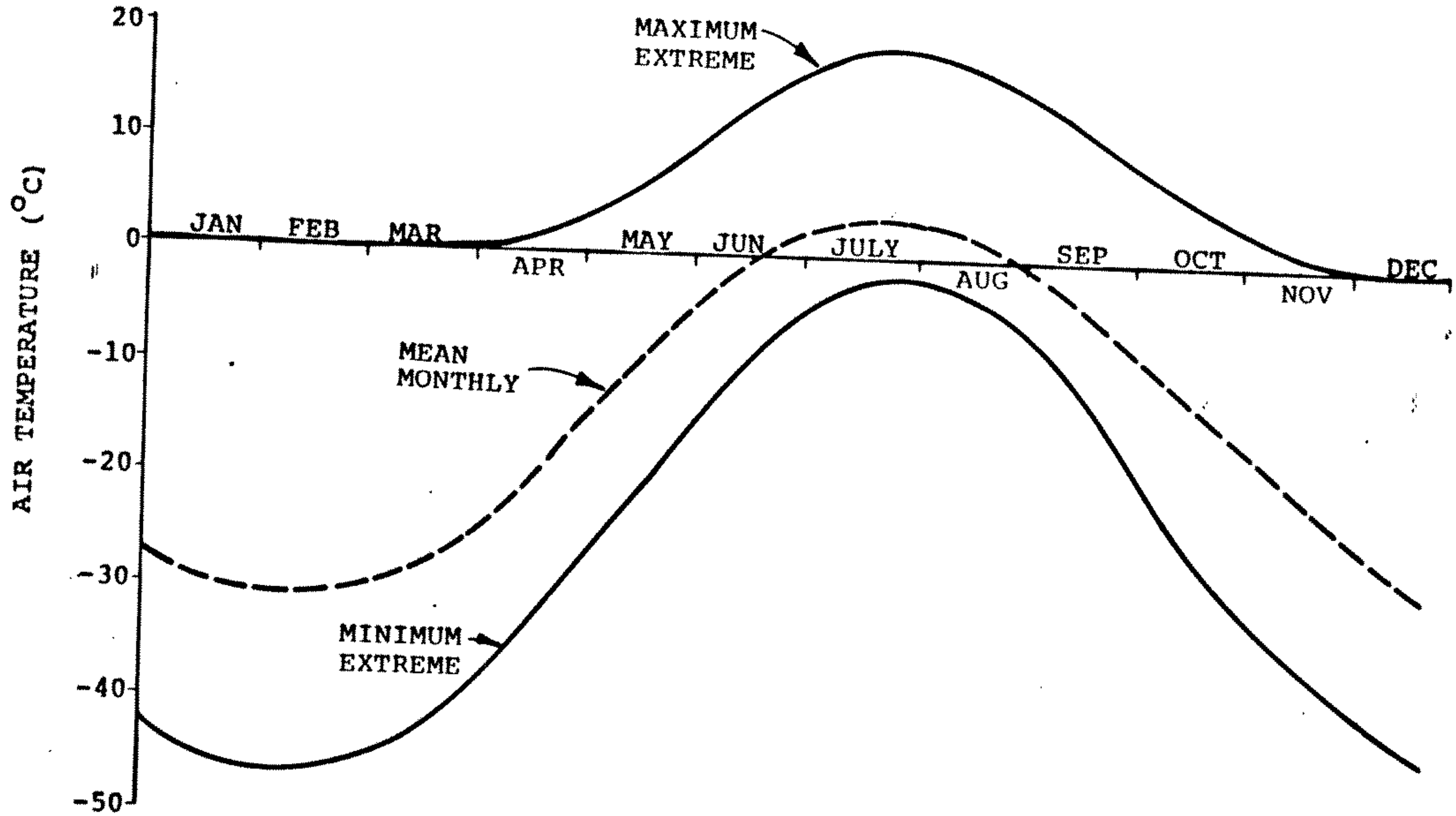


FIGURE 2.3 AIR TEMPERATURE DISTRIBUTIONS IN "DIAPIR 87" AREA

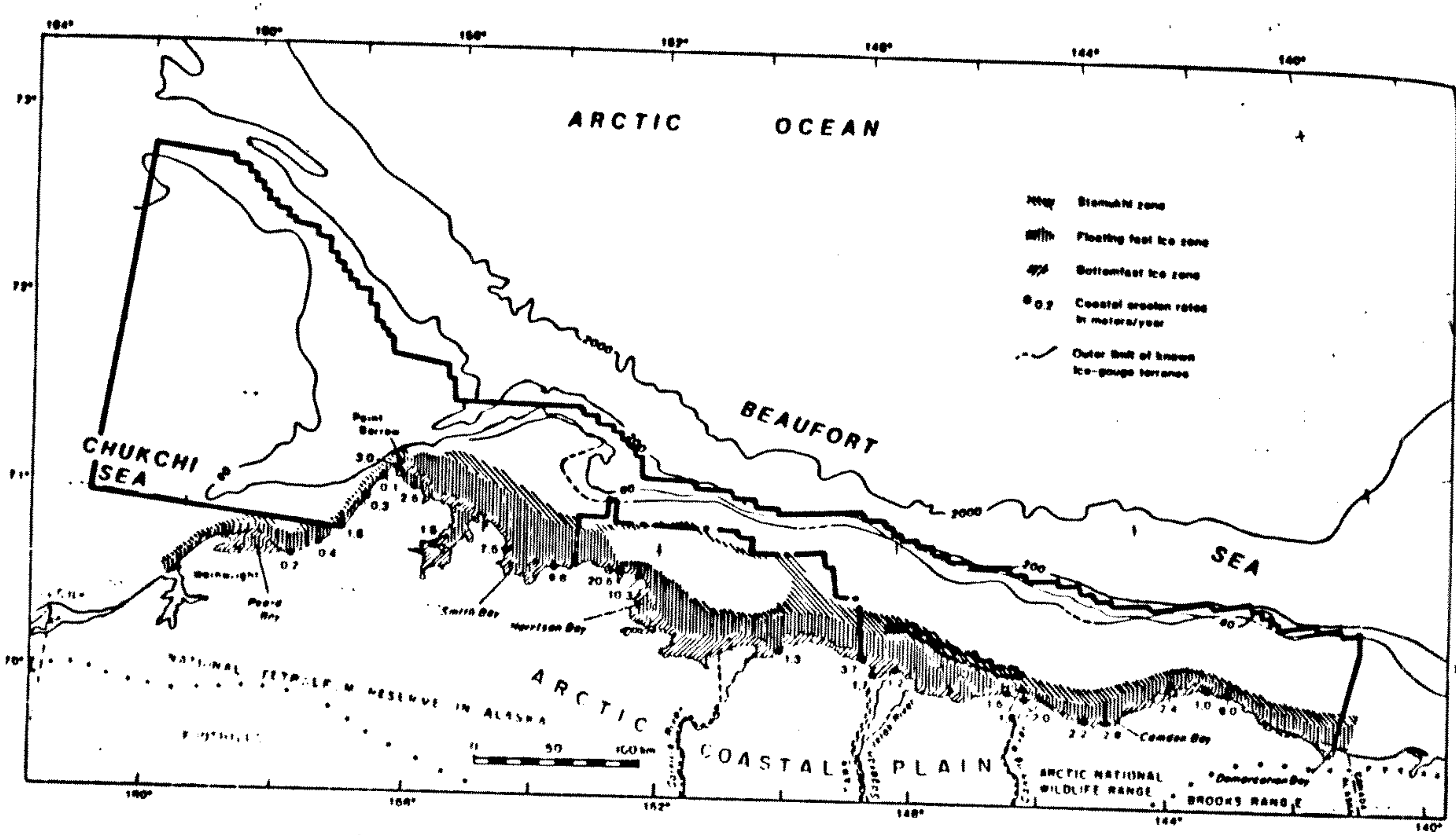


FIGURE 2.4 ICE ZONATION IN DIAPIR 87 AREA

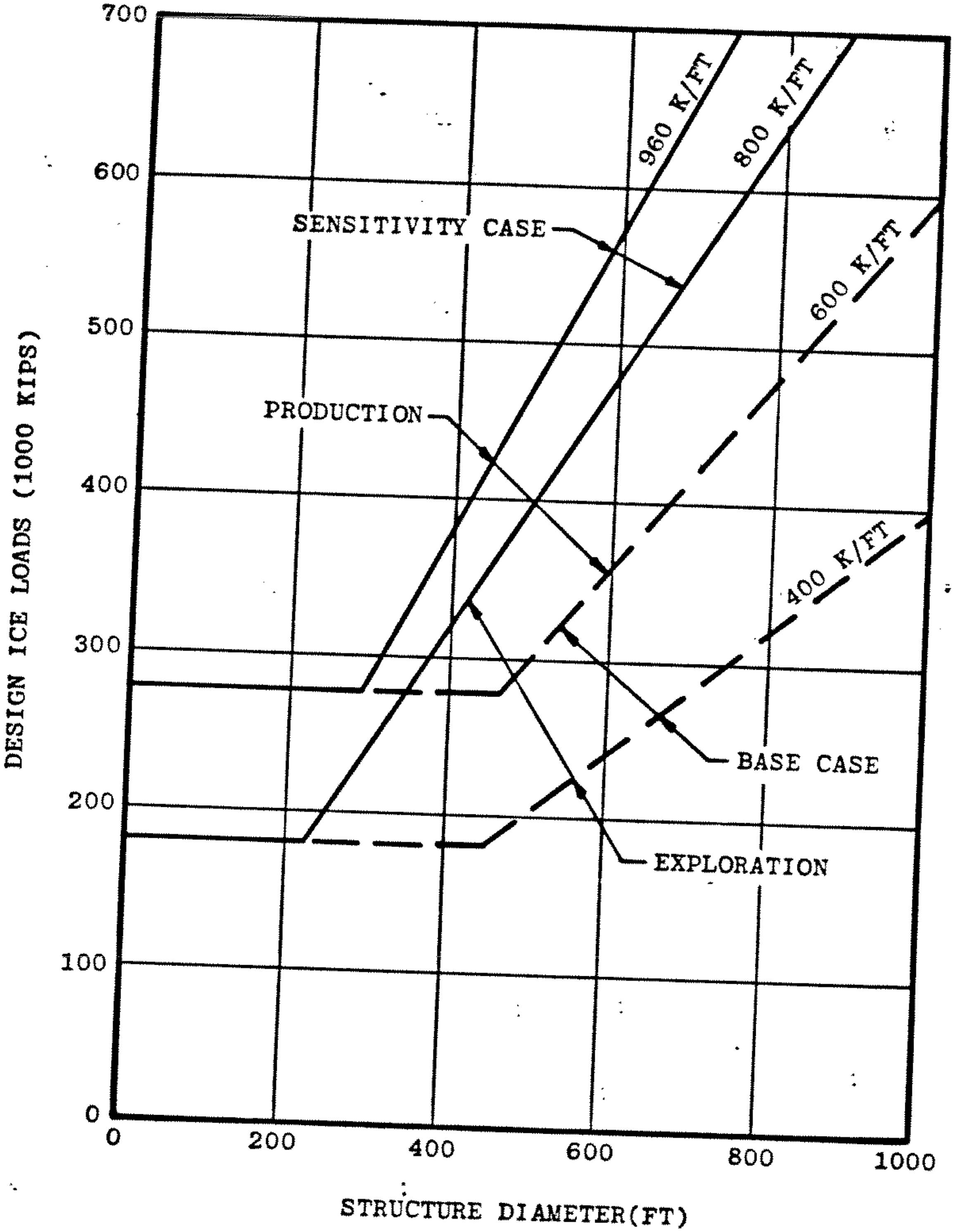


FIGURE 2.10 VERTICAL-SIDED STRUCTURE DESIGN ICE LOADS

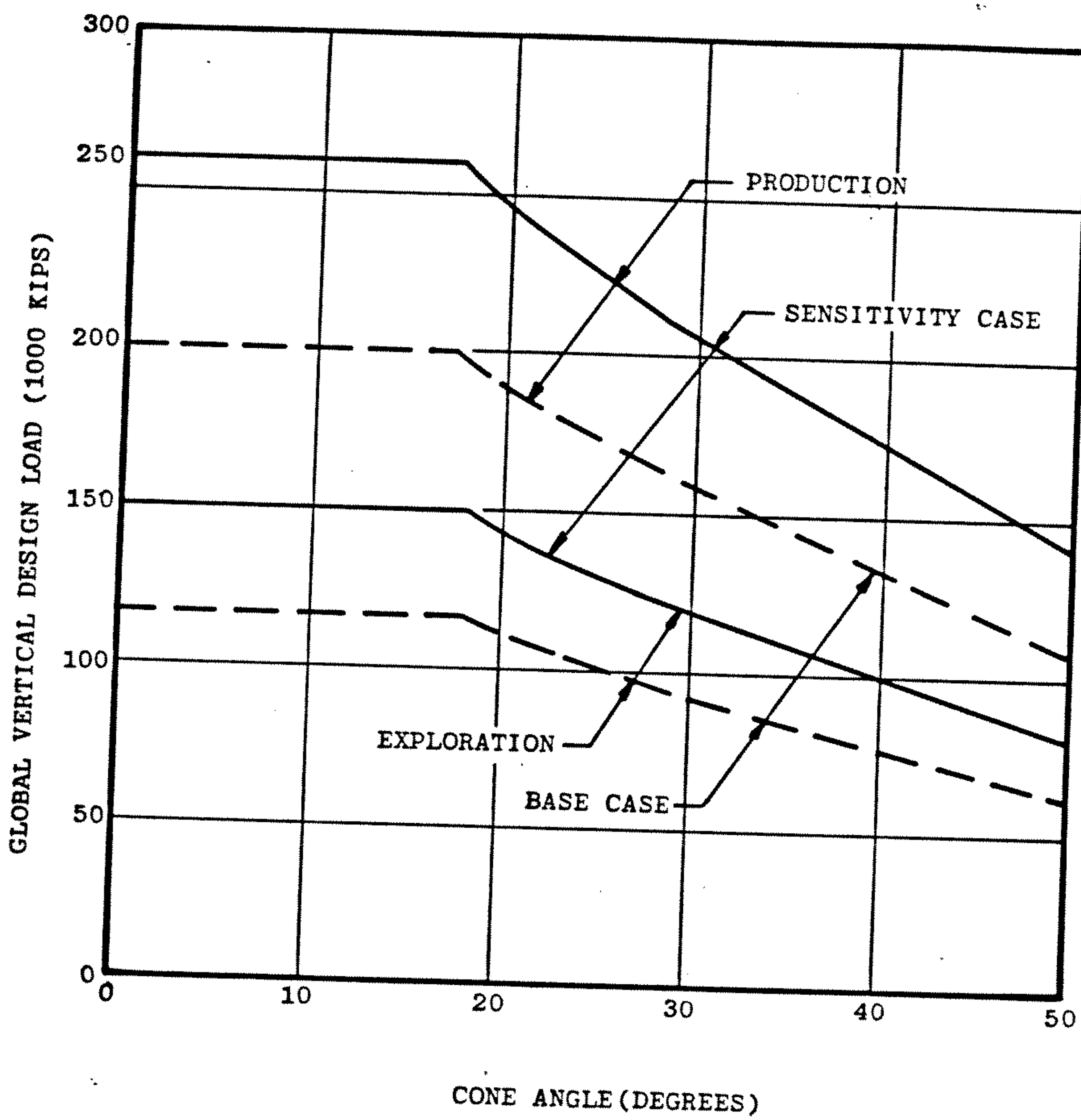


FIGURE 2.11 CONICAL STRUCTURE DESIGN ICE LOADS

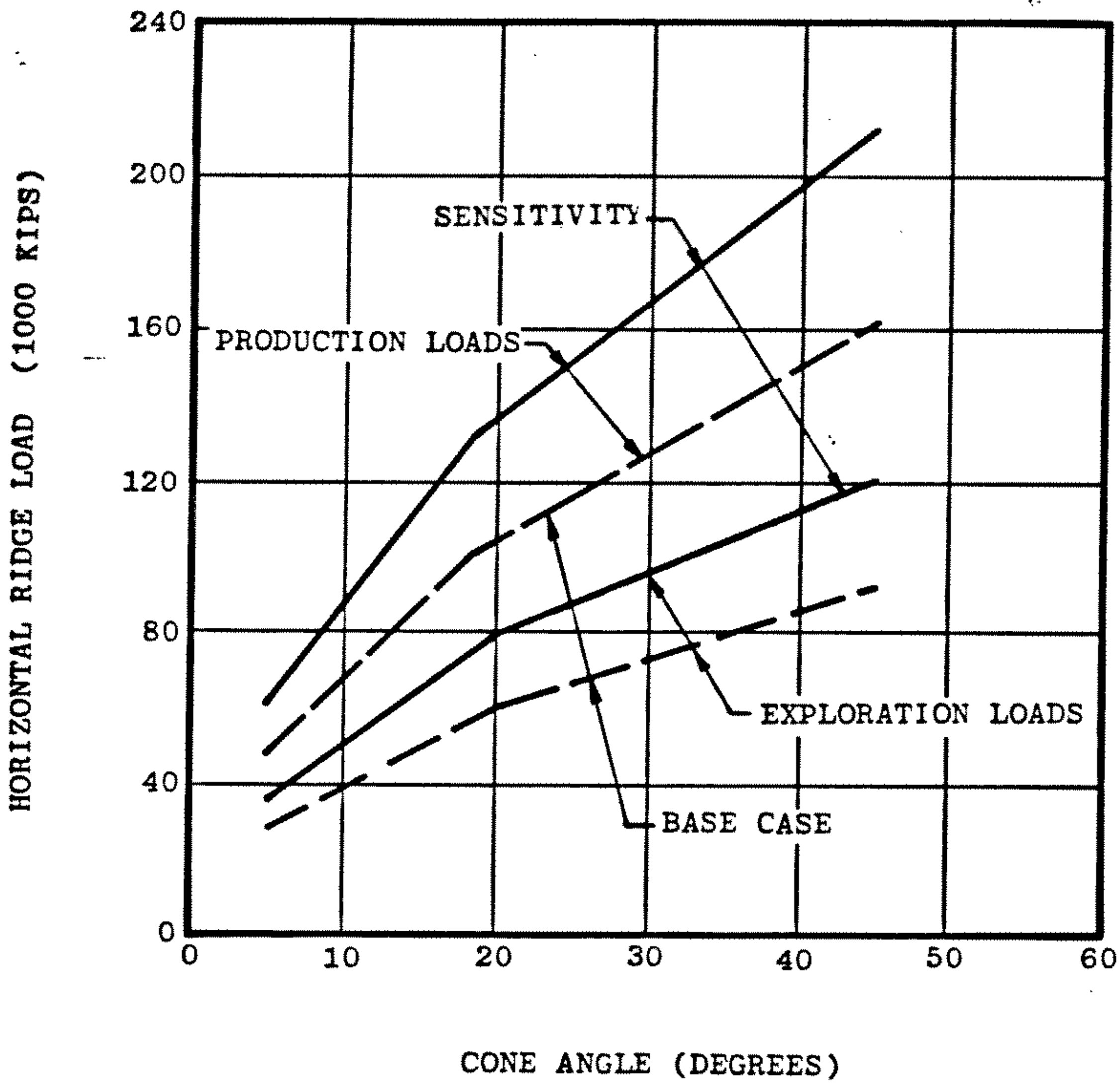


FIGURE 2.12 ICE LOADS ON CONICAL STRUCTURES

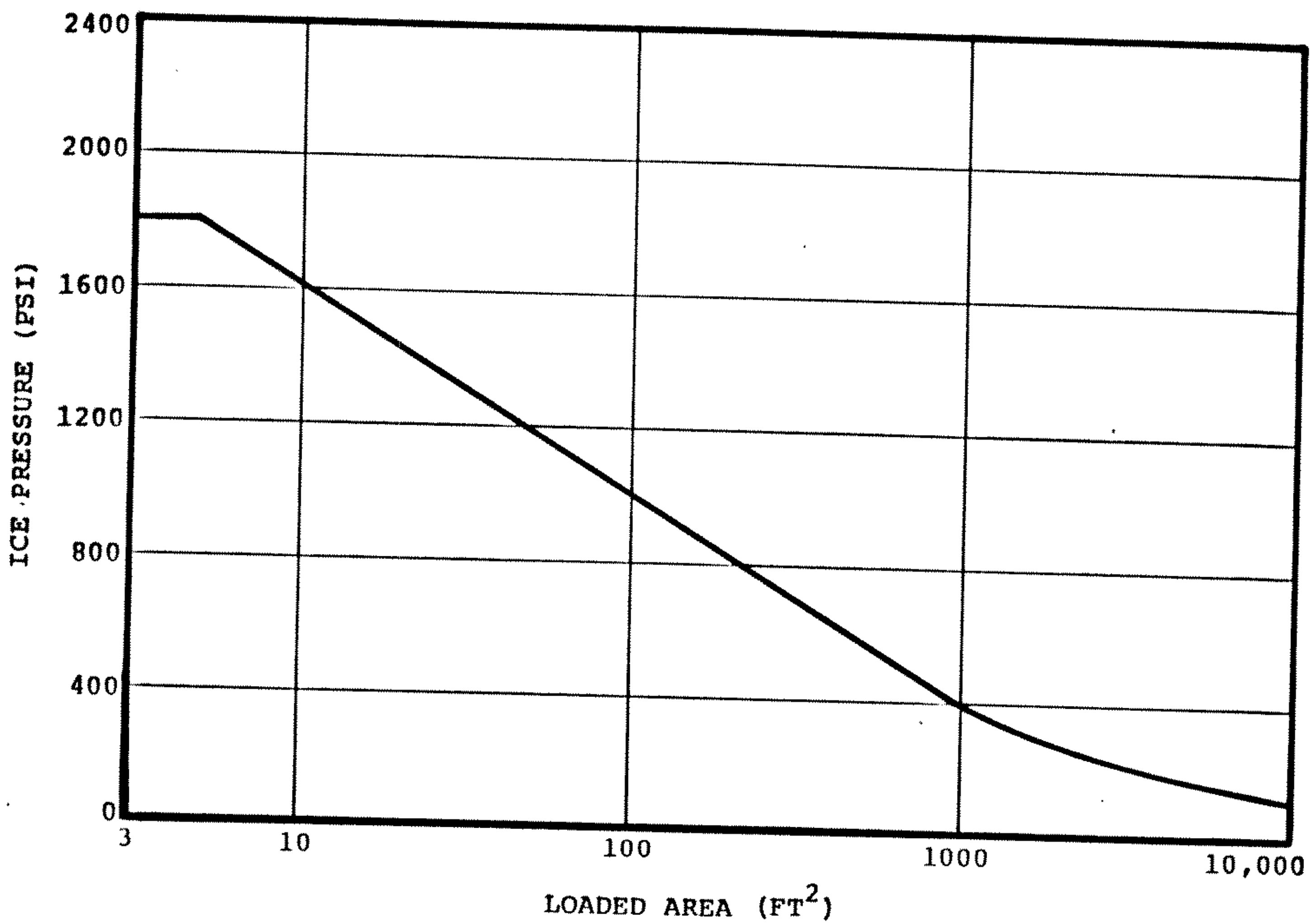


FIGURE 2.13 DESIGN PRESSURE-AREA CURVE

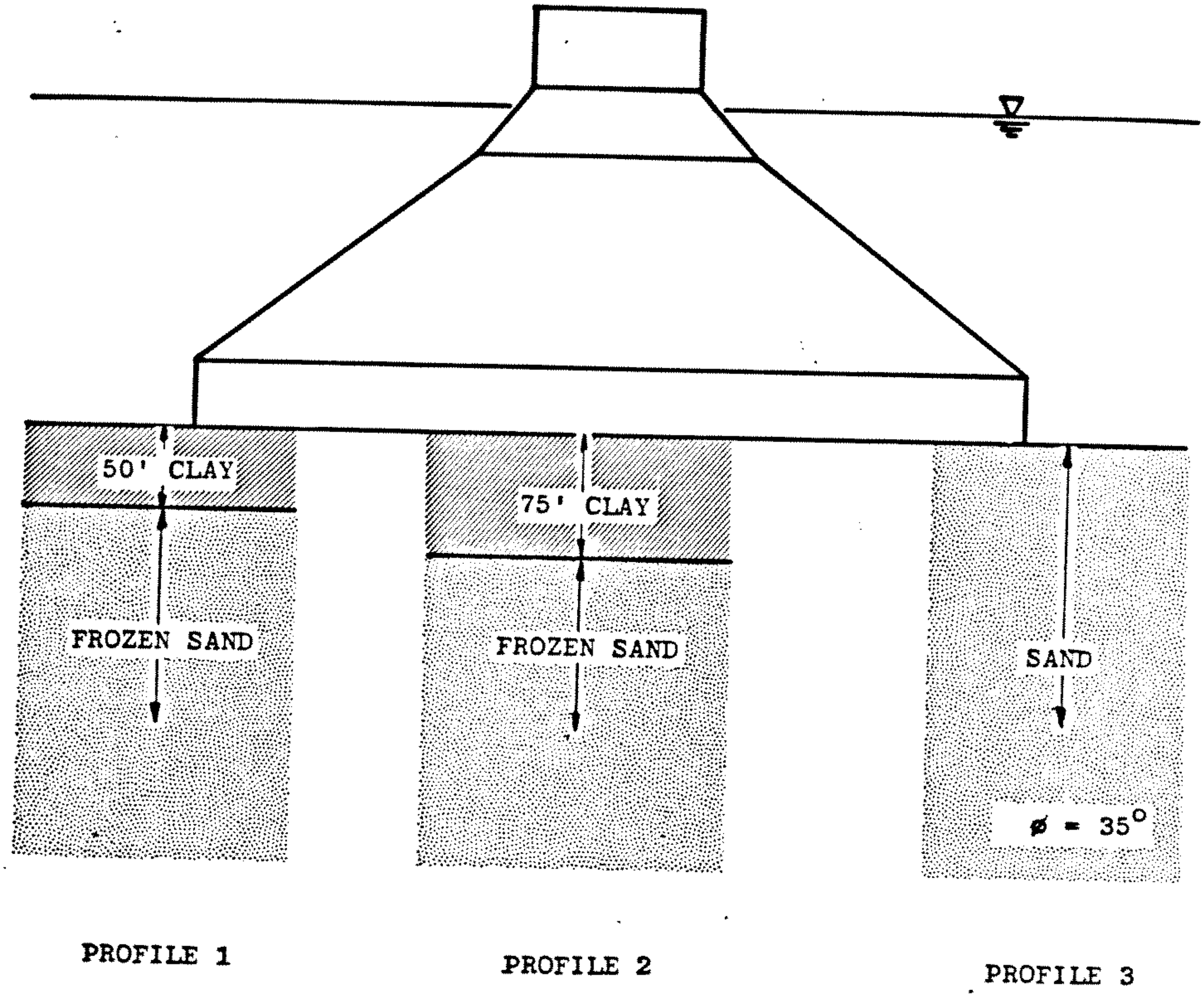


FIGURE 2.14 SOIL PROFILES CONSIDERED

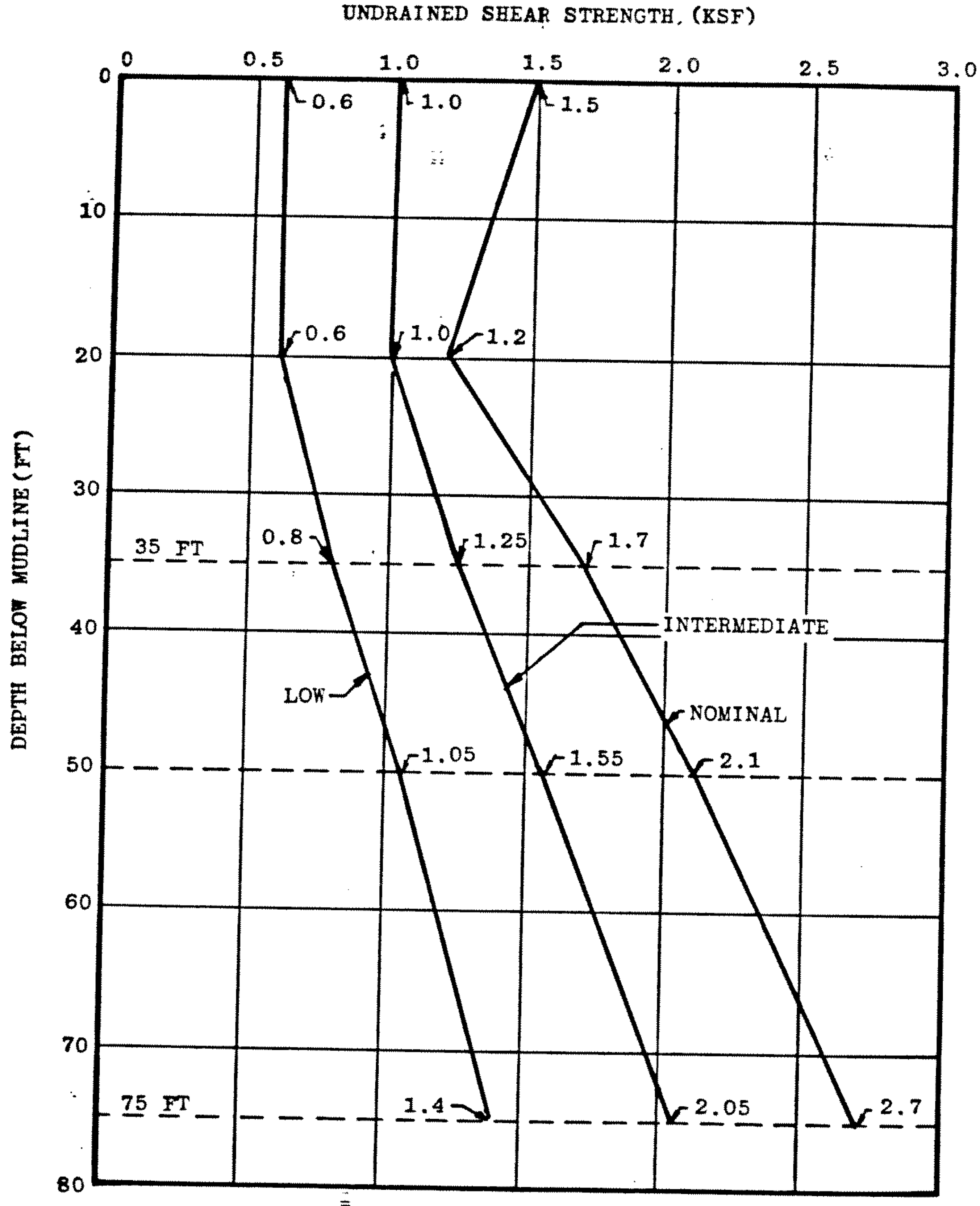


FIGURE 2.15 UNDRAINED SHEAR STRENGTH FOR PROFILES I AND II

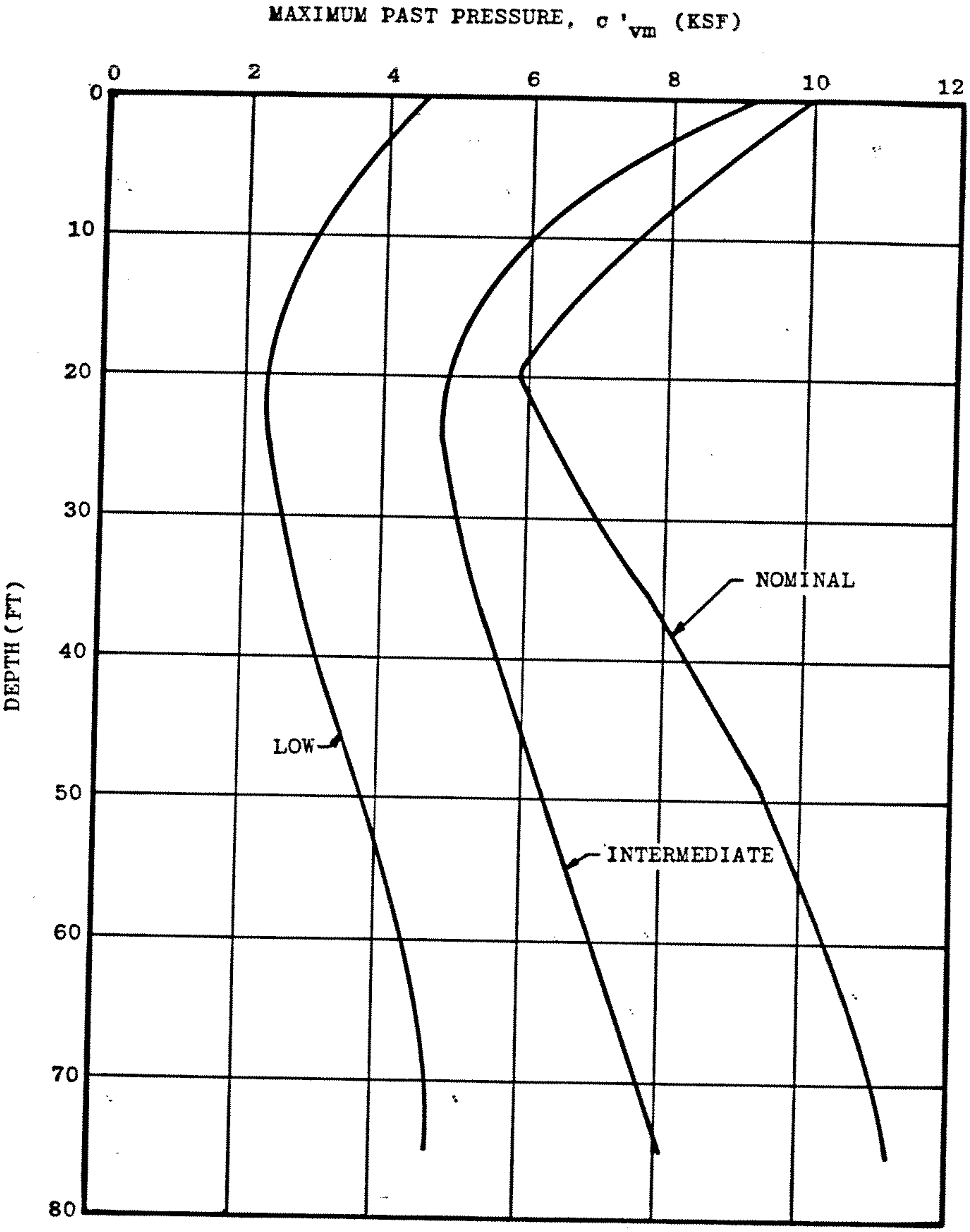


FIGURE 2.16 MAXIMUM PAST PRESSURES FOR PROFILES I AND II

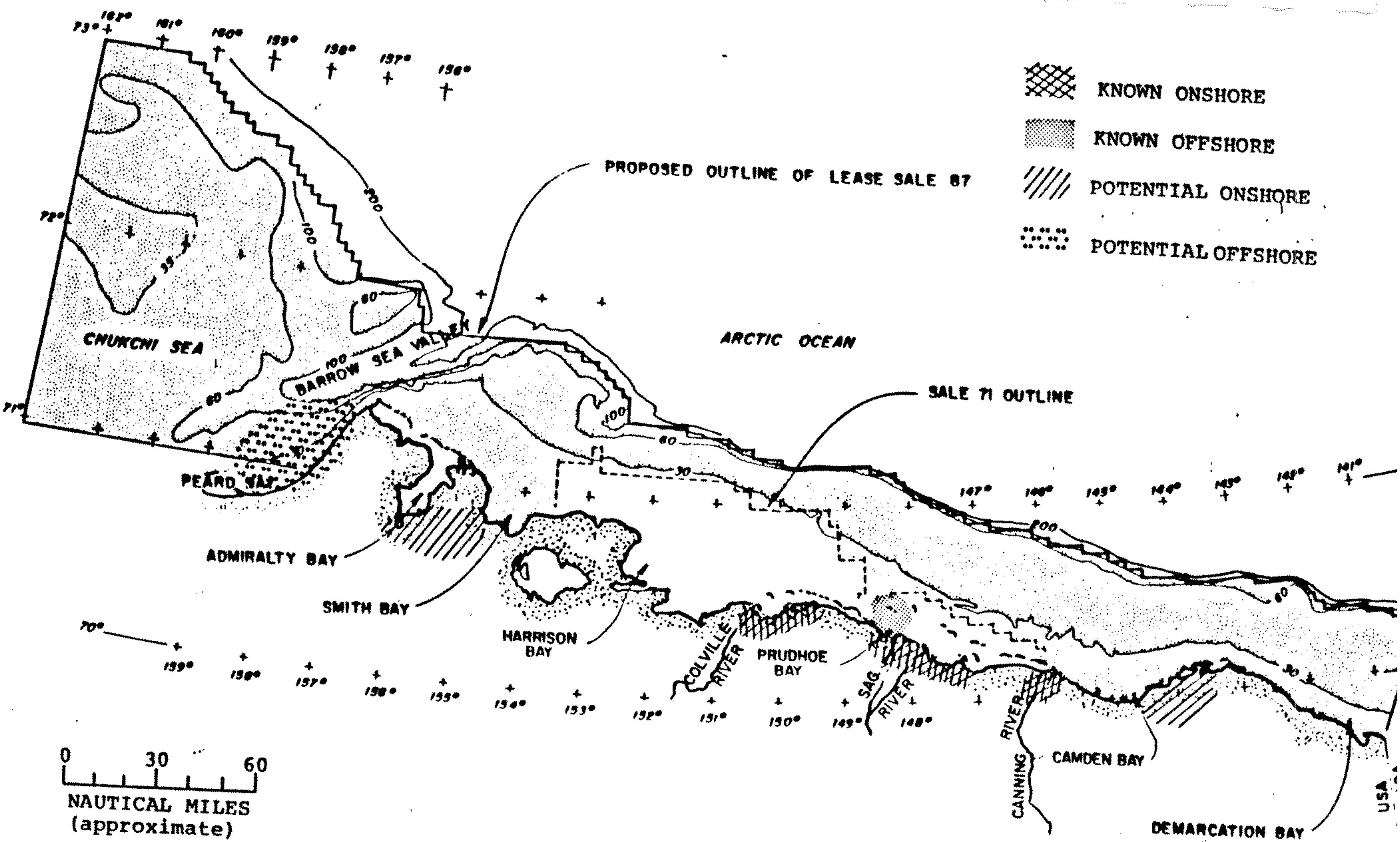


FIGURE 2.17 KNOWN AND POTENTIAL GRAVEL BORROW SOURCES ASSUMED FOR DIAPIR 87 STUDY

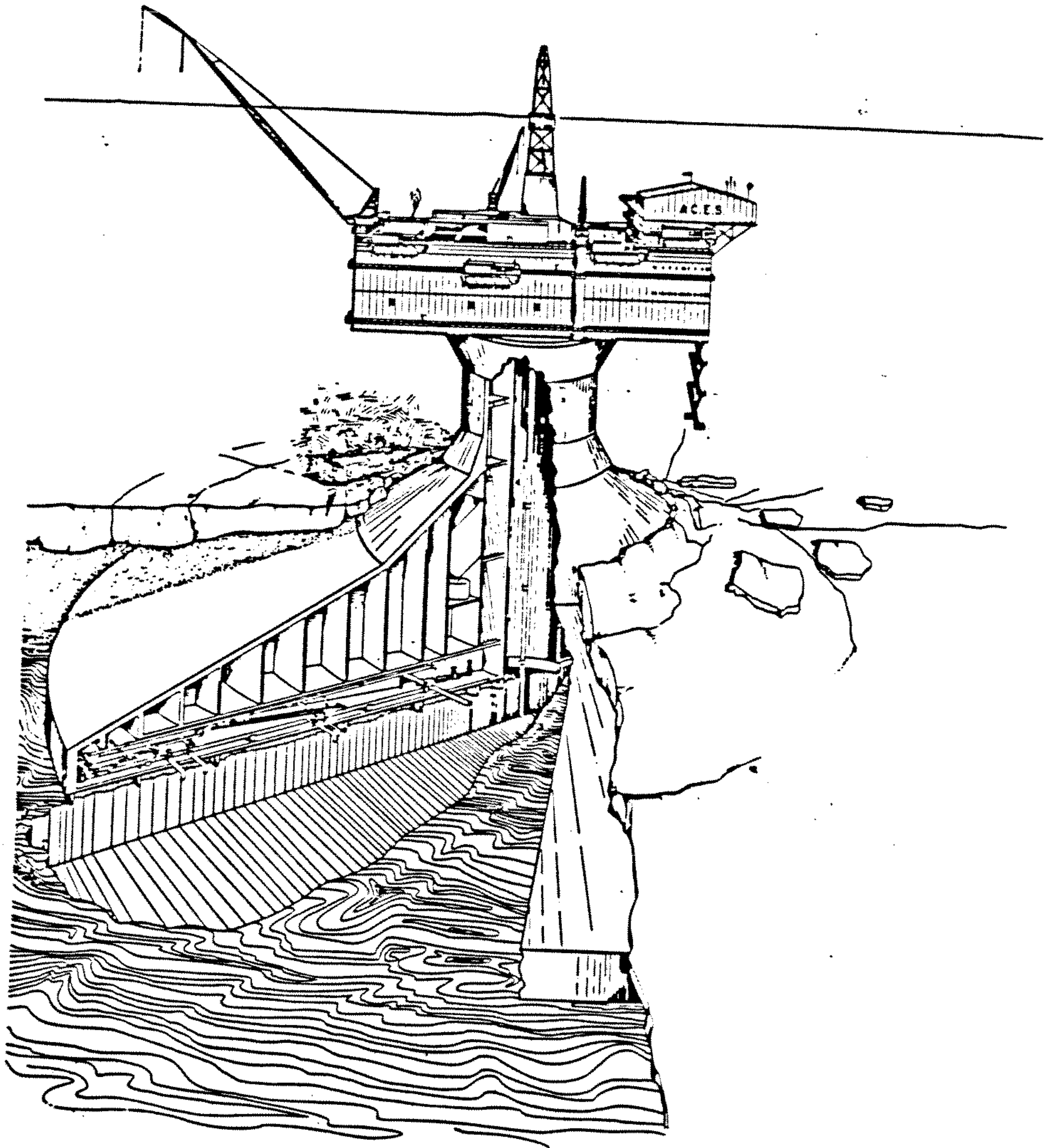
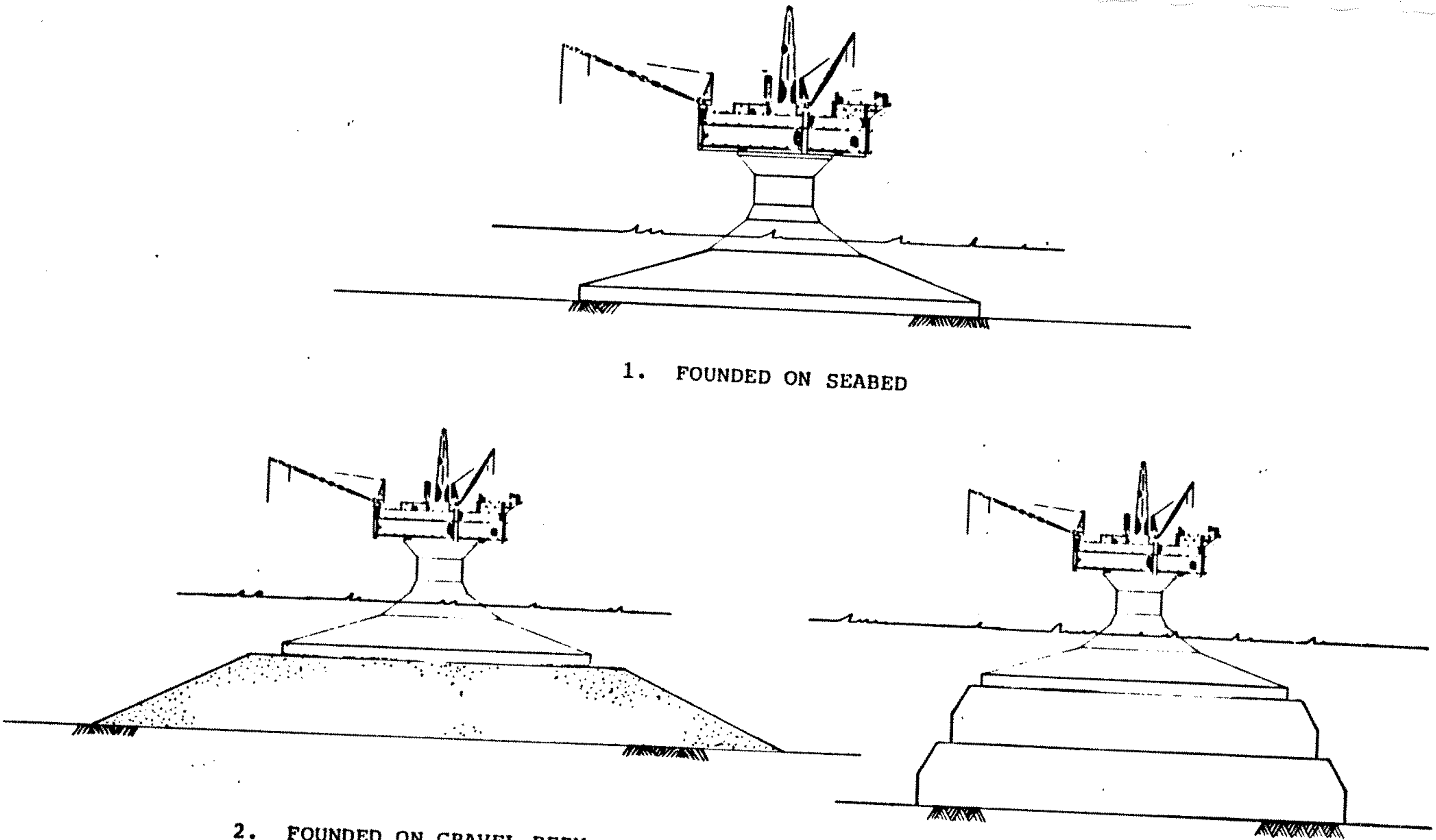


FIGURE 3.1 CONE CONCEPT



1. FOUNDED ON SEABED

2. FOUNDED ON GRAVEL BERM

3. FOUNDED ON SUBBASE SEGMENTS

FIGURE 3.2 APPLICATIONS OF CONE CONCEPT

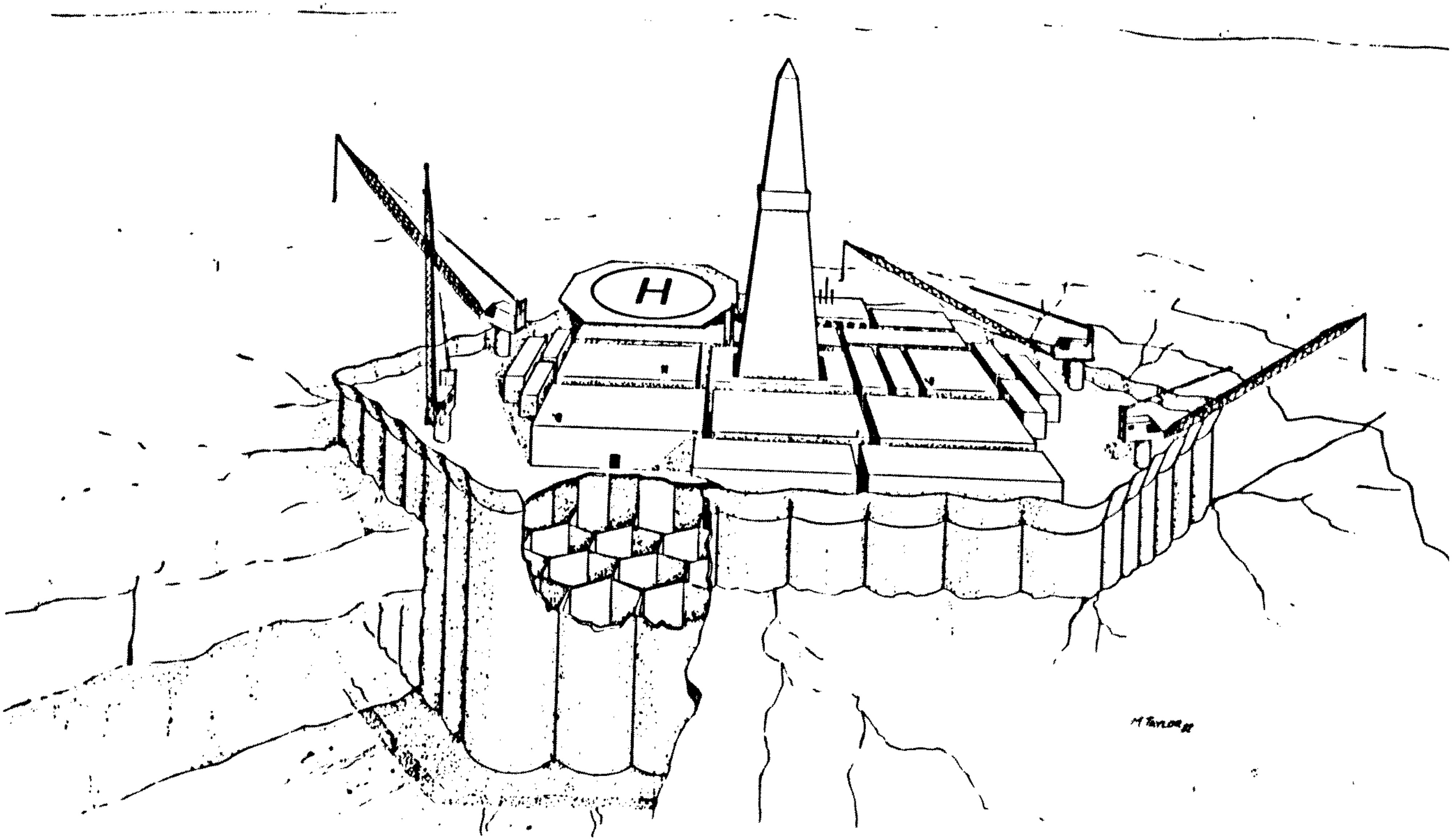
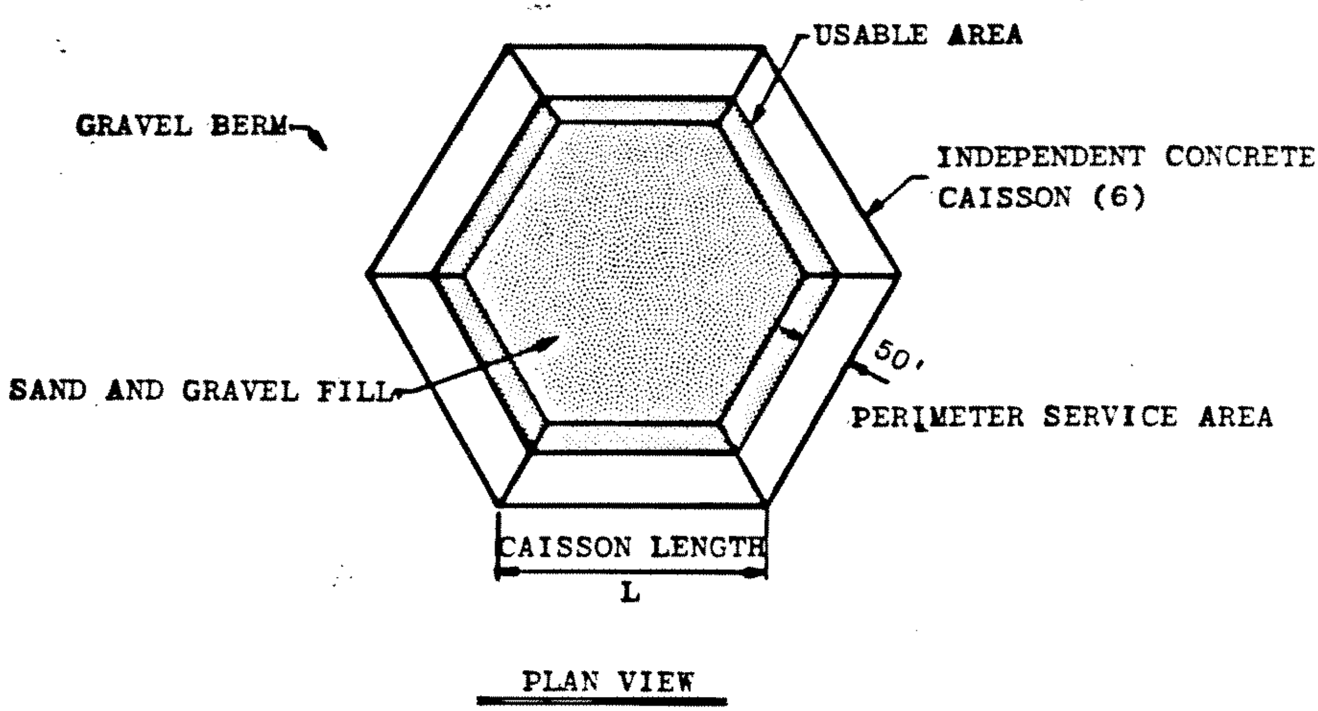


FIGURE 3.3 MONOLITHIC CAISSON CONCEPT



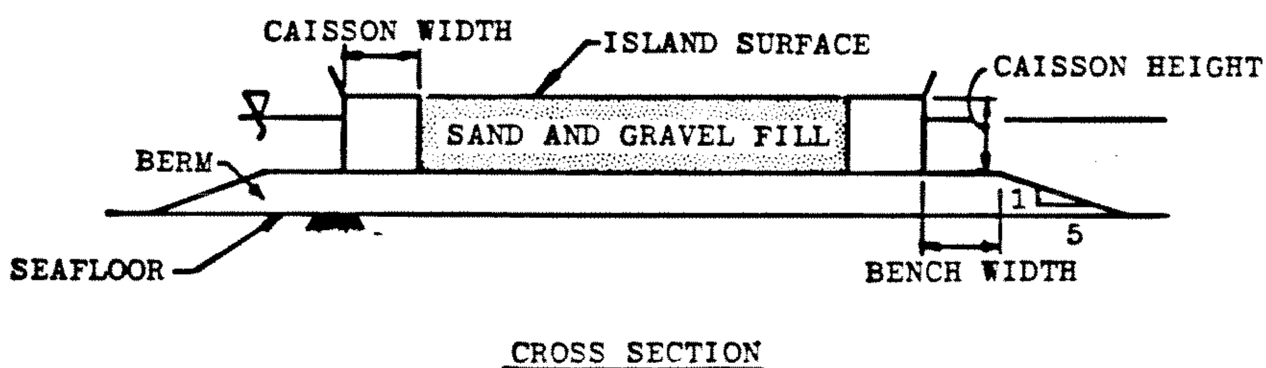


FIGURE 3.4 -- CAISSON-RETAINED ISLAND CONCEPT

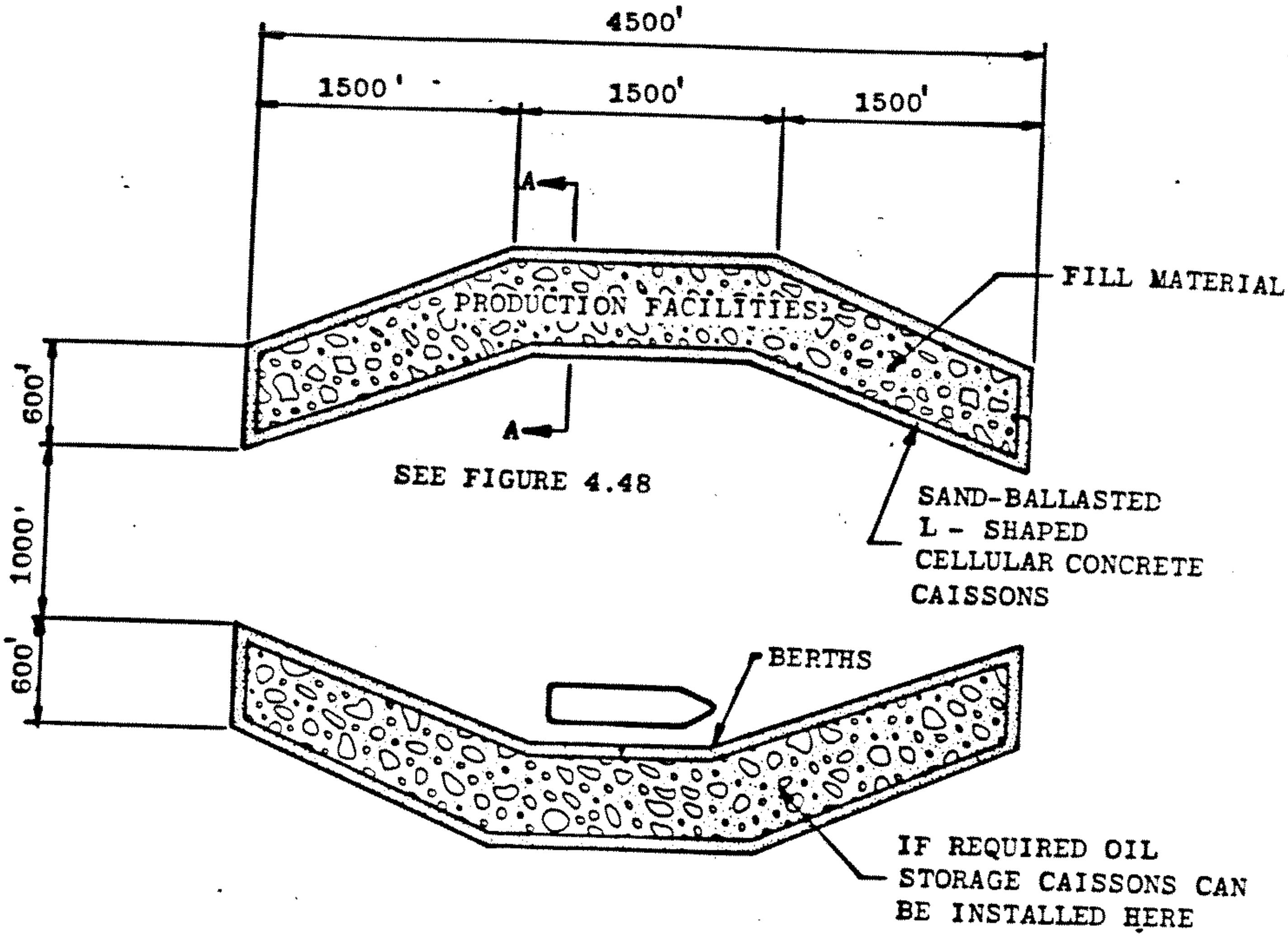


FIGURE 3.5 PRODUCTION AND LOADING ATOLL (SCHEME 1)

