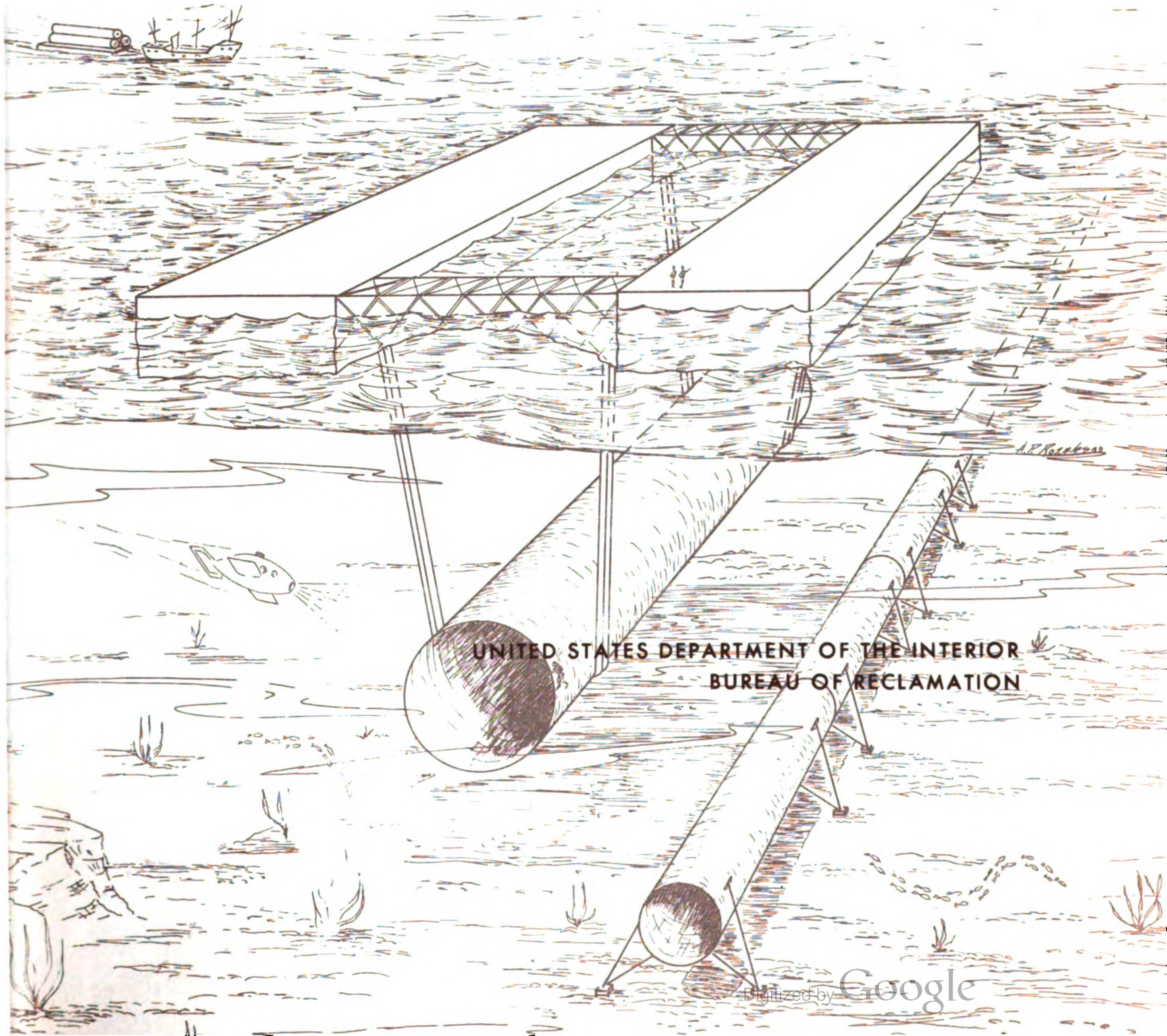
SPECIAL REPORT

CALIFORNIA UNDERSEA AQUEDUCT



UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF RECLAMATION

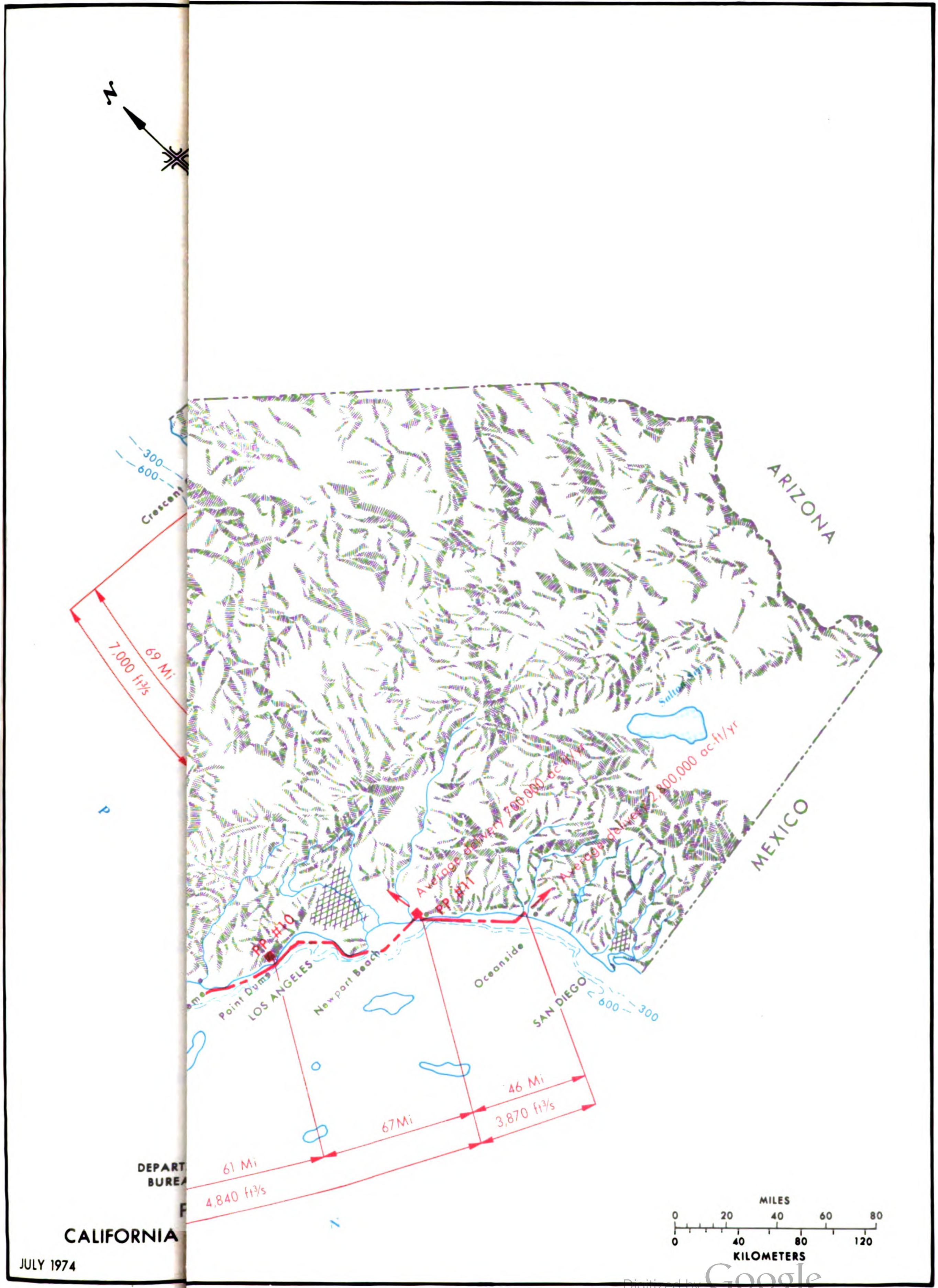
CALIFORNIA UNDERSEA AQUEDUCT RECONNAISSANCE INVESTIGATION

SPECIAL REPORT

January 1975

THIS REPORT WAS PREPARED PURSUANT TO FEDERAL RECLAMATION LAWS (ACT OF JUNE 17, 1902, 32 STAT. 388 AND ACTS AMENDATORY THEREOF OR SUPPLEMENTARY THERETO). PUBLICATION OF THE FINDINGS AND RECOMMENDATIONS HEREIN SHOULD NOT BE CONSTRUED AS REPRESENTING EITHER THE APPROVAL OR DISAPPROVAL OF THE SECRETARY OF THE INTERIOR. THE PURPOSE OF THIS REPORT IS TO PROVIDE INFORMATION AND ALTERNATIVES FOR FURTHER CONSIDERATION BY THE BUREAU OF RECLAMATION, THE SECRETARY OF THE INTERIOR, AND OTHER FEDERAL AGENCIES.

UNITED STATES
DEPARTMENT OF THE INTERIOR
Rogers C. B. Morton, Secretary
BUREAU OF RECLAMATION
G. G. Stamm, Commissioner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DEPART
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CALIFORNIA
JULY 1974

SUMMARY

An undersea aqueduct on the Continental Shelf off the coast of California could deliver about 4.0 million acre-feet of water annually to central and south coast areas. The cost of water would be about twice as much as the cost for similar deliveries using an inland route designed to be as free as possible of adverse environmental impacts.

The water supply for the Aqueduct would be provided from the Klamath and Eel Rivers. Preliminary water requirements studies indicate new municipal and industrial water supplies will be needed in southern California after 2020, with a projected buildup to 1.5 million acre-feet annually by 2050. In sizing the Aqueduct, 2.5 million acre-feet of water annually were assumed to be required to augment the flow of the Colorado River.

A very preliminary review indicates no major legal problems in construction of the Aqueduct. However, major adverse environmental impacts could result from construction, and therefore, much research would be required in any future planning.

The total construction cost, based on April 1973 prices, would be about $20 billion and the annual investment and OM&R costs about $1.8 billion. The major offshore facilities to be constructed would include: 599 miles of buoyant pipe conduit, 122 miles of buried, partly buried seabed and onshore-cut-and-cover conduit, 53 miles of undersea tunnels, 37 access chambers, 20 fault crossings, and 11 pumping plants and forebay reservoirs. Onshore facilities for the Aqueduct would be: dams, pumping plants, conveyance system, electrical facilities, and treatment facilities.

Existing oceanographic data concerned with hydrodynamics, marine soil, marine geology, and data concerning construction materials are both very scarce and widely dispersed. In this study, the Bureau of Reclamation has consolidated much of the available data, which will be made accessible to interested persons.

Conclusions

1. It would be engineeringly feasible to construct an undersea pipeline on the Continental Shelf off the coast of California to deliver water from northern California to points in central and southern California.

2. As nearly as can now be determined, the cost of delivering about 4.0 million acre-feet of water annually would be around $575 per acre-foot.

3. Oceanographic data on the Continental Shelf off the coast of California are very limited and widely dispersed. Future planning studies will require extensive research projects in all phases of oceanography, including marine biology and ecology, hydrodynamics, marine soils, marine geology, and materials.

4. Those responsible for future studies of this concept should seriously consider an ocean model test facility.

Recommendations

Based on present projections, water available to potential service areas should be sufficient until after year 2020; therefore, it is recommended that no further study of the Undersea Aqueduct concept be undertaken until needs are more pressing.

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PART A--UNDERSEA AQUEDUCT CONCEPT

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PART A--UNDERSEA AQUEDUCT CONCEPT

CHAPTER I. INTRODUCTION

The Undersea Aqueduct is a concept for conveying water from the north coast of California to areas of need in central and southern California. The concept includes a large conduit placed in the sea on the Continental Shelf and extending from the north coast to southern California. The conduit could be 30 feet or more in diameter, and lie about 300 feet below the surface of the sea. This concept involves an alternative water conveyance system, not an alternative source of water.

PURPOSE AND SCOPE

This report describes the results of an appraisal made to evaluate the technical, economic, and environmental practicability of the undersea conveyance concept. The plan concept illustrates the physical and environmental problems to be dealt with in constructing and operating the Aqueduct, and is used to arrive at an approximate magnitude of cost for the delivery of water.

Part A of the report describes the study, the general plan for the Aqueduct, and the main oceanic environmental considerations. Part B is concerned with dynamic as well as physical oceanography, and discusses maps used in route selection, hydrodynamics, marine geology and soils, and materials. Part C presents design considerations, descriptions of the offshore and onshore facilities, and an alternative inland plan and cost comparisons for the undersea and inland facilities. The report finalizes the present study and concludes that no further study is needed at the present time. It presents the technical data which were assembled as part of the study and which are now available for other uses. More details and supporting studies are contained in these appendixes:*

I - Appraisal Design and Estimates for the Offshore System
II - Geology
III - Hydrodynamics
IV - Soils Engineering

*A limited number of copies of the appendixes are available from the offices listed following page 124 of this report.

AUTHORITY

The report is authorized to be made by the Federal Reclamation laws (Acts of June 17, 1902, 32 Stat. 388), and acts amendatory thereof or supplementary thereto. Funds for the start of the study were included in the 1971 Appropriations for Public Works, P.L. 91-439.

PREVIOUS ACTIVITIES

National Engineering Science Company (NESCO)

An undersea pipeline using varied concepts has been suggested by many persons or organizations. Probably the most definitive of these suggestions was the plan prepared by the National Engineering Science Company (NESCO) in 1965. This organization, now dissolved, considered several possible undersea aqueduct concepts and evolved a preliminary plan that included the following criteria and features:

1. Initial diversion of about 3.3 million acre-feet per year from the Klamath River near its mouth in northern California. On-stream storage regulation would be required.

2. The conveyance pipeline would be an inverted siphon with no undersea pumping stations. Onshore headwater reservoirs would provide the force necessary to move water to the first delivery

reservoir onshore at Moss Landing near Salinas. A pumping plant at this location would furnish the required force for further conveyance to terminal facilities near Ventura.

3. The pipe would be located on the Continental Shelf at a depth of about 300 feet.

4. A basic concept was to use the buoyancy of freshwater versus seawater. By constructing the aqueduct of relatively light fiber-reinforced plastics, this buoyancy could overcome the lack of buoyancy of the pipe, resulting in a slightly buoyant structure which would be anchored to the bottom of the sea. This structure would also be flexible for accepting the stress and fatigue produced by sea forces.

NESCO stated that the plan developed from their studies would exceed the minimum planning requirements for future water use in southern California and would do so at a lower cost than that for other plans, somewhere around $50 to $60 per acre-foot.

Early in 1966 NESCO proposed to the Bureau of Reclamation that the company conduct a two-year study to evaluate the feasibility of constructing and operating an undersea aqueduct system as described above. This proposal was not accepted because the Bureau then had no specific authority to study a plan to import water from northern California to the southern California coastal area.

Prereconnaissance Study

A report and study on an undersea aqueduct were undertaken because of the statement of the managers on the part of the House in House Report No. 1065 to accompany S. 1788, 90th Congress, enacted by the Congress and approved as Public Law 90-254. The statement emphasized, on behalf of all the conferees, the importance they attached to a proposed reconnaissance study of subsurface offshore conveyance of water from the Eel-Klamath River areas to an appropriate terminal point in southern California. The statement indicated that the study should be given priority by the Department of the Interior and the Bureau of Reclamation with the expectation that the Bureau would submit a report on the study to the Congress no later than December 31, 1970.

Because of the time needed for the study, the budgetary situation, and the sizable fund requirement for a full-scale reconnaissance investigation, the Bureau of Reclamation found it would not be possible to complete the requested reconnaissance report by December 31, 1970. A two-stage alternative approach was proposed under which a preliminary appraisal or prereconnaissance study would be made in fiscal year 1969 with funds already budgeted.

The California Undersea Aqueduct Prereconnaissance Report was published in December 1969 by the Bureau of Reclamation. It included data obtained from two organizations under contract. Marine Advisers, Inc., of LaJolla, California, prepared a report on The Possible Effects of a Proposed Undersea Aqueduct on Marine Ecology and of the Marine Environment on the Aqueduct, February 1969. The Advanced Marine Technology Division of Litton Systems, Inc., El Segundo, California, furnished data in a report titled Ocean

Introduction

Environment and Design Considerations in a Prereconnaissance Study of a California Undersea Aqueduct, May 1969, revised June 1969.

Briefly, the prereconnaissance report on the study included these major elements:

1. A preliminary evaluation of potential requirements for import water in southern California and of potential supplies available for export from northwestern California.

2. An analysis of the state of knowledge regarding materials for the Aqueduct and accessories, the marine environment of the Aqueduct, construction and maintenance problems, and available information on tides, waves, currents, and other factors.

3. A determination of additional research and testing which would be required to provide data for a full-scale reconnaissance investigation.

4. The development of a program for a full-scale reconnaissance investigation.

Based on rough cost estimates prepared by National Engineering Science Company, as modified by the Bureau of Reclamation, the cost of water delivered through the Aqueduct could be competitive with the cost of water delivered from other potential sources. However, many complex engineering and other technical problems associated with the potential aqueduct were not well understood.

The prereconnaissance report indicated that a total fund requirement of $2,188,000 and a period of 5-1/2 years would be needed to complete the reconnaissance investigation. The program was to be divided into two phases. Phase 1, basic research would require three years and would provide data to determine the engineering feasibility of the Undersea Aqueduct. It was believed that a reliable assessment of engineering feasibility could be made at the end of two years. If the results were favorable, phase 2, reconnaissance studies, could begin at that time. They would extend an additional 3-1/2 years and would include engineering studies, designs and cost estimates, economic analyses, study of alternative projects, and preparation of a final report. The advice and expertise of many Federal and State agencies and nongovernmental entities would be required throughout the studies.

Study Work Plan

Based on the results of the prereconnaissance report, Congress approved funds in 1971 to initiate a full reconnaissance study and assigned the overall responsibility for the study to the Bureau of Reclamation. A study management team (SMT) was established, chaired by a regional representative and included members of Divisions of Design, Planning Coordination, and General Research of the Bureau's Engineering and Research Center.

The team developed a study work plan for a five-year reconnaissance investigation of the offshore California Undersea Aqueduct, and arranged for acquisition of outside assistance through consultants or from other Federal agencies and departments. The team's efforts culminated in a report, Study Work Plan for California Undersea Aqueduct Reconnaissance Investigation, dated September 1971.

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STUDY APPROACH

Government agencies, educational institutions, and private industry organizations where the necessary expertise was available for data gathering and analysis were contacted. In all, several hundred individuals and organizations were contacted either by letter or visits by members of the study management team.

The concept of a large undersea aqueduct made considerable work necessary to bring Bureau of Reclamation personnel involved up to a level of knowledge so that the appraisal investigations could begin.

As a first step they determined the state of the art regarding:

1. The environment of the Undersea Aqueduct, including marine ecology, underwater topography, nature and depth of bottom sediments, ocean bed stability, and seismicity.

2. Materials for pipeline and accessories, including structural and durability characteristics, availability, and manufacturing techniques.

3. Information on tides, waves, currents, forces, anchor stresses, and loss of buoyancy.

4. Problems associated with construction and maintenance.

A mid-point or interim report was planned to present a summary and analysis of all technical, conceptual, and environmental data. Decisions were to be made as to whether or not the reconnaissance study should continue further. After the study was underway, changing conditions and revised projections of population and water requirements indicated additional water supplies would not be needed in California until after year 2020. The decision was made to terminate the study with this appraisal report documenting the results of studies to date.

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COOPERATION

The Bureau of Reclamation gratefully acknowledges and appreciates the sincere help and support that was received during this study.

Information and assistance were provided by: the Department of the Navy, the National Oceanographic Atmospheric Administration, the U.S. Geological Survey, Litton Industries, Scripps Institution of Oceanography, California Division of Mines and Geology, and a number of oil companies. Their cooperation is summarized in the paragraphs which follow. A more complete listing is given in the individual appendixes.

Department of the Navy

Early in the data-gathering phase of the study, the Navy appointed Dr. Michael Yachnis as a coordinator from the Naval Facilities Engineering Command to assist the Bureau of Reclamation with those study items requiring contact with the Navy. A number of naval facilities were contacted, including the Naval Civil Engineering Laboratories (CEL) located at Port Hueneme, California, and the Naval Undersea Research and Development Center (NUC) located at San Diego, California.

The Bureau of Reclamation entered into two contracts with CEL. One was for marine soil engineering data and analysis, including overlay map sheets displaying sediment thickness for most of the Santa Barbara Channel area. The other was for the materials pilot program which included work on seawater screening for pipe materials and auxiliary materials, along with a general study on marine fouling. Field evaluation for the fouling study was made at the NUC tower platform near Mission Beach, California. Two contracts were completed with NUC, one for the acquisition and analysis of archival data concerned with waves, currents, and tsunamis, and the second for the study of statistical probabilistic loadings.

National Oceanographic and Atmospheric Administration

During the initial phase of searching for oceanographic data, a number of facilities located with the National Oceanographic and Atmospheric Administration (NOAA), Department of Commerce, were contacted. Because of the number of data centers involved, the administrator of the agency appointed Dr. Richard M. Morse as coordinator to work with and assist the Bureau.

Through the coordinator, the Bureau became familiar with the sea grant program administered by NOAA. In May 1972 a member of the Bureau study management team participated in an annual onsite review of ocean engineering proposals held at the University of California in Berkeley, California.

U.S. Geological Survey

Several field offices of the Department of the Interior's U.S. Geological Survey were contacted during the initial oceanographic data search. The U.S. Geological Survey, Office of Marine Geology, Menlo Park, California, under contract gathered existing marine geology data and prepared overlay map sheets showing sediment thickness and other geologic data on the Continental Shelf off the coast of California. Data from most of the Santa Barbara Channel area, however, were made available by CEL.

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Litton Industries

During the initial stages of the investigation, the Bureau of Reclamation obtained a number of volumes of general information from Litton Industries. Much of the data were originally accumulated and assembled by the National Engineering Science Company (NESCO) and by Litton Systems, Inc., which acquired NESCO.

Scripps Institution of Oceanography

To complete the data-gathering phase of the soils engineering and geology studies, a week was spent at the Scripps Institution of Oceanography. Discussions were held with a number of personnel concerning a wide variety of topics including submarine canyons, marine sediments, core sampling, high velocity currents, faults, geophysical profiling, bathymetry, and data retrieval. Dr. F. Shepard of the Institution made his private library available during the data search.

