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SUBSURFACE DEPLOYMENT OF NAVAL FACILITIES

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SUBSURFACE DEPLOYMENT OF NAVAL FACILITIES

Final Report

by

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13. ABSTRACT

This report documents a study designed to determine which Navy facilities and functions appear to be best suited for subsurface deployment in light of anticipated improvements in excavation capability within the next twenty years. Five categories of Naval facilities are analyzed and evaluated with respect to the benefits to be realized and the costs associated with their underground siting. Geological and hydrological considerations which may impact on the cost of any given excavation project are also outlined.

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1 INTRODUCTION

The overall objectives of this study are (1) to determine which Navy facilities and functions appear to be best suited for subsurface deployment in light of anticipated improvements in excavation capability within the next twenty years, and (2) to identify the corresponding benefits to be realized by the underground siting of these facilities.

Two basic assumptions lay the groundwork for this study program. First, it is assumed that the majority of people in this nation will exhibit a continually growing concern for our environment. This will manifest itself in greater demands for proper land utilization, reduced pollution, and overall improvement of the aesthetic quality of American life. The second assumption postulates that the U.S. will commit sufficient resources for research and development of new and/or improved underground excavation techniques over the next twenty years, and that these new techniques will result in significant improvements in excavation rates and substantial reductions in the cost of all phases of excavation.*

The Naval Facilities Engineering Command (NAVFAC) has undertaken this study program in an effort to see how the Navy might capitalize on advances in excavation technology in order to solve its anticipated social and environmental problems. A basic study constraint was that alternative surface options, such as relocation and high-rise construction, were not to be included in the analysis.

The following example is supplied to illustrate that indeed the first signs of environmental concern are already affecting today's Navy. Figure 1.1 shows a map of the San Diego area and the many Naval facilities

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*GRC has recently completed a study and computer simulation of rapid excavation techniques, under contract to the U.S. Bureau of Mines: Computer Simulation of Hard Rock Tunneling, Rept. No. CR-2-190, July 1972.

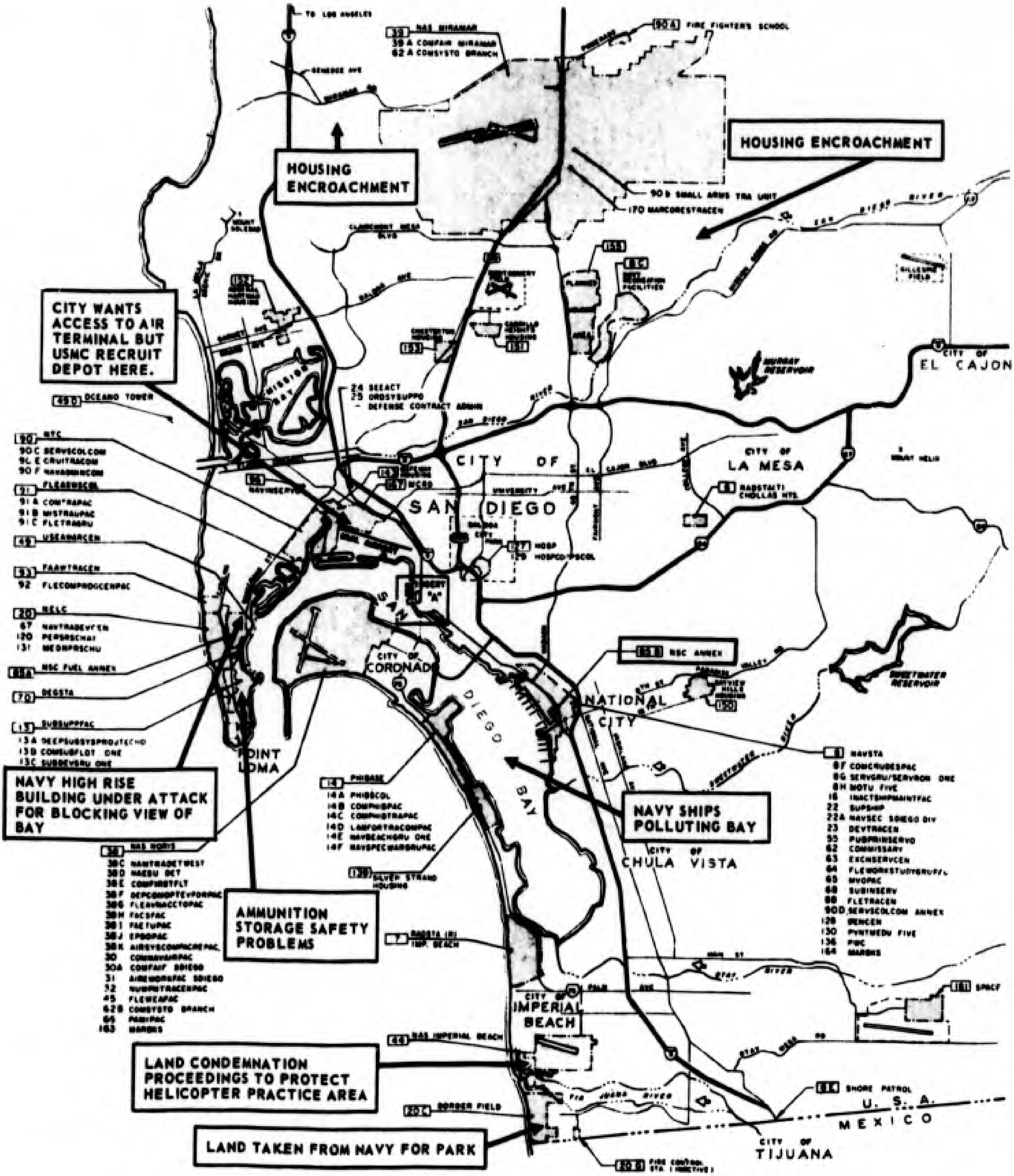

Figure 1.1. San Diego Encroachment Problems

located therein. The figure points out just a few of the problems facing the Navy as a result of its interactions with the surrounding community. The authors hasten to point out that this is not a worst case example, but rather a typical illustration of the many types of encroachment problems which are prevalent today in the United States.

The study program was divided into two phases. The first dealt with the selection of five types of Naval facilities which, if sited below ground, appeared to offer substantial benefits. In the process all Navy real property was considered and the five types of facilities were selected by analysis of the economics and environmental impact associated with their subsurface deployment. In the second phase of the study the selected facility types were analyzed in greater detail. After a traditional cost analysis, emphasis was placed on addressing those factors, usually considered intangible (e.g., environmental impact, aesthetics), which some day may play a major role in any deployment decision. Wherever possible, these intangibles were quantified. In some cases, data or judgment was supplied by experts in related fields, while in other instances no information was available and the authors resorted to their own "best guess." Parametric analysis was used extensively throughout this study in order to enable this report to remain useful as new developments take place. The authors and NAVFAC wish to point out at this time that they are most interested in the opinions (pro or con) of other members of the physical and social sciences communities regarding any of the parameters used in this report.

The facilities and functions considered in this study were those used to satisfy the general, everyday requirements of the Navy and not special projects such as Sanguine and Trident basing, which are normally the subject of their own in-depth study programs. In addition, decisions regarding the suitability and advantages of subsurface deployment for a given facility were made purely in the light of economic and social considerations. (Vulnerability and survivability in case of attack were not addressed.)

The five types of facilities analyzed in detail are:

(1) Administration buildings

(2) Medical facilities

(3) Aircraft maintenance facilities

(4) Ammunition storage facilities

(5) Miscellaneous storage facilities

This report is organized as follows. Section 2 provides a brief summary of the major conclusions reached as a result of this study effort. Section 3 outlines the selection process used in Phase I to arrive at the list of five facility types for Phase II study. Section 4 develops a methodology which can be used to assess the costs/benefits of subsurface deployment of these facilities. A discussion of the advantages and disadvantages of subsurface deployment for each of the five facilities comprises Section 5. Appendix I provides an overview of the factors affecting excavation costs, and establishes base-line costs representing current excavation capabilities for the geologic and hydrologic conditions of most interest to the Navy. (Since the vast majority of Naval installations are located on or near the sea coast, saturated soil or weathered marine rock can contribute significantly to the costs associated with the underground siting of Naval facilities, and consequently to the subsurface deployment decision itself.) Appendix II contains several mathematical derivations used in this analysis.

2 CONCLUSIONS

This section briefly outlines the general and facility-specific conclusions resulting from this study program. The reader is referred to Sec. 5.1, where the major assumptions used in the analysis are listed. Recommendations for possible follow-on study programs are discussed at the end of this section.

2.1 GENERAL

The most important factor capable of overriding the excavation costs associated with a subsurface facility is land value. In many areas of the United States, the Navy has installations on land which is valued (1972) at $500K/acre or more. Should this land continue to appreciate at its normal rate or higher (~10% per annum), subsurface deployment of many Naval facilities would become an attractive option within the next two decades even if one considers only small improvements in excavation technology.

In areas where land value is low (~$5000/acre), the underground siting of Naval facilities is uneconomical throughout the foreseeable future regardless of the geological conditions or any conceivable reduction in excavation cost, unless the surface facility is totally unacceptable to the surrounding community.

In those areas where land is expensive, the geological and hydrological conditions at the excavation site and the rate at which excavation technology is advanced are very important factors in determining when subsurface deployment becomes more economical than siting the facility above ground. The delay which results from the time needed for excavation of a subsurface facility must also be considered in a deployment decision.

The present value of some life-cycle costs (O&M, security, etc.) which extend over long time periods is often many times greater than the present value of the initial costs of land, construction, and excavation. Consequently, any life-cycle cost advantages or disadvantages resulting from the subsurface deployment of Naval facilities may be the major factor in the deployment decision, even if the difference is only a few tenths of one per cent per year. Unfortunately, differences of this nature are difficult to determine without a detailed study of a particular facility design and location--this was not possible in this study although in some instances cost advantages were postulated and parameterized.

The surface deployment of certain Naval facilities may result in a degradation of the environment (aesthetic quality, noise, etc.) for residents of the surrounding community. This community impact may have significant economic consequences which should weigh heavily in a subsurface deployment decision in those instances where the underground siting of the facility reduces the detrimental impact. Environmental effects may extend beyond the nominal life of the facility and when considered as such may constitute a major factor in the decision-making process.

In general, the underground siting of selected Naval facilities is an attractive and viable option for the Navy in the next two decades if: (1) land utilization and environmental quality continue to grow as major issues on the American scene, and (2) sufficient resources are committed to advancing technology in all phases of the excavation process.

2.2 SPECIFIC

2.2.1 Administration Buildings

The decision to place administration buildings below ground will, in most cases, be based primarily on a traditional cost analysis, i.e., a comparison of the costs of land, excavation, and construction for the surface versus subsurface facility. The reason is that, to the level of detail possible in this study, most life-cycle costs associated with the operation of an administration building appear to balance out in an analysis of surface versus subsurface deployment. There will probably be instances where the construction of a surface administration building would have a deleterious impact on the aesthetic quality of the surrounding community (e.g., blocking a scenic view). Efforts to preserve the environment in the community could result in a considerable financial setback for the Navy, which in turn may make subsurface deployment more attractive.

Because only a small amount of land is involved in the construction of an administration building, land utilization does not dominate the subsurface deployment decision. Only in areas where land is extremely expensive (e.g., downtown commercial and industrial acreage) does the underground siting of administration buildings appear economically attractive.

2.2.2 Medical Facilities

The analysis of medical facilities examined the total hospital complex, because up to 80% of the land used in such a complex is devoted to the many support functions which appear to be better suited for subsurface deployment than the main hospital building itself. The underground siting of these functions, e.g., maintenance, laundry service, laboratories, could free the surface area around the hospital for use as parks and picnic areas which presumably would be to the betterment of the patients confined for extended periods of time. This certainly could have substantial economic as well as humanitarian benefits.

Many Naval hospitals are now located in urban areas where land value is very high. In these instances, the subsurface deployment of selected medical facilities appears to be a particularly attractive option for the Navy in the next 20 years.

2.2.3 Aircraft Maintenance Facilities

Operation and maintenance costs comprise a major percentage of the total net cost of an aircraft maintenance facility. Consequently, a very small difference in O&M costs between a surface and subsurface facility would have a major impact on the deployment decision. The subsurface deployment of aircraft maintenance facilities would clearly be a massive undertaking requiring special considerations such as logistical systems for moving the aircraft around. At this time, it appears that these requirements would probably result in greater costs associated with the subsurface facility, unless land value was very high or the surface facility created an unacceptable community impact.

One major interaction between an aircraft maintenance facility and the surrounding community is the noise generated in the engine test cells and at the aircraft runup areas. The underground siting of these noise-creating areas was examined independently. If the noise (especially the low frequencies) could be sufficiently damped through the use of properly designed tunnels, the savings resulting from community goodwill might tend to make the subsurface deployment of engine test areas a cost-effective alternative.

2.2.4 Ammunition Storage Facilities

The decision as to whether or not the underground siting of ammunition storage facilities is cost effective is highly dependent upon the land value. Considerable savings in land costs and security should be achievable by the subsurface deployment of these facilities; however, these savings must compensate for the anticipated additional costs attributable to the operations and maintenance of such a facility. If one assumes that low-cost land would be used to site an ammunition storage facility (because this location should be away from populated areas), then the analysis shows conventional storage facilities to be more economical. However, if one remembers that Naval ammunition storage facilities must be located near the water and then further postulates that very little of this land will remain inexpensive in the future, then one concludes that subsurface deployment becomes an attractive option whenever land becomes expensive.

2.2.5 Miscellaneous Storage Facilities

Because Naval storage facilities provide service to the fleet, they usually occupy a considerable amount of land near the waterfront. This land is not only very expensive but also in many areas the neighboring communities are placing great pressure on the Navy to relinquish the land so it can be used for recreational purposes. As land availability has diminished and storage requirements increased, many storage facilities have become dispersed throughout a Naval installation. It has been estimated that this dispersal results in an increase of up to 35% in the cost of operating and maintaining a storage and supply facility. Therefore, considerable savings can be expected when a storage facility is centralized within a unified complex whether it is located above or below ground.

The underground siting of storage facilities provides a feasible alternative for achieving a consolidated storage complex which might not be possible on the surface because of land availability in areas appropriate for such an operation. This combined with the high land values in many major storage areas makes the subsurface deployment of storage facilities a potentially attractive option for the Navy in the future.

2.3 RECOMMENDATIONS FOR FURTHER STUDY

This study program was designed to provide a "first look" at the potential benefits to be derived by the subsurface deployment of Naval facilities. Because the study was limited in time and scope, certain aspects of the concept were treated in a cursory manner or neglected altogether. Time limitations prevented the detailed technical analysis of several questions posed in this report. Scope restrictions constrained the study to an examination of only those facilities satisfying the general everyday requirements of today's Navy. The following discussion is therefore intended to describe technical analyses not conducted in this program, and further, to briefly outline additional study efforts which could be undertaken to ascertain the potential benefits resulting from the subsurface deployment of other types of Naval facilities.

2.3.1 Noise

In Sec. 5.4, it was implicitly recognized that there are two major noise-producing operations at Naval air stations: routine flight operations (landing and takeoff noise) and aircraft engine maintenance (engine runup noise). Depressed runways designed to reduce the noise from routine flight operations were not considered in this study because they are not, in the strict sense, subsurface facilities. On the other hand, aircraft engine maintenance activities, where the engine remains stationary either in a test cell or on an aircraft tethered in a runup area, did not appear amenable to underground siting for noise control.

The subsurface deployment of engine test operations was examined under the assumption that tunnels could be used to suppress the low frequency noise which today can be heard considerable distances from the test area. There are significant technical issues which must be resolved in order to demonstrate the ultimate feasibility of noise suppression tunnels for engine testing. Three of the major issues are: (back-pressure problems in the test tunnel which might affect engine performance readings; (2) the wearing of the tunnel liner after repeated use; and (3) the noise reduction attainable by tunnel use.

The preliminary analysis performed in this study left several unanswered questions in the social impact area which should be considered further. They are:

- Of the numerous noise-related complaints made by residents living near Naval air facilities, what percentage is due to engine test activities as opposed to normal flight operations?
- What noise reduction would be required to eliminate these complaints?
- What alternative means are available for noise quieting which would compete with subsurface deployment as a possible solution?

With respect to the last issue, it should be noted that considerable effort is being expended in commercial aviation to develop quieter engines. The high bypass-ratio engines installed in the new commercial aircraft and retrofit in existing aircraft should meet the new noise standards. While similar engine quieting is desirable on Navy non-combat aircraft, combat aircraft will continue to be noisy because of the overriding need for high performance capability.

These noise-reducing programs and federal regulations must be regarded as the first steps taken toward reducing community noise well below present levels. The conflicting demands for high performance combat aircraft and low perceived noise level in the surrounding community are likely to compete repeatedly in the political arena for the setting of national and regional priorities. The Navy can benefit if it can show that all noise-quieting measures have been considered and evaluated for feasibility and cost.

2.3.2 Ammunition Storage

The subsurface deployment of ammunition storage facilities is considered in Sec. 5.5 using the assumption that the separation distances required between magazines below ground are equal to that required on the surface. Intuition indicates this to be unlikely. However, the problem is complex because the separation distances required will be a function of the geological conditions at the site and the type of ammunition stored. The relationships between geological conditions, type of ammunition, and the separation distances must be determined before the cost effectiveness of the underground siting of ammunition can be ascertained.

The question of how much a particular underground ammunition storage facility would cost is highly dependent on the configuration envisioned and the geology to be excavated. It has been estimated (Appendix I) that excavation costs in hard rock without the need for structural support or permanent lining can run as low as $20/yd^3 for conventional tunneling. Multiple drift or room-and-pillar mining on a large-scale project could further reduce this cost to perhaps $10/yd^3. The important issues here are whether this type of geology could be found in an area suitable for Naval ammunition storage and whether larger than magazine-capacity amounts of explosive in such underground caverns present unacceptable hazards due to the higher risk of sympathetic explosions. Further investigation is required to answer these questions.

2.3.3 Energy Conservation

The operating costs associated with heating and air conditioning the facilities studied in this program were assumed to be similar for the surface and subsurface cases. In many areas of the country, however, it might be easier to stabilize the temperature in a subsurface facility without substantial heating or air conditioning and thereby reduce the cost of operation. Today these potential cost savings do not appear significant in light of the other factors considered in this study, e.g., land and excavation costs. However, if the daily warnings about our potential energy crisis go unheeded, these cost savings might someday prove substantial. A greater analytical effort is required in this area to determine the potential savings in energy which might be derived by the subsurface deployment of selected Naval facilities.

The energy crisis has even broader, long-range implications for today's Navy. Of current interest is the fact that Senator Henry M. Jackson will soon introduce legislation calling for a $20-billion program of research and development aimed at making the United States self-sufficient in energy by 1983. On the scale of Project Apollo, this proposed R&D effort responds to a sense of urgency about our diminishing energy reserves and our growing dependence on imported sources of energy. Virtually all fuel for electric power plants along the east coast of the United States is imported. The impact of environmental regulations has begun accelerating the demand for petroleum and its products.

Thus, even more than a search for energy savings, the Naval facility planner should be concerned with the growing importance of the supply and demand of energy and how it is affecting the fundamental plans and policies of the government. New commitments and new facilities may be required of the Navy in response to a national policy which reaffirms that energy supply and production are key elements in our economy and must be protected as such. With this in mind, it is important to consider what impact the transport of petroleum in supertankers or the construction of off-shore nuclear power plants might have on Naval commitments and concomitantly on Naval facilities requirements. While this was beyond the scope of the present study, it is recommended as an area for further study.

2.3.4 The Navy of the Future

This study made no attempt to forecast how tomorrow's technological achievements will change today's Navy. Some of these developments could result in completely new kinds of Naval facilities which may require subsurface deployment for reasons other than those presently considered.

Underground facilities may someday play a greater role in Naval operations because of future developments such as:

- Improving effectiveness of satellite surveillance systems which could clearly require the subsurface deployment of any system this nation desired to keep a secret.
- The emergence, because of its continuing invulnerability, of the sea-based strategic missile system as our first line of deterrence against nuclear attack; and the importance of protecting its supportive basing and communications systems, which may dictate the need for underground or undersea emplacement of key supporting elements of this force.

- The increasing vulnerability of surface fleets which could lead to the need for an all-submarine Navy, including cargo and troop transport vessels, supported by undersea ports.

Projecting new technologies, their possible impact on Navy operations, and the role which subsurface deployment could play in these developments should be of major interest to the Navy planner.

3 SELECTION PROCESS

The first phase of the program dealt with the selection of five types of Naval facilities which appeared to be well suited for subsurface deployment. The five selected types were then studied in detail in Phase II.

The first step taken in the selection process was the categorization by function of all Navy real property except land. The resulting categories and their corresponding NAVFAC investment codes are shown in Table 3.1. The categories were selected such that all facilities within a given category represent like facilities which are utilized functionally to support similar requirements.

Notice that in most cases buildings and equipment for a given function are listed in different categories. For example, category No. 10 is buildings used for training, and category No. 11 is equipment (or facilities other than buildings) used for training, e.g., combat pool, projectile range, and drill field. This distinction within a given functional category was made because in many cases the buildings appeared suitable for subsurface deployment, whereas the equipment or facilities other than buildings did not. This approach therefore facilitated the selection process.

3.1 SUBJECTIVE ELIMINATION OF CATEGORIES

Table 3.2 contains a list of all categories eliminated from further consideration for subjective reasons. A discussion of the reasoning behind each elimination follows.

The first three categories in Table 3.2 deal, for the most part, with the actual operation of aircraft. This includes such items as runways, taxiways, flight operations buildings, and control towers. These categories were not considered further for reasons of practicality or because no real advantage to subsurface deployment could be ascertained.

TABLE 3.1
CATEGORIZATION OF FUNCTIONS AND FACILITIES

Functions and Facilities	Investment Category Codes
1. Aircraft Ground Areas	11110-11690
2. Aircraft Operations (bldg)	14111-14190
3. Aircraft Operations (equipment)	14910-14990
4. Communications (bldg)	13110-13190
5. Communications (equipment)	13200-13290 13510-13520
6. Navigatior (bldg)	13310-13390
7. Navigation (equipment)	13410-13490 13610-13690
8. POL Storage and Transport	12110-12690 41110-41290
9. Waterfront Operations	15110-16990
10. Training (bldg)	17110-17190
11. Training (equipment)	17910-17990
12. Production & Maintenance (aircraft)	21105-21190 22120-22190
13. Production & Maintenance (missiles)	21210-21290 22210-22290
14. Production & Maintenance (ships)	21310-21390 22310-22390
15. Production & Maintenance (other)	21410-21490 21710-21990 22730-22990
16. RDT&E Facilities	31010-39090
17. Ammunition Production, Maintenance & Storage	21510-21690 22520-22690 42112-42390
18. Storage (miscellaneous)	14210-14290 43110-45210
19. Medical	51010-55010
20. Administrative (bldg)	61010-62090
21. Administrative (equipment)	69010-69090
22. Housing/Messing	71120-72510
23. Personnel Support	73010-75090
24. Utilities	81110-84330 87110-89990
25. Transportation	85110-86090

TABLE 3.2

CATEGORIES DROPPED FOR SUBJECTIVE REASONS

1. Aircraft Ground Areas
2. Aircraft Operations (bldgs)
3. Aircraft Operations (equipment)
4. Communications (equipment)
5. Navigation (equipment)
6. Waterfront Operations
7. Training (equipment)
8. Production and Maintenance (ships)
9. Administration (equipment)
10. Transportation
11. Utilities

Categories 4, 5, 7, and 9 were eliminated because they deal with equipment such as antennas, beacons, drill fields, and flagpoles which are used to satisfy the corresponding functions but which obviously have no real place underground.

Waterfront Operations, No. 6, and Production and Maintenance (ships), No. 8, were both eliminated for the following reason. Although deployment of these facilities within vast mountain chambers is probably feasible in areas where the topography is suitable, the driving factor behind such a deployment would clearly be a reduction in vulnerability in the event of a surprise attack. Outside of the vulnerability issue, there does not appear to be any real advantage to ever undertaking such a massive project. The immense costs associated with placing heavy industries, which produce and maintain massive structures, readily appear to outweigh any potential savings due to land use or social benefits. These categories were therefore dropped from further consideration in this study.

Although subsurface transportation has considerable merit both for the Navy and the nation as a whole, the subject has been thoroughly studied and is not enough of an intrinsic Navy function to merit further examination at this time.