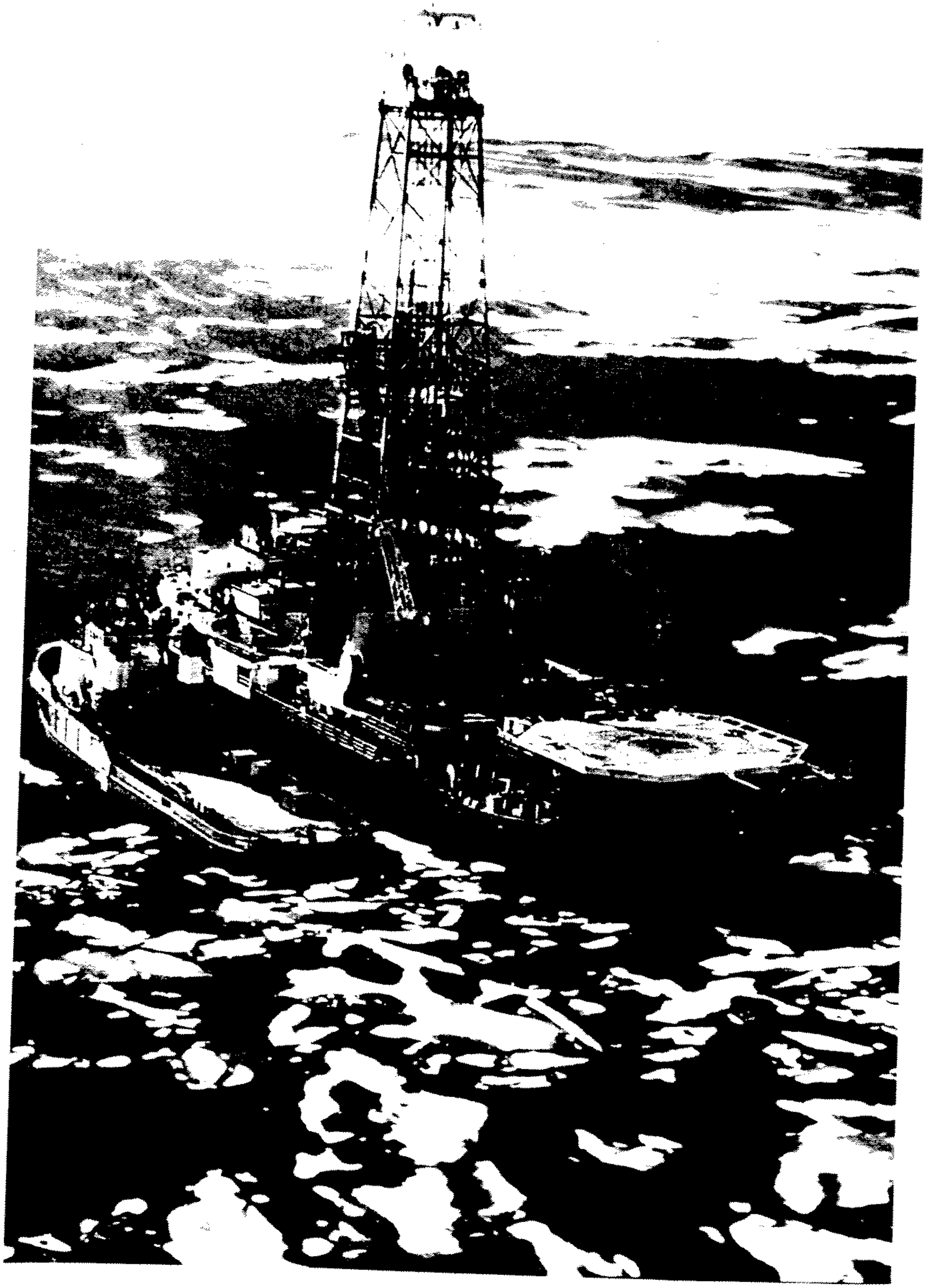


FIGURE 3.6 TURRET MOORED DRILLSHIP

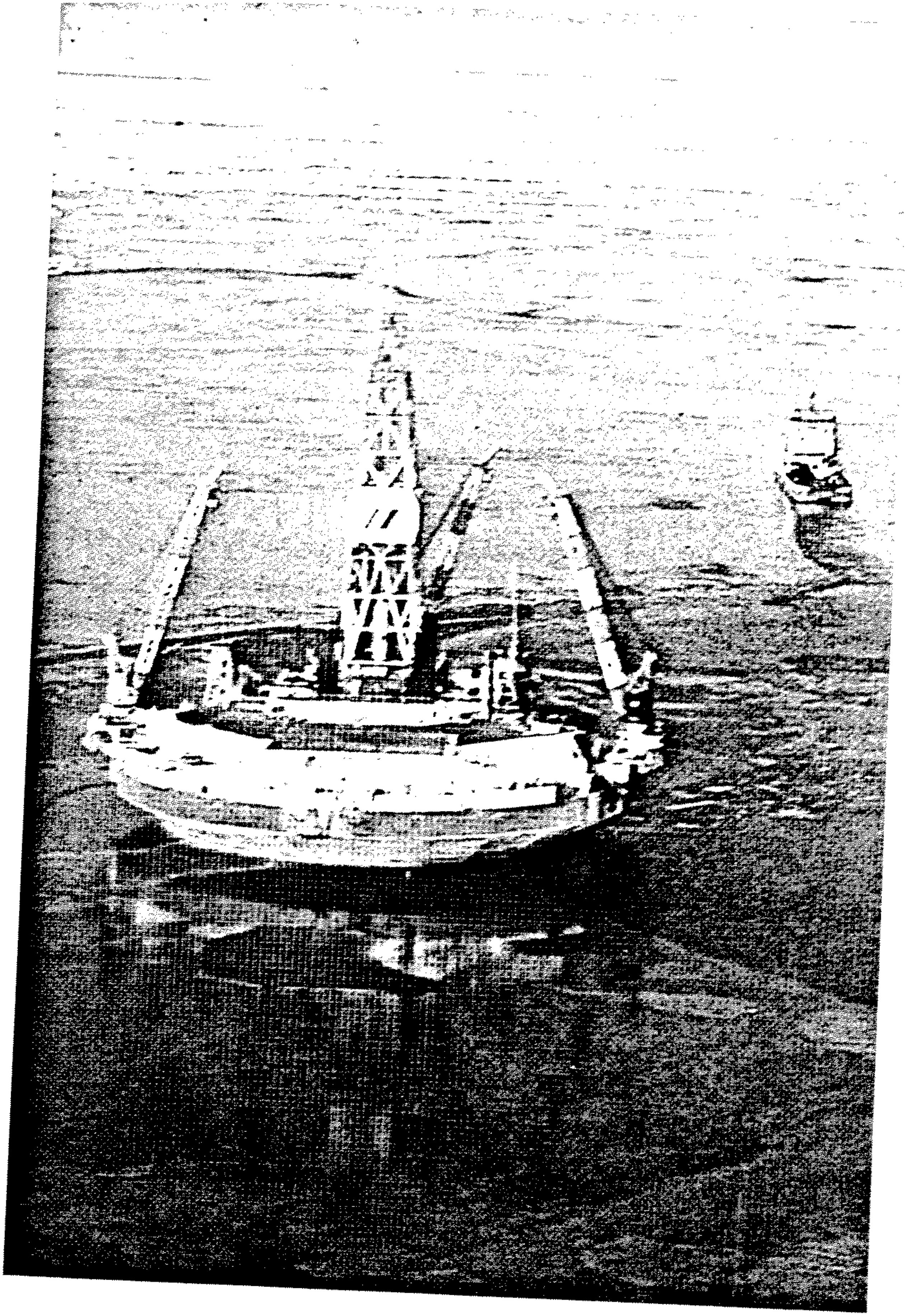


FIGURE 3.7 PURPOSE BUILT FLOATING DRILLING UNIT

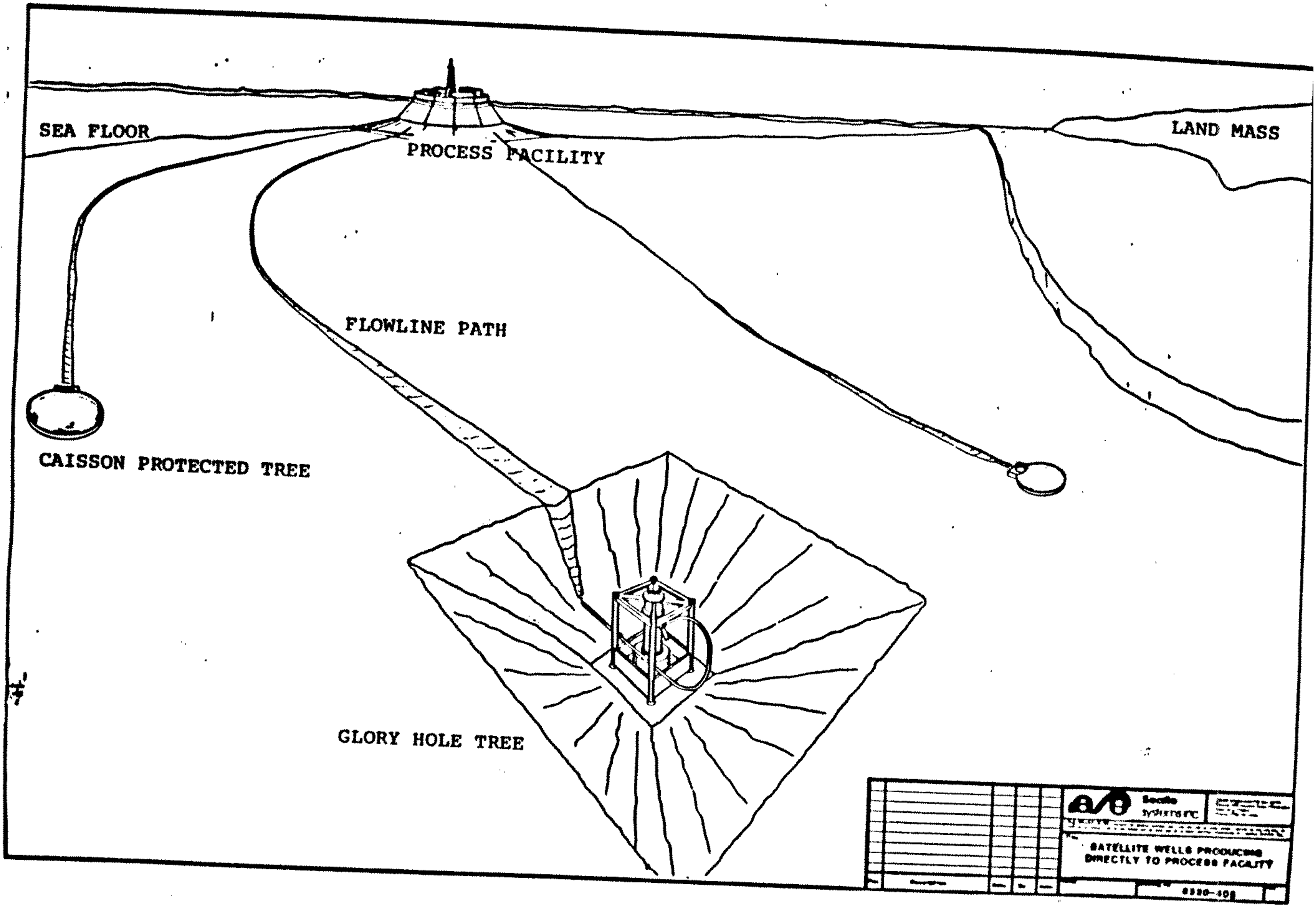


FIGURE 3.8 SATELLITE WELLS PRODUCING DIRECTLY TO PROCESS FACILITY

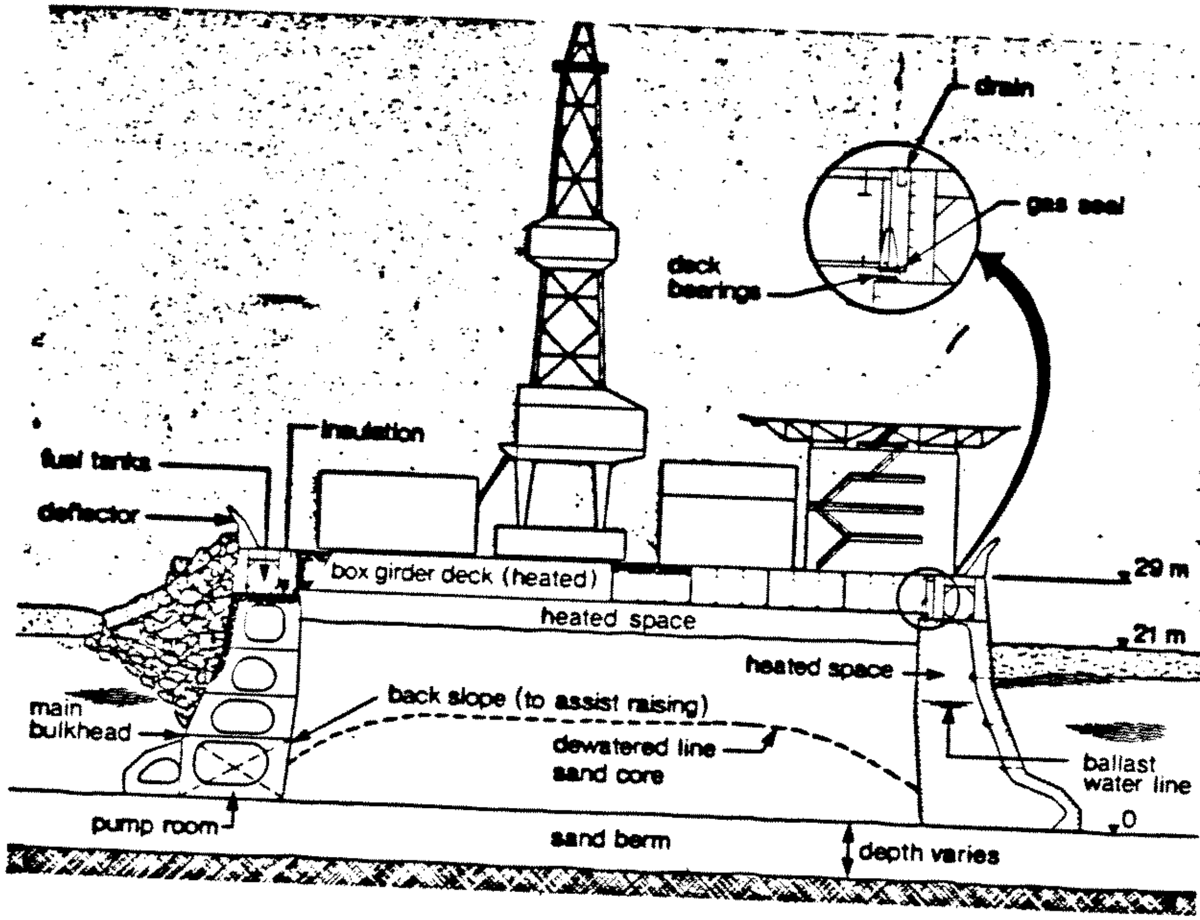


FIGURE 3.9 MOBILE ARCTIC CAISSON "MOLIQPAK"

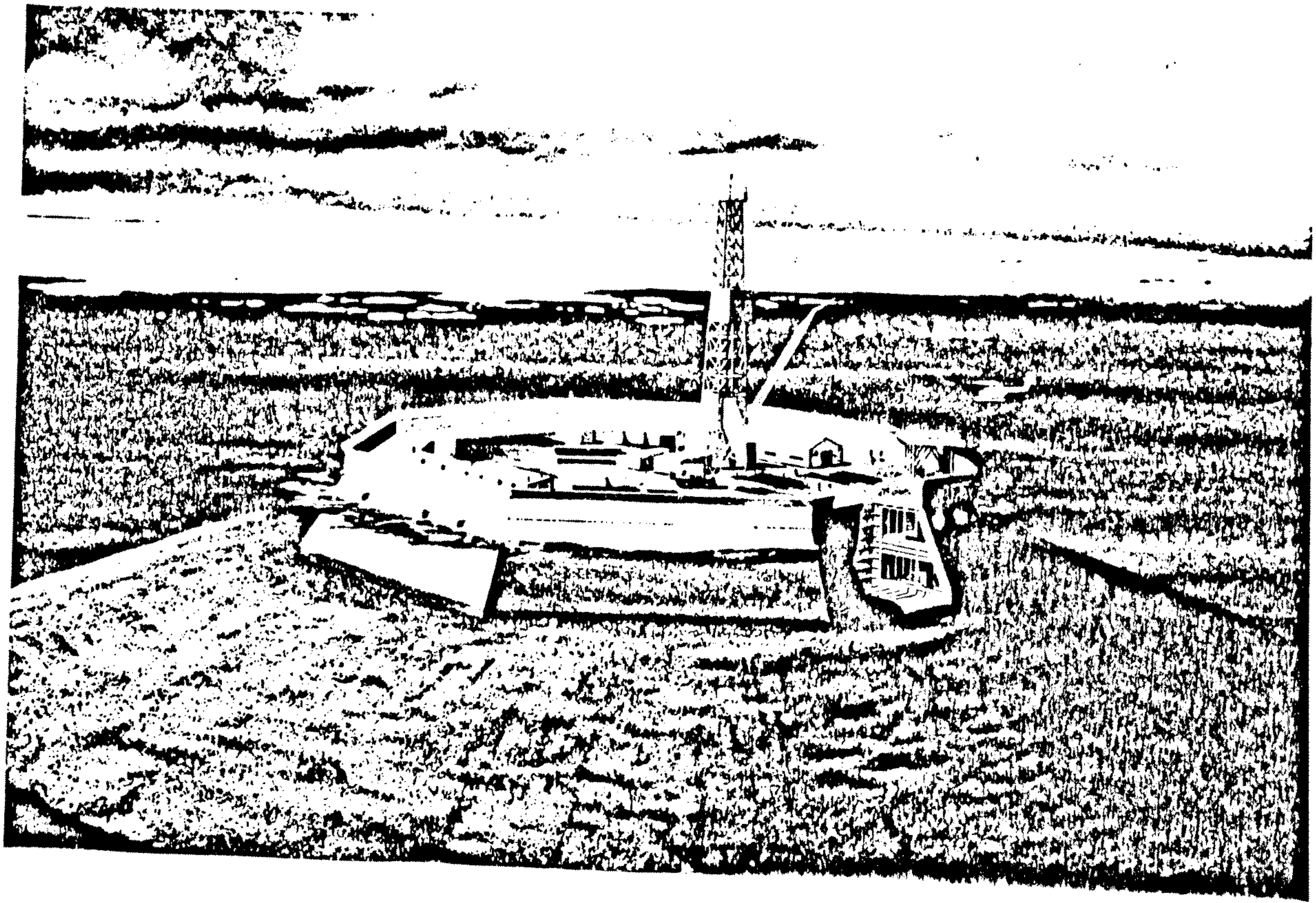


FIGURE 3.10 ANNULAR CAISSON RETAINED ISLAND (KADLUK)

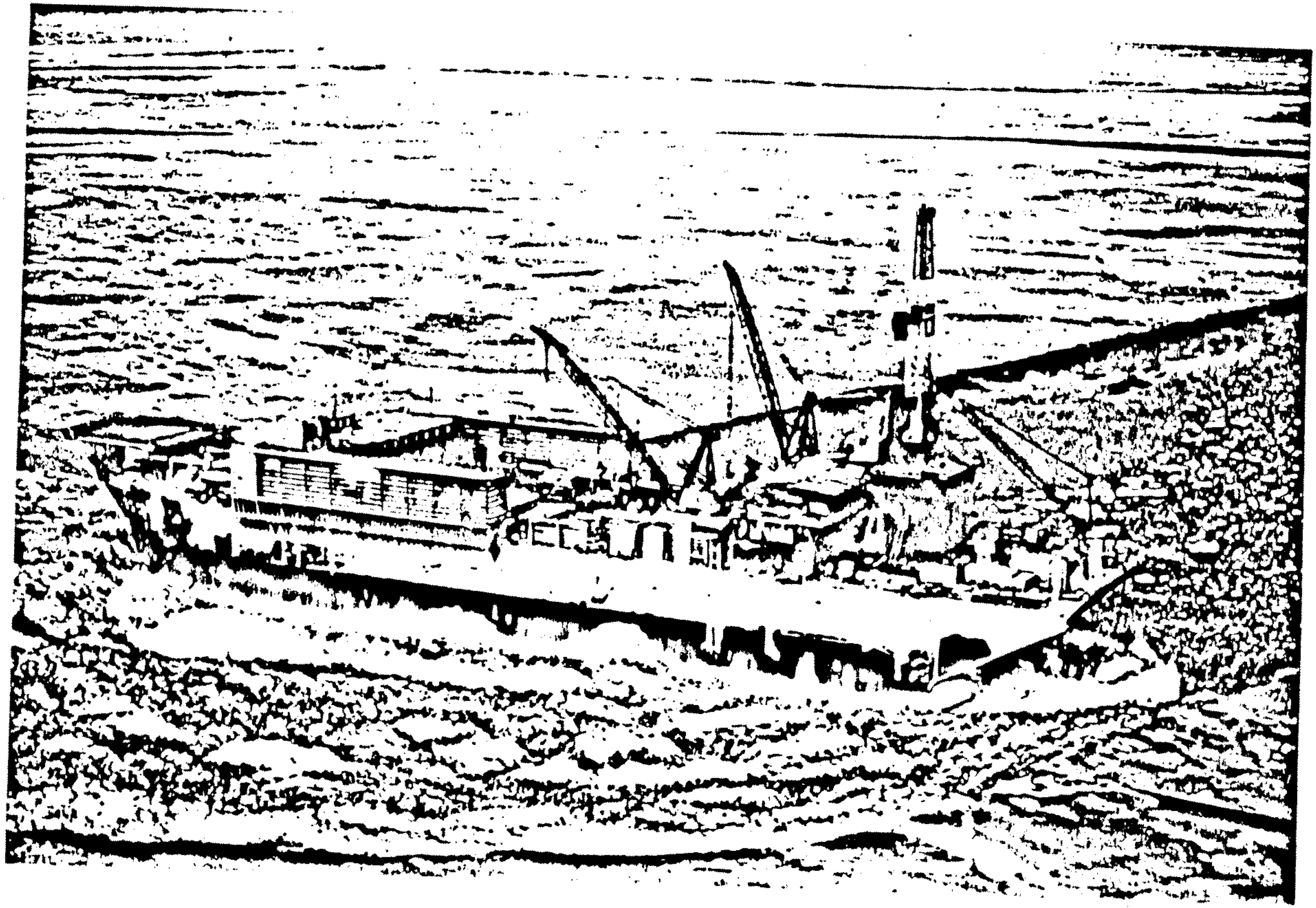


FIGURE 3.11 SINGLE STEEL DRILLING CAISSON (SSDC)

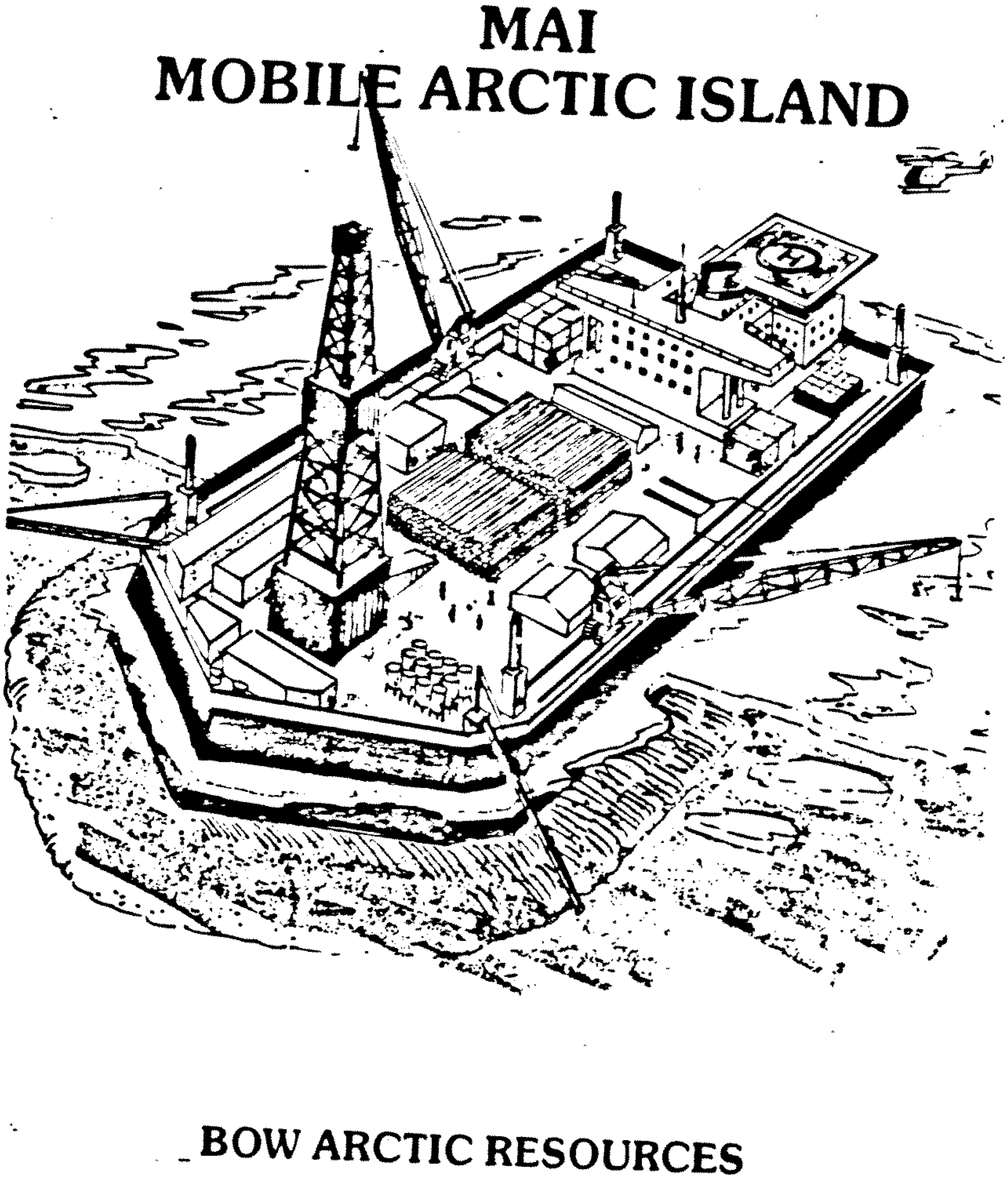
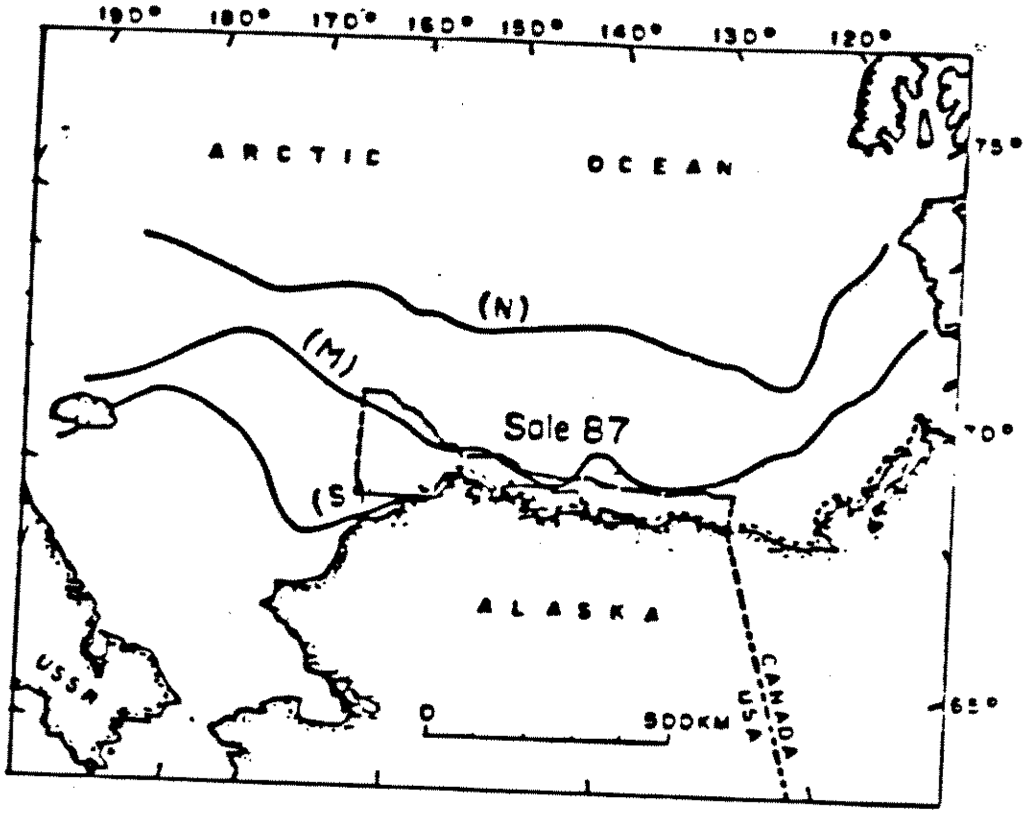
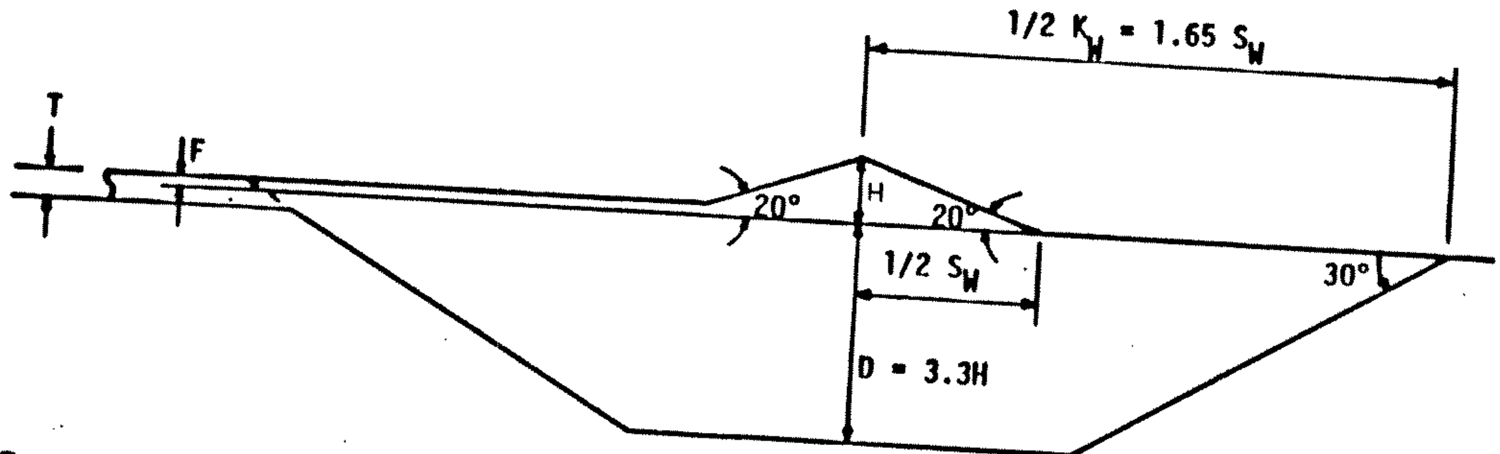


FIGURE 3.12 BOW VALLEY TANKER HULL CONCEPT



N = MOST MORTHERLY
M = MEDIAN
S = MOST SOUTHERLY
MAX. RETREAT END SEPTEMBER
BASED ON DATA 1954 - 70

FIGURE 2.5 SOUTHERN EDGE OF PACK ICE



T = ICE THICKNESS

D = KEEL DEPTH = 3.3H

H = SAIL HEIGHT

S_W = SAIL WIDTH = 2H/tan 20°

1/2 K_W = 1.65 S_W

F = FREE BOARD

FIGURE 2.6 STANDARD RIDGE PROFILE (KOVACS)

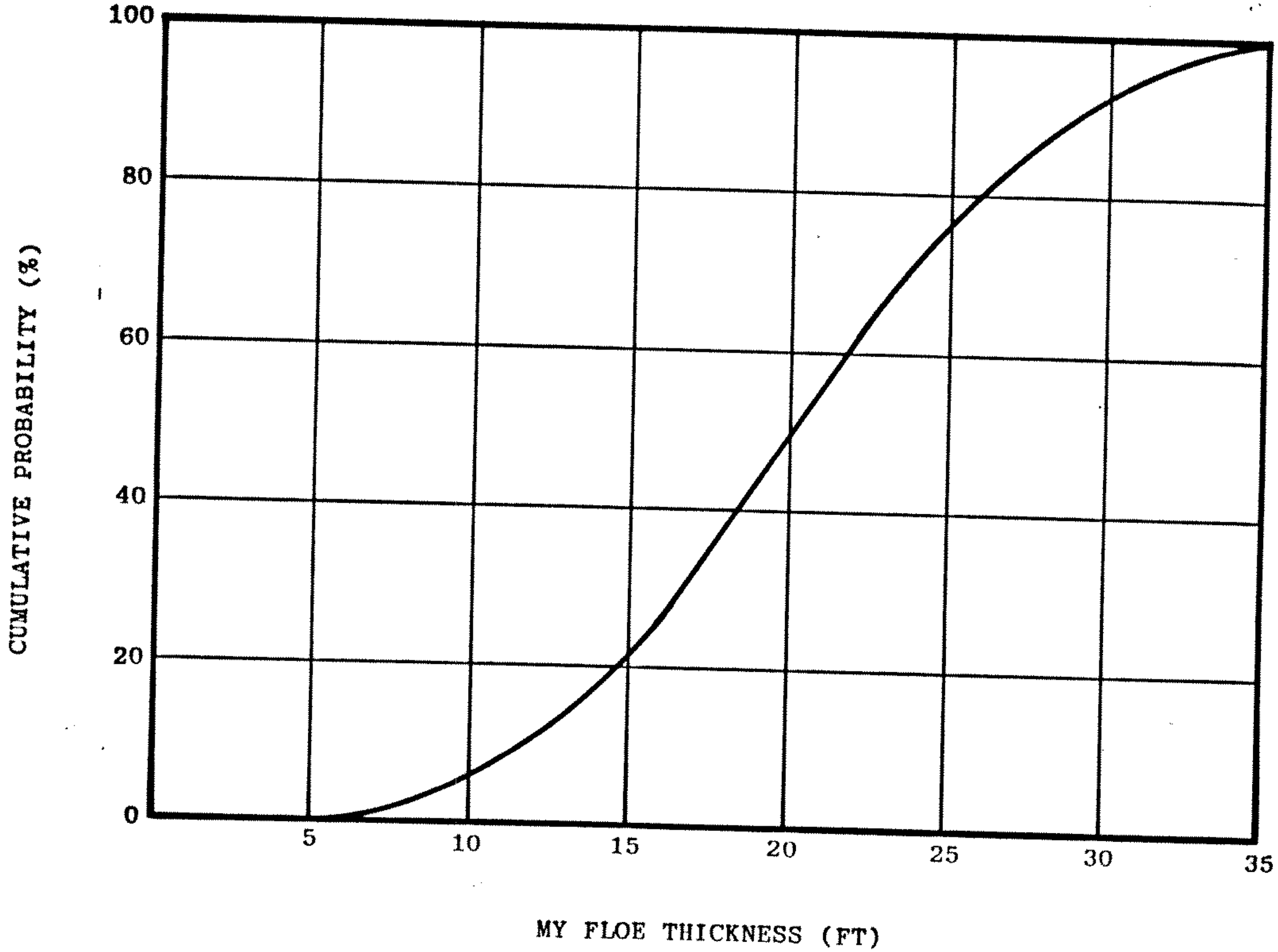


FIGURE 2.7 DISTRIBUTION OF MULTIYEAR FLOE THICKNESS

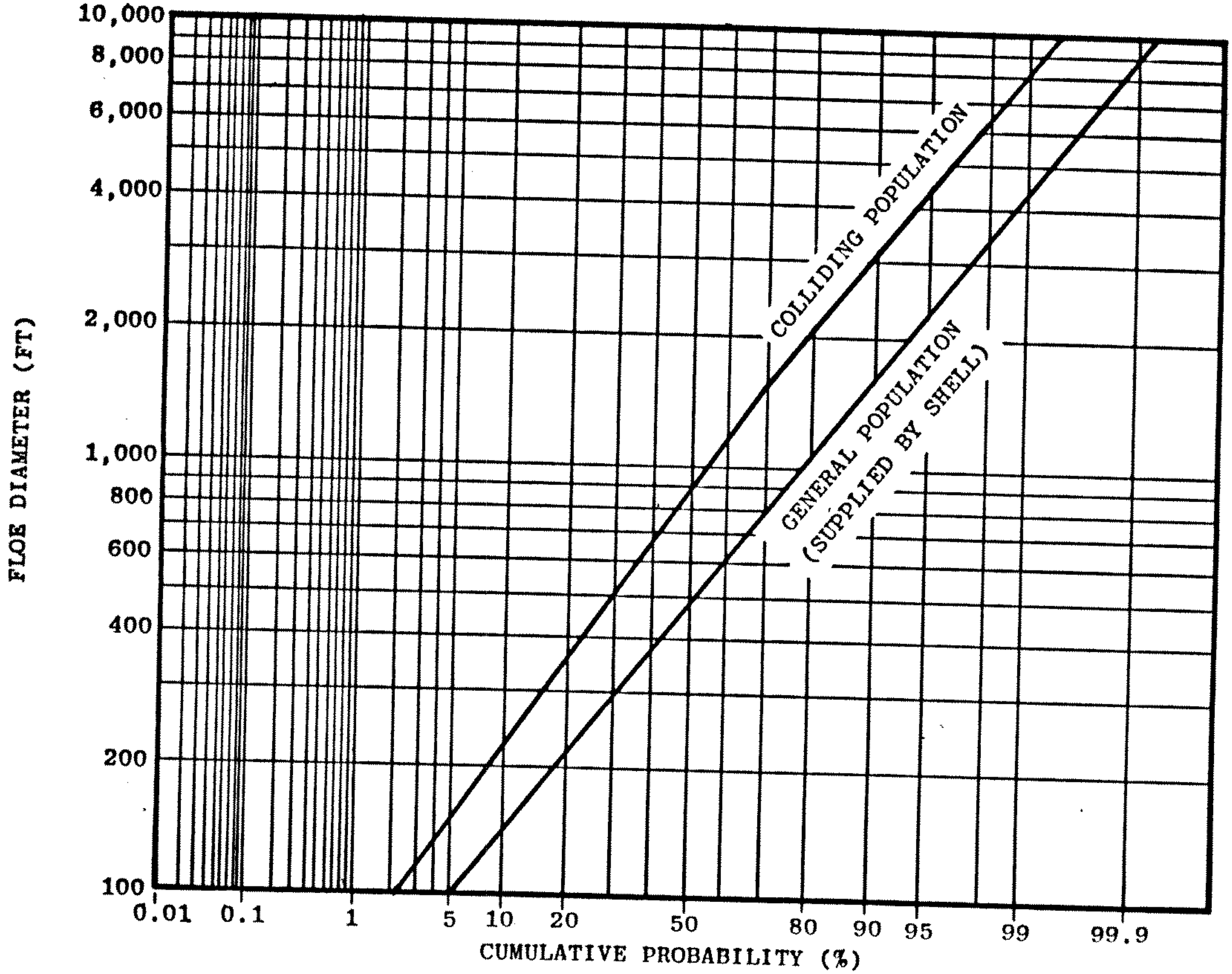


FIGURE 2.8 DISTRIBUTION OF MULTIYEAR FLOE DIAMETER

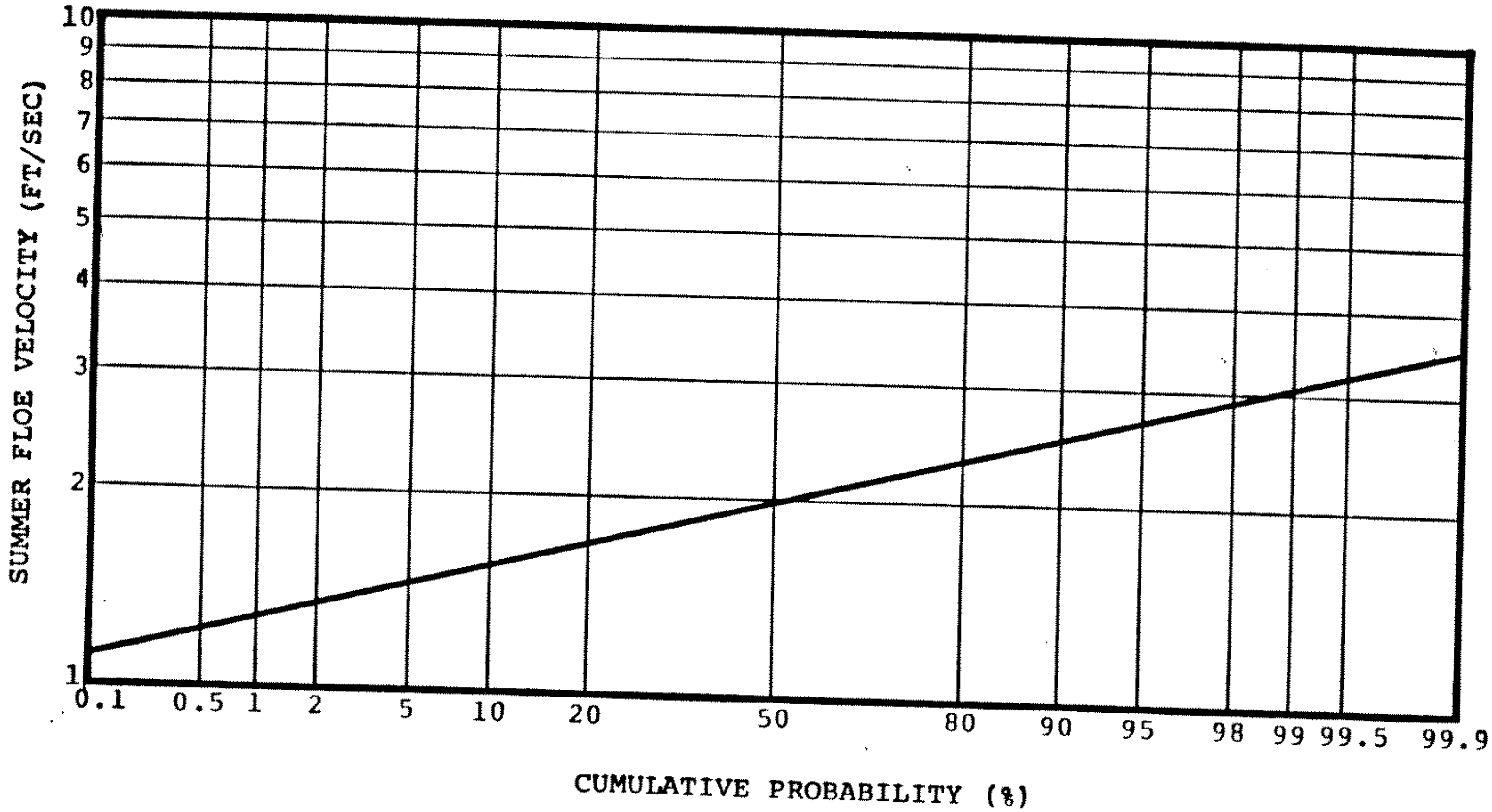


FIGURE 2.9 DISTRIBUTION OF SUMMER FLOE VELOCITY

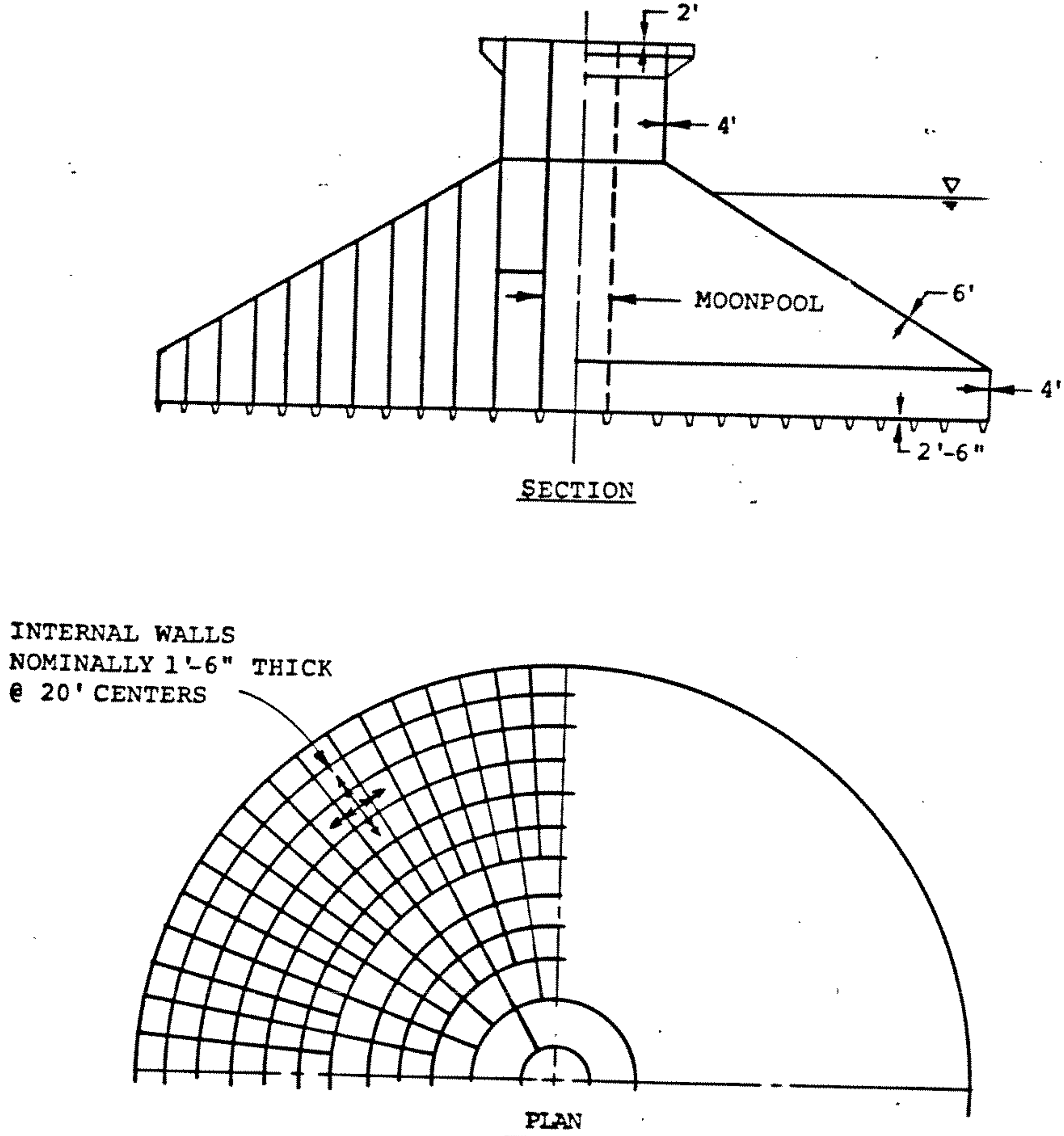


FIGURE 4.1 TYPICAL STRUCTURAL ARRANGEMENT OF CONE

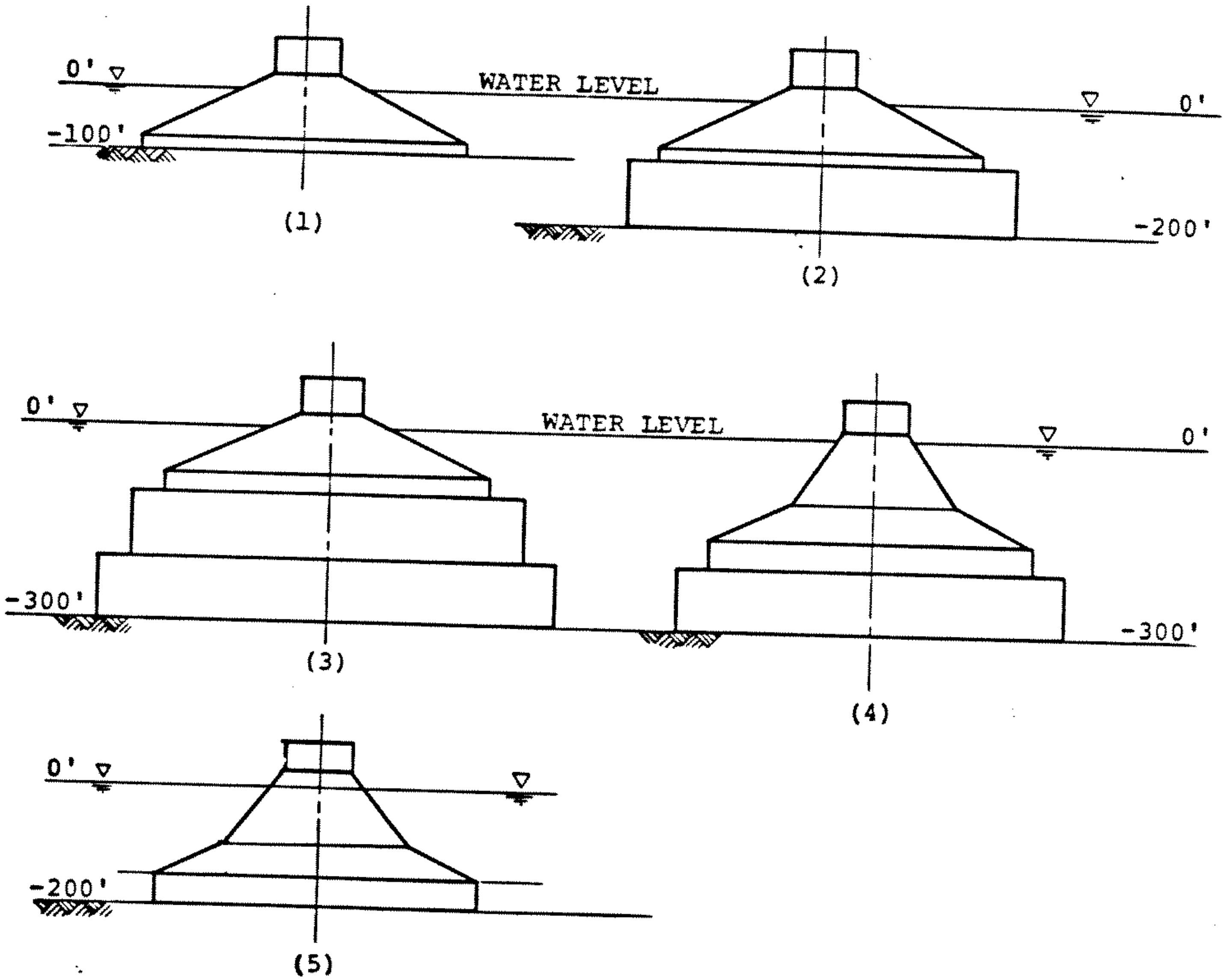


FIGURE 4.2 SCHEMATIC REPRESENTATION OF THE USE OF SUB-BASES WITH CONE STRUCTURES

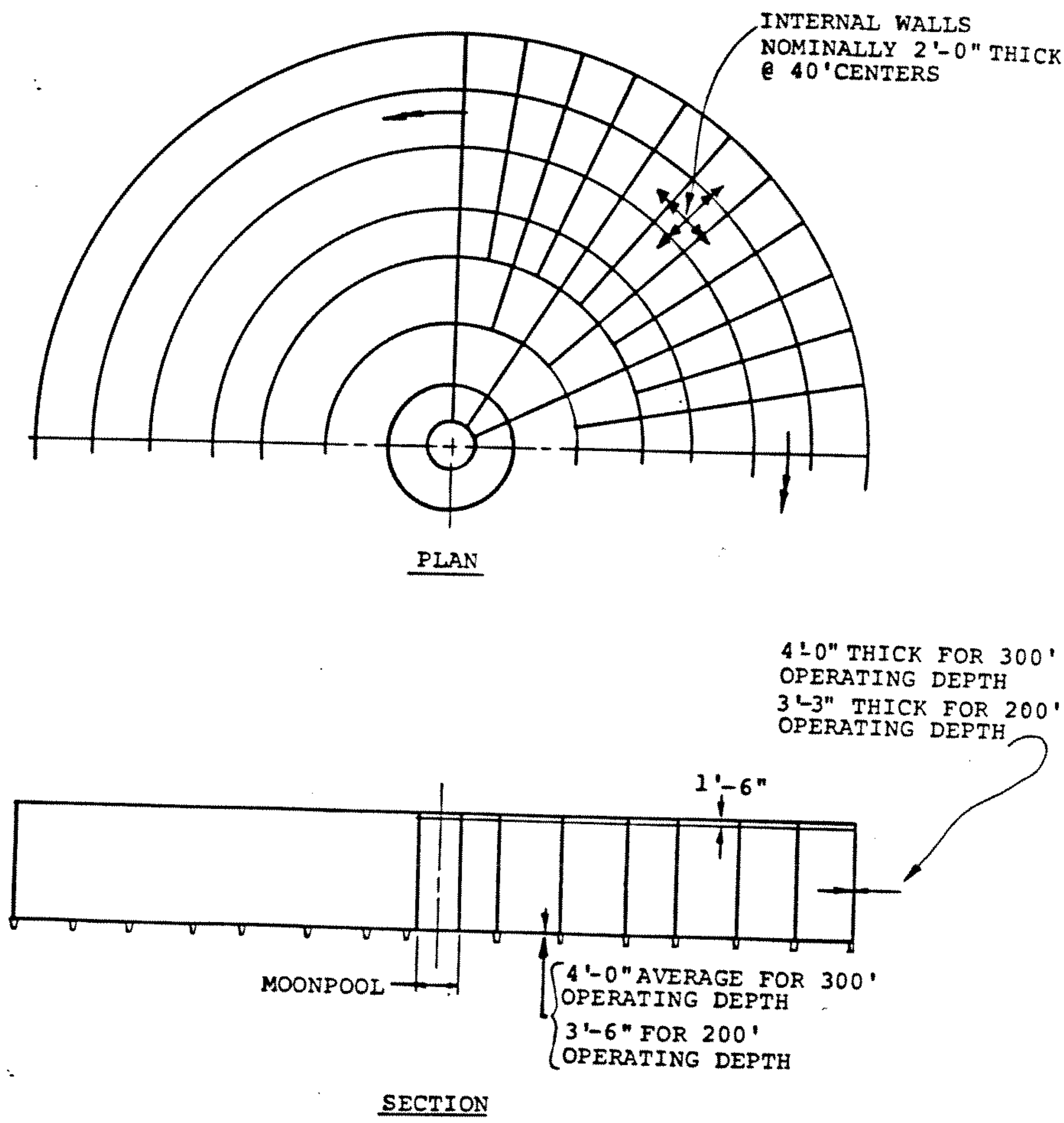


FIGURE 4.3 TYPICAL STRUCTURAL ARRANGEMENT OF SUB-BASE

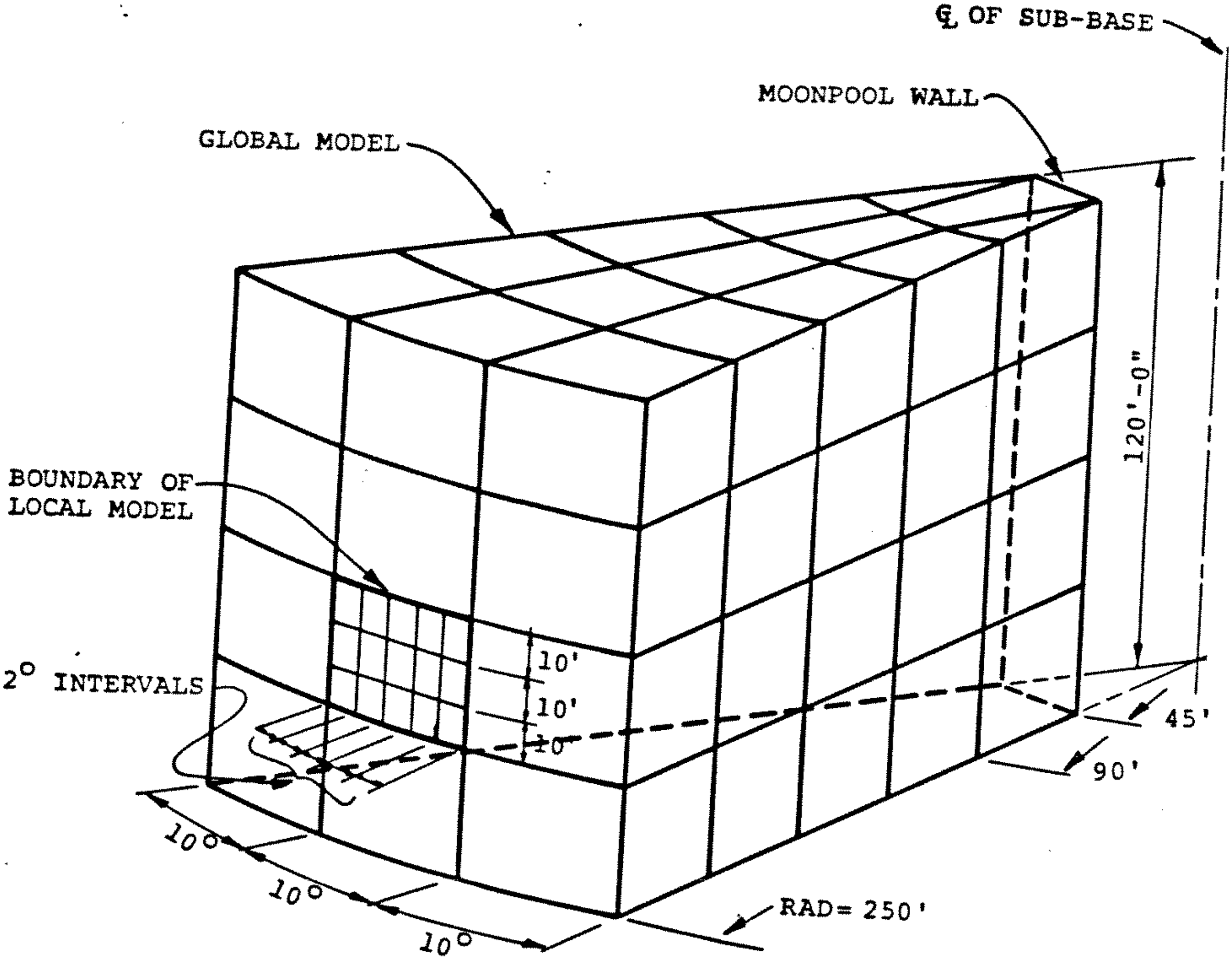


FIGURE 4.4 GLOBAL AND LOCAL MODELS FOR STRUCTURAL ANALYSIS OF SUB-BASE

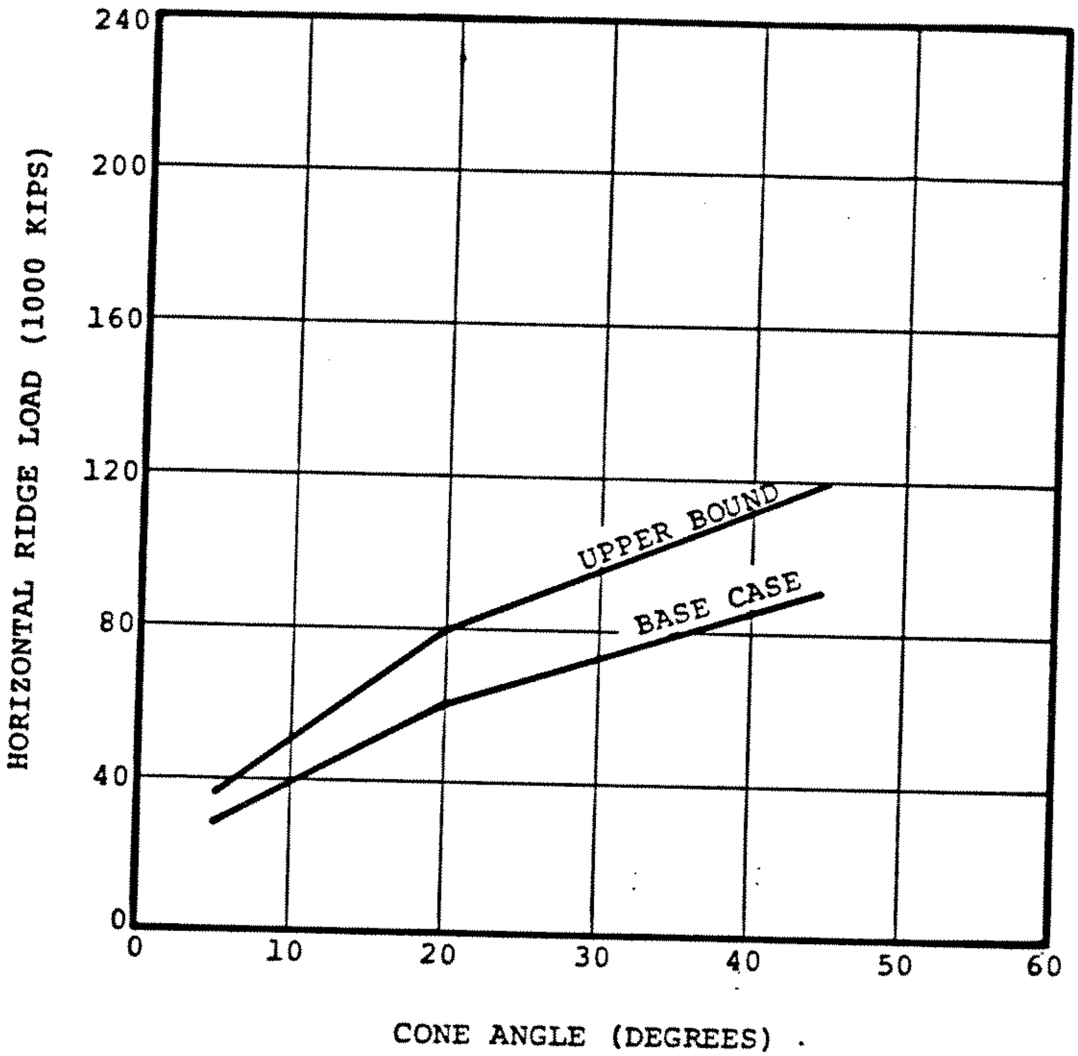
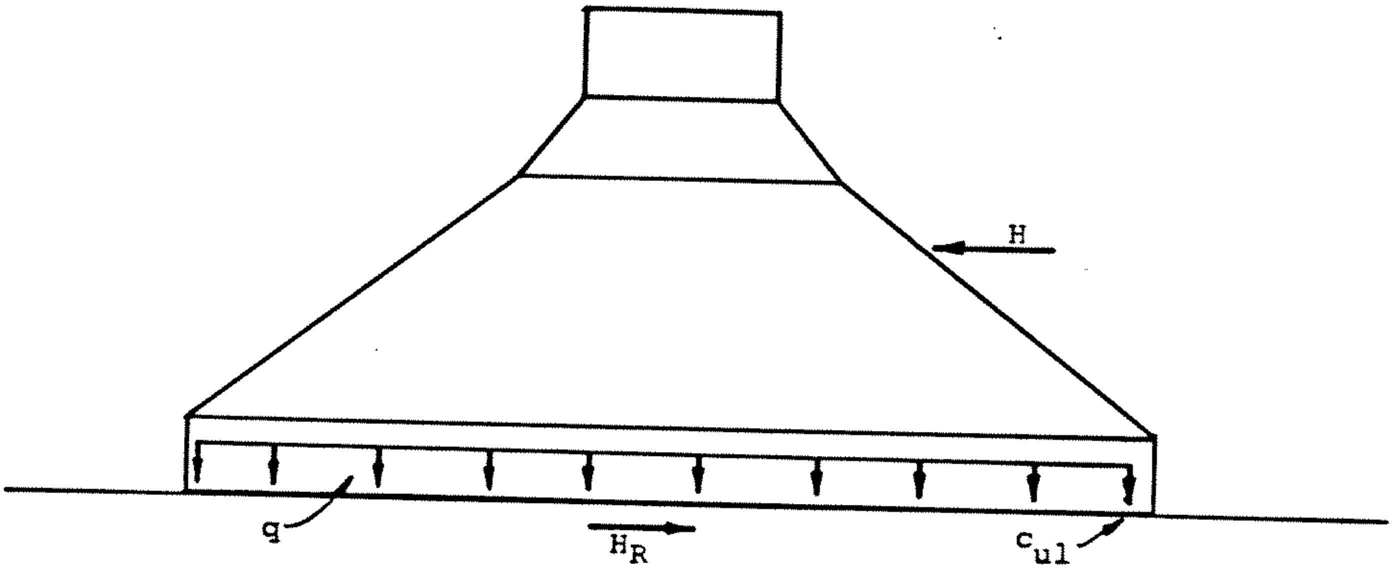