California Division of Mines and Geology

The Bureau of Reclamation received a series of geologic map sheets of the offshore California Continental Shelf from the State of California Division of Mines and Geology. Many of these maps were used in the preparation of base maps for the Aqueduct route selection studies.

Oil Companies

Oil companies with offshore drilling operations along the California coast were contacted during the search for soil and geology data. Useful data received from the companies were treated as confidential.

CHAPTER II. GENERAL PLAN

PLAN DESCRIPTION

In the plan concept for the California Undersea Aqueduct little attempt was made to optimize sizes of diversions or storage reservoirs. The optimizations would not significantly change the overall system cost.

Diversion Plans

Of the 4 million acre-foot annual diversion requirement for the Undersea Aqueduct, 1,200,000 acre-feet were assumed to be diverted from the Eel River and 2,800,000 acre-feet from the Klamath River. Such diversions, although not practical now, might be justified at some future date when the need for water is of sufficient concern and importance as to offset possible adverse environmental effects that might result from such development. Because of environmental and free-flowing river considerations, it seems likely that diversion might be allowed from the Eel before it is allowed from the Klamath. It was assumed that as much water as reasonably possible would be obtained from the Eel before looking to the Klamath as a source.

Eel River diversion. The flow of water in the Eel River would be partially regulated by storage. It would also be augmented by storage and diversion from the Upper Mad River. Even with this regulation, flows would be quite erratic. A base flow for fishery of about 1,100,000 acre-feet per year would be needed. This would provide for a minimum flow of about 2,000 cubic feet per second during fall and winter months, 1,000 cubic feet per second in the spring, and about 200 cubic feet per second during the summer. Water would be diverted to the Aqueduct only when the riverflow, both regulated and unregulated, exceeded these amounts.

To divert an average of 1,200,000 acre-feet per year would require a maximum diversion capability of 5,000 cubic feet per second. Because of the erratic flow of the river, this maximum diversion capability would be used only during one or two months during most years. The diversion structure would have necessary fish passage facilities. Water would be diverted through a gated structure along one riverbank, opening to a canal. Desilting would be accomplished in such a way that collected silt could be discharged back to the river. Water would be filtered and treated before it enters the Aqueduct to prevent growth of undesirable organisms in the undersea portions of the pipeline. All water entering the canal would be screened to prevent fish from entering the Aqueduct.

Klamath River diversion. Because of the character of the watershed, the Klamath River has a relatively high sustained flow during the dry season of the year. It is assumed that a substantial fishery flow will be required past any diversion point on the Klamath River. During an average year this flow would amount to about 2,700,000 acre-feet per year and would consist of flows of about 3,500 cubic feet per second during the fall, winter, and spring months, increasing to 5,000 cubic feet per second during the summer months. Diverting flows only in excess of the fishery flow would make it possible to divert 2,800,000 acre-feet per year, on the average, with a maximum diversion capacity of 7,000 cubic feet per second. The maximum diversion capacity would be used only during two to three months during an average year. Minimum diversions in an average year would probably be at least 1,000 cubic feet per second. The diversion structure would have facilities for fish passage and would have a small lock for river navigation. Water would be diverted to a concrete-lined canal. Although the silt load is less on the Klamath than in other north coast rivers, it would be necessary to have a settling basin and to filter and treat the water before it enters the Undersea Aqueduct. Collected silt would be discharged back to the river in such a way as to minimize environmental effects.

Treating the water before it enters the undersea pipeline would prevent the growth of undesirable organisms in the pipeline. All water being diverted would be screened to prevent fish from entering the diversion canal.

Storage Reservoirs

To minimize the size of the offshore pipeline, it would be desirable to provide reservoir storage to regulate flows seasonally and through dry years so that a constant flow could be maintained. Regulating the water diverted from the Eel and Klamath Rivers to provide a steady flow would require approximately 9 million acre-feet of storage capacity. It was assumed that all of this capacity could not be provided in the north coast area because of environmental considerations.

General Plan

If reservoir sites in the upper areas of the watersheds of the Eel River, the Van Duzen River, and the Mad River were used, 4 million acre-feet of storage would be provided. An additional 5 million acre-feet was needed to completely regulate the flow in the Aqueduct. A search was made for reservoir sites near the shoreline southward along the route of the Aqueduct. All sites of this kind, however, would have associated environmental problems. The most practical areas for storage reservoirs were in the Russian River Basin and in the Monterey Bay area.

Two possibilities for large reservoirs exist in the Russian River Basin. One would be enlarging Warm Springs Reservoir, which is now under construction by the Corps of Engineers; the other would be an enlarged Knights Valley Reservoir, which is authorized to be constructed by the Corps of Engineers. Either one of these sites could provide an additional 3 million acre-feet of regulatory storage. In the Monterey Bay area, within a radius of approximately 50 miles from the shoreline there are numerous reservoir sites. An additional 2 million acre-feet of storage was assumed to be available in this area, thus making a total available storage of 9 million acre-feet. From the Monterey area southward the flow in the offshore pipeline would be a constant amount throughout the year as well as from year to year.

Conveyance Facilities

The Aqueduct would be about 800 miles long, have a maximum pipe diameter of 34 feet, and a minimum pipe diameter of 19 feet at its terminus near Oceanside, California. The design calls for 599 miles of buoyant conduit, 122 miles of buried, partly buried, seabed, and onshore cut-and-cover conduit. There would also be 53 miles of undersea tunnels, 37 access chambers, 20 fault crossings, and 11 pumping plants with forebay reservoirs.

Capacity needed for the offshore pipeline would be 7,000 cubic feet per second from the Klamath River to the Eel River. At the Eel River an additional 5,000 cubic foot per second diversion would be added so that 12,000 cubic feet per second of conveyance capacity would be needed to the Russian River. Storage regulation in the Russian River Basin would permit a reduction in conveyance capacity to 7,000 cubic feet per second to the Monterey area. At Monterey Bay 200,000 acre-feet per year would be delivered. From the Monterey area southward to the vicinity of Santa Maria, the necessary capacity would be 5,250 cubic feet per second.

At Santa Maria 300,000 acre-feet per year would be delivered. From Santa Maria to Newport Beach area, conveyance capacity would be 4,840 cubic feet per second, and at that point 700,000 acre-feet per year would be delivered. Capacity from Newport Beach to Oceanside area would be about 3,870 cubic feet per second, with delivery of 2,800,000 acre-feet at the terminus of the offshore pipeline. Distribution facilities would be needed beyond the Aqueduct terminus and other points of delivery to serve areas of potential use, including a pipeline with capacity of about 3,800 cubic feet per second to convey water for augmentation of the Colorado River.

All deliveries would be at constant flow. Costs of re-regulating these flows and fitting them to local needs were assumed to be part of distribution system costs.

WATER REQUIREMENTS

This section lists the possible water requirements which might lead to construction of an undersea aqueduct along the California coast. Water needs in California would have first call on water developed in the north coastal area. An undersea aqueduct might also augment the Colorado River water supply.

Augmentation of the Colorado River

There is an urgent need for water to augment the Colorado River, but conclusive projections of future needs by year have not been made. Congress has declared a Federal responsibility for the first 2,500,000 acre-feet of augmentation in the Colorado River Basin Project Act of 1968 (Public Law 90-537), and various sources of augmentation water are being investigated. However, the feasibility and the potential contribution of those sources are presently unknown. For purposes of this study, it was assumed that an increment of augmentation of 2,500,000 acre-feet per year would be needed in or shortly after year 2020. Good quality water for augmentation could also improve the quality of Colorado River water available for California, Arizona, and treaty commitments to Mexico.

General Plan

Future Water Needs in California

Future water needs for California have been estimated based on the following assumptions.

1. Water from the Undersea Aqueduct would be too expensive for irrigation use.

2. Future water needs in the Central Valley would be met from Central Valley sources. Since these needs will probably be largely for irrigation, this would be consistent with item 1.

3. Primary customers for Undersea Aqueduct water in California would be coastal metropolitan areas from the San Francisco Bay area southward to the Mexican border.

4. In the areas mentioned in item 3, before Aqueduct water is needed, extensive use would be made of local supplies and wastewater reclamation and some use would be made of seawater desalination.

Based on these assumptions, water needs which might be supplied by an undersea aqueduct by the year 2050, and delivery points are:

Delivery point	M&I water needs (acre-feet)
San Francisco Bay area	200,000
Central Coastal area (San Luis Obispo to Santa Barbara)	300,000
Southern California (MWD system)	1,000,000
Total	1,500,000

General Plan

Undersea Aqueduct Water Deliveries

To meet the water requirements, delivery from the Undersea Aqueduct was assumed to commence shortly after the year 2020. Initial deliveries would be 2.5 million acre-feet for augmentation of the Colorado River. Supplemental California M&I needs would increase from zero in 2020 to 1.5 million acre-feet in 2050. By 2050 total water delivered by the Aqueduct would thus amount to 4 million acre-feet.

WATER SOURCES

The rivers of northwestern California are a plentiful source of water which might be developed to meet future needs in the southern part of the state. The principal rivers are the Klamath and Eel. The Klamath River has an average annual flow of about 11 million acre-feet and the Eel about 5 million acre-feet.

Klamath River

With a drainage area of over 12,000 square miles, the Klamath River is the largest river system in northwestern California. Its headwaters are in the Klamath Basin in Oregon and the Klamath mountains of northern California. Most runoff occurs shortly after winter storms; however, enough of the watershed is at higher elevations so that some snowmelt runoff occurs in late spring and early summer. For the most part, the soil and surficial rock of the drainage area are more permeable than other watersheds in northwestern California. Therefore, the Klamath River has a higher sustained base flow through the summer season than other streams in the area.

Eel River

The Eel River drains a little over 3,000 square miles of the California Coast Ranges. This watershed is characterized by relatively low mountains with little snowmelt runoff. Almost all runoff occurs shortly after winter storms. The soil in the watershed is shallow and the surficial rock has low permeability; thus there is very little base flow during the summer season.

Sediment

The sediment yield of northwestern California watersheds varies considerably. The sediment yield of the Eel River is greater than any other stream of comparable size in the United States. The amount of sediment discharged to the ocean by the Eel River is almost four times that discharged by the Klamath River. The Eel River averages about 20,000 acre-feet per year of sediment and Klamath about 5,000 acre-feet. The difference is even more dramatic when it is noted that the annual flow at the Klamath River is more than twice the flow of the Eel. In other words, the volume of sediment per unit volume of water in the Eel River is approximately eight times that in the Klamath. It is obvious that any diversion from the Eel River would require extensive works to deal with the sediment load of the stream.

LEGAL CONSIDERATIONS

To determine the source of water for the Aqueduct, consideration was given to two State laws and one Federal law. The State 1924 Initiative Act created the Klamath River Fish and Game District which extended from the ocean to the mouth of the Shasta River. This act prohibits the construction of any artificial obstruction on the river in that reach. In addition to this act, the Federal Wild and Scenic Rivers Act of 1968 requires that the Klamath River, from Iron Gate Dam to the ocean, be studied as a wild river in any ongoing development studies.

Another State Law, the California Wild and Scenic Rivers Act of 1972 prohibits construction of water impoundment structures on certain rivers of California's north coast. The act, locally known as the Behr Bill, after its chief author, bans dams and reservoirs on the Klamath, Trinity, Smith, Eel, and American River systems. However, the act states that:

> It is the intent of the Legislature, with respect to the Eel River and its tributaries, that after an initial period of 12 years following the effective date of this chapter, the Department of Water Resources shall report to the Legislature as to the need for water supply and flood control projects on the Eel River and its tributaries, and the Legislature shall hold public hearings to determine whether legislation should be enacted to delete all or any segment of the river from the system.

The Assistant Solicitor for International Marine Minerals, Division of Public Lands, has issued an opinion to help Federal agencies identify and evaluate any legal problems encountered in routing the Aqueduct along the Continental Shelf. Within a limit of 3 miles, the coastal states have been granted jurisdiction over the submerged lands on the Continental Shelf. Thus, rights-of-way from the State of California would be needed for installation of the Aqueduct in the areas where it would be within 3 miles of the California coastline.

Seaward of the 3-mile limit, the rights of the United States to use the beds of the high seas off the California shore for installation of the Aqueduct are clearly recognized under international law. However, these rights are subject to the exercise of due regard to cables and pipelines already in position.

The Continental Shelf of California includes many oil and gas leases with appurtenant structures, common carrier pipelines, and other structures and cables placed on the seabed under national and international law. The installation of an undersea aqueduct in or near these areas and structures would be contingent on not interfering with existing operations.

In addition to the aforementioned restrictions, certain areas of the Continental Shelf and the water above have been designated by the Department of Defense as restricted areas required for national defense. It would be necessary to clear any proposed routing of the Aqueduct with the Department to insure that there is no conflict of uses.

General Plan

Application for a permit to construct the Aqueduct would have to be made to the Corps of Engineers. The Corps of Engineers, under the Rivers and Harbors Act, has authority to prevent obstructions to navigation in the navigable waters of the United States, both within and outside the 3-mile limit.

Before the location of the Aqueduct is definitely determined, it would be necessary to contact the Bureau of Land Management, Geological Survey, Corps of Engineers, and the Department of Defense to ascertain locations and restrictions on any offshore leases, structures, and restricted areas.

Another area of concern is the construction of any facilities on or near the California coastline. The California Coastal Zone Conservation Act of 1972 (Proposition 20 of 1972) created six regional commissions and a State commission to control development along the coast. Any development taking place within the coastal zone permit area, which is generally all water and land within 1,000 yards of the ocean and all offshore waters and islands, must be approved by a permit granted by a coastal zone commission. A procedure has been established for filing application, which can lead through public hearings and appeals.

In summary it appears that there would be no major legal problems regarding installation of the Aqueduct in coastal waters outside of obtaining the necessary permits. However, regarding the construction of the necessary storage reservoir, particularly on the north coastal streams, present and future wild and scenic rivers acts, both State and Federal, could cause legal problems of unknown magnitude. If the project ever approaches the actual construction stage, there would probably be other specific legal considerations that are not now evident.

ENVIRONMENTAL CONSIDERATIONS

Any water storage or diversion proposal for northwestern California streams would impact on environmental values which now exist there. The two principal areas to consider are the fishery resources--sport and commercial--and the free-flowing undeveloped nature of the rivers. Wildlife resources, although affected by any development, would probably be a lesser consideration.

Sport Fishery

The fisheries of north coastal area streams are largely anadromous species such as king salmon, silver salmon, and steelhead trout. The Eel, Klamath, Trinity, and Smith River systems are widely recognized for the salmon and steelhead angling they provide. In excess of one-half of the State's entire salmon and steelhead resource originates in northwestern California. Of particular significance is the fact that at least 80 to 90 percent of all steelhead, a trophy species of great importance to anglers, is produced in north coast streams. So far as is known, the Klamath River supports the largest steelhead run in the country. The fish produced in these, and other north coastal streams, also contribute substantially to sport and commercial salmon fisheries in the ocean.

The life cycles of anadromous fish are of major significance in relation to potential water developments in the north coastal area. The stages of the life cycle spent in freshwater are exacting in their requirements. Anadromous fish must be able to migrate upstream from the ocean to suitable spawning areas, where adequate gravels and streamflow of proper temperature and quality must prevail during the spawning and egg incubation periods. Although most young king salmon migrate downstream to the ocean soon after hatching, juvenile silver salmon and steelhead may remain in freshwater for one or more years before migrating to the ocean. These latter species require a suitable habitat throughout the year.

Both king and silver salmon sustain an important sport fishery in ocean waters. This sport fishery extends along the entire northern California coast, but is concentrated near San Francisco, Fort Bragg, Humboldt Bay, and Trinidad Head.

During the king salmon runs, anglers concentrate in the estuary and lower riffle areas of the Klamath, Smith, and Eel Rivers. Anglers follow the runs upstream as the fish move to the spawning beds. Although sizable runs of silver salmon ascend the streams, relatively few are caught by anglers because of the short duration of the run and high, turbid streamflows.

A run of immature steelhead accompanies the fall run of king salmon. As these "half-pounders" enter the rivers in late summer and early fall, fishermen congregate at accessible points along the main streams. Resident rainbow trout are well distributed throughout the area and fishing is superb in many of the streams. The area also supports several fisheries unique to California such as those for coast cutthroat and the eulachon or candlefish. Sturgeon, shad, and smelt contribute to small but distinct fisheries in the coastal streams, notably the Klamath River. The inland high mountain rivers and lakes provide a variety of trout fishing.

Commercial Fishery

Commercial fishing is a basic industry of the north coastal area. Along with lumbering and agriculture, it plays a major role in the economy. The fishing ports which receive most of the fish landings north of San Francisco Bay are: Eureka, Fort Bragg, and Crescent City.

The relative contribution of streams of the north coastal area to the ocean salmon fishery has not been clearly determined. The results of several tagging studies suggest that, while north coastal area streams contribute to the commercial salmon catch in Oregon and Washington, their major contribution is to California waters.

Free-flowing Rivers

The Klamath and Eel Rivers both are partially controlled by dams and reservoirs; however, they have substantial reaches which are uncontrolled. This is particularly true of the lower portions of both rivers. Efforts have been made and are underway to preserve the free-flowing nature of these rivers. The legal provisions relative to these rivers were described in "Legal Considerations."

OFFSHORE ENVIRONMENTAL CONSIDERATIONS

Included in this section are a description of origin and use made of environmental data in designing the Undersea Aqueduct, and speculation on various environmental effects of the Aqueduct.

Before an undersea aqueduct is constructed, its effects on the undersea environment and ecology need to be fully understood. The California Continental Shelf waters support important commercial fisheries. A structure of the magnitude of an undersea aqueduct could affect these commercial operations both during construction and after the pipeline is in operation.

As a part of Reclamation's 1969 pre-reconnaissance study, a literature search and review was conducted of the possible effects of an undersea aqueduct on the marine ecology and environment. This study was conducted by Bendix Marine Advisors, Inc., under contract from Reclamation. It indicated that a buoyant undersea aqueduct might have a somewhat beneficial effect, in that it would act as an artificial reef and tend to attract large numbers of fish.

General Plan

Agency Contacts

During the course of this study, an attempt was made to obtain appraisals of the environmental impacts of an undersea aqueduct from various Federal and State agencies. Agencies contacted included:

National Marine Fisheries Service
Environmental Protection Agency
U.S. Fish and Wildlife Service
Bureau of Outdoor Recreation
U.S. Geological Survey
U.S. Forest Service
Marine Minerals Technology Center
Corps of Engineers
California Department of Fish and Game

Two general meetings seeking ideas and input on the offshore environmental aspects of the Aqueduct were held with these agencies. In addition, numerous individual contacts with the agencies were made, and limited meetings among a few of the agencies were held.

The California Department of Fish and Game had significant relative data and experience in the fields of ocean environment and ecology. Their data and experience relate primarily to their responsibilities in fishery regulation enforcement and associated data collection and monitoring.

Fishery Information

The usable information which the Department of Fish and Game had available related to catches of various types of fish by approximate location. The data were plotted on maps and showed such things as trawling areas, sport fishing areas, areas where various species were caught, and the locations of kelp beds. In analyzing these data, it became apparent that:

1. Trawling areas were quite widespread and would be affected by almost any location of the Aqueduct.

2. Trolling would be little affected by the Aqueduct.

3. Construction and operation of the Aqueduct might significantly affect bottom-associated marine resources such as shrimp, crab, abalone, and kelp beds on which data were readily available.

4. Considerable and costly additional research would be needed to obtain any additional information which would be usable in this present study.

As a result of these considerations, it was decided to prepare a set of overlay maps showing the probable locations of marine resources mentioned in item 3, namely, shrimp, crab, abalone, and kelp beds. In selecting the route for the Aqueduct, these areas have been avoided to the extent practical.

Impact of Aqueduct

The following ideas on the Aqueduct's impact are purely speculative, with additional research, analysis, and perhaps prototype testing necessary to verify their validity or importance. These ideas were developed in the process of the study while trying to determine how best to pursue studies of the marine environment. All of these areas should be the subject of further thought and attention before construction of an undersea aqueduct is seriously contemplated.

Physical presence. A buoyant pipeline would be an obstacle or physical barrier to movement. It is difficult to speculate as to what effect, if any, this might have on marine life. No doubt the pipeline would alter current velocities and directions at least in its immediate vicinity. This could alter patterns of sedimentation and sediment transport. A buried pipe would not present the same problems, but the alteration of the sea floor needed to place such a pipe could have permanent effects.

Artificial reef. A structure such as a buoyant pipeline might serve as an artificial reef, thus attracting fish. If there were possibilities of enhancing commercial and sport fisheries, this might be exploited, perhaps by feeding. If the effects were detrimental, that is causing increased fouling or the possibility of snagging the Aqueduct with trawling gear, measures might be taken to discourage the fish.

Temperature. The water entering the Aqueduct would on almost all occasions be a different temperature than the surrounding ocean environment. As a result, the Aqueduct pipe at a particular location could be either warmer or colder than the surrounding ocean water. The magnitude or effects of these temperature differences are not known.

Freshwater leaks. Under almost all operating situations, water pressure inside the Aqueduct would exceed water pressure in the ocean environment outside. Consequently, if a leak would occur in the pipe, freshwater would escape. Such a freshwater leak could vary from a barely detectable leak to a total rupture of the pipeline which could be a serious problem. Escape of freshwater into the marine environment could have detrimental effects on sea life in the vicinity. The amount of damage which might result would depend on the size of the break and duration of its occurrence.

Turbidity. Construction activities and some maintenance activities would no doubt result in displacing loose bottom sediments, causing increased turbidity in adjacent waters. The amount of turbidity could be minimized by careful planning and execution of those activities, but it would be virtually impossible to prevent some increase. This problem would be the most serious during construction of a buried pipeline, and less of a problem with a buoyant pipeline. In addition to the delivery of water, variations of this concept could possibly lend themselves to supplemental utilization such as fish farming, transmittal of communication lines, powerlines, as well as a number of other technical spinoffs.