Utilities were eliminated because many of them are already deployed below ground (e.g., sewers, pipe lines) or are not suited for subsurface deployment (e.g., fences, street lighting). Certain types of facilities included in this category, such as power-generating plants, might be advantageously placed below ground; however, at present little interest is shown in the construction of new facilities of this nature. The construction and subsurface deployment of future nuclear power-generating plants was not considered to be within the scope of this study.

3.2 ECONOMIC CONSIDERATIONS

The remaining facilities are listed in Table 3.3 along with some pertinent numerical data. The retained 14 categories have been combined into six. All buildings have been grouped, depending on their need or lack of need for special structural considerations or the installation of a substantial amount of large equipment. (A quick look at column 5 shows that those buildings with special requirements are in general significantly more expensive than those without such requirements.)[1]

Column 1 shows the total acquisition costs for all facilities comprising a given category.[2] The values shown are the summation of all costs of acquisition and improvements for the facilities for the various years in which they were incurred. For example, if a building was constructed in 1945 for $1M and in 1957 another wing was added for a cost of $0.5M the value reflected for acquisition cost would be $1.5M.

The replacement costs shown in column 2 represent the average cost (neglecting geographical and labor union considerations) to replace the given facility in the exact manner in which it was originally built.[2] Since the structure would probably be constructed differently today, the replacement cost is not an accurate number in absolute terms; however, it will prove satisfactory for the purpose intended here, which is to compare relative values.

The deficiency costs shown in column 3 are the programmed and unprogrammed construction projects required to meet existing deficiencies within the given category.[3] The values are in 1974 dollars.

TABLE 3.3

SUMMARY OF COSTS FOR CATEGORIES RETAINED

Facilities & Functions	(1) Acquisition Cost ($M)	(2) Replacement Cost ($M)	(3) Deficiency Cost ($M)	(4) Area (ft^2 × 10^6)	(5) Typical Cost per ft^2 ($)
1. Buildings requiring no special structure or installed equipment					
a. Training	394	1028	538	32	32
b. Administrative	361	1197	658	41	29
c. Housing/Messing	1984	4418	1132	196	23
d. Personnel Support	541	1482	970	60	25
e. Production & Maintenance (other)	236	630	332	30	21
2. Buildings requiring special structure or installed equipment					
a. Communications	155	286	124	5	45
b. Navigation	23	37	11	1	37
c. RDT&E	558	1236	612	23	58
d. Medical	250	636	667	13	49
e. Production & Maintenance (missile)	81	153	9	4	48
3. Production & Maintenance (aircraft)	540	1441	684	34	30
4. POL Storage & Transport	344	990	58	-	-
5. Ammunition Production, Maintenance & Storage	387	1161	185	45	37
6. Storage (miscellaneous)	676	2240	285	325	10

The values in column 4 are indicative of the amount of land used by each type of facility, and since land value will probably play a significant role in many subsurface deployment decisions, these numbers are supplied for comparative purposes.[2]

There are no entries in columns 4 and 5 for POL Storage and Transport because volume measurements are normally used to describe these facilities.

The total value (i.e., replacement cost) of all Naval facilities is estimated[2] to be roughly $32B, with buildings comprising more than one-third of this sum. Therefore, it was decided that the various types of buildings used by the Navy should be investigated to determine their suitability for subsurface deployment. In the interests of saving time, it was further decided that one representative type of building should be examined in detail from each of the two building categories shown in Table 3.3. Administrative buildings were selected from the first category and medical facilities were selected from the second.

Aircraft production and maintenance facilities were selected for further study in Phase II primarily because of the general interest currently being shown for better land utilization and reducing aircraft-generated noise at air installations. In addition, Table 3.3 shows that aircraft production and maintenance facilities represent considerable value to the Navy in terms of replacement costs and existing deficiencies. Aircraft maintenance facilities comprise the largest part of this category and were therefore emphasized in Phase II.

The POL storage and transport category was not considered further in this program essentially because such a large percentage of these facilities are already located below ground.[4]

The production, maintenance, and storage of ammunition appear to represent functions well suited for subsurface deployment. They are of considerable value to the Navy, they occupy substantial land areas, and they appear to offer important social benefits including safety and security. This category was therefore selected for further study in Phase II with ammunition storage facilities receiving greatest emphasis due to their tremendous use of land and their corresponding security problems.

The last category recommended for detailed analysis in Phase II was miscellaneous storage facilities. Although these facilities are relatively inexpensive to construct on the surface, subsurface deployment offers the potential for considerable savings in land, especially in light of the projected rates of increase in land value, and for substantial reductions in life-cycle operational cost if the presently required widespread distribution of storage can be reduced in favor of more efficient consolidated operations.

3.3 SUMMARY

The five types of facilities listed below were selected for further analysis in Phase II of this study program:

(a) Administration buildings
(b) Medical facilities
(c) Aircraft maintenance facilities
(d) Ammunition storage facilities
(e) Miscellaneous storage facilities

4 EVALUATION CRITERIA

4.1 OBJECTIVE

This section presents an approach to cost-comparison analysis for Naval facilities planning which is more broadly conceived than the traditional technique for comparing alternative facilities. The objective is to provide a methodology which may be used to evaluate a wide range of costs and benefits that reflect more comprehensively the advantages and disadvantages of placing selected Naval facilities underground. The methodology provides a means of factoring in the estimated costs of social and environmental impact.

Cost comparison is a basic part of the evaluation of proposed alternatives. It is typically applied to activities for which a "time stream" of costs and benefits can be identified. A major issue concerns the definitions of these costs.

Implicit in this type of cost-comparison analysis is that a common unit of measure, the dollar, be used to arrive at a total net cost for each alternative being considered. This need for dollar representations for each cost element has often precluded the diseconomies attributable, say, to smog, accidents, noise, security, and community impact within the same context as the more clearly identifiable costs of construction, operation, and maintenance. Although these non-dollar factors have not usually been entirely neglected, they have often been the object of considerably less attention than the monetary elements and therefore have played a secondary and not consistently effective role in the planning process.

At the heart of the problem is the issue of commensuration. To achieve equitable commensuration, such diverse elements as pounds of pollutants, man-hours of safety, and decibel hours of noise level must be represented in comparable dollar terms. In considering community impact, the value of the favorable response of one segment of the community must be measured against the cost of another segment's hostility.

With the rising concern in Congress and elsewhere of the impact on the environment and the regional population of new construction projects, the practice of failing to weigh equally the community and environmental impact against the value of the project is changing. Large projects with incontrovertible financial benefits are being halted for ecological reasons. Federal agencies once satisfied to justify the worth of their programs on a fiscal basis alone are now required to submit in addition an acceptable environmental impact statement before allocating funds. Highways and other civil works projects are being delayed while studies are made of the permanent effects such projects will have on the surrounding communities.

This increasing emphasis on social and environmental considerations should continue. However, there are few clear guidelines telling the planner what to include in his analysis and how. No such method exists today. Not even an accepted theoretical framework has been established by either economists or sociologists to quantify these sociological, ecological, and aesthetic effects. The present study will attempt to extend some of the analytical techniques which have been applied successfully in the past and use parametric analysis to include estimates of these other factors.

4.2 METHODOLOGY

A convenient point to start is to consider a common approach to the evaluation of the overall net cost of a project. If there is an initial cost, C_0, to construct a facility, followed by periodic costs C_1, C_2, C_3, ... in years 1, 2, 3, ... to operate and maintain a facility, the net cost of a facility having a lifetime of N years is:

$$\text{Net Cost} = C_0 + \frac{C_1}{1 + r} + \frac{C_2}{(1 + r)^2} + \ldots + \frac{C_N}{(1 + r)^N}$$

$$= \sum_{n=0}^{N} \frac{C_n}{(1 + r)^n} \qquad (1)$$

where C_0 = initial cost

C_n = cost in year n

r = discount rate per annum

N = life of the activity, years

The discount rate accounts for the "time-preference" for money (and goods and services) by reducing future costs and benefits to their present value. The choice of a particular discount rate is an unresolved issue in the analysis of federal investments. In practice, values employed range from zero to upwards of 6%. The widely used government borrowing rate is not necessarily the most appropriate but is often a convenient value for a first look at the alternatives. When possible, a "social time-preference discount rate" should be derived from the political consensus concerning the desired rate of economic growth. The analyst need not make a particular final decision. Rather, he may decide to treat the discount rate parametrically by establishing the overall net cost for several rates, thereby determining the sensitivity of the choice of alternatives to the decision concerning the discount rate.

Dollar benefits accrued in any year may be considered as negative costs in the above formulation. If, for example, in the year n there is a gross cost C_n^* and a gross benefit B_n^* (say, from capitalization of some equipment installed as part of the facility), the net cost (positive or negative) for year n would be

$$C_n = C_n^* - B_n^*$$

A useful generalization of the formulation given by Eq. 1 may be expressed as the integration of all spending rates reduced to present value over the lifetime of the activity:

$$V = \int_0^L \frac{R(t)}{e^{rt}} dt \qquad (2)$$

where V = net cost of the activity

$R(t)$ = spending rate at time t

L = lifetime of the activity

r = discount rate

Equation 2 gives the net cost for a project starting at time zero. For projects starting in the future, say, at time t_0, the integration limits should be changed to reflect the appropriate life of the activity over a time span from t_0 to $t_0 + L$.

The problem for the analyst is to construct a function R(t) which represents the composite of spending rates for land, construction, operation, maintenance, and any other costs which are relevant for the project including estimates for the costs of security, safety, environmental control, community relations, and other factors of importance. Each of these spending rates may start and end at different times in the life of the project and behave differently while active. Spending for land, for example, precedes excavation and construction. Operation and maintenance spending will not commence until the facility has been built and may vary throughout the facility lifetime. Costs related to environmental impact may begin at any time and may extend far beyond the nominal life of the building and more suitably define the length of time which should be considered as the "life of the activity."*

*The contributions of various general forms of the spending rate R(t) are presented in Appendix II.

Many of these cost categories can be identified by considering the list of evaluation criteria presented in Table 4.1 and inquiring which are important and how may they be expressed as spending rates. The function of such a check list is to alert the analyst to categories of potential cost and benefit which should be included in the evaluation process.

One added cost calculation completes the picture. If a lump-sum payment P is made at a time t_p rather than over a time interval, the contribution of this payment to the net cost is:

$$V_p = \frac{P}{e^{rt_p}} \tag{3}$$

In summary, the total net cost of a project is the sum of the contributions of all lump-sum payments and all spending rates over their respective time intervals, as expressed by:

$$V = \sum_j \frac{P_j}{e^{rt_j}} + \sum_i \int_{(t_1)_i}^{(t_2)_i} \frac{R_i(t)}{e^{rt}}\, dt \tag{4}$$

where
- V = present value of the total net cost of the project
- P_j = jth lump-sum payment at time t_j
- $R_i(t)$ = ith spending rate over the time interval $(t_1)_i$ to $(t_2)_i$, where $(t_2)_i$ may go to infinity for perceived permanent environmental or social effects
- r = discount rate
- t = time

TABLE 4.1

COST AND BENEFIT CRITERIA

1. Technical Feasibility
   - Construction capability
   - Logistics, construction & operation
   - Structural behavior
   - Interfacing with existing facilities

2. Economic Practicality
   - Excavation cost
   - Construction cost
   - Operation and maintenance cost
   - Land value
   - Financing
   - Budget priorities
   - Capitalization (liquidation)

3. Operational Capability
   - Suitability
   - Utility
   - Adaptability
   - Capacity
   - Accessibility
   - Reliability
   - Durability

4. Survivability
   - Vulnerability to nuclear warfare
   - Defensibility in limited warfare
   - Protection from civil disorder
   - Protection from natural disasters
   - Deterrent capability

5. Security
   - Visibility
   - Detectability
   - Surveillance capability

6. Habitability
   - Health
   - Comfort
   - Safety
   - Convenience

7. Aesthetic Quality
   - Attractiveness
   - Beauty
   - Cheerfulness
   - Dignity
   - Esteem

8. Community Impact
   - Obtrusiveness
   - Public approval
   - Ethnic acceptability
   - Employment opportunity
   - Community interaction
   - Compatibility
   - Encroachment

9. Environmental Impact
   - Land use planning
   - Natural resource conservation
   - Operational by-products
     - Noise
     - Air pollution
     - Water contamination
     - Thermal waste

10. Political and Legal Restraints
    - Political power
    - Labor regulations
    - Building codes
    - Legal restrictions
    - International treaty restrictions

Considerable care should be exercised in deriving cost estimates used for representing social and environmental costs. These costs are perhaps the least well understood and predictable of all that go into the estimator's equations. The reason is that there is generally both a spectrum and time variation of attitudes, both public and federal, toward any new construction project and it is not always, or even generally, possible to identify to what degree opposition or enthusiasm will be experienced as a result of going ahead. Greater emphasis on maintaining an open forum for communication with those who are likely to be affected by the new project is a clear necessity. The public attitude cannot be taken for granted. Use of opinion surveys, interaction with community, regional and national environmental action groups, and subjection of plans to critical review by experts on community or environmental affairs will alert the analyst to areas of potential conflict.

A recent phenomenon, but one which sets the standard for the foreseeable future, has been a growing public opposition to projects which are perceived to have an adverse impact on the environment or on the community life. The Naval facilities analyst must keep in mind that there may be a distinct difference between what he may view as spending federal funds on projects for which there is real need and which have minor impact on the environment and what the regional public may perceive as spending its money on projects of uncertain marginal value and adverse environmental or community impact.

The first step to be taken toward the development of cost estimates which reflect these environmental or community issues is to identify <u>who</u> is likely to be affected and <u>how</u> they will respond. This information aids the analyst in deciding whether these costs should be reflected as lump-sum amounts (such as might be expected for litigation expense in response to a suit filed by an environmental group or community interest coalition) or annual amounts (to reflect adverse effects from the operation of the facility). Also, the identification of those segments of the public which are likely to respond will guide the analyst in deciding what rate of growth, if any, this response should exhibit over the period of interest, say, either due to their growing number, or their growing influence (as a result of changing legislation, etc).

For projects which may cause permanent change in the community or on the environment, a 10- or 20-year project lifetime is no longer a valid assumption. The spending rates which are estimated to reflect these permanent effects should be extended further into the future.

5. EVALUATION OF SELECTED FACILITIES

5.1 INTRODUCTION

In this section the methodology developed in Sec. 4 is used to evaluate the suitability of each of the five facility types for subsurface deployment at some future date. For some of the facilities it is advantageous to evaluate an entire complex, e.g., a medical installation; in other instances, a single facility, like an administration building, is appropriate.

Both the initial costs (i.e., land, excavation, construction) associated with the overall construction of the facility and the life-cycle costs attributable to the existence and operation of the facility are considered. In each case initial costs are computed using values for the key parameters which are most representative of the particular facility type. Social and environmental costs are factored into the analysis whenever it is determined that a particular advantage (disadvantage) has significant economic consequences which could impact on the subsurface deployment decision. For example, security costs at an ammunition storage facility could be substantially reduced by the underground siting of and the controlled access to the ammunition magazines; on the other hand, it does not appear that safety in an administration building would be significantly enhanced or reduced by the underground siting of the facility. Therefore, the costs associated with security are factored into the analysis of ammunition storage facilities while the costs attributable to safety in an administration building are assumed to cancel out of the analysis. The reader should note that the net cost shown in the figures in this section include those costs which appear to be economically significant in a subsurface deployment decision. Adding the costs which are equal for surface and subsurface facilities would just displace the curves shown upward and would not affect the time at which subsurface deployment may become more attractive than surface deployment.

One can readily imagine that there are a great many variables which can be treated parametrically in this study. Consequently, before proceeding further with this analysis, it is necessary to state several assumptions which are used to fix many of the variables. Unfortunately, several of the assumptions used require additional analysis which was not possible within the constraints of this study. Nevertheless, these assumptions seem reasonable and permit greater emphasis to be placed on the more significant aspects in a subsurface deployment decision. The assumptions are:

(1) Time-preference for money, i.e., discount rate (r), is fixed at 6% per annum.

(2) The surface area required to site a given facility below ground is equal to one-tenth the land needed for a surface facility. The land saved by subsurface deployment will then be put to its best use.

(3) Land is purchased by a lump-sum payment at $t = t_0$.

(4) Anticipated improvements in excavation, which result in decreasing real costs (inflation being discounted), are realized linearly over a twenty-year time period.

(5) Excavation cost increases due to inflation rise at a rate of 3% per annum.

(6) Roughly the same total floor space is required for a given facility regardless of its siting.

(7) The cost of construction (materials and labor) rises at 6% per annum.

(8) The cost per square foot to construct* a facility is the same regardless of its siting.

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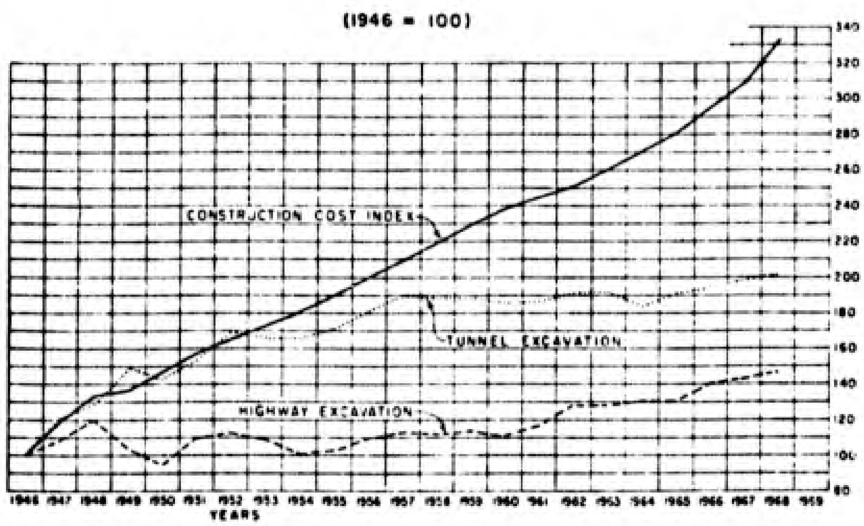
*Since the cost of excavation includes all costs associated with ground support and permanent lining; facility construction is considered to be the construction of exterior walls, supports, and interior partitions plus installation of all necessary equipment.

(9) Excavation rate is 20,000 yd^3/month and the construction rate is 20,000 ft^2/month.

Recent experience, as illustrated by the graph shown below, justifies the assumption that excavation costs will rise at a lower rate than construction costs. The figure is taken from an article by Ellis L. Armstrong which appeared in the Journal of the Construction Division of the ASCE Proceedings in October, 1970.



The factors listed below are treated parametrically:

(1) Land value

(2) Excavation cost

(3) Excavation cost improvement factor

The project start time is also allowed to vary in order to show the impact of anticipated improvements in excavation and increases in land value over the next two decades.

The price of land in 1972 is considered to range in value from \$5K to \$800K per acre. These values are representative of land prices in Norfolk, Virginia, and San Diego, California. The government recently purchased 545 acres of land near Camp Peary in York County, Virginia, for

\$2.71M (or \$5000/acre).[5] A good bit of this tract was either swamp land or subject to tidal action. A 495-acre tract is being purchased by the Navy in Norfolk for a total of \$17.4M (or \$35,000/acre).[5] The cost per acre ranged from \$6800 for an unused railroad storage area to \$450K for commercial land across the street from the main gate to the Naval Station. It is interesting to note that this latter purchase represents the last acre of land available to the Navy for expansion in the Norfolk area. Commercial and industrial land in San Diego was valued as high as \$800K/acre.[6] In many of the larger cities where the Navy has installations (e.g., Boston, San Francisco) land prices may go well above the \$800K figure. Land value has been appreciating at roughly 5% per annum for undeveloped land and at 10% or more in commercial and industrial areas.

One of the most important parameters in this analysis is the geology at the excavation site which is manifested in the excavation cost. The 1972 values considered in this analysis are \$30/yd^3 and \$150/yd^3. These include support and dewatering operations. These values represent a range of geological conditions from fairly intact rock requiring little support to poor quality rock and soils with water problems. Appendix I contains a detailed discussion of the analysis and supporting documentation which resulted in the two figures mentioned above.

An excavation cost improvement factor is applied to the excavation cost. This factor is assumed to result from the postulated R&D programs designed to advance excavation technology. The two values which are used in this analysis, 25% and 75%, result after 20 years. The improvements are assumed to occur linearly with time; i.e., after 10 years half the cost reduction is realized.

Operational and maintenance costs are estimated in most cases by referring to the costs of functionally similar facilities. (The cost-estimating procedure is sufficiently well understood and practiced so that it requires minimal comment here.) With regard to where the O&M costs for subsurface facilities would be greater or less than surface facilities, no unequivocal conclusion can be drawn. In some cases (see, for example, the discussion of storage facilities, Sec. 5.6) centralized, consolidated operations would provide a considerable reduction in O&M life-cycle costs, and this centralization could be facilitated by use of the subsurface as an alternative to purchasing additional surface land at a greater expense. But this, per se, does not demonstrate an inherent difference between surface and subsurface O&M costs. The more direct question of whether the cost of performing the primary functions of operation and maintenance is less or more expensive in an underground facility than in a surface one could not be answered in the time allowed. To answer questions of this nature in an absolute manner, rather than parametrically as we have chosen to do, would require a more detailed case study of the particular facility of concern. However, as a result of the parametric evaluation of the O&M costs for selected facilities of this study, the life-cycle O&M costs were found to be a major contribution to the overall net cost of a particular facility; and the sensitivity to these costs is great. A few percent difference in O&M costs is often enough to reverse a decision on which facility, surface or subsurface, is the most cost effective. It is suggested that as much of an analyst's attention should be directed toward familiarizing himself with the anticipated O&M costs (to permit a valid estimate of them for the purpose of life-cycle costing) as is directed toward the elements of land, construction, and excavation.

Many of the important factors which might enter into the decision-making process are either highly dependent upon the particular location and design of the facility or are complex problems requiring far more analysis than was possible in this study. Consequently, this section contains many generalizations which are helpful in the analysis but which should not be construed as all encompassing.

5.2 ADMINISTRATION BUILDINGS

5.2.1 Introduction

The analysis of the benefits offered by the underground siting of administration buildings revealed that, in most cases, the decision to place these facilities below ground will be based primarily on a traditional cost analysis, i.e., a comparison of the costs of land, excavation, and construction for the surface vs. subsurface facility. However, in some areas efforts to preserve the aesthetic quality of the surrounding community may tip the scales in favor of subsurface deployment.

Discussions with engineers and architects in Norfolk and San Diego failed to identify any advantages (disadvantages) associated with operational life-cycle costs (e.g., O&M, security, safety) which would be of major economic significance in a future subsurface deployment decision. Yearly operation and maintenance costs run roughly 3% of the construction cost of the facility. For a typical administration building this is approximately $25,000-$50,000. The combined operational costs associated with heat, air conditioning, and electricity should be roughly equal whether the facility is located above or below ground. A sewage pumping system would add costs to the subsurface facility; however, exterior maintenance costs would be reduced. Any savings in O&M would be relatively small and would not be a major factor in the subsurface deployment decision.

Security costs for a surface administration building are already minor and consequently potential security improvements as a result of subsurface deployment would be insignificant.

The costs associated with the survivability and safety of a building against natural disasters (floods, fires, earthquakes, etc.) are highly dependent upon the particular location being considered. In some locations the subsurface deployment of administration buildings could enhance the survivability of the facility in the event of an earthquake; however, flooding could be a far more serious hazard. Emergency exits, elevators, and sprinkler systems are all safety requirements which would have to be satisfied regardless of the siting of the facility. Therefore, it was determined that the combined life-cycle costs associated with the operation of a subsurface administration building would roughly equal the costs associated with a similar facility located on the surface.

There will be instances where the siting of a building on the surface will degrade the aesthetic value of the surrounding area which in turn may bring angry responses from the neighboring community. The Navy in the San Diego area is presently confronted with just such a situation. A high rise building (Naval Undersea Center) is being constructed on Pt. Loma (see Fig. 1.1). Citizen reaction has been vehement because the top of the building obstructs the view of San Diego Bay for some citizens living in a fairly expensive residential area. City officials, Congressional representatives, and lawyers are all involved in the controversy. It has been estimated by NAVFAC in San Diego that the costs associated with a work stoppage and then a redesign and rearrangement of the structure would amount to well over $1M, plus legal and administrative costs. Although it is impossible to predict the outcome of the above case, there is little doubt that it will hurt the Navy financially as well as resulting in a significant loss of community good will.*

5.2.2 <u>Analysis</u>

To illustrate the key parameters in a future decision regarding the subsurface deployment of administration buildings, it is helpful to select a typical facility for analysis. The administration building which houses the San Diego Branch of the Western Division of NAVFAC is so used. The two-story building has 55,000 sq ft of floor space and

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*It is interesting to note that in the November election an ordinance was passed which limits all future construction on Pt. Loma to a height of 30 ft.

occupies roughly 2/3 of an acre in a commercial and industrial area only a few city blocks from the waterfront. Land prices in most commercial and industrial areas bordering Naval installations in San Diego range in value from \$100K to \$800K per acre, with appreciation occurring at 5-10% per annum.[6] Using the values shown below we arrive at the curves presented in Fig. 5.1.