FIGURE 4.5 EXPLORATION ICE LOADS ON CONICAL STRUCTURES



$$H_R = c_{u1} \times \text{BASE AREA}$$

$$\text{F.S.} = H_R/H$$

FIGURE 4.6 SLIDING AT THE SKIRT TIP ON COHESIVE SOIL SITES

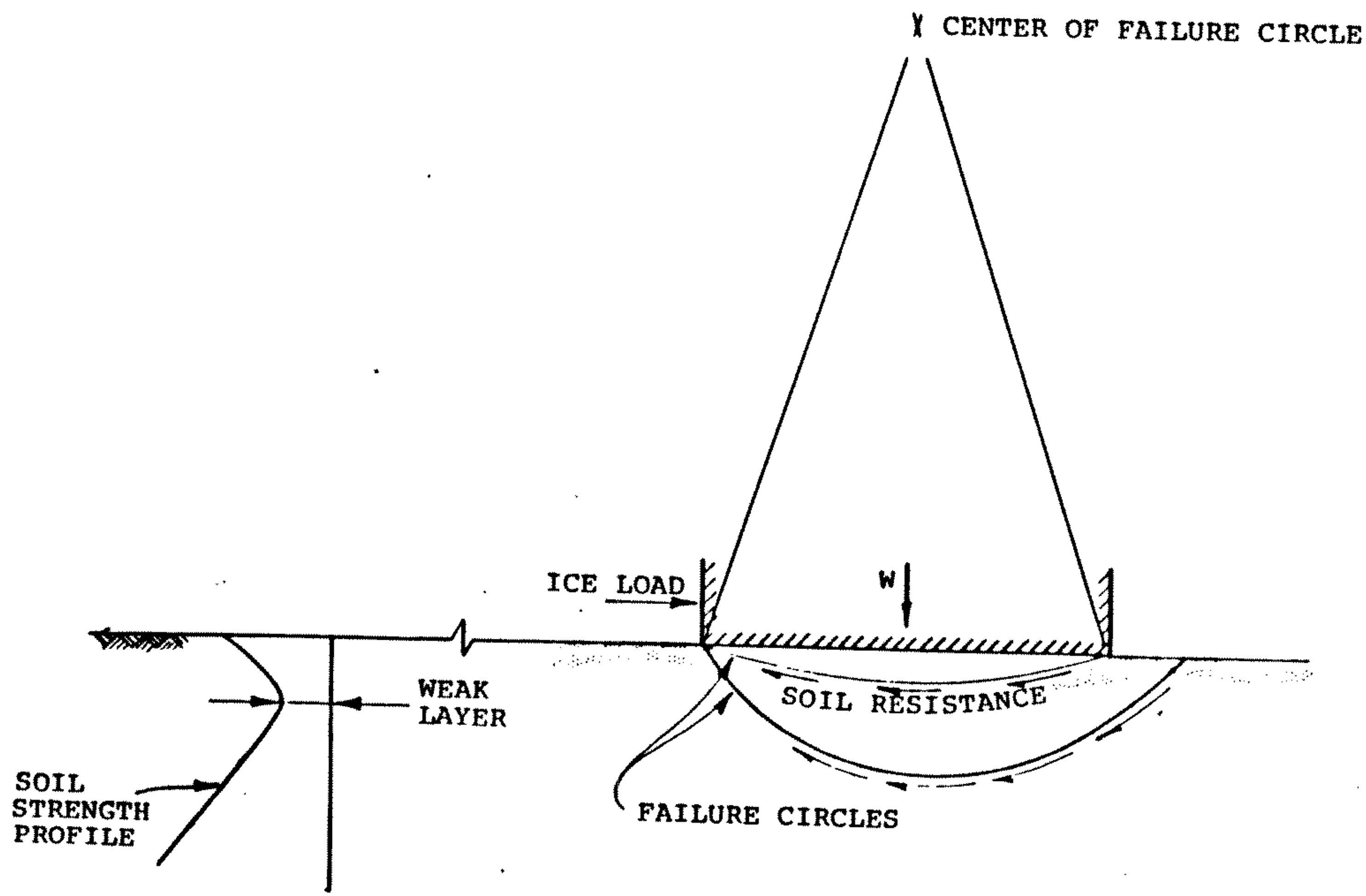


FIGURE 4.7 SHALLOW ROTATIONAL FAILURE MODE AND THE STABILITY PREDICTION METHOD ON COHESIVE SOIL SITES

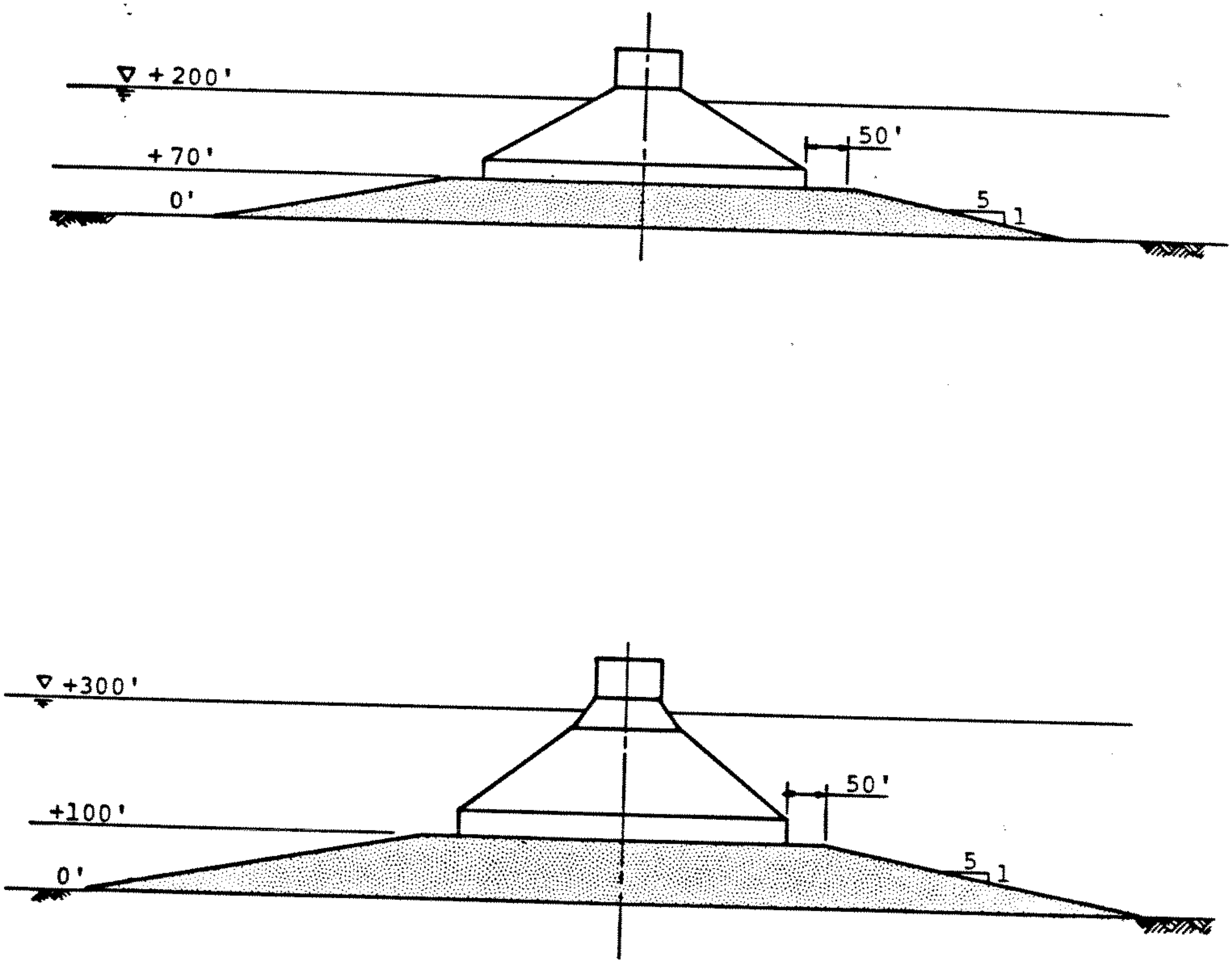
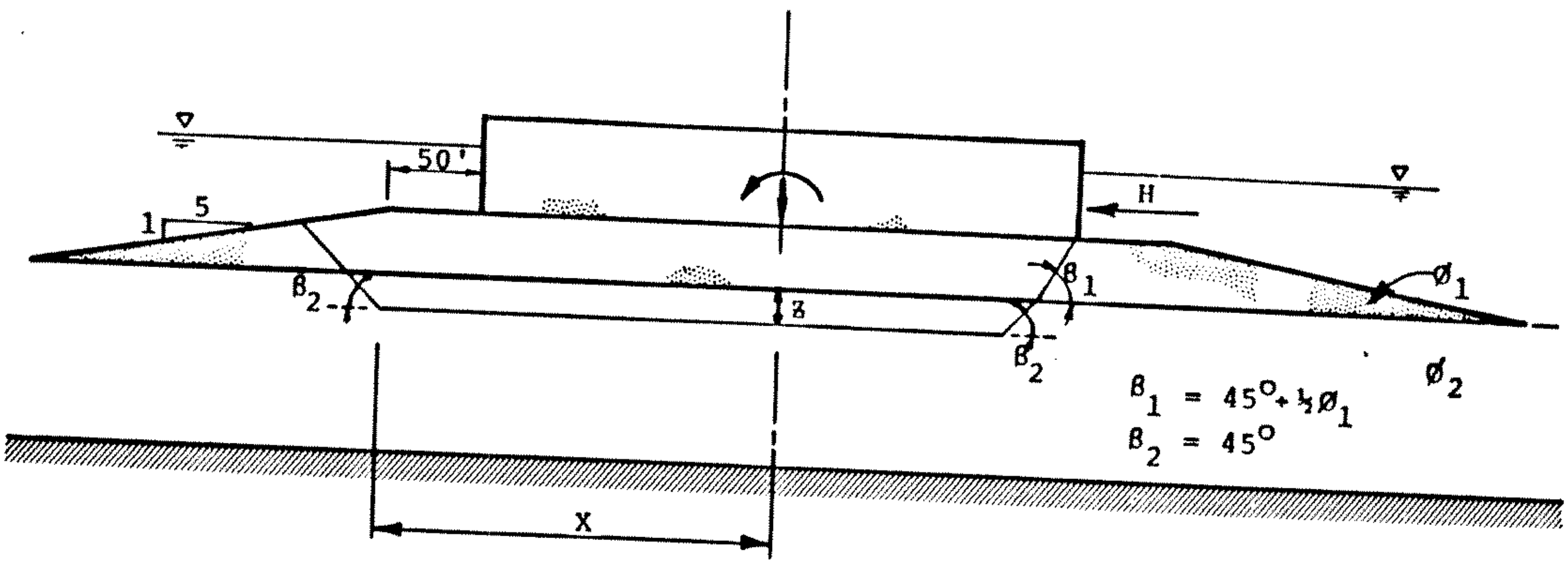
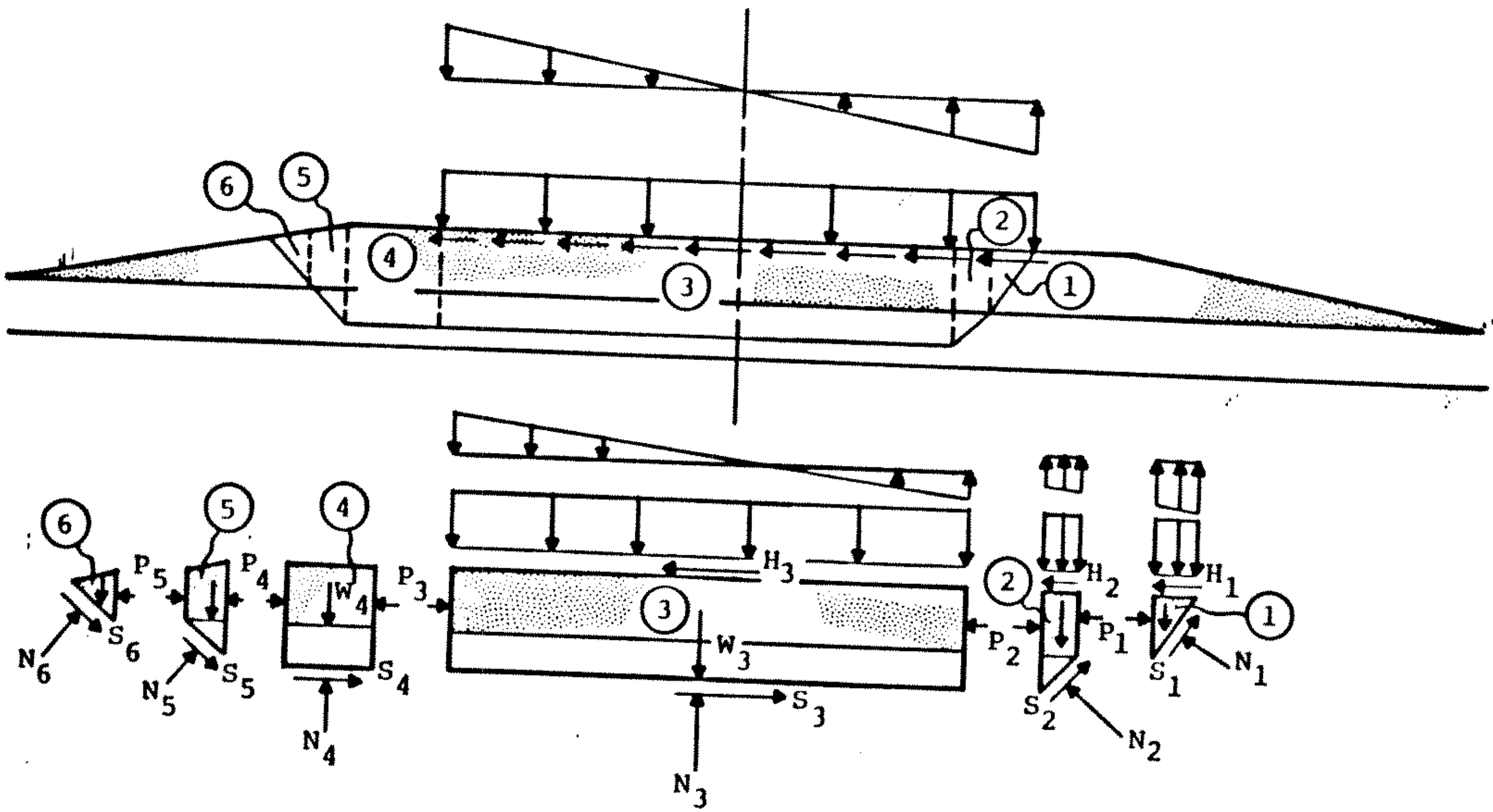


FIGURE 4.8 SCHEMATIC REPRESENTATION OF BERM OPTIONS WITH CONES



CHECK STABILITY FOR VARIOUS VALUES OF β AND X, AND DETERMINE CRITICAL SURFACE

FIGURE 4.9 SLIDING STABILITY OF BERM-STRUCTURE SYSTEM ON COHESIVE SOIL SITES



FOR EACH BLOCK: $\Sigma F_x = 0$, $\Sigma F_y = 0$ } FROM EQUILIBRIUM DETERMINE MAXIMUM ALLOWABLE HORIZONTAL LOAD AND MOMENT.

ALSO CONSIDER SIDE FRICTION RESISTANCE.

FIGURE 4.10 METHOD OF ANALYSIS FOR SLIDING STABILITY OF BERM-STRUCTURE SYSTEM ON COHESIVE SOIL SITES

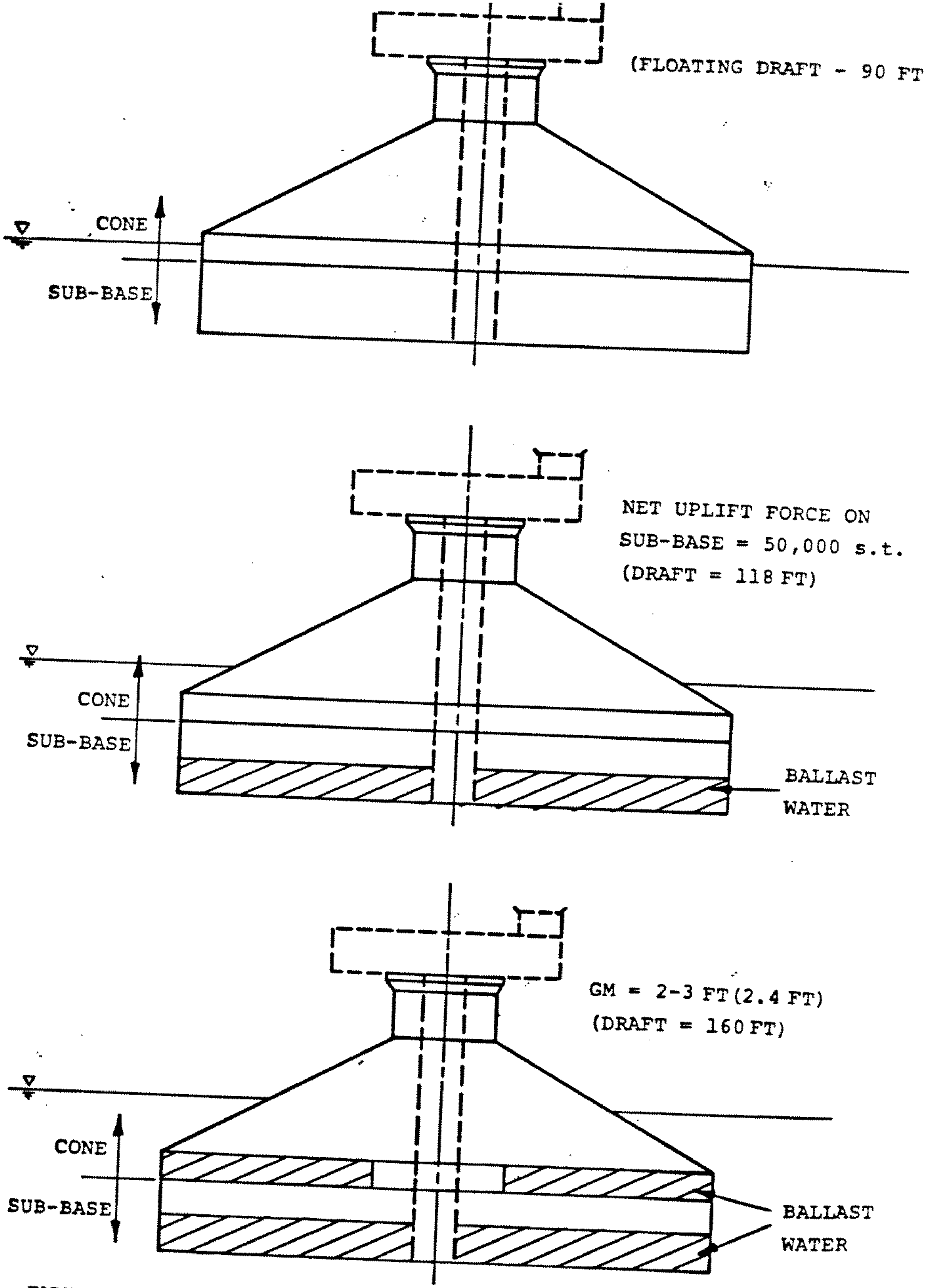
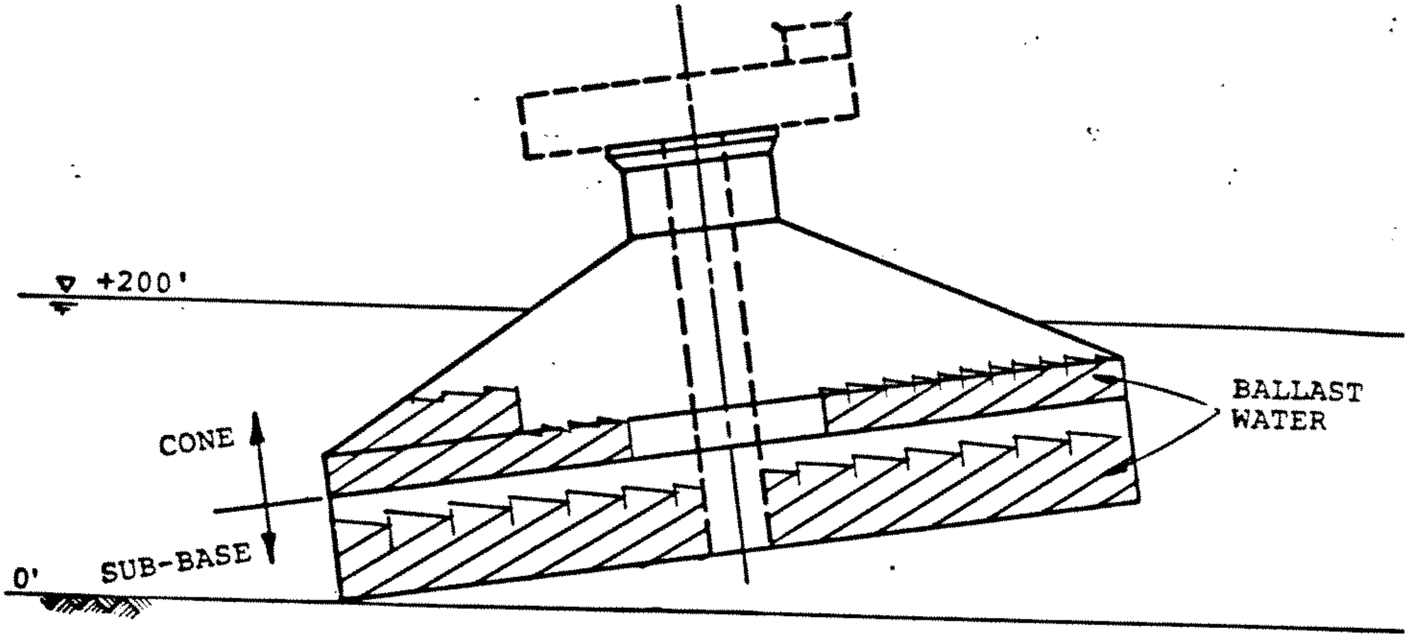


FIGURE 4.11 BALLASTING PROCEDURE FOR EXPLORATION CONES - SH. 1



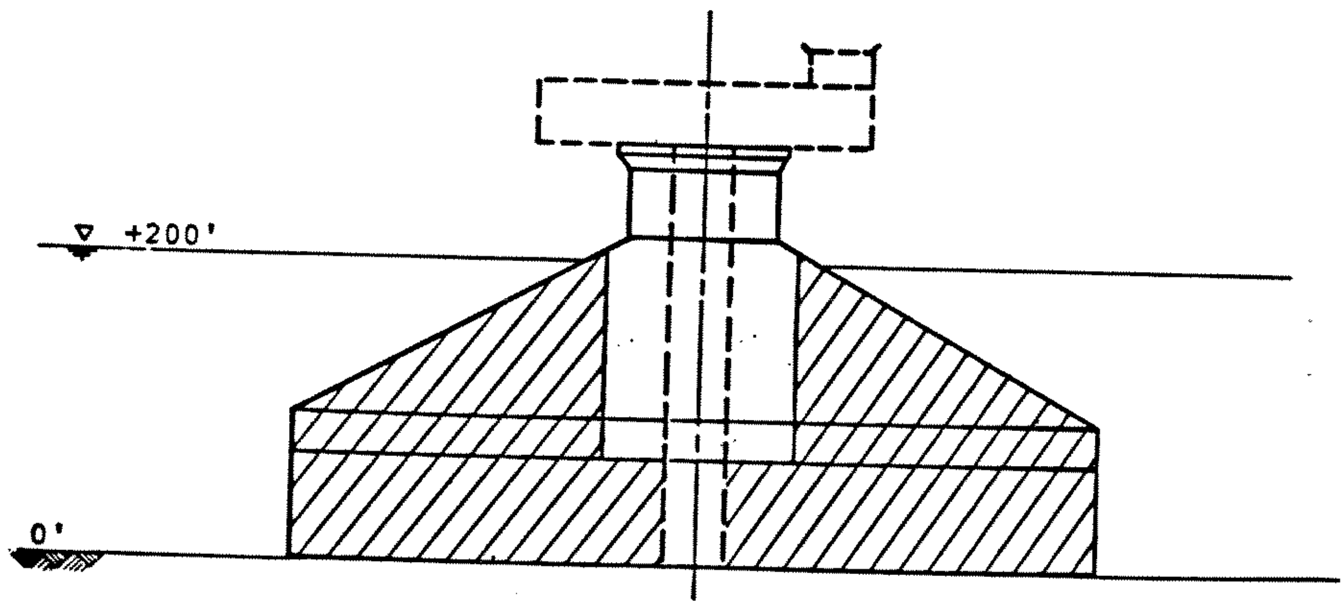


FIGURE 4.12 BALLASTING PROCEDURE FOR EXPLORATION CONES (CONT'D)

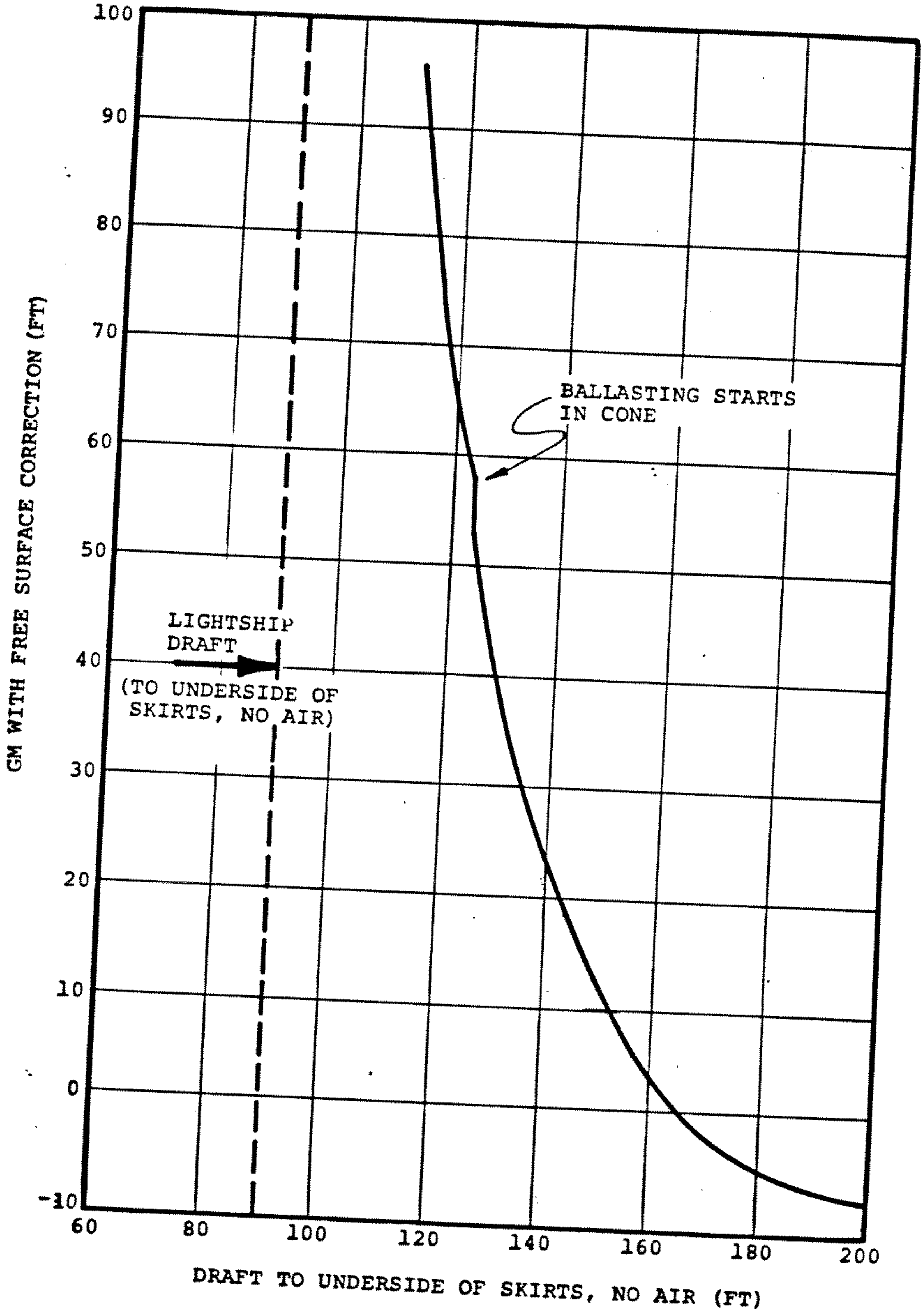
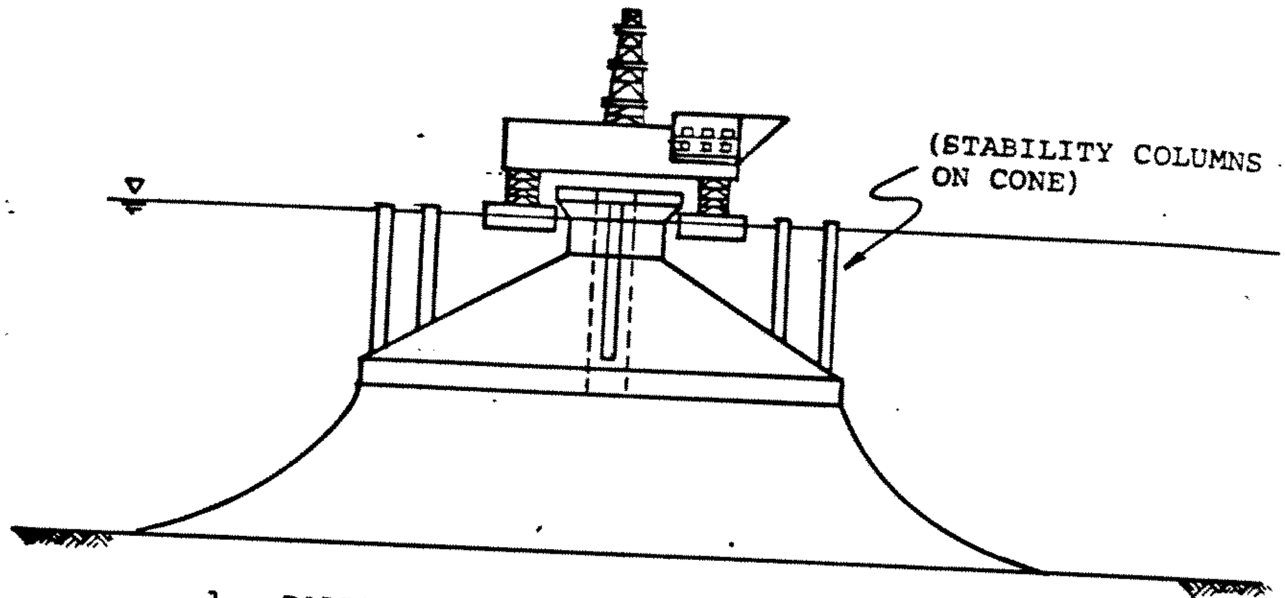
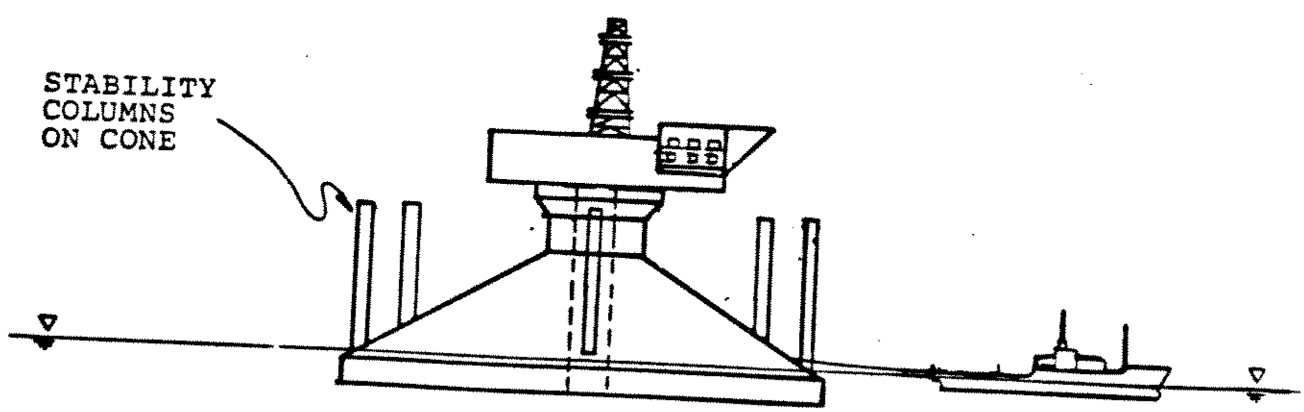


FIGURE 4.13 GM CURVE FOR SHALLOW CONE (EXPLORATION) +70 FT SUB-BASE (DECK WT INCLUDED)



1. BALLAST CONE.FLOAT IN DECK AND TOPSIDES SUPPORTED ON BARGES AND POSITION ABOVE CONE.



2. DEBALLAST CONE AND MATE WITH DECK. REMOVE DECK SUPPORT BARGES, COMPLETE HOOKUP AND DEBALLAST TO TOWING DRAFT.

FIGURE 4.14 <u>DECK MATING PROCEDURE</u>

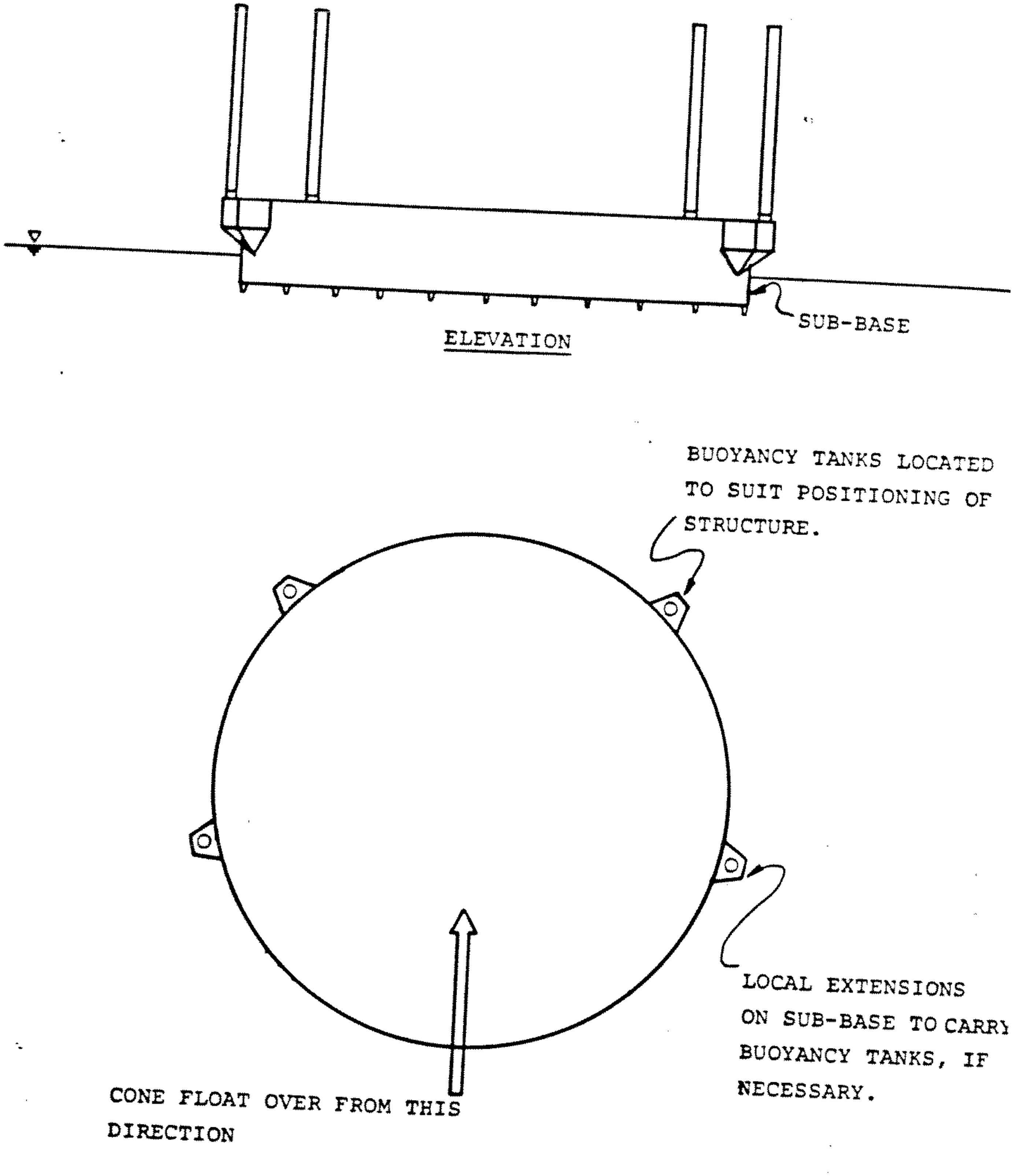


FIGURE 4.15 BUOYANCY TANKS ON SUB-BASE FOR CONE MATING

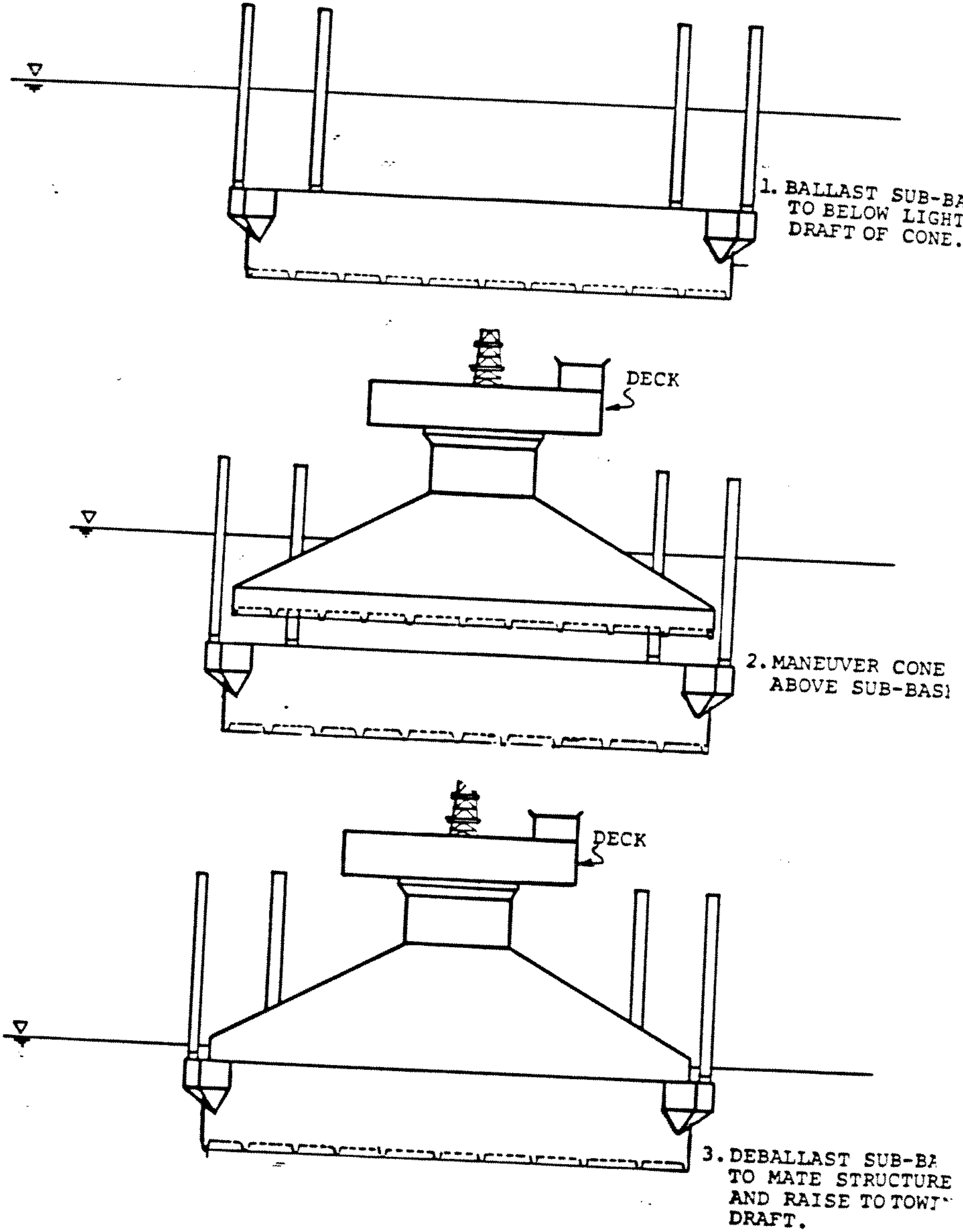


FIGURE 4.16 MATING OPERATIONS FOR CONE AND SUB-BASE

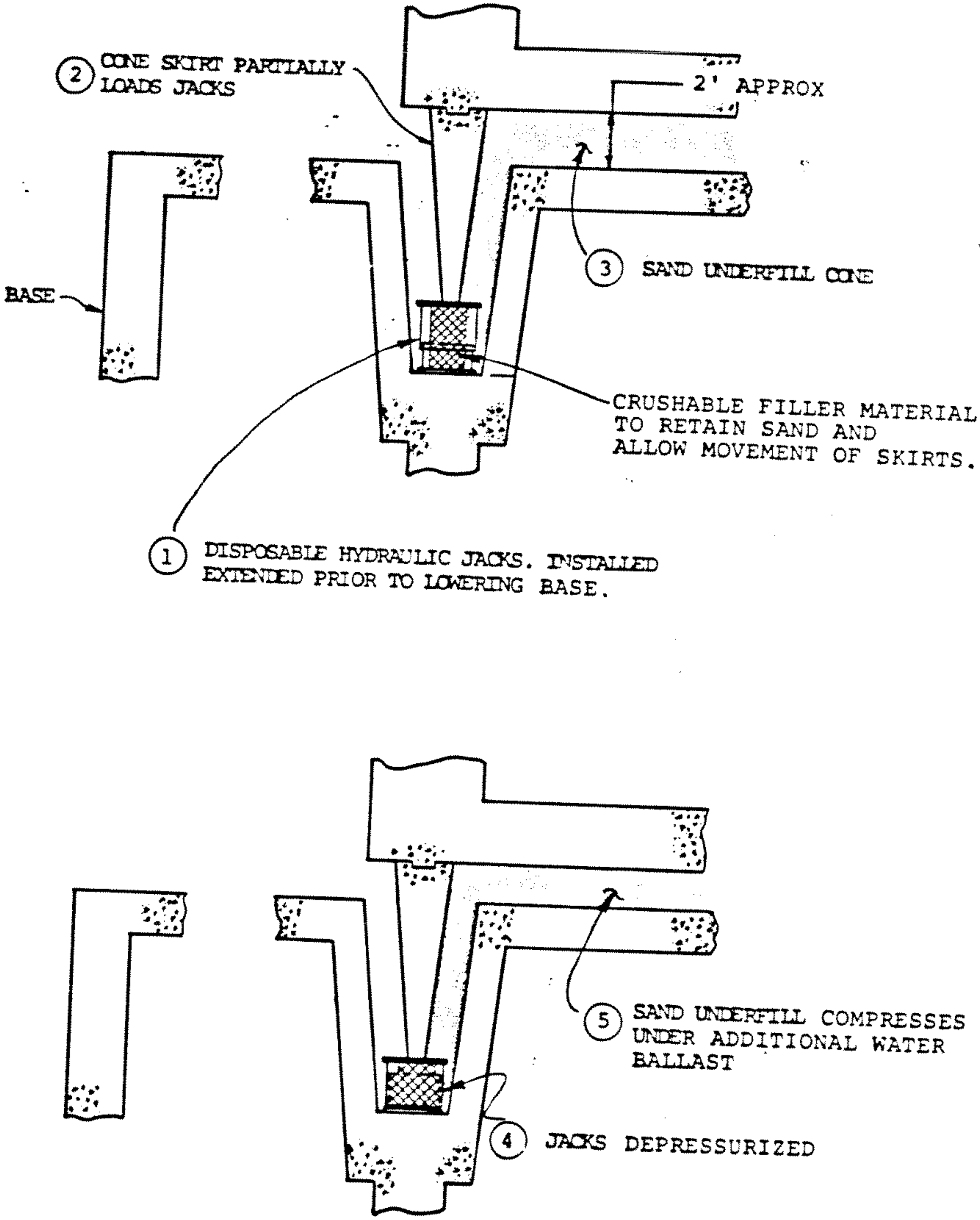
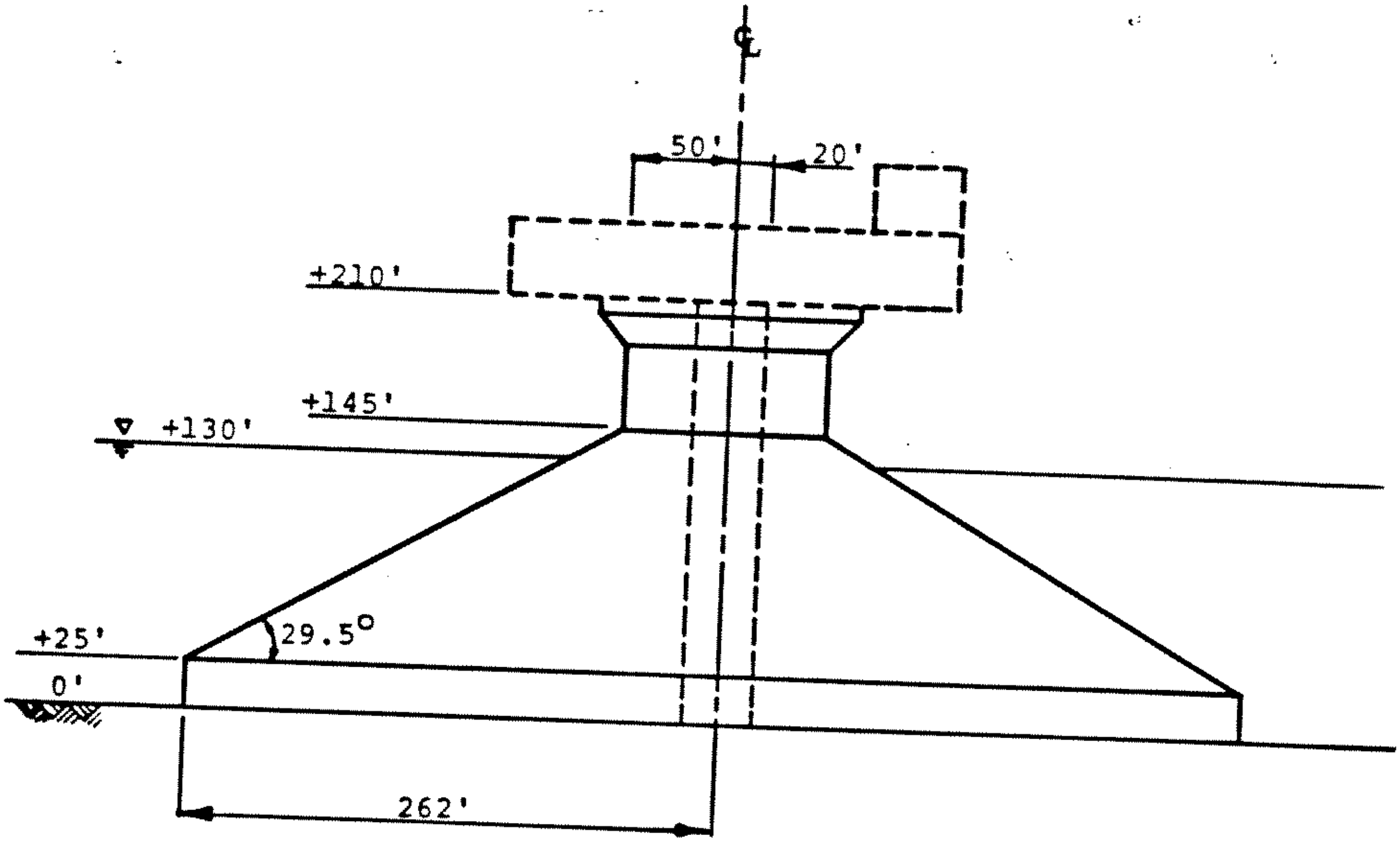
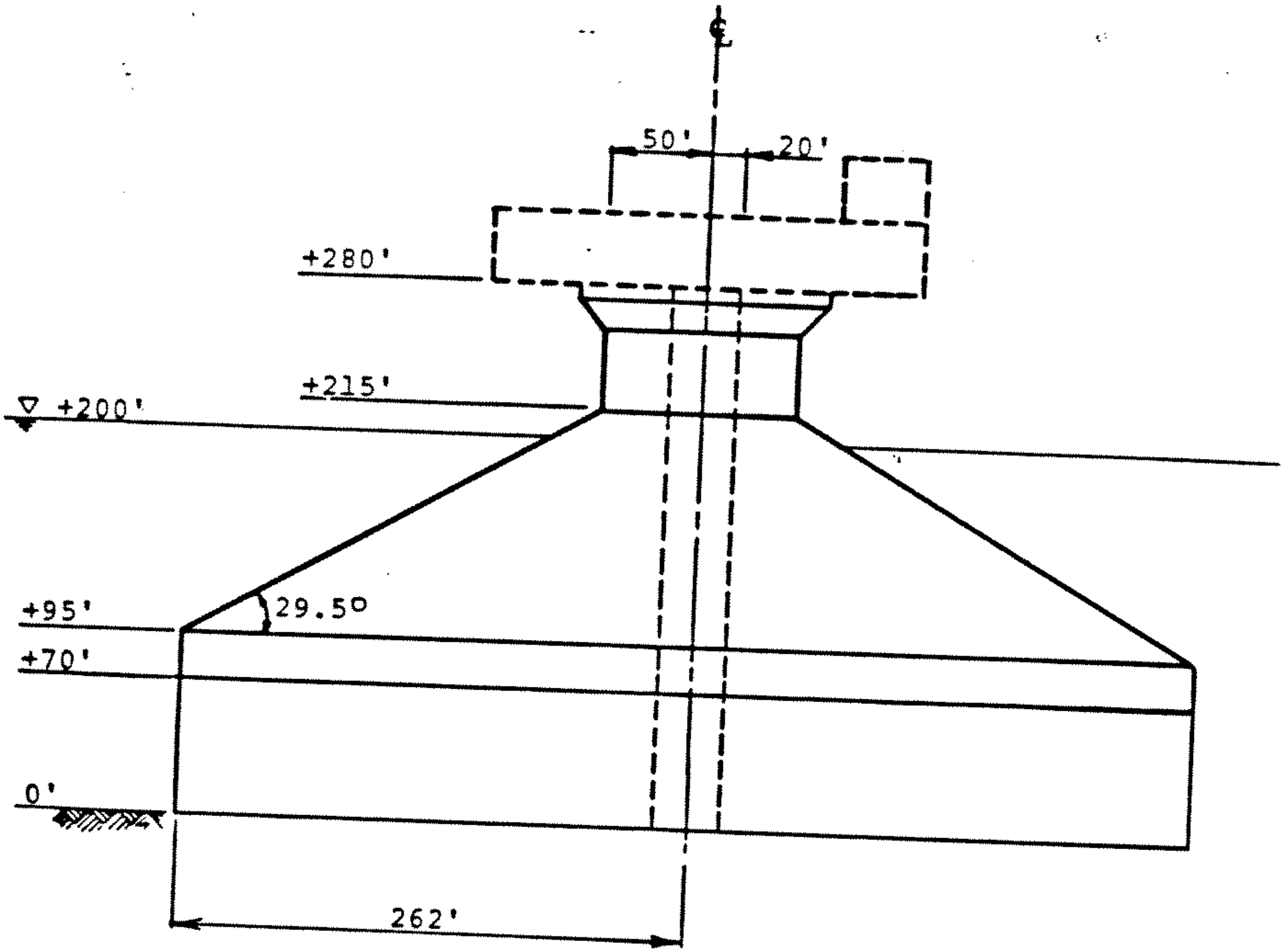


FIGURE 4.17 STAGES IN MAKING CONE TO SUB-BASE INTERFACE CONNECTION



CONC. WEIGHT: 348×10^3 s.t.
DRAFT (TO U/S BASE SLAB): 59'
STABLE UP TO: 104'
(TIPPING ANGLE TO 130' = 5.7°)

FIGURE 4.18 EXPLORATION CONES - SYSTEM 1: SHALLOW CONE (WORKING RANGE 60 FT - 130 FT; BASE ICE LOAD, CLAY, c_u = 0.6 KSF)



COMBINED STRUCTURE*

CONC. WEIGHT: 561 x 10^3 s.t

DRAFT (TO U/S BASE SLAB): 83'

STABLE UP TO: 154'

(TIPPING ANGLE TO 200' = 10.0°)

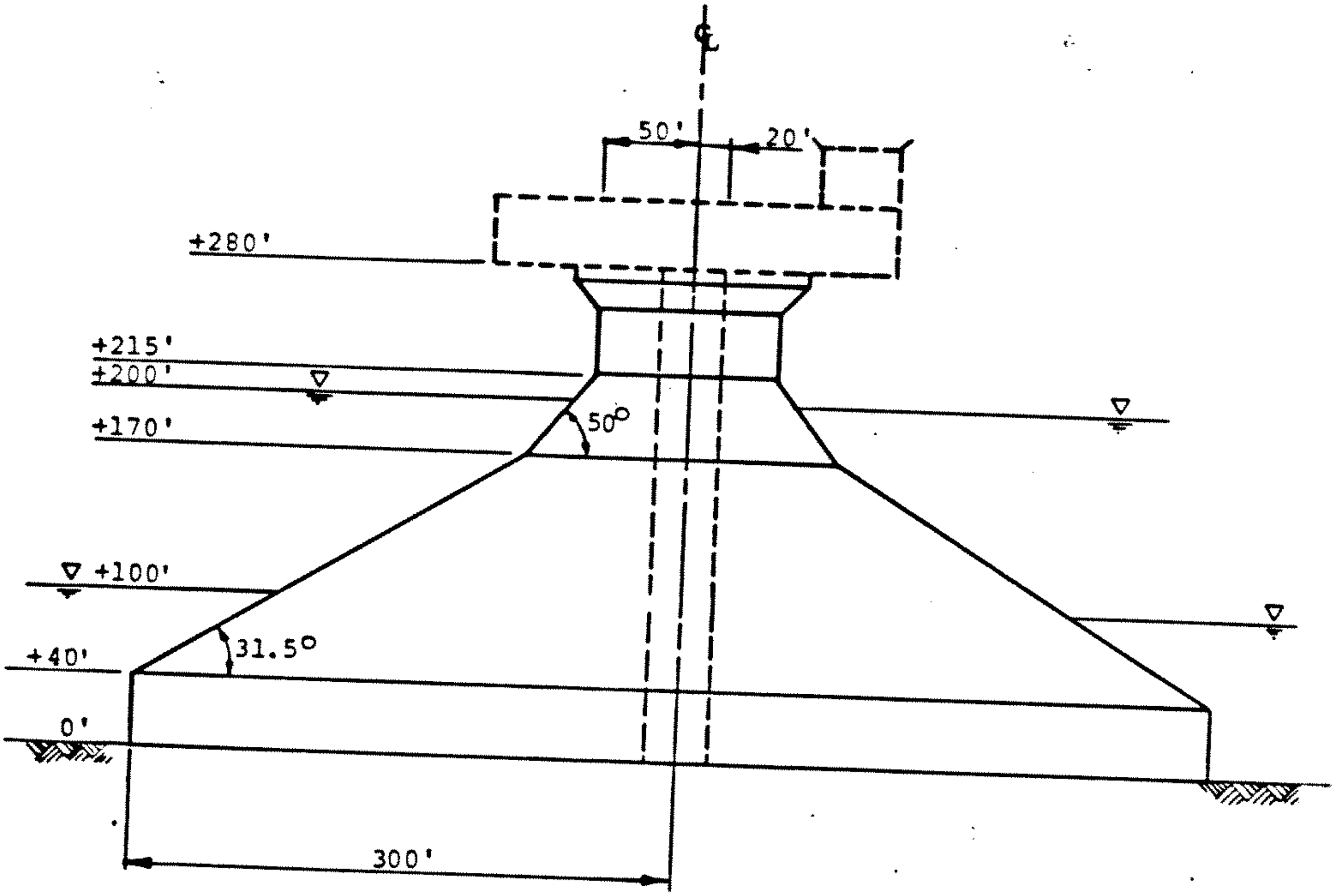
*WORKING RANGE 130'-200'

SEPARATED SUB-BASE

CONC WEIGHT: 213 x 10^3 s.t.

