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CORROSION SURVEY OF STEEL SHEET PILING

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CORROSION SURVEY OF STEEL SHEET PILING

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by

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OBJECT OF TASK

To make a systematic study of the corrosion of steel sheet piling in marine environments, in order to improve the design and construction of future installations as well as predict the life of existing structures; and to establish the value and effectiveness of cathodic protection.

ABSTRACT

In a survey of the corrosion occuring on steel sheet piling at eight Naval harbors a parallel series of samples were cut from three piles at each harbor and the corrosion losses were determined by Laboratory analyses. A technical literature survey revealed additional data on the corrosion of steel sheet piling and the effectiveness of cathodic protection.

Investigation showed that the greatest rate of corrosion of steel sheet piling is in the splash zone and at about 2 feet below MLW. The vertical distribution of the intensity of corrosion is the same as that found in the literature.

No protective maintenance coatings had been applied from MLW to the top of the pile at any of the eight harbors investigated. Coating piles fully before driving them increases their life, especially from MLW into the mud zone. Cathodic protection has been in use at Puget Sound Naval Shipyard for the last six years and appears to have retarded corrosion of the piling below MLW.

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INTRODUCTION

The corrosion of steel piling in marine exposure is a problem of considerable concern to the Bureau of Yards and Docks. Navy activities are located throughout the world, and steel piling must be maintained under a wide range of environmental conditions.

Steel pile which extends from below the mud on the bottom of a harbor into the atmosphere above the tidal range exhibits varying rates of corrosion over the entire length of the piling. It is well known that steel piling, if unprotected, exhibits the greatest corrosion in the area of the splash zone above the high water mark. Occasionally the area at the mud line also shows accelerated attack.

Cathodic protection is considered an effective means for protecting the areas of steel piling that are constantly wet. The extent to which the protection carries into the tidal and splash zones has not been completely defined. Data on the mitigation of corrosion in this area is most important, for the Bureau can use it in estimating the service life of existing installations and for designing improved new construction. Of considerable concern is the justifiable extent to which cathodic protection can be used, especially in the tidal zone.

The Bureau of Yards and Docks initiated an Engineering Investigation, (YS-60-29-17), "Corrosion Survey of Steel Sheet Piling" at the Naval Civil Engineering Laboratory to determine the extent of steel sheet piling deterioration at eight Naval activities.

The purpose of this investigation* is to compile sufficient data to improve the design and construction of future installations as well as to have factual information which can be used for estimating the service life of existing and possible future installations.

A primary objective of this study was to determine whether cathodic methods of protecting piling justify the expense of a cathodic protection system.

* BUDOCKS ltr D-420C/SS:mvs NP/PtHue/N8 of 27 Feb 1959.

APPROACH

Literature Survey

The initial approach to the investigation was a search of the published literature for discussions or test results of piling corrosion studies. Particular attention was directed toward finding references on the use of cathodic protection in the tidal and splash zones. The National Association of Corrosion Engineers punch-card abstracts were used as well as indices of various technical journals.

Field Investigation

Eight harbors were selected so that the effect of varying environmental conditions could be determined and a questionnaire was sent to them to obtain data and background information prior to cutting actual samples of steel piling at these activities. A copy of the questionnaire appears in Appendix A, along with a list of previous corrosion surveys.

Several methods of cutting samples from the steel sheet piling were considered. Any procedure used to cut the piling would have to provide samples from atmospheric, tidal and underwater zones. Several methods and types of cutting tools were considered. In order to be practical, little or no staging and simple cutting tools were desired. With the assistance of the Rigging Loft personnel at the Long Beach Naval Shipyard, a simplified procedure was evolved to obtain the necessary samples. A standard acetylene torch was used for cutting above water, Figure 1. The underwater cutting was accomplished using an arc cutting torch. Diving equipment was recommended for underwater work, Figure 2.

Figure 3 shows the location along the piling where samples were to be cut.

A project scientist from the Laboratory was present at each activity to monitor the sample cutting. In several instances the samples of piling below the mud line could not be obtained because the pile had been driven into rock. Immediately after each sample was cut it was identified and tagged by the NCEL representative. After the samples had all been obtained they were carefully packaged and shipped to NCEL for laboratory evaluation.

A sketch, Figure 4, shows the suggested patching plate assembly for plugging the holes cut in the piling. The strong back bar was worked through the hole in the pile, positioned centrally, and the nut on the machine screw was tightened until the steel patch was tight against the pile and completely covered the hole. The steel patch was then welded along all four sides and the nut secured by a weld spot.

Figure 1. Cutting sample from piling above water.

Figure 2. Underwater diving equipment.