PART B--OCEANOGRAPHY

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PHOTOGRAPHS

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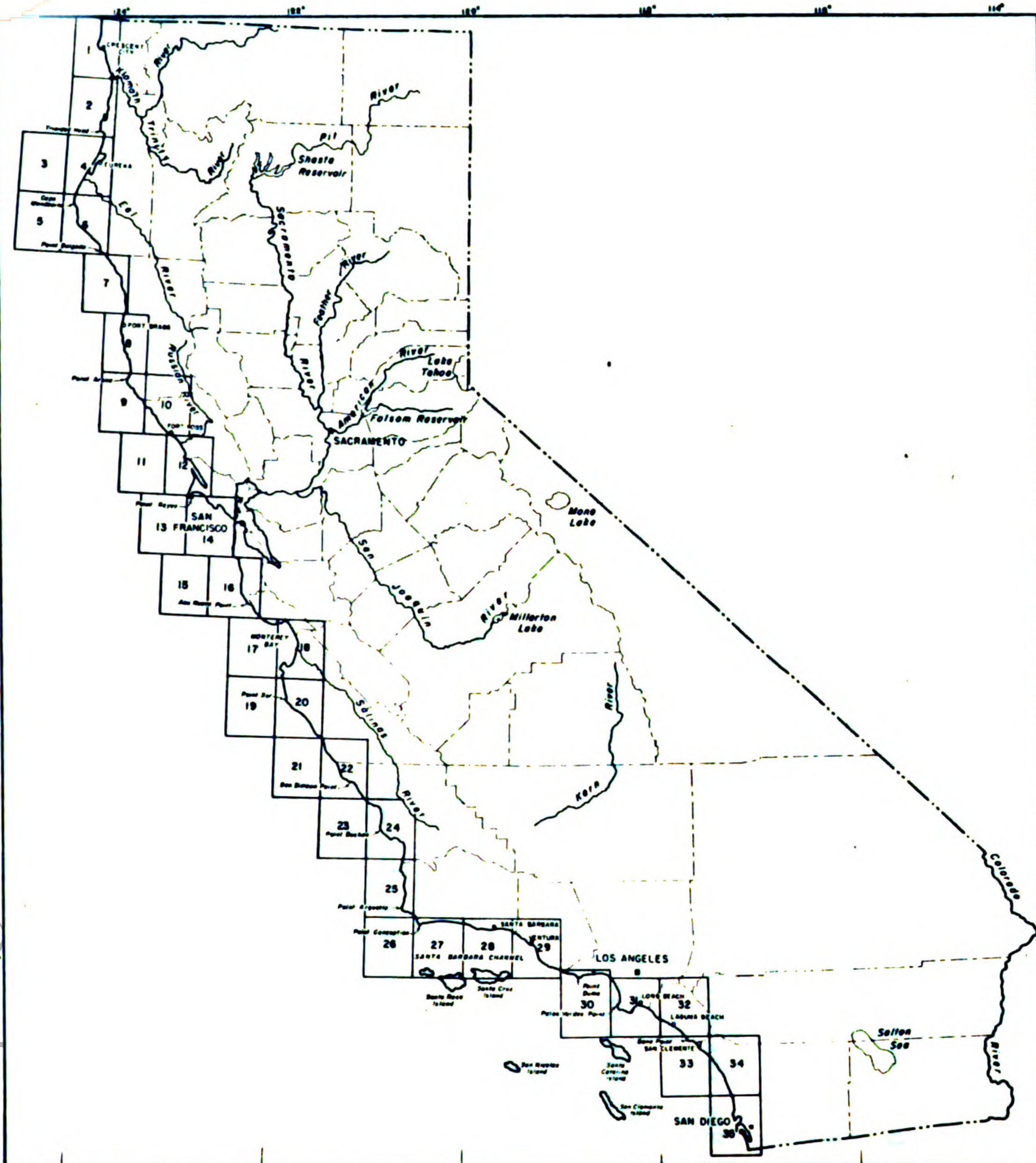
[a] Official U.S. Navy Photograph

DRAWING



NOTES: See the following maps and explanation sheets which have been prepared for this study at a scale of 1:125,000.

1. Base maps, 35 sheets, Drawing Numbers 1211-208-3 through 1211-208-37.

2. Surficial Bottom Materials overlay maps, 31 sheets, Drawing Numbers 1211-208-38 through 1211-208-68, and Explanation, Drawing Number 1211-208-231.

3. Thickness of Unconsolidated Sediments overlay maps, 31 sheets, Drawing Numbers 1211-208-114 through 1211-208-144, and Explanation, Drawing Number 1211-208-113.

4. Bedrock Geology, Earthquake Epicenters and Faults overlay maps, 35 sheets, Drawing Numbers 1211-208-162 through 1211-208-196 and Explanation, Drawing Number 1211-208-161.

5. Seismic Reflection Track Line overlay maps, 32 sheets, Drawing Numbers 1211-208-198 through 1211-208-229, and Explanation, Drawing Number 1211-208-197.

6. Detailed Canyon Survey maps, 27 sheets, Drawing Numbers 1211-D-3 through 1211-D-29 and Explanation, 2 sheets, Drawing Numbers 1211-D-1 and 1211-D-2.

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
CALIFORNIA UNDERSEA AQUEDUCT
Reconnaissance Investigation
OCEANOGRAPHIC STUDY PROGRAM
MARINE GEOLOGY STUDY

GENERAL LOCATION MAP AND INDEX TO SHEETS

DRAWN........ SUBMITTED Charles L. Howard
TRACED........ RECOMMENDED........
CHECKED C.H. .... APPROVED R. E. [illegible]
SACRAMENTO, CALIFORNIA JUNE 1973 1211-208-334

PART B--OCEANOGRAPHY

CHAPTER III. ROUTE MAPPING AND BATHYMETRY

ROUTE MAPPING

At the outset of the study a search was made for a suitable base map on which to display data necessary for route selection. Nautical charts at various scales were available from the U.S. Coast and Geodetic Survey. The California Division of Mines and Geology furnished a series of maps with bathymetry to a usable depth covering the entire California coastline at a scale of approximately 1:125,000. These maps have a bathymetric contour interval of 10 fathoms (60 feet) out to the 200-fathom (1,200 foot) line. Each map sheet covers 30 minutes of longitude and latitude and is marked with the California State coordinate system. All pertinent data were placed on overlays for the 35 base sheets to provide flexibility in comparing the various parameters during route selection. To ensure registration, base sheets and all overlays were mounted on lucite boards with pegs at the four corners. A board, a set of punched base maps, and sufficient overlay material were furnished each agency for use in submitting the data required under its contract. An index to the base maps is provided in drawing 1211-208-334.

The overlays and the number of sheets involved were:

Base maps showing bathymetry	35
Legal boundaries	13
Shell fish	22
Kelp beds	9
Physical obstructions	15
Density of ocean water	22
Bottom currents	26
Tsunamis	28

Wave surge	23
Surficial bottom materials	31
Thickness of unconsolidated sediments	31
Bedrock geology, earthquake epicenters, and faults	35
Seismic reflection track lines	32

Base sheets and the completed overlays are available for review in the Bureau of Reclamation's Mid-Pacific Regional Office in Sacramento.

BATHYMETRY

The Continental Shelf was considered to be that portion of the continental margin with an inclination of less than 3 degrees, and which exists between the coastline and the continental slope. When there is no noticeable shelf break, the outer margin of the shelf is considered to occur at 100 fathoms (600 feet). The continental slope extends from the edge of the Continental Shelf and has an inclination of 3 degrees or greater. The area included in this study was inshore from the 100-fathom contour (600 feet) which in places was beyond the shelf break and on the continental slope.

In general, the California Continental Shelf is variable in width, inclination, and water depth at shelf break; it is indented by about two dozen major submarine canyons. The overall trend of the bathymetric contour lines roughly follows the trend of the coastline except in nearshore areas, 0 to 20 fathoms, where the contours can become very irregular due to the prevalent rocky coastline; or near submarine canyons where the contours follow the edge of the canyons. The submarine canyons usually trend normal to the shelf contours. Three specific areas of irregular rocky bottom are:

1. The Point St. George Reef, offshore of Point St. George, north of Crescent City where the rocky bottom extends seaward more than 7 miles from shoreline;

2. Offshore of Point Delgada, the rocky area known as the Tolo Bank extends southward approximately 8 miles and is centered about 5 miles offshore and has a maximum width of about 3 miles; and

3. The rocky area surrounding the Farallon Islands offshore of San Francisco.

Between the Oregon border and Cape Mendocino, the shelf width varies from 10 to 21 miles; from Cape Mendocino to Point Conception, the width is generally between 5 and 10 miles with a maximum of 15 miles and a minimum of 0.8 miles; from Point Conception to San Clemente, the width is generally between 3 and 10 miles, with a maximum width of 14.7 miles and a minimum of 1 mile. The shelf width is approximately 1 mile in several areas south of Monterey and south of Palos Verdes Point, and widest off of San Francisco where it ranges between 17.6 and 30 miles. At the heads of some submarine canyons the outer edge of the shelf approaches within .05 to 0.5 mile of shore. Shelf break occurs anywhere from 60 to 600 feet of water depth, not including areas in the vicinity of submarine canyons.

In macrorelief the Continental Shelf as described is essentially flat, with slopes of less than 3 degrees. However, it should not be construed that the shelf is everywhere as "smooth" or flat as it appears in macrorelief. The microrelief of the shelf in many areas--nearshore or at depth--may have irregular features due to rock outcrops, gravel and cobble deposits, and former wave-cut benches. These features are not recognizable at the scale of the present studies.

In general the bathymetry of the Continental Shelf should not create undue design problems, excluding areas where submarine canyons indent the shelf. Generally the shelf is extremely flat with inclinations of less than 1 to 3 degrees. Shelf areas which should receive greatest attention are those in which the shelf break is near the Aqueduct route and where the continental slope is greater than 5 degrees. Aqueduct routes near shelf break could be subject to failures due to creep or slumping of the foundation materials. In many areas the 50-fathom contour is located at shelf break or beyond on the continental slope. Localized features such as irregular bathymetry due to rock outcrops, gravel deposits, former wave-cut benches, and small gullies will be encountered on the shelf which would slow construction activities. These features are not recognizable at the map scale used for the present study but could be delineated with continuous high resolution seismic profiling in conjunction with side scan sonar along a selected route.

CHAPTER IV. HYDRODYNAMICS

PURPOSE AND SCOPE

The Hydrodynamics Study was made to determine physical properties, ocean variables, and relationships that would need to be considered in the preparation of designs and estimates for the offshore system.

The hydrodynamic investigations were conducted in three phases:

1. Acquisition of archival data,
2. Data analysis, and
3. Hydrodynamic loading and scour studies.

In Phase 1, available literature and data sources were reviewed. Government and private institutions were contacted to fill in as many gaps in the data as possible. The data obtained were compiled in Phase 2 into forms that defined areas of high risk due to hydrodynamic forces. Variable magnitudes in terms of construction and maintenance requirements and extreme values or century risks were determined. Whenever possible the data were presented in statistical form for determination of probabilistic loadings on the Aqueduct. Phase 3 summarized available references, loading and scour data, and equations to aid in design and in making cost estimates.

The studies were geographically limited to the region bounded in latitude from Crescent City to San Diego and the water column between the 20- and 200-meter bathymetry contour lines.

Hydrodynamics

All the hydrodynamic studies considered importance of physical factors and their effects upon buried conduit, partially buried or conduit resting on seabed bottom, and conduit tethered to bottom supported by the denser ocean water. Table 1, compiled by Bureau and contractor personnel, summarizes these physical factors. All hydrodynamic data and studies were fed into the "Statistical and Probabilistic Loadings Study"[1] for further evaluation before use by the analytical design study task force team which prepared the appraisal design and estimate for the offshore system, Appendix I.

DATA SEARCH

A contract was completed with the Naval Undersea Research and Development Center (NUC) for the acquisition and analysis of archival data concerned with waves, currents, and water properties.

The NUC contractors visited and studied the archives of about 70 institutions where data relevant to the Undersea Aqueduct might be available. During the course of the data search, about 115 persons who have had experience in pertinent technology were contacted. These institutions and individuals were listed by Riffenburgh[2] and in Appendix III of this report.

In general, data were scarce, and were not random with respect to time or location. Most research work has been deep-sea oriented with little work on the shelf. Data occur in concentrated areas near institutes which teach oceanography. Between these areas of

1 Refer to reference listings at end of chapter.

Table 1. Hydrodynamic factors affecting the California Undersea Aqueduct[a] in place and during construction

Factor	Influence and source of variable
	IN PLACE
Density (high and low)	Controls buoyancy of pipeline, which influences vertical stress or movement (sinking, floating), affecting mooring. Density depends upon temperature and salinity.
Bottom surge	Horizontal oscillation of water over the sea floor causes horizontal stress or movement, plus lift. Surge depends on surface wave height and length which result from storm winds, and on bottom depth.
Bottom current	Horizontal continuous waterflow over the sea floor causes horizontal stress or movement, plus lift. Current depends on permanent current component, tides, and wind of long fetch and duration.
Tsunami surge	Occasional horizontal shock by waterflow over the sea floor causes horizontal stress or movement, plus lift. The solitary tsunami surge depends on the height of a seismic sea wave and the depth and slope of the sea floor.
	DURING CONSTRUCTION
Density (surface, 50 meter, 100 meter depth)	Controls buoyancy, affecting sinking, manipulation, installation, and repairing of pipe sections.
Waves on surface	Influences station-keeping and stability of platforms used in construction and maintenance operations. Wind caused.
Bottom surge	Oscillating flow affecting manipulation, installation, and repair of pipe sections, i.e., drag and lift. Surge depends on surface wave height and length resulting from storm winds, and on bottom depth.
Surface currents	Continuous surface waterflow affects station-keeping and sinking control of pipe sections. Current depends on permanent current component, tides, and wind of long fetch and duration.
Bottom currents	Continuous bottom waterflow affects manipulation, installation, and repairing of pipe sections by creating lift and drag.
Light transmittance	Incident daylight drops below the human threshold at 50 m. Transmittance shows the capability of the water to be artificially illuminated. At 50 m. and below nightwork will be as efficient as daywork.

[a] Table abstracted from reference 2.

concentrated data are large reaches of the California coast, especially along the northern part, where there are no data. Most of the data were obtained from near the water surface rather than near the ocean bottom which is the greater concern to this study. No measured velocity data for tsunamis or great storm surges were found. Also, the locations of extreme bottom currents were not available. Surface current data were averaged over rather large areas. Therefore, these meager current data were augmented by mathematical models, Airy wave theory, and solitary wave theory.

DATA ANALYSES

The results of the data analyses were summarized in the CUARO report by Riffenburgh[2]. The CUARO report discusses the 100-year extremes likely to occur in water density (both high and low), wind wave bottom surge, tsunami bottom surge, and to some extent bottom currents. The report also discusses and calculates the probabilities of coincidences of survival threats to the Aqueduct.

The century extremes (those which are likely to be observed at least once during a century) which have been tabulated in Appendix III and in the CUARO report are:

1. Lowest and highest extreme values of seawater density for 11 localities.

2. Greatest extreme bottom wave orbit surge velocity for eight localities.

3. Greatest extreme wave periods, lengths, and heights for eight localities.

4. Greatest extreme bottom current along the California coast.

5. A sample of horizontal water velocity due to an extreme tsunami as predicted by solitary wave theory for six depths at 10 latitudes.

The century risks for bottom currents, bottom surge due to surface waves, bottom surge due to tsunami, and water density were presented on overlay maps in three ranges of shading representing logical breakdown of the magnitude. The data appear on 140 maps covering 35 regions along the California coast. A set of Mylar copies of the overlays is available in Reclamation files.

Construction and maintenance variables, their averages, and deviations from the averages for density, surface wind waves and bottom surge, surface and bottom currents, and light transmittance are discussed in the CUARO report. Data are given for surface waves in the form of tables of averages and standard deviations of periods, lengths, and amplitudes for surface waves off the California coast for winter and summer at various latitudes for the 20-, 50-, 100-, and 200-meter bathymetry contours. Other construction variables are presented in graphical form on maps showing averages, standard deviations, data location, and sample size for:

1. Density at 0-, 50-, and 200-meter depth for both winter and summer

2. Surface wave amplitudes for both winter and summer.

3. Bottom wave orbit surge velocity for both winter and summer.

4. Surface current velocity for both winter and summer.

5. Bottom current velocity.

6. Light transmittance capability for both winter and summer.

All compilations of data and construction variable maps from the CUARO report have been included in Appendix III of this report.

DESIGN DATA REFERENCE BOOK

A hydrodynamic loading and scour task force team compiled a design data reference book[3] for the use of the analytical design task force team. This book consists of 206 pages, 90 figures, 6 tables, and cites 220 references applicable to the Aqueduct. This work is best summarized by briefly describing specific sections that follow its introductory material.

Fluid properties: The effects of temperature, pressure, and salinity on density and viscosity and of concentrated sediment on fluid density.

Buoyant force: The forces due to buoyant uplift for the various pipeline concepts.

Friction headloss and force on conduit: Friction factors and headloss for the conduit and power requirements to maintain flow in conduit.

Losses and fluid forces on conduit due to bends: Use of bend loss and bend force equations for appraisal design.

Hydrodynamic forces on conduit: Application of drag, lift, and inertia coefficients for both steady and oscillatory flow around cylinder.

Hydrodynamics

Water movement caused by waves and their effect upon the conduit: Orbit velocities and accelerations around the conduit near the ocean bottom that are produced by surface storm waves determined by Airy wave theory.

Scour: Critical velocity and tractive force criteria for both noncohesive and cohesive soils, and local scour.

Considerable portions of the first two sections and the last three sections have been incorporated into Appendix III.

FINDINGS

1. The hydrodynamic studies found data of sufficient quantity and quality for the appraisal study for the California Undersea Aqueduct. However, the expense and difficulty in obtaining these data indicate the need for an Ocean Engineering Data Center. This center could evaluate and assimilate data into useful forms for rapid access by military, Government, and private institutions.

2. Currents pose the greatest threat to the Aqueduct. Current data are virtually nonexistent. Bottom currents are the result of many phenomena such as tides, upwelling, internal waves, and wave orbit surges. Thus, they are subject to intense local variations.

3. There is very little documentation of scour experience around ocean structures in deep water. In regions of fine sediments, construction, and maintenance operation will have to be performed carefully so as not to cloud the water by disturbing the sediments. Nondisturbing construction techniques may need to be developed.

4. Proximity to shore greatly increases risk due to wave orbit surge, tsunami, and unstable water density. At locations near the shore, the Aqueduct should be buried to help prevent damage from these three variables. A 200-meter contour depth near shore does not offer protection against tsunami damage.

5. As would normally be expected, summer will be the best season for construction and routine maintenance.

6. Phenomena associated with undersea canyons are not thoroughly understood. Rims of canyons should be avoided because of high velocity, and canyon bottoms should also be avoided because of turbidity currents and other channelized velocity currents.

7. At depths of 50 meters or greater, artificial lighting will be needed for construction and maintenance during day as well as at night. Thus, undersea nightwork will be just as efficient as daywork.

8. Bottom currents and canyon phenomena need to be measured and studied prior to any further advanced planning stages where decisions will have to be made as to burying, bridging, or coming onto shore.

9. Wave orbit velocity data should be obtained on the ocean bed at depths of from 20 to 200 meters. Two independent investigators for the hydrodynamic studies came to the conclusion that the Airy theory is simplest to use and agrees with more complicated theories when applied to near the ocean bed. Thus, Airy theory was considered adequate for appraisal study.

10. Modeling technology needs to be improved or checked by means of onsite testing and data acquisition to confirm application of small models to very large conduits.

RESEARCH AND DATA NEEDS

Much further research and advance of technology are required for more precise cost estimates suitable for planning beyond the appraisal stage. Also, gaps in oceanographic data in the areas of waves, lift and drag forces, scour, marine fouling, and bottom currents, need to be filled. These research and data needs are discussed more thoroughly in Appendix III and may be useful to students, universities, and others who may be looking for, preparing, or evaluating possible research projects.

REFERENCES

[1] California Undersea Aqueduct Reconnaissance: Data Evaluation (CUARDE), Part II, Oceanography, R. H. Riffenburgh, Marine Environment Division, Undersea Surveillance and Ocean Science Department, NUC, San Diego, California, February 1973. Prepared under contract to USBR.

[2] California Undersea Aqueduct Reconnaissance: The Oceanography (CUARO), NUC TP 353, R. H. Riffenburgh, Marine Environment Division, Undersea Surveillance and Ocean Science Department, NUC, San Diego, California, August 1973. Prepared under contract to USBR.

[3] California Undersea Aqueduct, Hydrodynamic loading and scour, Design Data and Reference Book, USBR, December 1972, Unpublished. Draft on file at the USBR, Engineering and Research Center, Denver, Colorado.

CHAPTER V. MARINE GEOLOGY

PURPOSE AND SCOPE

The marine geology study was made to determine the bathymetric and geologic conditions on the Continental Shelf off California which affect the design and cost estimates for construction, operation, and maintenance of the proposed Aqueduct.

It is based on available data from various sources; no original fieldwork was performed by the Bureau of Reclamation. The data-gathering phase of this study was combined with the data-gathering phase of the marine soils study. During the data-gathering phase, contact was made by mail, phone, and personal visits with a large number of Government, education, and industrial organizations.

In addition, a literature search was performed and a bibliography of selected geological references was compiled. For details on sources of data, the reader is referred to the Marine Geology Study, Appendix II, Supplement A, Parts 1 and 3.

The quantity of geologic data available varied for different portions of the Continental Shelf and the data were widely scattered among various organizations. The most extensively studied portion of the Continental Shelf is from Point Conception to the Mexican border. The remainder of the shelf has been studied to a lesser degree with emphasis on the San Francisco-Monterey coastal area.

Marine Geology

The marine geology data were compiled on four sets of transparent plastic overlay maps at a scale of 1:125,000, approximately 1 inch equals 2 miles. The base maps used with these overlays--35 sheets covering the entire California coast--were described in Chapter III.

The overlays showed surficial bottom materials, thickness of unconsolidated sediments, bedrock geology, earthquake epicenters and faults, and seismic reflection track lines.

In addition to the overlays, 27 detailed canyon survey maps were prepared and an Earthquake Epicenter Listing, tabulated according to increasing latitude, was compiled for a 100-mile-wide strip centered on the coastline and covering the entire length of California. The listing is unpublished but available in the Mid-Pacific Regional Office.