DRAFT: 31'

FIGURE 4.19 EXPLORATION CONES - SYSTEM 1: SHALLOW CONE AND SUB-BASE (WORKING RANGE 60 FT - 200 FT; BASE ICE LOAD; CLAY, c_u = 0.6 KSF



CONC. WEIGHT: 548 x 10^3 s.t.
DRAFT (TO U/S BASE SLAB): 65'
ALWAYS STABLE (MIN GM = 2.95'
@ 170' DRAFT)

FIGURE 4.20 EXPLORATION CONES - SYSTEM 2: DEEP CONE (WORKING RANGE 120 FT - 200 FT; BASE ICE LOAD, CLAY, c_u = 0.6 KSF)

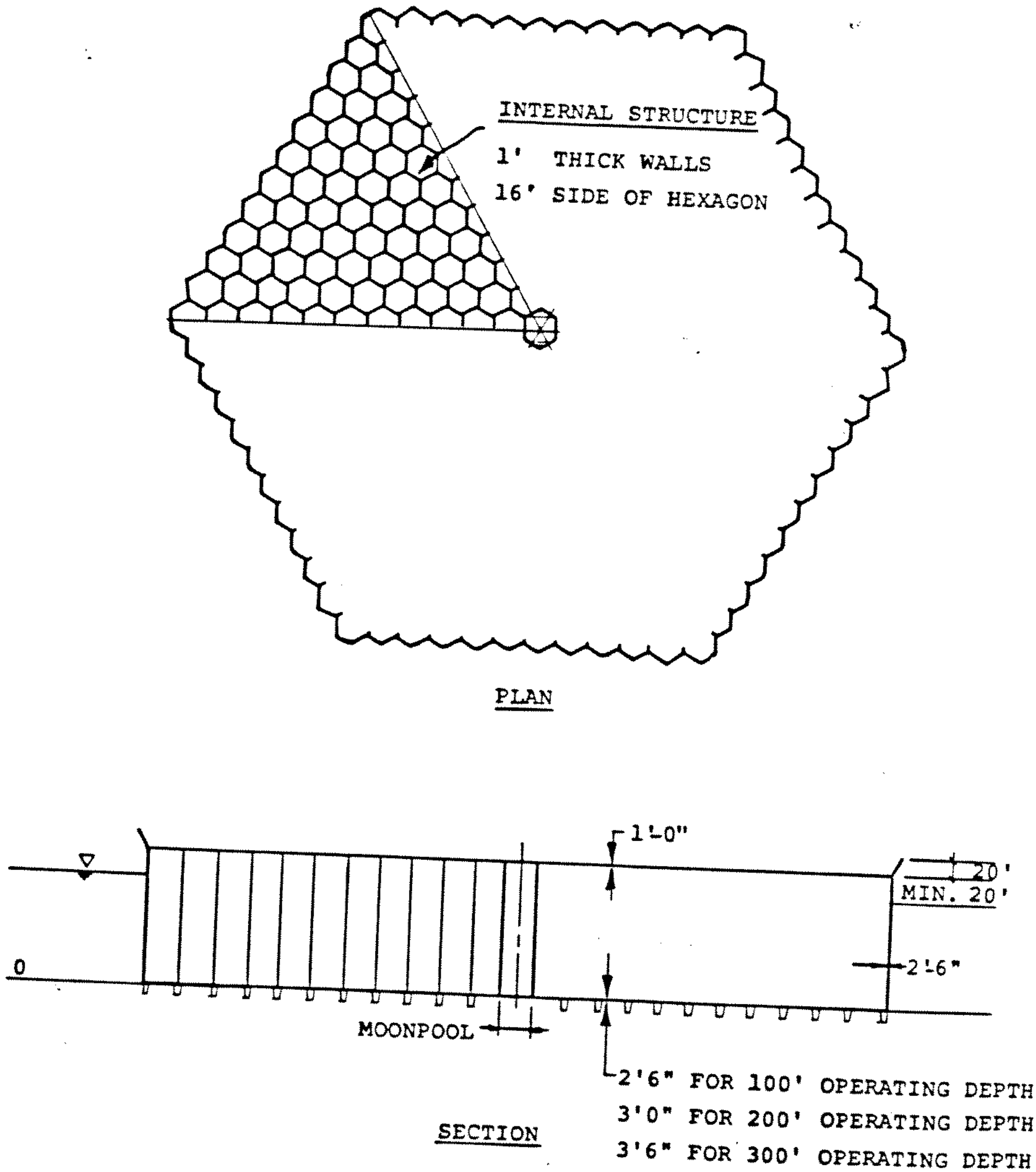


FIGURE 4.21 TYPICAL STRUCTURAL ARRANGEMENT OF EXPLORATION MONOLITHIC CAISSON

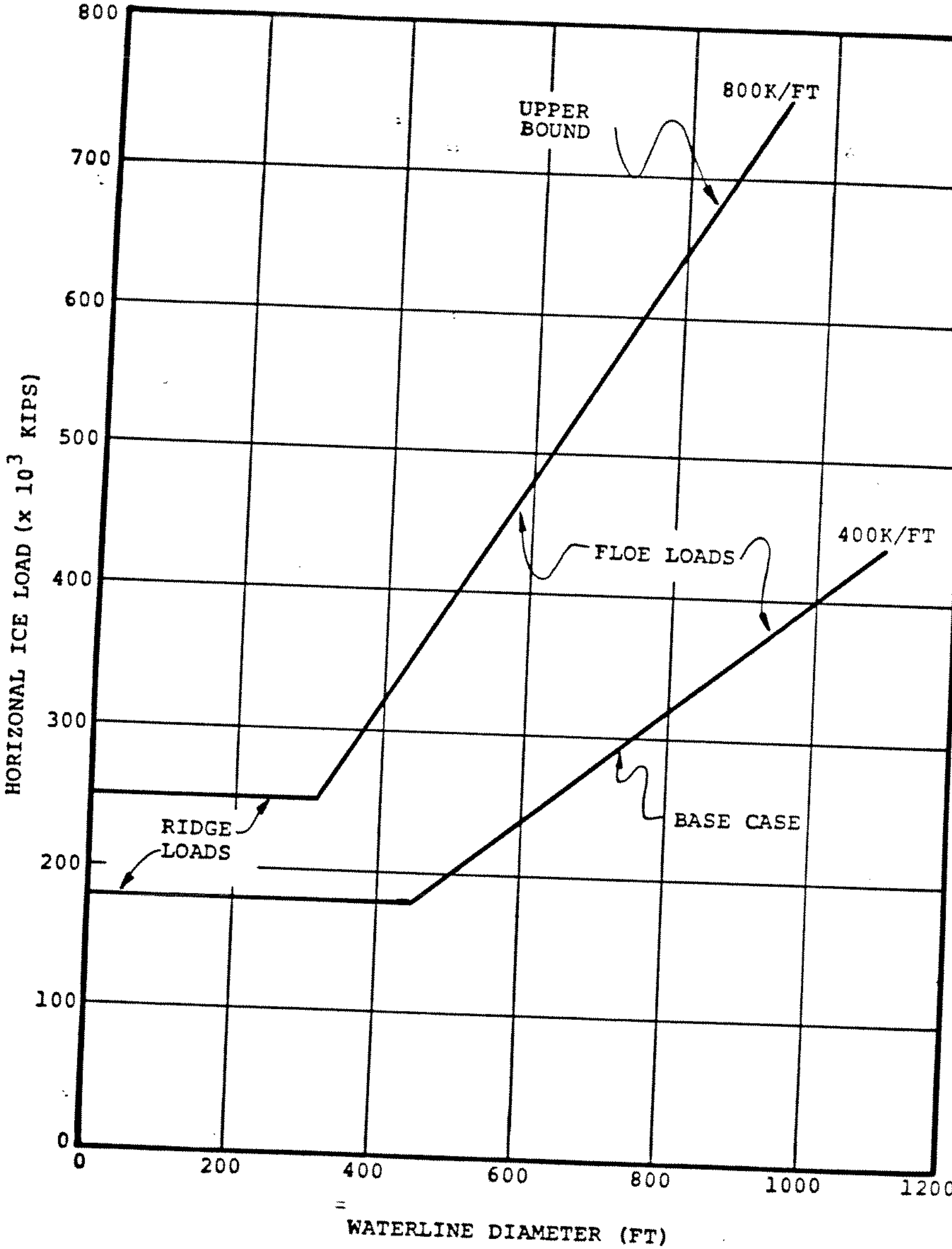
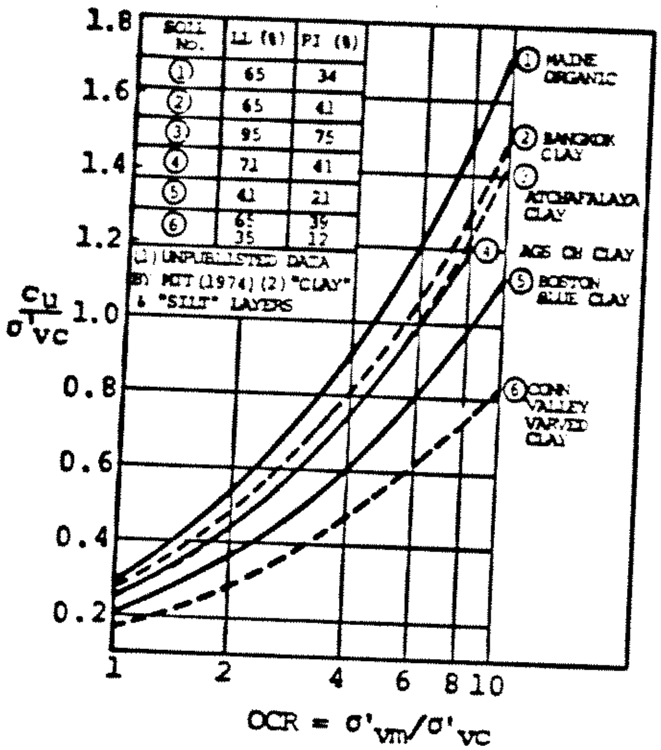
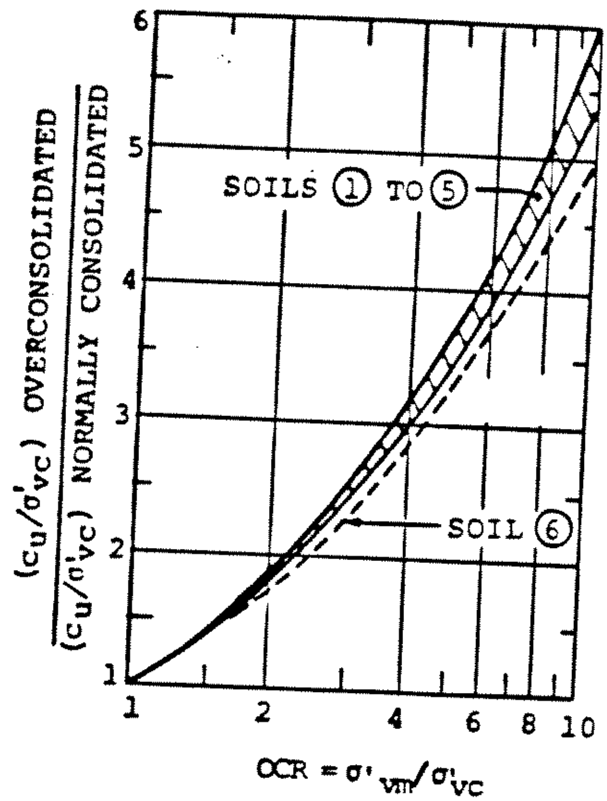


FIGURE 4.22 EXPLORATION ICE LOADS ON MONOLITHIC CAISSONS



Undrained strength ratio vs OCR from CK_oU direct simple shear tests on six clays



Relative increase in undrained strength ratio with OCR from CK_oU direct simple shear tests

$$\frac{(C_u/\sigma'_{vc})_{OC}}{(C_u/\sigma'_{vc})_{NC}} = OCR^m$$

$$(C_u/\sigma'_{vc})_{NC} = S$$

$$\Rightarrow \sigma'_{vm} = \left[\frac{C_u}{S\sigma'^{\,1-m}_{vc}}\right]^{1/m}$$

FIGURE 4.23 DETERMINATION OF MAXIMUM PAST PRESSURE (AFTER LADD AND EDGERS (5))

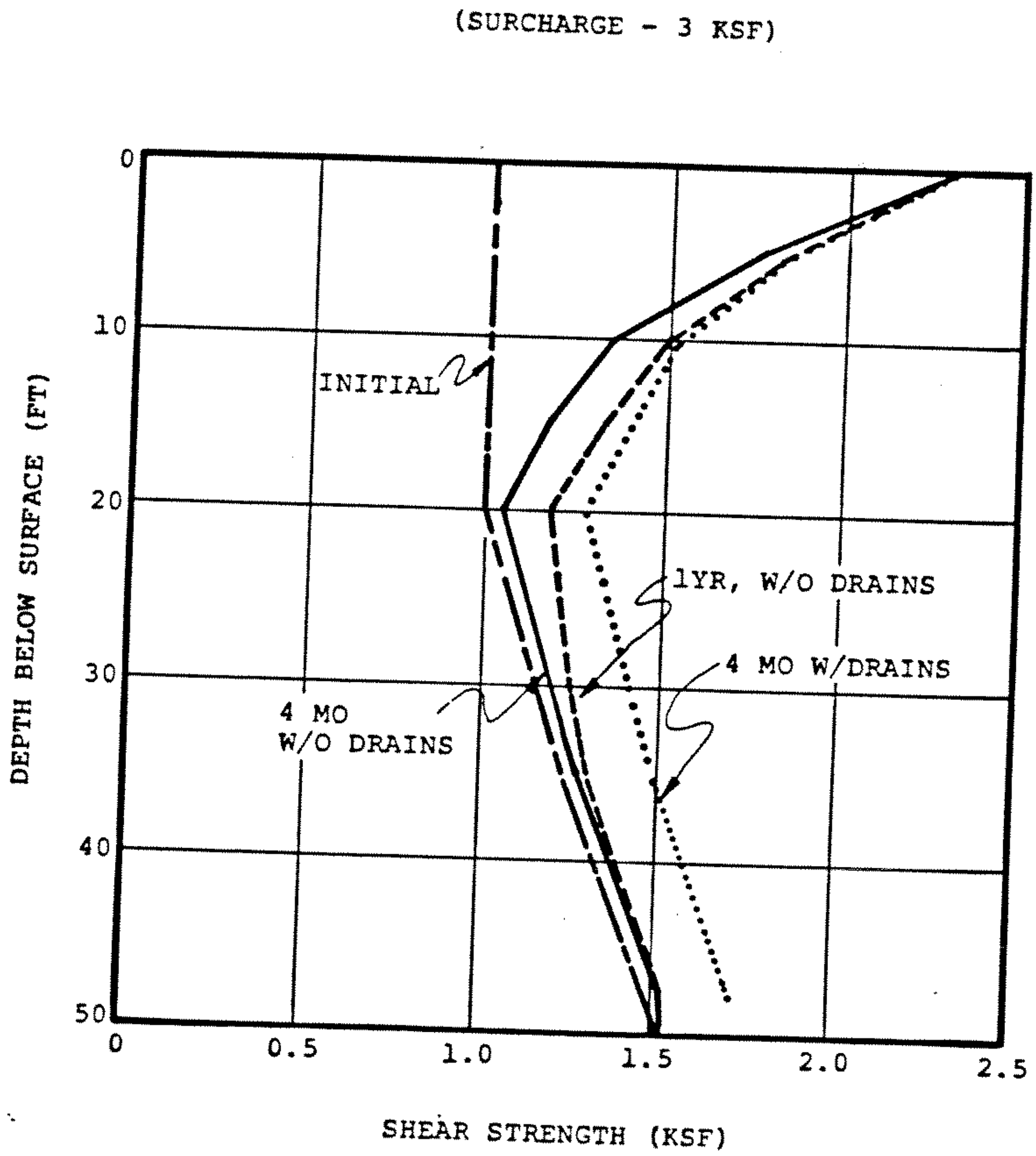
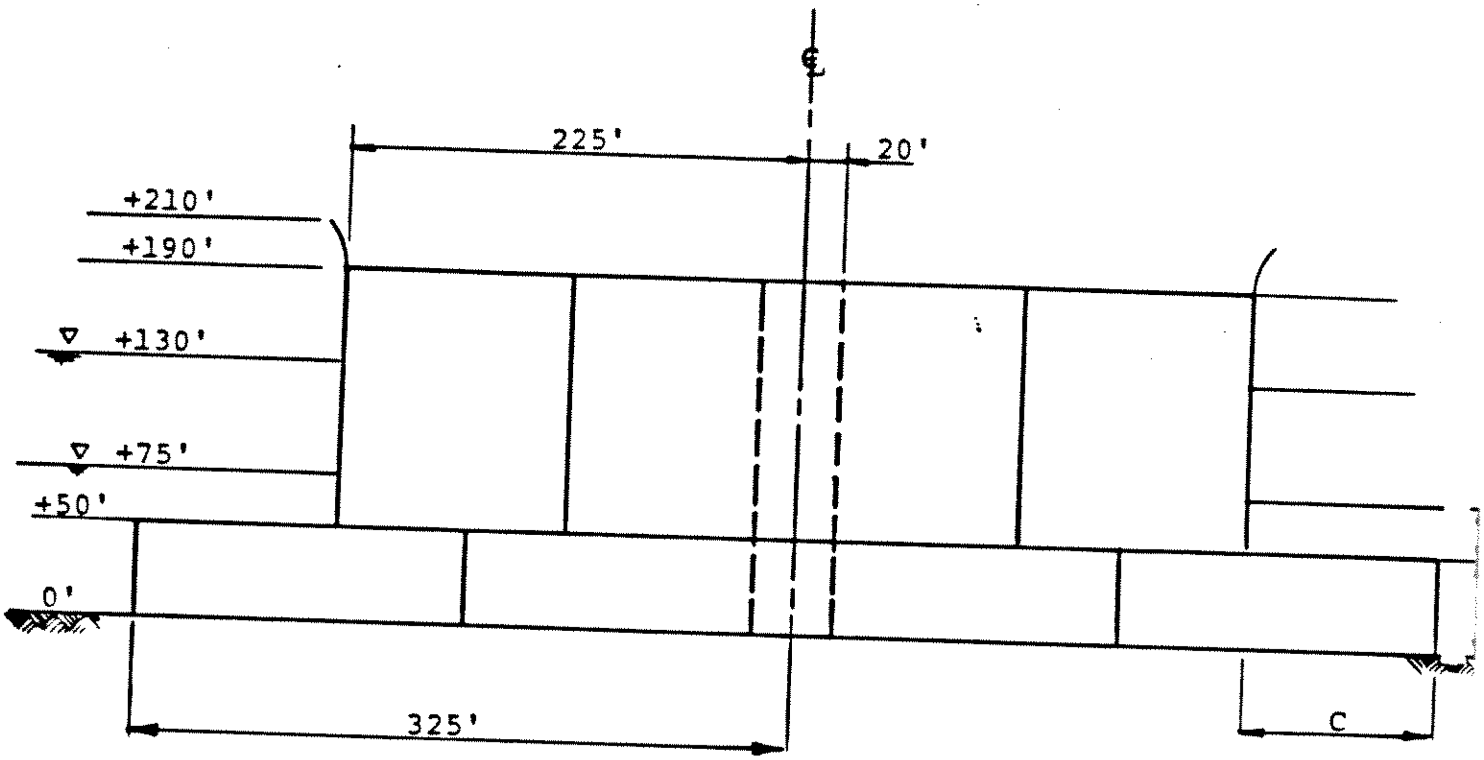


FIGURE 4.24 EXAMPLE OF STRENGTH GAIN IN COHESIVE SOILS USING WICK DRAINS



A = 25FT MIN. BELOW WATERLINE

C/B LIMITED TO 2 MAXIMUM FOR CANTILEVER RIGIDITY

CONC. WEIGHT: 323×10^3 s.t.
DRAFT (TO U/S BASE SLAB): 37'
NO. OF WICK DRAINS: 2400
FACTOR OF SAFETY ACHIEVED AFTER 4 MONTHS

FIGURE 4.25 EXPLORATION CAISSON (WORKING RANGE 75 FT - 130 FT; BASE ICE LOAD; CLAY, c_u = 0.6 KSF)

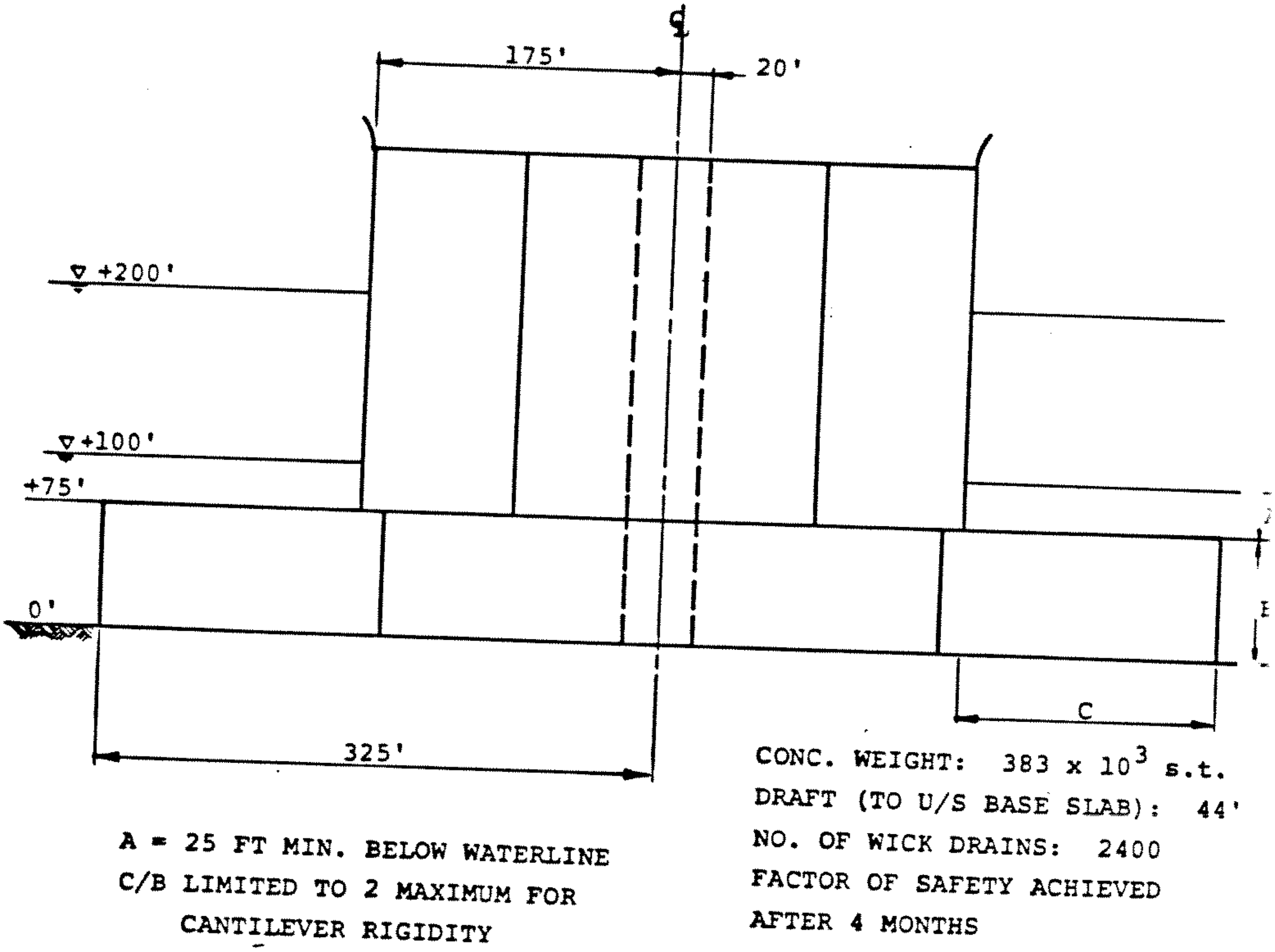


FIGURE 4.26 EXPLORATION CAISSON (WORKING RANGE 100 FT - 200 FT; BASE ICE LOAD, c_u = 0.6 KSF)

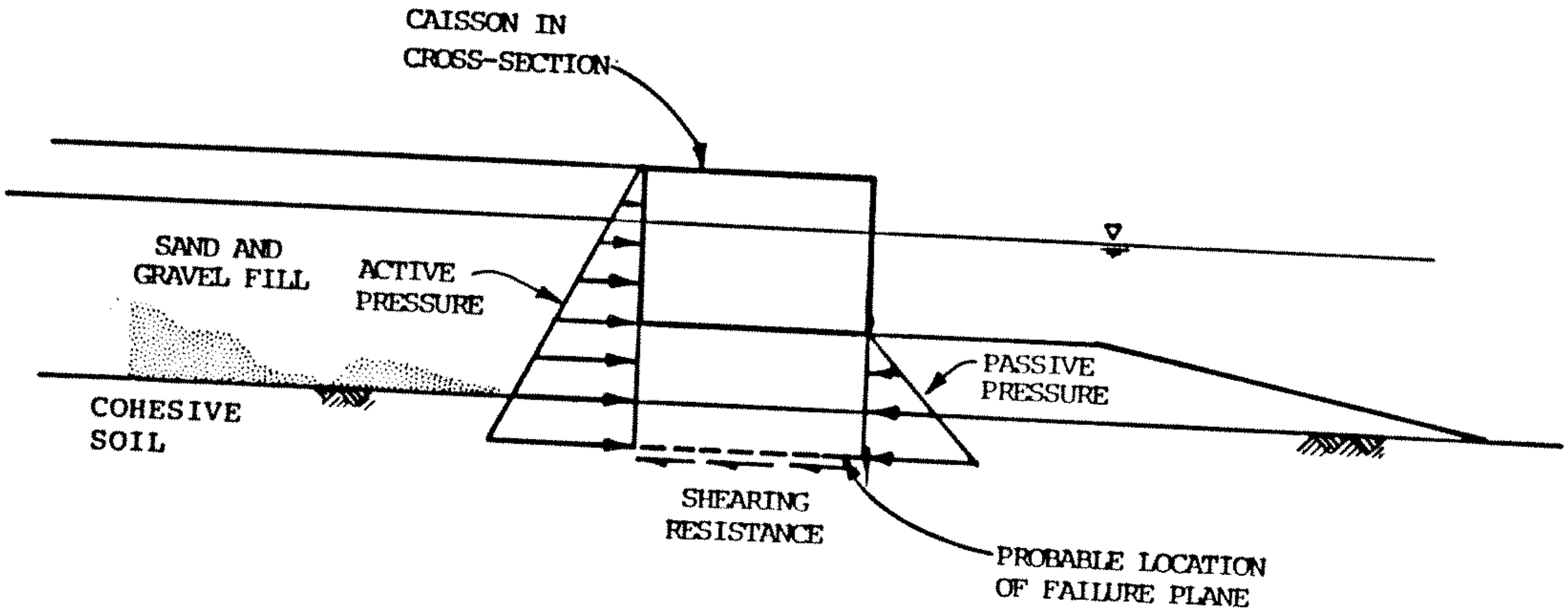


FIGURE 4.27 SIMPLIFIED OPERATING LOAD CONDITION ON CAISSON

NOTE: FAILURE MODES CORRESPOND TO THE LOAD CONDITIONS SHOWN IN THE PREVIOUS FIGURE.

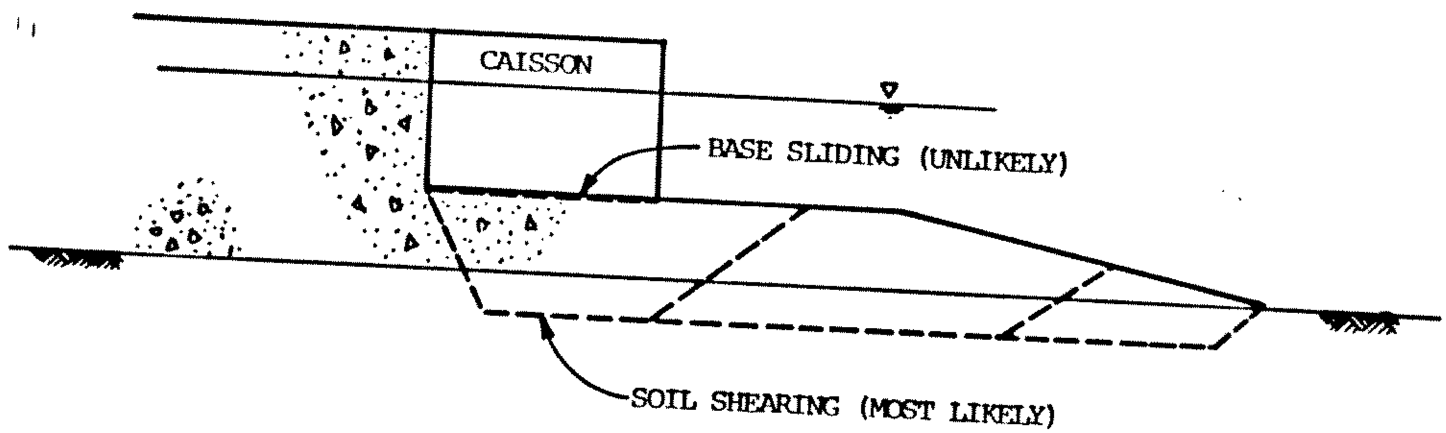


FIGURE 4.28 FAILURE MODES FOR INDIVIDUAL CAISSONS (ACTIVE LOAD FAILURE)