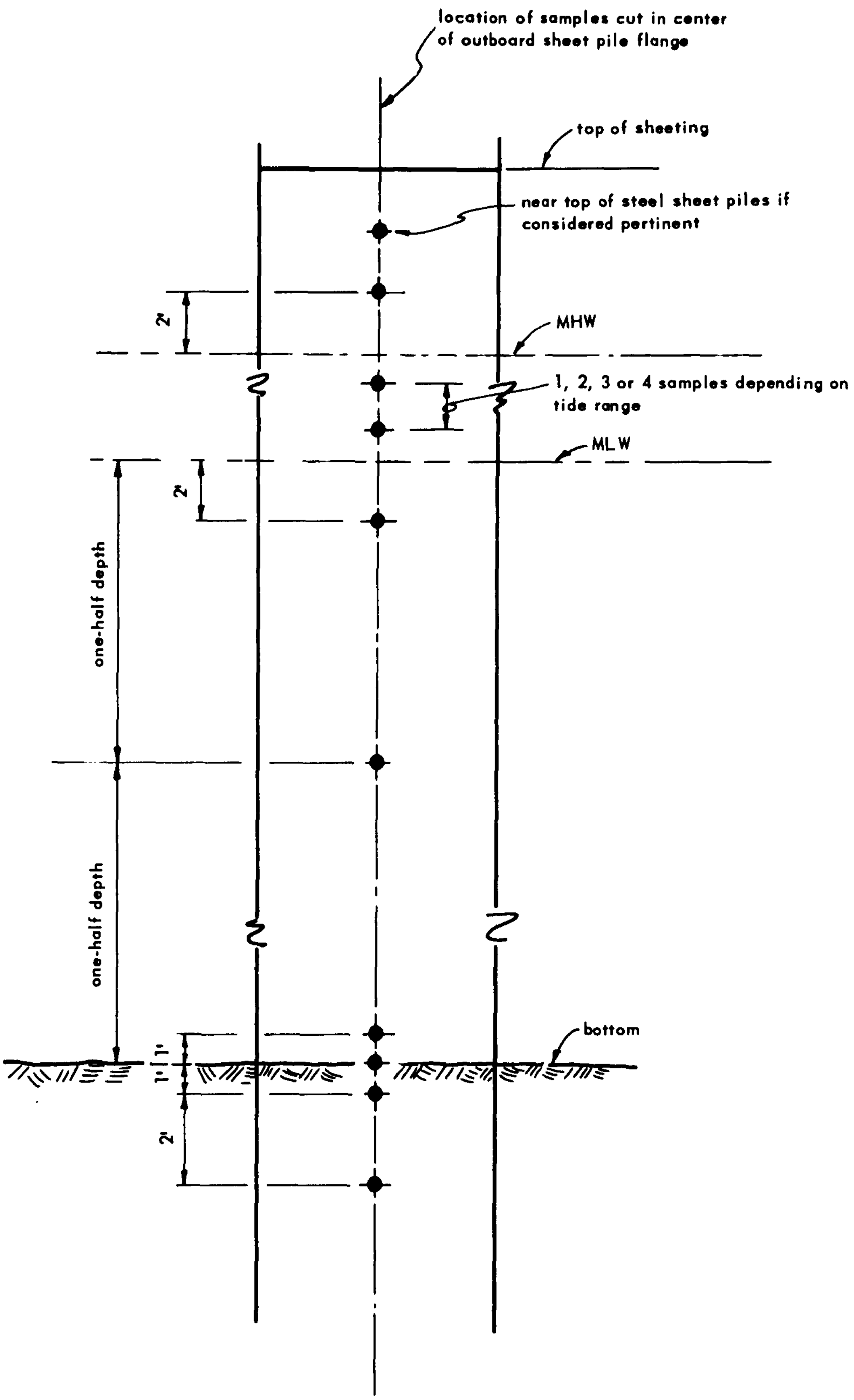

Figure 3. Location of samples cut to determine thickness of steel sheet piling.

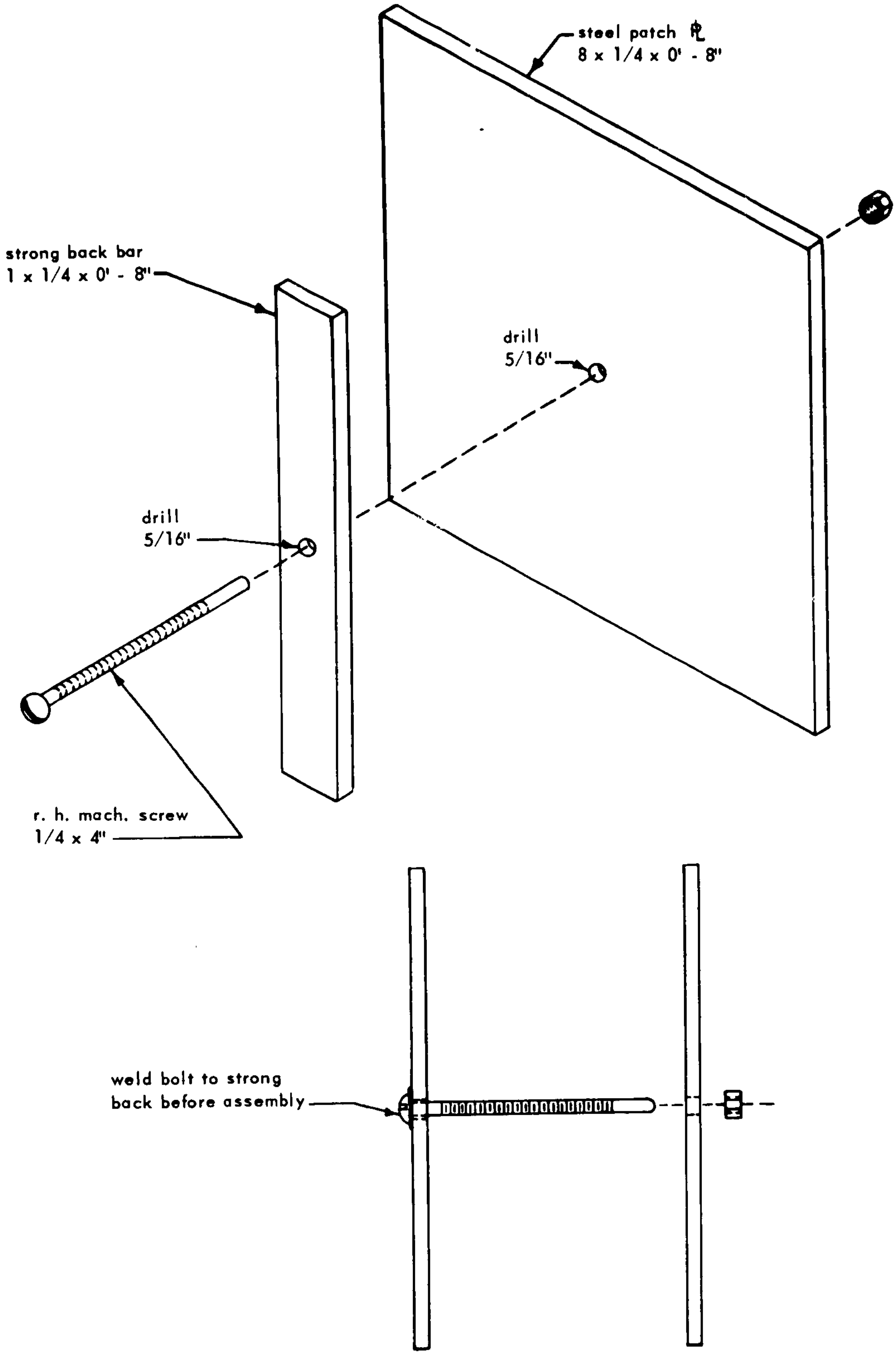

Figure 4. Design of patching plate assembly.

LABORATORY ANALYSIS

At the Laboratory all samples from an individual pile were grouped and photographed both from the front (harbor side) and from the back (land side). However, most of the heavy rust and scale had flaked off during shipment so the loose rust and scale remaining on the samples were removed with a spatula.

To prepare the rough samples for easy comparison, a circular sample was cut from each and milled to a uniform diameter of 1.813 inches. A 0.162-inch hole was drilled in the center of each finished sample. Photographs showing the samples obtained from one pile in each harbor appear in Appendix B.