ONSHORE GEOLOGY

General

The coastal area of California crosses three geologic provinces: the Coast Ranges province from the Oregon border to the Santa Ynez River; the Transverse Ranges province from the Santa Ynez River to the Los Angeles coastal basin; and the Peninsular Ranges province extending from the Los Angeles Basin to the Mexican border. The geology of these provinces reflects the complex plate tectonic, sedimentary, and igneous processes which are associated with the circum-Pacific orogenic belt that borders the Pacific Ocean along the continental margins of the Americas and Asia. Detailed onshore geology will be found in Appendix II.

OFFSHORE GEOLOGY

General Pre-Quaternary Geology

Oregon border to Point Conception. The shelf geology from the Oregon border to Point Conception reflects the northwest structural trend of folding and faulting of the adjacent Coast Ranges. The major east-west trending, active Mendocino fault zone lies offshore of Cape Mendocino. The post-Cretaceous, historically active San Andreas fault zone lies offshore between Point Arena and Point Delgada; north of Point Delgada, it continues offshore parallel to the coast, bending westward near the submarine Mattolle Canyon and into the Mendocino fault zone. The San Andreas fault zone is a short distance offshore at the mouth of the Russian River and for about 20 miles between Bolinas Bay and the shoreline southwest of San Francisco.

Santa Barbara Channel. The Santa Barbara Channel, east of Point Conception to the western boundary of the Los Angeles Basin, is within the western part of the Transverse Ranges province and includes the seaward portion of the Ventura Basin. The geology exhibits an east-west trend of folding and faulting. The Santa Barbara Channel area is comprised of predominantly marine, Early Cretaceous through late Pleistocene sedimentary rocks, consisting primarily of sandstones, shales, siltstones, and conglomerate, with some volcanic (middle Miocene) rocks.

Los Angeles to Mexican border. The geology of the offshore area south of the Santa Barbara Channel to the Mexican border is similar to the Peninsular Ranges province. The structural trend is northwesterly with associated folding and faulting. The Continental Shelf rocks are primarily marine sedimentary sandstones and shales of Paleocene through the Holocene age and middle Miocene volcanics.

General Quaternary Geology

During the Quaternary period, the California Continental Shelf has undergone several periods of erosion and deposition. The causes were twofold: one, the orogeny which occurred throughout the Pliocene and ended in middle Pleistocene period; and second, the Pleistocene fluctuations in sea level caused by glacial advances and regressions. The last maximum glacial advance occurred during the late Wisconsin stage, 20,000 to 17,000 years ago, with a corresponding low stand of sea level of about -360 to -407 feet below the present sea level (Curray, undated reprint).[1] The sea level rose and transgressed the Continental Shelf to near its present level between 18,000 years and 3,000 to 5,000 years ago. For the last 3,000 to 5,000 years, sea level has been fluctuating above and below its present position. The last transgression eroded the Continental Shelf and is in evidence over most of the shelf as a late Pleistocene unconformity. Late Pleistocene to Holocene sediments have been deposited on the shelf in various thicknesses since the beginning of the last rising of sea level, and consist mostly of unconsolidated to consolidated sediments of sand, silts, clays, and gravels.

SPECIAL STUDIES

Surficial Bottom Materials

The surficial bottom materials of the Continental Shelf consist primarily of sands, silts, and clays, with local occurrences of gravels and shells. The depth to which a particular sediment type extends below sea floor is unknown.

There are two primary methods of origin of the recent surficial shelf sediments: sediments deposited during earlier environments which are not now in equilibrium with their present environment, called relict sediments; and sediments which are now being supplied from rivers or by erosion of the coastal borders, called detrital sediments. The coarse fraction of the detrital sediments stays near the coast and is carried parallel to the shoreline by wave and current action.

Much of the nearshore sands accumulate in the heads of the submarine canyons near the coastline. The sediments eventually lose equilibrium and move down the canyon as a slow "river of sand," or as a faster-moving turbidity current--the actual method and speed of movement (possibly 4 miles per hour) is debated by oceanographers. The fine sediments--e.g., silt and clay size particles--are carried seaward in suspension, being deposited farther out on the shelf. Curray (undated reprint)[1] terms the coarse fraction sediments the _nearshore facies_, and the silts and clays the _shelf facies_.

In general, the surficial sediments of the California shelf zone grade from coarse to fine with distance from shoreline, except in zones of coarse relict sediments, or areas where currents may have carried coarse detrital sediments farther offshore. The distance from shore and the depth of water at which the transition from nearshore facies to shelf facies occurs is variable but usually is found between 25 and 40 fathoms. Many nearshore areas are devoid of sediments, exposing bedrock. The rocky zone usually occurs nearshore in water depths between 0 and 10 fathoms, and locally between 0 and 20 fathoms, or at shelf break. The rivers which carry most of the detrital sediments to the shelf are the Klamath, Eel, Russian, Sacramento-San Joaquin (which flows into San Francisco Bay and out through the Golden Gate), Salinas, Santa Maria, Santa Ynez, Ventura, Santa Clara, and several stream channels entering San Pedro Bay.

Thickness of Unconsolidated Sediments

The thickness of the unconsolidated sediments is largely controlled by several factors:

1. The late Pleistocene shelf bathymetry which resulted from transgression of rising sea levels;

2. Sediment sources and quantity of sediments derived from rivers and coastal erosion;

3. Continental Shelf currents which cause sediment transport and prevent deposition, leaving late Pleistocene or older bedrock exposed; and

4. Sediment transport from the heads of submarine canyons.

The degree of unconsolidation of the sediments is believed to decrease with depth below the sea floor, with the upper 4 feet being loose and soft due to reworking by wave action, recent deposition, and mixing by various forms of sea life. The types of sediments are known only for the surficial portion of the shelf as the patterns of sediment deposition changed during sea level fluctuations.

It is difficult to present a meaningful general picture of the configuration of unconsolidated sediment thickness. Several areas in the north coast have a basin-type deposition pattern with thicker sediments in the central portions of the shelf and thinner sediments towards the shelf break and shoreward. These areas are: off the Klamath River, maximum 160 feet thick; off the Eel River, 140 feet thick; and south of Point Arena to Point Reyes where a maximum thickness of 500 feet is reached. In the south, similar basinal areas are found near Point Arguello and Santa Ynez River, 100-140 feet thick; and off Ventura, 360 feet thick. In the remaining areas on the shelf, the unconsolidated sediment thickness varies from zero feet (especially nearshore) to 400 feet or greater.

Bedrock Geology

The bedrock geology of the Continental Shelf, underlying the unconsolidated sediments, consists mostly of marine sedimentary rocks, with some occurrences of metamorphic, granitic, and volcanic rocks. The actual lithology and physical condition (weathering, jointing, hardness, and strength) of individual rock units are not known. Extrapolation and interpretation of onshore data to the shelf become less reliable with distance from shore or when major offsetting faults such as the San Andreas are crossed.

An analysis of alternative routes at 10, 20, 50, and 70 fathoms shows that at 50 fathoms bedrock should occur within 40 feet of the sea floor along at least 58 percent of any route and at 10 fathoms can occur along as much as 85 percent.

Faulting and Seismicity

The California coastal area and the Continental Shelf are located within the tectonically active circum-Pacific seismic belt. This tectonism is reflected in the many earthquakes which have been recorded historically, or in recent times, by seismic instrumentation.

At least 13 quakes of estimated Richter magnitude 6 or greater have occurred in California in the period from 1812-1906; the four largest were as follows: 1812, near San Juan Capistrano and Santa Barbara Channel, magnitude 7-8; 1857, Fort Tejon, magnitude 8, caused damage in the Santa Barbara area; 1872, Owens Valley, magnitude 8.3+ (probably the greatest California earthquake); and 1906, San Francisco, magnitude 8.25, with over 270 miles of surface faulting. From 1906 through 1931, fourteen large magnitude quakes, varying from magnitude 6.0 to 7.3, have occurred in California, of which seven were located offshore. From 1932 to 1971, within 50 miles of the California coastline, 109 quakes of magnitude 5 or greater have occurred; 28 of them were located in the offshore area. The San Fernando earthquake of February 9, 1971, magnitude 6.4, caused extensive damage and crustal movement. It is the most recent large quake of record and was located onshore approximately 25 miles from the Santa Monica Bay coastline.

Faulting. The California coastal area has several historically active faults with the San Andreas fault zone, which has been the locus of major earthquakes, the most well known. The fault which extends onshore for much of the length of California is mostly offshore north of San Francisco. It exhibits historic crustal rupture for most of its observed length. Other historically active faults are the Seal Cove-San Gregorio, Carmel Canyon, Sur-Nacimiento, Murray, Newport-Inglewood, and Elsinore fault zones.

Many other faults which have evidence of Quaternary movement are located throughout the length of the study area, some of which--depending on route--would be crossed by the Aqueduct. These faults should be considered potential sources of seismic activity.

Seismicity. The area between the Oregon border and Trinidad Head is in a region of low to moderate seismicity. The largest earthquake of record in this area was magnitude 7.3 located west of the Continental Shelf.

Between Trinidad Head and Cape Mendocino is an area of high seismic activity. Numerous low magnitude earthquakes occurred in the area as have several major offshore quakes with magnitude 6.0 through 7.2.

From Point Delgada to the Russian River, the seismic history is unimpressive with only one moderate quake of magnitude 5.2, which occurred inland. It should be noted, however, that this area of the coast was strongly shaken and offsets occurred along the San Andreas fault during the 1906 San Francisco earthquake.

The region from San Francisco-Point Reyes south to Monterey Bay is one of moderate to high seismic activity. Numerous seismic events have occurred in the area with the largest of record being magnitude 8.3 in the 1906 San Francisco earthquake. Most of the moderate quakes of magnitude 5 to 6 have been located inland, except for an October 22, 1926, earthquake of magnitude 6.1 located in Monterey Bay.

The area south of Monterey Bay to Point Conception has had locally moderate to high seismic activity, but very few large magnitude quakes have occurred in the offshore area. The two largest earthquakes of record are a magnitude 7.7 located far inland on the White Wolf fault and a magnitude 7.3 quake, located offshore in the vicinity of the Murray fracture zone.

The Santa Barbara Channel area to the Los Angeles-Long Beach area is one of high seismic activity; numerous epicenters of magnitude 2 to 4 earthquakes have been recorded in the area. The largest recorded seismic events near the coast for this area were in the magnitude 6.0-6.8 range.

South of Newport Beach to Mexico, seismic activity has been generally low with only two magnitude 5 quakes having occurred during the period of record. The largest earthquake of record near this region was the 1915 magnitude 7.1 quake which was located in Mexico.

Detailed Canyon Survey

There are about two dozen canyon and sea valleys which incise the Continental Shelf. Some would be natural barriers requiring some form of aqueduct crossing or detour. The number of potential crossings is dependent on aqueduct route and varies as follows: 8 crossings on the 10-fathom route; 10 crossings on the 20-fathom route; 27 crossings on the 50-fathom route; and 35 crossings on the 70-fathom route. These crossings would range from 0.3 to about 7 miles long normal to the canyon axis, and have 60 to 1,980 feet of relief between the canyon rim and floor.

The submarine canyons which head nearshore can have considerable sediment buildup of sands and gravels at their heads. These sediments are moved down the coast by coastal currents and into the heads of the canyons where they accumulate until equilibrium is lost, and by some mode then flow down the canyons, by turbidity currents or slow creep.

The strength of the walls and edge of the submarine canyons is dependent on the bedrock geology, and individual physical characteristics such as jointing and fracturing. At present there are little data showing slumping or raveling of the canyon walls except in the Monterey Canyon where slides and slumps have been mapped. It is assumed, however, that the above conditions exist to some degree in all submarine canyons.

It should be noted that the Monterey submarine canyon is, in vertical dimensions, perhaps one of the world's largest canyons, either onshore or offshore (Shepard, 1963)[2], with a relief of over 1 mile at the 100-fathom contour.

FINDINGS

The following, in order of importance, are the findings on geologic conditions which will affect the design and route of the California Undersea Aqueduct.

Faulting and Seismicity

The San Andreas fault is the most potentially damaging fault known along and near the Continental Shelf as a whole. Severe surface rupture and shaking can be expected. The fault would be crossed at least three times from Cape Mendocino to Point Arena and the Aqueduct would parallel it for the entire length of California.

The other historically active and Quaternary faults which are located on the Continental Shelf should be considered for design purposes as potential sources of seismic activity or locations for surface rupture.

The effect of earthquakes on the Aqueduct will depend upon the proximity, frequency of occurrence, magnitude of the earthquakes, and dynamic response of the foundation. The foundation can vary from exposed bedrock to thick, unconsolidated sediments. Review of the historic records indicates that it is probable that some portion of the offshore study area will be subjected to a large magnitude

(6-8+) earthquake with an epicenter located within 50 miles of, or on the Continental Shelf, during the lifetime of the Aqueduct. Allen and others (1965)[3] concluded that for the entire southern California region an average magnitude 6.1 earthquake should occur each year, and a magnitude 8.0 earthquake once in 52 years. Similar studies for the northern California region were not found.

Richter (1958)[4] noted that ships have been reportedly jarred by seaquakes in quiet seas, causing captains to believe they had run aground. The shaking is noted as lasting 10 to 60 seconds or more and, according to one report, caused one ship to list 4 to 5 degrees. Earthquake loading such as this could be a factor in a buoyant pipe design.

Submarine Canyons

The submarine canyons form natural barriers to any selected aqueduct route, with crossing lengths, depending on route, ranging from less than 1/2 mile to 7 miles. Relief varies from 60 to 1,980 feet between canyon rim and floor. Water currents and turbidity currents in the canyon and at the canyon head make the area undesirable for a pipe crossing unless the pipe is buried in rock. If a canyon is bridged, the footings should be founded in rock. Footings on the canyon walls should be located well above possible disturbance by turbidity flows. In addition, the potential for landslides and slumps from the canyon walls exists in each submarine canyon, and would require further study.

Marine Geology

Thickness of Unconsolidated Sediments and Bedrock Geology

The desirable and undesirable foundation characteristics of the unconsolidated sediments and bedrock geology vary as to route and type of pipe concept selected for design.

In general the thickest unconsolidated sediments lie between the 20- and 50-fathom contours, and are up to 500 feet thick in some areas. Nondepositional areas and areas of less than 20 feet of unconsolidated sediments are found nearshore (0-10+ fathoms) or in deeper water near shelf break (50+ and 100 fathoms).

The bedrock geology of the Continental Shelf underlying the unconsolidated sediments or exposed on the shelf, consists mostly of marine sedimentary rocks with some occurrences of metamorphic, granitic, and volcanic rocks. The marine sedimentary rocks consist mainly of sandstones, siltstones, shales, and minor conglomerates. The actual physical condition of the rocks is not known, but is considered to be similar to their onshore equivalent rock types. Bedrock should occur within 40 feet of the sea floor for at least 58 percent of any aqueduct route between 10 and 70 fathoms, and can be as high as 85 percent nearshore at 10 fathoms.

The overall effect of the thickness of unconsolidated sediments versus bedrock on alternative design concepts is discussed in the following sections; further discussion of the design concepts related to the foundation is given in Soils Engineering, Appendix IV. All design concepts will be affected by seismicity, faulting, and submarine canyons.

Buried pipe concept. In order to avoid as much rock excavation as possible, the buried pipe concept is most feasible in easily excavated, unconsolidated sediments of 40-foot thickness or greater. Unconsolidated sediments of this thickness are found mostly between the 20- and 50-fathom contours, and could occur for approximately 30 to 40 percent of any selected route between those contours. The remaining 60 to 70 percent of the route would encounter variable thicknesses of rock in the upper 40 feet of the Continental Shelf.

The pipe should be buried to a depth sufficient to avoid the loose, soft, 1 to 4 feet of upper surficial materials containing plentiful animal life. In addition, the route of the pipe should not be near the edge of the steeper inclined slopes of the continental slope at shelf break, or the edges or heads of submarine canyons in order to avoid potential slides or slumps, creep, and turbidity currents.

Buoyant pipe concept. Due to potential hydrodynamic problems, such as wave action and tsunamis (discussed in Appendix III, Hydrodynamics), the buoyant pipe concept appears most feasible in water depths near 300 feet (50 fathoms). Securing the pipe would require anchors emplaced in rock or thick unconsolidated sediments to a depth sufficient to resist uplift. The physical condition and strength of the marine sedimentary rocks on the shelf are unknown and no estimate of the uplift holding capacity of the various rock types was attempted. Discussion of the uplift holding capacity for anchors set in unconsolidated sediments is given in Appendix IV, Soils Engineering.

It should be noted that this concept would be advantageous when crossing potentially active faults such as the San Andreas fault in northern California. Also, it would eliminate construction difficulties that could occur during construction from irregularities in the shelf bathymetry.

<u>Partially buried pipe</u>. Partially buried pipe appears most feasible in deeper water due to possible hydrodynamic considerations not discussed in this report. The pipe foundation would predominantly be in or on unconsolidated materials, for not less than 50 to 65 percent of any route between 20 and 70 fathoms. The upper 1 to 4+ feet of unconsolidated materials on the shelf are active due to wave action, animal activity, and continuing deposition. Parts of this zone are susceptible to liquefaction, settlement, creep, and sliding. The remaining thickness of unconsolidated sediments is believed to become firmer with depth. As in the buried pipe concept, the route selection should avoid the steeper inclination of the continental slope at shelf break, and heads of the submarine canyon.

Surficial Bottom Materials

In general the surficial sediments of the California shelf zone grade from coarse to fine with increasing distances from shoreline. The transition from nearshore facies (coarser sandy sediments) to shelf facies (finer sediments of clay and silt) occurs primarily between water depths of 25 to 40 fathoms. The engineering properties and problems which may occur with the surficial sediments are described in the chapter on Marine Soils.

FURTHER STUDIES

The data presented in Appendix II, Geology, along with the overlay maps are sufficient for the present investigation. If further studies are deemed necessary for a higher grade investigation, the following initial steps are recommended:

1. Review all geologic data presented in this study for gaps in data pertaining to a given aqueduct route or routes and design concepts used.

2. Review work done by others which postdates this study.

3. Based on item one, select areas for more detailed geologic investigations.

4. Perform field investigations in selected areas to determine the actual physical condition of the foundation sediment and bedrock types.

5. Run detailed high resolution profiles along the entire Aqueduct route, or portions of it, to delineate in detail unconsolidated sediment thickness and locations of faults.

6. If canyon crossings are used in the selected aqueduct design, study each crossing in detail.

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1 Curray, Joseph R. (Reprint undated), Late Quaternary History, Continental Shelves of the United States. (publisher not shown).

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3 Allen, C. R., et al (1965), Relationship between Seismicity and Geologic Structure in the Southern California Region. Bull. Seism. Soc. Amer., Vol. 55, p. 753-797.

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CHAPTER VI. MARINE SOILS

The marine soil studies were made to define the significant engineering properties of the Continental Shelf sediments which would affect the location, design, and construction of the Undersea Aqueduct. Where data were not available, soil parameters were estimated based on judgment and information derived from the literature search.

Foundations on the sea floor may fail by (1) overturning, (2) catastrophically sinking into the sediments, (3) sliding laterally due to currents, or downslope due to gravitational forces, and (4) tilting or excessive differential settlement. Design techniques must investigate and prevent these modes of failure.

DATA AVAILABILITY

During the literature search, records of numerous surficial sediment samples were found. These samples, however, represented less than 50 percent of the California coastline. The majority of these available data were concentrated in the Santa Barbara Channel, Monterey Bay, and San Francisco areas. The relatively undisturbed core samples were predominantly of cohesive soils; when sampling under water, clean sand samples were usually lost during the extraction process. Sampling data on Continental Shelf sediments at depth were available only at oil company platforms in the Santa Barbara Channel and at the proposed Bolsa Island site near Los Angeles.

Marine Soils

Extensive foundation investigations were performed by the Naval Civil Engineering Laboratories at depths of 100 and 600 feet in the Santa Barbara Channel. These data consisted of undisturbed push-tube sampling of the ocean floor to a depth of 10 feet, and detailed in-situ and laboratory settlement and strength tests.

Since sediment data at depth are so scarce on the Continental Shelf, sediments at depth were assumed to be the same as surficial ocean floor sediments. Grain size is a function of the distance from shore. The shelf sediments consist of clean sands and bedrock near the shore and surf zone. The ocean floor sediments are finer grained below the deeper shelf waters.

At water depth of 60 feet, a rock bottom and fine sand predominate, while at depth of 300 feet, mud and sandy mud are predominant. If sediment thickness is taken into consideration, the percentage of rock could be even higher because the grab sampling method of investigation tends to pick up soil even when an area is covered by a few inches of sand. Soil classifications changed in short subreaches in the shallower waters, while for larger areas in deeper waters the surficial soils were more uniform.

ENGINEERING PROPERTIES

Data on engineering properties of soils, settlement, shear strength, excavation, and liquefaction on the Continental Shelf are limited to the Santa Barbara Channel, Bolsa Island, and San Francisco Bay areas. Where data were not available, soil parameters were estimated based on judgment and information obtained from the literature search.

Sediments on the Continental Shelf are derived from streams, wind, sea cliff erosion, and organic remains. Much of this sediment is transported seaward on the ocean floor in the form of turbidity currents.

Settlement

Available data from the Santa Barbara Channel area indicate that both sandy and silty sediments are normally loaded, with in situ density and shearing strength increasing with depth.

Gradation data were available for about 50 percent of the coastline deposits. Medium and fine sands are distributed along the coastal area to depths near 60 feet, while very fine sand predominates in deeper portions to 180 feet. Coarse silt is widely distributed in the deeper waters.

At the Bolsa Island site near Los Angeles, loose, silty fine sand was encountered in the top 2 to 4 feet. Looseness was attributed to the effects of ocean currents, plant life, and wave action. Sediments at the site were dense, and silty sands increased in firmness and density with depth. If all nearshore fine sands are similar, there should be no significant settlement problem during and after Aqueduct construction.

Settlement-time curves for the 4- and 6-foot-diameter ocean floor platforms located on Santa Barbara Channel silt show that under 118 and 150 pounds per square foot loads, they settled 1.6 inches in 8 days and 6 inches in about a year's time. The slope of the curves indicates movements will continue for several years and probably exceed a foot. Naval Civil Engineering Laboratories has reported problems with footings tipping and sliding when placed on loose soils at mud line.