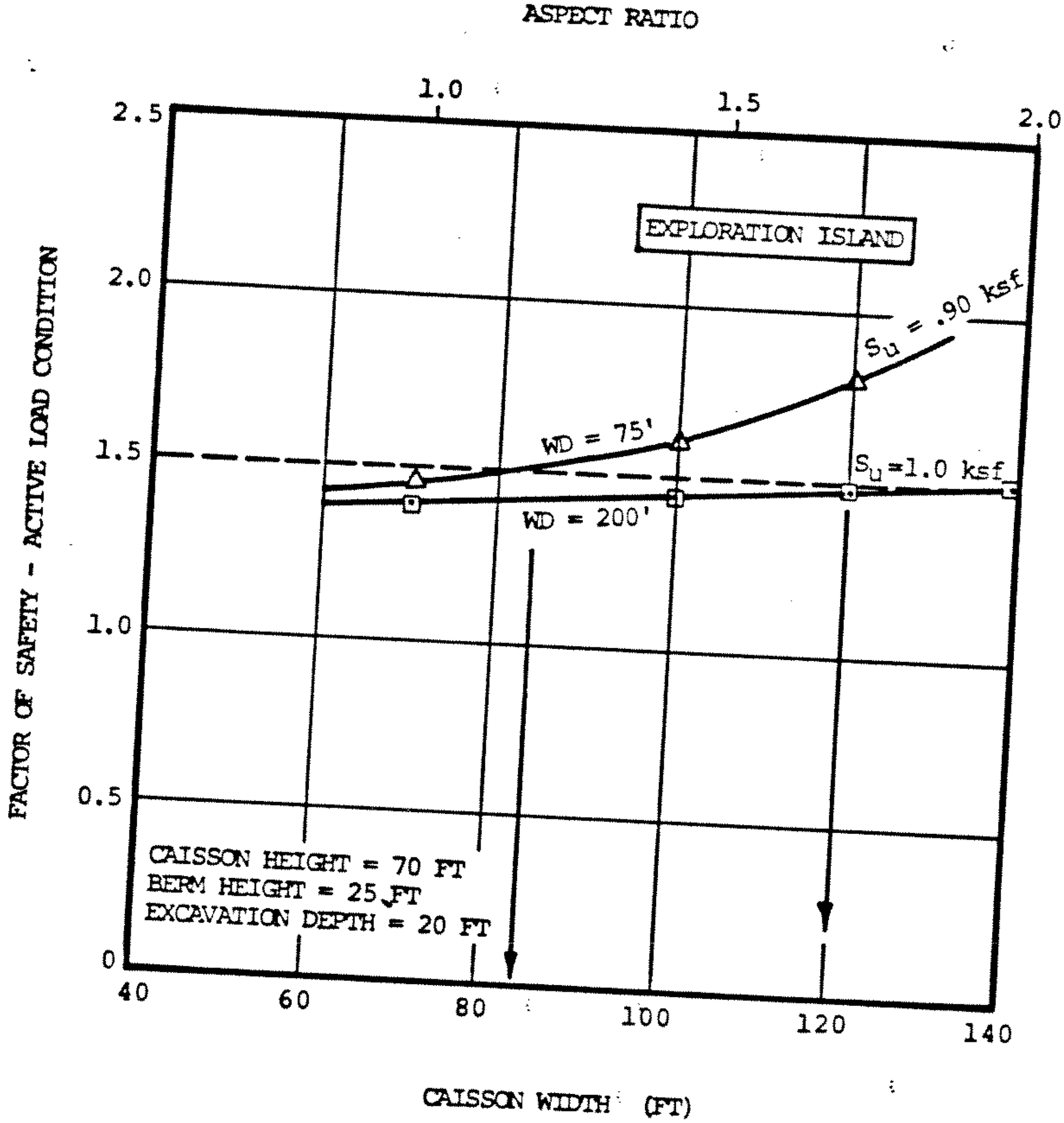


FIGURE 4.29 RELATIONSHIP BETWEEN SAFETY FACTOR AND CAISSON WIDTH

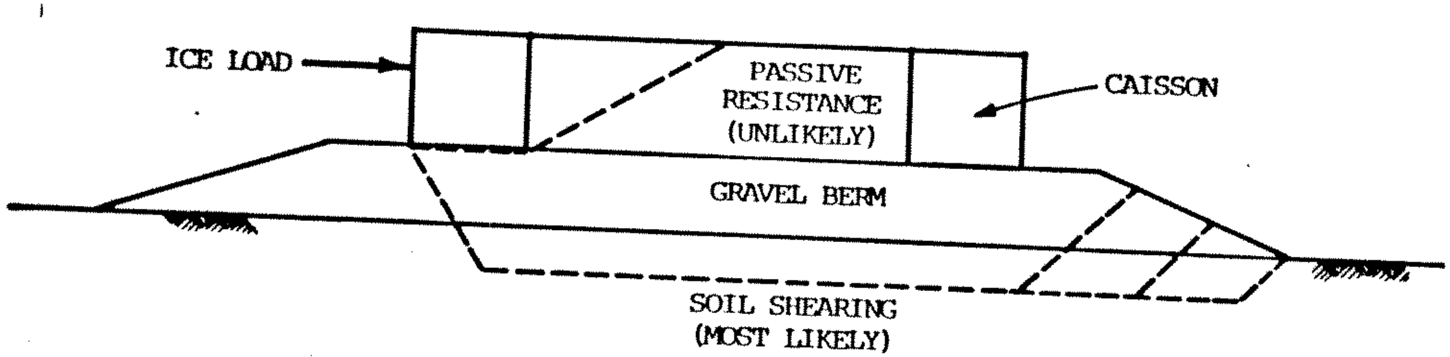


FIGURE 4.30 FAILURE MODES UNDER ICE LOAD

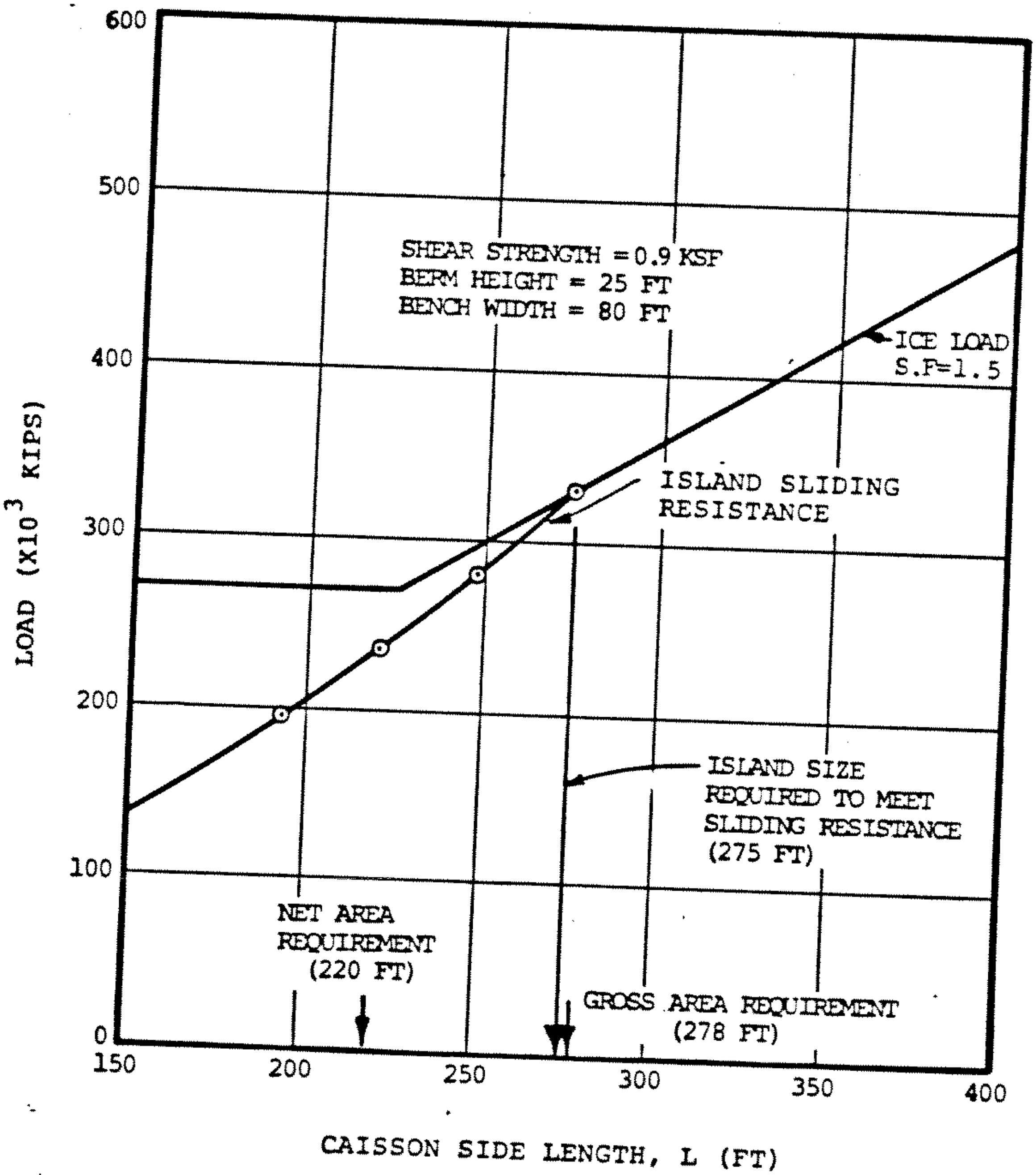


FIGURE 4.31 DETERMINATION OF CAISSON RETAINED ISLAND SIZE

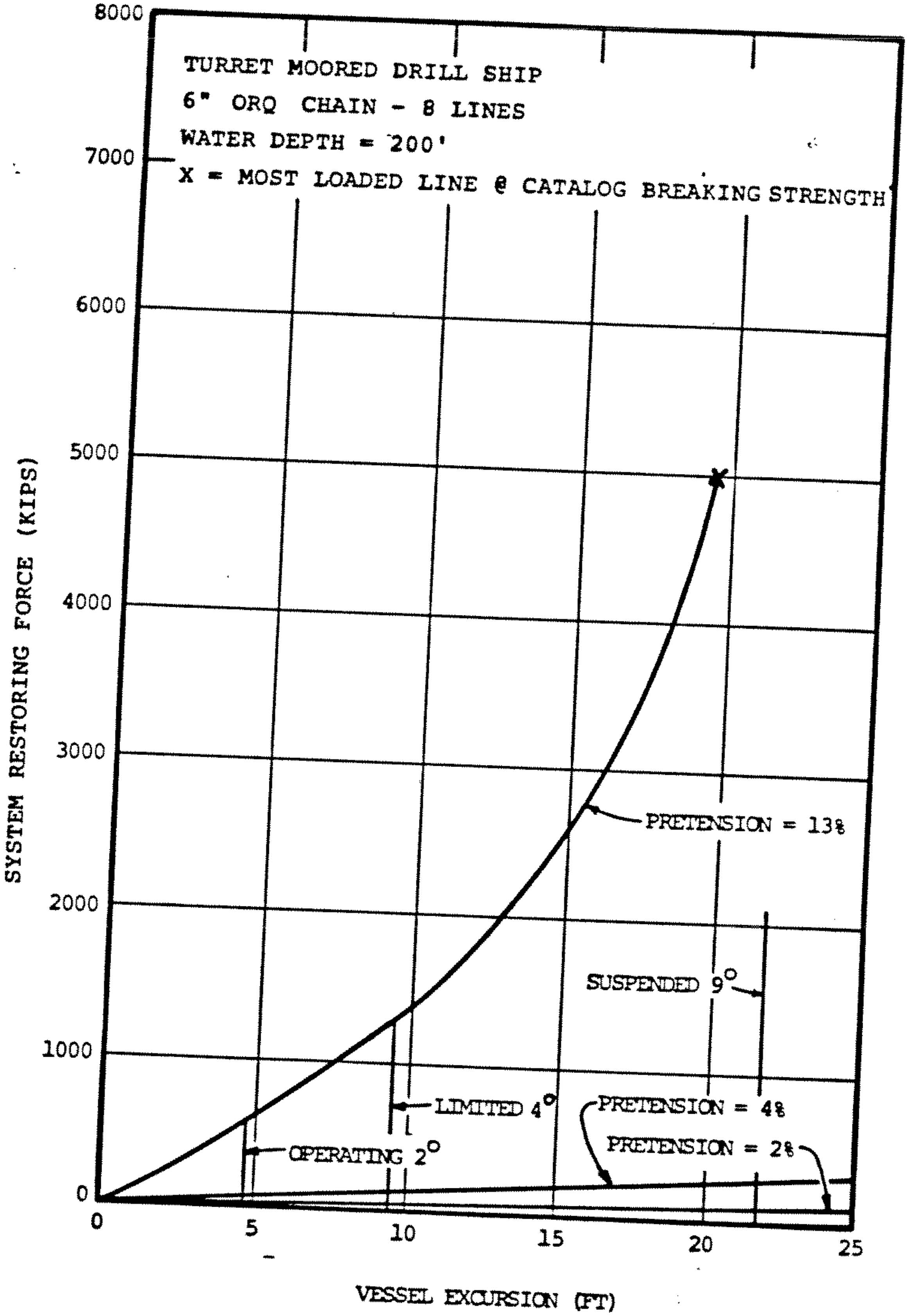


FIGURE 4.32 RESTORING FORCE FOR TURRET MOORED DRILL SHIP

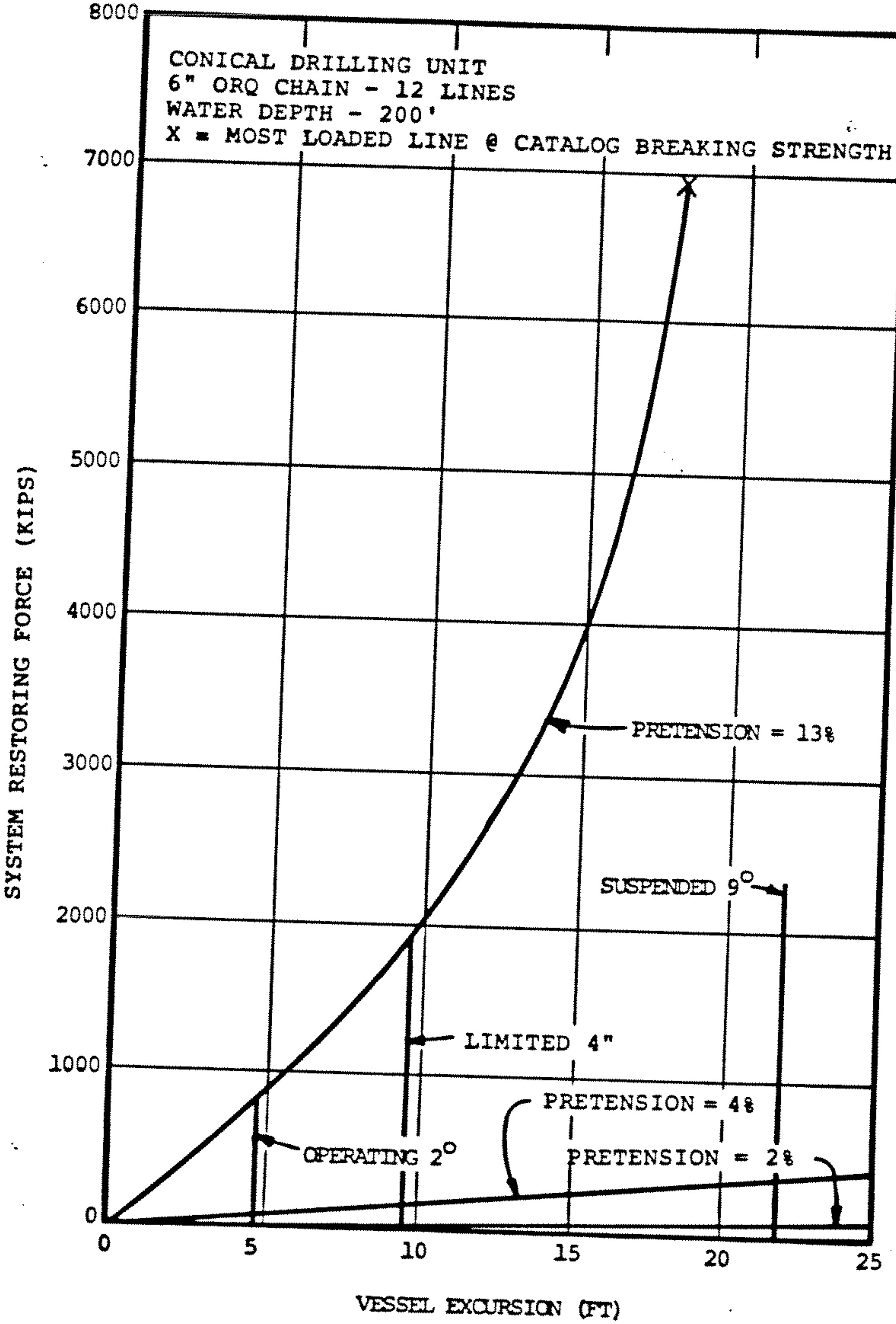


FIGURE 4.33 RESTORING FORCE FOR CONICAL DRILLING UNIT

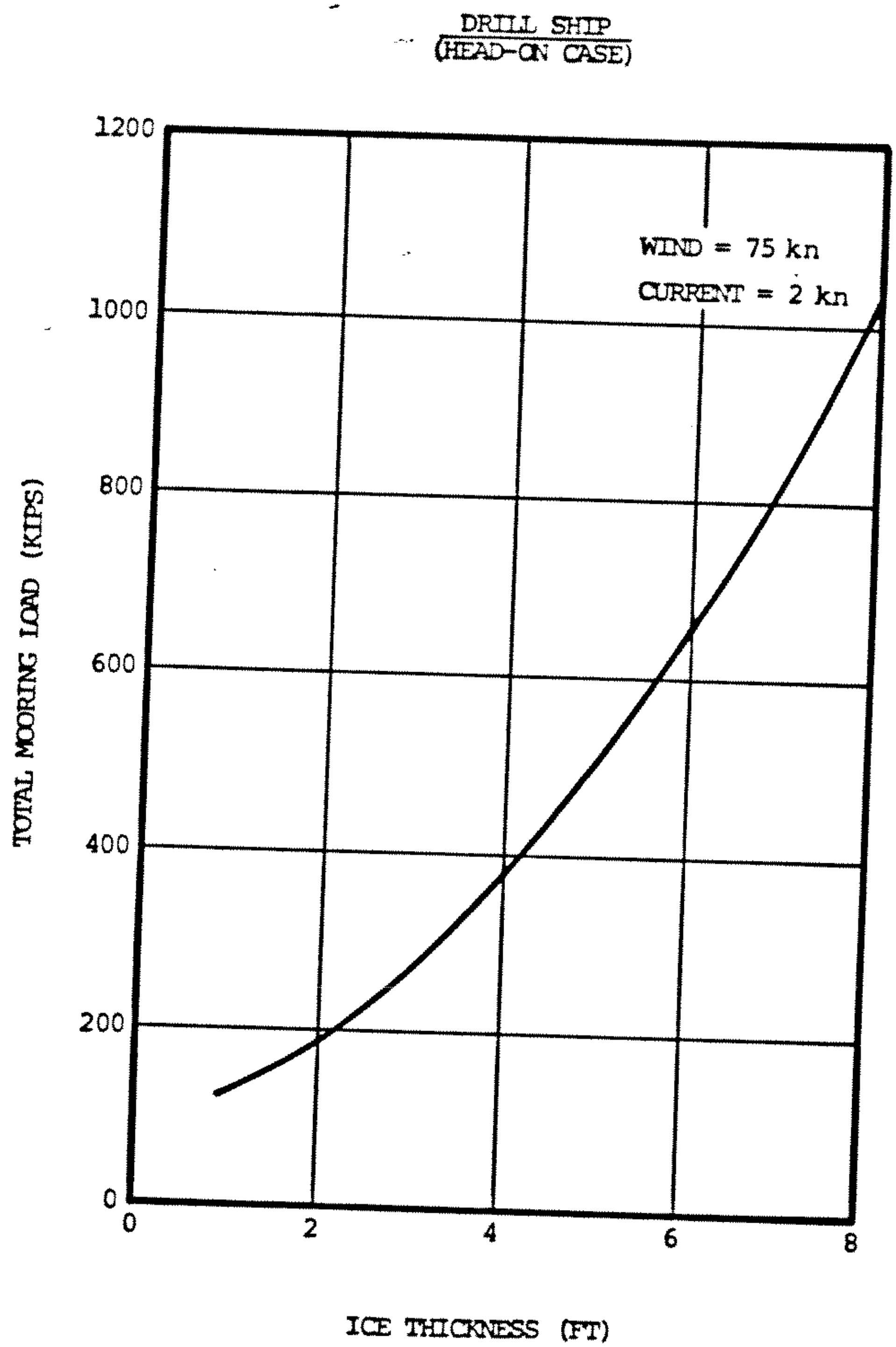


FIGURE 4.34 ENVIRONMENTAL LOADS ON TURRET MOORED DRILL SHIP

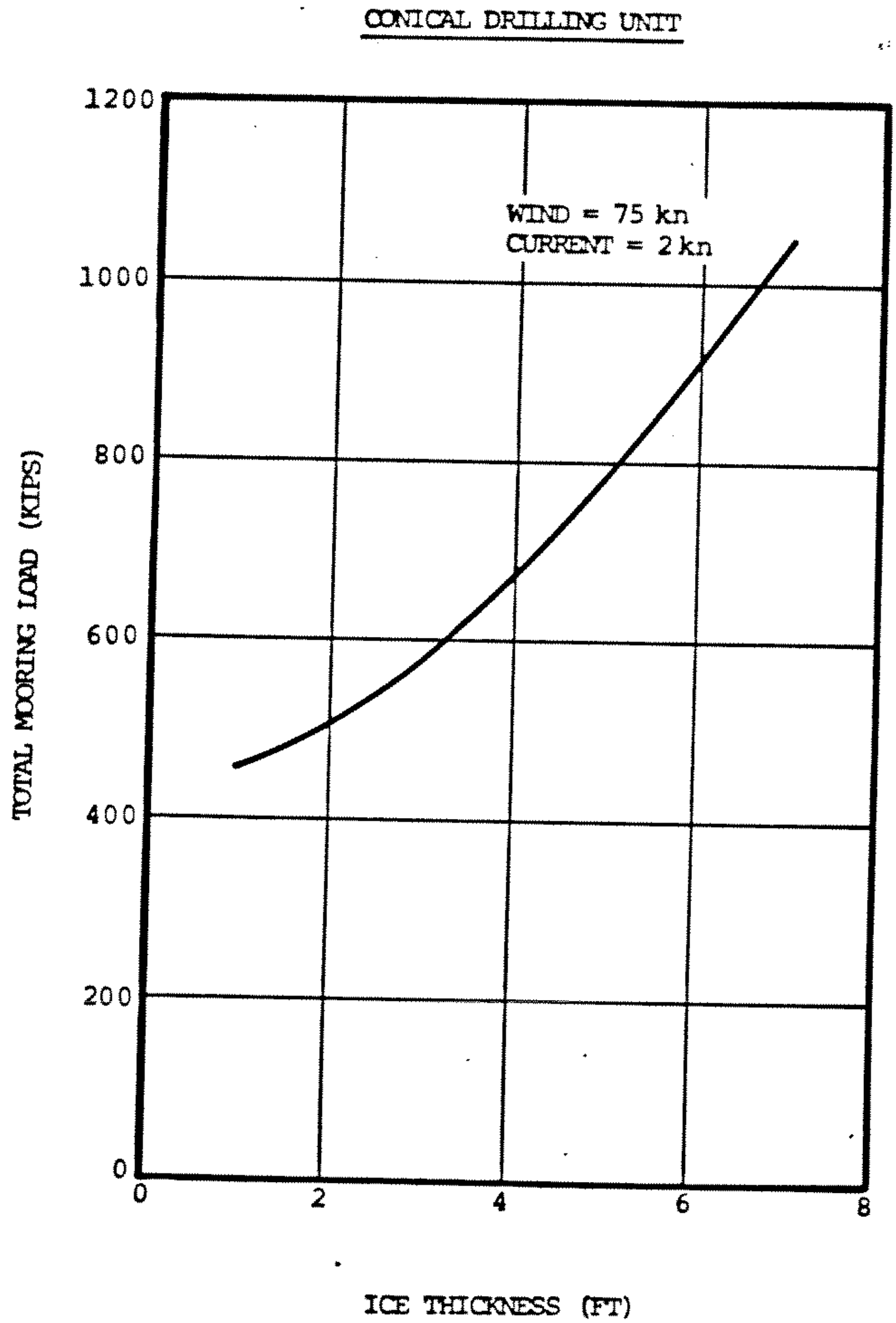


FIGURE 4.35 ENVIRONMENTAL LOADS ON CONICAL DRILLING UNIT

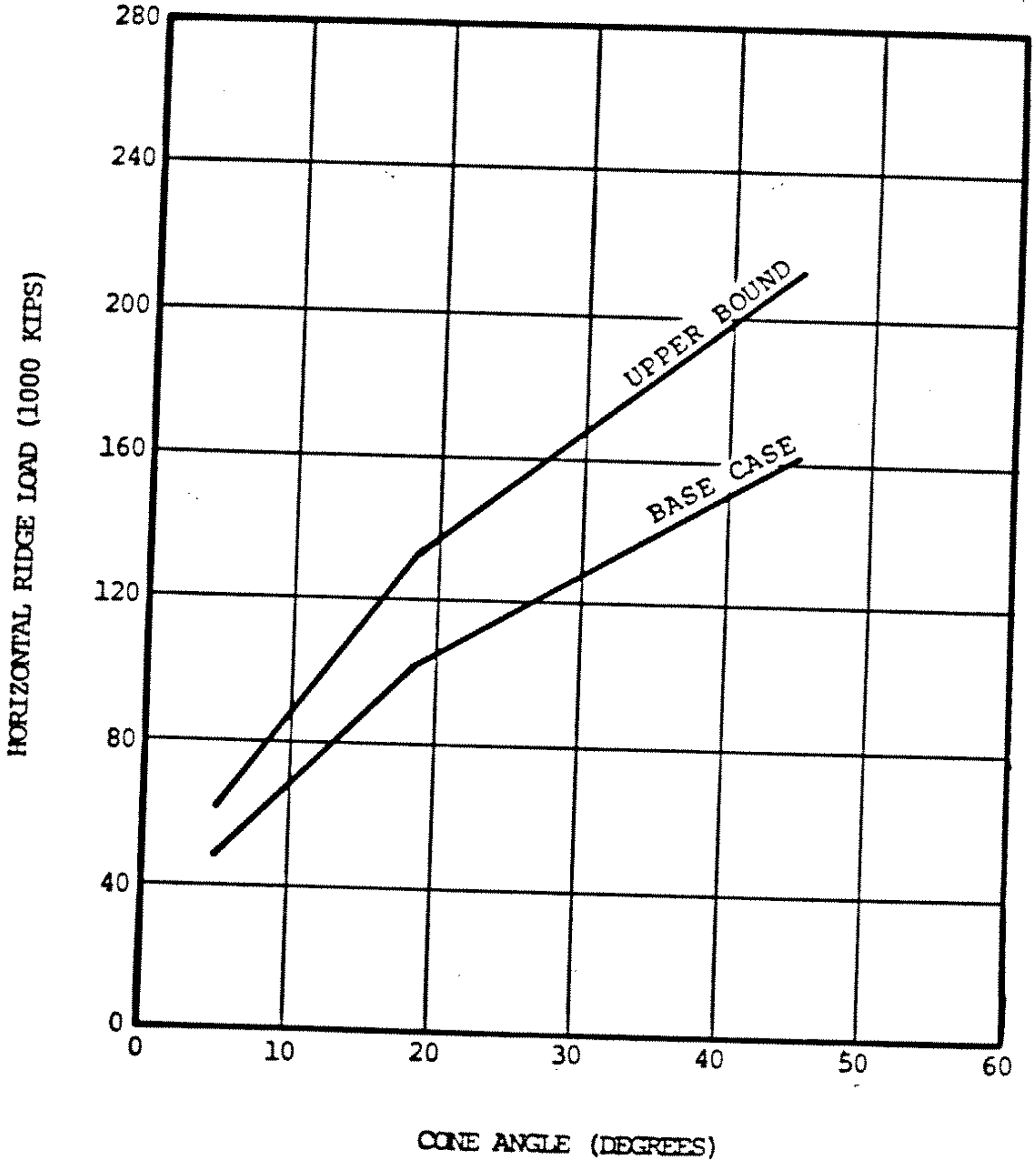


FIGURE 4.36 PRODUCTION ICE LOADS ON CONICAL STRUCTURES

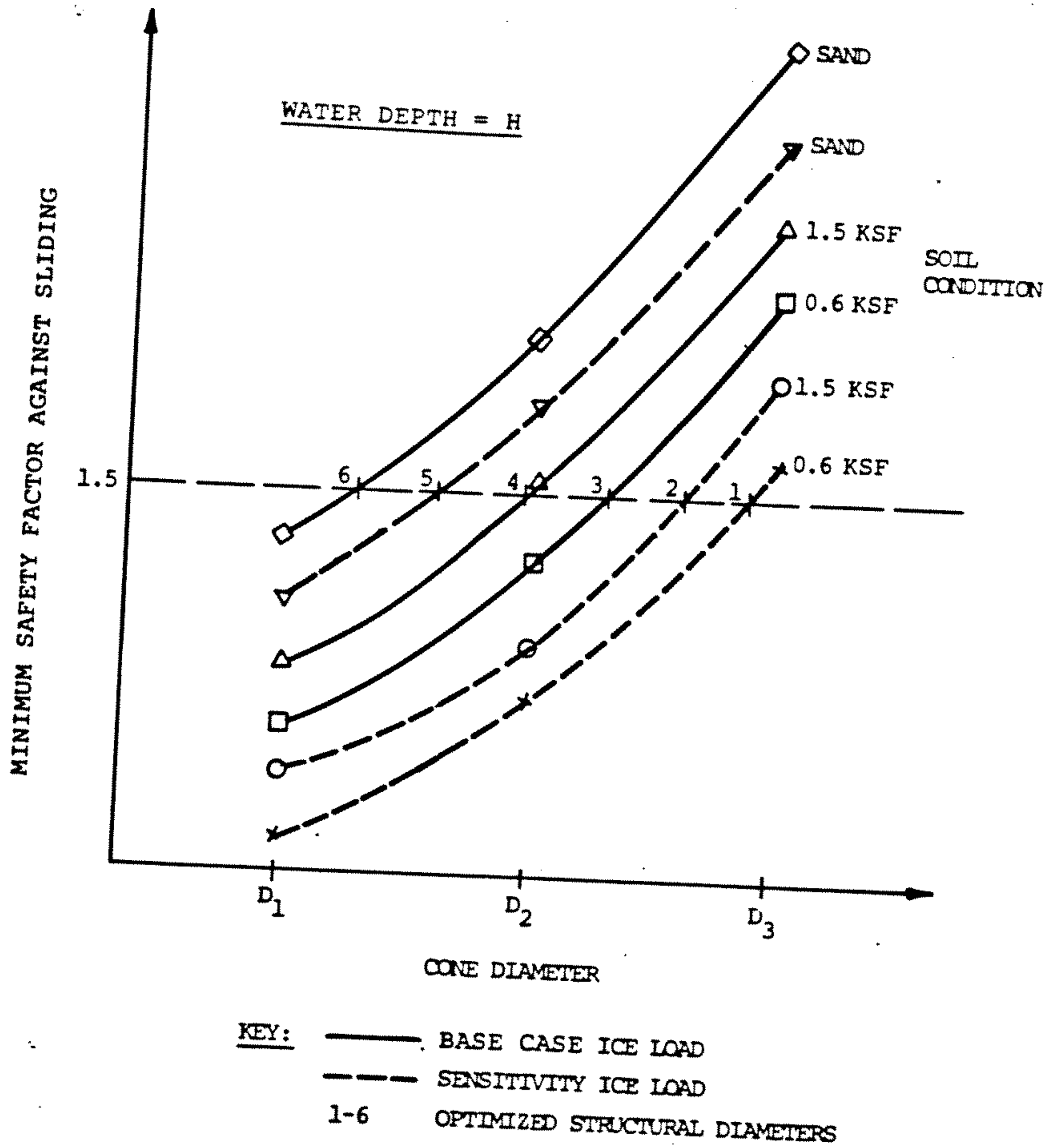


FIGURE 4.37 TYPICAL SAFETY FACTOR CURVES FOR A GIVEN WATER DEPTH

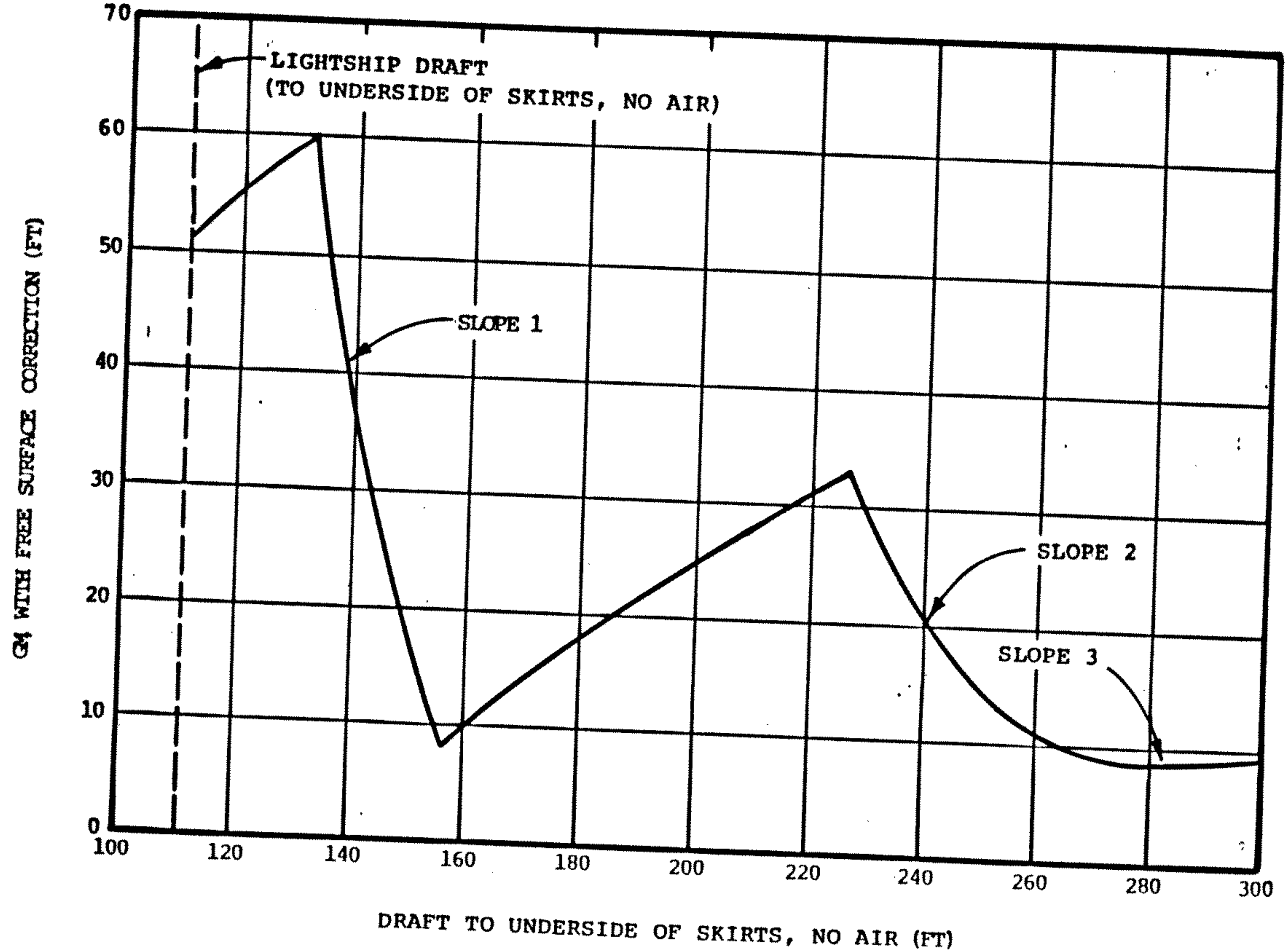
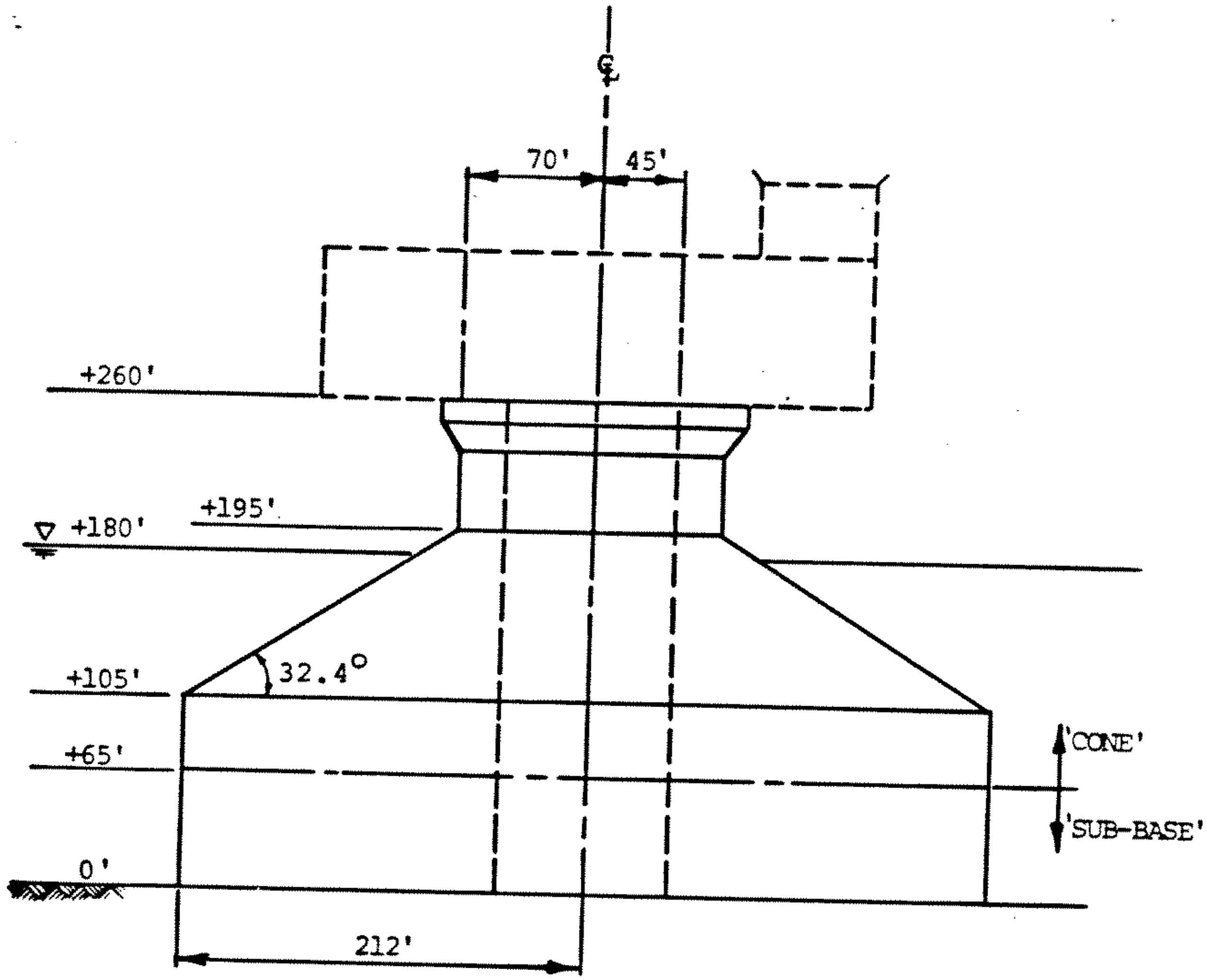
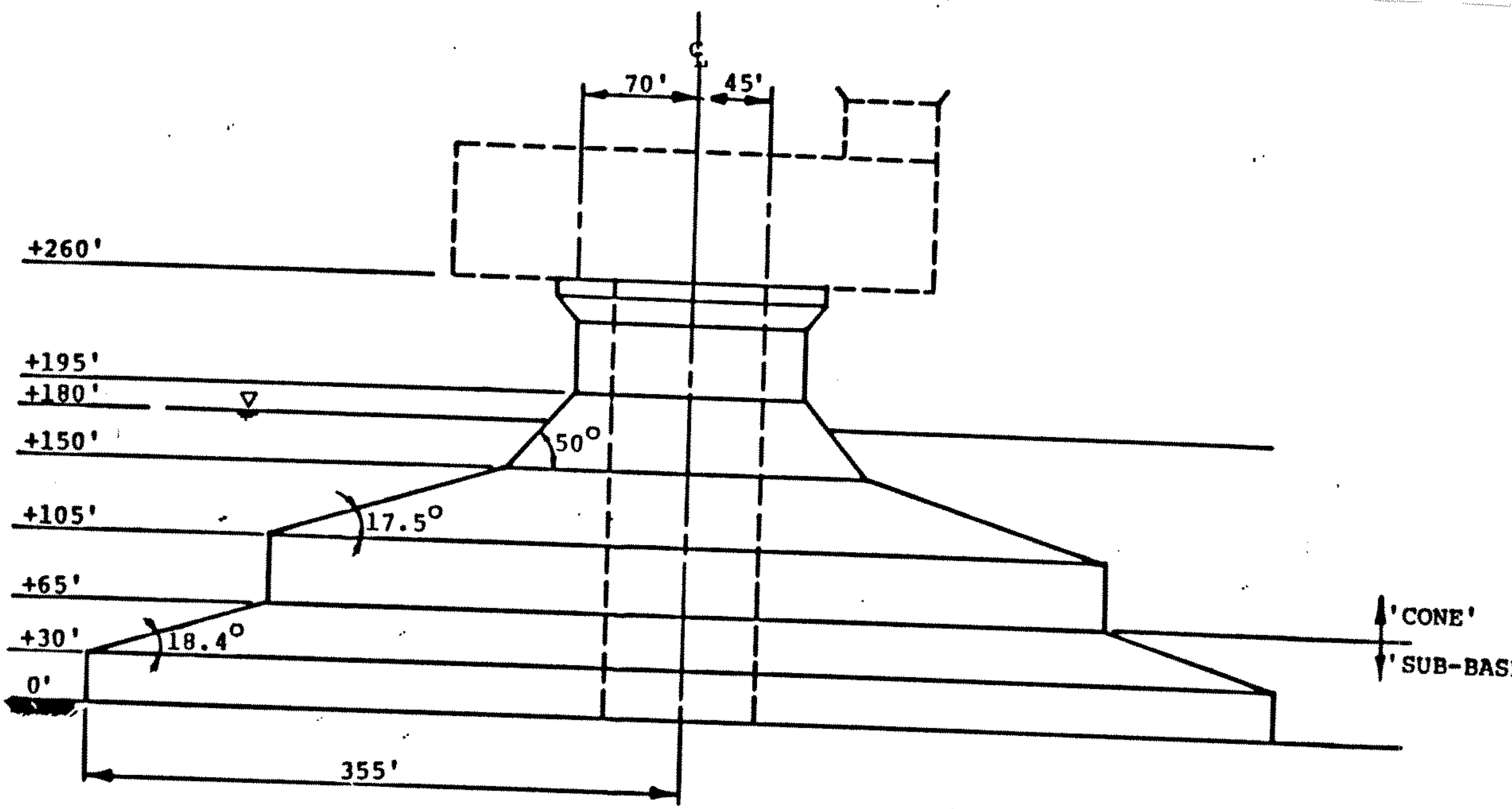


FIGURE 4.39 GM CURVE FOR PRODUCTION CONE (SENSITIVITY ICE, CLAY, c_u = 1.5 KSF) - DECK WT INCLUDED



CONC. WEIGHT: 371 x 10^3 s.t.
DRAFT (TO U/S BASE SLAB): 91'
STABLE UP TO: 146'
(TIPPING ANGLE TO 180' = 9.1°)

FIGURE 4.40 OPTIMIZED PRODUCTION CONE ; 180 FT WATER DEPTH; BASE AND SENSITIVITY LOADS; SAND, Ø = 35°



COMBINED STRUCTURE

CONC. WEIGHT : 640×10^3 s.t.

DRAFT (TO U/S BASE SLAB): 61'

STABLE UP TO : 130'

(TIPPING ANGLE TO 180' = 8.0°)

SEPARATED CONE

CONC. WEIGHT : 286×10^3 s.t.

DRAFT : 54'

STABLE UP TO : 71'

SEPARATED SUB-BASE

CONC. WEIGHT : 354×10^3 s.t.

DRAFT : 28'

FIGURE 4.41 OPTIMIZED PRODUCTION CONE; 180 FT WATER DEPTH; SENSITIVITY ICE LOAD; CLAY, c_u = 0.6 KSF

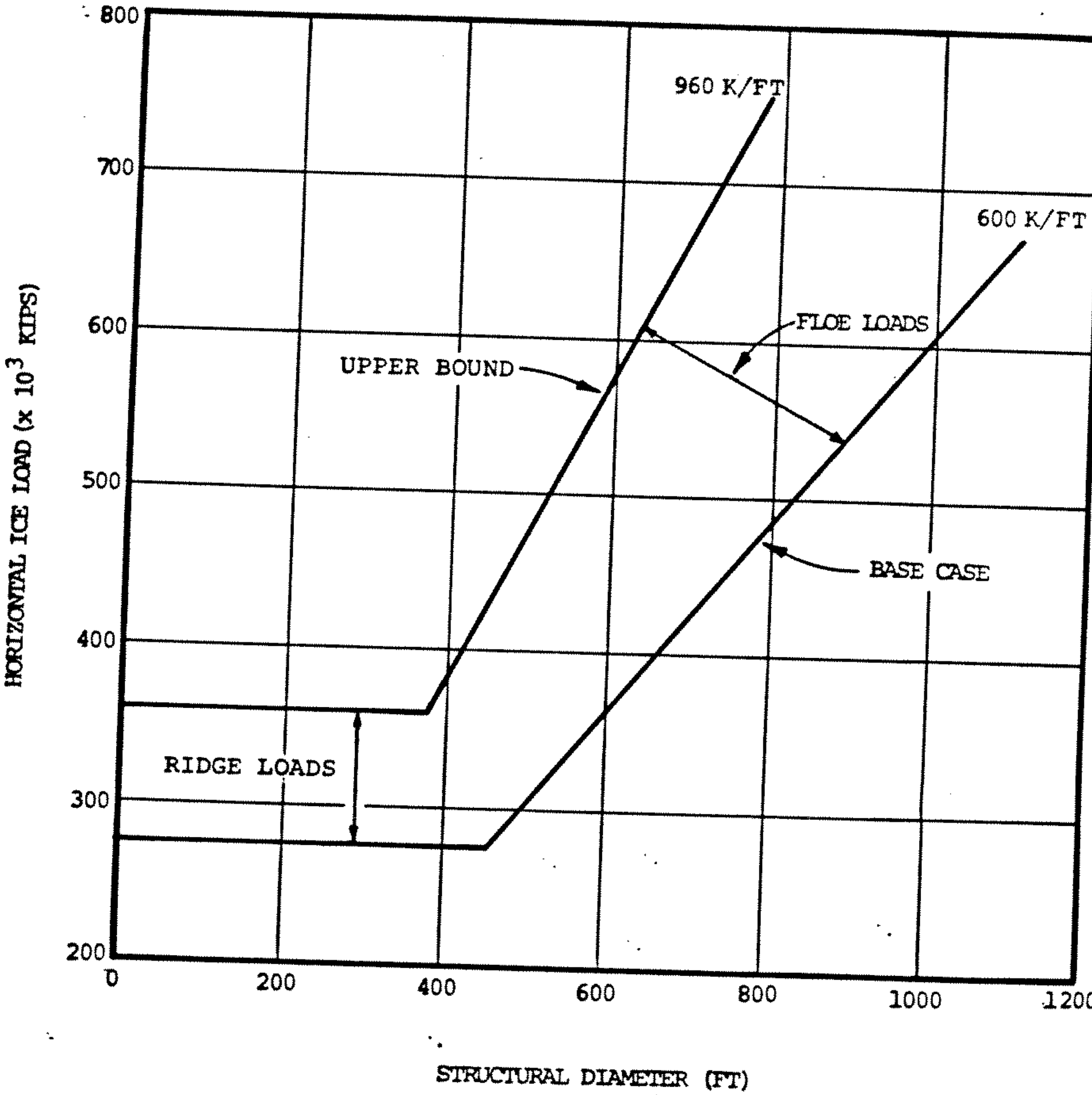
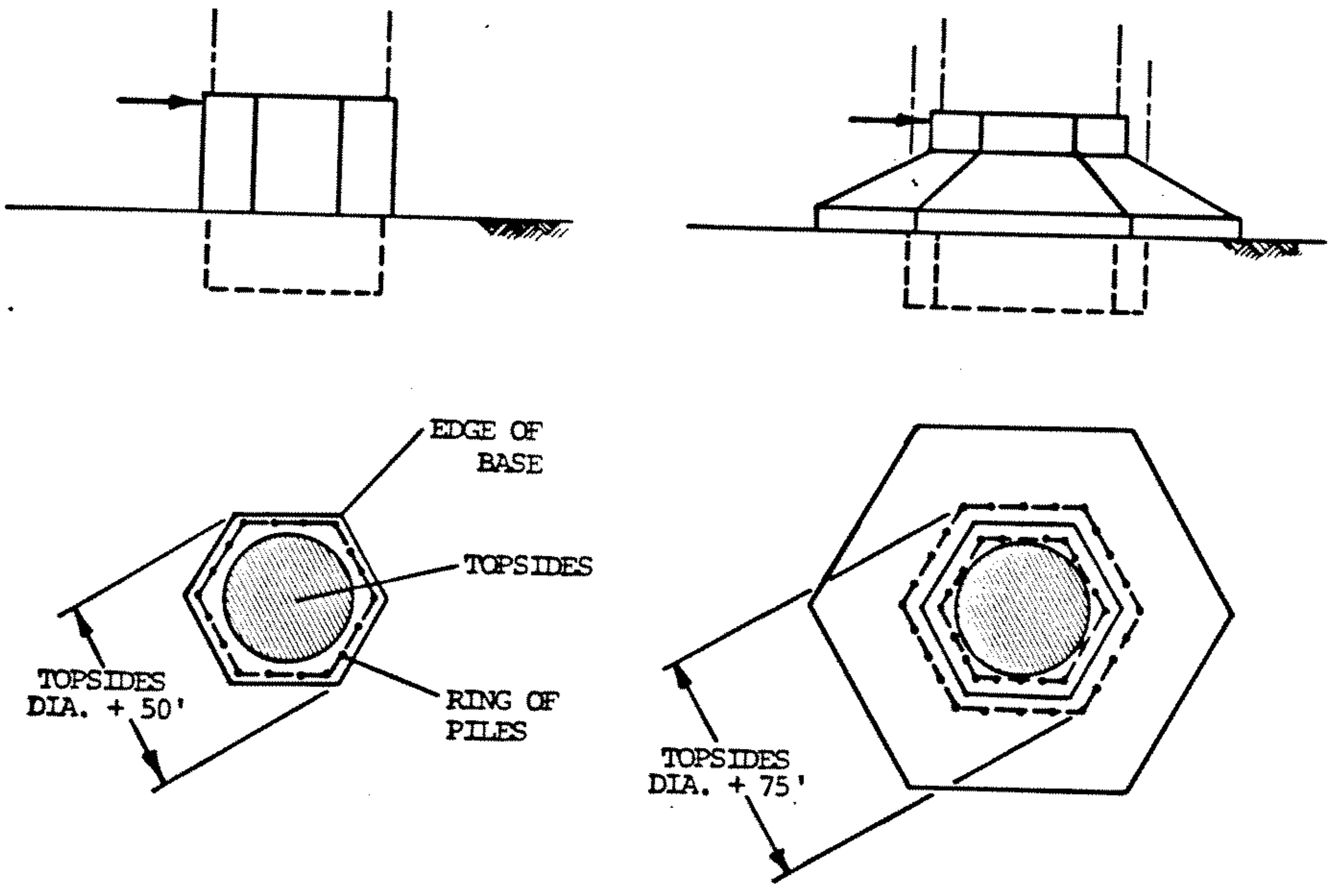


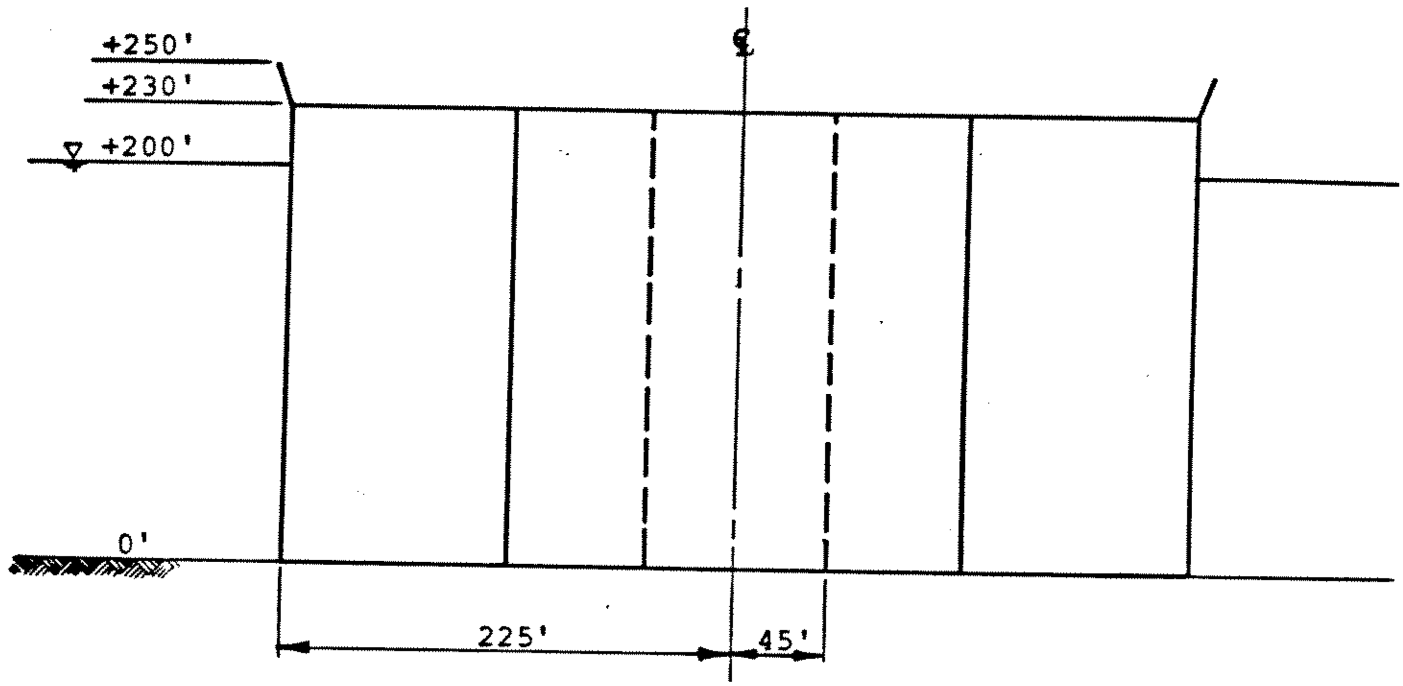
FIGURE 4.42 PRODUCTION ICE LOADS ON MONOLITHIC CAISSONS



(a) SINGLE RING OF PILES

(b) DOUBLE RING OF PILES WITH WIDENED BASE

FIGURE 4.43 PILE LAYOUTS CONSIDERED



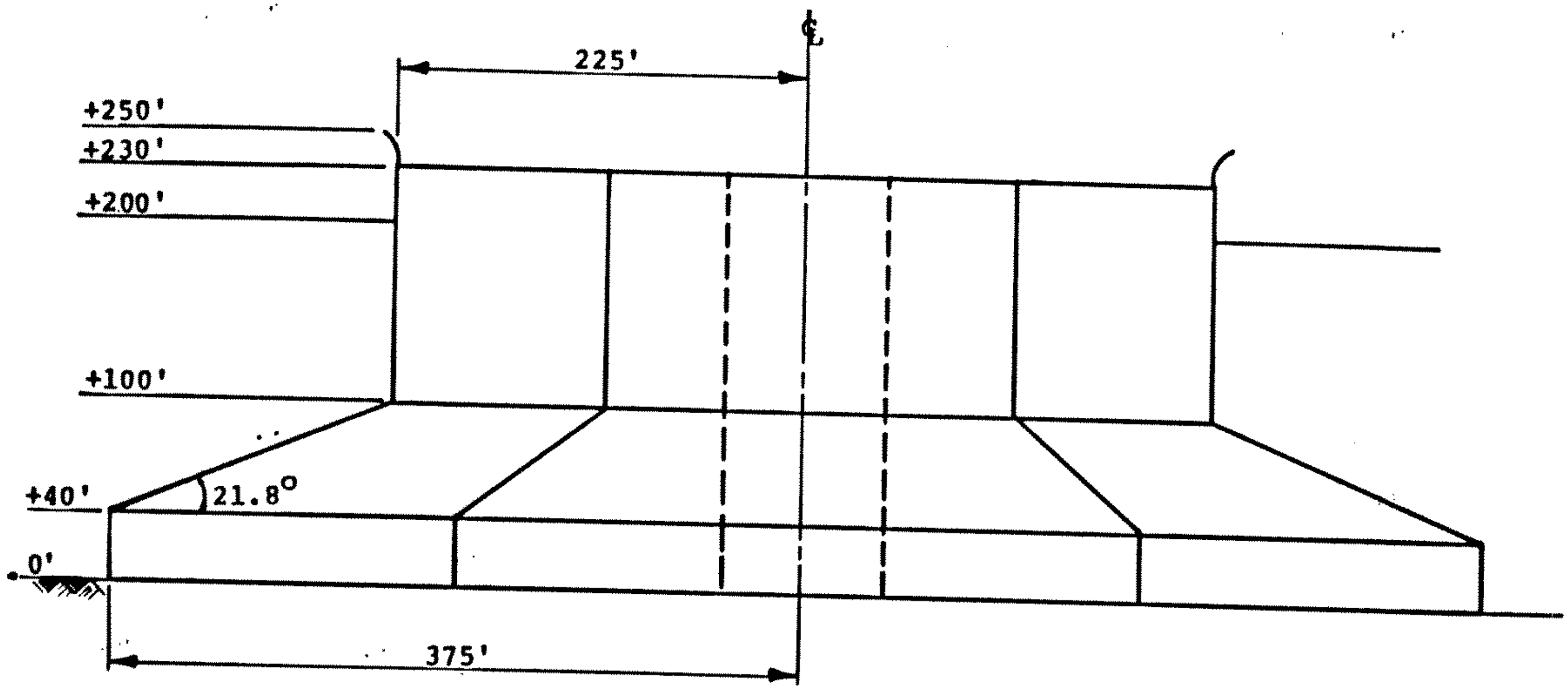
CONC. WEIGHT : 261 x 10^3 s.t.

DRAFT (TO U/S SKIRTS (no air): 77 FT

NO. OF WICK DRAINS: NONE

SAND BALLAST REQUIRED

FIGURE 4.44 OPTIMIZED PRODUCTION CAISSON (200,000 BOPD) 200 FT WATER DEPTH; BASE AND SENSITIVITY ICE LOADS; SAND, Ø = 35°



CONC. WEIGHT: 441×10^3 s.t.

DRAFT (TO U/S SKIRTS, NO AIR): 47'

NO OF WICK DRAINS: 3215

FIGURE 4.45 OPTIMIZED PRODUCTION CAISSON (200,000 BOPD) 200 FT WATER DEPTH; BASE ICE LOAD; CLAY, c_u = 0.6 KSF

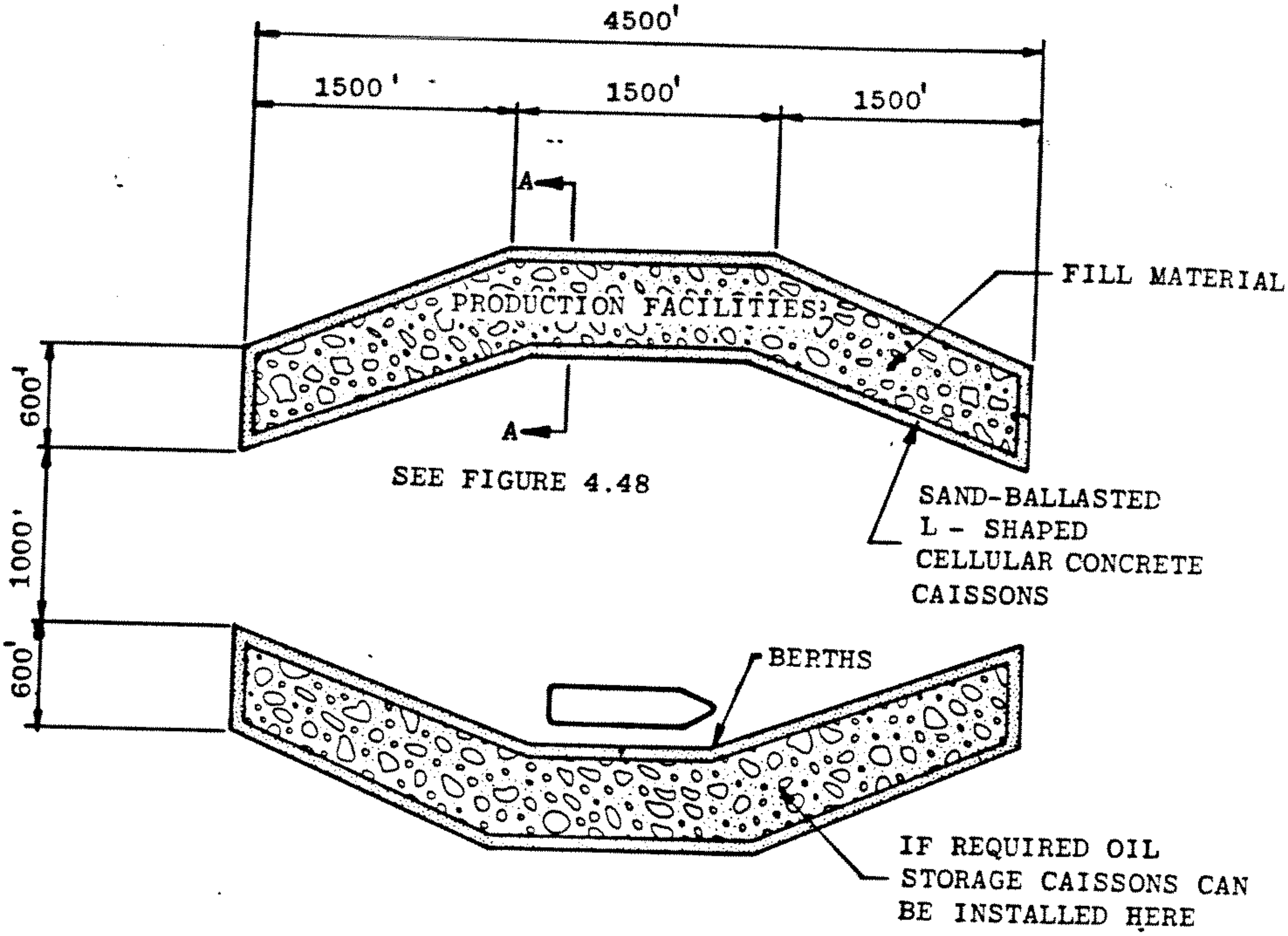


FIGURE 4.46 PRODUCTION AND LOADING ATOLL (SCHEME 1)

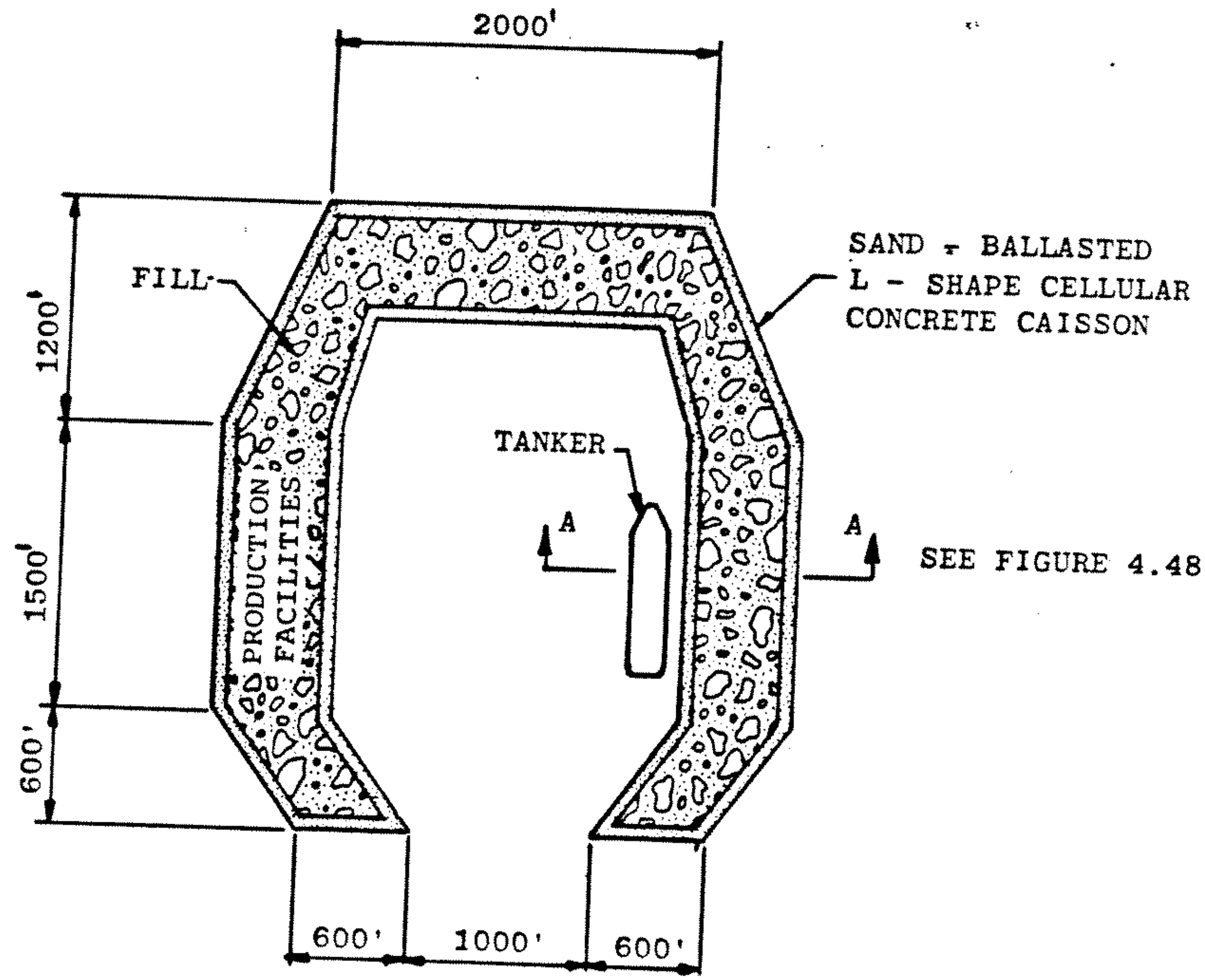
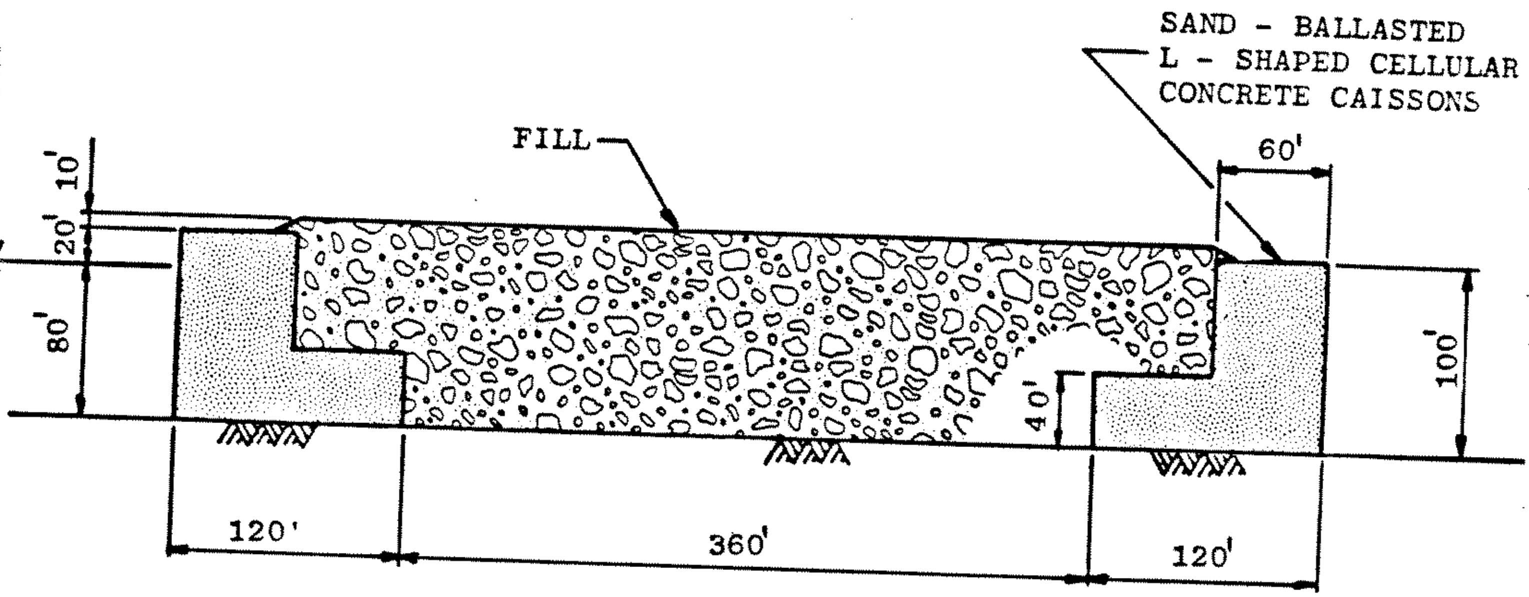


FIGURE 4.47 PRODUCTION AND LOADING ATOLL (SCHEME 2)