After being cut to the uniform size the samples were cleaned to bare metal by placing them in an inhibited hydrochloric acid bath at 160 - 180 F for 30 minutes. The samples were first rinsed in distilled water and then in acetone which contained 5 percent (by volume) concentrated ammonia solution. After air drying, the weight loss and the minimum residual thickness were determined. The average loss in thickness was then calculated in mils per year (mpy) for each sample and a profile of the corrosion losses on each pile was obtained by plotting the corrosion losses of the sample against their location on the pile, Appendix C.

Additional photographs were taken to show the appearance of the circular samples after cleaning. One photograph shows the pitting and corrosion attack on the face of the pile. A second photograph shows the edge of the sample and illustrates the relative thickness of the pile at various locations along the pile, Appendix B.

RESULTS

Results of Literature Survey

The review of the technical papers which discussed the application of cathodic protection to steel piling showed that cathodic protection is frequently used in combination with paint coatings, sheathing and concrete capping.

The highest rate of corrosion to steel piling used in the construction of jetties, wharfs, piers, dock walls, caissons, cofferdams, etc. was reported to be in the region of periodic wetting by sea water.[1, 2, 3, 4, 5, 6, 7] Experimental measured corrosion rates during periodic wetting increased with concentration of chloride ion up to 8 percent by weight of sodium chloride in water.[1] Above this concentration the corrosion rate decreases because of the reduction in solubility of oxygen in the solution. During periodic wetting in sea water, thin films of electrolytic solution saturated with oxygen are formed on the surface of the piling throughout the tidal zone. Between this area of the pile and the area of the pile in sea water, corrosion cells are produced by the different oxygen concentrations. The area of the piling in the relatively oxygen-poor sea water is anodic to the exposed area, and the rate of corrosion in this area is reported to be very intense because of the short lines of current flow produced in the electrolytic corrosion cell. The high rate of corrosion is maintained by the continual change in the anodic and cathodic areas during rising and lowering of the tide, and the high concentration of oxygen in the thin film of sea water causes rapid deplorization in this area.[7]

Solution-potential measurements made on uncoupled steel specimens showed that the plates in the tidal zone were strongly cathodic with respect to the plates constantly under water.[6] Thus, when electrically coupled, the continuously immersed specimen would act as a sacrificial anode for the steel specimen in the tidal zone.

A differential aeration cell also occurs at the mud line because of the lower oxygen content below the mud line (anodic area).[3, 5, 6, 7] However, the intensity of corrosion in this area is less than that occurring in the tidal area.

As sea water temperature increases, fouling growth rates increase. The corrosion rate of unprotected steel also increases with the increase in sea water temperature. However, excess fouling protects the steel and reduces the tendency toward increased corrosion.[5]

During solution (or corrosion) of a section of steel piling acting as an anode, electrons flow from the anodic area through the steel to the cathodic area of the piling and release an equivalent amount of hydrogen from the water at the surface of the cathode. Calcareous deposits produced by cathodic current retain cathodic hydrogen and reduce the corrosion rate as well as the current required for cathodic protection. With no protection, oxygen removes this polarizing layer of hydrogen thus permitting corrosion to continue in the anodic area. Bacteria (vibrio desulfricans) can also cause cathode deplorization during reduction of the sulfate ion.

Many factors influence the electrochemical processes of corrosion. Mill scale is cathodic to the metal, the faces of metal crystals are cathodic to the edges, and metal grains of lower carbon content are cathodic to metal grains of higher carbon content. Corrosion potentials as high as 0.2 volt have been shown to result from these heterogeneities.[8]

Cathodic protection makes the piling surfaces the cathode and effectively reverses the natural corrosion processes; under ideal conditions, it completely protects steel from corroding. A large pier costing some $4,000,000 with an expected life of 15 years without protection was shown to have an expected life of 50 years when cathodically protected.[9] Installation of cathodic protection for this particular pier cost about $96,000 and requires an annual expenditure of $6,300 for operation and maintenance. This raises the total cost of the pier with cathodic protection to about $4,411,000 over a 50-year period. This gives an annual depreciation cost of about $88,200 over 50 years compared to a depreciation cost of about $267,000 for a 15-year expected life.

Cathodic protection of steel piling requires good electrical conductivity. The resistance of sea water is so low that it is an ideal conductor for cathodic current. In the tidal area, electrical conductivity between an anode and the steel piling occurs only where continuity exists between the surface film of sea water on the piling and the main body of sea water. Because the piling in the tidal area are moistened by the fluctuating tide, an impressed current will only protect about one-half of the area between high and low water mark.[5, 10, 11, 12, 13] It has been shown that the full length of a steel pile can be satisfactorily protected if a film of sea water is maintained on that surface of the pile extending above the sea water.[14] For wide application of this type of cathodic protection in the periodic moistening zone, it would be necessary to determine the admissible fixed time for operating a periodic sprinkling system, and to calculate water consumption and current requirements.

The literature survey indicates a preference for protecting steel piling in sea water environment by a combination of a protective coating and cathodic protection.[11, 12, 13, 15] It is usually advantageous to coat the entire pile before driving it so as to lower the current requirement.[15] Even a defective coating is better than none at all.[12]

Protection of steel piling in the tidal and atmospheric zones is the major problem in piling protection.[2] The British found that cathodically protecting steel piling in the absence of a protective coating causes calcareous deposits to form and extend about two-thirds of the way up the inter-tidal range. No corrosion of the piles was observed in the region covered by the deposit. They also report that steel piling can be completely protected by over-lapping coating and cathodic protection.[16] They use a quick-drying coating, applied during periods of low tide, to protect the piling above mid tide.

Because the formation of alkali at the cathode is an inevitable feature of cathodic protection in sea water, the presence of saponifiable components in the protective paint coating should be avoided.[13]

To insure good electrical conductivity between the piles they must all be electrically continuous. During construction it is possible to electrically bond the piles through the reinforcing mats of the decking concrete or by use of welded steel bars between piles.[11, 15]

Cathodic protection can be used to prevent corrosion of the reinforcing steel in concrete piles, but if too high a current density is used, corrosion products build up on the reinforcing steel and produce spalling and reduce concrete strength.[10] Thin monel sheathing was used satisfactorily to protect steel piles in the tidal and atmospheric zones in conjunction with cathodic protection in the continuously immersed zone. It was reported that continuously immersed steel in contact with monel in the tidal zone did not show increased rate of corrosion.[5] In fact, when the steel pile contains a monel jacket in the tidal zone it is easier protected below MLW (mean low water) by an impressed current than when the monel jacket is absent.[17]

Studies are being directed toward an improved alloy steel to replace the steel presently used for fabricating steel piles. A nickel-phosphorous steel (0.5 Ni, 0.5 Cu, 0.12 P) was reported to show three times the resistance of ordinary steel sheet piling to pitting attack. Sheet-pile steel containing 0.35 percent copper also gave excellent results in sea water.[4] A silicon (2.3 %) aluminum (0.5 - 1.5 %) steel shows considerably higher oxidation resistance than mild steel except for atmospheres containing high proportions of steam or sulfur-bearing gases.[18] Pitting in alloy steel containing chromium (3.9 %) and aluminum (1.3 %) was one-third that of unalloyed steel after three years immersion in calm sea water.[19] Marine atmospheric exposure very close to the waters' edge showed beneficial effects of aluminum alloyed steel.