It also appears that long-term emplacements on the ocean floor have been undercut because of scouring or undermining by organisms feeding on the ocean floor sediments.

In the Bolsa Island area, settlement data of nearshore sand indicate that footings placed 5 feet below ground surface were satisfactory for design loadings of 6,000 to 8,000 pounds per square foot. These data indicate ocean floor sand is a much more competent foundation material than the finer grained silts. Case histories on ocean floor structures confirm this.

Shearing Strength

In the Santa Barbara Channel area, available data indicate that the silty sediments at depth are loaded normally and are stronger than the San Francisco Bay and Gulf of Mexico sediments. Near Pitas Point and the Sea Con test sites, shearing strength of Santa Barbara Channel silt is quite poor. Shearing strengths are less than 1.0 pound per square inch or 144 pounds per square foot in the upper 1 to 3 feet of sediment; therefore, to prevent bearing capacity failures, structures placed at mud line must be designed for low loads. Pile foundations will also be necessary if heavy structures such as access chambers are to be constructed along the pipeline. Data indicate that shearing strength of nearshore fine sands, at depth, in the Bolsa Island area is quite high.

Liquefaction

From the available data, it appears a large portion of the ocean floor sediments may be susceptible to liquefaction. Soils that liquefy usually possess a median grain diameter between 0.3 and 0.02 millimeter, have a relative density less than 75 percent and an effective overburden less than 2 kilograms per square centimeter (28 pounds per square inch). The fine sands, silty sands, and silts if not moderately compacted are susceptible to liquefaction. Data indicate the upper few feet of the ocean floor sediments are in a loose condition, and therefore, more vulnerable to liquefaction. At the Bolsa Island site, however, the nearshore clean fine sands may be sufficiently dense in situ to reduce the liquefaction potential.

EXCAVATION

Excavation slopes may have to be quite flat if attempted in silty soils. In sandy soils excavation slopes should not exceed the angle of repose. Steeper construction side slopes are possible if temporary bulkheads are used during excavation.

FOUNDATION DESIGN CONSIDERATIONS

In selecting a pipeline route, to reduce slumping hazards, the flattest ocean floor areas where slopes are less than 5 degrees should be traversed whenever possible. The desirability of available material for pipeline foundations is ranked as follows: (1) rock, (2) coarse sand and gravel, (3) fine sand, (4) silty sand, (5) silt, and (6) clay.

Since the upper 2 to 4 feet of the ocean floor is loose material due to living organisms and wave action, footings should be placed to a greater depth. Considering the susceptibility of the sediments to liquefaction and scour, all embedment anchors should be in rock or at least 20 feet below the ocean floor.

The buoyant pipe concept would be feasible where the water depth is about 300 feet. Here, the finer grained silty sediments prevail. Anchors could be set in rock or sediments and the pipe installed above the mud line with little disturbance to the ocean floor environment. Deeply placed anchors are recommended to assure embedment in firmer materials and to reduce the liquefaction hazard at footings by increasing the overburden. From a foundation standpoint, the buoyant pipe concept would permit large differential movements in the foundation soils without causing distress to the Aqueduct. This concept would be highly desirable where the Aqueduct crosses fault zones.

The buried pipe concept would appear desirable for use in shallow water where sediments must be at least 40 to 50 feet deep.

Marine Soils

Rock excavation is very expensive which negates the use of this pipe concept in many shallow water areas. Burying the pipe would also reduce the scour hazard to the existing ocean floor surface. Because of the liquefaction and scour hazard, it would be desirable to bury the top of the pipe at least 10 feet below the ocean floor. Desirable subsoils for this pipe concept are clean gravels and sands.

Backfilling around the pipe could cause flotation problems. Care should be taken so that the weight of the pipe plus backfill is equivalent to the weight of the subsoils removed to insure minimal settlement during construction. Many oil companies do not backfill ocean-floor pipe trenches because sediments moving along the floor will drift into the trench and fill it. It might also be possible to use this method.

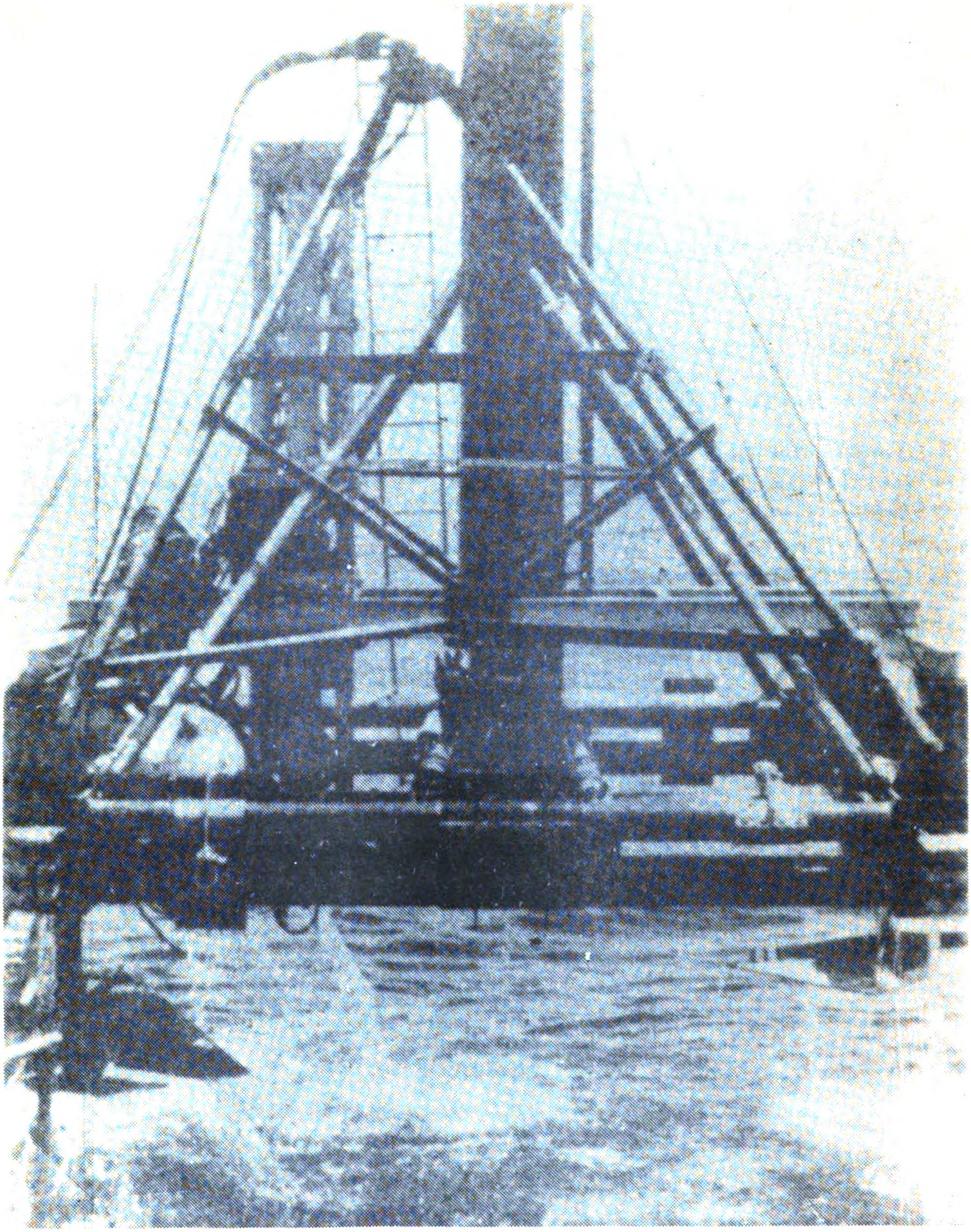
Resting the pipeline wholly or partially on the ocean floor would probably be the most economical method of laying it. If the pipeline rests on rock or clean sands and gravel, the settlement should be insignificant. Where excessively loose silts and sandy silts are traversed, preloading the subsoils to 125 percent of the design load should improve the foundation conditions. Because of wave action and animal organisms, the pipe invert should be about 8 feet below sea floor to assure adequate support capacity at the pipe bottom. If the pipe is constructed on sloping terrain, the pipe would be in the path of and obstruct all loose surface soils subject to liquefaction and would also cause significant scour. Studies relating to scour of surficial sediments are found in the Hydrodynamics section.

Marine Soils

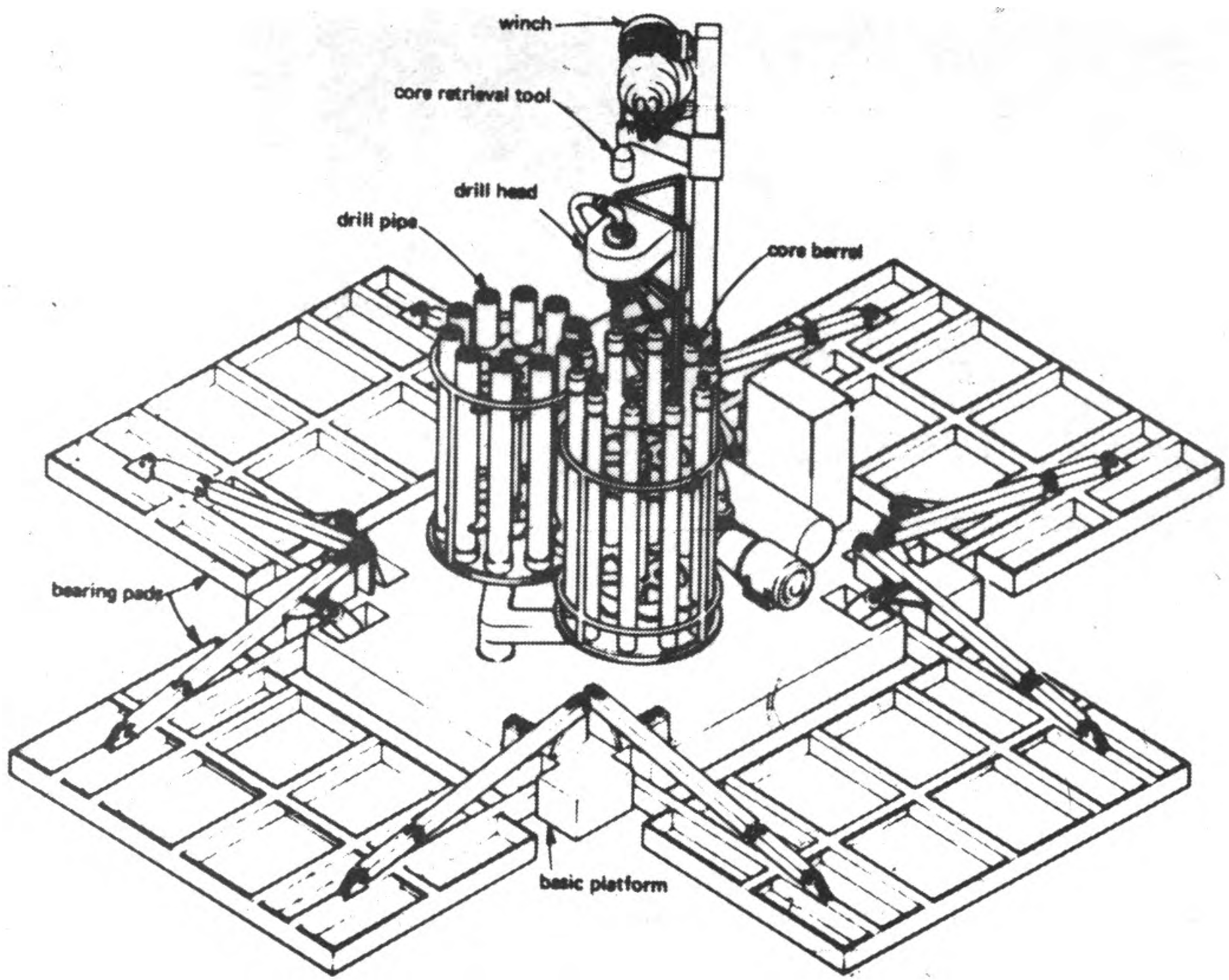
Whenever the Aqueduct passes through the surf zone, water depth 0 to 40 feet, it should be buried in the ocean floor rock formations to protect the pipe from wave action.

The submarine canyons, which in many cases reach fairly close to shore, intercept sands that travel along the beaches and tend to build up at the mouth of each canyon. During storms, wave action and currents may trigger slides which cause the sand to flow continuously through the canyons and out to sea.

Submarine canyons might be crossed by bridge or the pipe could be buried in the rock walls or on the bottom. Another possibility would be to bring the Aqueduct onshore to bypass the canyons.



Deep ocean test in place and observation system.



Assembly view of remotely controlled seafloor corer

CHAPTER VII. MATERIALS

PURPOSE AND SCOPE

Although information is available on behavior of materials in coastal and surface seawaters, data are scarce on performance of materials for construction of very large diameter pipe in deep waters as envisioned for the California Undersea Aqueduct. Information on materials embedded in the bottom sediments is almost nonexistent. A materials pilot program including laboratory and field exposures was developed to identify material suitable for construction of an undersea pipeline.

The Naval Civil Engineering Laboratories (CEL) conducted seawater screening tests on pipe materials and auxiliary pipe materials under contract. The contract also included a general marine fouling study which, because of time limitations, was never completed. Specimens were positioned at depths of 50 and 300 feet in such a way that the effects from exposure to seawater, contact with bottom sediments, as well as embedment in the sediment could be evaluated. In addition to the saltwater screening studies, a freshwater screening study was made by the Bureau's Denver Engineering and Research Center.

Critical strain tests were performed by the Naval Undersea Research and Development Center in San Diego, California. These tests determined the strain level at which candidate composite pipe materials of fiber-reinforced plastic would perform satisfactorily for long periods at an ocean depth of 50 feet.

Materials

The material pilot program originally scheduled to include a 24-month exposure period was curtailed to 12 months. The planned 2-year exposure testing would have been the minimum time expected to establish reliable trends in physical property changes.

A number of specimens are still available at the ocean sites for the evaluation and testing. A search has been made by the Bureau and the Navy in order to find a sponsor to conclude the program but none has been found. The freshwater creep tests on the fiber-reinforced plastic composite materials are continuing under another research program.

MATERIAL REQUIREMENTS

Based on available literature concerning design and construction in an ocean environment, characteristics for materials for an undersea aqueduct were determined. A high strength-to-weight ratio is needed to obtain maximum strength at minimum weight. The material must also be durable, resisting fracture, fatigue and creep, as well as corrosion, marine borers, and fouling. Because of the large quantity of material required, availability and cost were also considered.

Materials

SEAWATER EXPOSURE STUDIES

The 50-foot exposure site was located in the vicinity of Pitas Point, west of Ventura, California; the 300-foot site was located in the vicinity of San Diego, California.

Specimens from the 50-foot test site were retrieved after 54, 187, and 392 days of exposure. Only the concrete specimens were recovered at the 300-foot depth after 173 days of exposure.

The candidate pipe materials exposed were:

1. Portland cement concrete
2. Mild carbon steel with:
   a. Glass-fiber-mat reinforced coal-tar enamel coating
   b. Modified phenolic coating
3. Fiber-reinforced plastic composites of these resins:
   a. Polyester
   b. Epoxy
   c. Vinyl ester

Auxiliary materials exposed were:

1. Nuts, bolts, and washers made of these metals or alloys:
   a. Titanium
   b. Silicon bronze
   c. Nickel-copper alloy (Monel)
   d. Austinitic stainless steels (2 types, 304 and 316)
   e. Galvanized steel
2. Synthetic materials including:
   a. Polypropylene
   b. Polycarbonate
   c. Polyethylene
   d. Fluorocarbon
   e. Polyvinylchloride
   f. Acrylic
   g. Butyl
   h. Neoprene

Materials

Visual Inspection Results

In the evaluation of the specimens the first step following retrieval was visual inspection by a marine biologist. The types, number, and distribution of organisms on the test specimens were noted and recorded. The pipe and auxiliary materials were then removed from the test rack and inspected for visible signs of deterioration and damage.

After 54 days at the 50-foot exposure depth, all samples possessed a film of bacteria and diatoms. Relatively few species of resident macroscopic fouling organisms were observed.

After 187 days at 50 feet, the surfaces of all panels exposed to the seawater environment were covered with a 1/16-inch layer of encrustations. Small barnacles, 1/8-inch diameter, were found at all the sediment-seawater interfaces where the surface of the panels was otherwise clean. Some starfish found on the test panels were presumed to be feeding on the barnacles.

After 392 days of exposure at the 50-foot depth, the surfaces of all test panels exposed above the sediment in the seawater environment were covered with a layer of encrusting bryozoan. This growth could be mistaken for a layer of fine bottoms sediment; removal of the growth required scraping. The buried section of the test panels was free of barnacles and bryozoan growth. However, attached to the polyester resin panel were 6 wormtubes made of fine sand. The layer of glass-fiber mat on the coal-tar coated, steel panel buried in the sediment was intact, while some sections of the covering, exposed above the sediment layer, were torn. Hydrogen sulfide in the form of black mud was detected underneath the metal and plastic panels serving as spacers.

After 173 days of exposure at the 300-foot depth, the top of the concrete blocks contained about 25 tubeworms, but no other fouling organisms. The inside surface of the blocks was colored black from hydrogen sulfide produced by sulfate-reducing bacteria in the anaerobic environment. The concrete exposed to the bottom sediment was free of marine growths. The titanium band which held the concrete blocks together had some light growth of hydroids and several tubeworms. Spacer materials consisting of neoprene and butyl rubber, plexiglass, and polyethylene were free of marine growth even though they had been exposed to hydrogen sulfide.

Laboratory Test Results

After visual evaluations, the specimens were moved to the laboratory to determine the effect of exposure on their mechanical properties. There was no evidence of rusting on either system of coated steel panels during the 392-day exposure period at the 50-foot depth. Barnacles as well as other fouling organisms gradually attached to those portions of the painted panels above the mud which by the end of the 392-day exposure, were completely covered with fouling. Neither the fouling nor exposure at or below the mud line caused any deterioration of the phenolic coating system, thus providing essentially complete protection to the panel in all areas. The coal-tar enamel system, although providing complete protection to the panel, showed initial signs of fouling damage and erosion on the portion above the mud line.

After 54 days of exposure, several resin-starved areas were noted on the fiber-reinforced plastic test panels. These resin-starved areas were also noted after 187 and 392 days of exposure. Depressions were noted in the soft waxy surface of one side of the vinyl ester test panels. These depressions were found under the barnacles. Although the surface area of the depressions was observed to be proportional to exposure time, no increase in depth was noted. Table 2 shows the results of the mechanical tests performed on the test panels initially and after recovery from a 50-foot depth. The distribution of marine organisms on the fiber-reinforced plastic coated steel panels after 187 days at 50-foot depth is shown on table 3.

The mechanical properties of the concrete test specimens after recovery and after storage in 73°F. fog are given in table 4.

Visual inspection revealed no evidence of deterioration of the nonmetallic auxiliary materials. Evaluation of the metallic auxiliary materials showed no visible deterioration on the titanium sheet or fasteners. On the nickel-copper alloy fasteners incipient crevice corrosion was noted under some of the fastener heads and nuts after 392 days although no deterioration was observed after

Table 2. Mechanical properties, fiber-reinforced plastic composites (50-foot depth, ocean exposure and freshwater exposure)

Plastic resin	Position on panel[a]	Nominal exposure time (months)	Tensile strength (psi) Seawater	Tensile strength (psi) Freshwater	Compressive strength (psi) Seawater	Compressive strength (psi) Freshwater	Flexural strength (psi) Seawater	Flexural strength (psi) Freshwater	Shear strength Seawater (psi)
Epoxy	-	0	12,711	11,000	22,729	23,830	20,499	18,000	11,689
	Top	2	13,111	-	25,727	23,864	21,290	18,520	11,473
	"	6	13,177	14,470	19,760	24,810	25,765	20,560	11,662
	"	12	13,944	11,920	21,316	22,360	27,695	14,520	11,610
	Middle	2	13,396		26,816		14,745		11,964
	"	6	15,591		23,002		23,682		11,961
	"	12	10,931		17,285		23,290		11,191
	Bottom	2	12,964		26,613		17,271		11,749
	"	6	13,907		22,966		24,882		11,352
	"	12	12,229		20,574		25,120		10,677
Polyester	-	0	18,538	16,120	20,457	22,805	26,143	24,535	14,079
	Top	2	14,838	-	21,054	21,238	17,113	25,330	11,732
	"	6	12,054	16,450	18,295	18,820	22,353	19,100	11,668
	"	12	14,300	15,050	13,568	16,530	18,404	14,650	12,264
	Middle	2	11,364		16,541		17,590		10,908
	"	6	14,070		17,139		23,206		13,042
	"	12	13,580		17,658		20,723		11,653
	Bottom	2	12,175		21,195		19,447		11,634
	"	6	15,880		16,068		23,111		12,104
	"	12	11,848		16,383		20,238		12,289
Vinyl ester	-	0	18,226	18,790	30,548	27,660	25,925	27,060	13,956
	Top	2	18,151	-	29,664	24,330	27,352	29,572	12,774
	"	6	15,870	22,230	22,449	20,576	23,067	24,830	14,083
	"	12	16,417	16,840	24,617	20,730	23,159	15,970	12,322
	Middle	2	18,430		28,110		29,416		12,937
	"	6	19,278		28,699		28,923		13,072
	"	12	18,629		26,320		22,137		13,353
	Bottom	2	18,101		27,029		25,140		12,159
	"	6	15,787		25,823		22,539		12,781
	"	12	18,939		26,076		26,371		13,133

[a] Top - in seawater or freshwater; middle - at seawater, bottom sediment interface; bottom - in sediment.