SECTION A-A

FIGURE 4.48 ELEVATION OF PRODUCTION AND LOADING ATOLL

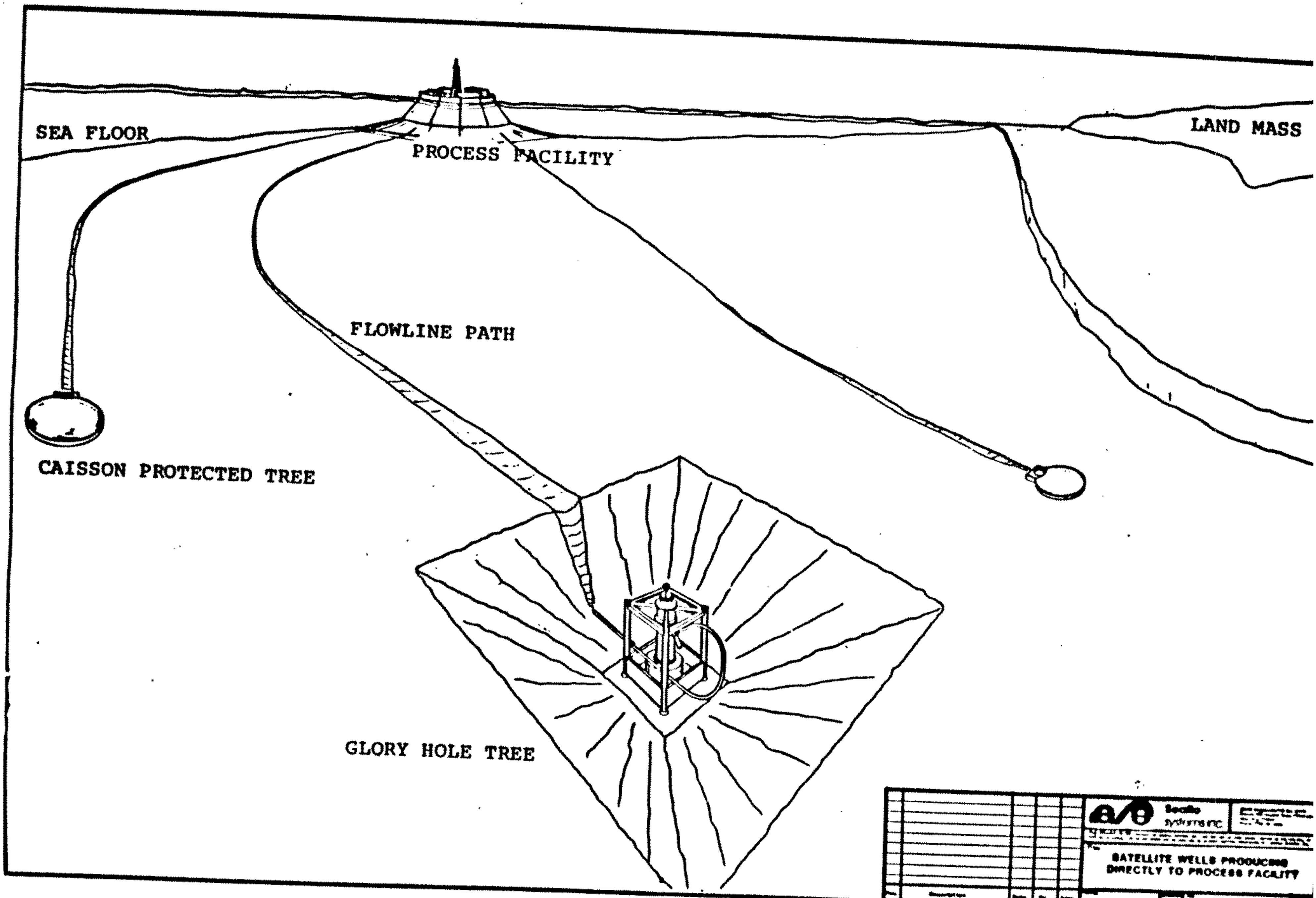


FIGURE 4.49 SATELLITE WELLS PRODUCING DIRECTLY TO PROCESS FACILITY

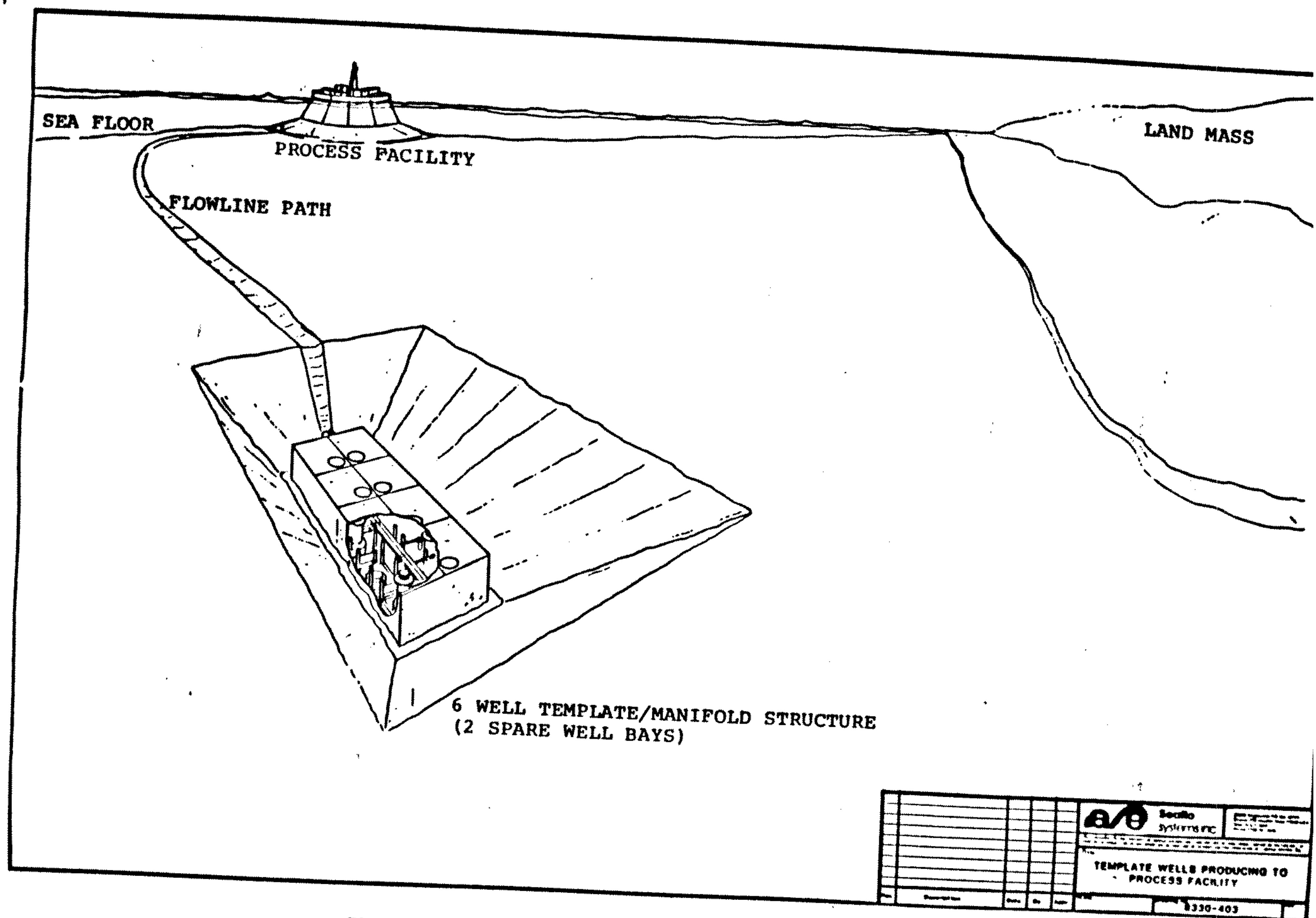


FIGURE 4.50 TEMPLATE WELLS PRODUCING PROCESS FACILITY

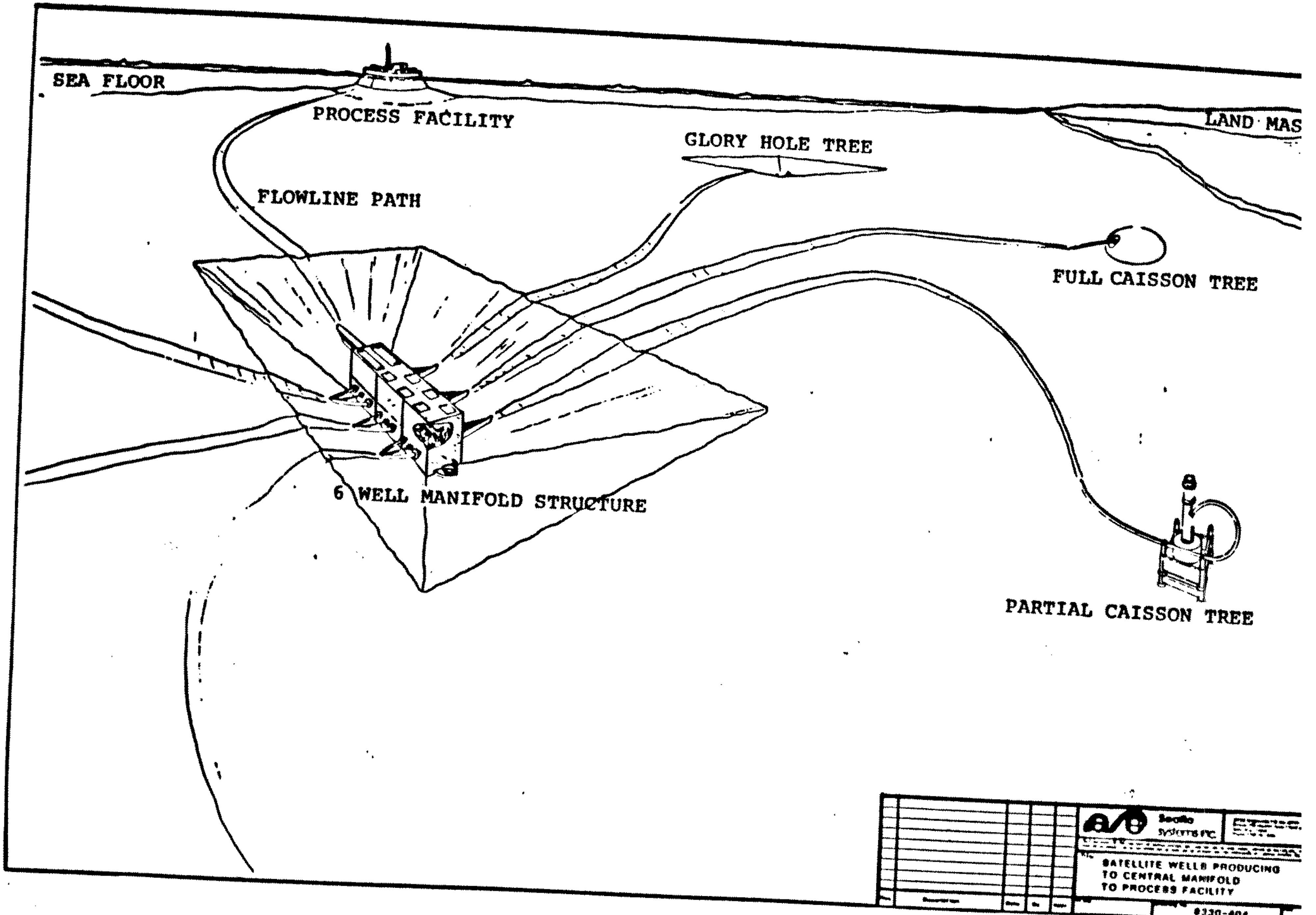


FIGURE 4.51 SATELLITE WELLS PRODUCING TO CENTRAL MANIFOLD TO PROCESS FACILITY

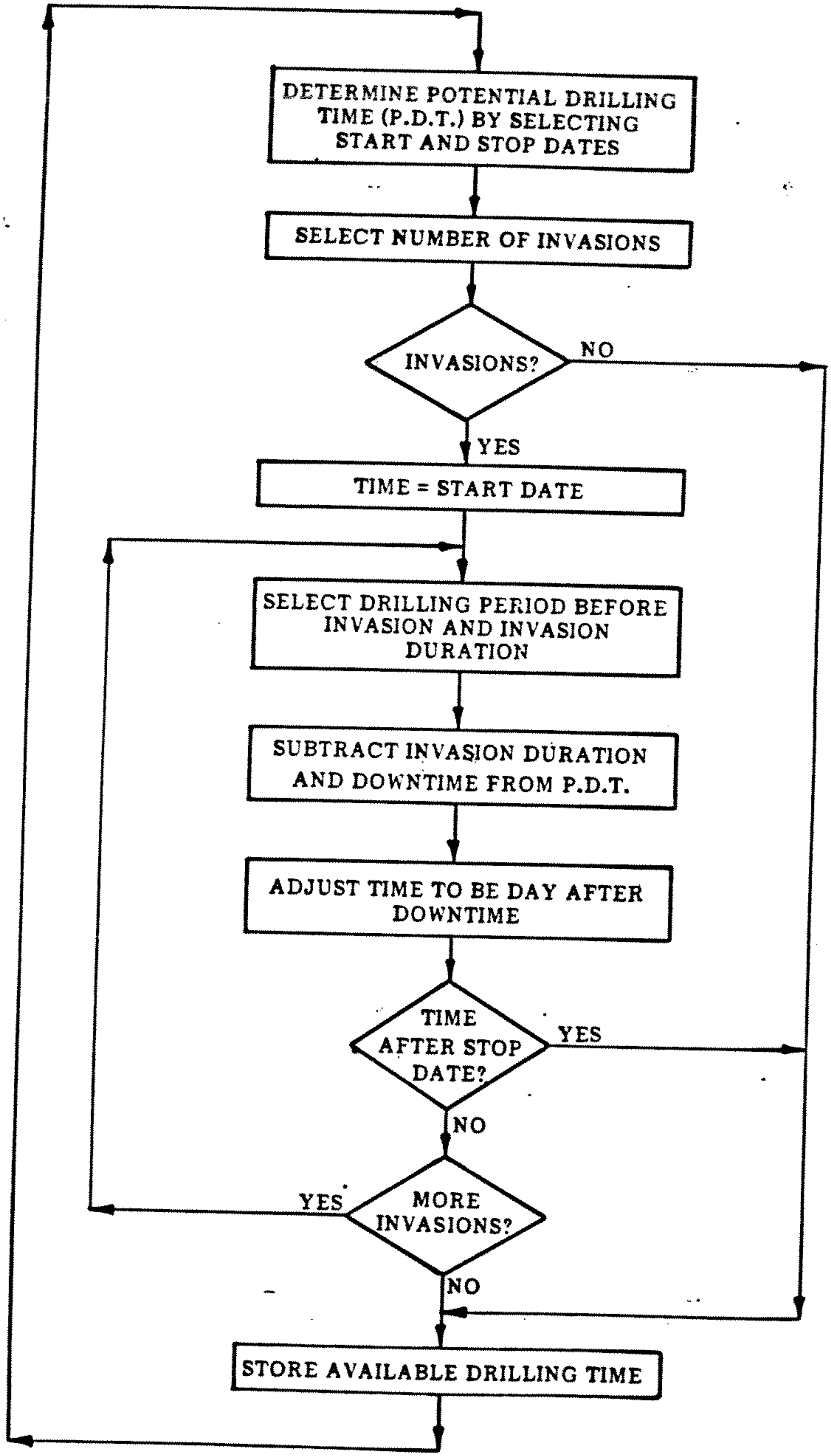


FIGURE 4.52 FLOATING DRILLING RISK ALGORITHM FOR AOGA 35 DATA

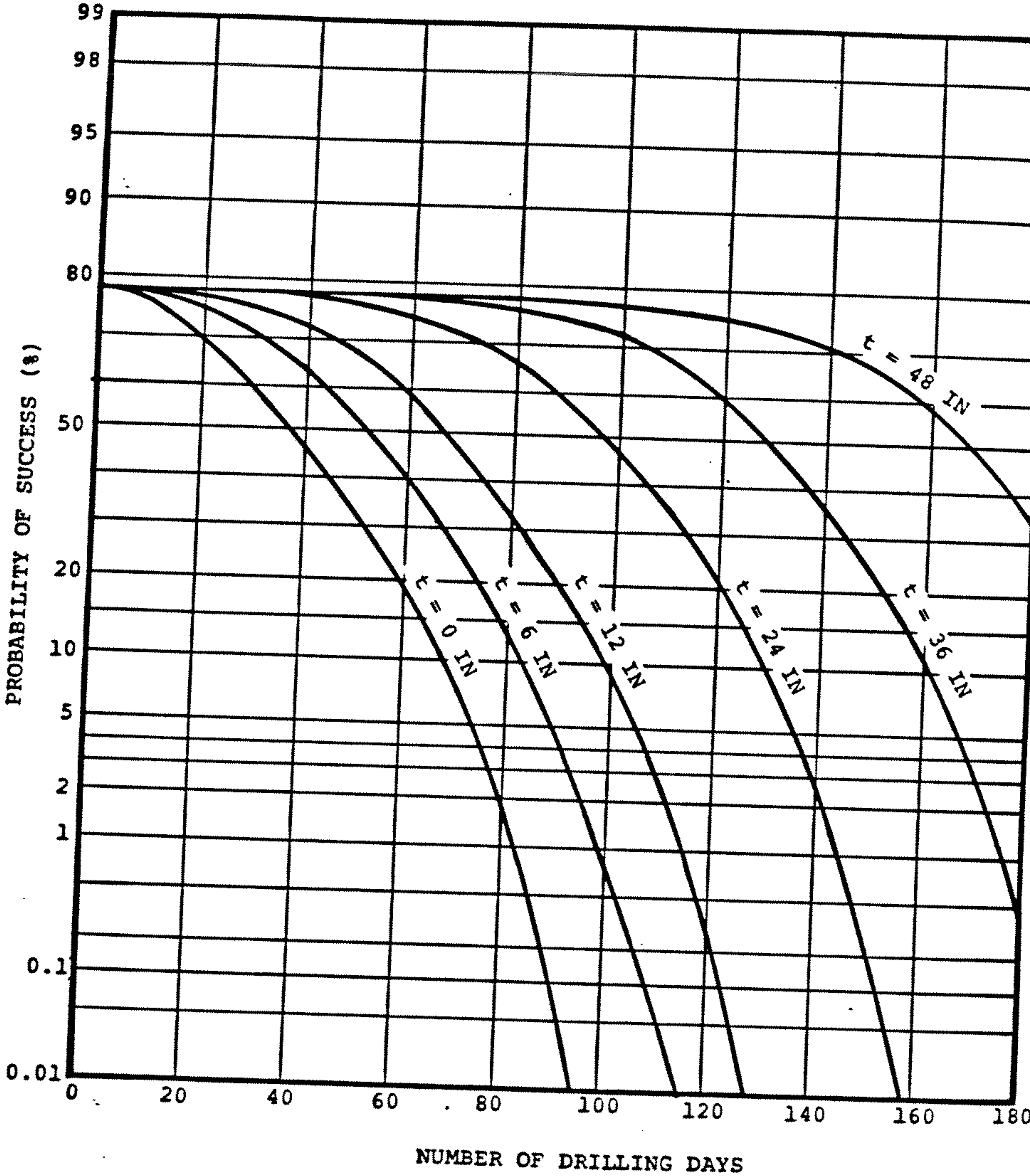


FIGURE 4.53 DRILLING SEASON LENGTH PROBABILITIES AT CAMDEN BAY SITE BASED ON AOGA 35 DATA

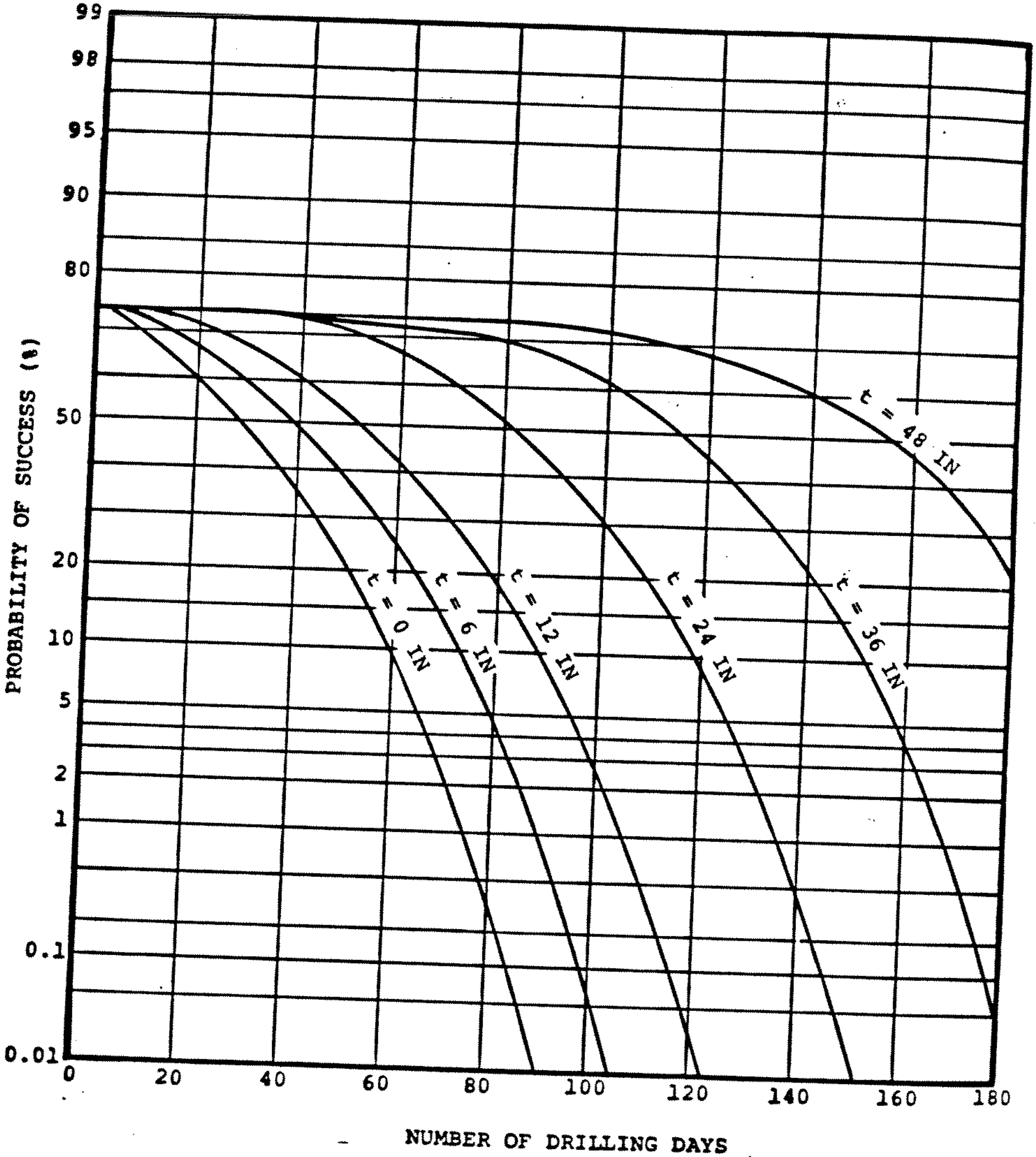


FIGURE 4.54 DRILLING SEASON LENGTH PROBABILITIES AT CAPE HALKETT SITE BASED ON AOGA 35 DATA

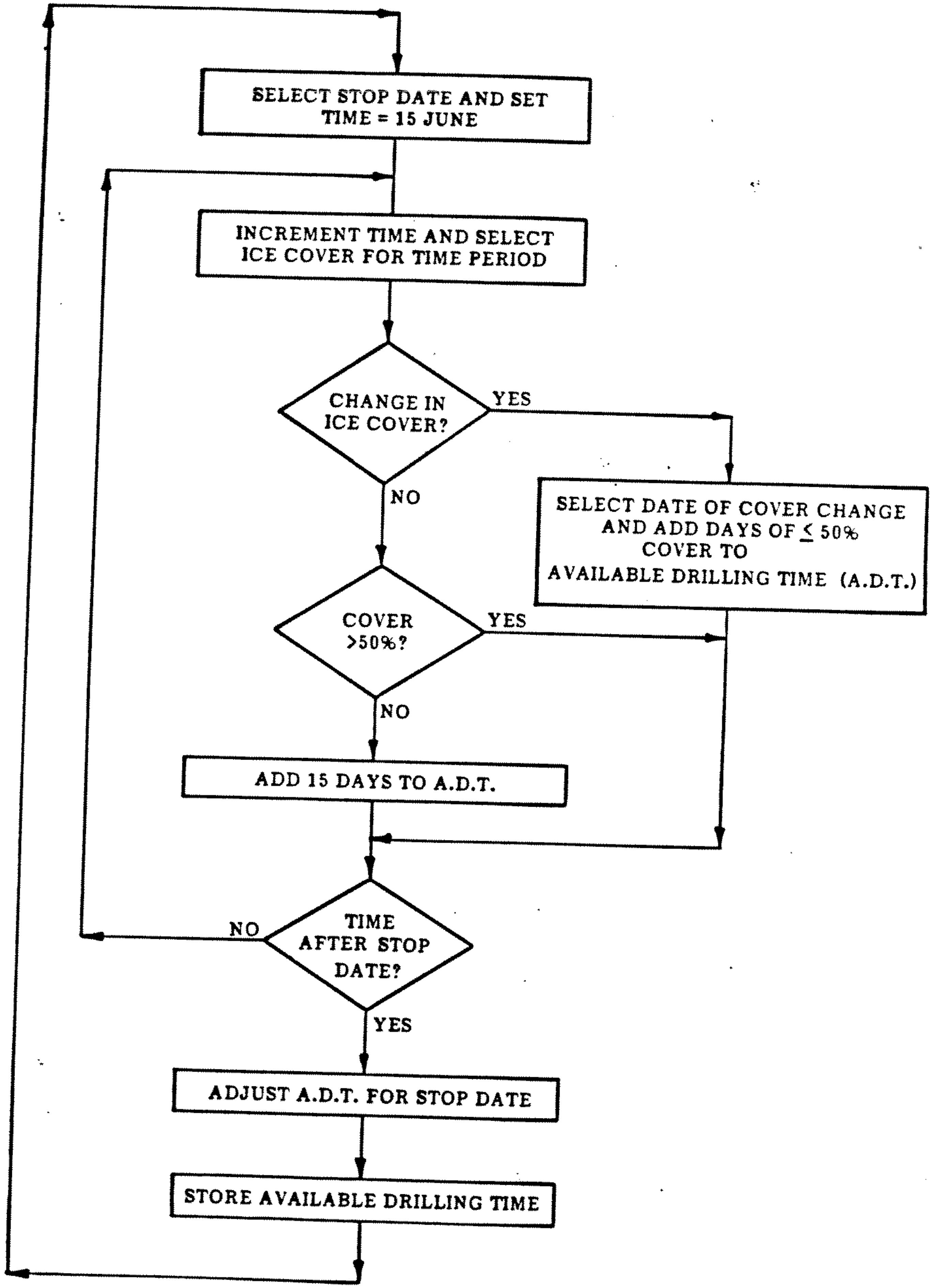


FIGURE 4.55 <u>FLOATING DRILLING RISK ALGORITHM FOR THE NWS DATA</u>

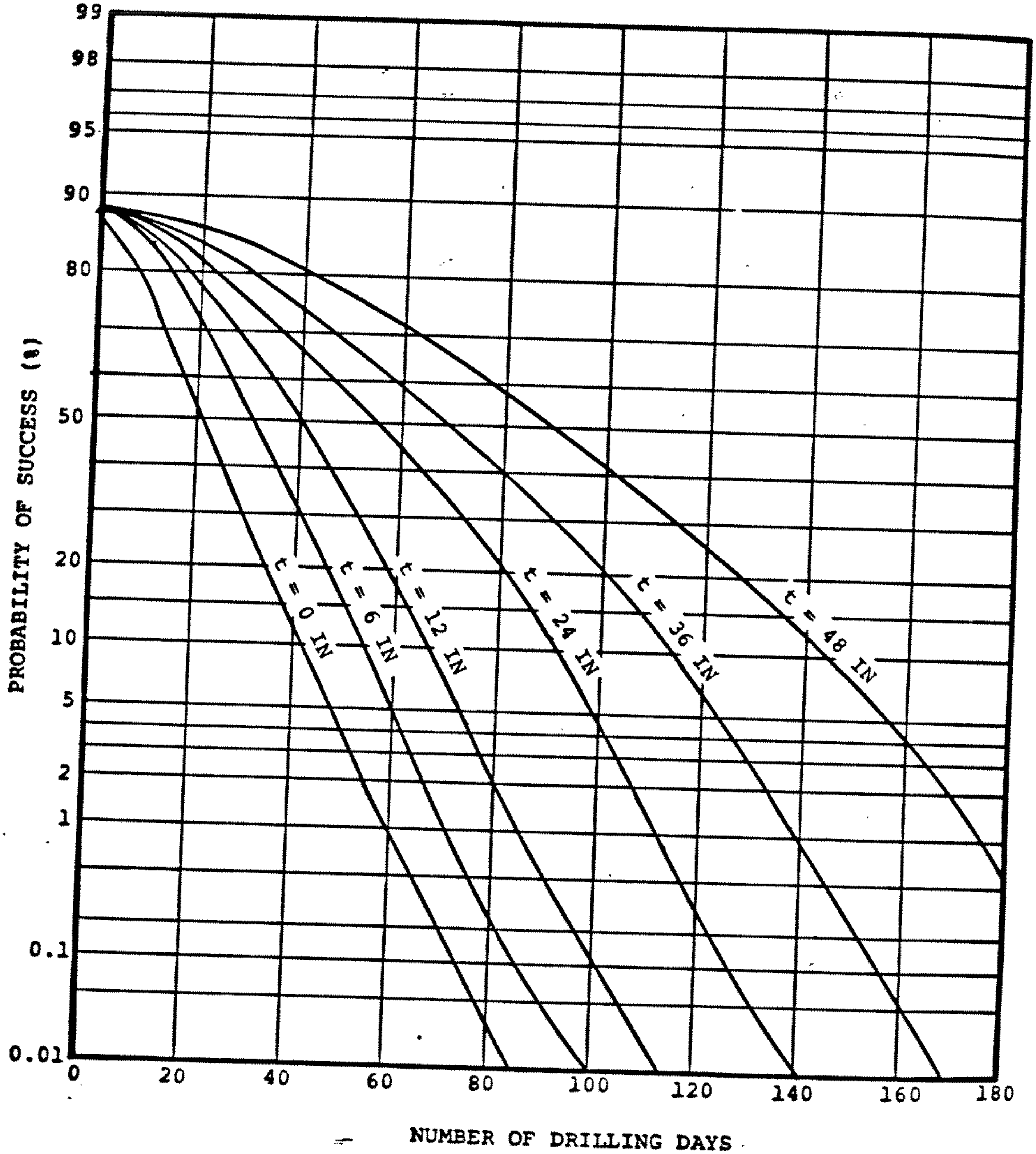


FIGURE 4.56 DRILLING SEASON LENGTH PROBABILITIES AT CHUKCHI SEA SITE BASED ON NWS DATA

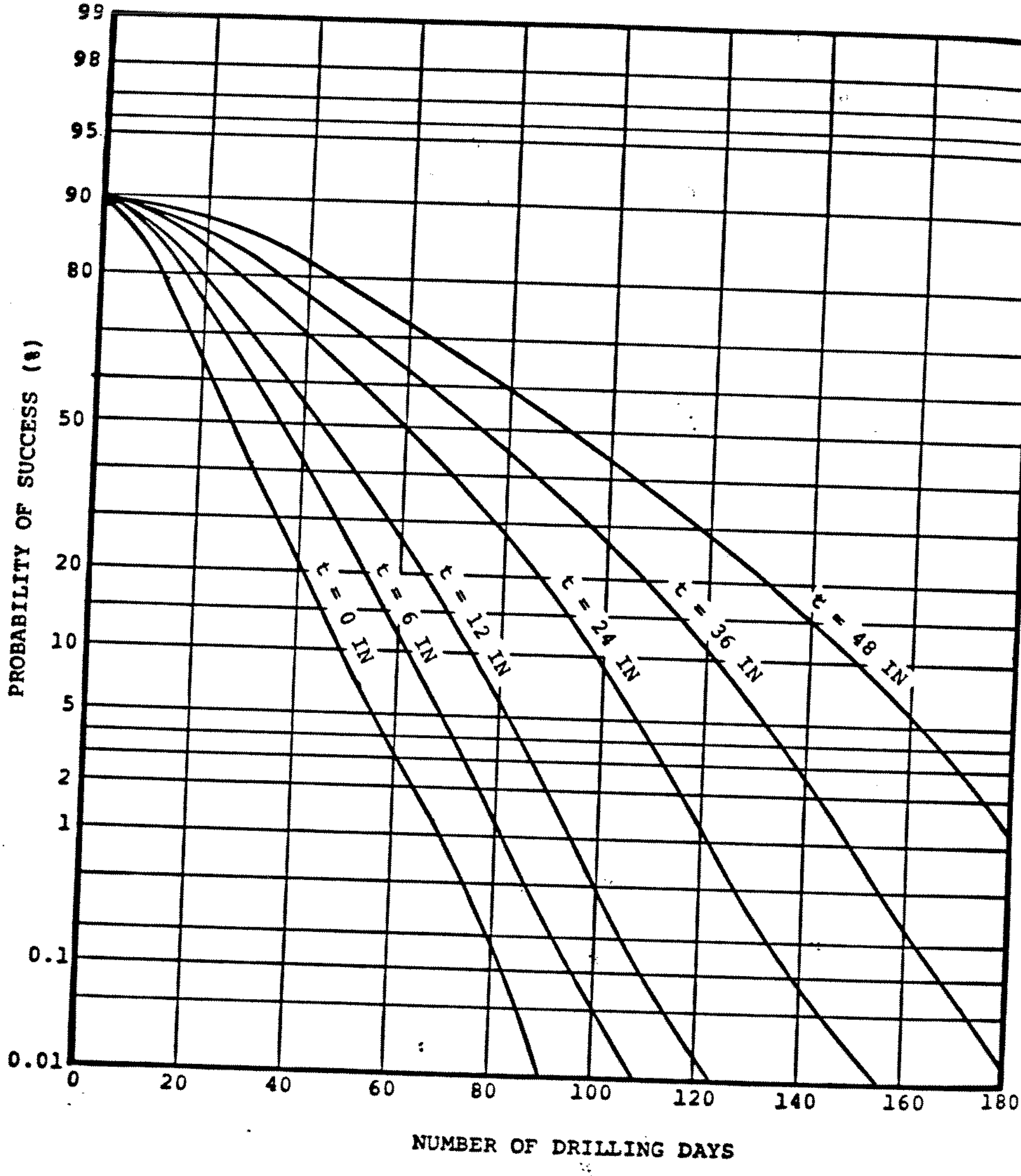


FIGURE 4.57 DRILLING SEASON LENGTH PROBABILITIES AT CAPE HALKETT SITE BASED ON NWS DATA

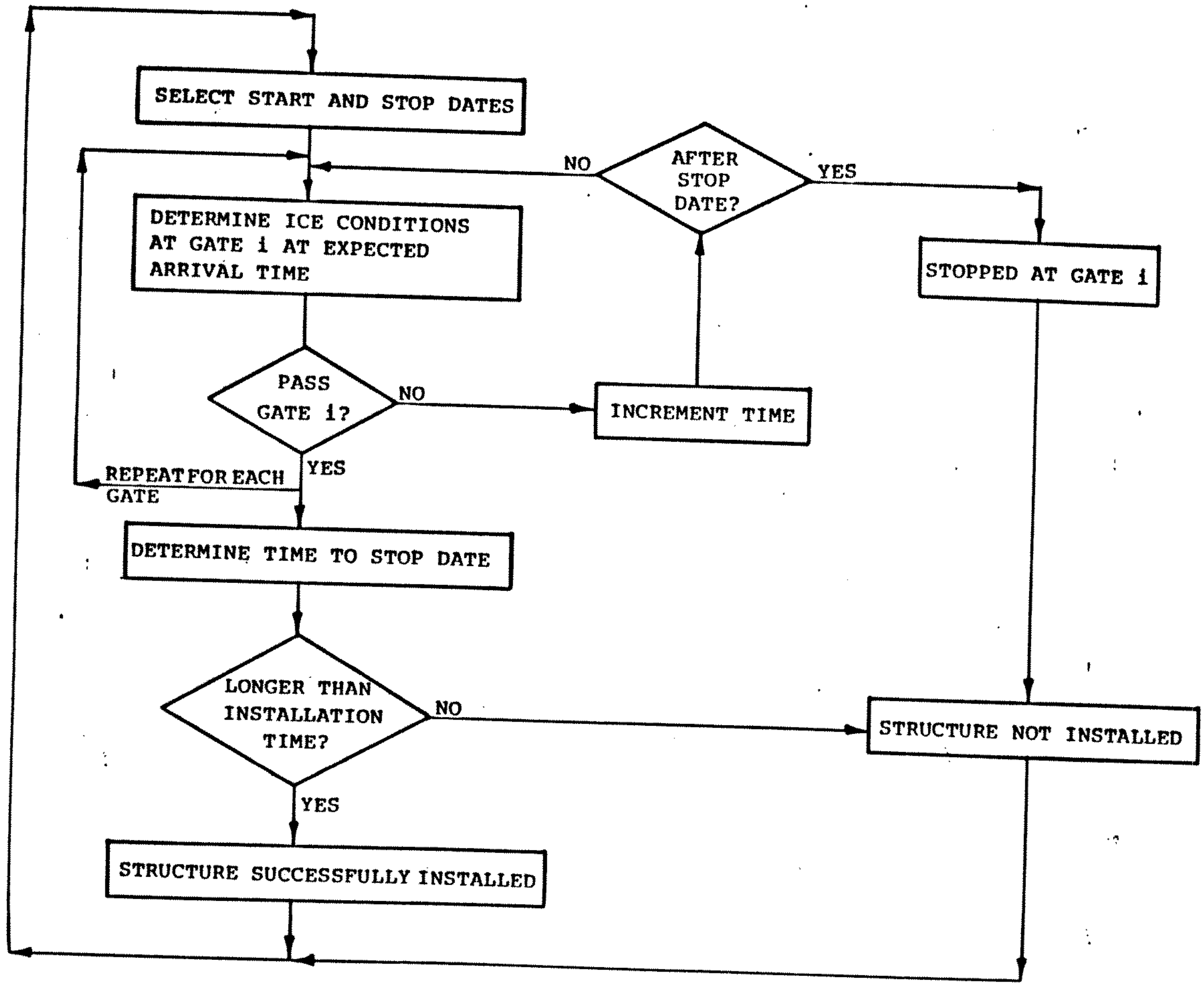


FIGURE 4.58 TOWING AND INSTALLATION ALGORITHM

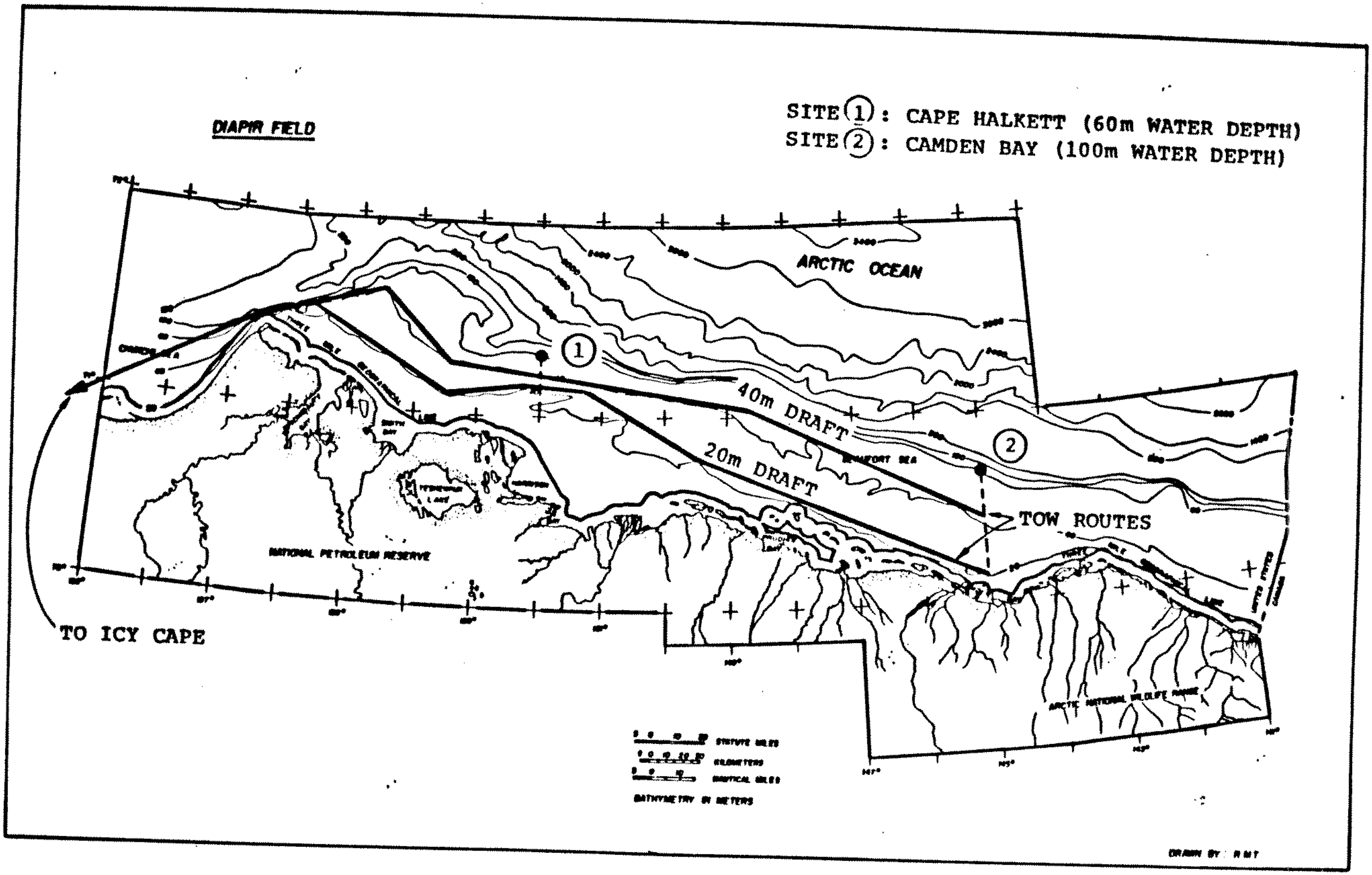


FIGURE 4.59 <u>TOW ROUTES AND SITES USED FOR RISK ANALYSIS</u>

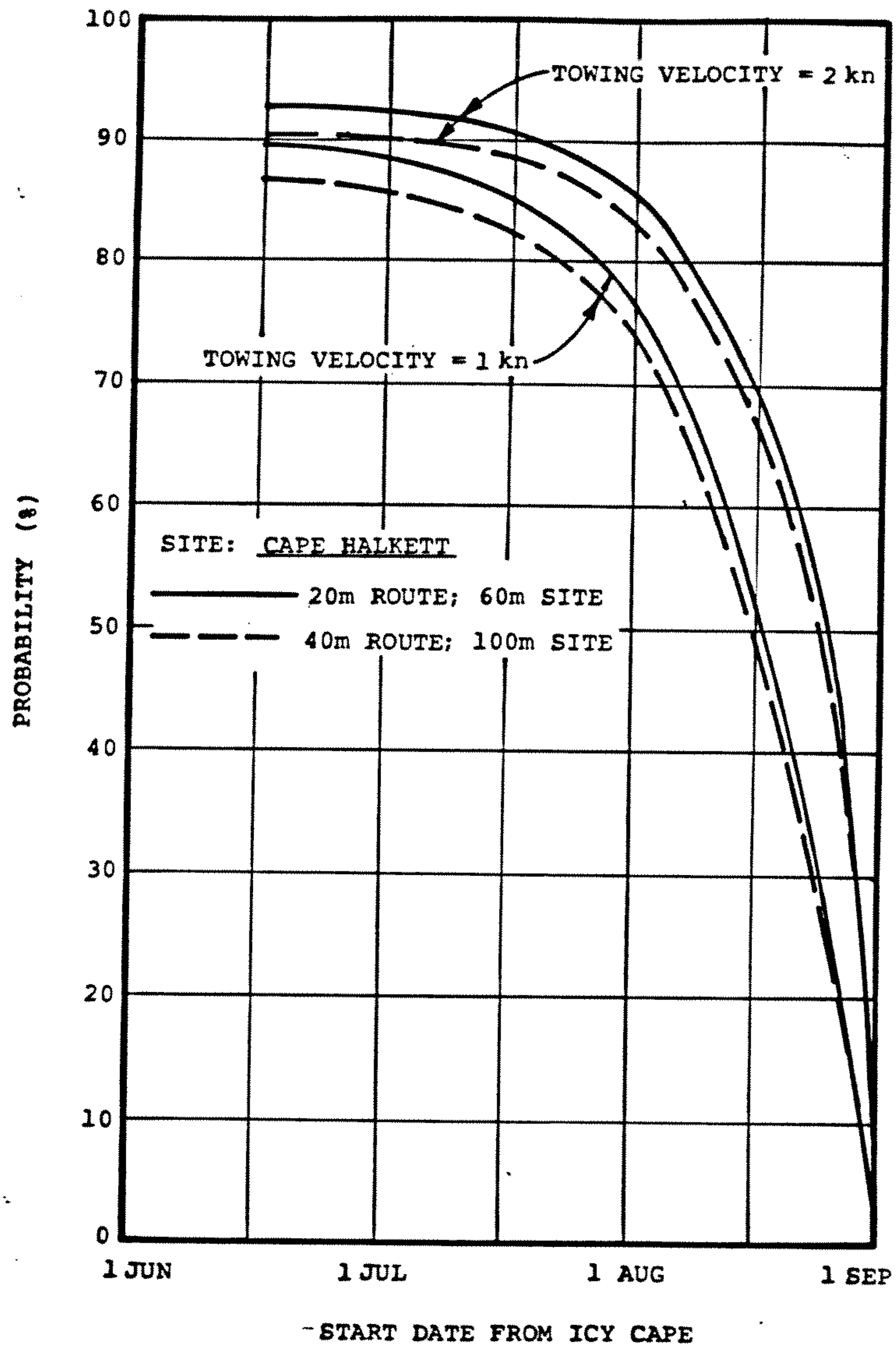


FIGURE 4.60 PROBABILITY OF SUCCESSFULLY INSTALLING STRUCTURE OFF CAPE HALKETT

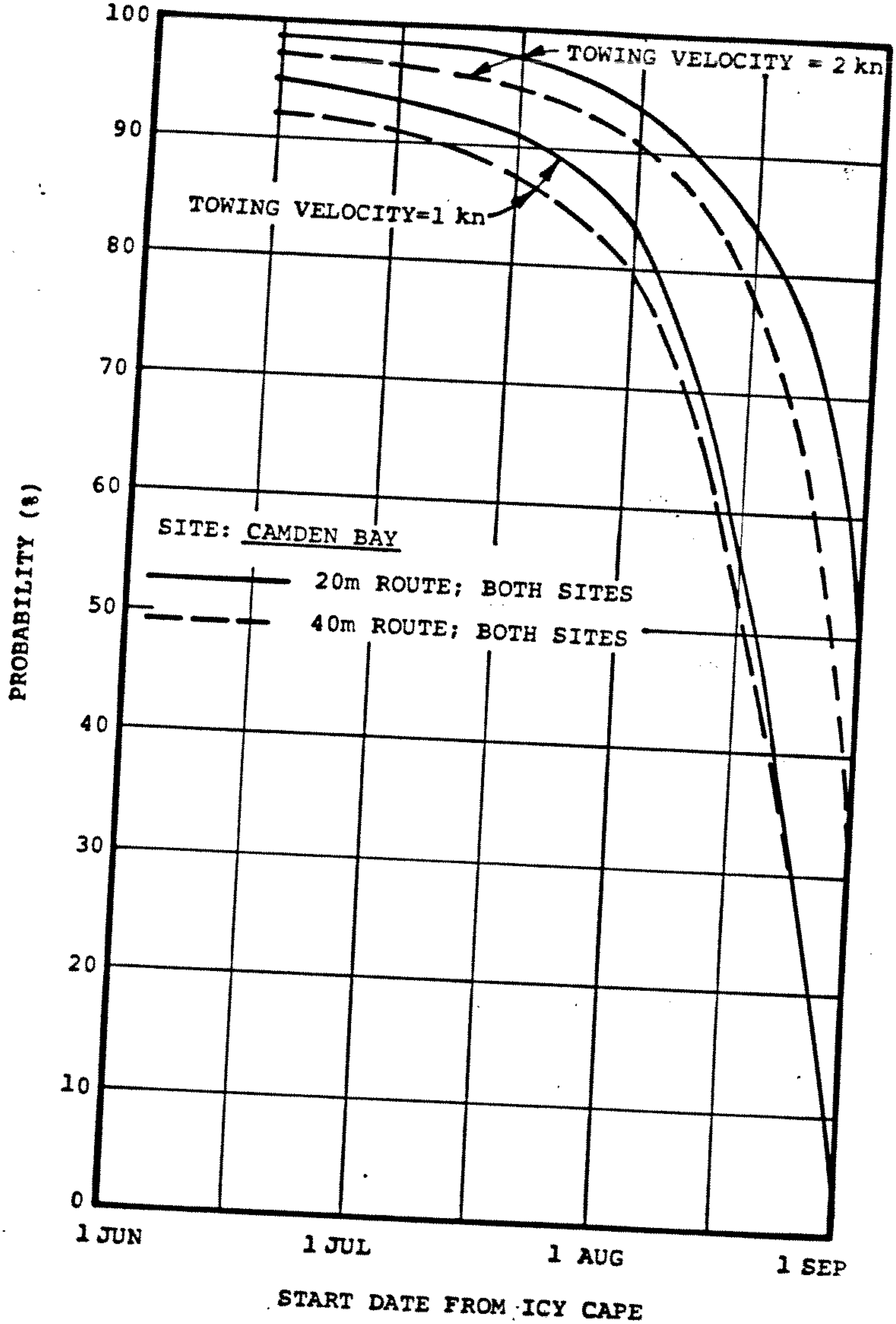


FIGURE 4.61 PROBABIITY OF SUCCESSFULLY INSTALLING STRUCTURE OFF CAMDEN BAY

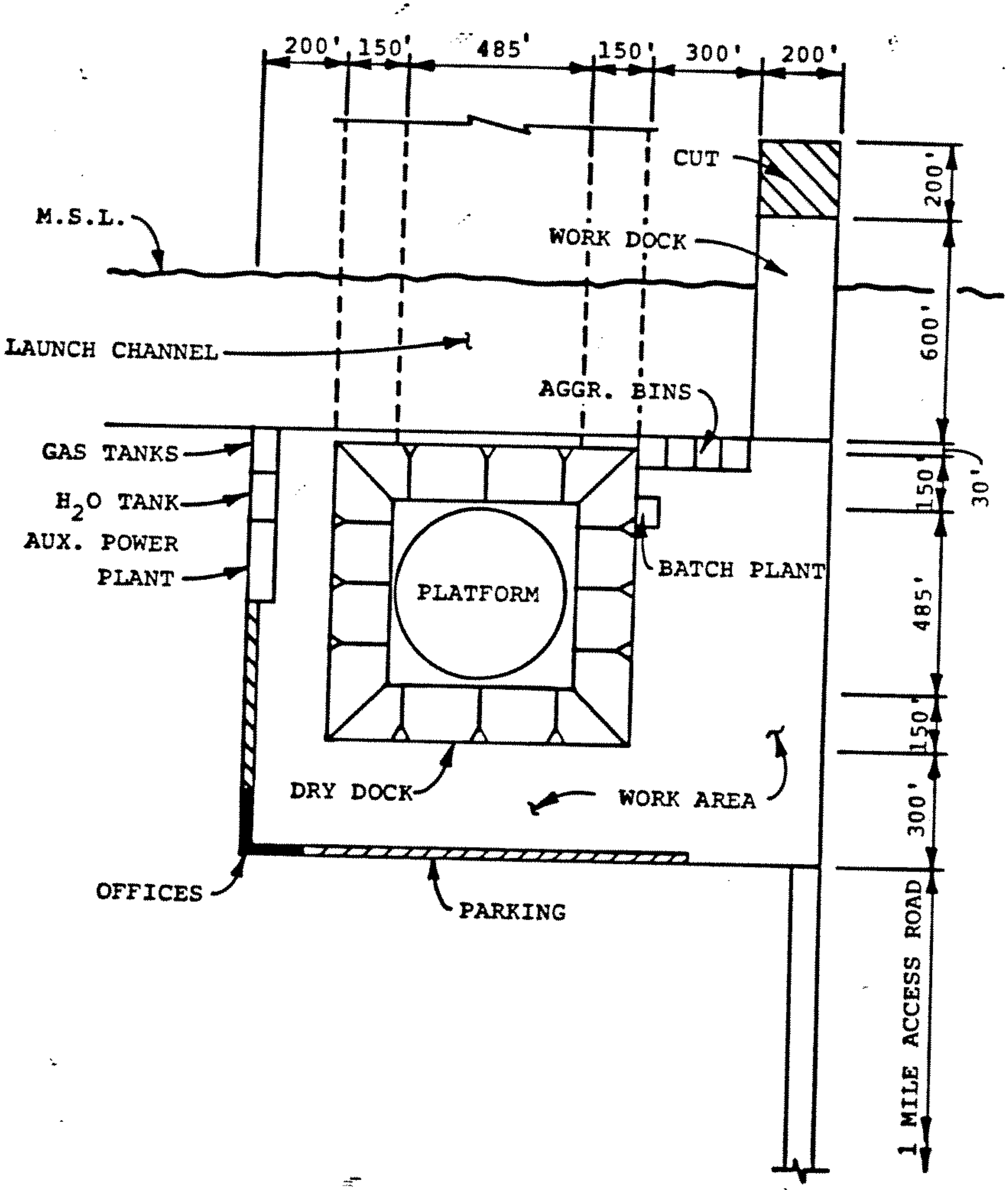


FIGURE 5.1 PLAN OF TYPICAL GRAVING YARD FOR CONSTRUCTION OF MONOLITHIC CONCRETE STRUCTURES

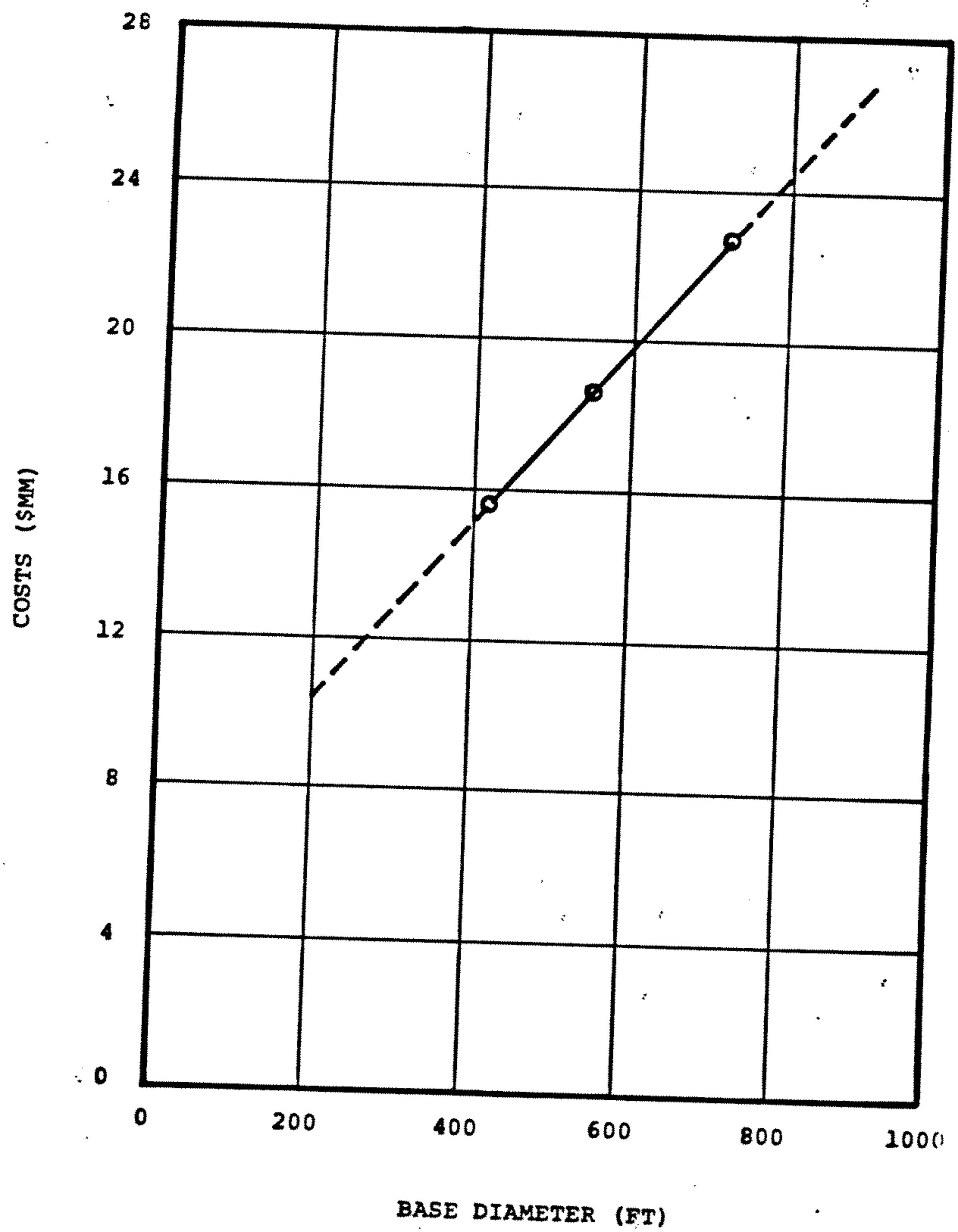


FIGURE 5.2 **GRAVING YARD CONSTRUCTION COST**

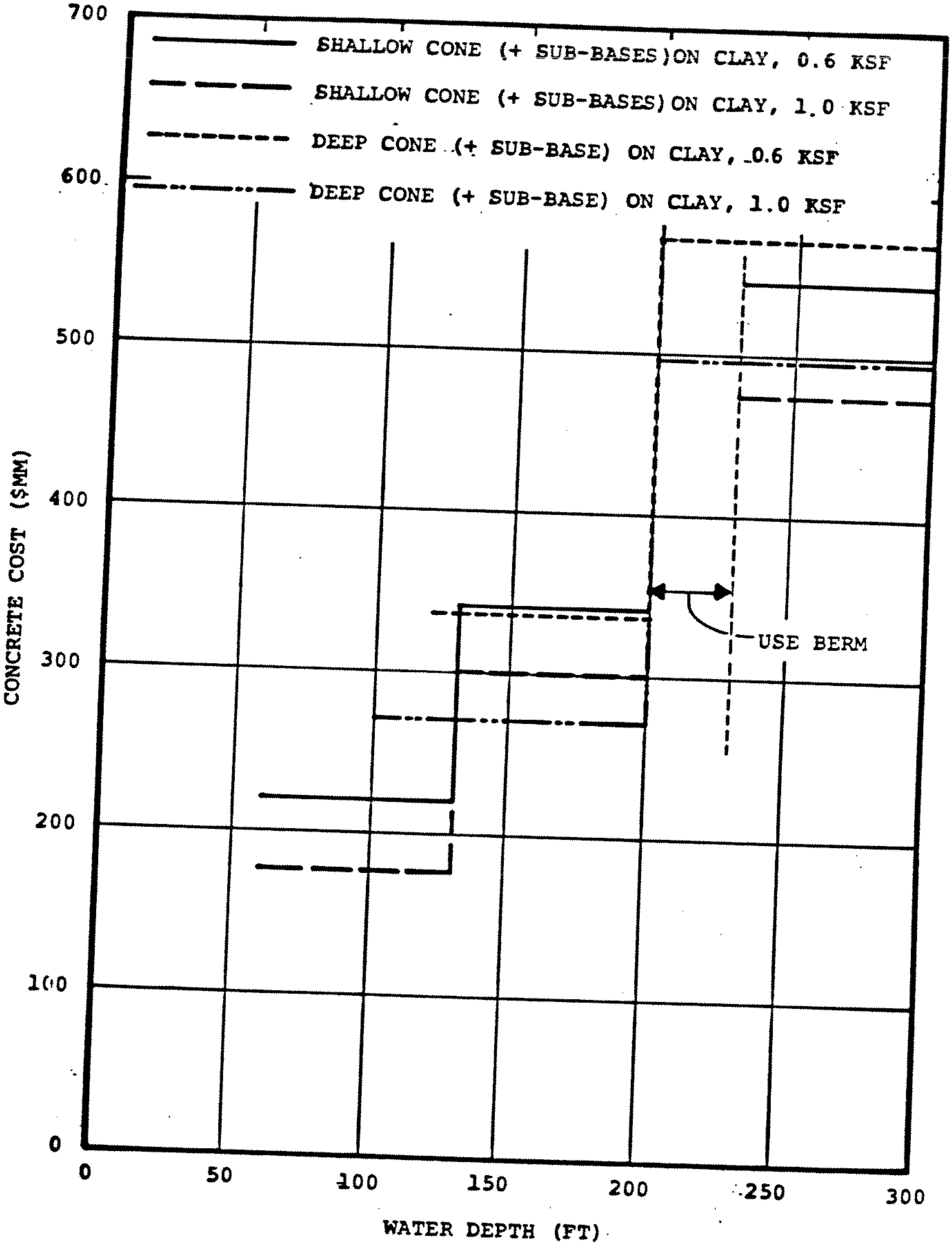


FIGURE 5.3 VARIATION OF CONCRETE STRUCTURE CONSTRUCTION COSTS WITH WATER DEPTH FOR EXPLORATION CONES - BASIC ICE LOADS

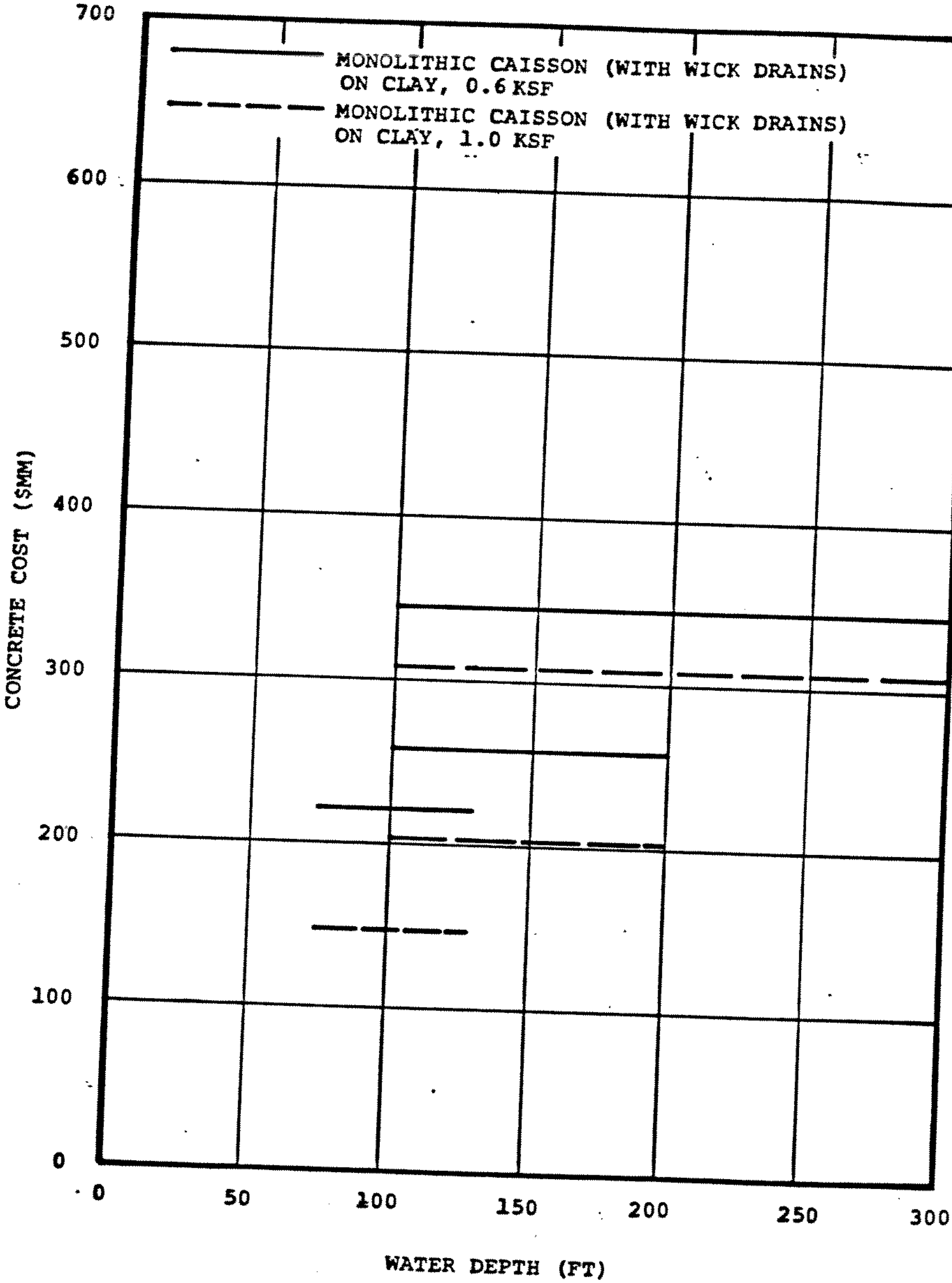


FIGURE 5.4 VARIATION OF CONCRETE STRUCTURE CONSTRUCTION COSTS WITH WATER DEPTH FOR EXPLORATION CAISSONS - BASIC ICE LOAD

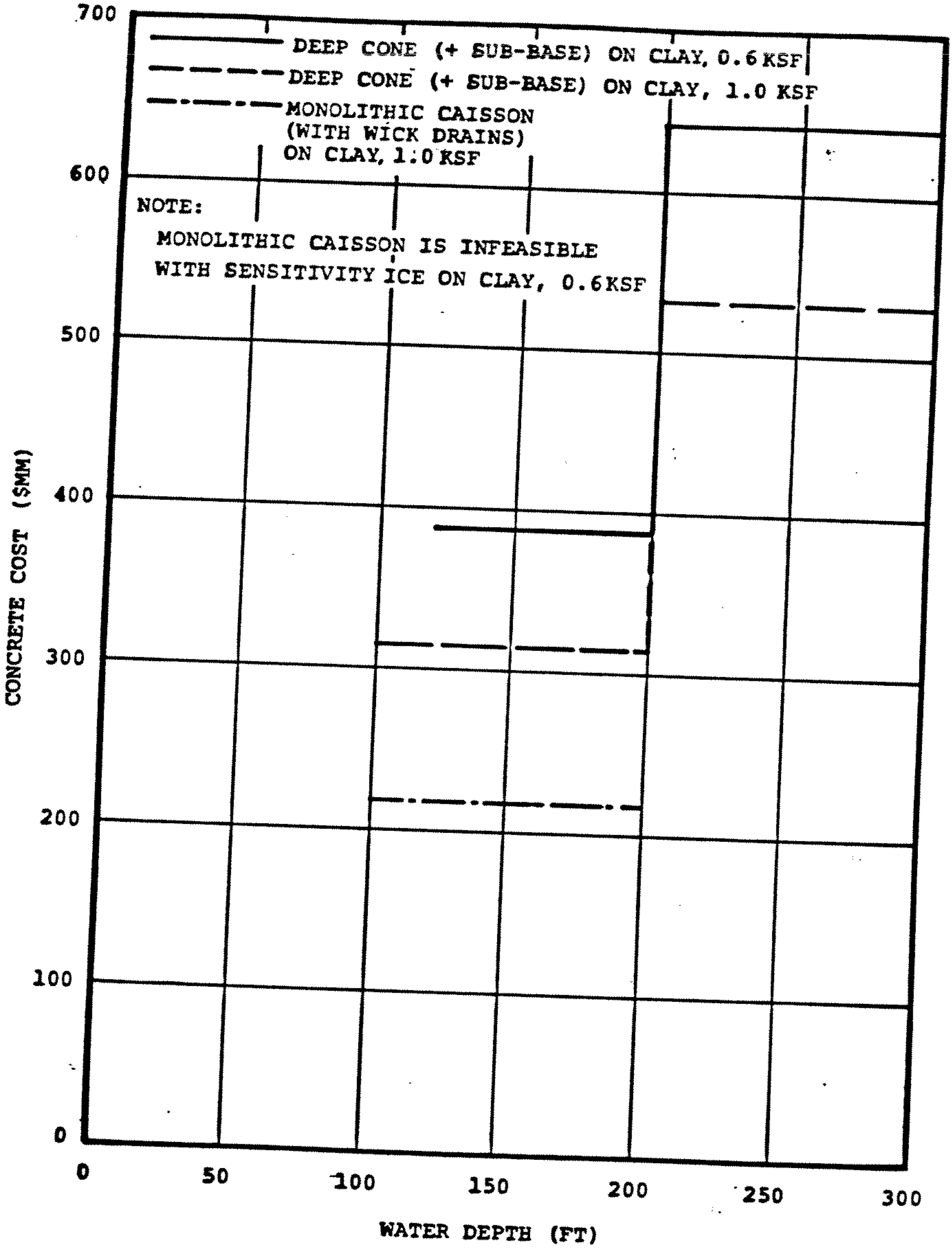


FIGURE 5.5 VARIATION OF CONCRETE STRUCTURE CONSTRUCTION COSTS WITH WATER DEPTH FOR EXPLORATION CONES AND CAISSONS - SENSITIVITY ICE LOADS

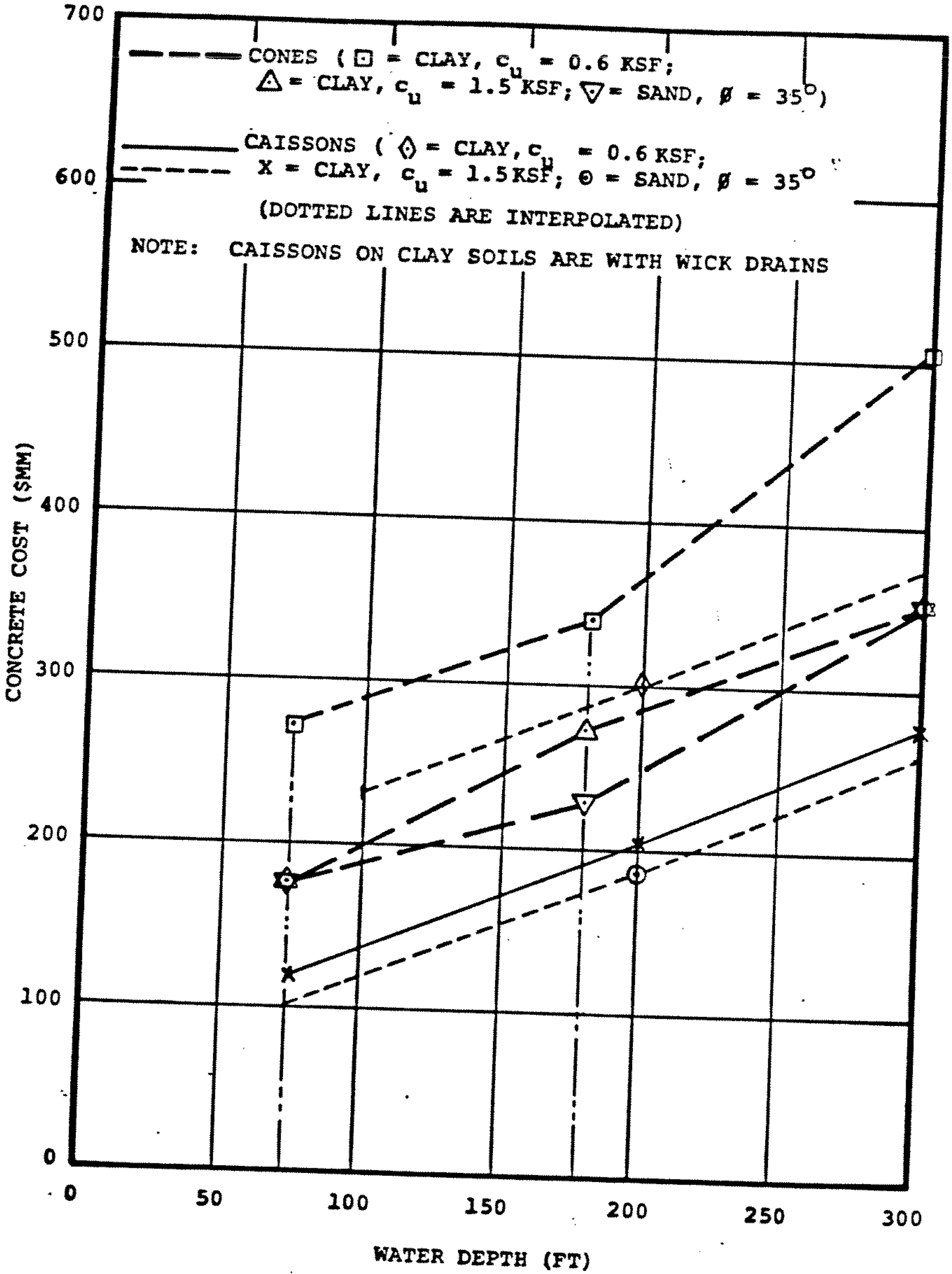


FIGURE 5.6 VARIATION OF CONCRETE STRUCTURE CONSTRUCTION COSTS WITH WATER DEPTH FOR PRODUCTION CONES AND CAISSONS (200,000 BOPD) - BASIC ICE LOADS

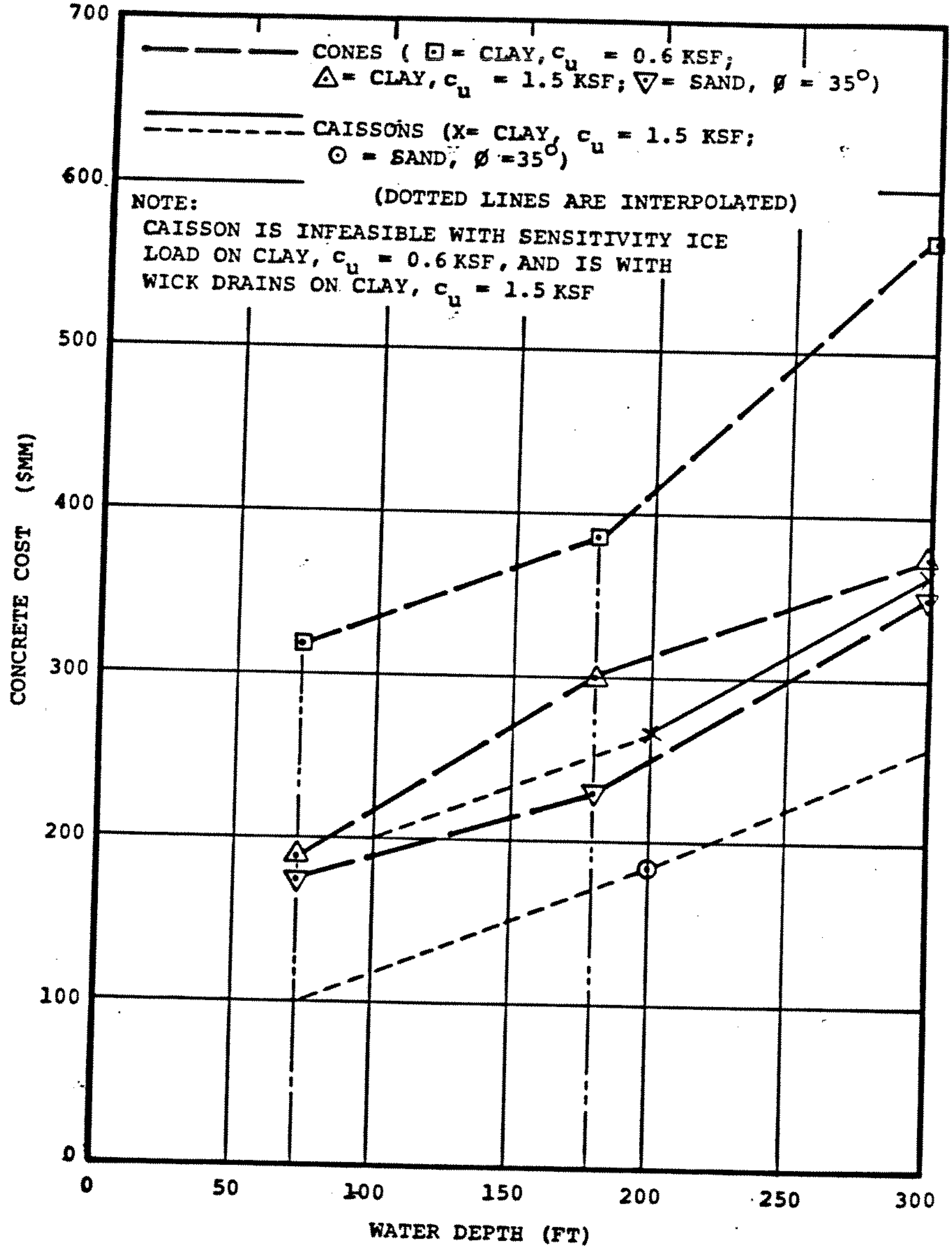


FIGURE 5.7 VARIATION OF CONCRETE STRUCTURE CONSTRUCTION COSTS WITH WATER DEPTH FOR PRODUCTION CONES AND CAISSONS (200,000 BOPD) - SENSITIVITY ICE LOADS