Land required for surface facility	.65 acres
Initial land value	\$100K and \$800K per acre
Land appreciation rate	5% and 10% per annum
Construction cost	\$30/ft^2
Floor space required	55,000 ft^2
Excavation cost	\$30/yd^3 and \$150/yd^3
Excavation volume	35,000 yd^3
Excavation improvement factor	75%

The bottom graph shows that, at the lower values of land and land appreciation rate, subsurface deployment is not an economical option regardless of the geology or state of excavation technology. However, where land is very expensive (upper graph), the underground siting of even a relatively small facility becomes attractive within the next two decades.

One can readily see from the curves that in those instances where the surface facility would create a community disturbance of the nature described above, the subsurface deployment of Naval buildings may be one of very few options. In the future the Navy (and other organizations) will probably be faced with more and more laws prohibiting the construction of facilities which degrade the aesthetic quality of a given region.

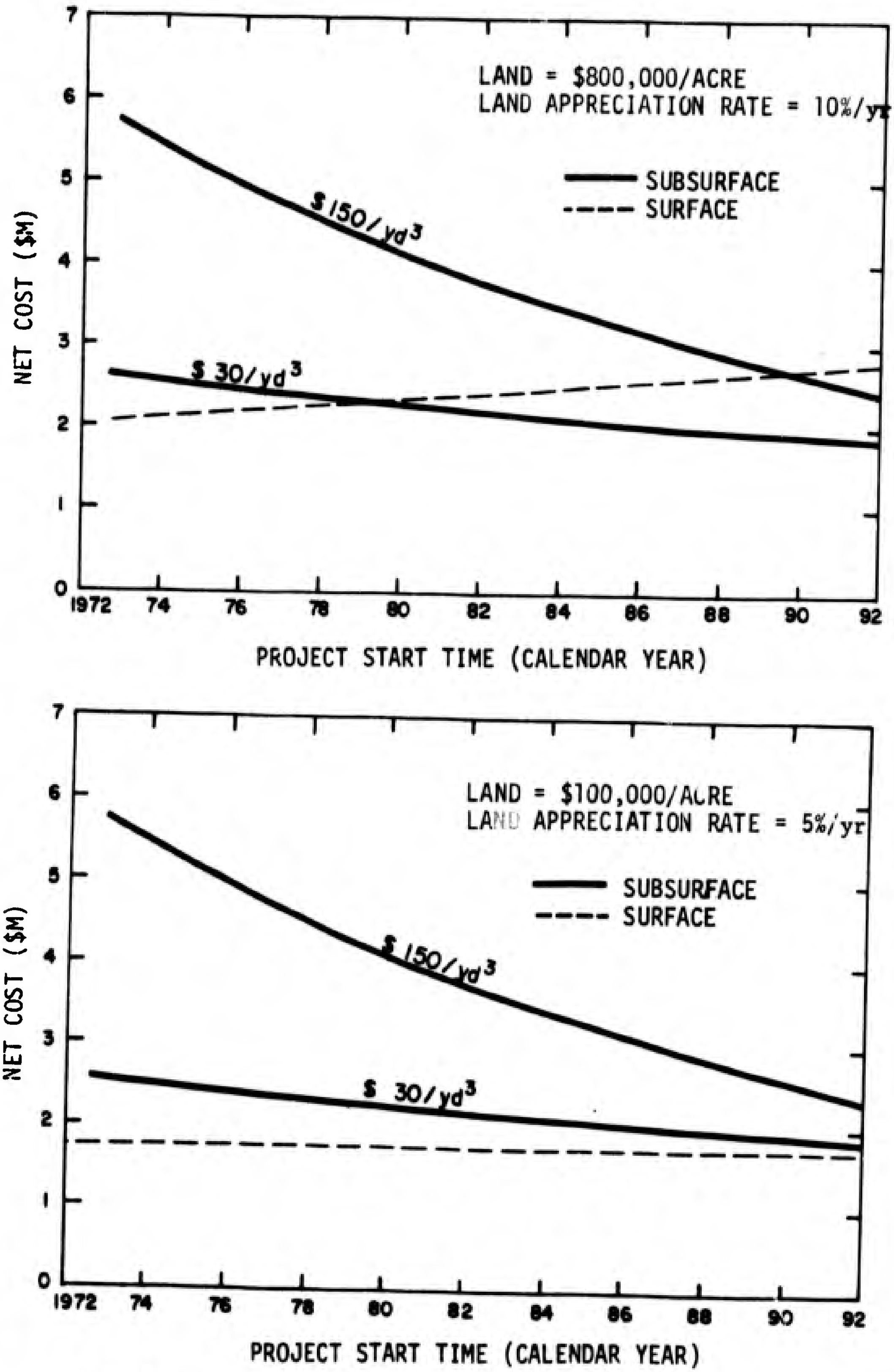

Figure 5.1. Subsurface Deployment of Administrative Buildings

5.3 MEDICAL FACILITIES

5.3.1 Introduction

The authors conclude that the subsurface deployment of hospitals is a feasible option for the Navy; however, other alternatives appear to be more advantageous. As stated earlier, land utilization is one of the dominant factors favoring the underground siting of Naval facilities. In the case of a medical complex, it is not the main hospital building which occupies the largest area; the majority of land (up to 80%) is used to satisfy the many support functions. For example, the San Diego facility (the Navy's largest) consists of 77 buildings of which only about 20% directly involve patients and many of these deal primarily with outpatients. The subsurface deployment of many of these support functions, which may degrade the overall appearance of the complex, could not only free land for additional facilities, but it could provide land for parks and picnic areas around the hospital.

Although the study did not specifically address the possible psychological problems arising from the underground siting of hospitals, competent medical opinion was sought. Dr. Joseph T. Horgan (Captain, USN), executive officer of the Portsmouth Naval Hospital, described loneliness and depression as two of the major problems facing patients confined in a hospital for an extended period of time. He felt that the seclusion in a subsurface hospital would probably have deleterious effects on these long-term patients unless considerable effort (expense) was undertaken in the design of patients' quarters to compensate for the missing communication with the outside world. Dr. Horgan also pointed out that certain hormones appear to operate on a diurnal cycle and the absence of day and night requires the body to make certain adjustments. An illustration of how present medical opinion stands on the idea of subsurface hospitals is given by the fact that there are nine coronary care units in the Portsmouth Naval Hospital and only one is windowless. It is rarely used and then only as a last resort.

It therefore appears that the *optimum* approach would place facilities for ancillary functions below ground. Several hospitals which have basements have found that food service, laundry and laboratory facilities, and operating suites are easily placed below ground with no adverse effects. Future developments in hospital operations may enable even greater utilization of the subsurface. Three major trends in the medical field which support this contention are: (1) greater reliance on outpatient care, (2) increasing automation including computerized laboratories, and (3) greater centralization through the use of computers. It is clear that these developments could readily be adapted to future use of the subsurface.

Figure 5.2 presents a schematic representation of a future hospital concept which capitalizes on the anticipated improvements in excavation capability. The only portion of the building above ground is the receiving area, emergency entrances, and the rooms for patients confined for extended periods of time. Below ground are found the central computer facility and numerous other functions adaptable to subsurface deployment. Large volumes are excavated to capitalize on economies of scale, and the facility is spread out horizontally to reduce the high structure costs which accompany deep structures in the poor geology characteristic of most Naval installations.

Additional facilities are connected to the central complex by a series of tunnels similar to the spokes of a wheel. This facilitates control and materials transport.

Recent hospital construction (e.g., in Roosevelt Roads, Puerto Rico) shows that the Navy considers aesthetically pleasing surroundings to be of great significance to the morale and well being of its patients. This hospital was built to maximize the number of windows with a view of the sea. Note that the concept in Fig. 5.2 frees the surface of much of its usual steel and concrete and permits the development of parks and

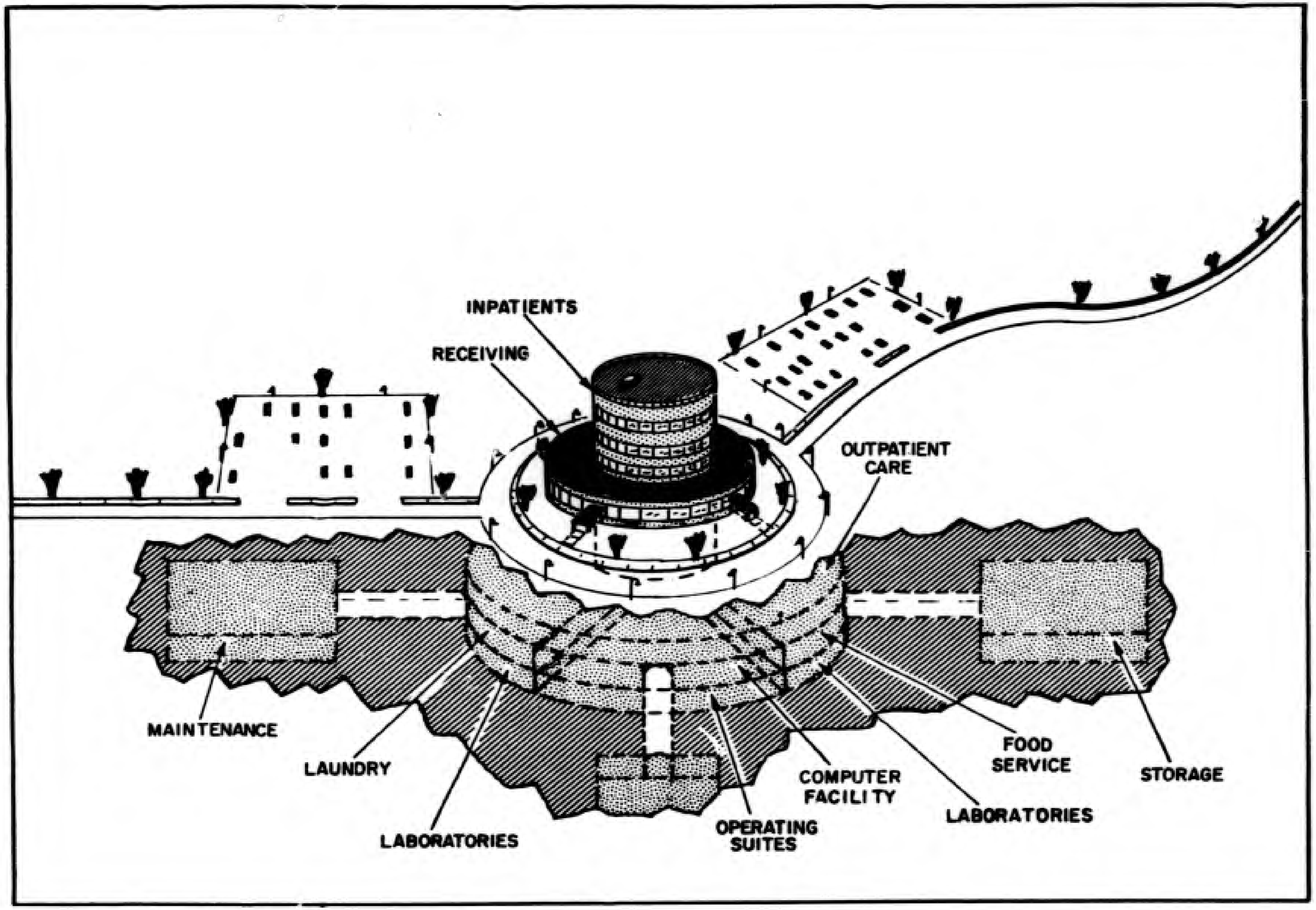

Figure 5.2. Future Hospital Concept

picnic areas. The concept illustrates the utilization of both the surface and the subsurface simultaneously.

5.3.2 Analysis

The values shown in Table 5.1 are considered representative of the land, excavation, and construction costs and requirements which would be found today in the building of medical facilities. The Naval hospitals in Portsmouth, Virginia, and San Diego, California, each occupies close to 100 acres of land in urban areas where land value is high and appreciating rapidly.

The analysis assumes a 20% land utilization rate; i.e., of the 100 acres of land required for the surface facility, only 20 acres are actually used for buildings. The average building is considered to be two stories high (30 ft), and the excavation volume includes the same volume as the surface facility plus roughly 10% for connecting tunnels and access shafts.

Figure 5.3 shows a comparison of the net costs for the surface and subsurface hospital complex as a function of time. Using the values above, one would expect subsurface medical facilities of the nature outlined in this section to appear economical after 1985. If, however, a greater effort is placed on advancing excavation technology, i.e., excavation improvement factor = 75%, one finds subsurface deployment an attractive option 3 or 4 years earlier. In areas where the geology is good, i.e., excavation cost = $\$30/yd^3$, the underground siting of medical facilities appears to be attractive in the 1970s.

The advantages (disadvantages) associated with the underground siting of medical facilities, suggest that, in at least one aspect, the potential exists for economically significant benefits.

TABLE 5.1
COST CHARACTERISTICS FOR MEDICAL FACILITIES

Land	
Land required for surface facility	100 acres
Initial land value	\$500K/acre
Land appreciation rate	10% per annum
Construction	
Floor space required	1.6M ft^2
Construction cost	\$50/ft^2
Excavation	
Excavation volume	1M yd^3
Excavation cost	\$150/yd^3
Excavation improvement factor	25%

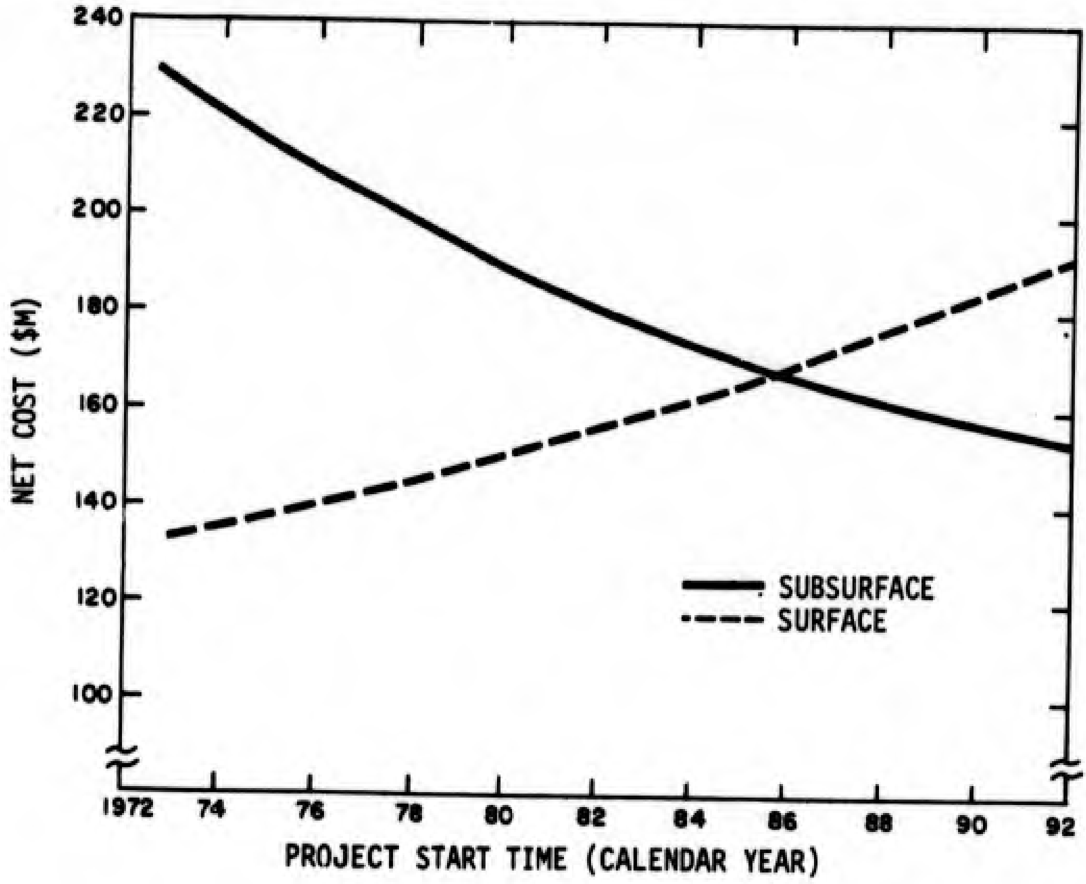

Figure 5.3. Subsurface Deployment of Medical Facilities

As with administration buildings, the costs of medical facilities attributable to safety and survivability seem, in general, neither increased nor diminished as a consequence of subsurface deployment.

The costs of operation (heat, light, air conditioning) also seem to balance out for the most part. In some locations heating costs would rise with subsurface deployment while air conditioning costs would fall, and vice versa. The logistics of moving supplies and equipment around an underground complex and to and from the surface might require more sophisticated materials handling systems than presently used. Although this would present no insurmountable technical problems (in fact it would probably result in substantial improvements over present systems), it would probably require greater expenditure.

On the other hand, maintenance costs associated with exterior painting, roof repair, window cleaning, venetian blinds, and insect screens, a major expense, would clearly be reduced by the underground siting of the medical complex, Maintenance costs at the San Diego Hospital run roughly $1M/yr; however, $3M or more are really needed because, in many instances, buildings are not repainted, windows are not cleaned, etc., because of a shortage of funds.[7]

Security, a major problem (at least in San Diego,[7] where televisions, microscopes, and dental equipment are among the more commonly pilfered items), would probably be facilitated by the controlled access to the underground medical facility.

Discussions with architects and engineers at both San Diego and Norfolk revealed that the additional expenditures required to make a surface facility aesthetically pleasing run roughly 3-5% of the cost of constructing the facility. This depends, of course, on the proposed location, the particular design, and the degree to which members of the surrounding community value aesthetics. If one assumed that the cost of constructing an aesthetically pleasing surface facility was 4% of the construction cost, an additional \$3.2M would have to be added to the total net cost of the surface facility (Fig. 5.3).

It is clear that the net saving (+ or -) from combining the costs attributable to aesthetics, maintenance, security, and materials handling systems would not significantly alter the results presented in Fig. 5.3. In other words, the dominant factors thus far in a future decision regarding the underground siting of medical facilities are, in order of importance, initial land value, in situ geology, and excavation technology.

If indeed it is true that desire to get well is often a determining factor in the recovery of a patient confined for an extended period of time and further that loneliness and depression are often the major stumbling blocks reducing this desire, then it appears that pleasant surroundings, including parks and picnic areas, have the potential to increase the rate of recovery. The economic consequences (as well as the humanitarian benefits) might be substantial. We illustrate this point for an increase in the rate of recovery of, say 10%. The saving to the Navy in the 2000-bed San Diego Hospital alone, for one year, assuming a 75% occupancy rate per day and a cost of roughly \$50 per occupied bed per day,[8] is:

$$0.10 \times 0.75 \times 2000 \times 365 \times 50 = \$2.74\text{M/yr}$$

This figure does not include the saving in salary which the government has to pay all active duty military personnel who are confined to the hospital. Finally, it does not include the incalculable humanitarian benefits.

In summation, then, the subsurface deployment of medical facilities (other than those for confined patients) appears to be a potentially attractive option for the Navy in areas where land value is high. This is especially true if the in situ geology is good and excavation costs are substantially reduced. Significant economic and humanitarian benefits may also be derived by the underground siting of medical installations if the surface area surrounding the hospital is devoted to the development of pleasing grounds.

5.4 AIRCRAFT MAINTENANCE FACILITIES

5.4.1 Introduction

As pointed out in Sec. 3.2, aircraft maintenance facilities currently represent considerable value to the Navy in terms of replacement costs and existing deficiencies (Table 3.3). They also require relatively large land areas and have potential adverse environmental and community interactions because of noise generated during jet engine runup and test operations. This section examines aircraft maintenance to establish if, and under what conditions, subsurface deployment might hold some advantage in the future. Before proceeding to the analysis, a brief review of the current impact of these operations on land utilization and noise generation around existing air stations is given to provide a perspective.

Included under aircraft maintenance is both minor servicing and repair as well as major overhaul. Minor repairs are usually accomplished in hangars that may also serve as storage for unused aircraft. Major overhaul, on the other hand, involves extensive operations entailing complete aircraft disassemblement and testing of individual components from the engine to the structure. These activities are normally accomplished in a large complex of buildings that include hangars, power check facilities, etc. Collectively this complex is called a Naval Air Rework Facility or NARF.

Aircraft maintenance structures take up a large percentage of the total area at a given air station, particularly if the station has a NARF complex. For example, 35% of the building area at the Norfolk NAS and 25% at North Island NAS is used for aircraft maintenance.

On the other hand, a comparison of the total land occupied relative to the total available at a given station generally shows aircraft maintenance occupying a very small percentage--e.g., ~3% in Norfolk. As one would expect, most of the land is used for runways, taxiways, and aprons, or is contiguous, semi-improved, or unimproved land serving as safety or noise buffer zones.

The major issue today regarding land utilization is not so much the total land occupied by air stations, but the marginal land required around the perimeter where most facilities, including aircraft maintenance are located. Pressures from neighboring communities to develop and use this land is growing and even today affecting the mission of some air stations. Consider the Los Alamitos Naval Air Station in California. Here noise restrictions imposed by neighboring communities reduced the operational capability of the station by more than 50%, with little change in operating costs. Another case is the Virginia Beach Air Station near Oceana, Virginia. Here pressures from land developers to build homes immediately adjacent to the airfield may force the government to buy some 5700 acres of land (~$35K/acre) in composite noise rating (CNR) zone 3 contours if the base is not to suffer the same reduced operational capability as Los Alamitos.[9] Pressures for marginal land and noise/community interactions are indeed costly issues affecting air stations today, and are likely to continue to grow in the future.

The question addressed here then is whether subsurface deployment of aircraft maintenance facilities can help reduce these problems. One can envision a large complex of maintenance facilities located under existing runways and taxiways where aircraft are lowered using elevators similar to that used in aircraft carriers. Moreover, one can envision underground power check facilities that use long, large diameter tunnels to couple jet engine noise into the surrounding earth (emitting low velocity noiseless gas only) or to carry the exhaust away to some less densely populated area.

The following sections examine the implications of such a hypothetical NARF and power check complex. An engine overhaul and power check complex is examined separately from the total NARF complex because its unique noise implications might warrant siting it below ground, independent of the total complex.

5.4.2 Analysis of a NARF Complex

The following analysis compares a surface and subsurface NARF complex having the following general characteristics:

LAND

Land required for surface facility	90 acres
Initial land value	\$10K-100K/acre
Land appreciation rate	10%/yr

CONSTRUCTION

Floor space required	1.5M ft^2
Construction cost (surface)	\$30/ft^2
(subsurface)	\$32/ft^2

EXCAVATION

Excavation volume (30 ft ceiling)	1.7M yd^3
Excavation cost	\$30-150/yd^3
Excavation improvement factor	75%

<u>O&M</u>

O&M costs	$\$30/ft^2/yr$
O&M escalation rate	6%/yr
Lifetime	20 yr

This hypothetical complex is based on a review of NARF facilities at the Norfolk and North Island air stations. It assumes one-story buildings with average heights of 30 ft and combined floor space of 1.5M ft^2. For comparison, the NARF complex at North Island consists of approximately 1.8M ft^2 with building heights ranging between 59 ft (two-story) to 21 ft (one-story).

Note that land used for the surface installation is 90 acres. This assumes buildings utilize 40% of the land with the remainder taken up by roadways, taxiways, parking aprons, fire spacing, etc. This is consistent with a land utilization factor of 42% (relative to improved land) at the Norfolk air station.

The range of land costs and appreciation rate, $10K to 100K/acre and 10% respectively, is representative of current and projected land values adjacent to air stations in the Norfolk and Virginia Beach regions.[5,6]

The construction costs (excluding excavation) are $\$30/ft^2$ for the surface facility and $\$32/ft^2$ for the subsurface. These are typical unit costs for maintenance hangars taken from Ref. 1. An additional $\$2/ft^2$ is added for the subsurface facility to account for special equipment requirements such as large, heavy-duty elevators for aircraft handling, ventilation, additional lighting, etc.