Table 3. Distribution of marine organisms on FRP/coated steel panels after 187 days at 50 feet

Material	Buried in sediment	Sediment-seawater interface[a]		Exposed to seawater	
		Inside	Outside	Inside	Outside
EPON 828	No growth, clean	5 barnacles per sq. in. 1/8" diam.	15 barnacles per sq. in. 1/8" diam.	5 barnacles per sq. ft., 3/4" diam. and some 1/4" diam.	30 barnacles per sq. ft., 3/4" diam.
Atlac	No growth, clean	3 barnacles per sq. inch 1/8" diam.	20 barnacles per sq. inch 1/8" diam.	10 barnacles per sq. ft.	5 barnacles per sq. ft., 1/8" to 1/4" diam.
Derakane	No growth, clean	15 barnacles per sq. inch 1/8" diam.	5 barnacles per sq. inch 1/8" diam.	80 barnacles per sq. ft., 3/4" diam. Several tubeworms, a colony of encrusting bryozoan	100 barnacles per sq. ft., 3/4" diam.
Coated steel	No growth,	3 barnacles per sq. inch 1/8" diam.	6 barnacles per sq. inch 1/8" diam.	100 barnacles per sq. ft., 3/4" diam. Felt torn where barnacles were removed.	125 barnacles per sq. ft., 3/4" diam. (Phenoline 300)

[a] Approximately 6-inch-wide area.

Table 4. Mechanical properties of concrete test specimens

Concrete mixture	Depth of oceanic storage ft	Estimated mean annual seawater temperature at indicated depth, °F	Age when tested, days	Compressive strength of 3 cylinders (referential), lb/in^2**			Compressive strength of portions of beams broken in flexure, lb/in^2***						Rupture modulus of beams, lb/in^2*						Number of beams tested	Number of beam portions tested
							Average		Maximum		Minimum		Average		Maximum		Minimum			
				Average	Maximum	Minimum	Referential	Oceanic	Referential	Oceanic	Referential	Oceanic	Referential	Oceanic	Referential	Oceanic	Referential	Oceanic		
M	–	–	28	–	–	–	7,820[a]	–	8,500[a]	–	7,400[a]	–	840[a]	–	890[a]	–	750[a]	–	4	8
T	–	–	28	–	–	–	7,460[a]	–	7,740[a]	–	7,110[a]	–	810[a]	–	870[a]	–	740[a]	–	3	6
M	50	54±5	156	9,910[a]	9,950[a]	9,870[a]	9,160[a]	8,510[b]	10,010[a]	9,320[b]	8,250[a]	7,360[b]	925[a]	855[b]	965[a]	885[b]	900[a]	805[b]	3	6
M	50	54±5	289	9,870[a]	10,400[a]	9,250[a]	9,750[a]	9,110[c]	10,230[a]	10,530[c]	9,330[a]	7,740[c]	810[a]	890[c]	860[a]	960[c]	740[a]	820[c]	3	6
M	300	50±1	387	10,150[a]	10,190[a]	10,120[a]	10,690[a]	9,820[d]	10,940[a]	10,680[d]	10,420[a]	9,460[d]	830[a]	860[d]	850[a]	900[d]	810[a]	830[d]	3	6
M	50	54±5	494	10,510[a]	10,880[a]	9,970[a]	–	9,610[e]	–	10,380[e]	–	8,850[e]	–	970[e]	–	1,020[e]	–	930[e]	3	6
T[f]	–	–	497	–	–	–	9,910[a]	–	10,170[a]	–	9,170[a]	–	860[a]	–	935[a]	–	785[a]	–	3	6

* To nearest 5 lb/in^2, as per ASTM C78-64.

** To nearest 10 lb/in^2, as per ASTM C617-71a.

*** To nearest 10 lb/in^2, as per ASTM C116-68.

[a] Cured in 73°F fog until tested at age shown.

[b] Cured in 73°F fog for first 101 days, then stored in ocean for 54 days, then stored in 73°F fog for 1 day, then tested at age shown.

[c] Cured in 73°F fog for first 101 days, then stored in ocean for 187 days, then stored in 73°F fog for 1 day, then tested at age shown.

[d] Cured in 73°F fog for first 101 days, then stored in ocean for 285 days, then stored in 73°F fog for 1 day, then tested at age shown.

[e] Cured in 73°F fog for first 101 days, then stored in ocean for 392 days, then stored in 73°F fog for 1 day, then tested at age shown.

[f] Substituted for M referential beams which became expended when tests at age 387 days were completed.

54 and 187 days of exposure at 50 feet. The silicon bronze fasteners exposed to the seawater were uniformly corroded after exposure except at crevices where significantly reduced attack was observed. The fasteners exposed to the bottom sediments remained uncorroded after 392 days. The Type 304 stainless steel fasteners used to assemble the test racks displayed crevice corrosion and pitting. The maximum depths of the corrosion at crevices were 0.002 inch after 54 days, 0.008 inch after 187 days, and 0.019 inch after 392 days. The Type 316 stainless steel fasteners were not attacked after 54 and 187 days at 50 feet of depth. After 392 days, crevice corrosion up to 0.005 inch deep was noted under two of the four heads. The zinc coating (galvanize) on the steel was completely gone at exposed surfaces after 187 days. However, the coating was intact in the crevices under the boltheads and nuts and on the shank of the bolts. Corrosion on the fasteners after 392 days made disassembly difficult but did not significantly reduce their strength.

FRESHWATER EXPOSURE STUDIES

In the freshwater exposure studies conducted by the Bureau, duplicate samples of all candidate pipe materials except for the steel and concrete blocks were exposed to Denver tap water in a tank that was continuously fed with freshwater. The average temperature of the water was 64°F. After freshwater exposure of 60, 180, and 365 days, panels of the plastic-fiberglass composite materials were removed and specimens cut for compressive, tensile, and flexural testing. The concrete specimens, provided by CEL, were tested after 180 and 365 days of exposure.

The tensile, compressive, and flexural strength test results are presented in table 2, page 79. At the end of one year, the tensile strengths for the three fiber-reinforced plastic composites (polyester, epoxy, and vinyl ester) were not significantly affected. The compressive strength of the epoxy composite remained essentially unchanged after a year, while the polyester and vinyl ester composites experienced a slight reduction. The 12-month water exposure data indicated only a slight reduction in flexural strength for the epoxy composite with a moderate reduction for the polyester and vinyl ester composites.

Creep data for 100 days on the three fiber-reinforced plastic composites for environments in air and water showed primary creep occurring between the first 30 to 40 days with a variable decreasing rate. In air, the epoxy composite shows a creep rate of 0.0001 inch per day, half the rate experienced by the polyester and vinyl ester composites. In water, the creep rate for all three composites is about 1.5 times their creep rate observed in air.

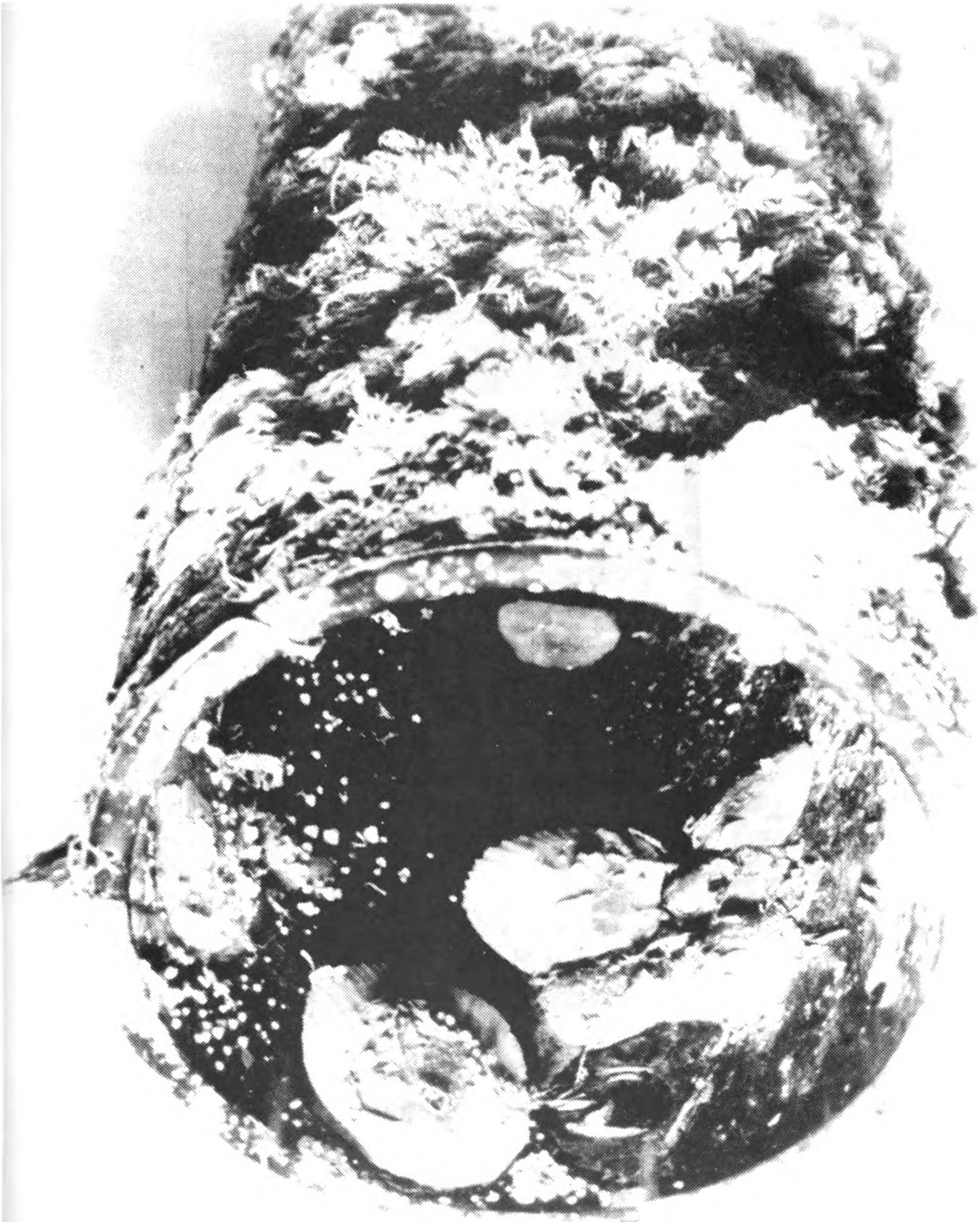
Water softening and absorption tests for the three composite materials, after 12-month water exposure, indicate that only the vinyl ester composite had slightly softened, and had also absorbed more water than the polyester and epoxy composites. The results of limited tests made on the concrete specimens show, as expected, some strength gain in freshwater due to continued curing. The concrete was of high strength and appeared to be of good quality.

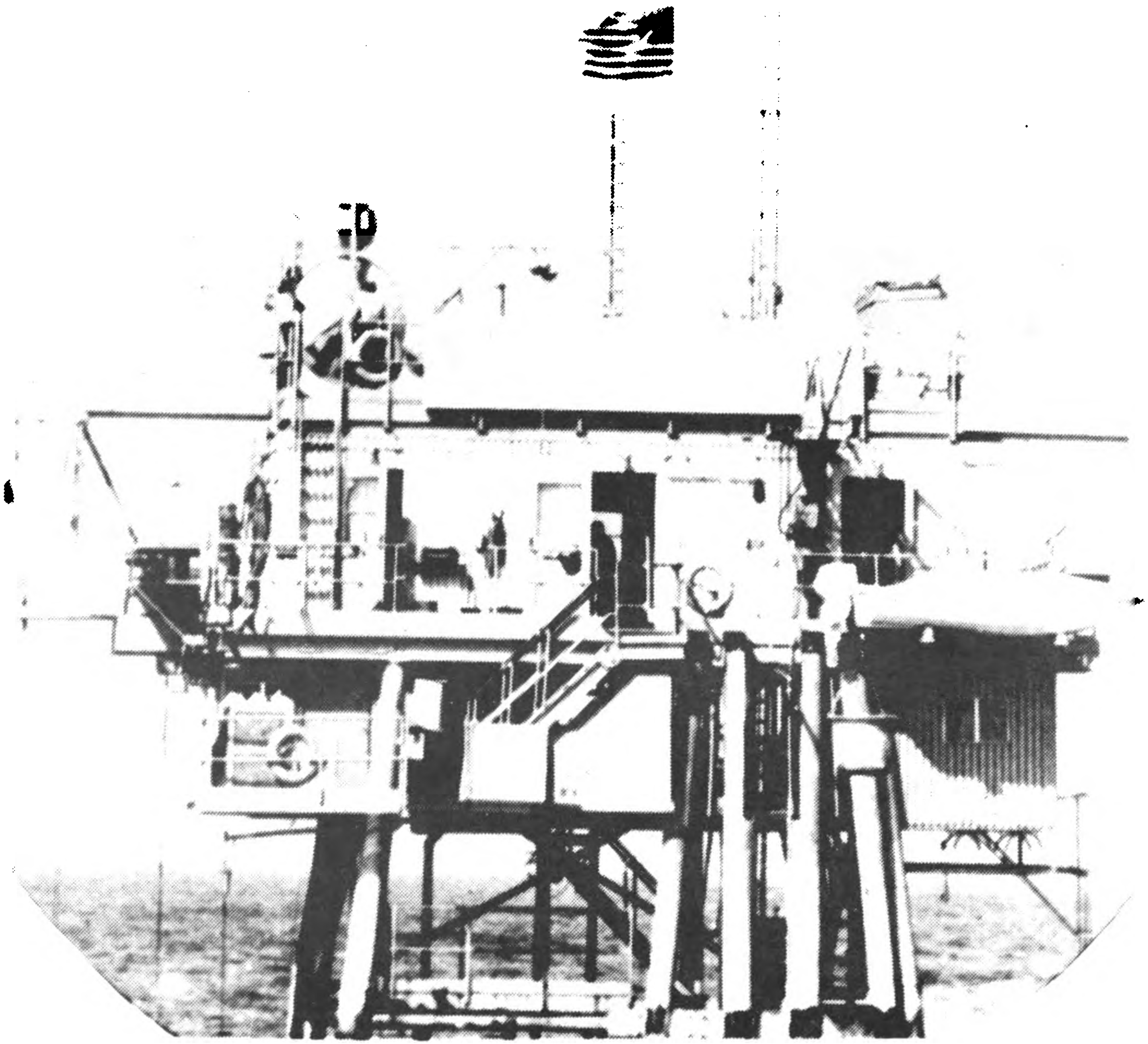
CRITICAL STRAIN TESTS

A rack containing 180 specimens of the three different composite materials at six strain levels was exposed to the ocean environment at a depth of 50 feet at the Naval Undersea Center Oceanographic Research Tower located near San Diego, California. The exposure period lasted about 13 months.

Observations were made daily for 20 days, weekly for 10 weeks, and then monthly the remainder of the exposure period. After 4 months, biological fouling of the rack was progressing at a rapid rate, requiring weekly cleaning so that encrusting organisms could not establish themselves on the specimens.

There was no significant change in the visual readings taken over the entire observation period. However, it was very difficult to sight hairline cracks in the material. Most of the higher deflection specimens exhibited plastic deformation after removal from the rack. No specimens were stressed beyond initial failure.





NUC research tower used for material testing program

REFERENCES

For further information regarding performance of materials in the ocean environment, please refer to the following publications:

1 "Materials Pilot Program in Support of California Undersea Aqueduct Reconnaissance Investigation" Special Report 52-023, Naval Civil Engineering Laboratories, August 1973.

2 "Materials for Ocean Engineering" Koichi Masabucki, The MIT Press, Massachusetts Institute of Technology, Cambridge, Mass., 1970.

3 "Ocean Engineering - System Planning and Design," John F. Braktz, John Wiley and Sons, Inc., 1968.

4 "Handbook of Fiberglass and Advanced Plastics Composites," edited by George Lubin, Von Nostrand Reinkold Company, 1969.

5 "Corrosion of Alloys in Hydrospace," Technical Note N-1224, F. M. Reinhart and J. F. Jenkins, Naval Civil Engineering Laboratory, 1972.

6 "Guidelines for Selection of Marine Materials," The International Nickel Company, Inc., 1966.

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8 "Handbook of Ocean and Underwater Engineering."

9 "Materials Performance and the Deep Sea," ASTM Special Technical Publication No. STP445, June 1968.

PART C--FACILITIES AND COSTS

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(artist's conception)

PART C--FACILITIES AND COSTS

CHAPTER VIII. CALIFORNIA UNDERSEA AQUEDUCT FACILITIES

OFFSHORE SYSTEM

This chapter discusses the design considerations for the offshore system with the appurtenant onshore facilities, and describes the operation and maintenance of the system. Included in the offshore system are all features such as the conduit, inlet and outlet tunnels, and appurtenant onshore structures such as pumping plants, reservoirs, and conduits from the pumping plants to the shoreline. These facilities are shown on the frontispiece. (For a more detailed discussion of the facilities and cost estimates, the reader is referred to Appendix I, Appraisal Design and Estimate for the Offshore System.) Information on possible operating problems associated with an undersea aqueduct is also presented.

Design Procedure

The initial step was to assemble the design data, most of which came from reports prepared under contract for the California Undersea Aqueduct and included hydrodynamics, marine soils and geology, route mapping, and materials. The Report on Alternative Concepts, prepared prior to the appraisal designs, was also available. Plan and profile drawings were prepared showing the Aqueduct route, pumping plant locations, and hydraulic gradients.

Preliminary diameters and estimates of quantities for the Aqueduct were determined for concrete, steel, and fiber-reinforced plastic (FRP) pipe. The economic diameters for concrete and steel pipe were nearly identical. The pipe estimates were based on a preliminary route plotted on a set of 35 overlay maps. These overlays, covering the coastline from Crescent City in the north to San Diego in the south, showed graphically the bathymetry, soils and geologic conditions, fishery data, obstacles, hydrographic data, and environmental data.

Final pipe diameters were determined graphically by modifying cost data from previous Bureau projects. Although steel or concrete pipe was used primarily where the Aqueduct was routed to or near the coast, the design was based primarily on a buoyant aqueduct using the FRP pipe. The decision to use FRP pipe was based on data which showed it to be less expensive than steel or concrete pipe; increased future use of this new material should further reduce its cost. The buoyant route would be shorter because of the smaller number of bends required, and it would also minimize the environmental impact and the intrusion into legal boundaries.

The FRP and steel pipe and tunnel sections were designed using conventional methods. A computer program for large diameter prestressed concrete cylinder pipe, modified to withstand required handling loads, was used in designing the concrete conduit. Anchorage for the buried pipe was designed to withstand liquefaction loads where applicable.

Water-hammer Study

The pumping plant for each of the 11 pumping reaches would be located at about sea level, with a forebay reservoir having a water elevation of 50 feet above sea level. As this in effect would isolate each reach, for the water-hammer study the pressure surges for one pump reach could be made and findings applied to the other pump reaches. The results of the study showed that to avoid water column separation the portion of the Aqueduct near sea level should be placed about 35 feet below the forebay water surface elevation.

In the reach with gravity flow, the constant flow of about 5,250 cubic feet per second would be controlled by valves located at the pumping plant. To provide the necessary head to overcome the friction head loss in the gravity reach the intake structure would be located at elevation 200. Water hammer was not considered a problem for the appraisal design for this gravity reach.

Pipe Design

Assuming a pipe wall thickness proportional to the pipe diameter, comparisons were made between the twin-barrel and single-barrel pipe concept. There appears to be no significant reason why the diameters of the magnitude required for a single barrel could not be manufactured and installed.

A twin-barrel aqueduct might have a higher degree of reliability over the single-barrel aqueduct. However, most hazards that could disrupt service in a single barrel would probably also be capable of disrupting service in twin barrels. Additional pumping plants would be required for the twin barrel because the friction head loss would be about 2.8 times greater than for a single barrel, which would also increase the power costs.

The pipe is designed for a net internal load equal to the internal pressure head minus the conduit depth below sea level. The economic pipe diameter, one of the most important considerations because of the cost, was determined by using a previously developed graphical method.

Pipe joints were designed to facilitate underwater connection and to provide flexibility where required. The flexible joints, as conceived at this time, would require further study before additional designs are undertaken.

Pipelines would require blocking at bends to offset the resultant hydrostatic and acceleration forces. In buried conduit, minor bends might need no blocking other than that provided by the passive earth pressure. In the buoyant pipe, however, the blocking must be provided by anchors.

Access to the Aqueduct would be provided at the undersea portal of each tunnel and at 25-mile intervals along the route. The two gates provided at each access to serve as a lock should be operated by remote control. The design calls for 37 access chambers.

The Aqueduct includes 599 miles of buoyant pipe and 122 miles of buried, partly-buried, seabed, and onshore cut-and-cover conduit.

Buoyant pipe. The buoyant pipe would be formed from fiber-reinforced plastic, by a filament winding process, using a polyester thermo-setting resin reinforced with continuous glass strands.

Advantages of FRP pipe include high strength-to-weight ratio, corrosion resistance, a smooth finish which would minimize friction head loss, and low installation cost. Uncertainties regarding the use of this type of pipe are wet strength, water absorption, fatigue strength, and long-term properties. The FRP pipe material was assumed to have an ultimate tensile strength of 100,000 pounds per square inch. However, because of the uncertainties mentioned above, the strength was arbitrarily reduced to 45,000 pounds per square inch. A safety factor of three was applied so that the allowable design stress of 15,000 pounds per square inch was used.

Lining or coatings for the pipe were not considered because of the smooth interior surface and the corrosion resistance of the material. The length of the pipe sections would be determined by the handling equipment. Pipe lengths could be several hundred feet long with a fusion process used to join the pipe at sea.

Buried or partly buried pipe. The buried pipe was designed for a minimum earth cover of 10 feet and an average cover of 12 feet. Potential liquefaction of the soil surrounding the pipe was a major consideration.

Partly buried pipe, used primarily in rock material, was assumed to have uniform bedding with backfill of rock and sand and would be seated on a pad of tremie concrete. Lift and drag forces on the partly buried pipe were considered minimal and therefore omitted in the cost studies.

Types of pipe considered for the buried or partly buried reaches of the Aqueduct were steel, prestressed concrete, and monolithic concrete.

For buried portions of the Aqueduct, lined and coated steel pipe having an allowable design stress of 20,000 pounds per square inch was considered. A continuous pipeline with sections fabricated above water and welded undersea appeared to be the most economical design. Sections were assumed to be 400 feet long.