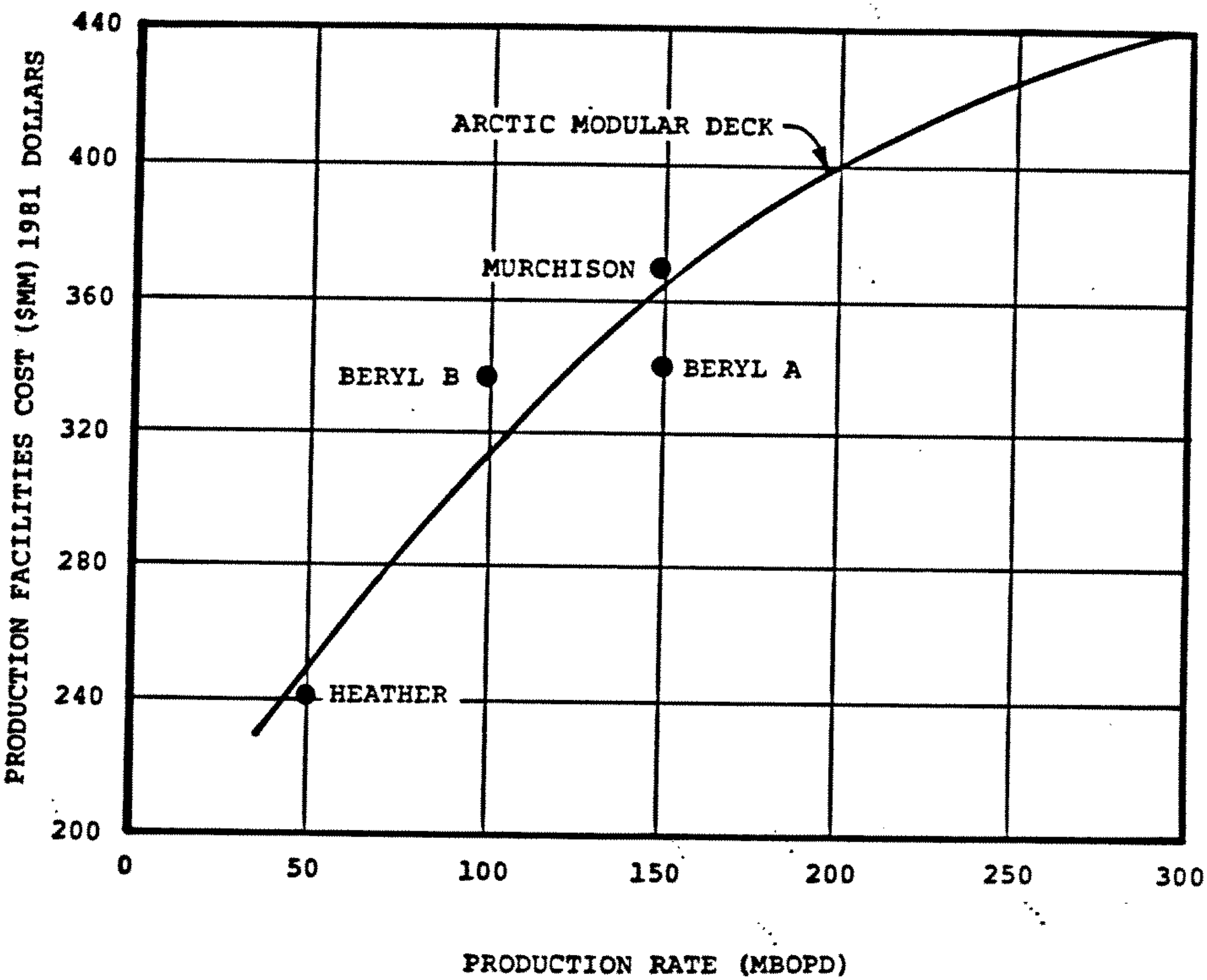
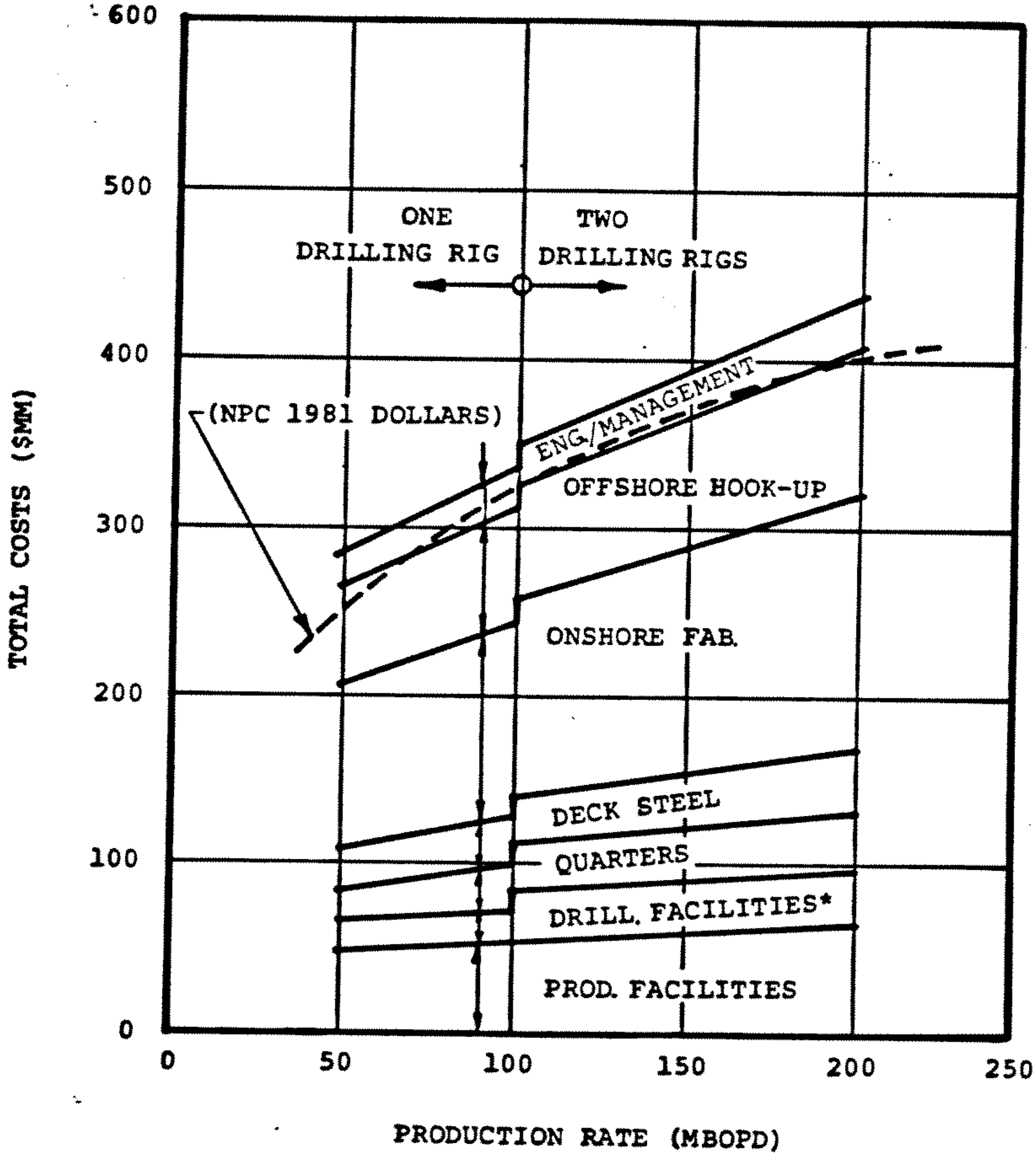


FIGURE 5.8 PRODUCTION RATE VS. TOPSIDES FACILITIES COST (NATIONAL PETROLEUM COUNCIL - REF. 12)



* CONSUMABLES EXCLUDED

FIGURE 5.9 **TOPSIDES COSTS (PRODUCTION STRUCTURES)**

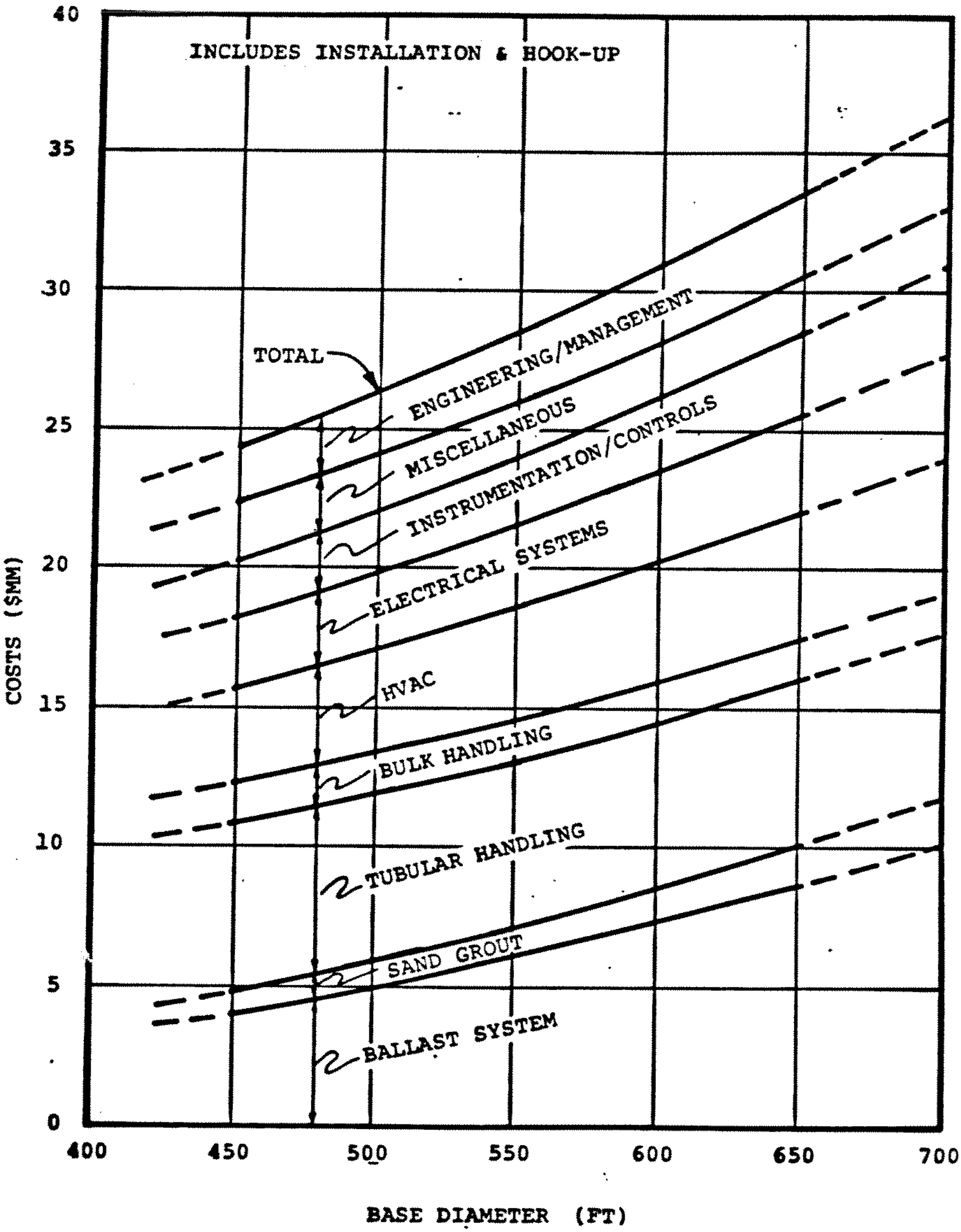


FIGURE 5.10 COSTS FOR M & E SYSTEMS INSIDE HULL (CONES AND CAISSONS)

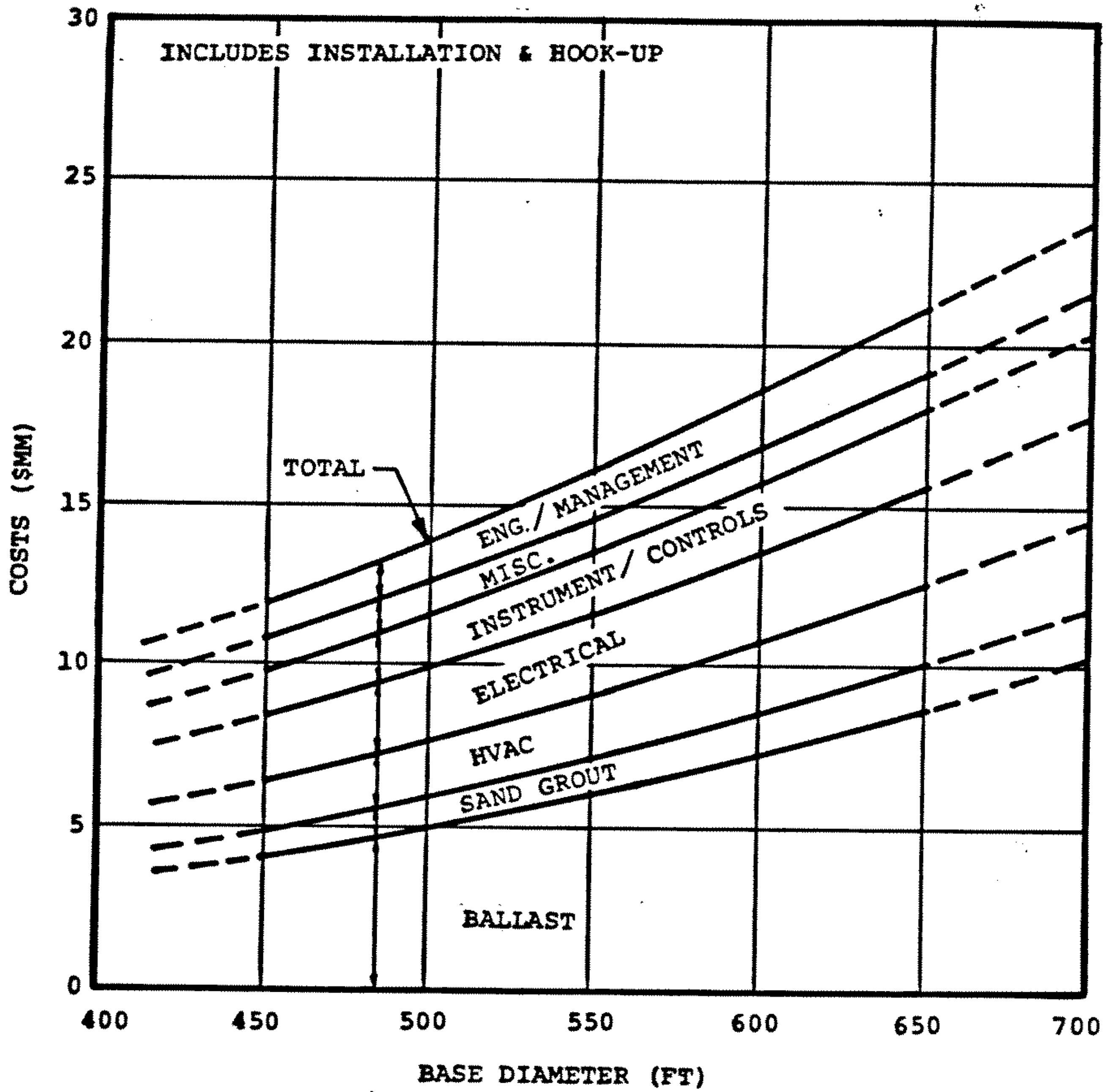


FIGURE 5.11 COSTS FOR M & E SYSTEMS INSIDE HULL (SUB-BASES)

BRIAN WATT ASSOCIATES, INC. CONSULTING ENGINEERS HOUSTON, TEXAS	CLIENT: JOINT INDUSTRY CLIENTS PROJECT:	FILING CODE: 211 JOB NO. PAGE 10 OF
SYSTEM: SYSTEM COSTS		ORIGINATOR JWB DATE: 11/20/83
CALCULATION FOR: MARINE OPERATIONS AT CONSTRUCTION SITE		REVIEWER: DATE: REVISION: RESULTS:

8. Submergence Test for Sub Base

Assumptions.

- Operation to last 2 weeks
- One Generator / Pump Barge @ $40,000/day
- 4 - 9000 HP tugs @ $15,000/day each
- Misc. Support @ $20,000/day (total)
- Operatives 15 x 8 x 50 = $ 6,000/day.

Costs:-

		$
Generator/Pump Barge:	14 x 40,000 =	560,000
Tugs: 4 x 14 x 15,000	=	840,000
Misc. Support 14 x 20,000	=	280,000
Operatives 14 x 6,000	=	84,000
Engg and Management 8%	=	86,000
TOTAL	$	1,090,000

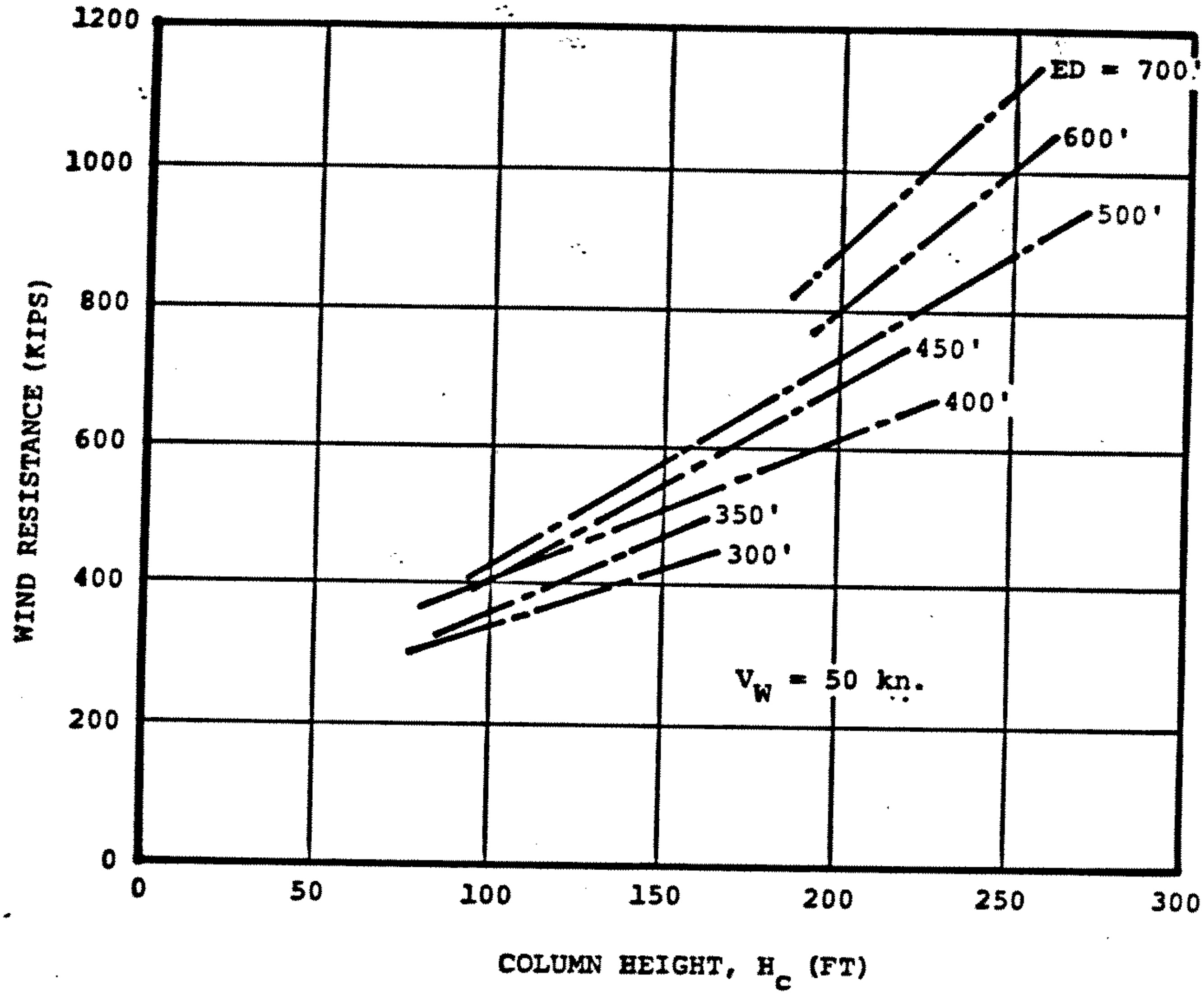
say $ 1.1 MM.

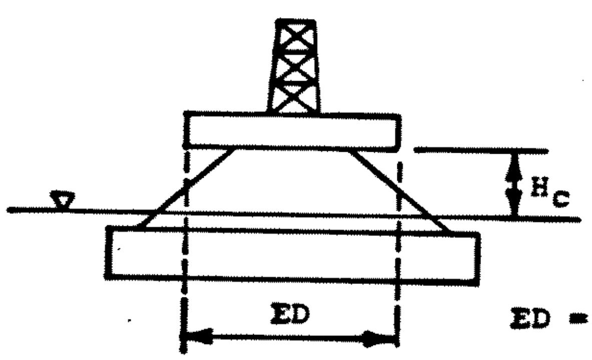
9. Submergence Test for Cone or Caisson.

Use Cost for Sub Base $ 1.1 MM

FILING CODE:

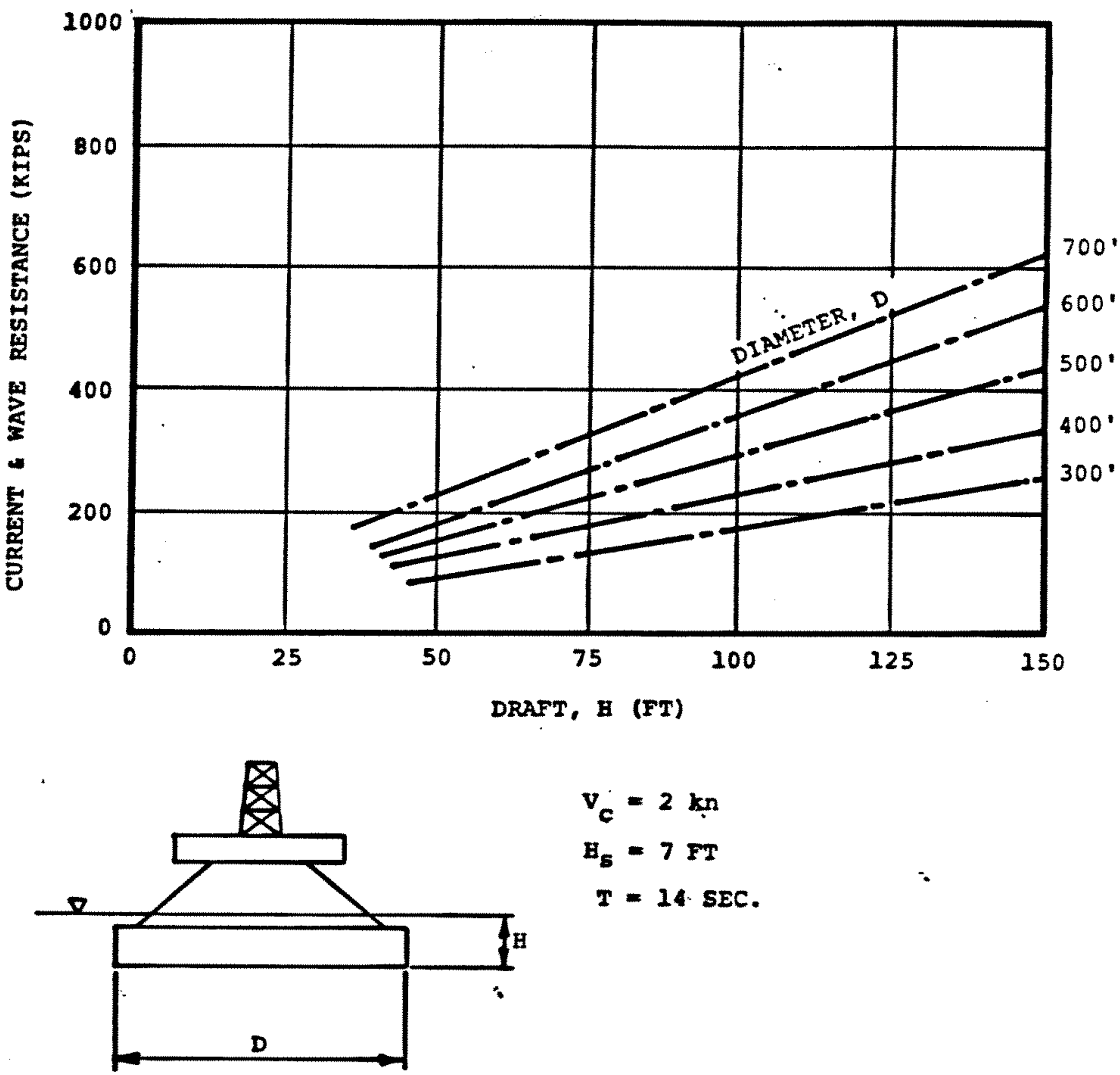
FIGURE 5.12 SAMPLE SHEET SHOWING LEVEL OF DETAIL USED IN COSTING MARINE OPERATIONS





ED = EFFECTIVE DIAMETER

FIGURE 5.13 **WIND RESISTANCE**



INDICATED TUG HORSEPOWER, (IHP) REQUIRED = 60.61 x WIND, WAVE, & CURRENT RESISTANCE IN KIPS.

FIGURE 5.14 <u>CURRENT AND WAVE RESISTANCE ON CONES</u>

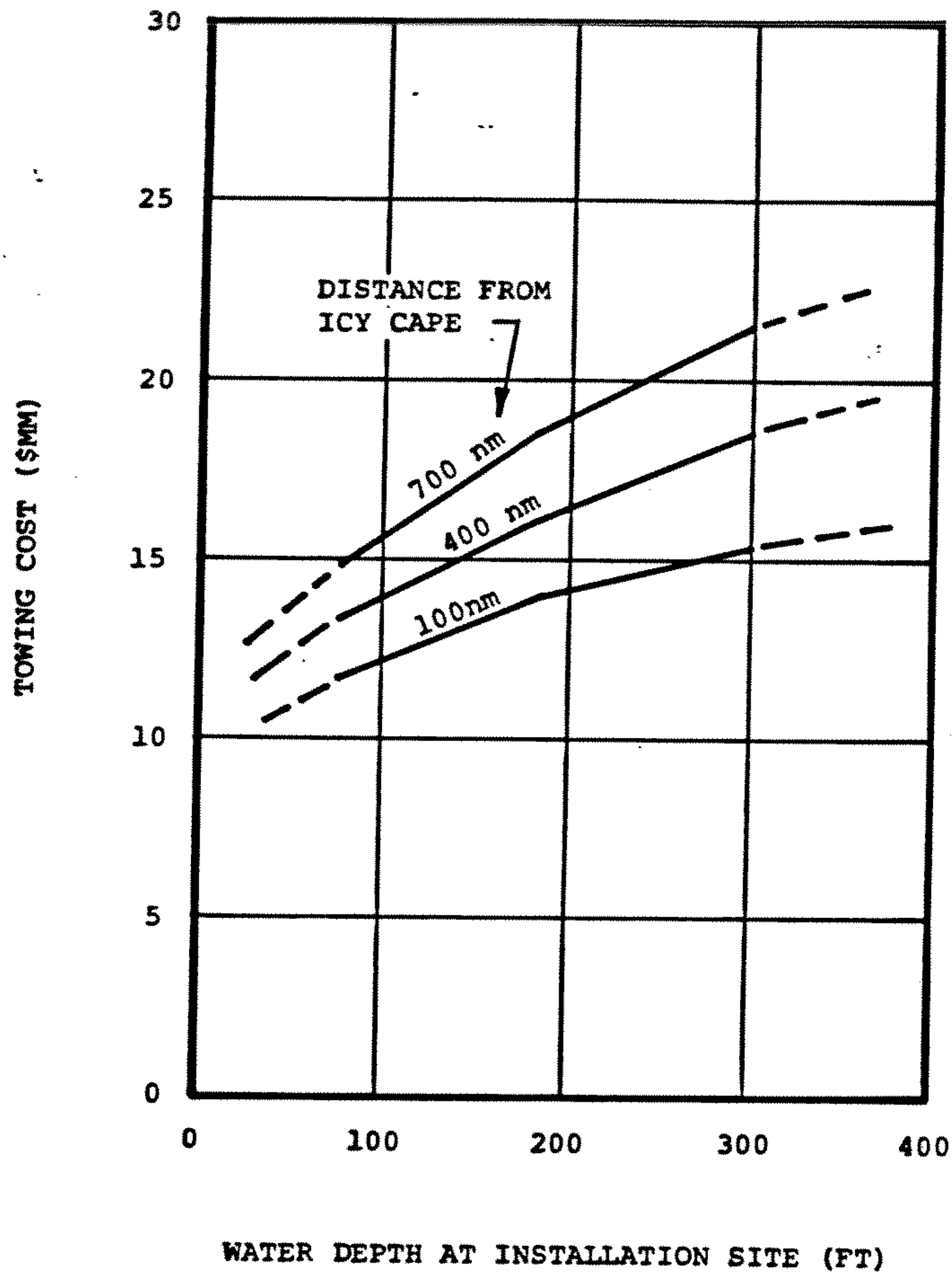
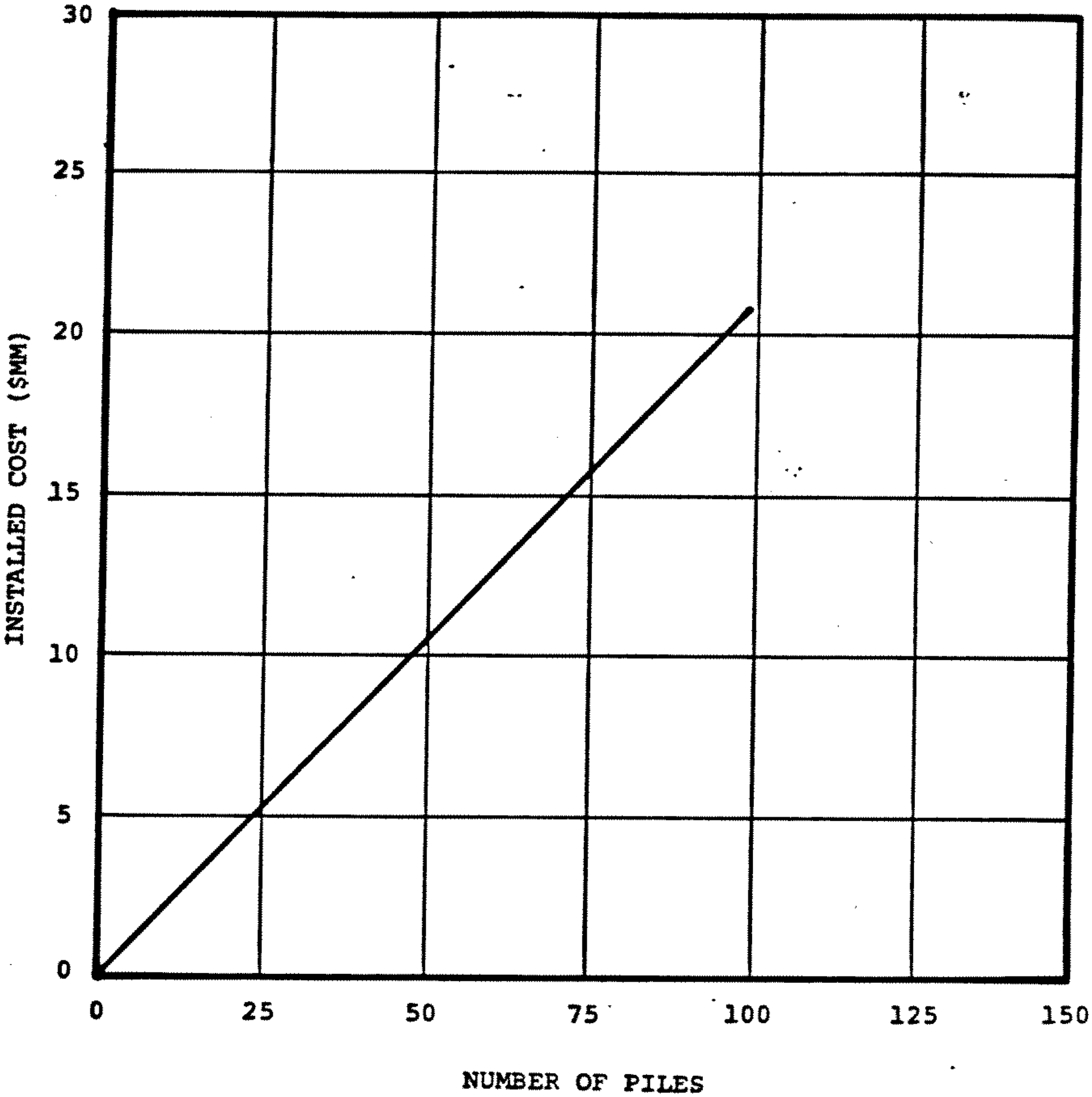


FIGURE 5.15 <u>TOWING COSTS FROM SEATTLE</u>



(7' DIA, 100 FT LONG x 4" THICK)

FIGURE 5.16 COSTS OF SPUD PILES

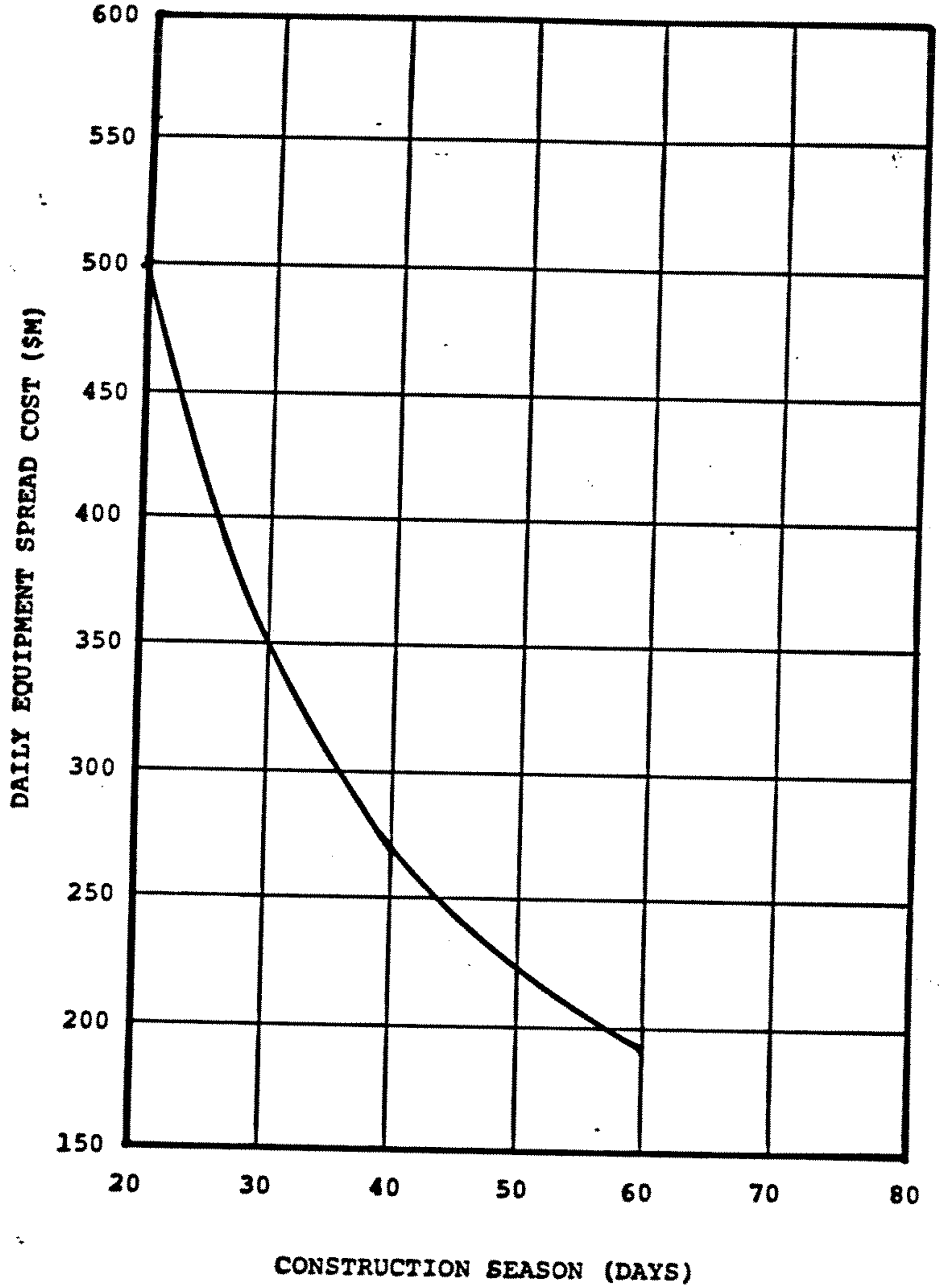


FIGURE 5.17 VARIATION OF DAILY EQUIPMENT SPREAD COST WITH CONSTRUCTION SEASON FOR EQUIPMENT SPREAD A (DREDGE LOCAL TO SITE)

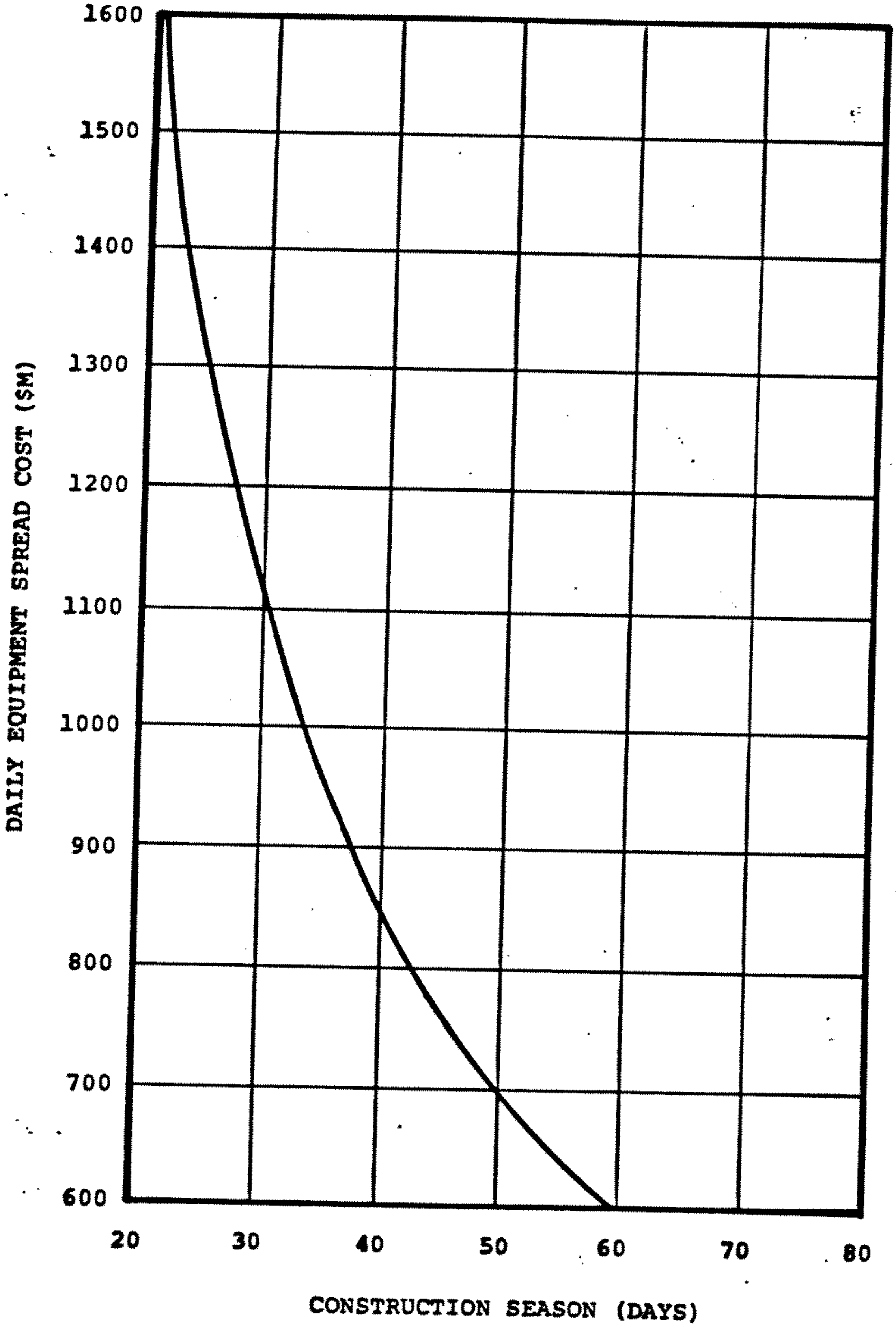


FIGURE 5.18 VARIATION OF DAILY EQUIPMENT SPREAD COST WITH CONSTRUCTION SEASON FOR EQUIPMENT SPREAD B (DREDGE AND HAUL FROM OFFSHORE SOURCE)

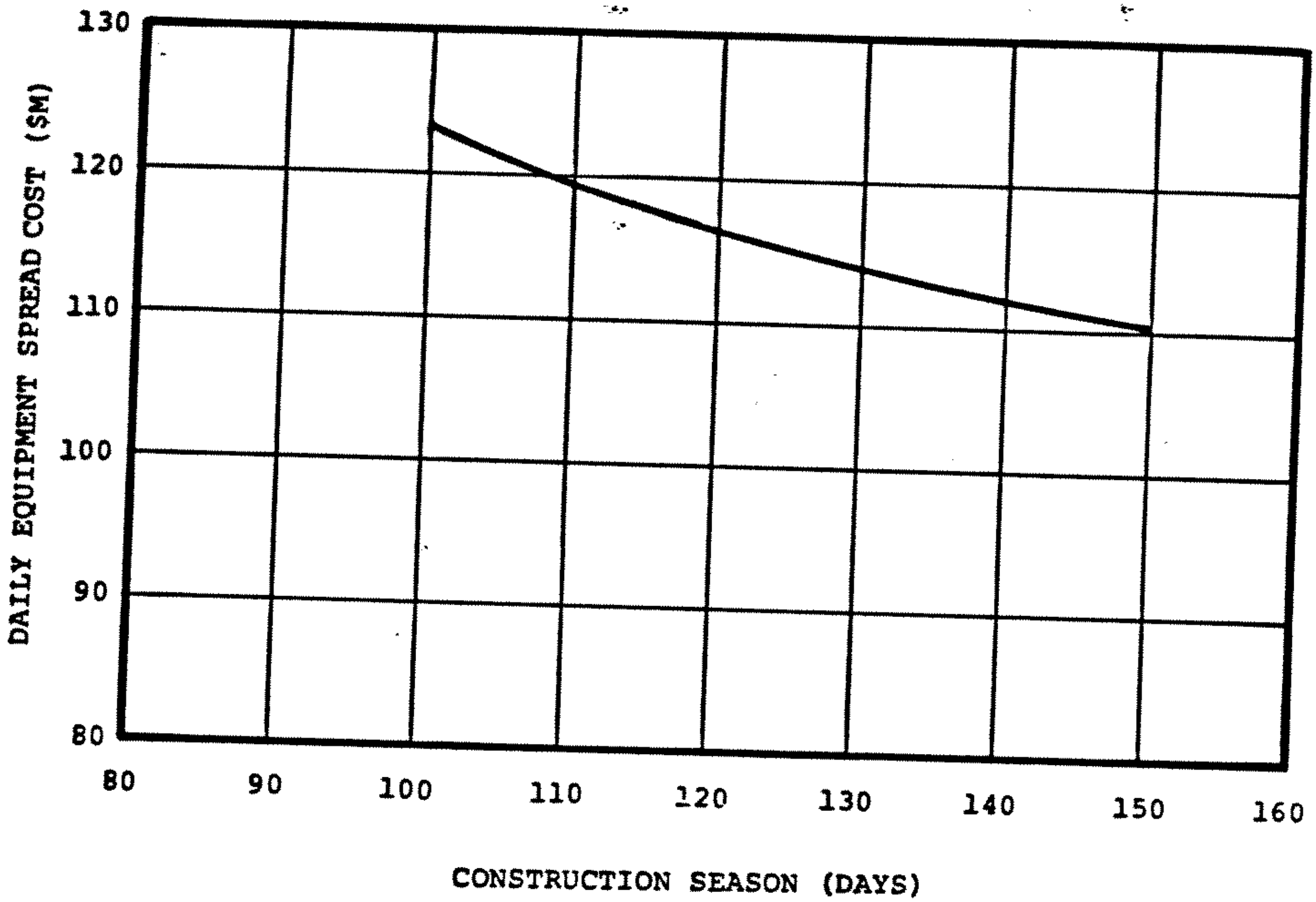


FIGURE 5.19 VARIATION OF DAILY EQUIPMENT SPREAD COST WITH CONSTRUCTION SEASON FOR EQUIPMENT SPREAD C (EXCAVATION AND HAUL FROM LAND SOURCE TO DOCKING FACILITY)

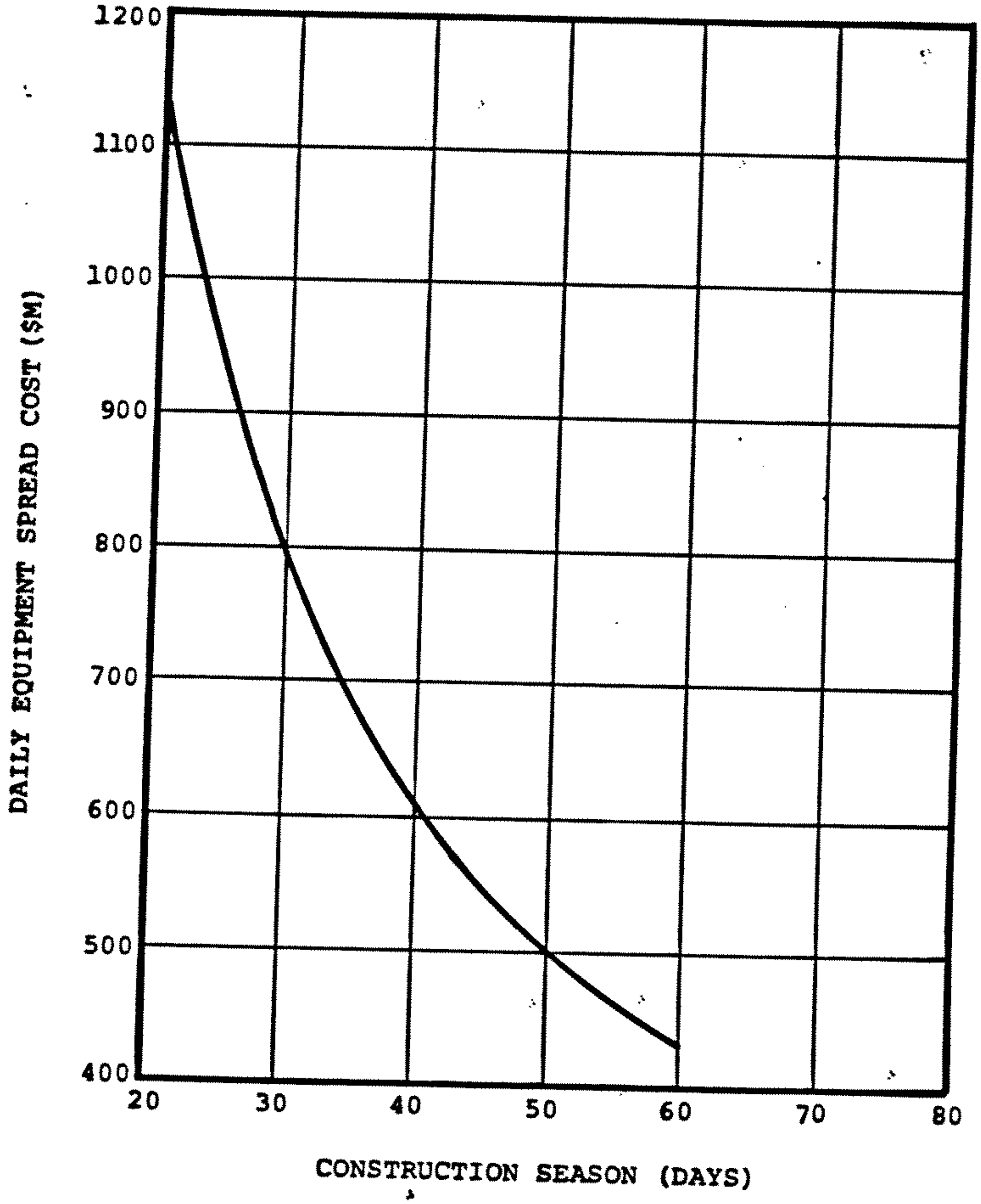


FIGURE 5.20 VARIATION OF DAILY EQUIPMENT SPREAD COST WITH CONSTRUCTION SEASON FOR EQUIPMENT SPREAD D (HAUL FROM DOCK FACILITY TO SITE)

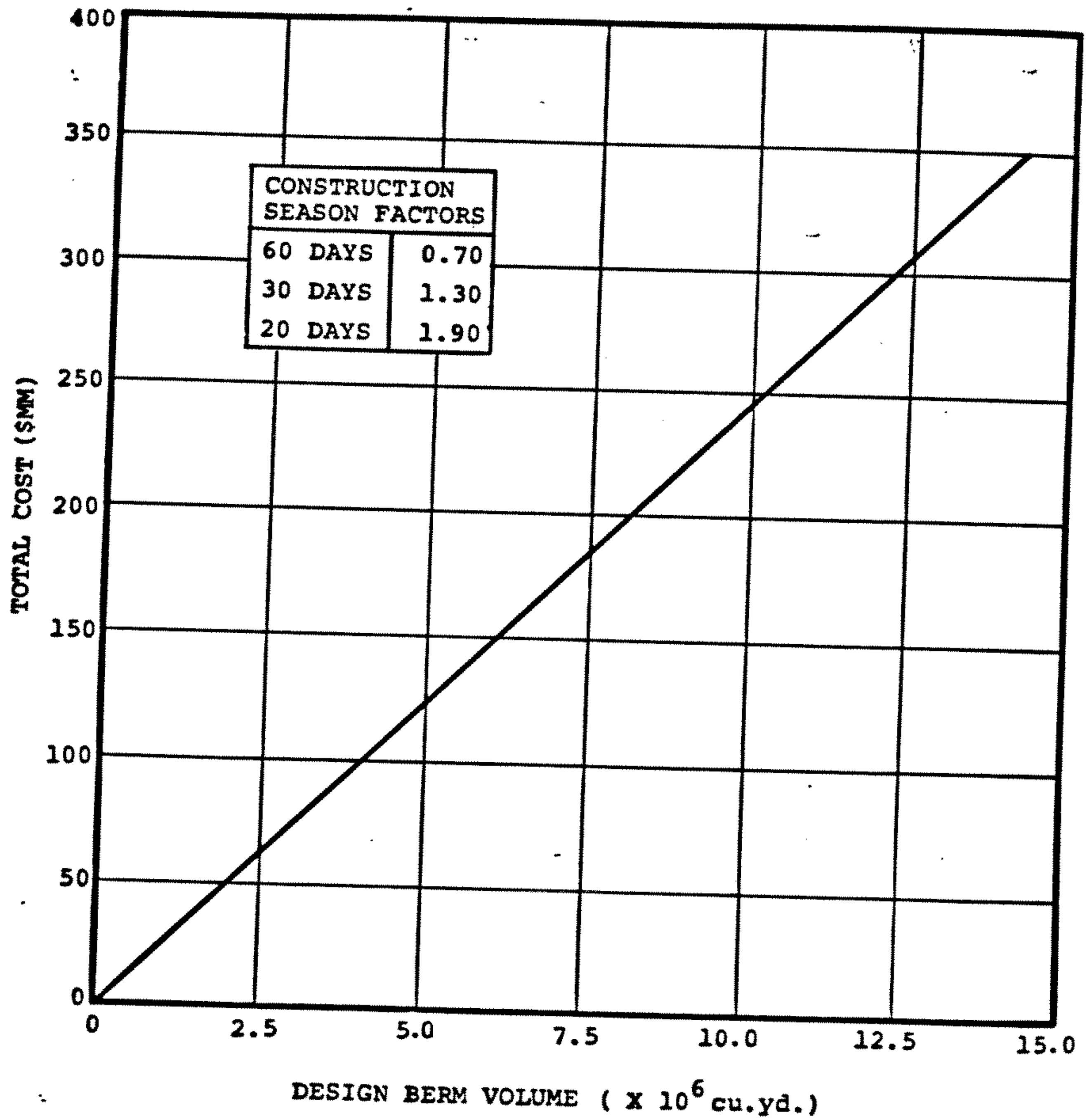


FIGURE 5.21 VARIATION OF TOTAL COST WITH BERM VOLUME (EQUIPMENT SPREAD A) (40-DAY CONSTRUCTION SEASON)

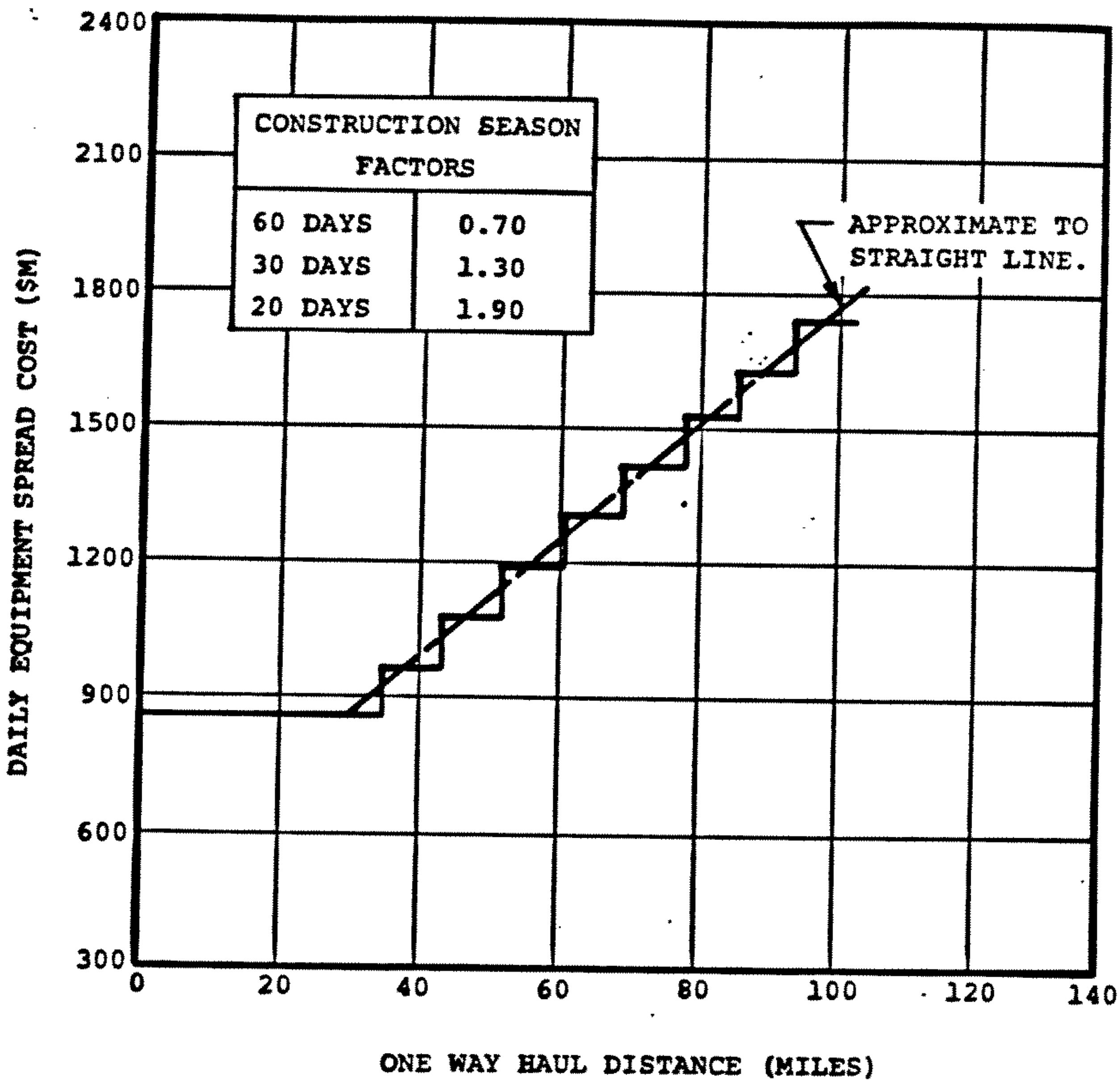


FIGURE 5.22 VARIATION IN EQUIPMENT SPREAD COST WITH HAUL DISTANCE FOR EQUIPMENT SPREAD B MAINTAINING CONSTANT PRODUCTION RATE OF 66,000 CU.YD/DAY (40-DAY CONSTRUCTION SEASON)

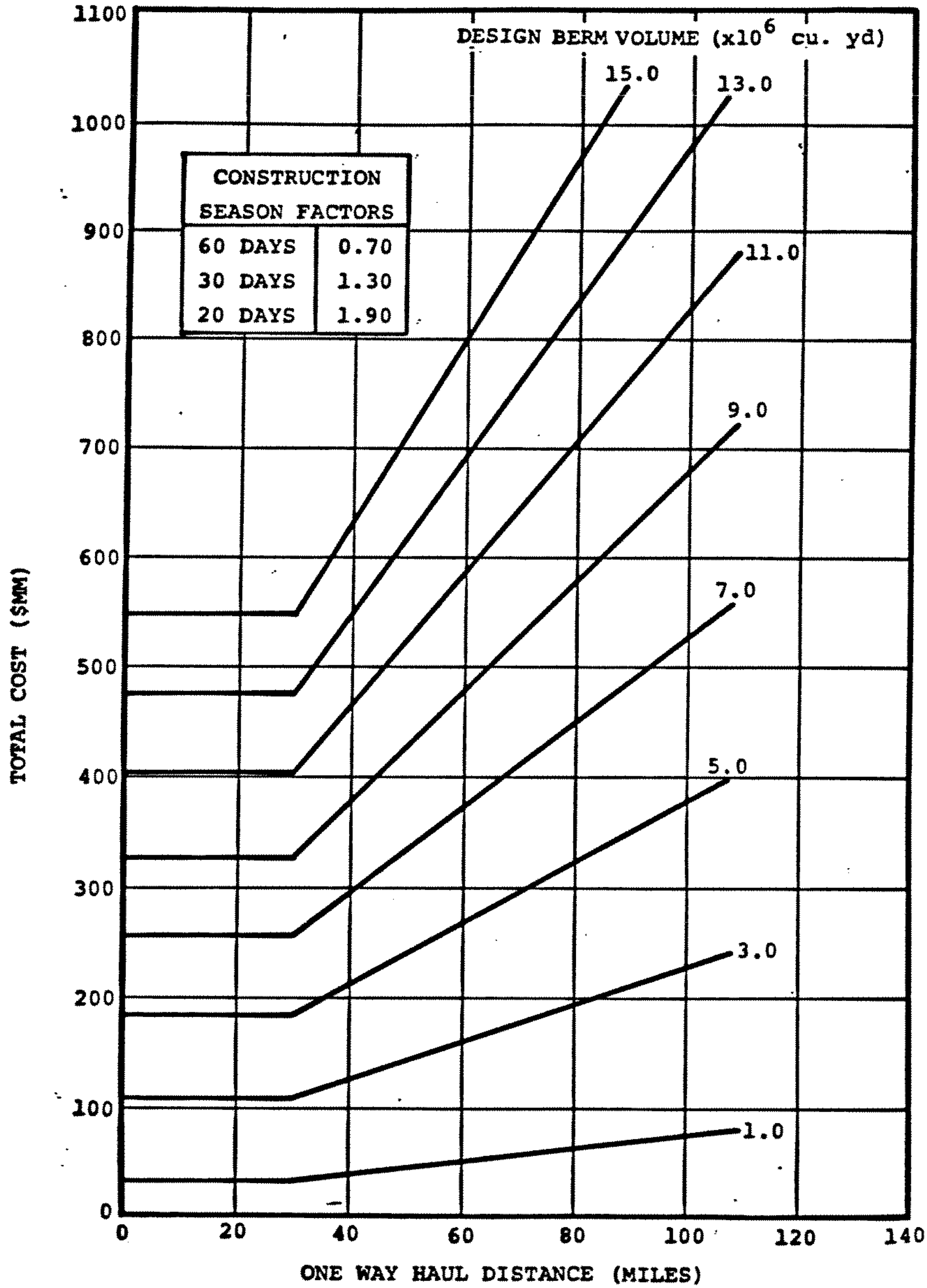


FIGURE 5.23 VARIATION OF TOTAL COST WITH HAUL DISTANCE (EQUIPMENT SPREAD B) (40-DAY CONSTRUCTION SEASON)