Cost of operations and maintenance for the surface facility is assumed to be $\$30/ft^2$/year ($42M/annum total). This is consistent with the $\$31/ft^2$/year average cost experienced at the NARF facility in Norfolk.[10]

The major percentage of O&M costs are operational and only a small percentage maintenance (1.6% at Norfolk). This is understandable if one realizes that several thousand people (4600 at Norfolk) are employed in the operations of a large NARF complex. Their salaries alone amount to $45M or more per year. Clearly the possible maintenance advantage of subsurface deployment (i.e., reduced exterior building maintenance, etc.) is not a significant cost factor here.

An important related issue is the potential impact subsurface deployment might have on operating costs. It is clear that additional handling of aircraft would be necessary: not only vertical lowering and raising but also horizontal movement due to limited accessibility to the surface. This handling would probably impact adversely because of the time, equipment, and operating personnel involved. This impact of O&M is examined parametrically here. In other words, the consequences of a ±1-4% variance in O&M relative to surface deployment over a 20 year time frame is examined.

In the following pages land, excavation, construction, and O&M costs are shown to be the driving factors in the decision to locate below ground. Factors such as safety, security, and aesthetics, are not expected to be significantly different for subsurface facilities; noise is an exception.*

Regarding safety, our discussions with operating personnel at the NARF facilities in Norfolk and San Diego revealed that subsurface deployment has some advantage in eliminating fire spacing requirements between surface buildings. On the other hand, limited accessibility to the surface may pose an evacuation problem in the case of emergency or fire.

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*Noise impact is also very important and is considered separately in the next section under power check facilities.

Security is not a dominant factor here since surface facilities generally have only a nominal security force concerned mainly with guarding aircraft containing sensitive equipment. For example, the NARF facility at Norfolk has seven guard posts manned by fewer than 20 guards.

Figure 5.4 gives net cost versus calendar year curves showing the impact of land value and excavation costs, including improvements for the hypothetical NARF complex outlined.

An examination of these curves suggests the following:

1. If land is relatively inexpensive today ($10K/acre) subsurface deployment appears to be uneconomical within the next 20 years even with good geology ($30/yd^3) and a 75% cost improvement factor.

2. For land that is relatively expensive today ($100K/acre), subsurface deployment remains uneconomical for bad geology ($150/yd^3) even with an excavation improvement factor of 75%. For a technological best case ($30/yd^3 and 75%) it does become economical within the 20-year time frame.

Using the technological best case for land initially at $100K/acre, Fig. 5.5 shows the impact of O&M costs. Included in the net cost plotted here are both the initial construction and investment costs discussed previously and also costs of operating and maintaining the complex over a 20-year period. Even when discounted to present value these costs are large, the order of $1B. Clearly, O&M has a substantial impact on the life-cycle costs of a NARF complex.

The family of solid curves in Fig. 5.5 show the impact of various levels of O&M cost on the decision to locate underground. They represent subsurface costs that include, respectively, a +4%, 0%, and -4% O&M cost variance with the surface facility. It is clear from these results that

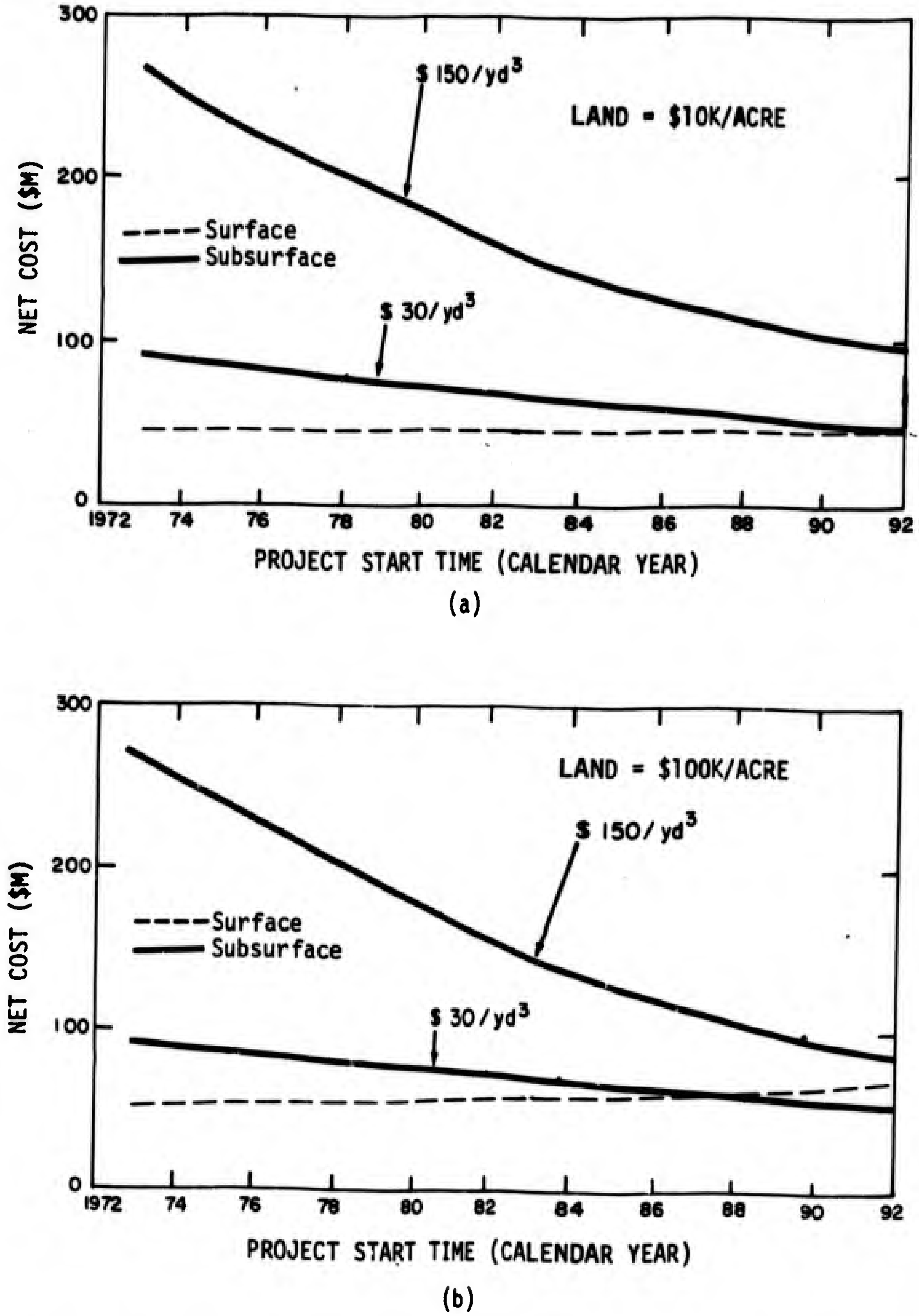

Figure 5.4. Effect of Land Value and Geology on Subsurface NARF Facilities

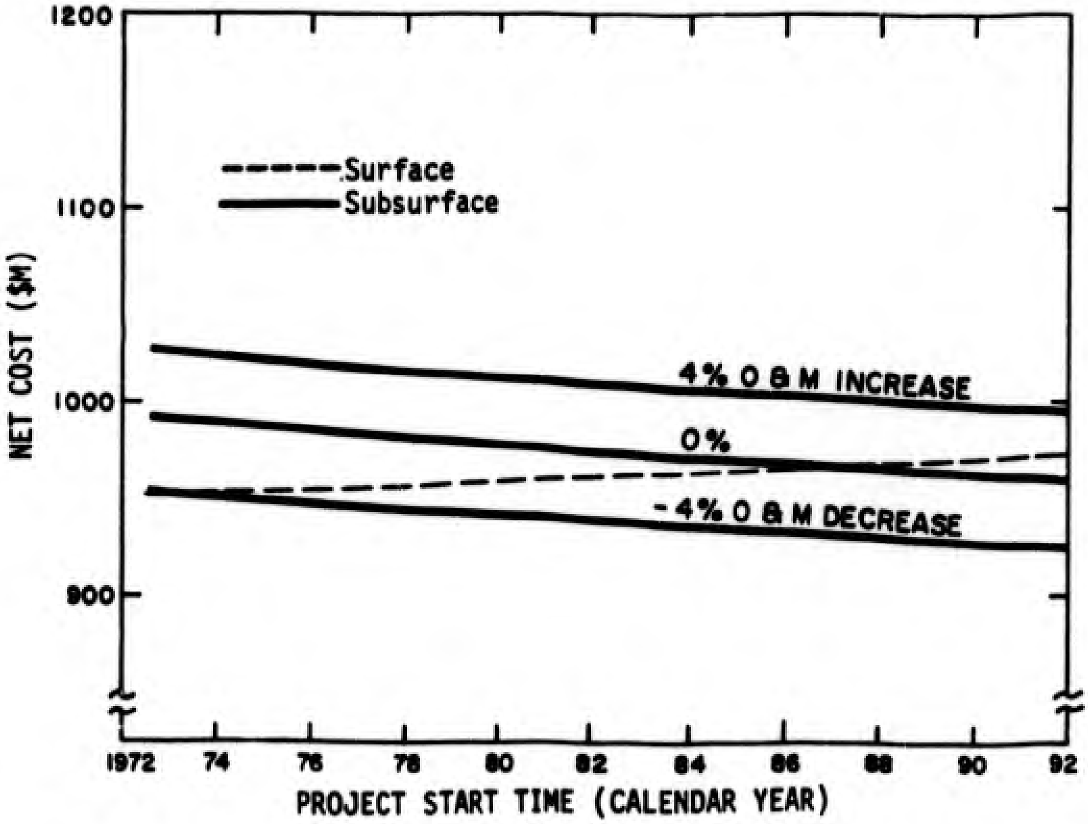

Figure 5.5. Effect of O&M Costs on Subsurface NARF Facilities

O&M costs are a very important and sensitive parameter. A ±4% variance can change our conclusions completely.

As was pointed out earlier, it is very likely that O&M costs will increase with subsurface deployment. Even if one assumes a relatively small (1%*) increase, the break even point for this technologically best case is shifted from 1987 to 1991.

From all these observations one comes to the following general conclusions regarding subsurface deployment of NARF complexes: It does not appear feasible within the next 20 years except under very ideal and extreme conditions. These conditions are:

1. Land values exceeding $100K/acre today with a projected appreciation of 10% or greater
2. Excavation costs of the order of $30/yd^3 today with at least a 25% reduction over the next 20 years; or excavation costs of $150/yd^3 with a reduction exceeding 75% over the next 20 years
3. Very little change in O&M costs (< 1% relative to the surface) resulting from subsurface deployment

5.4.3 Analysis of an Aircraft Engine Overhaul and Power Check Complex

The following analysis compares a surface and subsurface engine overhaul and power check complex on the basis of land, excavation, construction, and noise-related costs. It assumes a hypothetical complex of the following general characteristics.

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*To put this into perspective, 1% is equivalent to $450,000/year in 1972. If one assumes 90% of these costs are labor related, this reduces to approximately $400,000/year. At a $10,000/year average salary (Norfolk experience) this is equivalent to the time of 40 new employees. In other words, at 1%, 40 new employees would be required for additional equipment handling, etc., due to subsurface employment. This is not unreasonable compared to the 4000 already employed at such a facility.

LAND

Land required for surface complex	15 acres
Land appreciation rate	10%/annum
Initial land value	$10-100K/acre

CONSTRUCTION

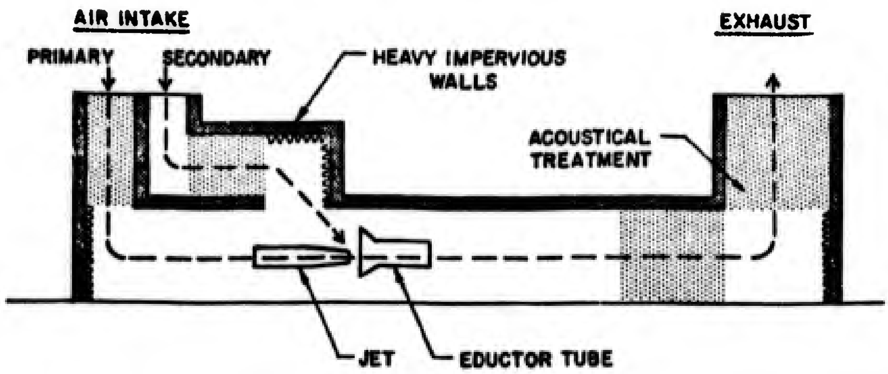
Floor space required	100,000 ft^2
Construction cost	$50/ft^2

EXCAVATION

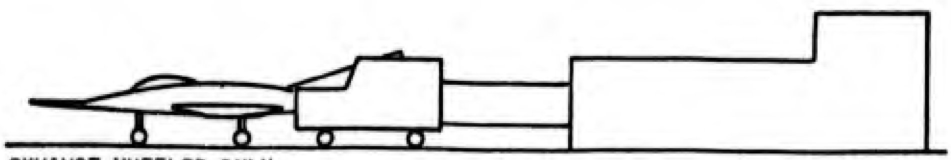
Excavation volume	300,000 yd^3
Excavation cost	$30-150/yd^3
Excavation improvement factor	75%

As envisioned, this complex includes in one centralized area both engine overhaul shops and test cells used for controlling noise during engine runup operations. Test cell configurations used today are shown in Fig. 5.6: Fig. 5.6a for engines tested out of the aircraft, and Fig. 5.6b for engines tested in the aircraft. These configurations represent state of the art in attempts at containing and attenuating the engine roar generated from turbulent mixing of hot jet exhaust gases with the atmosphere, and also the high-pitched fan noise of the newer turbofan jets. Enhanced attenuation results from muffling and absorbing the sound energy using jets of water directed at the exhaust plume as well as acoustical materials lining the walls of the cell. Noise that cannot be absorbed is directed 90° upward and carried out the exhaust stack with the hot gases.

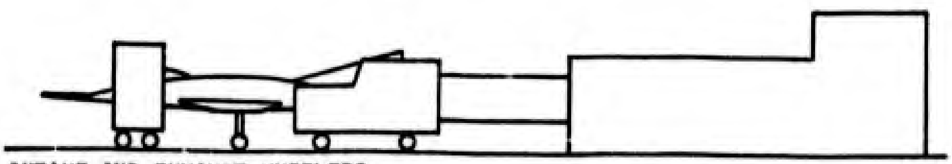
This escaping noise, for the most part, is composed of low-frequency components which are more difficult to muffle without an extended sound-attenuating system. Unfortunately a significant part of the sound emitted by a jet aircraft during ground runup is low frequency, as shown in Fig. 5.7. Moreover, these components are not well attenuated by the atmosphere and even though directed upward, atmospheric refraction can cause



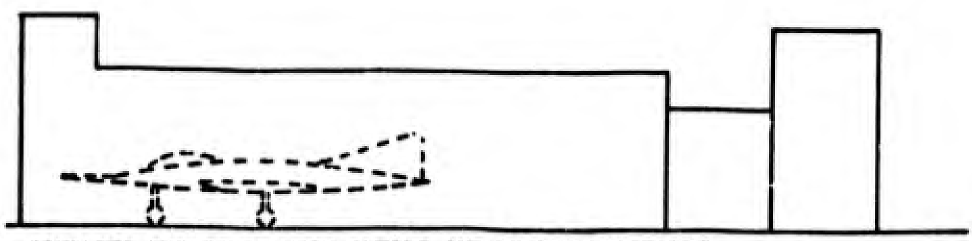
(a) Engine test cell



EXHAUST MUFFLER ONLY
APPROXIMATE NOISE REDUCTION 15-30 dB



INTAKE AND EXHAUST MUFFLERS
APPROXIMATE NOISE REDUCTION 20-35 dB



COMPLETE ENCLOSURE WITH INTAKE AND EXHAUST MUFFLERS
APPROXIMATE NOISE REDUCTION 30-50 dB

(b) Ground Runup Enclosure

Figure 5.6. Jet Engine Noise Control Facilities

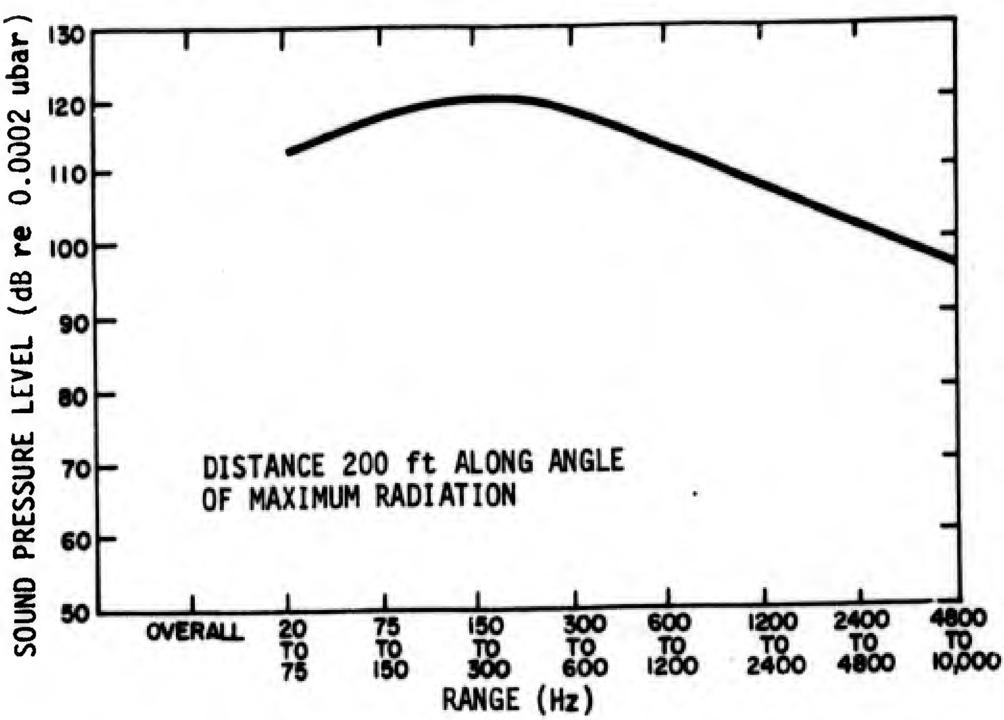


Figure 5.7. Typical Sound Pressure Levels of Single Engine Jet Aircraft During Ground Runup

them to return to the earth's surface some distance from the cell. Indeed one can often hear the low frequency rumble of engines being tested on North Island while across the bay in San Diego.

Uncontrolled noise in general is becoming a major public concern today, one with potential high-cost implications. Moreover, this concern is likely to continue in the future particularly in view of the recently passed Noise Control Act of 1972 which states:

> ...that inadequately controlled noise presents a growing danger to the health and welfare of the Nation's population; and that Federal action is essential to deal with major noise sources in commerce, and other products, control of which require national uniformity of treatment...

This act empowers the Environmental Protection Agency to set and enforce standards and also paves the way for citizens' suits to enforce noise control requirements. For example, note Sec. 12 of the Noise Control Act:

CITIZEN SUITS

Sec. 12 Any person may commence a civil action on his own behalf against any person (including the United States) for violation of this act or against the Administrator of EPA or FAA for failure to perform any non-discretionary duty under this act. No action may be commenced until 60 days after notice of violation or if the Administrator is already diligently prosecuting a civil action. The Administrator may intervene as a matter of right in costs of litigation (including reasonable attorney and expert witness fees) to any party. Nothing in the section restricts any right which any person may have under any other statute or the common law to enforce a noise control requirement.

This analysis assumes that costs associated with overall noise-community interactions can indeed be identified and that a percentage of these can be attributed primarily to engine runup operations. In other words it assumes that better control of noise generated during runup operations will help reduce the overall noise problem around air stations and therefore help reduce noise-related costs. These assumptions are not completely arbitrary since landing and takeoff noise generally radiates more strongly in one direction, along runway approaches, while engine runup noise can radiate in two equally strong directions. This suggests the possibility that landing and runup noise contours might not overlap in all cases (see Fig. 5.8) and that noise-related costs might in fact be divisible.

The analysis further presumes that subsurface deployment of test cells offers definite noise control advantages. Unfortunately, time did not permit a detailed examination of this assumption including the related technical issues. Nonetheless, it is recognized that long tunnels might be used to better control low-frequency sound or at the very least the exhaust gases and sound might be transported to areas where population density is low.

It is interesting to note that engineers at both North Island in San Diego and Virginia Beach have considered this possibility. At North Island a tunnel to the ocean was investigated; at Virginia Beach a long, earth-mounded corrugated steel tube was proposed. The North Island concept was rejected because of water egress problems at the ocean end of the tube; the Virginia Beach concept was never fully analyzed. Clear technical issues identified by these engineers requiring future examination before subsurface tunnels might prove feasible include:

1. Back-pressure problems that might affect engine performance readings.

2. The wearing of tunnel liner after repeated use.

Included in the hypothetical subsurface engine overhaul and power check complex, then, is an allowance for three 18-ft-diameter tunnels extending 1 mi away from the complex. These tunnels are to be used to

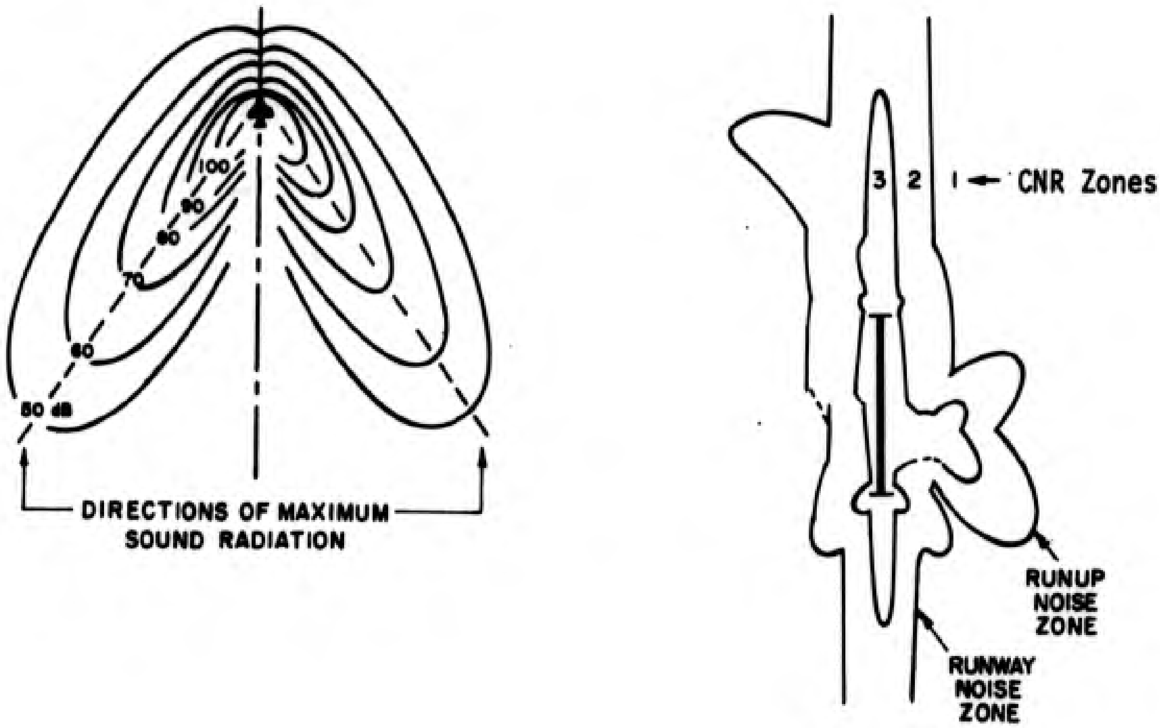


Figure 5.8. Runway/Runup Noise Contour Interaction

transport exhaust gases from test cells located within the complex to a region of low population density. The 300,000 yd^3 excavation volume given previously accounts for these tunnels.

The approach taken in bringing noise-community interaction costs into the analysis is as follows: a noise spending function of $200,000 per year increasing at a rate of 15% is assumed. These are due to runup operations when no form of noise control is used, and reflect costs to the Navy resulting from such things as law suits, requirements to buy up contiguous land for noise buffer zones, etc.

Although difficult to assess, the noise costs used here are reasonable for this comparison if one considers the following: at the Virginia Beach Air Station the cost of buying some 5700 acres of noise buffer zone land within zone 3 CNR contours is estimated at $184M. Table 5.2 presents similar data for various air stations in California. On the average, 5000 acres at $15,000/acre or $75M is representative of conditions here. On this basis, then, the initial costs attributed to runup operations in this study are only 0.1% for Virginia Beach and 0.3% for California of the potential costs of buying buffer zone property today. Moreover, the projected increase in noise costs assumed here is taken at 15% per annum reflecting a combined appreciation of land value (10%) and an additional factor accounting for population growth, increased community awareness, and also legal powers to act (i.e., the civil suits provision of the Noise Control Act of 1972).