Several possible methods of extending the life of steel piling in sea water are summed up in references 5 and 7 as follows:

1. Paint coatings covering only the continuously submerged portion accelerate the already high corrosion rate in the tidal zone. Galvanic action would be very severe at any breaks in this coating below mean low tides.

2. Monel sheathing above mean low tide would be expected to prolong the life of the splash and atmospheric zones.

3. Paint coating above mean low tide would greatly reduce the sacrificial corrosion in the area below mean low tide. Breaks in the paint film would expose a very small cathodic area and would not cause any appreciable accelerated attack in the bare steel below mean low tide.

4. Cathodic protection below mean low tide and a paint coating above mean low tide would give almost complete protection except at breaks in the paint coating. At these breaks, pitting would occur in the steel.

5. Cathodic protection below mean low water and monel sheathing above mean low water is reported to give complete protection to the steel piling. However, once the monel sheathing is punctured, salt water enters the void between the sheath and the steel pile and corrosion of the steel occurs.[20]

As expressed by Schaufele:[21] "The insatiable appetite of nature must have sustenance, preferably coatings and/or anodes rather than structural members. To keep various structural members - timbers, piling, etc. - in balance, it is necessary to inspect, repair or replace at regular intervals."

Results of Questionnaire

The data obtained from the questionnaire appear in Table I. The mean warm water temperatures ranged from 87 F at Key West to 50 F at Bremerton, and the mean cold water temperatures varied from 35 F at Boston to 80 F at Coco Solo. It should be noted that the water temperatures were taken at varying depths, from 2 feet below MLW (mean low water) at Key West to 22 feet below MLW at Boston. The water temperature near the surface at these eight stations, especially in the summer months or during periods of prolonged sunshine, would be expected to be higher than the temperature at greater depths. Thus the corrosion rates in the tidal and atmospheric zones would be affected more by the air and near-surface temperature than by the deeper water temperature.

The fouling appears to be heavier in the areas of warmer, year-round temperatures; but in some areas, Alameda, Coco Solo and Norfolk, for example, both fouling growth and corrosion in the tidal zone were considerably reduced by floating oil resulting from spillage and small boat activity in the harbor.

In four of the harbors examined, the piles had been coated before they were driven. At Key West, Pearl Harbor and Coco Solo, the piles were given a full length coating of a bituminous material, and at Norfolk, their top 10 feet were coated before they were driven into place in the harbor. No piling maintenance after installation was reported except at Bremerton where cathodic protection was applied in 1954, approximately eight years after the piles had been driven.

The cathodic protection system at Bremerton was designed by the contractor as a permanent installation. It is an impressed current system using rectified alternating current and graphite anodes. Seventy thousand square feet of piling is under protection. Details of the system are given on page 27.

The tidal area appears to be slightly protected but the atmospheric zone not at all.

Table I. Questionnaire Data

Station	Mean Temperature of Water			Mean Tidal Range	Water Depth Below MLW*	Fouling				Piling [
						Tidal Zone		Below MLW*		
	High	Low	Depth Taken (feet)			Am't	Type	Am't	Type	Thickness
Boston	65	35	22	10	0-5	none	-	light	fauna	3/8
Norfolk	86	49	15	2.8	20	light (c)	flora	medium	flora	-
Key West	87	71.5	2	1.3	15	light	flora	heavy	flora	1/2
(Atlantic side) Coco Solo	84	80	-	0.9	10-25	light (c)	fauna	medium	fauna	1/2
San Diego	78	61	10	4.9	12	heavy	fauna	medium	fauna	3/8
Alameda	-	-	-	4.7	-	none	(c)	none	(c)	1/2
Bremerton	52	48	20	8	40	light	fauna	medium	fauna	1/2
Pearl Harbor	81	72	15	1.2	20	none	-	heavy	fauna	1/2 3/8 (d)

*Mean Low Water

a - Concrete was poured behind deteriorated piling when corrosion occured (no dates given).
b - These surveys are available.
c - Floating oil present on piling.
d - 1/2 inch flange; 3/8 inch web.

Table I. Questionnaire Data

Fouling				Piling Data		Coated Before Being Driven	Coatings Used	Maintenance	Previous Surveys
Tidal Zone		Below MLW*		Thickness	Dates Driven				
Am't	Type	Am't	Type						
none	-	light	fauna	3/8	March 1942	no	-	none	yes (b)
light (c)	flora	medium	flora	-	May 1933	top- 10 ft.	Bituminous	none (a)	no
light	flora	heavy	flora	1/2	1938	full length	-	none	no
light (c)	fauna	medium	fauna	1/2	1933	-	-	none	yes [illegible])
heavy	fauna	medium	fauna	3/8	1942	-	-	-	no
none	(c)	none	(c)	1/2	1939	none	-	none	yes (b)
light	fauna	medium	fauna	1/2	1946	none	-	Cathodic 1954	yes
none	-	heavy	fauna	1/2 3/8 (d)	1946	full length	34Yb	none	no

rrosion occured (no dates given).

2

Four stations, Boston, Coco Solo, Alameda and Puget Sound reported that the corrosion of steel piling in their respective harbors had been surveyed previously. These reports are available at the stations, Appendix A.

The previous survey made at Alameda recommended that if corrosion in the splash zone developed to a considerable extent, a protective coating should be applied above MLW.

Results from Each Harbor

<u>Boston Naval Shipyard, Boston, Massachusetts</u>. The area of most severe corrosion at this shipyard appeared to be on the sheet piling bulkhead facing north approximately 500 feet north of Dry Dock No. 5. A total of twenty-two test samples were cut from the three test piles. Samples at both one and three feet below the mud line on pile No. 2 were not cut because of an over-stressed condition reported on the pile at this location. Figure 5 shows the general appearance of the piling in the sample cutting area.

The Boston Naval Shipyard reported that thickness measurements of steel sheet piling are being taken at regular intervals at two test locations in the shipyard, and at five locations at the South Boston Annex. The greatest measured loss since 1954 was reported on pile No. 6 at the shipyard. The greatest corrosion to this pile was calculated to be 24 mpy over a five-year period. These corrosion rates were determined from MLW to about 4 feet above MHW.