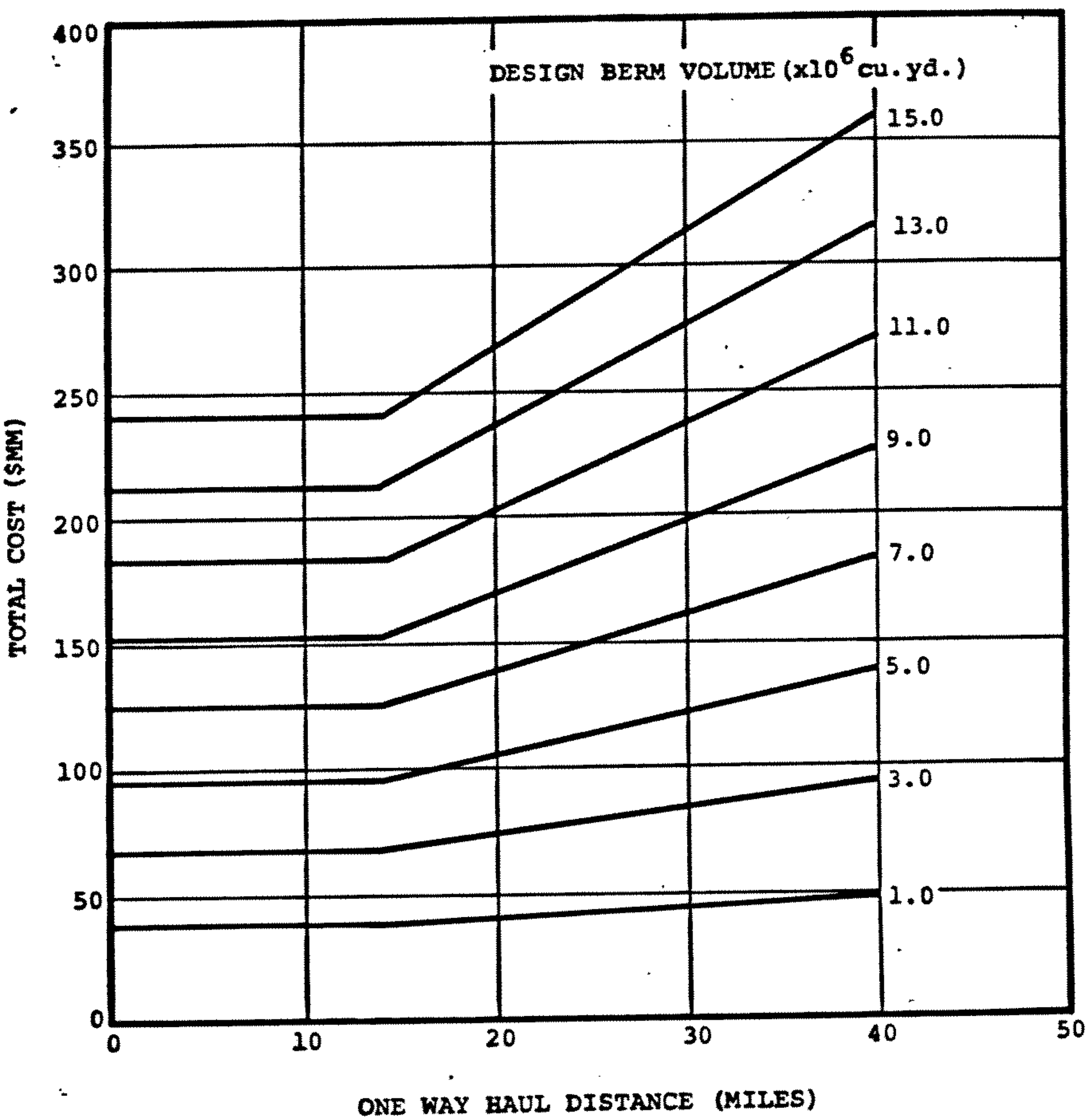


FIGURE 5.24 VARIATION OF TOTAL COST WITH HAUL DISTANCE FROM LAND BORROW SOURCE TO DOCKING FACILITY (EQUIPMENT SPREAD C) (135-DAY CONSTRUCTION SEASON (WINTER CONSTRUCTION))

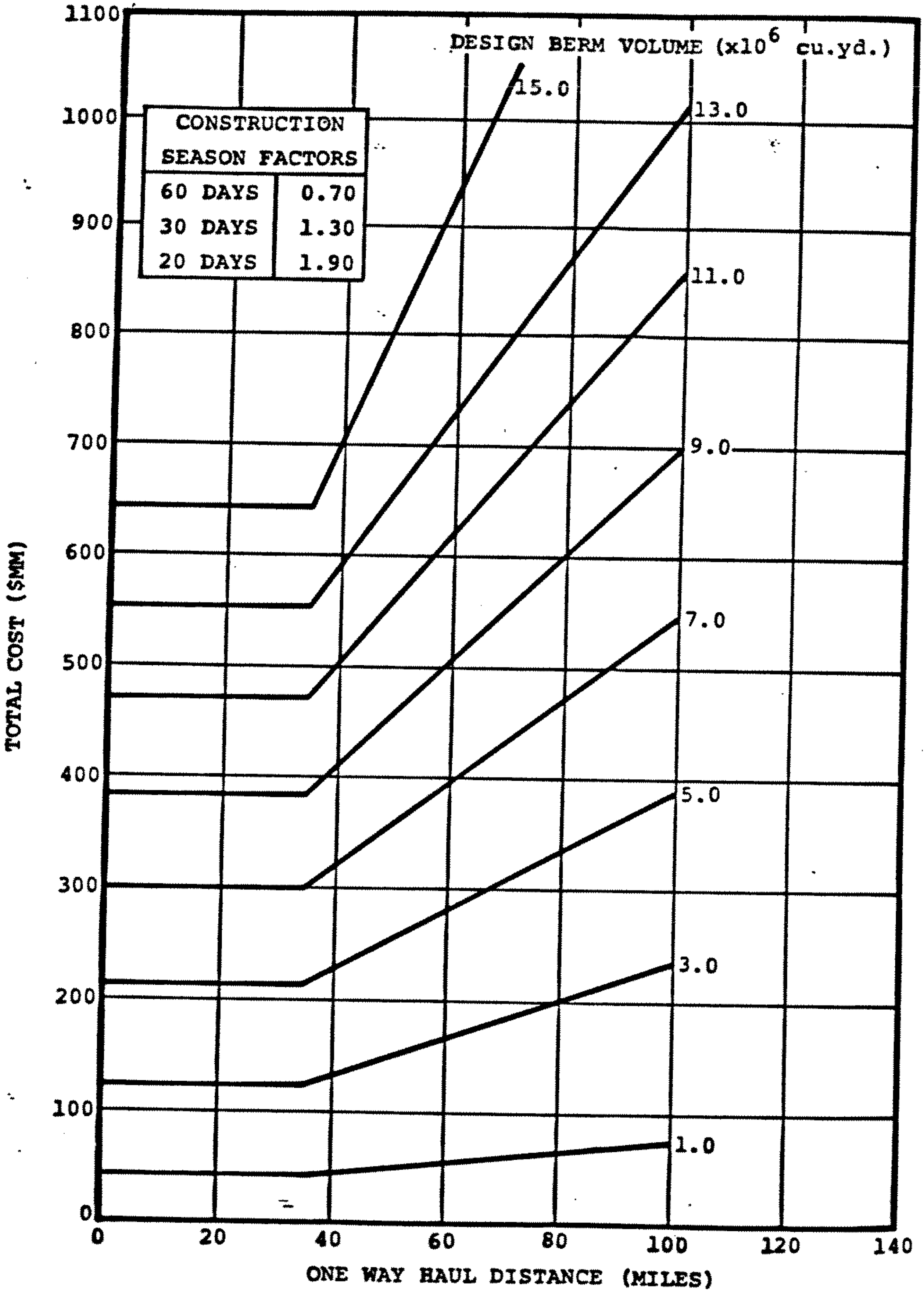
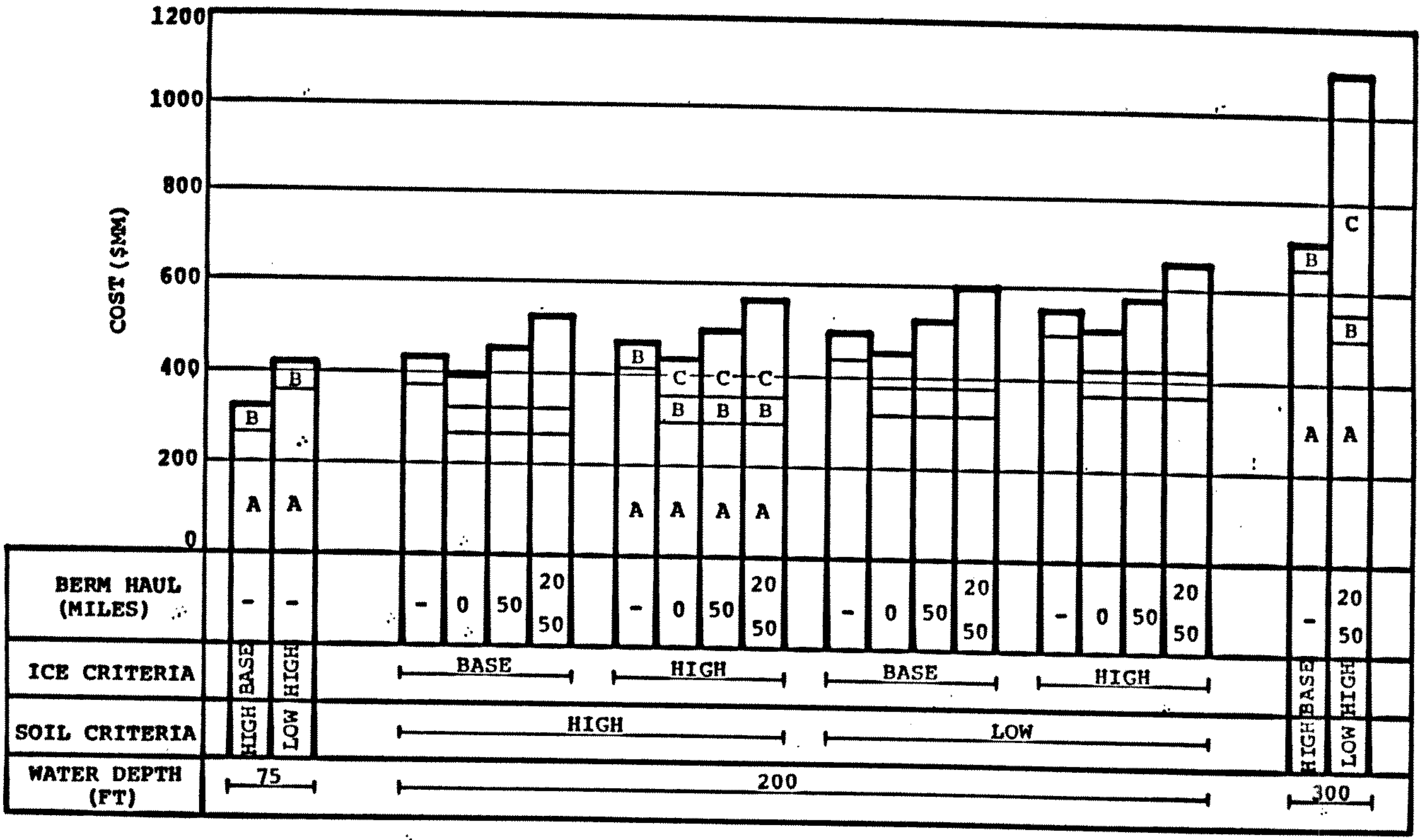


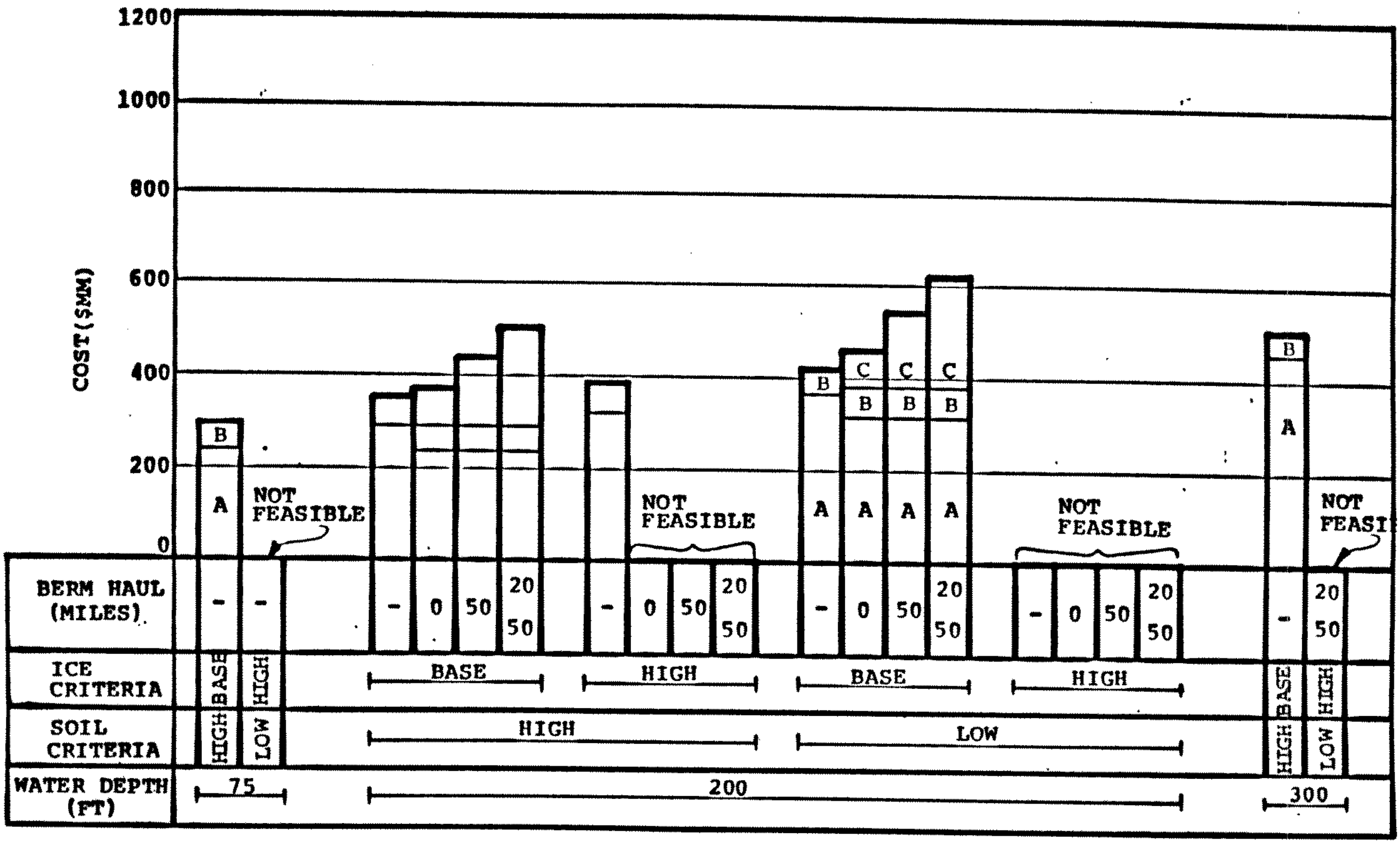
FIGURE 5.25 VARIATION OF TOTAL COST WITH HAUL DISTANCE FROM DOCKING FACILITY TO ISLAND LOCATION (EQUIPMENT SPREAD D) (40-DAY CONSTRUCTION SEASON)



NOTES:

1. SOIL DATA: HIGH = CLAY, c_u =1.0 KSF; LOW = CLAY, c_u = 0.6 KSF
2. BERM HAUL DATA: 0 = ON SITE DREDGING; 50 = 50 MILE HAUL FROM OFFSHORE SOURCE, 20/50 = 20 MILE HAUL FROM ONSHORE SOURCE TO DOCK + 50 MILES FROM DOCK SITE.
3. COST DATA: A = STRUCTURE INSTALLED COST: B = TOPSIDES & DECK; C = BERM CONSTRUCTION.

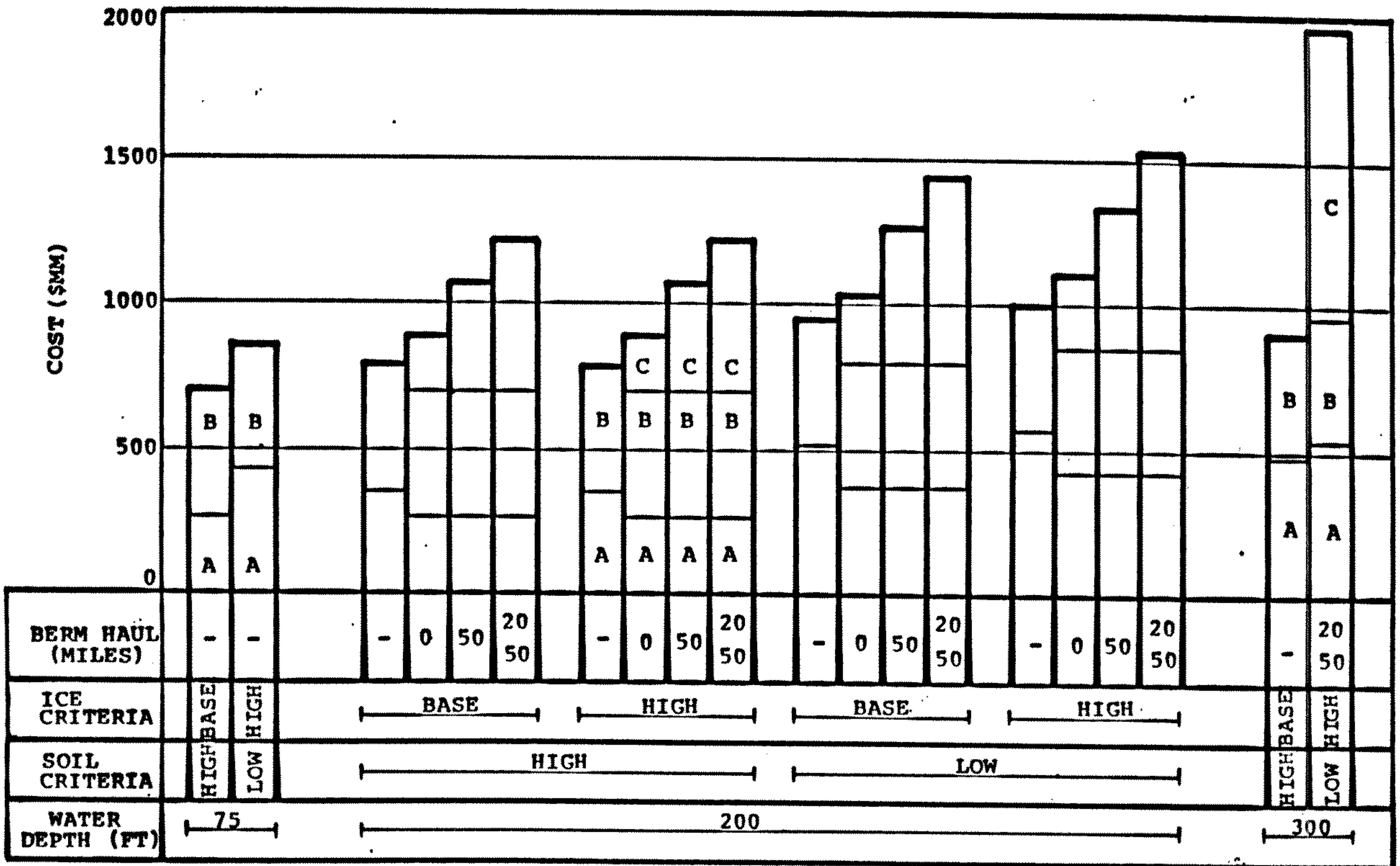
FIGURE 5.26 TYPICAL SCENARIO COSTS - EXPLORATION CONES



NOTES:

1. SOIL DATA: HIGH = CLAY, c_u = 1.0 KSF; LOW = CLAY, c_u = 0.6 KSF
2. BERM HAUL DATA: 0 = ON SITE DREDGING; 50 = 50 MILE HAUL FROM OFFSHORE SOURCE; $\left.\begin{matrix}20\\50\end{matrix}\right\}$ = 20 MILE HAUL FROM ONSHORE SOURCE TO DOCK + 50 MILES FROM DOCK TO SIT
3. COST DATA: A = STRUCTURE INSTALLED COST; B = TOPSIDES AND DECK; C = BERM CONSTRUC

FIGURE 5.27 TYPICAL SCENARIO COSTS - EXPLORATION CAISSONS



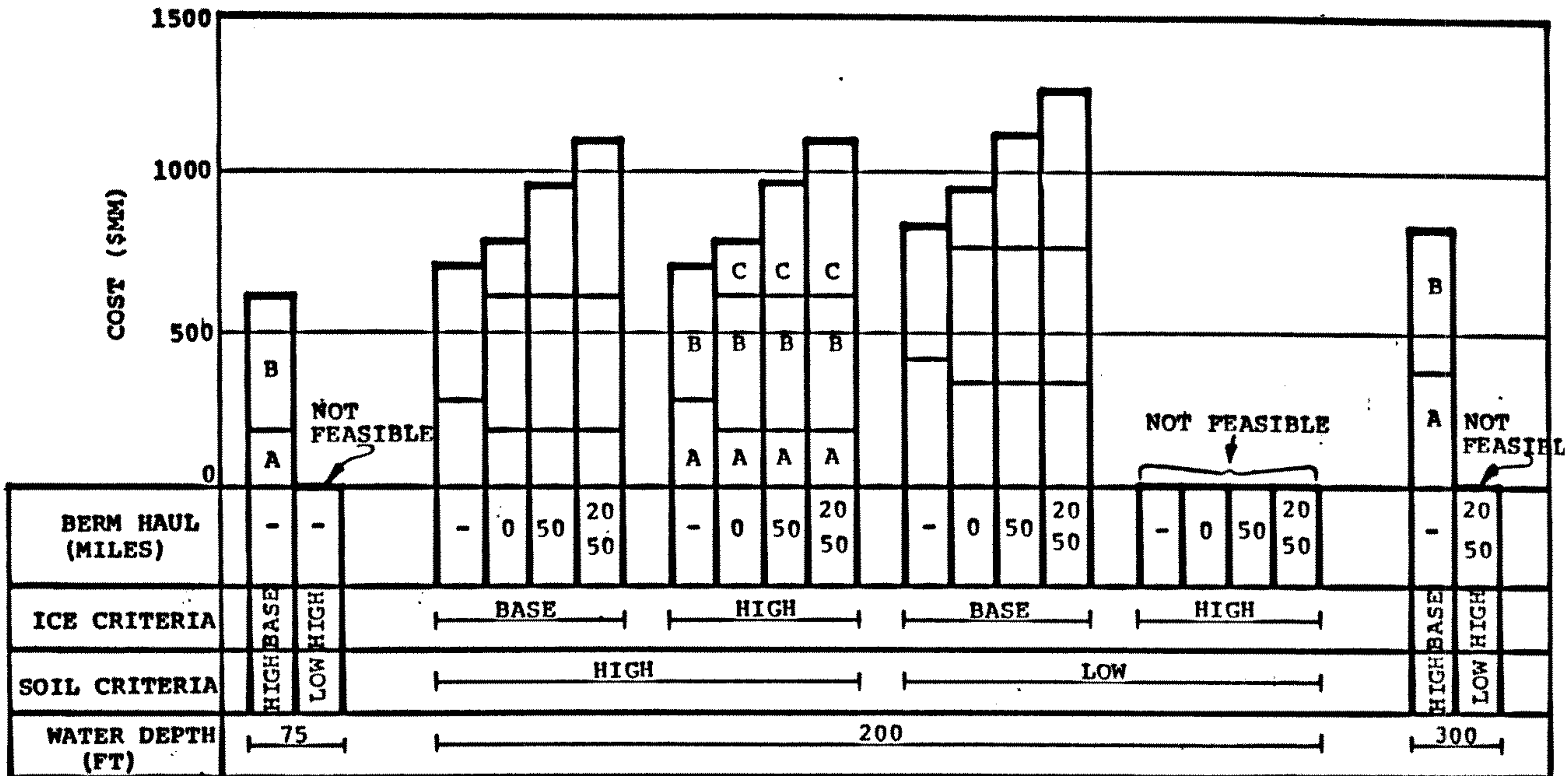
NOTES: 1. SOIL DATA: HIGH = SAND, ϕ = 35; LOW = CLAY, c_u = 0.6 KSF

2. BERM HAUL DATA: 0 = ON SITE DREDGING; 50 = 50 MILE HAUL FROM OFFSHORE SOURCE; $\left.\begin{matrix}20\\50\end{matrix}\right\}$ = 20 MILE HAUL FROM ONSHORE SOURCE TO DOCK + 50 MILES FROM DOCK TO SITE

3. COST DATA: A = STRUCTURE INSTALLED COST; B = TOPSIDES AND DECK; C = BERM CONSTRUCTION

4. STRUCTURE COSTS AND BERM COSTS ARE CONSTANT WITH VARYING PRODUCTION RATE

FIGURE 5.28 TYPICAL SCENARIO COSTS - PRODUCTION CONES (200,000 BOPD)



NOTES:

1. SOIL DATA: HIGH = SAND, $\emptyset=35^{o}$; LOW=CLAY, $c_u=0.6$ KSF
2. BERM HAUL DATA: 0 = ON SITE DREDGING; 50=50 MILE HAUL FROM OFFSHORE SOURCE: $\left.\begin{matrix}20\\50\end{matrix}\right\}$ = 20 MILE HAUL FROM ONSHORE SOURCE TO DOCK + 50 MILES FROM DOCK TO SITE
3. COST DATA: A = STRUCTURE INSTALLED COST: B=TOPSIDES & DECK: C= BERM CONSTRUCTION

FIGURE 5.29 TYPICAL SCENARIO COSTS - PRODUCTION CAISSONS (200,000 BOPD)

NOTE: COST INCLUDES CONSTRUCTION, TRANSPORTATION, INSTALLATION, & TOPSIDES.

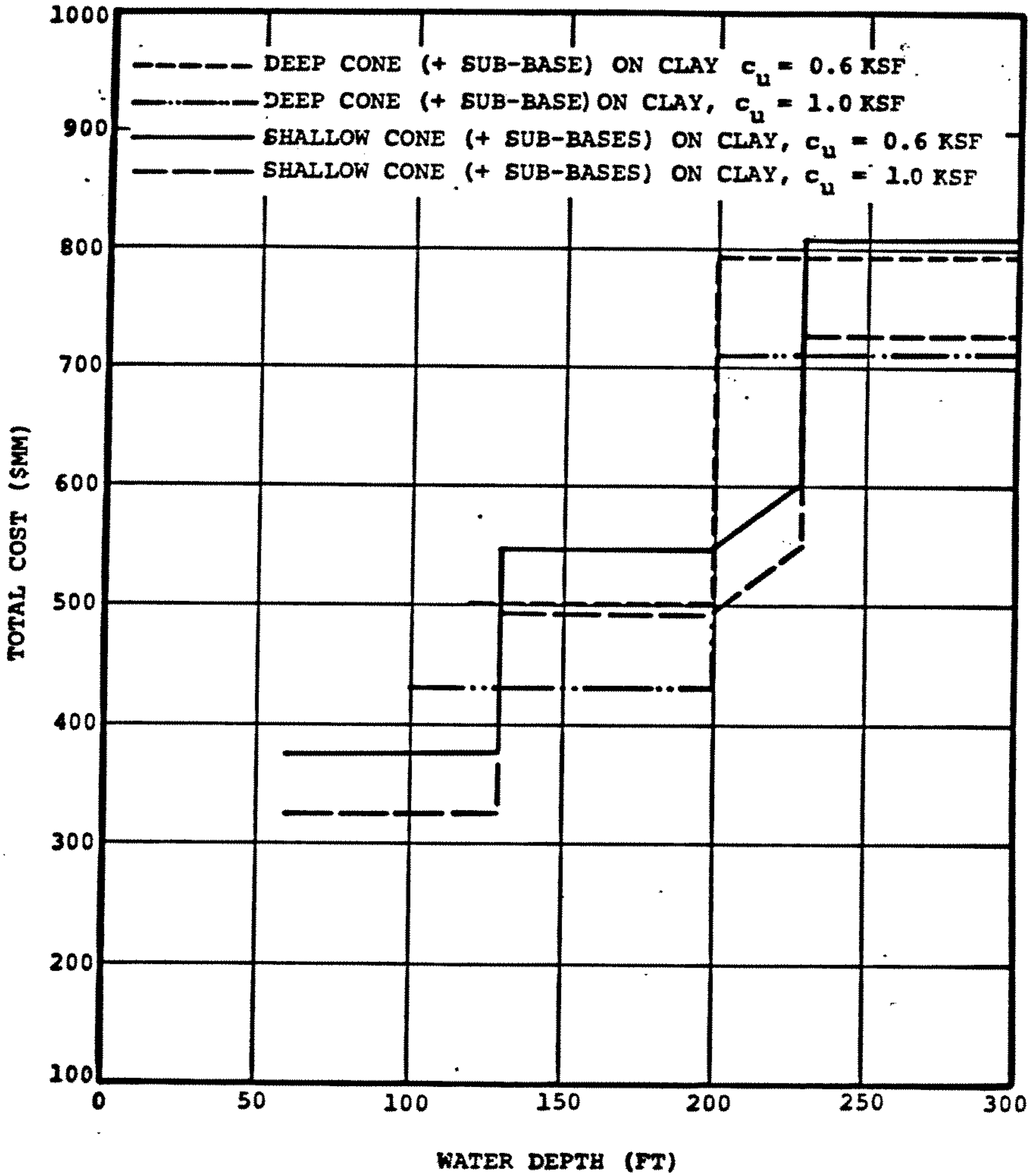


FIGURE 5.30 VARIATION OF COST WITH WATER DEPTH FOR EXPLORATION CONES - BASE ICE LOADS

NOTE: COST INCLUDES CONSTRUCTION, TRANSPORTATION, INSTALLATION, & TOPSIDES.

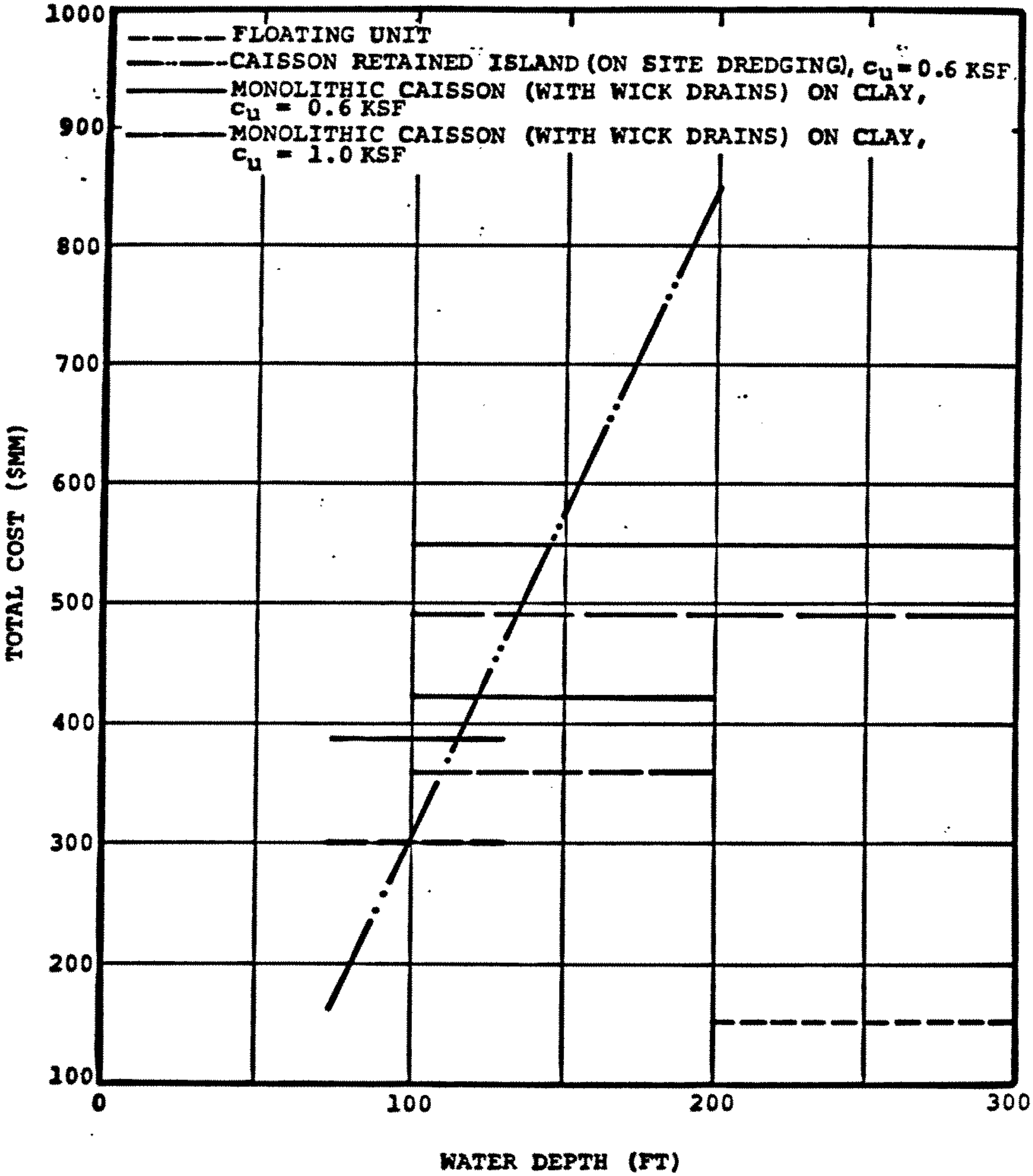


FIGURE 5.31 VARIATION OF COST WITH WATER DEPTH FOR EXPLORATION CAISSONS, CAISSON RETAINED ISLANDS, AND FLOATING UNITS - BASE ICE LOADS

NOTE: COST INCLUDES CONSTRUCTION, TRANSPORTATION, INSTALLATION, & TOPSIDES.

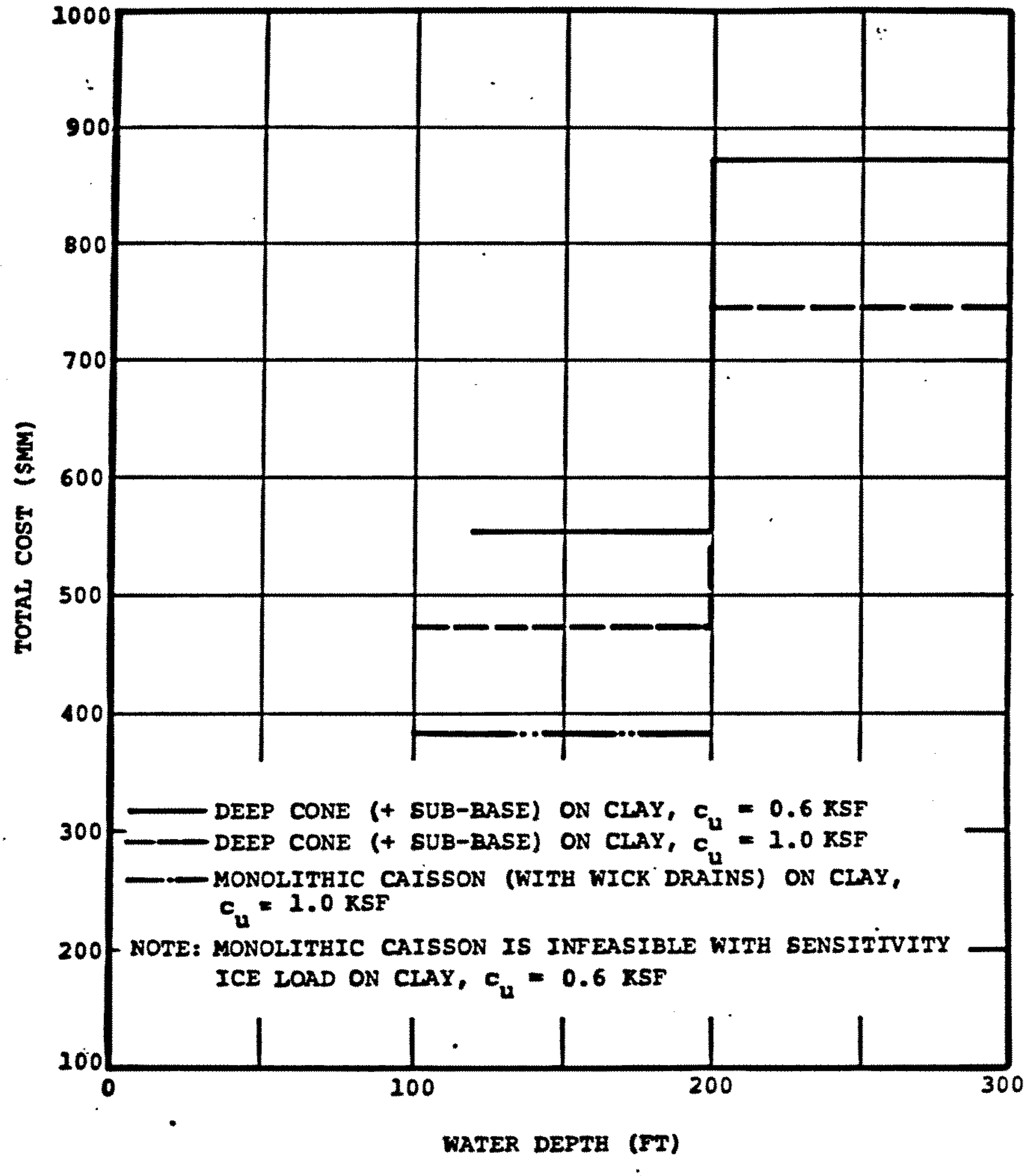


FIGURE 5.32 VARIATION OF COST WITH WATER DEPTH FOR EXPLORATION CONES AND CAISSONS - SENSITIVITY ICE LOADS

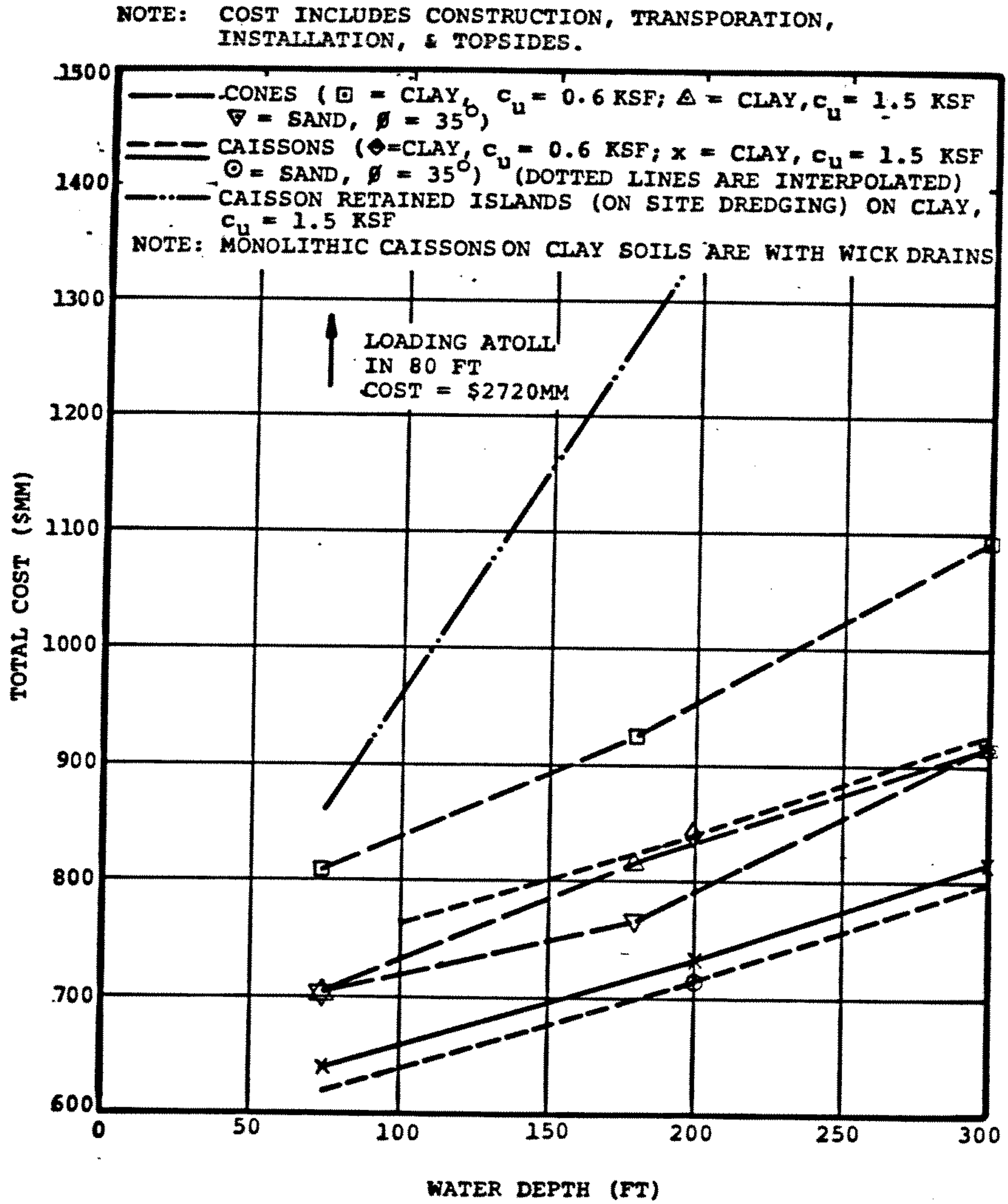


FIGURE 5.33 VARIATION OF COST WITH WATER DEPTH FOR PRODUCTION (200,000 BOPD) CONCEPTS - BASE ICE LOADS

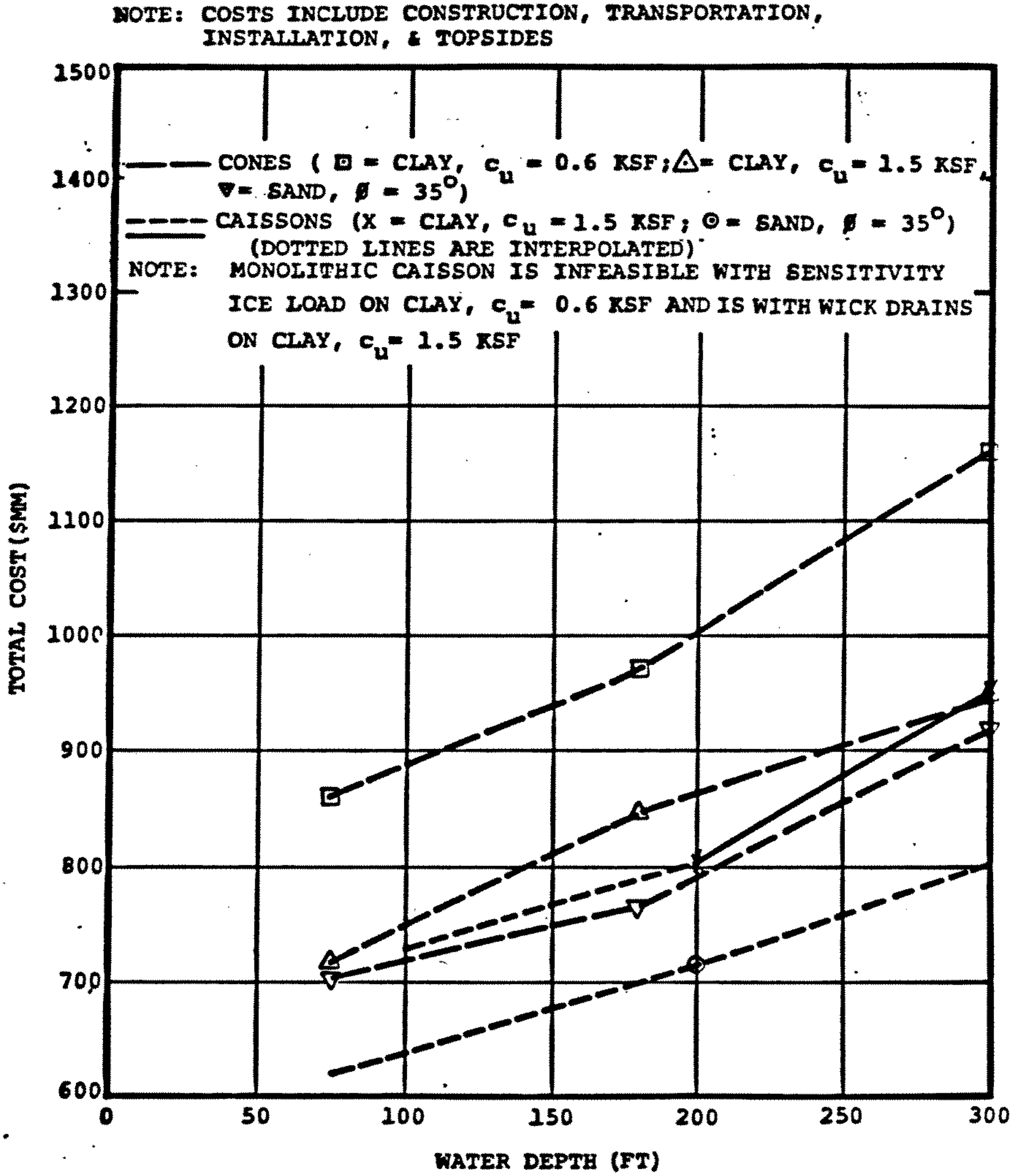
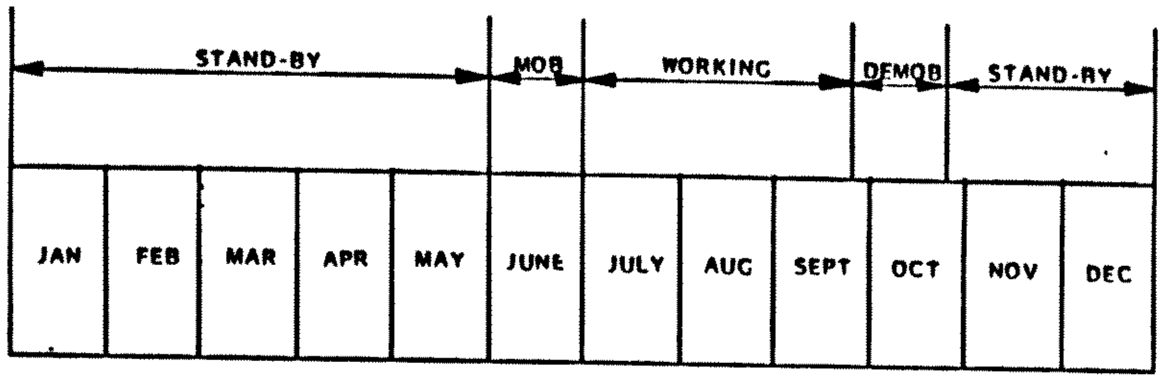
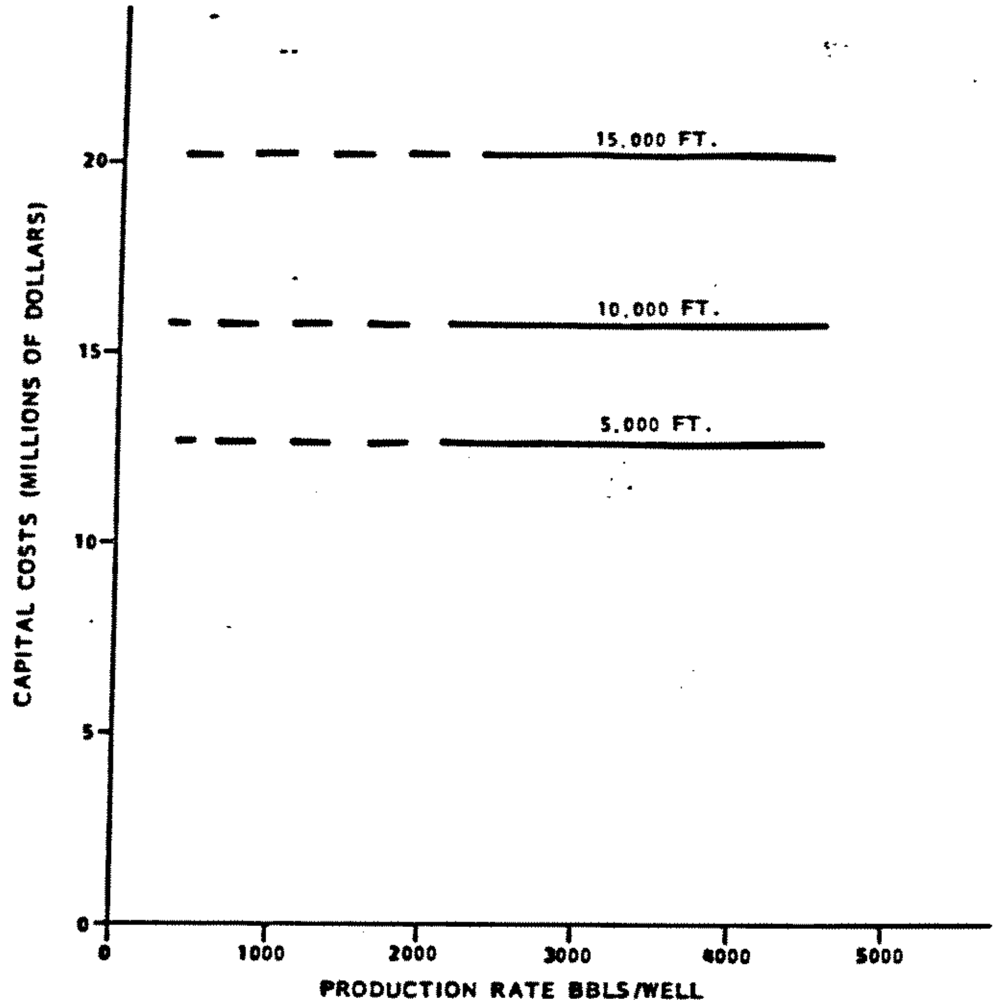


FIGURE 5.34 VARIATION OF COST WITH WATER DEPTH FOR PRODUCTION (200,000 BOPD) CONCEPTS - SENSITIVITY ICE LOADS



WORKING................80 DAYS @ $160,000/DAY
MOBILIZATION.......... 30 DAYS @ $135,000/DAY (.85)
DEMOBILIZATION........30 DAYS @ $135,000/DAY (.85)
STAND-BY (WINTER)...225 DAYS @ $120,000/DAY (.75)

FIGURE 5.35 FLOATING DRILLING DAY RATE BREAKDOWN



NOTES: THE FOLLOWING COSTS ARE NOT INCLUDED

1.	MOBILIZATION-DEMOBILIZATION	$8.1 MILLION
2.	DRILLING RIG WINTER STAND-BY	$27.0 MILLION
3.	GLORY HOLE DREDGING	$2.8 MILLION
4.	WELL PROTECTIVE STRUCTURE	$1.0 MILLION

FIGURE 5.36 SINGLE WELL COST

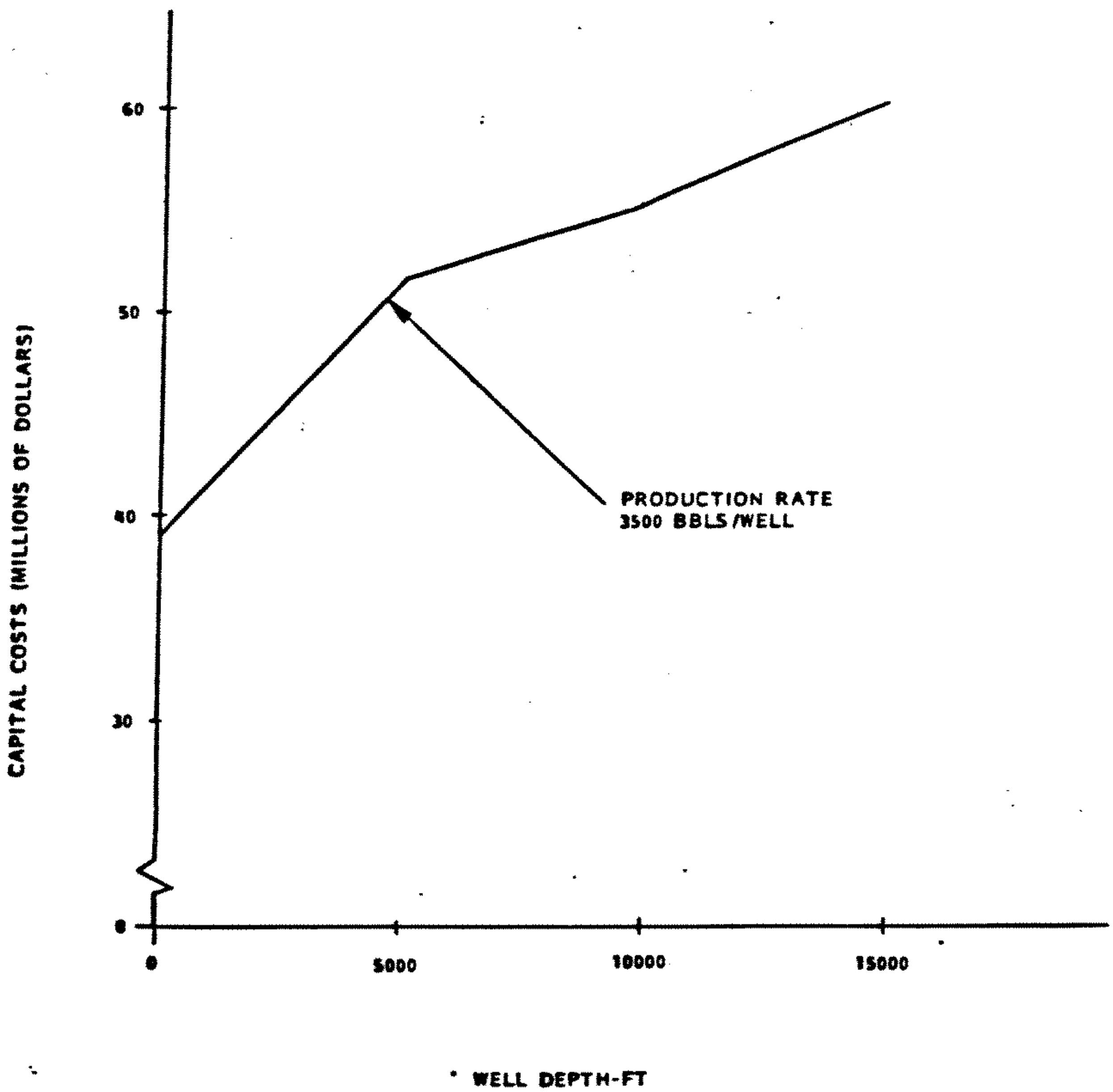


FIGURE 5.37 <u>TOTAL SATELLITE WELL COST</u>

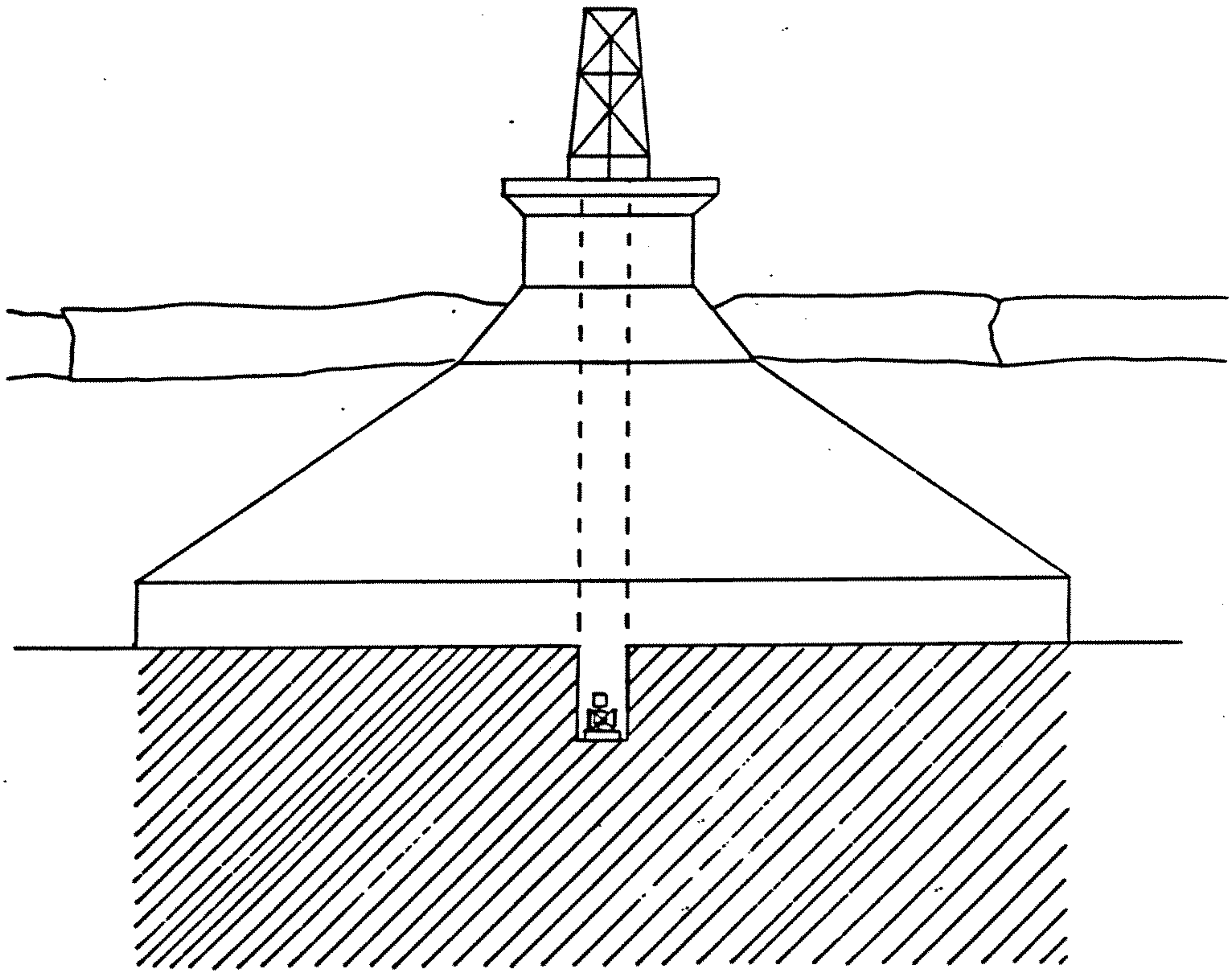


FIGURE 5.38 <u>SUBSEA WELL DRILLED WITH CONICAL BOTTOM SUPPORTED DRILLING UNIT</u>