The precast, prestressed concrete pipe was designed with a 6,000 pounds per square inch concrete core with a thickness equal to 1/16th of the pipe diameter. A steel cylinder in the core would have a yield point stress of 33,000 pounds per square inch, a diameter 4 inches greater than the inside diameter of the core, and a thickness of about 0.06 inch. For corrosion protection, the concrete which covers the prestressed steel should be increased from the usual 1-1/2 inches to 2 inches.

Monolithic concrete pipe lengths of 300 feet were used to minimize the number of underwater joints. Economy might be achieved by using precast, prestressed concrete pipe as a core.

Twenty crossings of fault zones will be required. Where the buried Aqueduct crosses fault or shear zones, joints should allow shortening, elongation, or rotation, but should not allow offsets between sections of pipe.

Seabed pipe. To withstand the differential head, the seabed pipe would have a prestressed concrete cylinder pipe for an inner core. It would be encased in a monolithic concrete shell post-tensioned to withstand handling loads.

The drag force, due to velocity currents associated with surface waves, is estimated to be equal to about 12,000 pounds per lineal foot of conduit. The frictional resistance of the conduit on the bottom sand would be more than adequate to offset the drag force. The lift force resulting from surface waves would be minimal in contrast to the conduit weight. Riprap protection would be provided to prevent excessive scour along the conduit.

Anchorage Requirements

Anchorage requirements were based on hydrodynamics, buoyancy, liquefaction, and fouling sources in saltwater.

Four types of anchors--auger, grouted reinforced bar, water jet, and explosive--were considered. Anchor cables should consist of a flexible fiberglass material that is resistant to corrosion.

The weight of the freshwater inside the pipe would be lighter than the surrounding seawater, with a buoyant effect on the pipe. The net buoyancy is the weight of the seawater displaced minus the weight of the freshwater in the pipe minus the weight of the pipe. The buoyant load on a 34-foot-diameter FRP pipe would be about 826 pounds per lineal foot.

Fouling could decrease or possibly offset entirely the buoyant force of the FRP pipe. Although variables affect the growth of fouling, only very limited data were available on the thickness and weight of fouling which could be expected. For this study it was assumed a 1-inch thickness of fouling having a specific gravity of 1.3 would occur. The net fouling weight on a pipe with a 34-foot inside diameter would be about 153 pounds per lineal foot of pipe.

The anchoring system was designed to take the horizontal wave loads and would be more than adequate to take vertical wave loads. The anchor design assumes the wave would act perpendicular to the pipe and that the maximum loads due to waves would occur simultaneously along the entire distance between anchors.

The anchors were designed for an ultimate horizontal load of 2 million pounds. The maximum spacing of the anchors would vary with the diameter of the pipe. As the tsunami load on the pipeline would be quite small compared to either the average or extreme wave, the wave loads would govern.

A ring would be placed around and cemented to the FRP pipe at each anchor point. Additional cables would be attached at every fourth anchor to limit longitudinal movement. Two types of anchor bases were used, one for rock foundation and one for overburden material.

Buried concrete or steel pipe if located in fine material susceptible to liquefaction during seismic activity would require anchorage. The density of the liquefied material is about twice the density of seawater, thus producing a buoyance of around 128 pounds per cubic foot of displaced material. Anchorage capacities for the buried aqueduct conduit anchors would be in the magnitude of 100,000 to 200,000 pounds each.

Partly buried pipe was usually embedded in rock and would require no anchorage. In transition zones where the pipe could be partly buried in unconsolidated material susceptible to liquefaction, the anchorage requirement would be small. Concrete pipe lying on the seabed would not require anchorage.

Submarine Canyon Bridges

The many canyons where high currents and landslides are known to occur along the California coast present a hazard to the buoyant pipe. No data have been collected during a canyon storm; therefore, the magnitude of forces is unknown, but it is believed that it would not be feasible to construct structures in the canyons, or to span them with suspension-type bridges. The alternatives would be tunnels under or around the canyon requiring relatively sound rock and probably an onland heading, or buried conduit skirting the canyon.

Tunnel Design

Where rock conditions are favorable, the entrance or exit of the Aqueduct from the ocean should be by tunnel. Where considerable thickness of overburden exists, a cut-and-cover section for entrance or exit from the ocean might be desirable.

About 53 miles of tunnels would be required. Each tunnel would start with an onshore portal and continue out to sea to a depth of 50 to 150 feet. The tunnels would be bored. Estimates for this study are based on 100 percent monolithic concrete lining, with steel liner in reaches where the hydrostatic head exceeds 150 feet.

California Undersea Aqueduct Facilities

Pumping Plants

Pumping plants would be used to supply the head required to deliver the water to southern California in order to recover the friction head loss.

For the cost estimates, it was assumed that there would be a forebay reservoir at each pumping plant. Pumping plants were located where the Aqueduct alinement is in close proximity of the shore, or where it comes ashore for storage reservoirs at water delivery points or in order to avoid underwater canyons.

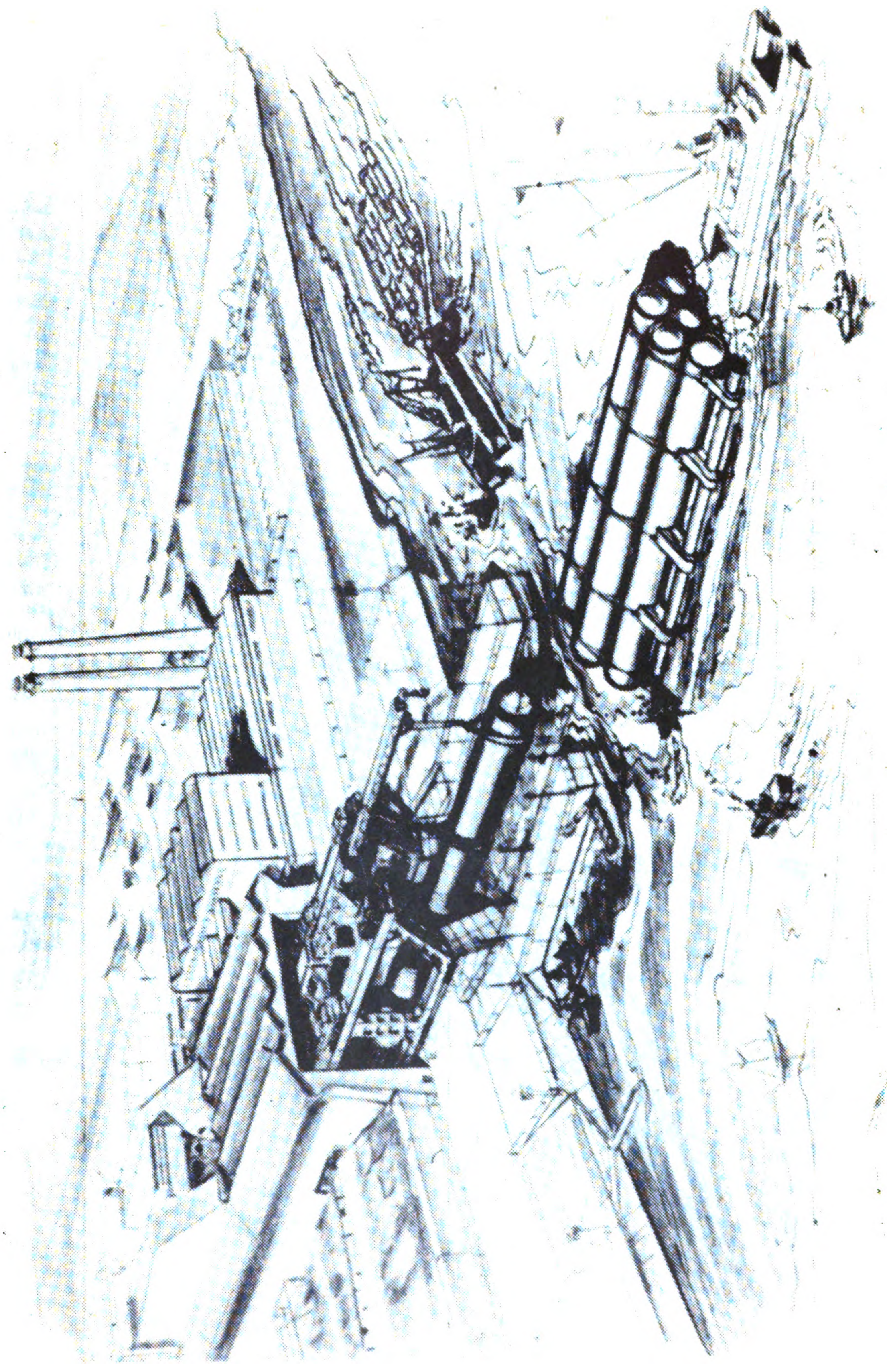
Pumping plant design was complicated because of the variable flow in the northern portion of the Aqueduct where upstream storage is limited. Vertical centrifugal pumps were used because they perform well over a wide range of heads.

In the northern section several sets of pumps, with each set rated for different flows, would be used in each plant. Thus, for each range of flow and corresponding head, only one set of pumps would be operating.

In the southern portion where the flow would be constant, a more economical design is possible. Each plant would have one set of four vertical centrifugal pumps (three units plus one standby unit).

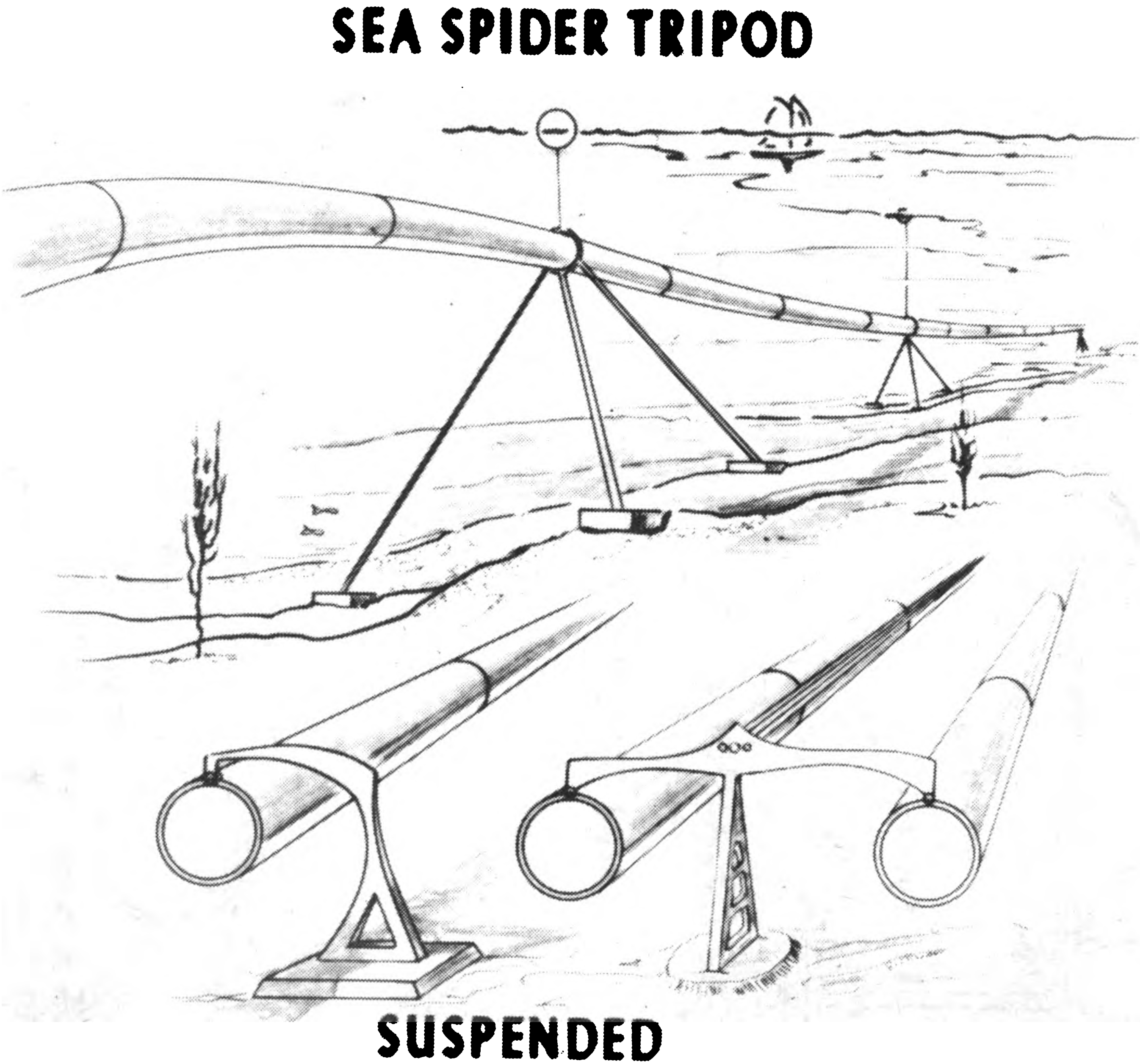
Drawings

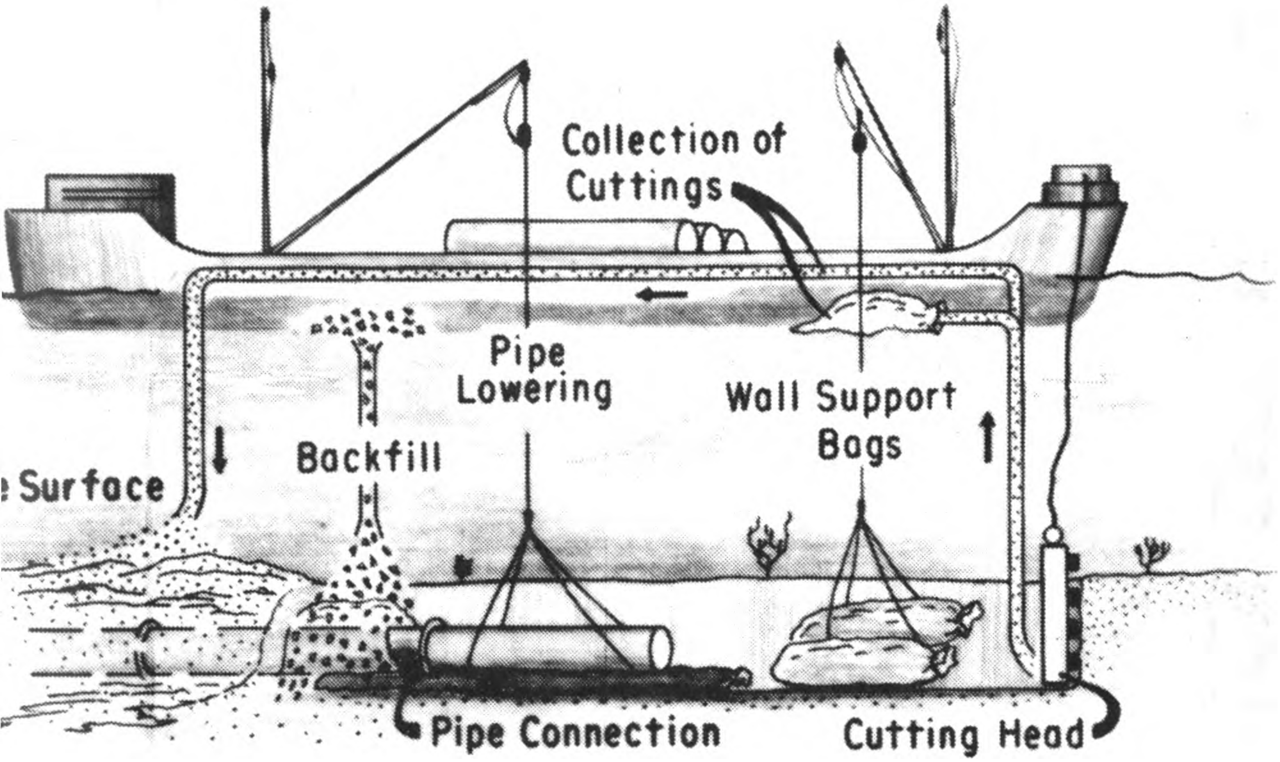
The artist's conceptions which follow are representative of conceptual design features which were evaluated during the design phase of the study.



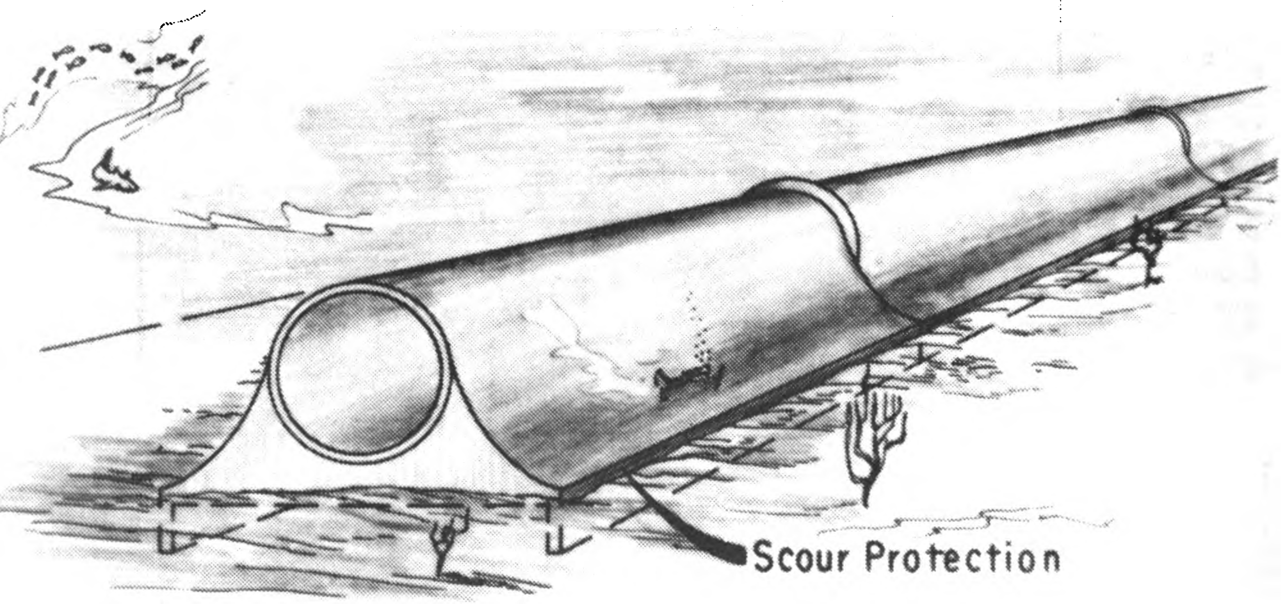
ASSEMBLY PLANT

SUBMERSIBLE DITCH DREDGE

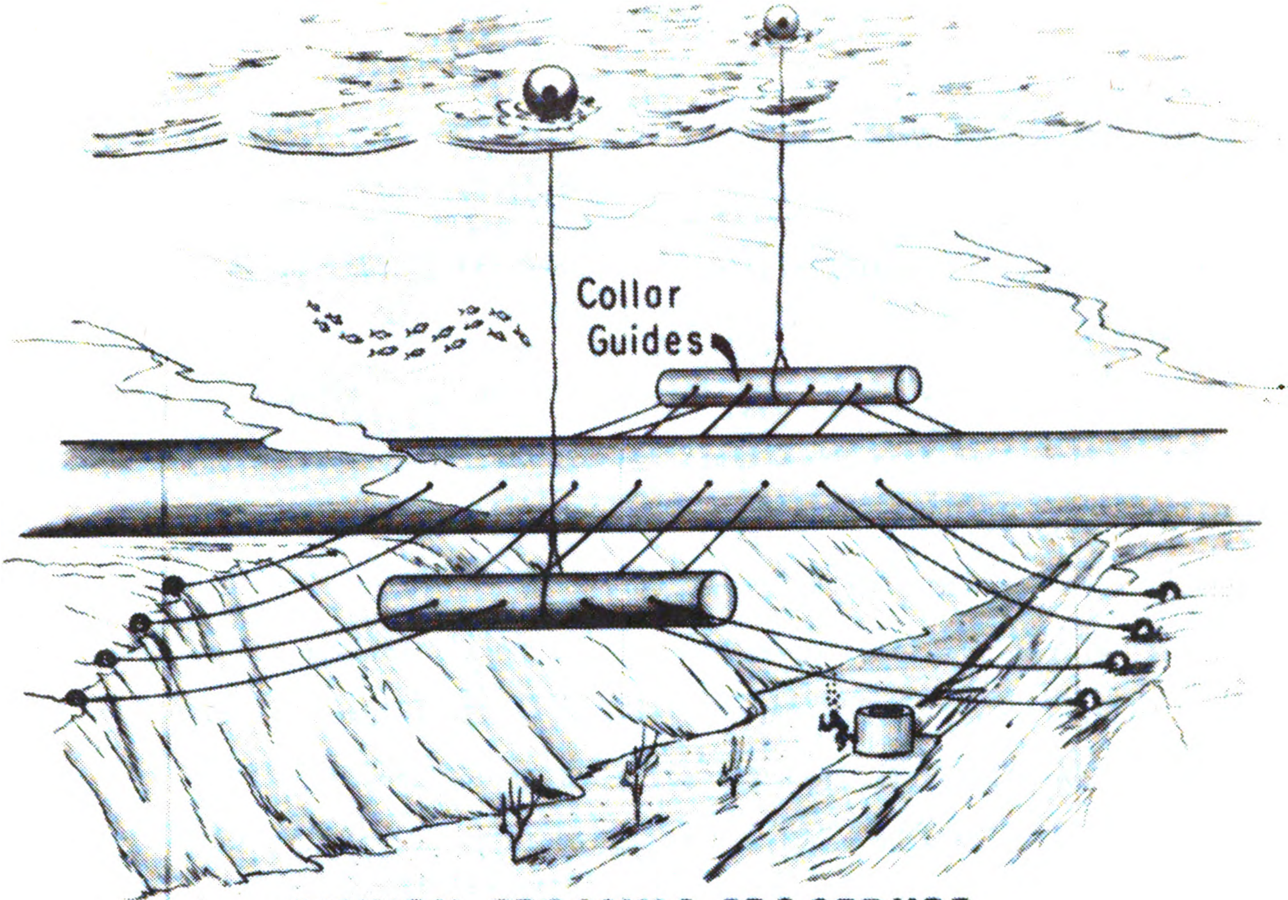

SEA SPIDER TRIPOD
SUSPENDED



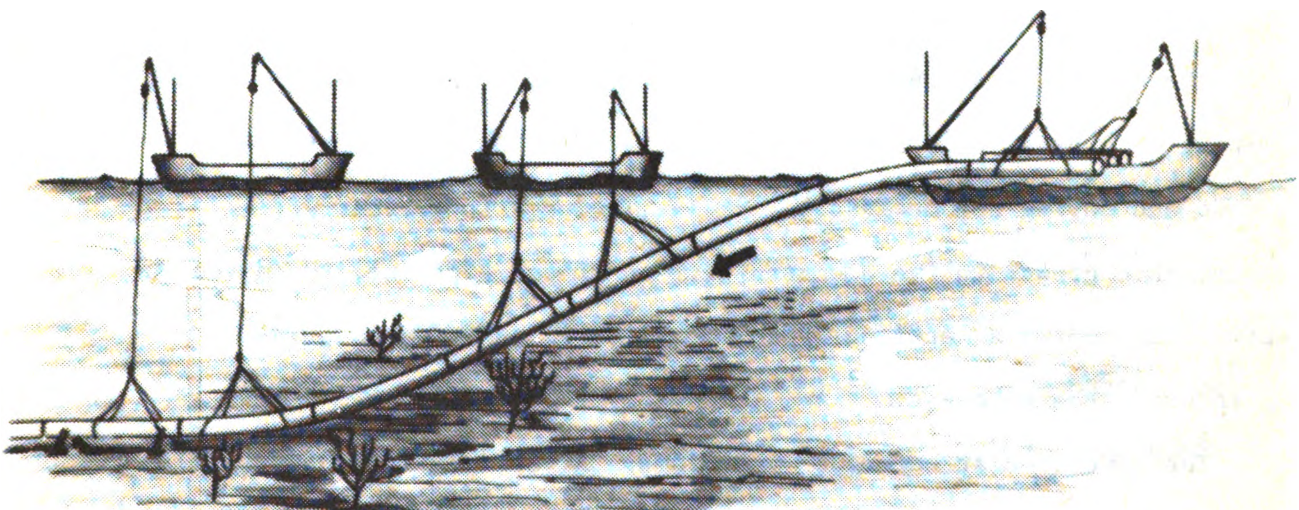
PIPE BURYING SYSTEM



INTEGRAL PIPE & ANCHOR RESTING ON SEABED



CANYON CROSSING PROCEDURE



INSTALLATION PROCEDURE - PIPE LAYING

APPURTENANT ONSHORE FACILITIES

The Aqueduct system would require a number of onshore features. These include dams, pumping plants, conveyance, and water treatment facilities.