Using the noise spending function assumed when no form of noise control is used, the analysis then postulates various improvements and examines parametrically the relative advantage of surface versus subsurface noise control measured over a 20-year time frame. This is shown in Fig. 5.9. Specifically, 50% and 75% reductions in noise costs are presumed possible using surface techniques (i.e., Fig. 5.6). This is compared to 50%, 75%, and 95% reductions if one went below ground using tunnels. In this way the relative advantages of surface versus subsurface deployment

TABLE 5.2

LAND WITHIN COMPOSITE NOISE RATING ZONE 3 CONTOURS - REPRESENTATIVE AIR STATIONS IN CALIFORNIA[6]

INSTALLATION	ESTIMATED ACREAGE CNR ZONE 3 *	ESTIMATED COST PER ACRE	ESTIMATED ESCALATION % PER ANNUM
NAF El Centro	9461	$200 - $1000	2
NAF China Lake	9	$300 - $1000	10
NAS Imperial Beach	18	$8000 - $160,000	11
NAS Miramar	5110	$3500 - $140,000	7
NAS North Island	588	$30,000 - $80,000	7
NAS Point Mugu	2049	$6000 - $10,000	5–6
MCAS El Toro	6484	$6000 - $14,000	5–6
MCAS Yuma	9622	$200 - $5000	Unknown

* For current flight and ground runup operations

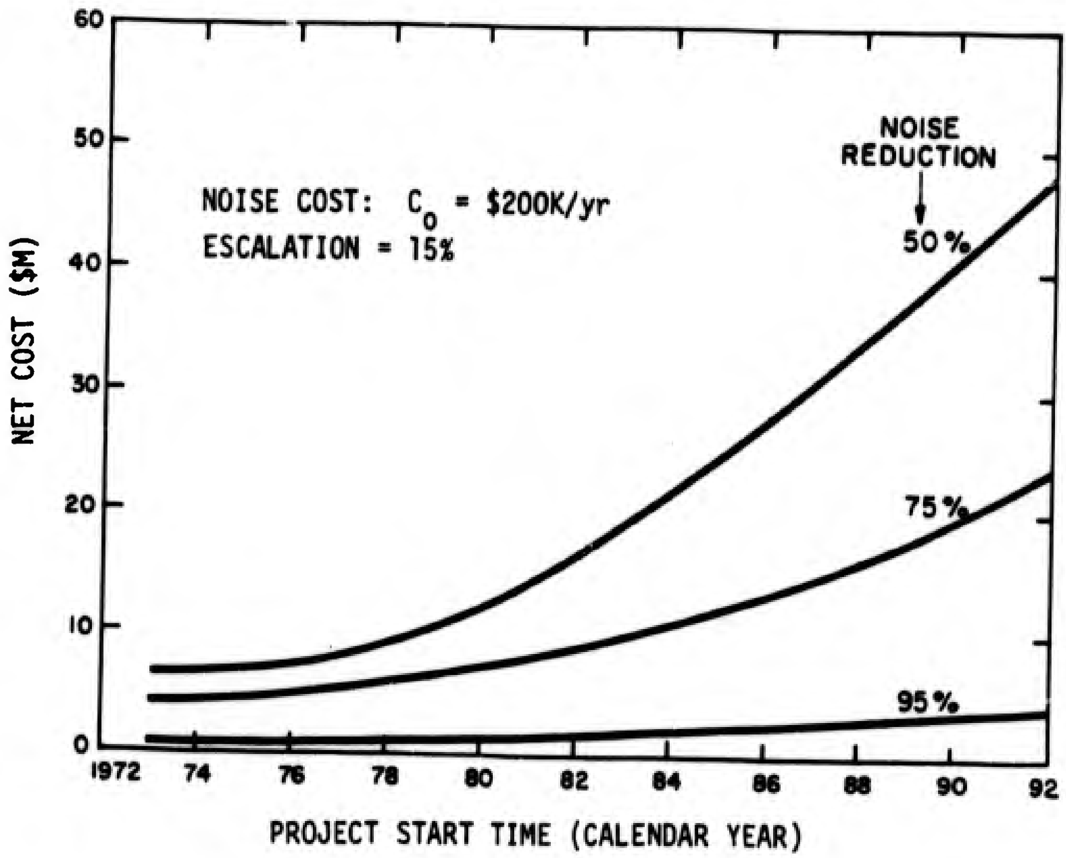


Figure 5.9. Assumed Noise Costs for Various Reduction Factors

are compared accounting for the fact that noise can be controlled to some extent even without going below ground.

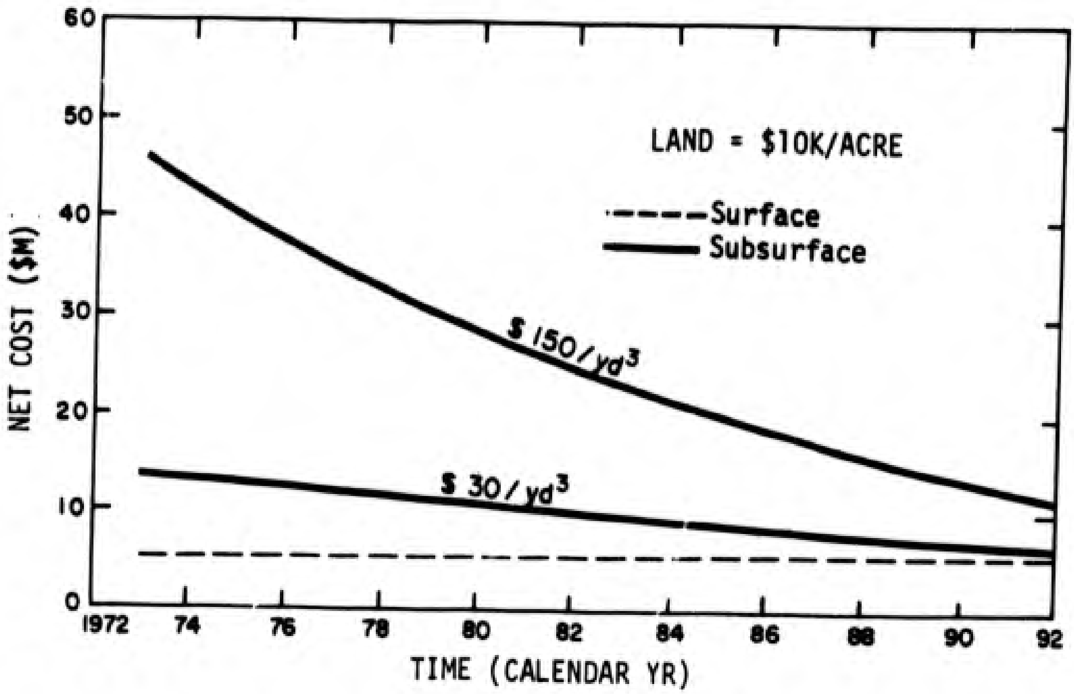
The results of the analysis are presented in Figs. 5.10 through 5.12. Figure 5.10 shows the effect of geology and land value excluding noise costs and Figs. 5.11 and 5.12 include noise costs.

Considering geology and land costs alone it is clear from Fig. 5.10 that subsurface deployment becomes economical after 1987 under the following rather ideal conditions:

1. Land values are high today (>$100K/acre) and continue to appreciate at least 10% per annum in the future.
2. Excavation costs are less than ~$75/yd^3 today with a 75% improvement projected over the next 20 years.

Figure 5.11 shows the results when noise costs are accounted for. Figures 5.11a and b are for $150/yd^3 and $30/yd^3 initial excavation costs respectively. Note that the initial land value used here is $10K/acre and that the excavation improvement factor is only 25%. These results, therefore, represent a relatively conservative case.

Noise can have a significant impact on the decision to deploy underground if improvements in noise reduction can in fact be realized by going below ground. Consider the $150/yd^3 case (Fig. 5.11a): at the same 50% reduction in noise costs for both surface and subsurface, the subsurface remains uneconomical. If subsurface reductions of 75% or 95% are possible, this option becomes economical in 1991 or 1986, respectively. For the $30/yd^3 excavation costs the impact is even greater. Here 75% and 95% subsurface reductions show subsurface deployment becoming economical in 1975 and 1973, respectively.



LAND APPRECIATION RATE = 10%
CONSTRUCTION COST = $50/ft^2
EXCAVATION IMPROVEMENT = 75%

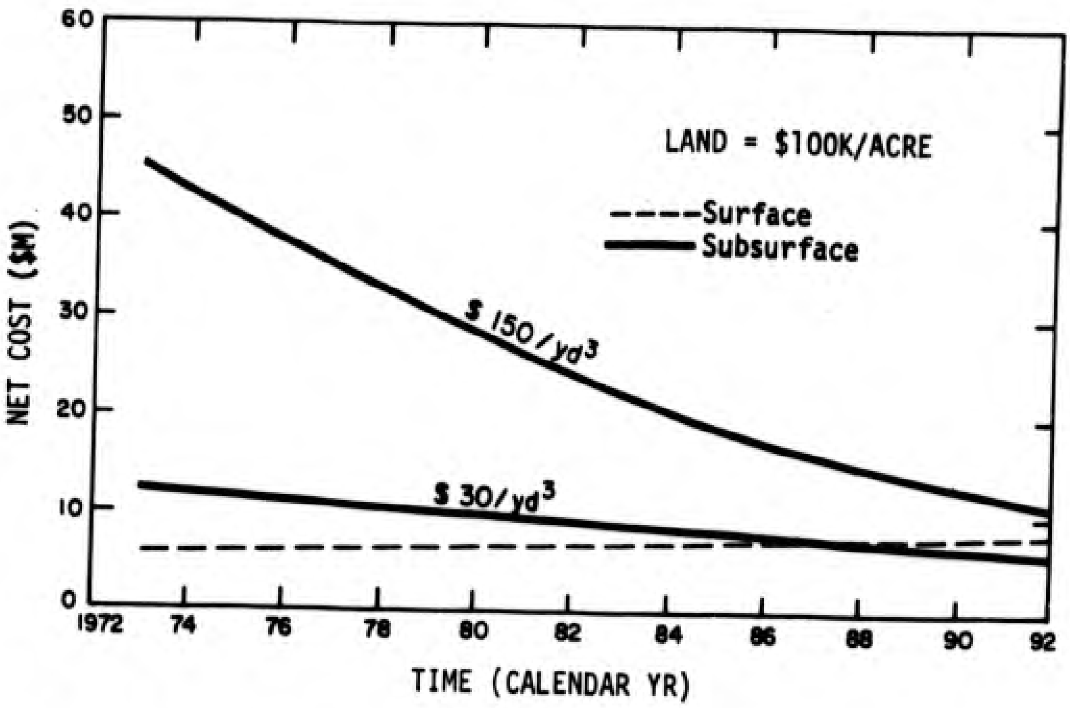
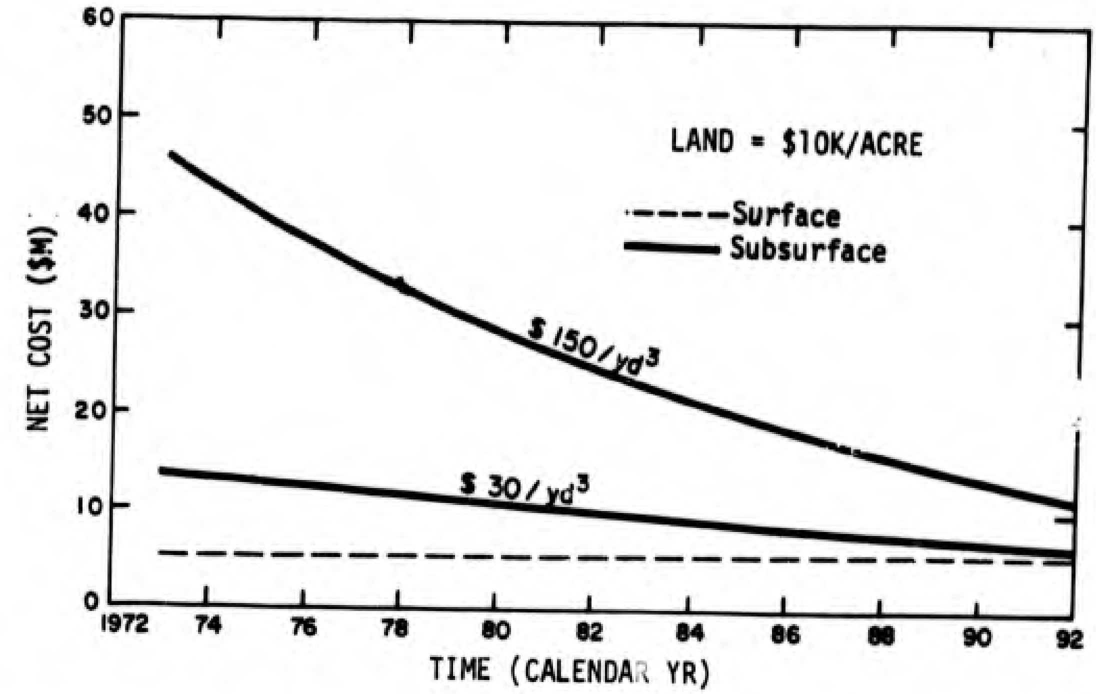


Figure 5.10. Effect of Geology and Land Value



LAND APPRECIATION RATE = 10%
CONSTRUCTION COST = $50/ft²
EXCAVATION IMPROVEMENT = 75%

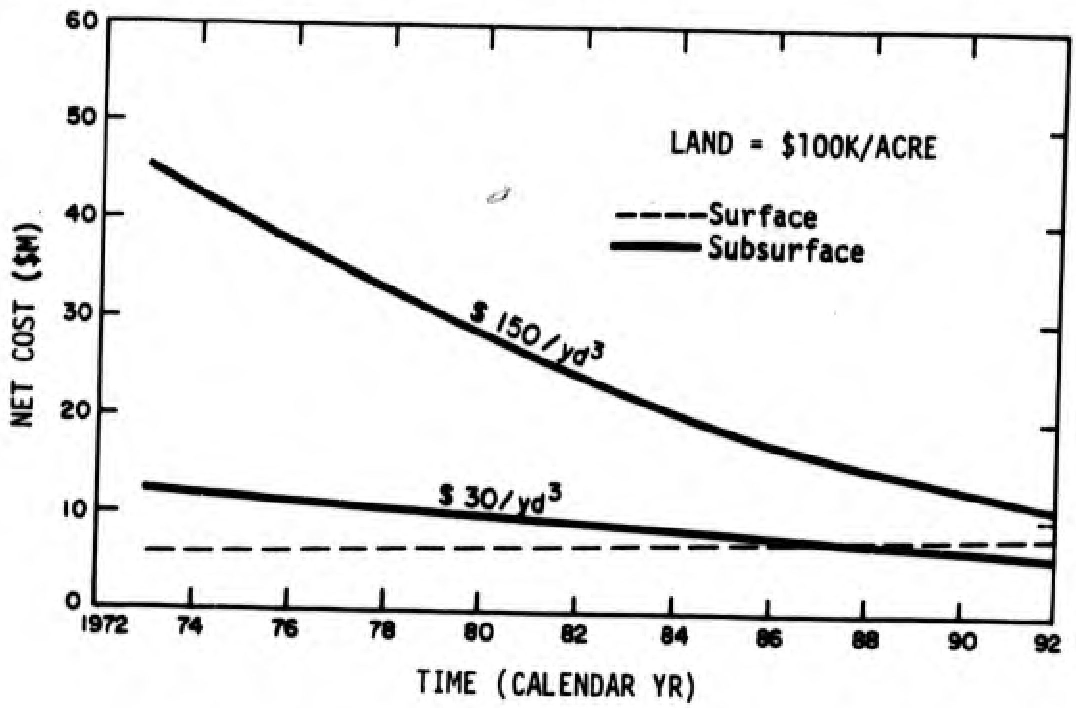


Figure 5.10. Effect of Geology and Land Value

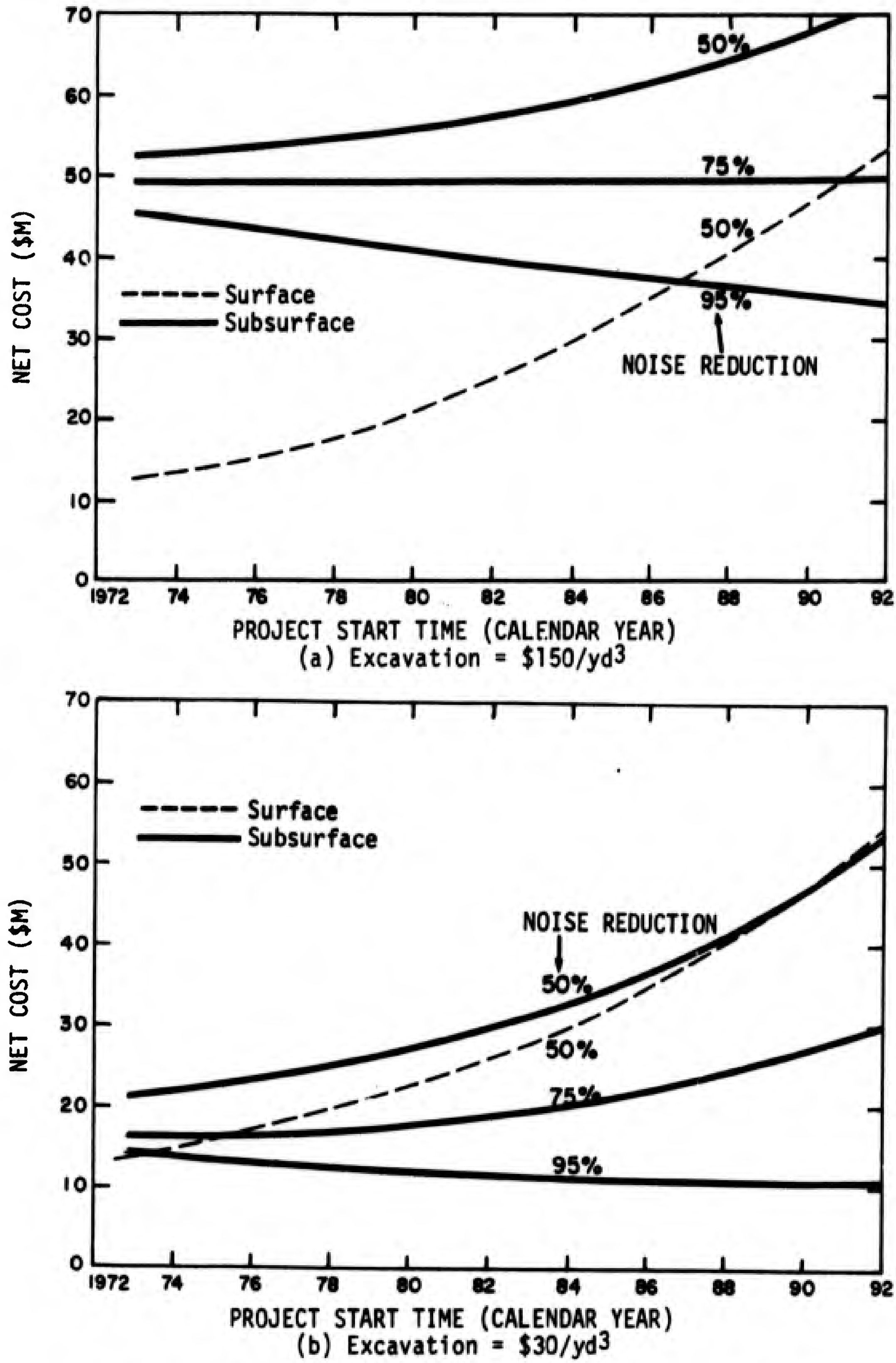


Figure 5.11. Net Cost Including Allowance for Noise

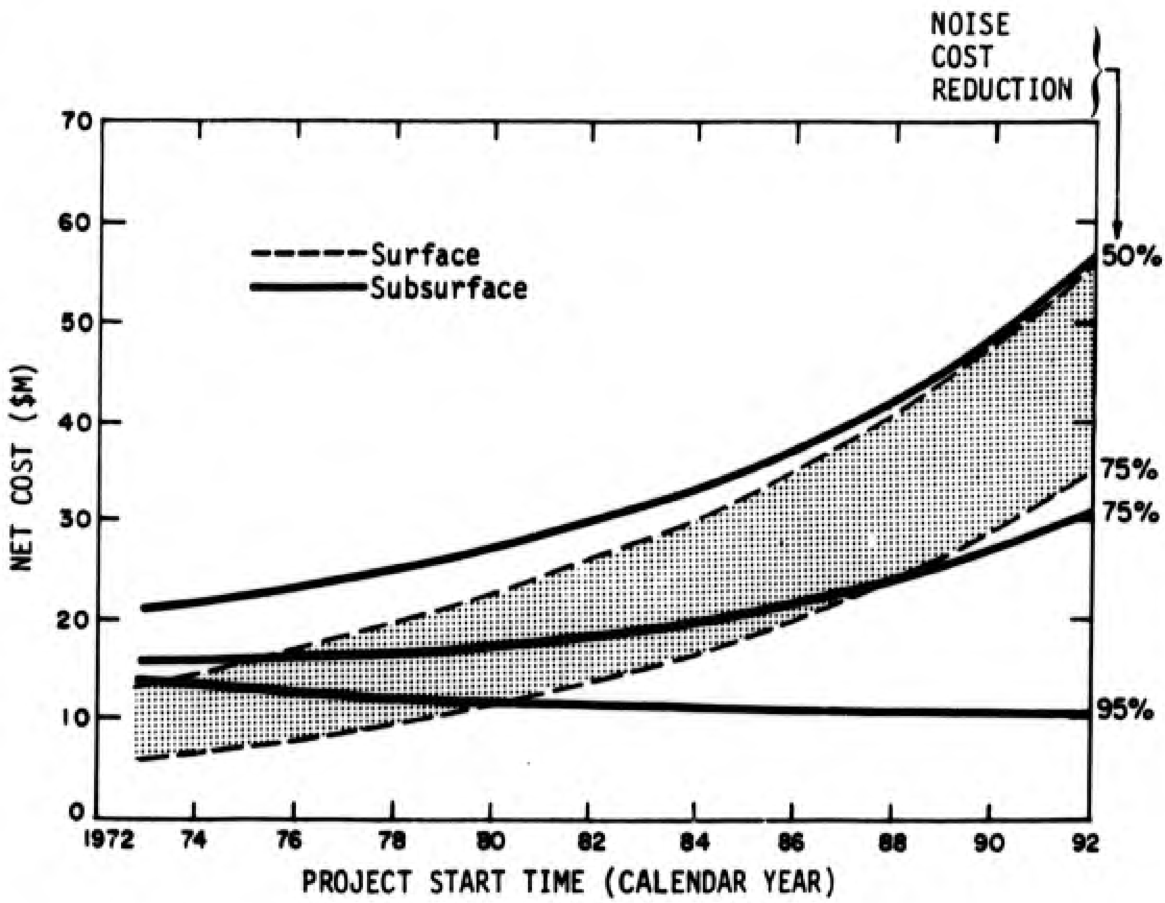


Figure 5.12. Sensitivity to Surface Noise Reduction Factor

The sensitivity of these results to the surface reduction factor used is shown in Fig. 5.12. The same data presented in Fig. 5.11b is shown here, together with a curve corresponding to 75% reduction in noise cost for the surface facility. Note, though, that even assuming 75% reductions in surface costs, economical subsurface deployment is still feasible within the next 20 years if still greater reductions are possible by going below ground.