One pile selected for use in this investigation was 5 feet from pile No. 6 and the other two were 100 feet away. The deepest water was about 5 feet below MLW at the center pile. The mud line on the pile at 100 feet east and at 100 feet west of the center pile was about 1.7 feet and 0.4 feet respectively above MLW. No protective coating or cathodic protection was in use at this test location. The tidal range was 10 feet and the water temperature ranged from 35 - 65 Fahrenheit. Light fouling, principally marine animals, was observed at this test location. The piles were 3/8 inch thick when driven in March 1942, Table I.

The greatest corrosion rate was 8.2 mpy at about one foot above MLW on the center pile. The next greatest corrosion was 7.9 mpy at the mud line on the pile 100 feet east of the center pile. The mud line at this location was 1.7 feet above MLW.

Minimum average corrosion losses were found at one foot above the mud line, just above mid tidal range and at 2 feet above MHW in the splash zone, Appendix C.

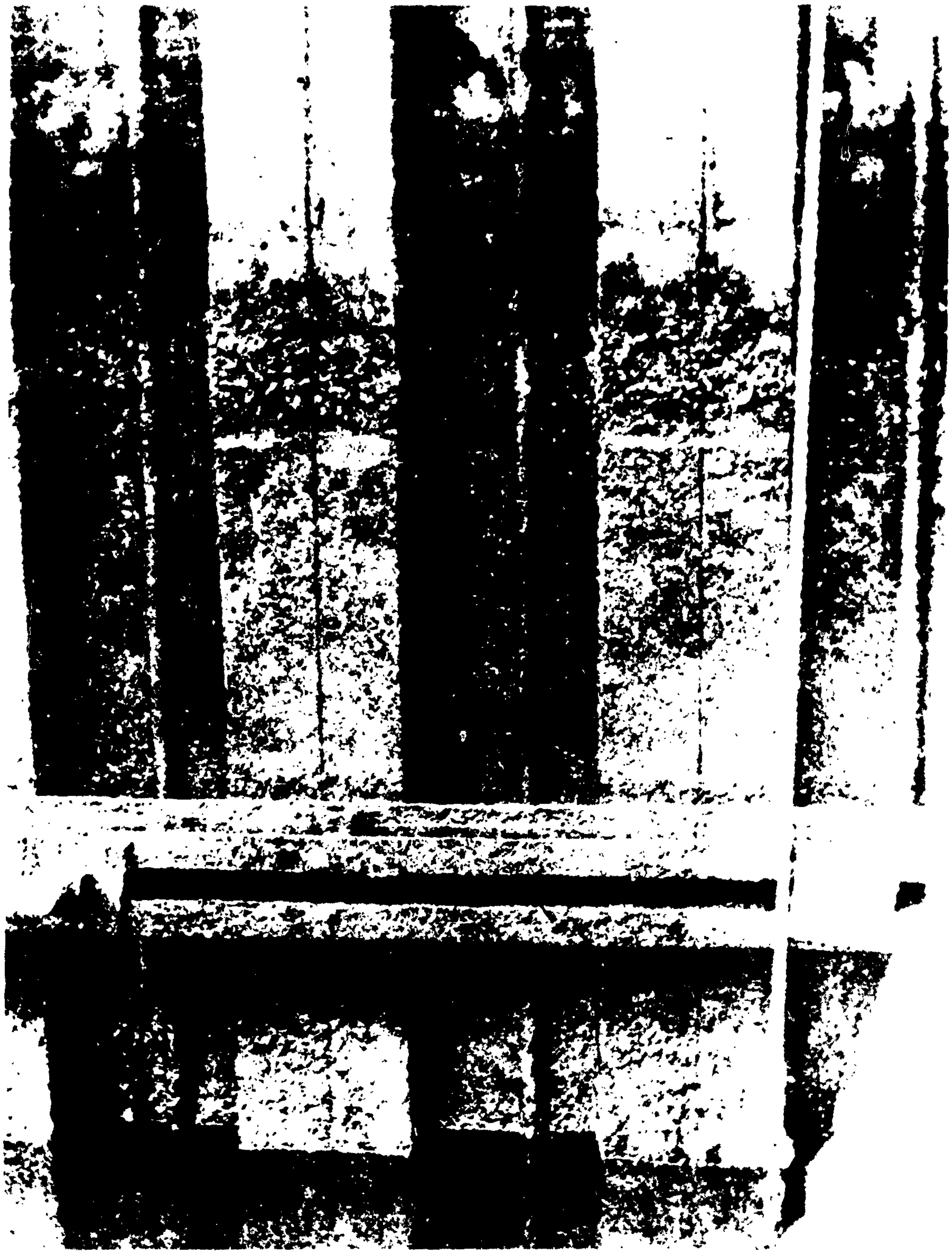

Figure 5. Test area, Boston.

The corrosion rate in the splash zone was slightly lower than that for the area about one foot below MHW. The sample taken at the 2 foot level above MHW was only 2 feet below a 1.5-foot concrete capping. Also the test area was in a section of the harbor sufficiently narrow to minimize wave and spray action during periods of high tide. Under these conditions, the corrosion in the area just below MHW would be expected to be more severe than that in the splash zone.

Calculated from the minimum thickness measurements at the thinnest section, about 59 percent of the pile remains in the area about 2 feet above MLW after 17 years exposure, Table II. The average thickness for all piling in this zone was calculated to be about 81 percent of the original thickness of 3/8 inch. The relative thicknesses are shown in the photographs of the cleaned sample discs, Appendix B.

A study of the corrosion occurring at the Boston Naval Shipyard, was made by Ebasco in 1950. The amount of metal loss occurring at that time, according to the study, would not justify cost of installation of cathodic protection. Starting in 1954 the shipyard has been conducting its own comparative survey of corrosion at the Boston Naval Shipyard, the South Boston Annex and the Bethlehem-Simpson Yard, see Appendix A.

<u>Norfolk Naval Shipyard, Portsmouth, Virginia</u>. The area of most severe corrosion to steel sheet piling at Norfolk Naval Shipyard was reported in the questionnaire to be at the entrance to Dry Dock No. 2, sheet pile wing wall, cofferdam section, Berths No. 13 and No. 14.