The water supply for the Aqueduct would require diversion of 4 million acre-feet from the Klamath and Eel Rivers. Of this 1.2 million acre-feet would be diverted from the Eel River and 2.8 million acre-feet from the Klamath River.

To regulate the water diverted from the Eel and Klamath Rivers would require about 9.0 million acre-feet of storage capacity. By using reservoir sites in the upper Eel River Basin, about 4.0 million acre-feet of the required storage could be provided. Enlargement of one or two existing or potential reservoirs in the Russian River Basin could provide an additional 3.0 million acre-feet of storage. The remainder of the required storage, about 2.0 million acre-feet, could be obtained from reservoir sites near the Monterey Bay area.

The diversion on the Eel would be through a gated structure opening to a canal with a maximum capacity of 5,000 cubic feet per second and having the necessary fish facilities. To prevent any undesirable growth in the undersea portion of the pipeline, the diverted water would enter a settling basin, be filtered and treated prior to entering the Aqueduct.

The diversion structure on the Klamath River, similar to that on the Eel, would have a maximum capacity of about 7,000 cubic feet per second. In addition to fish facilities and treatment facilities, the structure would have a small lock for river navigation.

As the design of all the onshore facilities required no new research techniques, normal Bureau appraisal design techniques were used.

OPERATION AND MAINTENANCE

Operation and maintenance of the proposed California Undersea Aqueduct poses unique problems not previously encountered in a large-scale water project operation. In order to provide the minimum reaction time to adverse incidents affecting system integrity and operational capability, it is assumed that five operating complexes would be needed. The complex in the vicinity of Monterey Bay would be the headquarters. The five complexes are:

Complex No. 1. Located at Humboldt Bay, would have responsibility for the inlet sections of the Aqueduct and pumping plants 1, 2, and 3.

Complex No. 2. Located at Jenner, would have responsibility for the pumping plants 4, 5, and 6, Russian River storage, and conveyance to and from this storage to pumping plant 6.

Complex No. 3. Located in the vicinity of Monterey Bay, would be the primary control center, responsible for the Aqueduct off-shore features, as well as storage in the vicinity of Monterey Bay, and conveyance to and from this storage to plant 7. The complex would also be responsible for the onshore gravity reach and pumping plant 7.

Complex No. 4. Located at Santa Barbara, would be responsible for pumping plants 8, 9, and 10.

Complex No. 5. Located at San Diego, would be responsible for pumping plant 11 and terminal delivery facilities.

Conduits

Operation and maintenance of the Undersea Aqueduct has no parallel in any existing physical facility. The conduit would be a composite of buoyant, resting, and buried reaches, with various sizes in each reach. The inlet and outlet sections to each pumping plant would be buried in the surf zone and to depths of 200 feet below sea level. The conduit would then emerge from the ocean floor through flexible, shock-absorbing transitions into the buoyant line. The buoyant line would be at various depths between 200 and 400 feet below sea level.

The buoyant line would be subject to marine fouling, puncture, separation, and incipient deteriorations, all of which would require rectification, but are unquantified at present.

The buried (and resting) portion of the line would be relatively protected from the ocean environment, but could be subject to galvanic deterioration, and alkali or acid soils. Buried portions can be compared to existing tunnels, powerplant conduits, and pumping plant discharge pipes, although most of those are not as large or as long as the Aqueduct.

California Undersea Aqueduct Facilities

The Aqueduct would have no "turnouts," and it is difficult to envision flow control devices such as checks, although each pump unit would be valved. Operation would depend on head at the pumping plants to overcome hydraulic losses in the conduit. None of the Aqueduct would ever experience pressure below atmospheric; and except during construction, potential for ocean inflows would be very small and leaks would be from the inside out, but in some instances might present a problem. Operational incidents might produce internal dynamic hydraulic conditions that would be detrimental. Accordingly, operational control must be coordinated and monitored to insure that such events do not occur. These controls would include as a minimum, accurate flow measuring, accurate pressure measuring, and infinitely variable flow control pump discharges.

Physical monitoring of the Aqueduct in this remote hostile environment could probably be accomplished by stationary buoys along the Aqueduct that would report and relay requisite data to a central data-logging computerized control center. Using normal hydrologic radio frequencies, these buoys would have to be stationed near the limit of line-of-sight transmission which, because of earth curvature, might be as little as 40 kilometers for an ordinary antenna 30 meters high. These buoys could serve other earth science tasks, such as meteorologic and seismic data platforms as well as navigation. If satellite relay capability is available, the buoys could be at a much greater distance, limited by the expanse of

Aqueduct from which data are required. Provision of sophisticated energy sources such as wind chargers or solar cells on the buoys could provide power for the monitoring equipment. It might be practical to use long wave (subsonic) transmission and convey the intelligence directly through the ocean water. No estimates of this type monitoring have been included in view of the expectation of the system's meeting the 100-year risk criteria.

Data are meager concerning the rate and extent of fouling of objects in the sea, and fouling varies from little or none to luxurious and rapid. Observations from the specimen implants in the ocean will provide first-hand information for the time of observation at that location. Photos of the Andrea Doria, 75-100 meters deep, indicate little growth over many years. Pictures of railroad locomotive axles in the Bahamas at relatively shallow depths of 10-20 meters, show little growth; however, all other equipment and materials of that 1863 sinking have disintegrated. Rust of the axles and constant sloughing of oxides may have prohibited buildup. Photographs show considerable plant growth on the ships in Eniwetok Atoll sunk at various depths during atomic bomb tests. The material fouling study provides some additional data.

Accordingly, to predict loss in buoyancy from encrustation and attached growth on the exterior of the Aqueduct is conjecture at best. It is assumed that a significant growth would not be encountered at the depths planned. Verification of this assumption could be accomplished by various observation techniques to include submersibles, observation platforms, or electronic monitoring with remote sensings.

Included in the estimates is only the level of capability for examination of the fouling. Initially, using contract services, visual examination from submersibles might be considered, then use of an operating maintenance vessel and ultimately, if required, a maintenance vehicle.

At the present envisioned construction time, up to 10 years, the fouling problem must be considered and resolved.

A substantial vessel would be required to provide the surveillance necessary and to provide submersible support. Special design such as catamarans, hydrofoils, and air cushion vehicles should be considered in the selection of surveillance capability. It is not too extreme to consider the art state may develop a triphibious vehicle for the examination.

Pumping Plants

The pumping plants identified would not be entirely different from existing facilities. Most or all of the plants would be operated by remote control. This control would be located in the Monterey operating center. Operating personnel consist of a 24-hour watch by four control room operators and their assistants at the center, with a similar complement at each of the four field sections. Each of the five sections would monitor remote plants on a continuous basis, and a roving patrol of operator-maintenance men would visit each plant daily.

Maintenance personnel required were estimated on the basis of the operating San Luis-Dos Amigos-Tracy and O'Neill plants, and as envisioned for a project similar to the Central Valley Project but operating as a separate entity.

The large rotating machinery of the project and portions of the fixed installation such as valves and valve seats would be maintained at a separate facility in Complex 3. Each complex would have a port facility. Equipment requiring major repairs would be transported by highway to the port, then shipped by water to the Complex 3 maintenance activity. Stator and rotor windings would be accomplished on site, as would other minor repairs by the team of mechanics/technicians assigned to that complex.

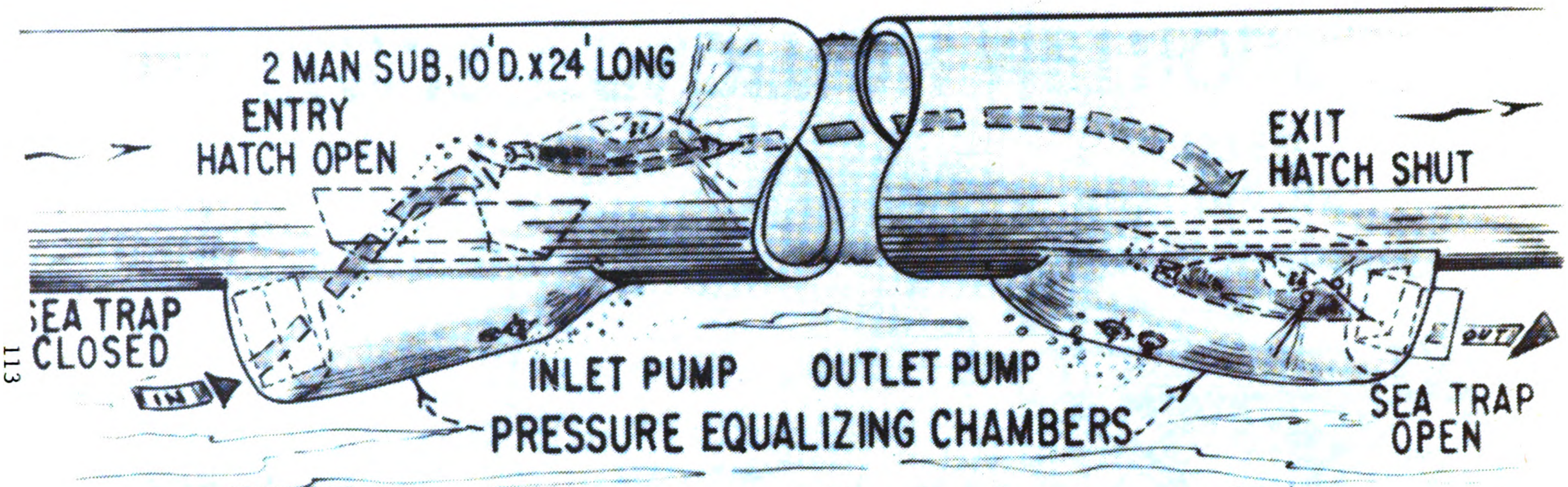
Water Treatment

Water would be treated to prevent entrance of sediment and organisms to the pipeline. Since once in operation, it would be very expensive, if not impossible, to clean the interior of the pipeline, the water treatment expense is deemed a reasonable trade-off. Most of the water would be for M&I purposes and would ultimately need thorough treatment before use, so, in effect, the water would be treated before it enters the pipeline rather than after it is delivered to water distributing agencies.

INSPECTION

Artist's Conception

DRY ATMOSPHERE REPAIR



Hatches, Equalizing Valves and Chamber Openings could be operated electronically with a high pressure pneumatic back-up actuating capability.

AQUEDUCT LOCK-OUT UNITS

REPAIR-CONDITION METHODS

CHAPTER IX. INLAND ALTERNATIVE PLAN

FACILITIES

For comparison purposes estimates were made for a comparable inland alternative delivery system. Every effort was made to make the inland alternative comparable physically as well as environmentally with the offshore aqueduct. Diversions from the Klamath and Eel Rivers would be identical. Storage in the Eel, Van Duzen, and Mad River Basins was assumed to be the same, that is, 4 million acre-feet. For the inland alternative, water would be pumped from the Klamath and Eel Rivers to a Glenn Reservoir complex with an active storage capacity of 5 million acre-feet on the west side of the Sacramento Valley.

Conveyance south of Glenn Reservoir would be by canal and pipeline. It was assumed that approximately one-half of the distance would be canal and one-half would be closed conduit. Capacity would be 5,600 cubic feet per second to the vicinity of the Delta pumping plants, where 300 cubic feet per second would be provided for Bay area needs. From the Delta pumping plants to the vicinity of Lancaster, California, the conveyance capacity would be 5,300 cubic feet per second. Near Lancaster a turnout would be provided to deliver 1,500 second feet to the Los Angeles area. The Aqueduct would continue at a capacity of 3,800 cubic feet per second to intersect the Colorado River Aqueduct in the vicinity of Desert Hot Springs. Delivery points provided would be comparable to those provided by the Undersea Aqueduct, with cost of facilities for distribution approximately the same. Both the Undersea Aqueduct and the inland alternative would require facilities to distribute water from their terminal points for Colorado River augmentation.

OPERATION AND MAINTENANCE

To provide continuous operation and maintenance of the system, a field headquarters would be established near the center of the project with sections as follows:

1. An inlet section on the Klamath River with three pumping plants.

2. An inlet section on the Eel River with three plants and associated dams and storage to include the Glenn Storage Complex.

3. Pumping plants comparable to those of the State Water Project to include:

Delta	Wind Gap
Dos Amigos	Edmonston
Buena Vista	Pear Blossom

The Edmonston plant would be a secondary maintenance complex for those plants from Wind Gap southerly.

The alternative overland route includes 935 miles, approximately one-half of which would be tunnels and closed conduits 19.5 to 29 feet in diameter, and one-half open concrete-lined canal. The need for treatment facilities for this alternative route would be similar to that for the offshore route.

CHAPTER X. COSTS

CONSTRUCTION COSTS

The total construction cost for the California Undersea Aqueduct is estimated at about $20.028 billion. For comparison purposes, a preliminary estimate was also prepared for an inland aqueduct route with similar accomplishments. The total cost of this system is about $10.186 billion.

All costs are based on April 1973 price levels and include contingencies, engineering, administration, and service facilities. The costs do not include right-of-way, interest during construction, or water distribution enroute or beyond the Oceanside (offshore) and Desert Hot Springs (inland) terminal points.

Offshore Facilities

The major portion of the Aqueduct construction cost is associated with the offshore pipeline, with the cost of the fiber-reinforced pipe (FRP) constituting nearly one-half of the total construction cost. This cost is based on the present limited technology of manufacturing this type of pipe and installing it on the Continental Shelf. As technology advances in both the manufacturing and ocean construction, the relative cost of the FRP pipe could be reduced substantially.

Since the early stages of the study it has been recognized that the limitation of water storage on north coast streams, for environmental reasons, would significantly increase the cost of the project. The cost per mile of the northern reach could be reduced by about $5.5 million per mile, or roughly 20 percent if constant flow could be used.

In arriving at the economic pipe diameter, costs for both FRP and steel pipe are based on preliminary estimates of the costs per pound of pipe material. Using smaller pipe diameters could decrease the pipe costs but would increase the power and pumping plant costs. However, it appears a change of several feet in pipe diameter would not significantly change the overall cost.

The cost for miscellaneous items such as surveillance equipment, air valves, data acquisition equipment, etc., was assumed to be 5 percent.

Table 5 summarizes the total construction costs for the Undersea Aqueduct. Details of cost estimates are described in Appendix I, Appraisal Design and Estimate for the Offshore System.

Costs

Table 5. Construction costs - Undersea Aqueduct

Description	Costs
Offshore portion	
FRP conduit	$5,760,000,000
Buried, half-buried, sea bed and onshore cut-and-cover conduit	2,424,600,000
Undersea tunnels	979,900,000
Access chambers	9,000,000
Fault crossings	27,400,000
Pumping plants and valve structures	717,400,000
Forebay reservoirs	22,000,000
Subtotal of above items	9,940,300,000
Unlisted items (5 percent)	496,700,000
Subtotal	10,437,000,000
Contingencies (25 percent)	2,563,000,000
Field cost	$13,000,000,000
Engineering, administration, service facilities (27 percent)	3,500,000,000
Total offshore costs	$16,500,000,000
Onshore portion	
Dams	$1,878,000,000
Pumping plants	362,000,000
Conveyance system	1,032,000,000
Electrical facilities	12,000,000
Water treatment facilities	244,000,000
Total onshore costs[a]	$3,528,000,000
TOTAL UNDERSEA AQUEDUCT	$20,028,000,000

[a] Includes contingencies and indirect costs.

Costs

Alternative Inland Plan

Table 6 shows the total construction costs for the inland alternative route, including contingencies and indirect costs.

Table 6. Construction costs - inland alternative

Description	Cost
Dams	$1,000,000,000
Pumping plants	1,343,000,000
Conveyance system	7,550,000,000
Electrical facilities	49,000,000
Water treatment facilities	244,000,000
Total inland alternative	$10,186,000,000

OPERATION AND MAINTENANCE

Undersea Aqueduct

Estimated annual operation, maintenance, replacement, and power costs for the Undersea Aqueduct are:

Pumping plants	$19,500,000
Conduit	2,600,000
Dams and reservoirs	600,000
Water treatment	26,900,000
Total annual OM&R	$49,600,000
Power	151,600,000
Total annual OMR&P costs	$201,200,000

Obviously, the type of construction and system design would have significant effects on OM&R costs. Expected design and construction would provide a system that would meet the 100-year risk criteria; therefore, O&M costs could be substantially less than for a system with a built-in failure rate of say once in 20 years.

Inland Alternative

Estimated annual operation, maintenance, replacement, and power costs for the inland alternative:

Pumping plants	$19,700,000
Conduit	2,300,000
Dams and reservoirs	600,000
Water treatment	25,500,000
Total annual OM&R	$48,100,000
Power	323,200,000
Total annual OMR&P costs	$371,300,000

In estimating the OM&R costs of the inland alternative, the type of construction and its design would have a significant effect on the costs. Accordingly, the estimates are formulated on the basis of the

100-year risk design, with allowances only for catastrophic destruction of the system in localized areas as by earthquakes. Such destruction is assumed to be a contractual repair and not a continuing OM&R function. However, sinking fund estimates are included for such repair on the 100-year basis. The design includes allowances for the 8.0 Richter quake without damage to the conduit except by displacement.

COST OF WATER

Table 7 presents a summary of the cost per acre-foot of water at full development for both the California Undersea Aqueduct and an alternative inland route. Interest during construction was added to the construction cost to determine the investment cost. The annual equivalent cost was calculated using an interest rate of 5-7/8 percent over a 50- and a 100-year period. For either time frame the cost of water via the offshore route is about 50 percent greater than via the inland route. For a normal 50-year repayment period the costs per acre-foot would be $575 and $380 via the offshore and inland routes, respectively.

For both plans the period of construction is assumed to be 10 years, the contingencies are taken to be about 25 percent of the construction cost, and the indirect costs about 27 percent of the field costs. This approach unduly favors the offshore route because its construction has many more uncertain and unknown factors than the inland route. Other factors not evaluated which will tend to

Table 7. Annual cost of water at full development

	50 years	100 years
California Undersea Aqueduct		
Construction costs	$20,028,000,000	$20,028,000,000
Interest during construction[a]	5,883,000,000	5,883,000,000
Total investment	25,911,000,000	25,911,000,000
Annual equivalent[a]	1,606,500,000	1,528,700,000
Annual OMR&P[b]	201,200,000	201,200,000
Total annual costs	1,807,700,000	1,729,900,000
Annual equivalent water delivered (acre-feet)	3,145,000	3,360,000
Annual cost per acre-foot	575	515
Inland alternative		
Construction costs	$10,186,000,000	$10,186,000,000
Interest during construction[a]	2,992,000,000	2,992,000,000
Total investment	13,178,000,000	13,178,000,000
Annual equivalent[a]	817,000,000	777,500,000
Annual OMR&P[b]	371,300,000	371,300,000
Total annual costs	1,188,300,000	1,148,800,000
Annual equivalent water delivered (acre-feet)	3,145,000	3,360,000
Annual cost per acre-foot	378	342
Say	380	340

[a] 5-7/8 percent interest rate.
[b] Annual at full development.

make the cost spread between the plans greater than shown are: (1) the inland route has energy recovery potential which was not evaluated in determining the cost of water, and (2) the inland route terminus at Desert Hot Springs is closer and at a more favorable elevation for exchange with Colorado River water and for service to Imperial Valley than the offshore terminus at Oceanside.

Copies of this report and appendixes are available at the Engineering and Research Center, Denver, Colorado, and at the Mid-Pacific Regional Office in Sacramento, California. Supporting data for Appendixes I, III, and IV, can be reviewed at the Engineering and Research Center, and for Appendix II at the Mid-Pacific Regional Office.

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