From these observations, one concludes: if noise/community interaction costs attributable to runup operations are significant today (> \$200K/year) and are projected to increase in the future (> 15%/year) and if tunnels prove more effective for noise control than present-day surface test cells (i.e., by factors of at least 50% compared to the surface cell), subsurface deployment appears to be feasible within the next 20 years under the following general land and excavation costs constraints:

1. Land values at least \$10K/acre projected to increase at 10%/year

2. Excavation costs as high as \$150/yd^3 with at least a 25% reduction projected in the next 20 years

On the other hand, if noise/community interaction costs are <u>not</u> significant or if subsurface deployment <u>cannot</u> achieve at least a 50% reduction in these costs relative to the surface, subsurface deployment is only feasible under the following rather ideal conditions:

1. Land values greater than \$100K/acre today increasing at 10% per annum

2. Excavation costs less than ~75%/yd^3 today with a projected 75% improvement in the next 20 years.

5.5 AMMUNITION STORAGE FACILITIES

5.5.1 Introduction

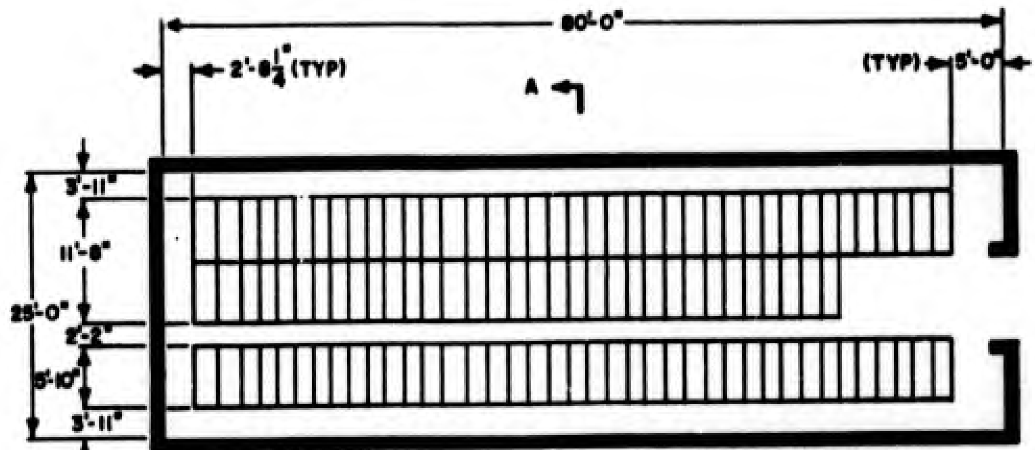
Standard high-explosive storage magazines are arch-type structures measuring 25 ft × 50 ft or 25 ft × 80 ft with maximum allowable explosive weight limits of 250,000 lb and 500,000 lb, respectively. The magazine is intended for storage of high-explosive, bomb-type ammunition and other explosive hazard material (referred to as Class 7 material) for which the most stringent requirements governing quantity and separation distance must be met. Figure 5.13 shows a typical 25 ft × 80 ft high-explosive magazine and the corresponding storage instructions for MK-36 MODS 1, 2, 3 mines.[11]

The quantity and separation distance requirements for storage of Class 7 high explosives are shown in Tables 5.3 and 5.4. Prescribed distances between magazines and inhabited buildings are shown in Table 5.3. These represent distances at which inhabited buildings will not be subjected to substantial structural damage in the event of accident. Intermagazine distances are shown in Table 5.4. These distances are supposed to protect against the propagation of an explosion from one magazine to another by sympathetic detonation, flying fragments, and fire. These distances are for standard Navy reinforced concrete, earth covered, barricaded, arch-type magazines.

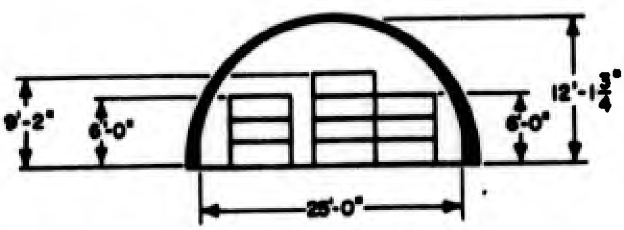
Standard arch-type magazine areas should be arranged in blocks of not more than 200 magazines, with blocks separated by not less than 1400 ft. With the above requirements in mind it is easy to see why Naval weapons storage areas use a tremendous amount of land.

Figure 5.14 shows the configuration of a typical Naval weapons station with the location of the ammunition storage magazines and inhabited buildings highlighted. Figure 5.15 illustrates a conceptual underground storage network for high explosives. In this concept the storage network

High Explosive Magazine



OVERHEAD VIEW



SECTION A-A

STORAGE INSTRUCTIONS

1. Mark off isles with a chalk line.
2. Stow outside columns from rear to front.
3. Stow inboard column from rear to front.
4. Section A-A illustrates the height pallets are to be stored.
5. If possible, individual lots should be stored together.
6. If light pallets are received, they are to be placed as the top pallet in the front stack of each lot.
7. Grounding is to be accomplished by placing copper wire under all bottom pallets and connecting the wire to a ground strip or rod.
8. Use a 6,000 pound forklift truck to transport, position, and set pallets in the magazine.

Figure 5.13 High-Explosive Magazine with Storage Instructions

TABLE 5.3

QUANTITY AND DISTANCE REQUIREMENTS FOR CLASS 7 ITEMS[12]

Quantity In Pounds Of Explosives		Distance In Feet From Explosive Hazard[1]	
Over	Not Over	To Inhabited Buildings	To Passenger Railroads And Public Highways
0	30,000	1,235	745
30,000	35,000	1,310	785
35,000	40,000	1,370	820
40,000	45,000	1,425	855
45,000	50,000	1,475	885
50,000	55,000	1,520	910
55,000	60,000	1,565	940
60,000	65,000	1,610	965
65,000	70,000	1,650	990
70,000	75,000	1,685	1,010
75,000	80,000	1,725	1,035
80,000	85,000	1,760	1,055
85,000	90,000	1,795	1,075
90,000	95,000	1,825	1,095
95,000	100,000	1,855	1,115
100,000	125,000	2,115	1,270
125,000	150,000	2,350	1,410
150,000	175,000	2,565	1,540
175,000	200,000	2,770	1,660
200,000	225,000	2,965	1,780
225,000	250,000	3,150	1,890
250,000	275,000	3,250	1,950
275,000	300,000	3,345	2,005
300,000	325,000	3,440	2,065
325,000	350,000	3,525	2,115
350,000	375,000	3,605	2,165
375,000	400,000	3,685	2,210
400,000	425,000	3,760	2,250
425,000	450,000	3,830	2,300
450,000	475,000	3,900	2,340
475,000	500,000	3,970	2,380
List of items (examples only):		Bombs; Comp "A" loaded 5" projectiles; detonators; demolition explosives; torpedo and missile warheads; rockets and components having mass-detonating characteristics.	

NOTE (1) Lesser distances for up to and including 50 pounds of explosives may be used if blast fragments and debris can be completely confined as in certain test firing cells.

TABLE 5.4

SAFETY DISTANCES--INTERMAGAZINE SEPARATIONS FOR CLASS 7 MATERIALS--STANDARD (ARCH-TYPE) MAGAZINES[12]

Quantity In Pounds Of Explosives		Distance In Feet Between Magazines				
		Unmodified[1]	Modified[2]		Other Special Use[3, 4]	
Over	Not Over	Bar[5]	Bar[5]	Unbar[6]	Bar[5]	Unbar[6]
0	4,000				35[7]	70
4,000	10,000				50	100
10,000	30,000				75	140
30,000	50,000				85	165
50,000	70,000				95	185
70,000	100,000				110	210
0	500,000	210	185[2]	360[2]		

[1]Construction is at least equivalent in strength to the requirements of Bureau of Yards and Docks Drawings 357428 through 357430 dated 9 August 1944.

[2]Constructed according to the Navy drawings of note 1 above and modified in accordance with Navy Bureau of Yards and Docks Drawing 626739 dated 19 March 1954 or new magazines constructed according to Navy Bureau of Yards and Docks Drawings 627954-627957 dated 5 April 1954.

[3]Construction relatively comparable to that of magazines of note 2.

[4]Special Use Magazine shall mean an earth-covered, reinforced concrete, arch-type magazine designed or used for a maximum quantity of 100,000 pounds or less of mass-detonating explosives, whose construction is relatively comparable to that of the standard magazines of note 2.

[5]Magazines are considered barricaded when they are so located that the earth-covered sides or backs are toward ("Toward" as applied to the location of magazines with respect to each other shall mean that straight lines pass through the parts of the magazines (side-to-side, unbarricaded door end to back, or the like).) each other, or the front of one magazine with a door barricade is toward an earth-covered side, back, or barricaded front of another magazine.

[6]Magazines are considered unbarricaded when they are so located that the front of one magazine without a door barricade is toward (as defined in note 5) an earth-covered side or back of another magazine.

[7]Keyport magazines require only 30 feet (center to center).

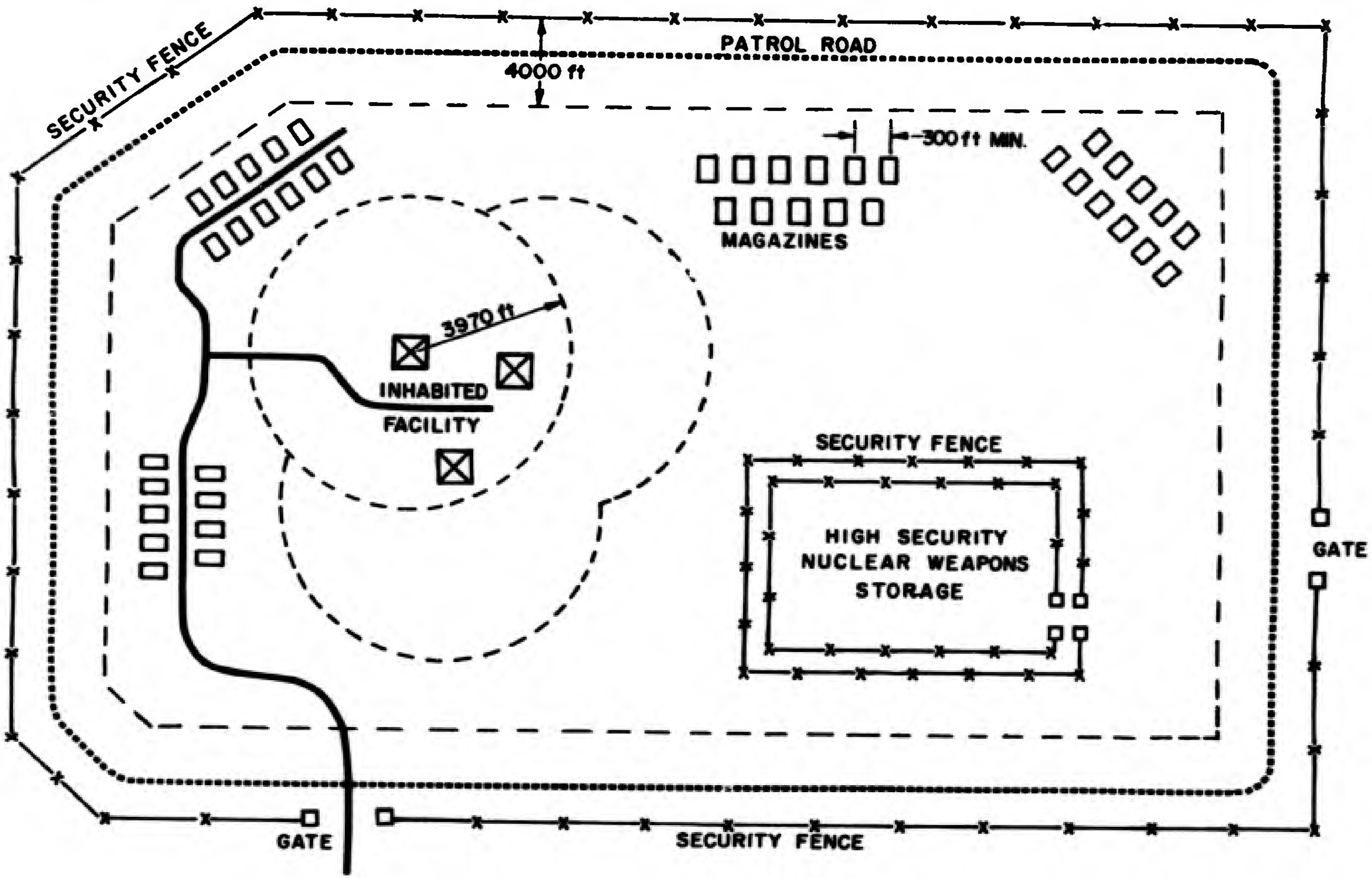


Figure 5.14. Typical Weapons Storage Configuration

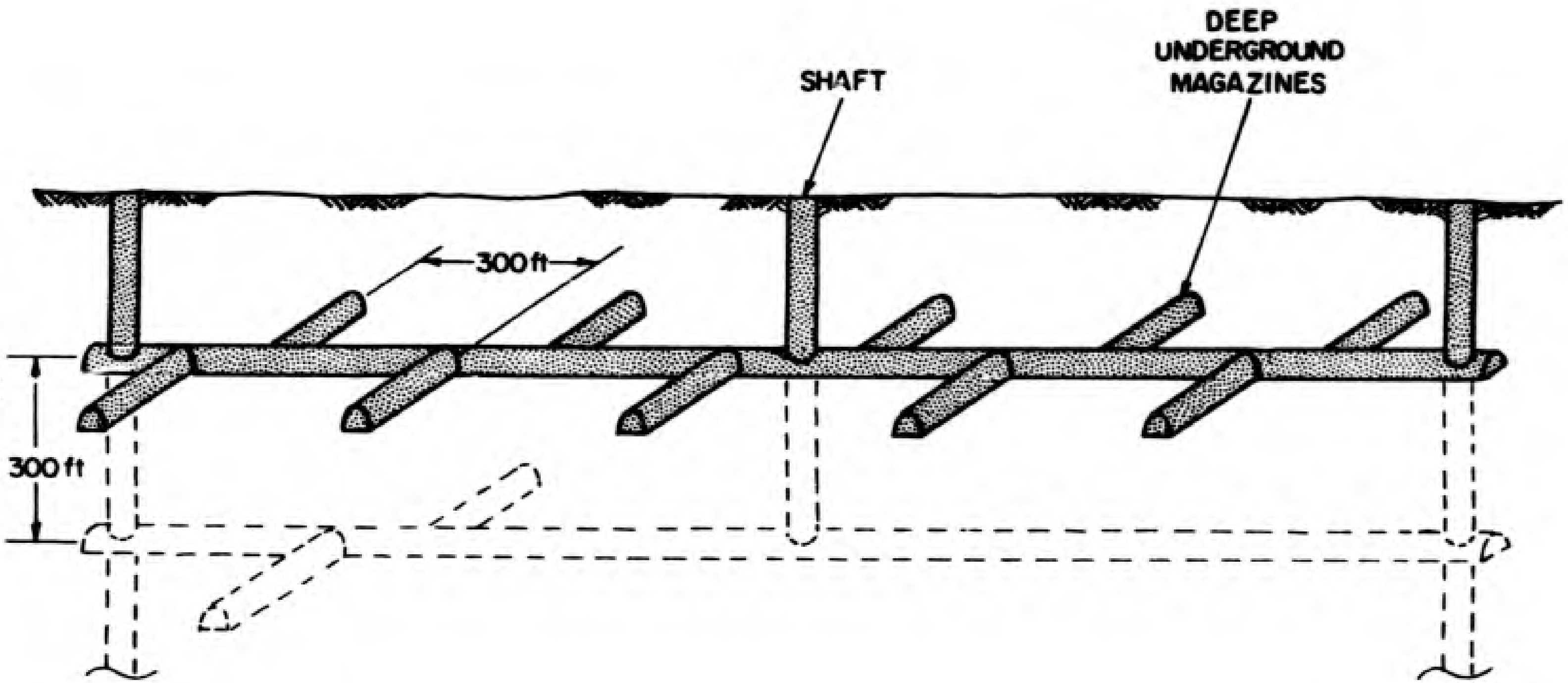


Figure 5.15. Underground Weapons Storage Concept

is arranged both horizontally and vertically to afford at least as great a protection from blast, fire, and fragments as that provided by conventional storage areas. The actual separation distances required in the underground concept is highly dependent upon the geological conditions existing at the site. For the sake of the following analysis, it was conservatively assumed that the required separation distances would be the same whether or not the facility was placed above or below ground.

5.5.2 Analysis

A major Naval weapons station such as the one located at Yorktown, Virginia, which occupies 13,600 acres of land, could conceivably be contained in a far smaller area (e.g., 1360 acres) if the ammunition was stored below ground level. Another saving to be realized by the subsurface deployment of ammunition storage facilities is in the area of security. The security force required to police the Yorktown facility is comprised of roughly 300 men and numerous vehicles. Controlled access portals to the magazines could reduce this expense up to 90%. Assuming an annual salary of $10,000 per year per man plus a substantial reduction in cost due to the use of fewer vehicles provides a saving of over $3M per year.

However, this security saving would have to be balanced against the likely increases in O&M costs for such an underground complex. The network of underground magazines, being located deep underground for safety reasons rather than at the surface for convenience, would probably necessitate the installation and utilization of complex weapons handling equipment similar to that which is used aboard ship for weapon transfer. Weapons handling at the underground complex should increase the overall O&M costs for the weapons facility.

The O&M costs for the Yorktown weapons station were $18.3M for FY 72--suggesting that $5-7/ft^2/yr is a suitable range for O&M for this type of facility. A deep underground storage complex might be expected to have costs in the range of, say, $10-12/ft^2/yr. Table 5.5 presents the data used for a comparison between a conventional weapons storage complex and a deep underground facility. The curves presented in Fig. 5.16 have been drawn using this data.

The analysis shows that in areas where land value is low, the saving in land costs due to the underground siting of ammunition facilities does not appear to compensate for the cost of excavation and the anticipated additional expenditures attributable to higher O&M costs. The deciding factor is obviously the price of land. If one assumes that ammunition storage facilities should be located far from populated areas and that the land values in these areas will be low, then the analysis above shows that conventional ammunition storage is advantageous for the next twenty years or so. However, if one remembers that Naval ammunition storage areas must be located near the water, and one further assumes that, in the future, very little of this land will remain at such a low cost, a far different result is obtained. If the analysis had considered an initial land value of, say, $50K/acre then one finds underground ammunition storage an attractive option in the 1970's.

5.6 MISCELLANEOUS STORAGE FACILITIES

5.6.1 Introduction

The Naval Supply Corps motto of "Service to the Fleet" identifies the close interrelationship which the storage and supply activities must have with the sea-going operational functions of the Navy. If the Supply Corp provides the supermarket service of equipment and supplies to the fleet, then the storage facilities must provide quick and convenient access to these supplies and must provide for the large volume and sometimes specialized storage needed for the back-up inventory. Convenience of logistics, economy of operation, and flexibility of utilization to adapt to future needs are the key words in planning for future Naval storage. In many aspects, underground facilities may offer significant advantages over existing facilities.

TABLE 5.5

COST CHARACTERISTICS FOR AMMUNITION STORAGE FACILITIES

Land	
Land required for surface facility	13,600 acres
Initial land value	\$5,000/acre
Land appreciation rate	10%/yr
Construction	
Floor space required	3M ft^2
Construction cost	\$10/ft^2
Excavation	
Excavation volume	1M yd^3
Excavation cost	\$150/yd^3
Excavation improvement factor	75%
Operations & Maintenance	
O&M cost (surface)	\$5-7/ft^2/yr
O&M cost (subsurface)	\$10-12/ft^2/yr
O&M escalation rate	6%/yr
Security	
Security cost (surface)	\$3M/yr
Security cost (subsurface)	\$300K/yr
Security cost escalation	6%/yr
Lifetime	20 yr

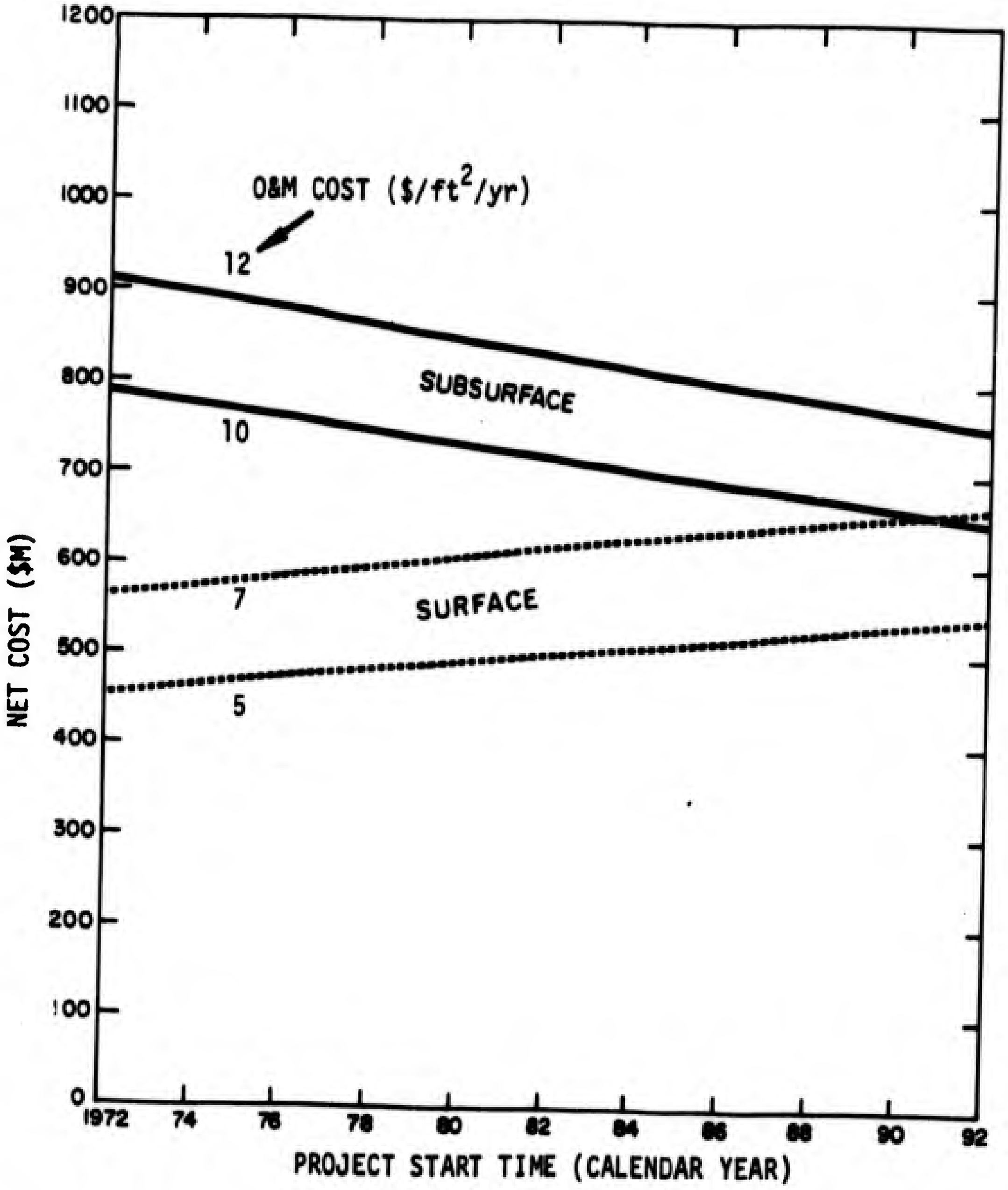


Figure 5.16. Subsurface Deployment of Ammunition Storage Facilities

One of the major changes that has occurred in the nature of storage requirements for the Navy in the past decade has been an increasing trend toward storage of modular components. This change to modularity saves repair time, reduces the number of highly specialized personnel required on board Navy ships, and increases the reliability of the fleet but, inevitably, also increases the amount of storage space that is required near the Naval bases, shipyards, and repair facilities. As a result, Naval supply facilities have had to expand into the space available, leading to an unavoidable decentralization of storage and duplication of transport activities and administrative effort to maintain the flow of supplies to the fleet and to related shore establishments.

The largest of these complexes is located in the San Diego area where the Navy has 19 acres of covered storage in the downtown waterfront area, 24 acres of covered and 300 acres of open (boat) storage on the Naval Station to the south of town, and an additional 238 acres to the west of Pt. Loma which is used primarily for ammunition and fuel storage (see Fig. 1.1). This dispersal of storage, particularly that between the downtown and Naval Station supply centers, is estimated to lead to an increase of at least 35% in operating costs due to the inefficiencies of transport and logistics.[13]

Other impacts were also noted. Because of the recreational potential of the waterfront region now occupied by the Naval Supply Center in downtown San Diego, considerable pressure is brought to bear on the Navy, not only not to expand its existing storage area but also to relinquish whatever land it can so that this land may be used to the benefit of the local community. This attitude has made the land so scarce that commercial parking lots located several blocks away must be used. This condition places the San Diego facility in a category along with other major metropolitan areas of high congestion where an economical alternative has been to exploit the third dimension, vertically up or down, for facility expansion. Earthquake hazard in California limits the desirable number of stories above ground for most facilities. It is therefore important to consider what benefits are offered by the subsurface as a means of expanding, or just consolidating the storage facilities which exist at this supply center.