The tidal range in this area is 2.79 feet, the water temperature varies from 49 F - 86 F, the fouling is light to medium, mostly flora, and the piling are in 20 feet of water, Table I. Before the piles were driven in 1933, the top 10 feet received a brush coat of bitumastic material. One test pile included in this investigation was driven in December 1941. A view of representative test piling in the area appears in Figure 6. Inspection of the piling in the test area revealed that holes had corroded completely through the piling about one foot below MLW. This area was just above the lower limit of the original protective coating. Considerable patching had been done to prevent flow of back fill material through the holes.

Reference to Appendix C shows that the maximum corrosion to the steel sheet piling investigated at Norfolk was approximately 17 mpy in the anodic area 2 feet below the MLW. The average corrosion at half-water depth and below varied from 2 to 2.5 mpy. In the area from MLW up a protective film of oil resulting from spillage and small boat operation appeared to have coated the piling and augmented the slight protection given by the bituminous protective coating which remained on the piling. Only a very slight amount of the original bitumastic material was in evidence on the piling at or near MLW.

Table II. Percent of Original Pile Remaining

Level (feet)		Boston *Avg.	Boston Min.	Puget Sound Avg.	Puget Sound Min.	San Diego Avg.	San Diego Min.	Alameda Avg.	Alameda Min.	Norfolk Avg.	Norfolk Min.	Key West Avg.	Key West Min.	Pearl Harbor Avg.	Pearl Harbor Min.	Coco Solo Avg.	Coco Solo Min.
	+12	95.5	84.8														
Mean High Water	+10			86.6	73.0	93.5	56.8	91.3	74.2								
	9	89.4	73.1														
	8																
				96.0	88.0	71.8	34.9										
	6	94.3	82.3					100	98.4					85.9	61.9		
				93.1	85.8							54.3	37.8				
	4					92.4	68.8			89.8	54.2						
		88.5	75.7	91.9	82.0			83.8	64.4			68.1	16.8	93.1	65.3	51.6	15.8
	+2																
		80.9	59.2	93.7	83.4	70.1	34.9	89.8	80.0	90.8	78.2			96.0	80.5		
												93.9	76.4			88.0	71.2
Mean Low Water	0																
	-2	75.0	69.6	87.6	77.0	77.7	60.5	91.9	79.2	58.5	9.0	82.8	53.4	87.5	77.8	74.4	57.2
One-half Depth				92.1	82.6	81.2	63.4	88.6	78.2	84.4	63.8	88.7	69.0	89.6	73.0	77.2	49.4
Mud Line	+1	94.4	95.2	94.3	82.8	87.8	75.2	92.6	75.0	90.0	78.6	87.2	74.6	93.7	86.2	87.7	63.6
	0	78.1	63.7	96.4	88.6	94.3	90.4	98.6	96.8	91.0	82.4	87.0	79.6	93.2	86.6	88.5	72.2
	-1	92.8	84.8	95.3	89.6	92.5	89.4	98.0	94.8	94.0	84.6			96.8	88.0	93.8	81.6
	-3	81.6	78.2	95.1	88.0	64.6	56.2			93.6	88.4			96.0	82.0	94.4	80.6
Years in Service		17		13		17		20		27		21		13		24	

*Avg. = Average based on weight loss
*Min. = Minimum based on thickness
~~~~ = MHW
~~~~

Figure 6. Test area, Norfolk.

Thickness measurements of the test samples showed that maximum corrosion occurred at 2 feet below MLW, and that about 9 percent of the original piling thickness remained after 26 years, Table II. The perforations noted above were also in this area. Weight loss measurements showed that 58 percent of the piling remains in this area. From the splash zone 2 feet above MHW, the thinnest section showed about 54 percent of the piling remaining.

The relative thicknesses are shown in the photographs of the cleaned sample discs, Appendix B.

Key West Naval Station, Key West, Florida. The piling at the Key West Naval Station which were selected for this engineering investigation, were located along a quay wall built in 1938 of MZ-27 sections, 1/2 inch thick, Figure 7. The piling were coated full length prior to being driven, but no data were available concerning type of coating, thickness or application. No evidence of the original coating could be found at the time the samples were taken. The water along the quay wall was about 15 feet deep with a tidal range of 1.3 feet and a temperature range from 71.5 - 87.0 Fahrenheit. Fouling ranged from light in the tidal zone to heavy below MLW and consisted mostly of flora. No piling has been replaced to date along the quay.

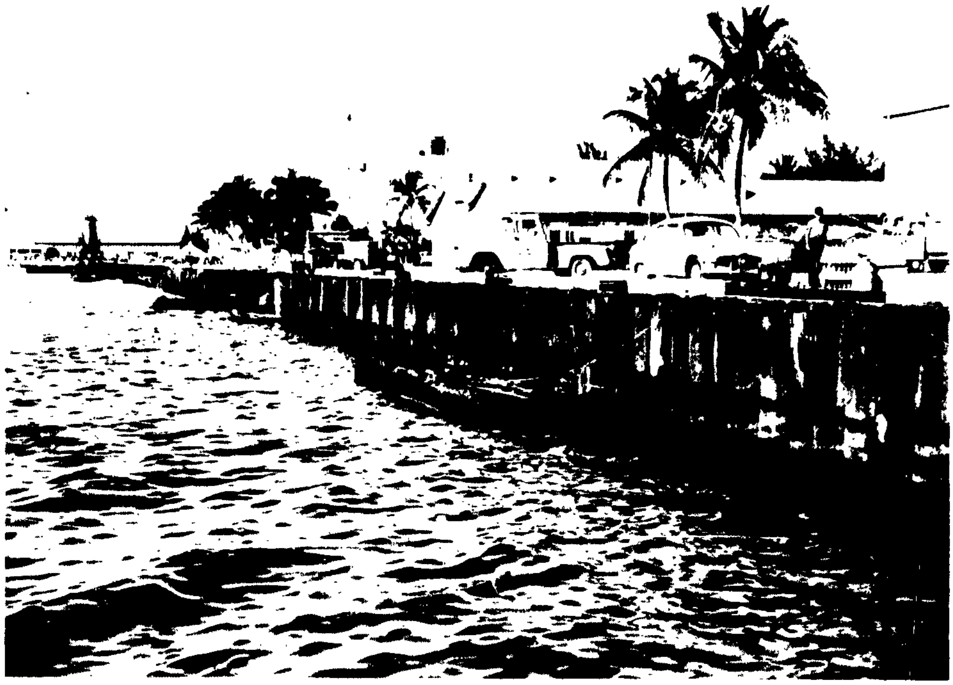

Figure 7. Key West quay test area.

Twenty samples were cut from the three piles at Key West. No samples could be obtained below the mud line because the piles were imbedded in coral. In the areas where the samples were cut, corrosion at inner corners had penetrated completely through the piling in the splash zone.