It is necessary to be more specific in describing what kinds of supply facilities are of greatest significance to the Navy. One should differentiate bin and bulk storage from other types of storage. Bin storage connotes storage of small parts and subassemblies which may be stored multiply in bins which are arrayed in rows and tiers and accessed either manually or automatically for retrieval and acquisition. Bulk storage is storage of larger components, assemblies, and bulk materials, e.g., gun turrets, pumps, and machinery. The majority of Naval stores fall into one of these two categories which will be the subject of evaluation in this section. Storage for cold storage and fresh provisions will not be investigated. Generally, this is but a small part of the space used for all storage.

By way of example, the breakdown in storage space at the San Diego supply center is shown below:

Bulk	1.5 million ft^2
Bin	0.2 million ft^2
Cold	0.03 million ft^2
Fresh Provisions	0.006 million ft^2

5.6.2 Analysis

It takes 829 personnel to run the San Diego Naval Supply Facility, fully half of whom are required to administer the day-to-day logistics and accounting of the operation. Total O&M costs for the Naval Supply Center, San Diego, for fiscal year 1972 were $11,148,000.[13] Of this total, $348,236 was spent in maintenance and $175,640 on other public works type of expenses including utilities, grounds maintenance, and trash collection. Therefore, $10,624,124 of the costs were for operations which, it has been estimated, could be reduced by a third if a centralized storage and supply facility, either surface of subsurface, were utilized. The following O&M costs have been selected as representative of storage and supply functions for the analysis to follow:

	Unit O&M Cost (1973) ($\$/ft^2/yr$)	Escalation Rate (%/yr)
Surface, dispersed	6.80	6
Surface, centralized	4.65	6
Subsurface, centralized	4.65	6

An ideal storage facility is considered to be a wide span, single floor area having minimum clear spans of 30 ft to aid logistics and allow flexibility when needed for storage of new types of parts and equipment. It is precisely for this reason that most storage facilities are low-rise buildings which cover large surface areas. This is also the reason for considering underground emplacement as an alternative for future supply facilities, especially when land values are high and land availability is low.

Land value, land availability, and O&M costs are particularly important in evaluating the desirability of underground storage facilities because storage structures themselves, which have simple designs, are less expensive and therefore comprise a smaller part of the net cost than perhaps any other Naval facility. Suitable storage structures cost only $10-$20/ft^2; facilities to be used for training, production, maintenance, R&D, communications, and administrative operations all may cost from $20 to $60 per square foot to build. Also, the larger the structures, the lower the unit cost; and storage sturctures inherently tend to be large. Thus, as a percentage of the total cost of the project, land cost, and operation and maintenance costs should play a greater role in storage facility planning than for other types of facilities.

These estimates of the low cost of constructing surface storage structures are drawn from existing facilities and have been verified by comparing them to current estimating results for labor and materials required to construct facilities similar to existing types. Though laborious, this method gives excellent assurance of valid estimates for facilities not too different from those in present usage which have been specified in sufficient detail. However, it is not with the same confidence that the analyst can estimate costs of constructing markedly different types of storage facilities, i.e., underground. Furthermore, there is a lack of data to support any convenient conclusion about what underground storage facilities might cost relative to surface facilities because, in regions of particular interest to the Navy, there are few such facilities in existence.

Heuristically, it is argued that surface and subsurface construction costs are equal. "Construction" here refers only to the usual exterior walls and interior partitions and supports, and not to excavation, permanent lining, and support of the underground cavity (which are considered separately as excavation costs). One should save on these walls slightly over surface construction as a result of the elimination of windows and external architectural details (aesthetic improvements are generally not thought to be as necessary for storage structures as for other types of buildings, but even when added they generally increase the total cost of construction less than 5%). Whatever saving is realized here is likely to be spent otherwise on underground construction, on such features as ramps leading to surface loading and unloading docks required for subsurface storage facilities. No rigorous estimates have been attempted for the differences in construction costs which may be expected between surface and subsurface siting.

Table 5.6 summarizes values of the parameters which have been selected to represent storage facilities' costs, surface and subsurface,

TABLE 5.6

COST CHARACTERISTICS FOR STORAGE FACILITIES

Land	
Land required for surface facility*	25 acres
Initial land value	\$5000/acre and \$500K/acre
Land appreciation rate	10%/yr
Construction	
Floor space required	1M ft^2
Construction cost	\$10/ft^2
Excavation	
Excavation volume	1.25M yd^3
Excavation cost	\$30/yd^3 and \$150/yd^3
Excavation improvement factor	25% and 75%
Operation and Maintenance	
O&M costs (1973), centralized	\$4.65/ft^2/yr
O&M costs (1973), decentralized	\$6.80/ft^2/yr
O&M cost escalation rate	6%/yr
Lifetime	20 yr

*Includes land for surface structures and loading/unloading docks; does not include parking space or roads.

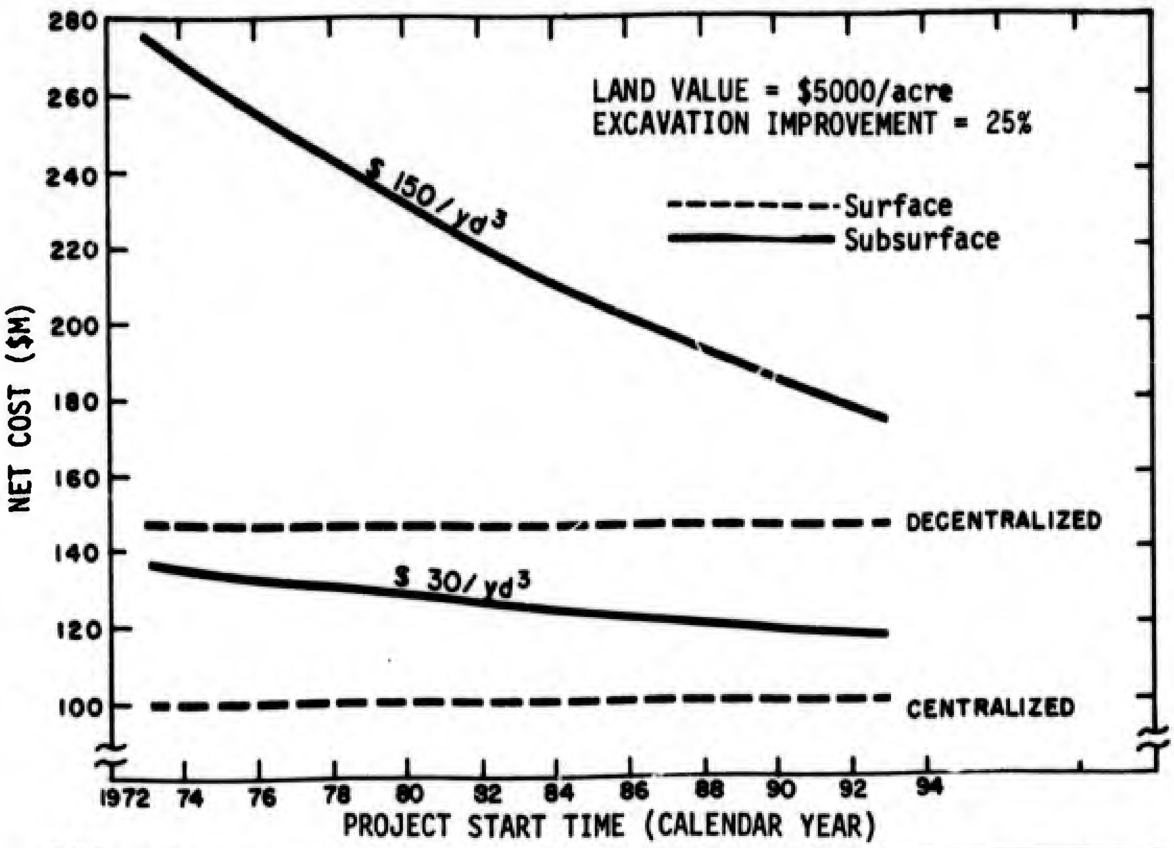
for a usable storage floor space of 1M ft^2. The range of possible net cost calculations, using these values, is shown in the net cost curves of Fig. 5.17.

Upon inspection of this figure, one may draw conclusions regarding the desirability of placing future storage facilities below the ground. Considerable savings is expected when a storage and supply operation is centralized within a unified, coordinated complex of facilities rather than spread out in widely scattered multiple supply centers, and this conclusion is valid whether the facilities themselves are above or below ground. The saving being referred to here is applicable primarily to a major supply center such as that typified by the Naval Supply Center in San Diego, but it may also be expected to apply to smaller storage and supply operations and to the facilities themselves.

The subsurface environment provides means of achieving this consolidation of storage and supply in the areas appropriate for such a centralized operation. In the figures one sees depicted the comparison between the net costs of centralized, subsurface storage and supply facilities and the surface equivalents, both centralized and decentralized, for various conditions of land value, excavation cost, and the 20-year improvement achieved in these excavation costs.

The analysis and comparative results show that underground subsurface facilities may be preferred to surface facilities if the following conditions are met:

- Excavation costs should be sufficiently low (generally in the neighborhood of $50/$yd^3$ or below) so that the added cost of excavation does not exceed the expected savings from consolidation of operation. Land cost which would be required to achieve this consolidation of operation with surface storage by purchasing additional surface land should be prohibitively high.



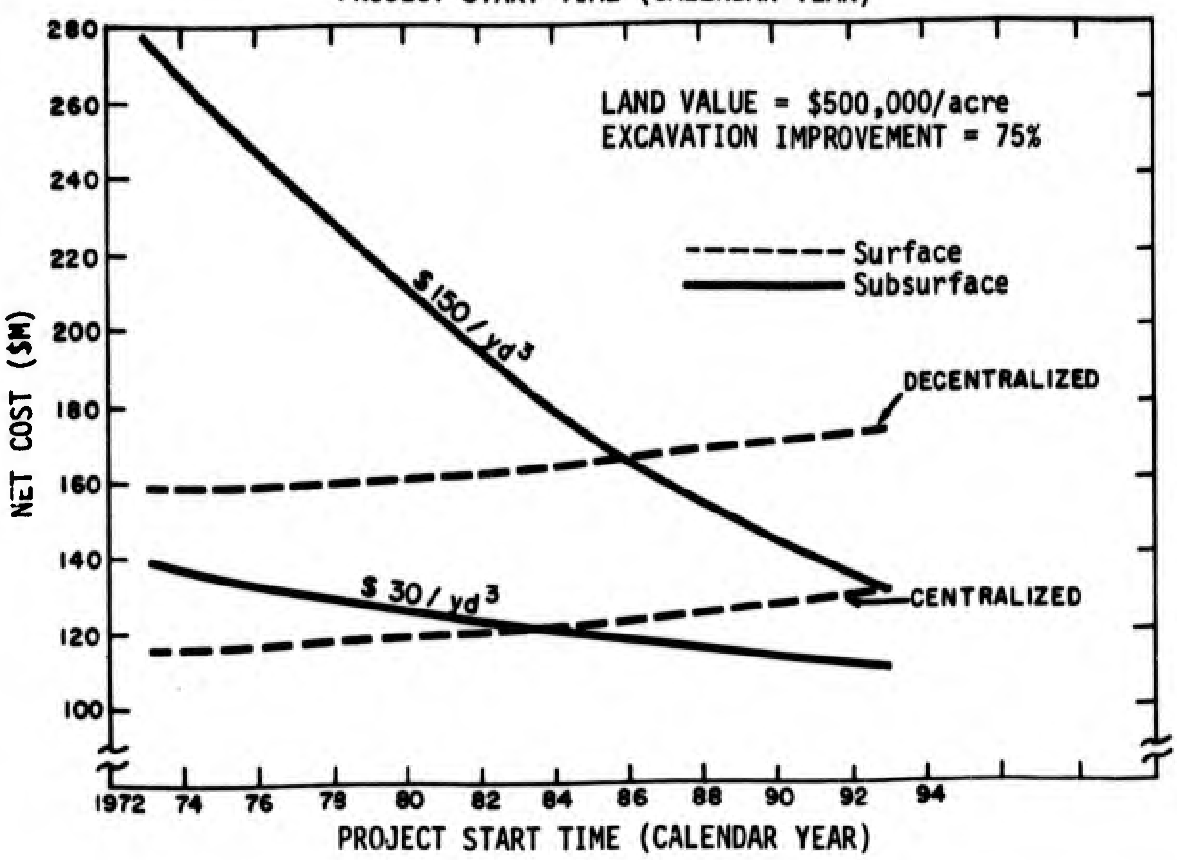


Figure 5.17. Cost Comparison for Storage Facilities

- The delay, if any, in availability of additional (or replacement) storage space due to the time elapsed during excavation and subsurface site preparation should not be a prohibitive factor in planning for the storage facility.

There do not appear to be any significant operational disadvantages to placing storage and supply functions underground. Logistics within a subsurface facility are likely to be similar to those on the surface. Ramps and elevators, where required, will present no insuperable difficulties and may in fact motivate the further development of improved material handling concepts such as automated storage and retrieval of bin parts. The underground working environment, given the appropriate environmental control system, is not likely to be significantly different than for surface storage. Systems probably will be required to ensure that proper humidity and ventilation are maintained in the surface facility, but what added expense might be incurred may be returned in the form of a more uniform storage environment and lower heating and cooling costs. These storage environment benefits may be of appreciable importance to the increasingly voluminous storage for temperature sensitive electronic gear for new generation weapon systems and computer operations.

In brief, the decision to put future storage facilites underground can be based on the cost of land, excavation, construction, and operation of the complex. There are indications that under the circumstances of low excavation cost, high land value (or low availability), and expected reduction in operating costs due to consolidation of operations, storage and supply facilities could be economically located underground.

APPENDIX I

EXCAVATION COSTS*

1 INTRODUCTION

We are concerned here primarily with economic feasibility, or cost, and how it might vary with excavation site characteristics and with advances in excavation technology in the future. Specifically, the following points are made:

- A parametric approach, assuming 25% and 75% reduction in excavation costs, is used to account for future advances in technology.
- Although many factors affect current excavation costs, geologic and hydrologic conditions appear to be the most significant: e.g., historical data shows excavation of a 20-ft-diameter tunnel varying between $600/linear foot in dry competent rock to as high as $3500/linear foot in wet crushed rock or unconsolidated soils.[14]
- Subsurface conditions of most interest and their correlation with costs were established by the following steps:
  1. A review was made of the operational requirements including location of the selected facilities in two representative areas: Norfolk and San Diego. This review indicated that voluminous structures deployed in either saturated soils or medium to hard rock should be emphasized.
  2. For these conditions, estimates representing 1972 excavation capability were made using published data supplemented with information supplied by cost and design personnel at the Naval Facilities Engineering Command.

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*As used in the main text of this study, excavation costs include costs associated with permanent structural liner and dewatering operations as required.

- The analysis concluded that excavation costs ranging in value from $\$30/yd^3$ to $\$150/yd^3$ of available space cover a broad spectrum of subsurface conditions including saturated soils and rock. These were therefore used as parametric values in the study.

2 PREDICTING FUTURE TRENDS IN EXCAVATION TECHNOLOGY

Recent reports of studies undertaken by the National Research Council (NRC),[15,16] the Organization for Economic Cooperation and Development (OECD),[17] and many other groups[18] have examined the impact of improved underground excavation techniques in the future. The National Research Council has forecast that, if industrial and governmental research and development were to continue at the levels and in the direction of past efforts, real costs of excavation would not be significantly reduced; that is, sustained rates of advance for tunneling would rise only 100% in soft-medium rock and 33% in hard rock over the next 20 years. An expanded research program could provide the base of knowledge needed for achieving a 30%-50% reduction of cost and a trebling of the sustained rate of advance of excavation.

Although based on the judgment and experience of respected and knowledgeable individuals, there is still considerable uncertainty associated with such projections. Even if the excavation techniques presently under theoretical or laboratory research ultimately prove practical in the difficult field environment, there is still much uncertainty regarding policy decisions and research and development priorities that would provide the needed direction and funding.

In view of these inherent difficulties, the approach taken in this study was to treat improvements in cost of excavation not as a single number but as a range of possible values. In this way one can assess the implications of various levels of improvement and produce a report that will remain useful in the future. This approach allows one to establish what level of improvement is necessary to make underground deployment feasible. In this study, improvements of 25% and 75% were used.

3 CURRENT EXCAVATION CAPABILITY

The problem of estimating the cost of excavation is difficult even for a well-defined project at a known location. The problem becomes magnified when one attempts to establish reliable estimates for use in broad feasibility studies.

This section reviews some of the major factors affecting excavation costs, and discusses the method whereby costs representing current excavation capability were established.

3.1 A PERSPECTIVE OF UNDERGROUND CONSTRUCTION

The process of designing and constructing an underground facility, including the excavation technique to be used, is based to a large extent on engineering judgment tempered by previous experience. Many factors can affect the facility design and cost as well as the ultimate operation, performance, and cost of the excavation system itself. Some of the more important are listed in Table I-1.

It is generally recognized, though, that the geological and hydrological conditions encountered at a given site more than any other factor determine the degree of difficulty, the daily progress, and ultimately the cost of a given project. The geologic medium is truly the key variable in the total construction picture. It impacts directly and strongly on most aspects, but particularly the following major problems, of underground construction:

1. Excavation and removal of in situ soil or rock

2. Support of unstable soil or rock around the excavation

3. Control of ground-water inflow

In general one can identify two broad classes of geologic conditions: hard rock and soft ground. Hard rock means any strongly cemented aggregate of minerals that requires a high-energy technique such as drill and

TABLE I-1

GENERAL FACTORS AFFECTING THE DESIGN AND COST OF UNDERGROUND CONSTRUCTION

PHYSICAL FACTORS	ECONOMIC-POLITICAL FACTORS
LOCATION & ACCESSIBILITY	**AVAILABILITY & COST OF RESOURCES IN PROJECT TIME FRAME**
Urban	Labor
Rural	Material
GEOLOGY & HYDROLOGY	Equipment
Rock or soil type, structure, properties	Financing
In situ stress conditions	**LEGAL & ORGANIZATIONAL**
Subterranean temperature	Health & Safety requirements
Location & variation of phreatic surface	Union demands
General flow conditions	Contractual
GENERAL ENVIRONMENT	Management & scheduling
Climate	**FLEXIBILITY OF COMPLETION DATE**
Altitude	Military threat
OPERATIONAL REQUIREMENTS	Impact of delays
Intended use	**TECHNICAL FACTORS**
Operational life (permanent, temporary)	Geological surveying & prediction techniques
General configuration (no. of tunnels, shafts, chambers & proximity, geometry, etc.)	Construction methods
Depth, alignment, grade requirements	Accepted design practices
Environmental control requirements (ground water, air quality, etc.)	

blast for excavation. It includes rocks that are relatively "soft" on any scale of rock hardness, such as weakly cemented sandstones, limestones, conglomerates and some shales; and also rocks such as basalts and granites that are "hard" on a rock hardness scale. By soft ground is meant any sediments (gravels, sands, silts), residual soils (clay), or highly fractured and weathered rock that require low-energy processes such as conventional hand-controlled excavating equipment. As a rule, one would expect hard-rock geologies to occur at variable depths covered with a mantle of soft ground (loose sediments or fractured and weathering rock).

The physical characteristics of hard rock that impact strongly on underground construction capability and costs include: its strength, free water content and defects in the rock mass including the degree of jointing or faulting, chemical or hydrothermal weathering, etc.

Important characteristics of soil include: (1) the type of ground (i.e., clay, sand, gravel) and (2) whether construction is above or below the water table.

One can easily see that highly faulted rock or flowing soil presents an immediate problem of controlling the sides of the excavation from collapse. This in turn reflects on costs in three ways: (1) the cost of materials for both temporary support and final structure or lining; (2) the labor cost for installation of these supports; and (3) the cost of the time lost during installation because excavation operations must stop. On the other hand, sound rock or hard soils, although they do not generally present a support problem, entail problems of fracturing the material into fragments suitable for removal by a materials handling systems.

The location of the water table below the ground surface is another important factor governing working conditions and affecting excavation methods and costs. In a cross section of the ground the water table may be expected to occur as a somewhat flattened replica of the surface topography. In temperate to humid climates it may occur a few feet to a few dozen feet below the surface. In arid climates it is commonly a few hundred feet below the surface. In marshes and swamps the water table practically coincides with the ground surface, as it does at the edge of permanent water bodies such as lakes, streams, and coastal areas (of particular relevance to excavation for Naval facilities).

The strength characteristics of certain soils may change, depending on whether they are above or below the water table. Below the water table, weak flowing soil conditions coupled with inflowing water require special water control and support requirements that can be expensive and may result in considerable delays in excavation operations. Even in hard rock, major inflows can occur from zones of jointed, faulted, or weathered rock that also demand expensive water control procedures and adversely affect construction times and total costs.

Although geological and hydrological conditions are the chief independent factors in determining project costs, at present a small percentage (<2%) of the total cost of a typical project is generally allocated to pre-excavation geological investigations.[19] This probably reflects the fact that the scope and extent of the geological survey are a compromise between technical desirability and economic feasibility. Moreover, the point of compromise may not be reached objectively in many instances. Budgetary considerations of sponsoring agencies, political considerations, etc., may also play a major role in the decision process.

As an example, there were only two bore holes made prior to the excavation of the massive underground defense complex in Cheyenne Mountain for the North American Air Defense Command (NORAD).[20] Further geological exploration was scheduled but never funded because of a controversy about the project itself. When funding for continuation of the project was eventually released, it was allocated for excavation alone, not geological exploration, and partly as a result, poor geology was encountered unexpectedly at a critical intersection of two project chambers. Eventually new plans had to be drawn up, rotating the original design in an attempt to avoid bad ground. Even then extensive and costly reinforcement was necessary at the worst intersection.

3.2 CURRENT COSTS OF EXCAVATION

The resource and time constraints of this study imposed two immediate problems: (1) deciding what subsurface conditions are most likely to be prevalent in future deployment of the selected Naval facilities; and, (2) establishing adequate correlations between these subsurface conditions and the cost to be used as a base line in the parametric analysis.

The approach taken in solving these problems consisted of three major steps:

1. A review of the operational and dimensional requirements of each facility.
2. A brief review of the general geologic conditions prevalent about two representative Naval installations: Norfolk and San Diego.
3. A review of available literature and personal communications with design and cost engineers to arrive at approximate costs for the geologies of most interest.

Step 1 was intended to quickly establish what type of excavation tunnel, shaft, or chamber, would likely be the major contributor to total cost. Clearly, a comprehensive packaging, operations and construction logistics study would be necessary to establish detailed configurations for each facility. Since this was not possible within the time constraints of this study, it was assumed that chambers would predominate.

This assumption is not completely arbitrary, though. Our review of facility requirements did indicate large volumes of available space (300,000 yd^3 or more) and centralized operations are desirable. This suggests that optimal configurations would probably consist of large interconnected chambers with tunnels and shafts used primarily for access and ventilation.

In Step 2, a brief investigation was made to establish what general subsurface conditions are of most interest to this study. Again time constraints limited consideration to two representative Naval installations: Norfolk and San Diego. Our investigation consisted only of a brief review of readily available literature and personal communications with geologists and soil engineers at the local Naval Facilities Engineering Command Headquarters and U.S. Geologic Survey Office.

From this review it was concluded that two broad classes of geology are representative of conditions in these areas: medium to hard rock and saturated sandy/clay soils. The following paragraphs briefly elaborate.

Norfolk lies on the Atlantic Coastal Plain, a broad geologic expanse consisting mainly of alternating layered deposits of sand, clay, and gravel laid down in the sea when it encroached onto the eastern edge of the continent at various times during ages past. In cross section, these deposits resemble a gigantic wedge ranging in thickness from a few feet near the inland edge to several thousand feet along the Virginia coast. In Norfolk, therefore, sandy/clay soils predominate for considerable depths. Moreover, the water table in this area, charged by runoff from the highlands to the west, tends to remain high (3 to 5 ft from the surface) throughout the year. Indeed, in the past because of the water problem, deep excavations have been avoided whenever possible.