At the time that the samples were cut a maintenance program had started. Rusted piling, Figure 8, was cleaned of rust by chipping and a protective paint coating was then applied from MLW to the top of the piling. The rust adhering to the vertical area of the piling between the upper and lower brackets, Figure 8, had not been chipped away in this photograph. A comparison with the remaining area from which the rust had been chipped shows the heavy rusting which had occurred along this quay wall.

Figure 9 shows a close-up of a section of the piling after the paint coating had been applied. The results of pitting can be seen in this photograph.

The maximum corrosion rate, 19 mpy, occurred in the splash zone 2 feet above MHW. Another area of high corrosion rate, 10.3 mpy, occurred at 2 feet below MLW, Appendix C. The minimum corrosion was found in the area at half tide.

Figure 8. Piling corrosion at Key West.

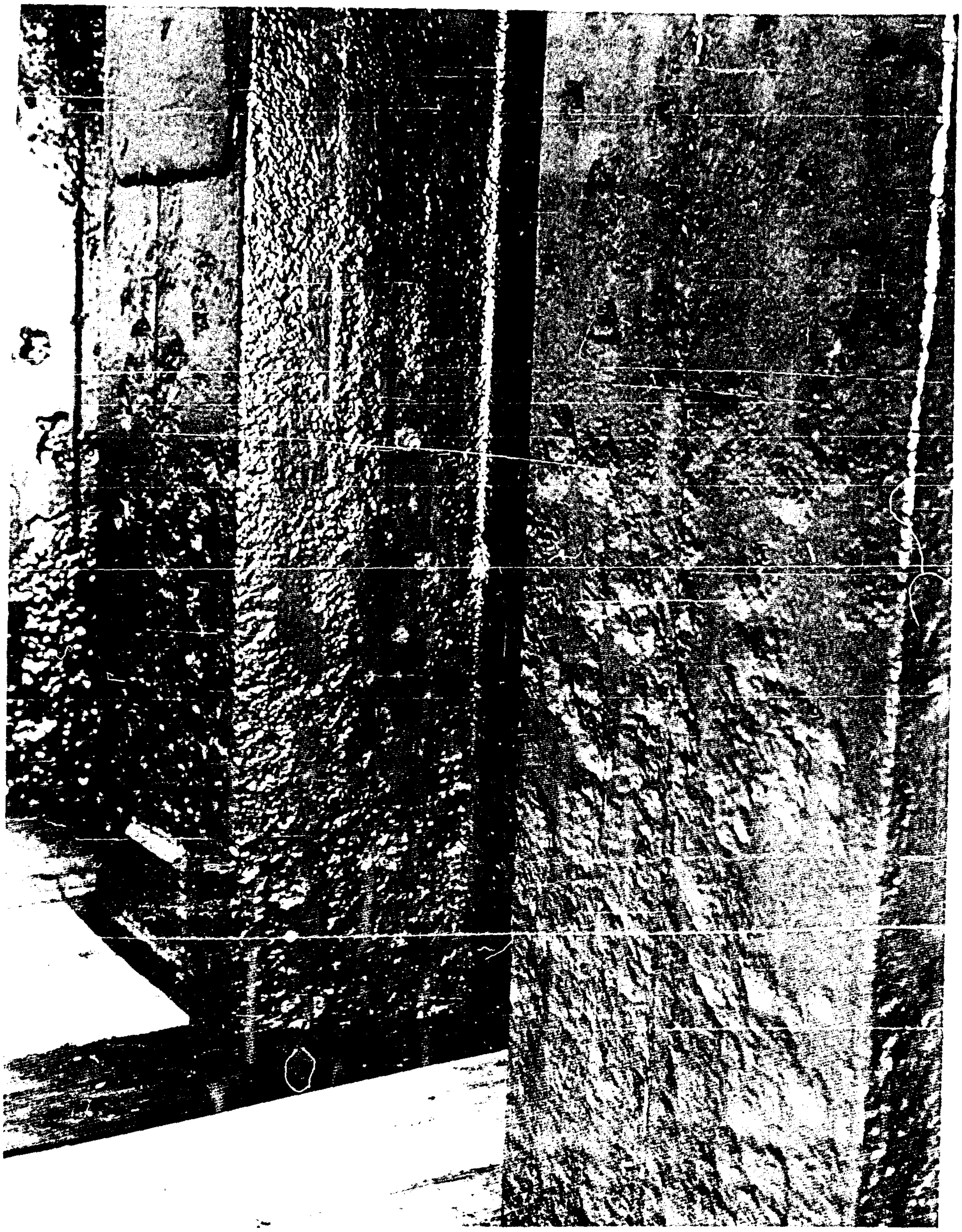

Figure 9. Coated section of piling showing effects of pitting, Key West.

The area of maximum corrosion based on measurements of the minimum thickness of each test sample is the splash zone. A minimum of 17 percent of the original piling thickness remains in this area after 21 years. The average piling weight remaining in this same area was 68 percent, Table II. A minimum thickness of about 38 percent of the original piling remains at an elevation of 4.5 feet above MHW whereas 53 percent of the piling thickness remains at 2 feet below MLW. The average weight of piling remaining below MHW ranged from 83 - 94 percent.

The relative thicknesses along the length of a representative pile are shown in the photographs of the cleaned sample discs, Appendix B.

No previous survey of the corrosion occurring to steel sheet piling has been made at the U. S. Naval Station, Key West, Florida.

U. S. Naval Station, Coco Solo, Canal Zone. Samples were cut from piles of Pier No. 2, Figures 10 and 11. This pier was constructed of closed steel-sheet-pile caissons, filled with earth. The deck consisted of a 6-inch concrete slab resting on the fill and having a peripheral reinforced concrete cap beam. This pier was constructed in 1935. Twenty-four samples were cut from the three piles at Coco Solo. The water depth in the test area was 22 feet, the temperature ranged from 80 - 84 F, the tidal range was 0.9 feet and the fouling ranged from light in the tidal zone to medium below MLW and was predominantly fauna, Table I.

Observations made at the time of cutting the samples revealed that corrosion intensity on the piling progressed rather uniformly from inboard to the outboard end along the pier. Also above high water corrosion appeared severe. No attempt had been made to apply a protective coating to the piling during periods of low tide. Cathodic protection has not been used on this pier. However, from time to time the piling in the tidal zone have become coated with floating oil which appears to have retarded corrosion.