The San Diego coastal geology differs from Norfolk primarily because of its proximity to the coastal mountain range. Here bedrock is closer to the surface--even exposed in many areas of the city; for example, the Pt. Loma Peninsula (Fig. 1.1). This rock consists largely of consolidated and cemented marine deposits (siltstone, sandstone, conglomerate, etc.) lying on a granitic and metamorphic basement complex some 3000 ft below the surface.[21,22] As in Norfolk, there are regions, particularly in low lying areas near the coastline or along the bay, where saturated soil conditions occur, but in this case the depth to bedrock tends to be comparatively shallow. Clearly, there is some possibility for excavation in bedrock in the San Diego area.*

Our next step was to establish order-of-magnitude costs, representative of 1972 excavation capability, for large structures in both saturated soil and rock. Emphasis was on utilizing readily available information, supplemented as necessary with discussion and estimates made by cost and design personnel at the Naval Facilities Engineering Command and other organizations. The results are shown in Figs. I-1 for rock, and Figs. I-2 and I-3 for soils. Each figure gives unit costs in terms of dollars per available volume (i.e., the excavation volume less than the volume of the structural liner).

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*The reader should not infer that the question of geology reduces to a few simple considerations. Our purpose in this brief review was only to establish generalized conditions that reflect conditions in Norfolk and San Diego. It is hoped that they have some relevance to other Naval installations as well. Clearly each area and each potential site has its own peculiar problems that only detailed region and siting studies can hope to illuminate.

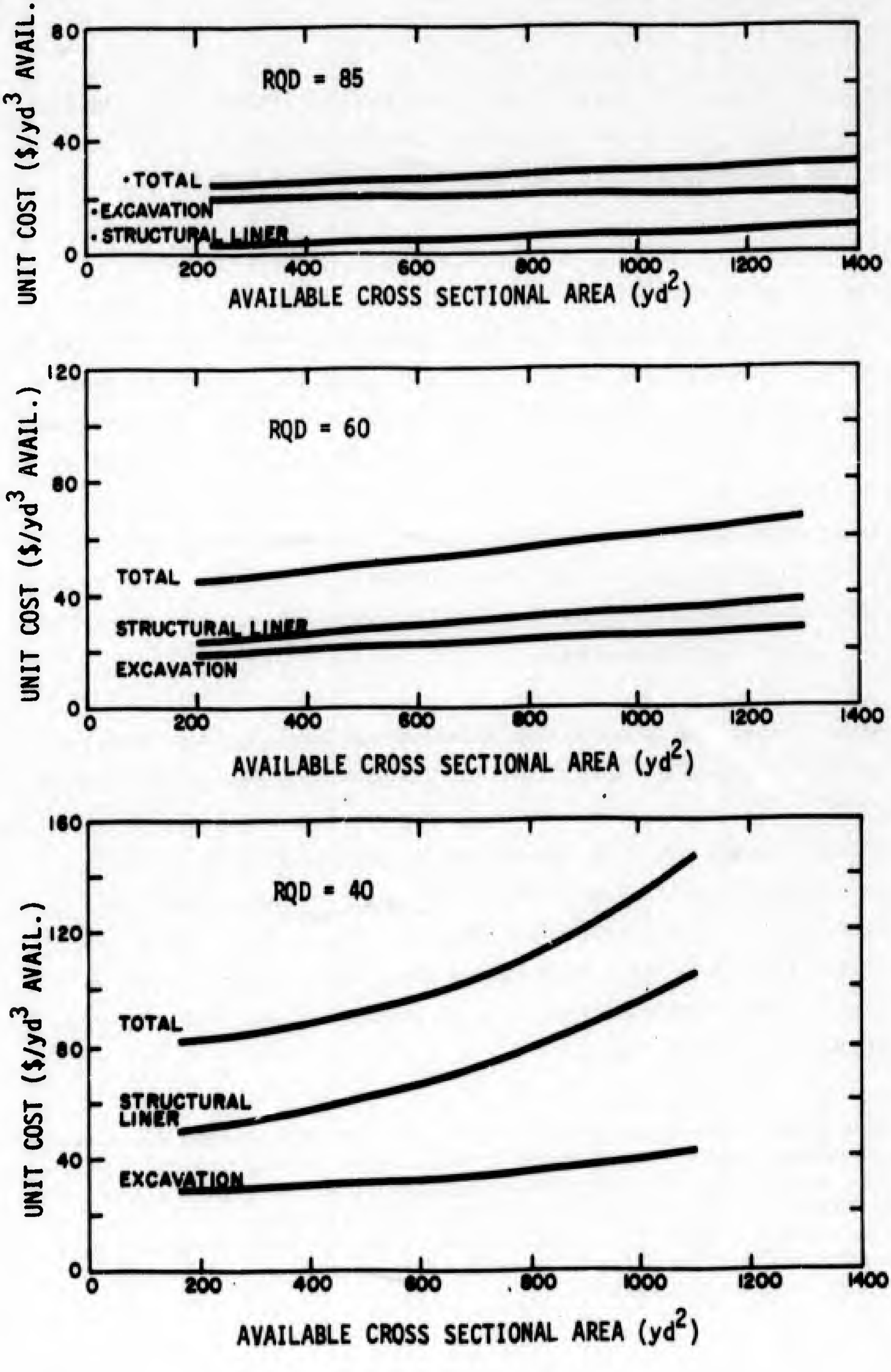

Figure 1.1. Representative 1970-72 Construction Cost for Underground Rock Chambers

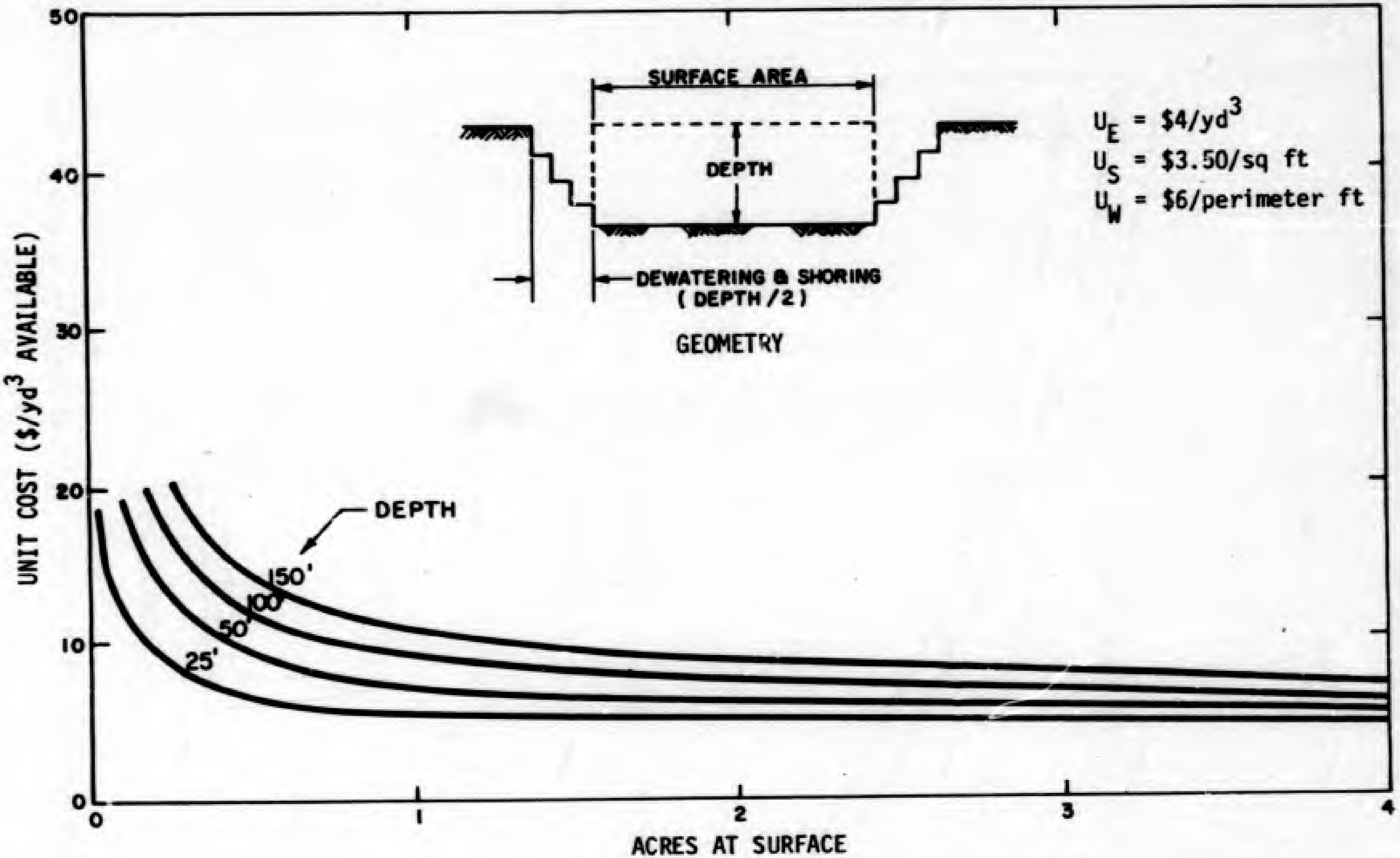

Figure I-2. Representative 1970-72 Surface Excavation Costs

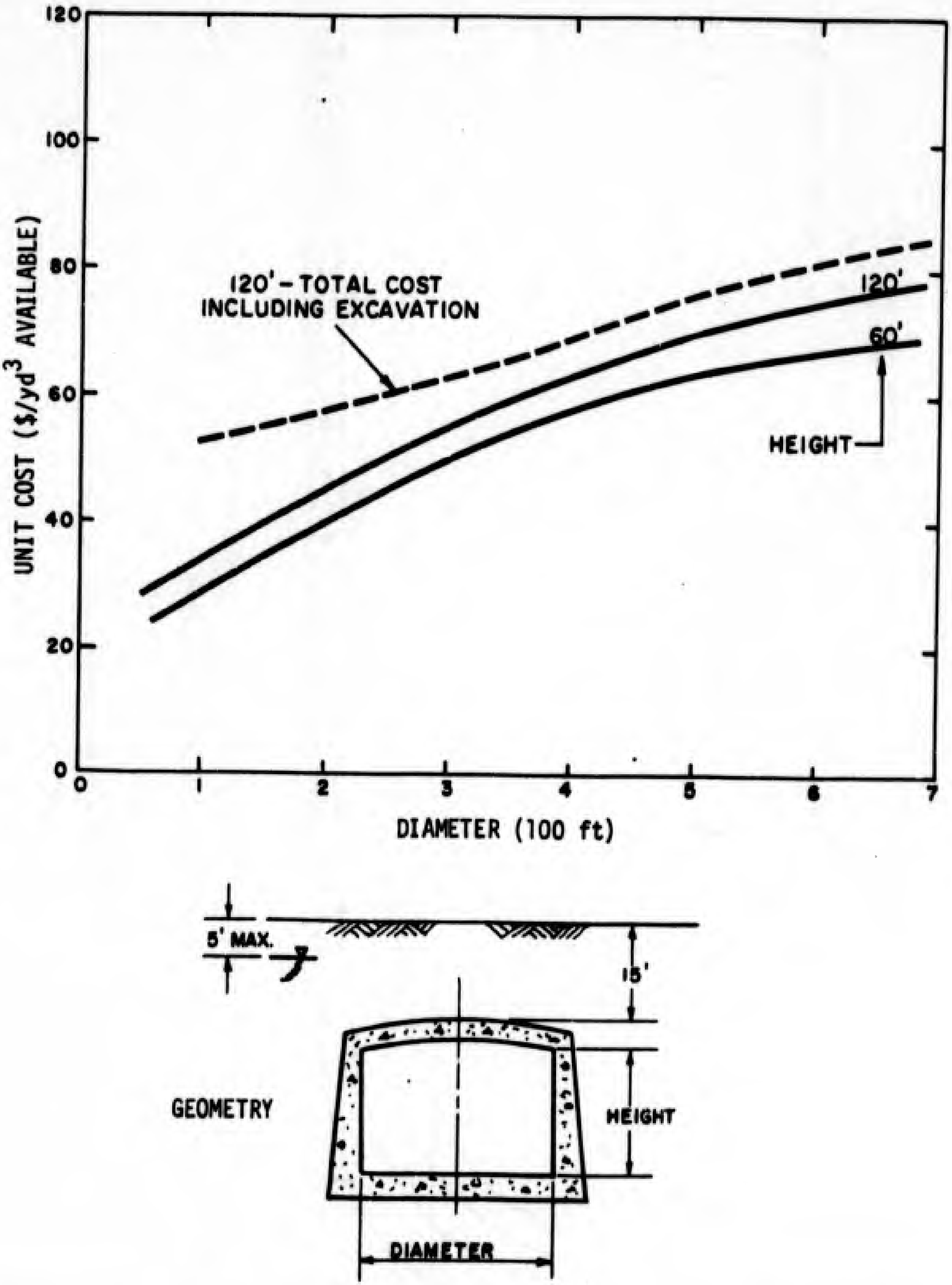

Figure I-3. Representative 1972 Structural Liner Costs in Saturated Soil

In Fig. I-1, (for rock chambers) the total cost, the cost of the excavation, and the cost of the permanent structural lining, including an allowance for temporary support, are broken down separately. These are given as a function of available cross sectional area of the chamber for three values of Rock Quality Designation (RQD): 85, 65 and 40.* These values, in order of decreasing rock quality, reflect on the ability of the rock to support structural loads as influenced by the degree of fracturing and jointing present.

The data shown in Fig. I-1 is based on information given in Ref. 24. Although Ref. 24 is concerned primarily with underground siting of nuclear power plants, the excavation and structural requirements of the rock chambers required can generally be applied here as well. The bulk of the engineering analysis in Ref. 24 was directed toward definition of the gallery liners as dictated by the quality of the rock medium. The reader should refer there for the details of the calculations, only the significant assumptions are outlined here.

The analysis of rock chambers included a larger number of parametric variations and resulted in a decision to adopt a parabolic horseshoe cross section with a reinforced concrete liner. The shape and liner design are based on the following properties and loading conditions:

Rock type:

Granite

Rock quality:

85, 60 and 40 RQD

Configuration:

Parabolic horseshoe

- horizontal span < 100 ft
- arch rise to span ratio 1/8

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*RQD is based on examining core borings. It is obtained by measuring the total length of all unweathered pieces of core greater than 4 inches and dividing by the core length. The result is expressed as a percentage.[23]

Liner:

4 in. minimum thickness

Steel yield strength - 60,000 psi

Concrete compressive strength - 4,000 psi

Reinforcing steel - 1%

Loading:

Structure dead weight

Rock load dependent on quality

Seismic force:

- 0.5 g's containment areas
- 0.25 g's all other areas

Unit Costs:*

Excavation $20/yd^3$

Reinforced concrete $100/yd^3$ in place

Temporary support:

RQD = 60: $2/ft^2$ of surface area for wire and rock bolts

RQD = 40: $6/ft^2$ of surface area for mesh, rock bolts, ties, and shotcrete

The following points relevant to our study should be noted: Implicit in the design and cost data is a provision to allow ground water to drain around the structure, through a porous layer to a sump storage where it can be monitored and pumped from the facility. This was to eliminate excessive hydrostatic loading. It is recognized that this technique has potential problems that require more detailed examination.

In addition it was pointed out that excavation (excluding lining) in a softer rock of the same RQD such as sandstone or limestone (i.e.

*Unit costs were derived by averaging the experience of several large underground hydroelectric power plants and the Cheyenne Mountain NORAD facility.

would be 15 to 20% less than granite, or ~ $\$17/yd^3$. Finally, the sensitivity of the liner thickness and cost to seismic loading was examined and indicated only a 5 to 10% increase for these effects.

Returning again to Fig. I-1, the reader will note that the total unit excavation cost is very sensitive to rock quality. For a chamber cross section of 1500 yd^2, it varies from $\$30/yd^3$ (RQD = 85) to as high as $\$150/yd^3$ (RQD = 40). This large variation is due primarily to liner requirements. In the poor quality rock, the analysis indicates walls up to 25 ft thick may be required for support.

It is perhaps relevant to note that unit costs as low as $5 to $10 per cubic yard have been proposed.[25] These are based on using mining techniques to excavate large underground chambers in good quality rock. In general their relevance is dependent on the flexibility one has in selecting a good site and in taking advantage of the economies associated with large productions spread over a number of years. They assume such conditions as: (1) good quality uniform rock where spans are limited to take maximum advantage of the natural load carrying capability of the rock and to minimize support requirements (i.e. room and pillar construction); (2) water inflow is not a problem; (3) continuous excavation progress is possible; and (4) there are minimal site accessibility problems or legal and organizational constraints. Since these represent somewhat ideal conditions, the $\$30/yd^3$ lower bound discussed above is used in this study.

With the exception of tunnels, construction of large underground structures in soils generally implies open excavations. If a large deep subterranean cavity is required, a rock site or some other alternative is normally chosen.* In this study, therefore, 1972 base-line costs for excavation in saturated soils were obtained assuming open cut excavations of relatively shallow depths.

Figure I-2 gives representative excavation costs (excluding permanent liner) as a function of depth and surface area excavated. The data is presented in terms of dollars per volume of available space, excluding volumes excavated for dewatering and shoring, and is based on the following general assumptions:[28]

1. A staged well-point dewatering system of the following characteristics:
   - 20 ft maximum vertical distance between tiers
   - A 2/1 (vertical to horizontal) net embankment slope for dewatering and soil stabilization
   - Cost of well pointing (U_W) including equipment, installation and operation - $6 per perimeter foot of header for each stage.
2. Shoring on all sides of the excavation at each tier level having the following characteristics:
   - Steel sheet piling (~22 psf)
   - Cost (U_S) (installed and pulled): $3.50/ft^2 of wall surface.
3. Cost of excavation (U_E) assuming wet sand/clay conditions: $4/yd^3 (in situ) excavated.

*References 26 and 27 show that under certain conditions it is theoretically possible to excavate a subterranean cavern in soil without excessive liner requirements by taking advantage of the natural arching action of the soil mass. Nonetheless, lack of reliable analysis and design procedure over a variety of conditions, as well as safe and efficient methods of construction, particularly in saturated soils, generally preclude subsurface excavation in soils today.

Note in Fig. I-2 that, for surface areas greater than one acre and depths less than 150 ft, excavation costs* range between $\$5/yd^3$ and $\$10/yd^3$. For surface areas less than one acre, costs increase exponentially reaching $\$20/yd^3$ at 1/4 acre for a depth of 150 ft. This trend reflects the increased importance of perimeter related costs (i.e., dewatering and shoring) when the gross volume of the excavation decreases. In the limit as the surface area becomes very small a region is approached where the assumptions forming the basis of the curves no longer apply.† Consequently, the curves are shown truncated at about $\$20/yd^3$.

Figure I-3 gives representative costs for reinforced concrete structural liners supporting saturated soil. The data is presented in terms of dollars per unit volume of space available within the liner and is based on the following assumptions (cost information again provided by Naval Facilities Engineering Command personnel):

<u>Soil</u>

Saturated sandy/clay: $\sim 110\ lb/ft^3$ (dry density)

$K_o \sim 0.6$ (lateral stress ratio)

<u>Configuration</u>

- Cylindrical liner
- Top and bottom slabs domed or internally supported
- 15 ft maximum soil cover

<u>Liner</u> - Reinforced Concrete

Concrete compressive strength 4000 psi

Steel yield strength - 60,000 psi

Working stress design - ACI 1963 code

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*More precisely, the lower limit approaches $\$4/yd^3$ asymptotically as the area becomes infinite.

†In this region, shaft excavation techniques would apply. Excavation costs for shafts are of the order of $\$60/yd^3$.

Loading:

Horizontal compression assuming hydrostatic soil ($K_o \sim 0.6$) and water loading

Unit Costs

- Reinforced concrete - $190/yd^3 in place
- Waterproofing - $0.70/ft^2 of surface

20% contingency factor

The analysis to determine required thickness of concrete assumed a very simple configuration, and considered hydrostatic soil and water loading only. The emphasis here was on order of magnitude estimates, rather than detailed structural analyses.

Note in Fig. I-3 that liner unit costs (solid lines) increase with depth and size of structure, ranging from $20/yd^3 to $80/yd^3 for diameters of 100 ft to several hundred feet and heights of 60 ft to 120 ft.* For the 120-ft case, excavation costs (from Fig. I-2) are added to give total unit costs shown as the dashed line in Fig. I-3. With this as a basis and extrapolating to other depths, we can see that total costs do not vary beyond the order of $50/yd^3 to $90/yd^3.

Finally, reviewing Fig. I-1 for rock chambers and Figs. I-2 and I-3 for saturated soils leads to the conclusion that total excavation costs of the order of $30/yd^3 to $150/yd^3 will cover a wide range of geologic and hydrologic conditions including those of interest in this study. Consequently these values were used as lower and upper bounds representing 1972 excavation capability.

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*The calculations indicate a ~ 20% reduction in liner costs is possible if hydrostatic water loading can be avoided.

APPENDIX II

DERIVATIONS OF NET COST EQUATIONS

The equations which show the contribution of various general forms of the spending rate R(t) are derived below:

(a) For a constant spending rate over a finite time interval:

$R(t) = k \quad (k = \text{constant})$

$$\int_{t_1}^{t_2} \frac{k}{e^{rt}}\, dt = \frac{k}{r}\left(\frac{1}{e^{rt_1}} - \frac{1}{e^{rt_2}}\right) \qquad \text{(II-1)}$$

(b) For a constant spending rate extending indefinitely into the future:*

$R(t) = k$

$$\int_{t_1}^{\infty} \frac{k}{e^{rt}}\, dt = \frac{k}{r}\, e^{-rt_1} \qquad \text{(II-2)}$$

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*This and subsequent equations for spending rates extending indefinitely into the future will be convenient forms to represent instances of permanent ecological damage or long-lasting sociological impact as a perceived result of facility construction.

(c) For a linearly increasing (or decreasing) spending rate over a finite time interval:

$$R(t) = kt$$

$$\int_{t_1}^{t_2} \frac{kt}{e^{rt}}\, dt = \frac{k}{r^2}\left(\frac{1}{e^{rt_1}} - \frac{1}{e^{rt_2}} + \frac{rt_1}{e^{rt_1}} - \frac{rt_2}{e^{rt_2}}\right) \qquad \text{(II-3)}$$

(d) For a linear spending rate extending indefinitely into the future:

$$R(t) = kt$$

$$\int_{t_1}^{\infty} \frac{kt}{e^{rt}}\, dt = \frac{k}{r^2}\, e^{-rt_1}\, (1 + rt_1) \qquad \text{(II-4)}$$

(e) For any higher order spending rate over a finite time interval:

$$R(t) = kt^n$$

$$\int_{t_1}^{t_2} \frac{kt^n}{e^{rt}}\, dt = \frac{k}{r^{n+1}}\left\{\frac{1}{e^{rt_1}}\left[(rt_1)^n + n(rt_1)^{n-1} + n(n-1)\,(rt_1)^{n-2} + \ldots + n!\right] - \frac{1}{e^{rt_2}}\left[(rt_2)^n + n(rt_2)^{n-1} + n(n-1)\,(rt_2)^{n-2} + \ldots + n!\right]\right\}$$

(II-5)

(f) For any higher order spending rate extending indefinitely into the future:

$$R(t) = kt^n$$

$$\int_{t_1}^{\infty} \frac{kt^n}{e^{rt}}\,dt = \frac{k}{r^{n+1}}\,e^{-rt_1}\left[(rt_1)^n + n(rt_1)^{n-1} + n(n-1)\,(rt_1)^{n-2} + \ldots + n!\right] \tag{II-6}$$

(g) For an exponential spending rate over a finite time interval:

$$R(t) = ke^{ct}$$

$$\int_{t_1}^{t_2} \frac{ke^{ct}}{e^{rt}}\,dt = \frac{k}{r-c}\left[\frac{1}{e^{(r-c)t_1}} - \frac{1}{e^{(r-c)t_2}}\right] \qquad c < r \qquad \text{(II-7)}$$

$$= k(t_2 - t_1) \qquad c = r \qquad \text{(II-8)}$$

$$= \frac{k}{c-r}\left[e^{(c-r)t_2} - e^{(c-r)t_1}\right] \qquad c > r \qquad \text{(II-9)}$$

(h) For an exponential spending rate extending indefinitely into the future:

$$R(t) = ke^{ct} \qquad c < r \qquad \text{(II-10)}$$

$$\int_{t_1}^{\infty} \frac{ke^{ct}}{e^{rt}}\,dt = \frac{k}{r-c}\,e^{-(r-c)t_1} \tag{II-11}$$

Most spending rates of interest can be approximated by linear combinations of the above ten cases. For example, a spending rate curve which fits a generalized nth-order polynomial,

$$R(t) = C_0 + C_1 t + C_2 t^2 + \ldots + C_m t^m$$

can be evaluated by successive applications of the power-law form of Eq. II-5.

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