The maximum corrosion rate, based on the thickness of the thinnest portion of the test sample, of 17.3 mpy was found to be in the splash zone about 2 feet above MHW. From 2 feet below MLW downward the maximum corrosion rate decreased rather uniformly from 8.8 mpy to 4.0 mpy at one foot below the mud line. From this point downward the corrosion rate remained constant, Appendix C.

The average corrosion rate in the splash zone, based on overall weight loss measurement, was 10 mpy. After 24 years of exposure, an average of about 51 percent of the steel in the piling remains in the splash zone, Table II. A previous survey of the corrosion occurring at this Naval Station is available, Appendix A.

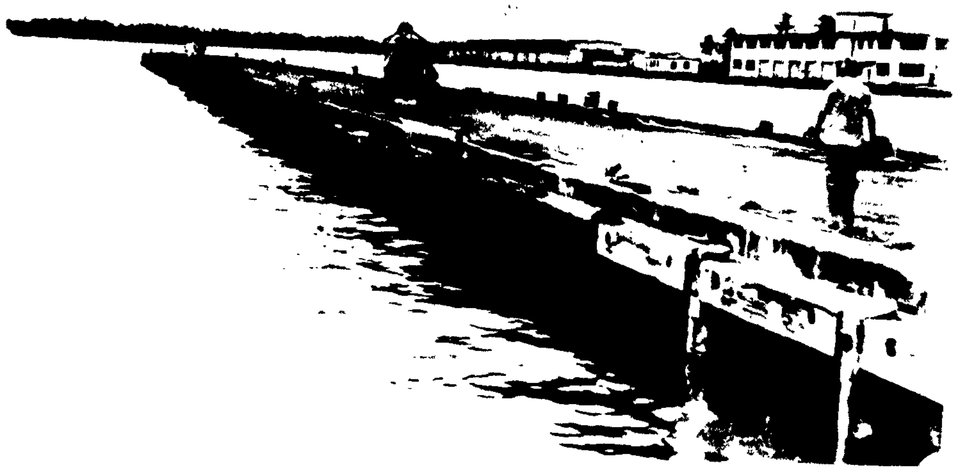

Figure 10. Pier No. 2, Coco Solo, Canal Zone.

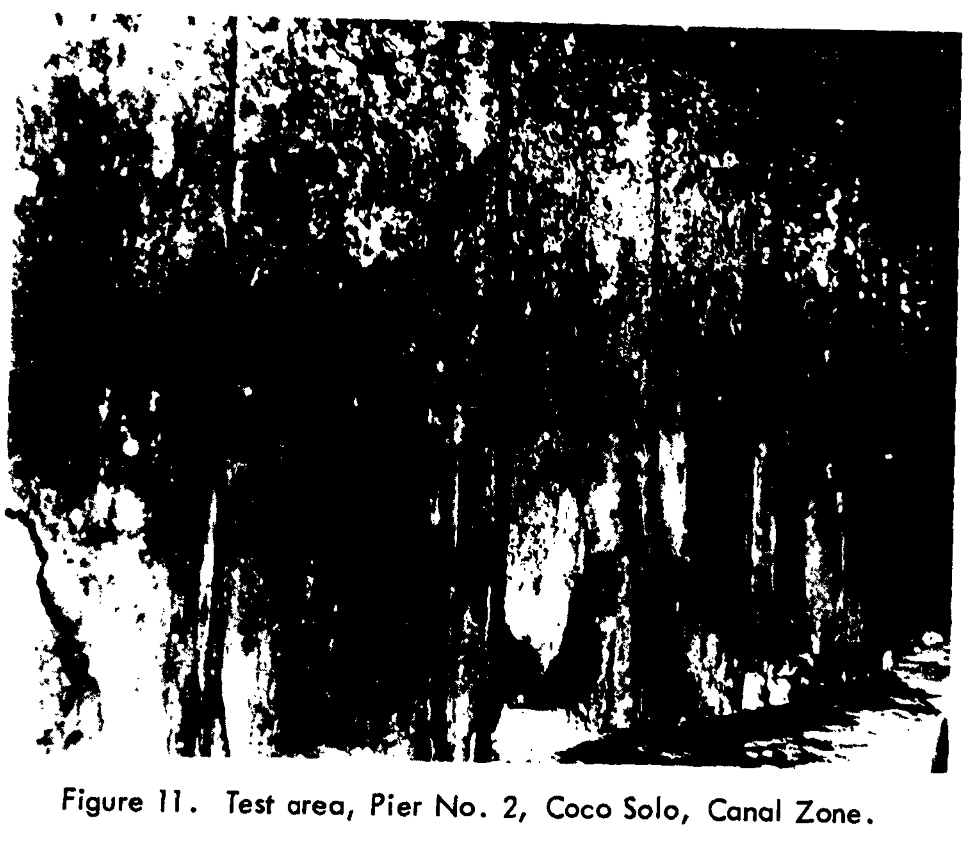

Figure 11. Test area, Pier No. 2, Coco Solo, Canal Zone.

U. S. Naval Station, San Diego, California. The only area in the harbor using sheet piling is the "wet basin." Currently, this area is being used to bring in small craft from naval vessels; from the wet basin they are lifted up onto land and given a hull reconditioning. The harbor in this area is reported to receive discharge from sewage treatment plants and has little regular change of water other than that caused by tidal action.

The depth of water in the test piling area was 12 feet below MLW, the mean tidal range was 4.9 feet and the water temperature varied from 61 - 78 Fahrenheit. The fouling varied from heavy in the tidal area to medium below MLW and was predominately fauna. The piling on the inner walls of the basin were DP-2 sections, 3/8 inch thick, Figure 12, and along the outer wall were Z-type, 1/2 inch thick. The piling were driven in 1942, Table I.

Figure 12. Sheet pile, wet basin, San Diego.

The maximum rate of corrosion, 14 mpy occurred at approximately one foot above MLW and again at about 2 feet above MHW, in the splash zone, Figure 13. A high rate of 12.6 mpy was found 3 feet below the mud line. The average rates of corrosion based on weight loss measurements were found to be about 7 mpy 2 feet above MHW, 8 mpy one foot above MLW and 10 mpy at 3 feet below the mud line, Appendix C.

Corrosion in the lower levels of the tidal range was aggravated by the continuous scraping effect from camels and small boats coming along side of the piling. An appreciable thickness of oxide scale could not form thus reversing the anodic-cathodic relationship normally present in the MLW area.

The high rate of corrosion found 3 feet below the mud line can only be explained by a lower pH in this zone or an oxygen concentration cell. The effects produced by the sewage disposal effluent in the basin and the slight stagnation in this area were not analyzed.

About 35 percent of the original piling weight remains in the upper and lower tidal zones, Table II.

No previous surveys of the corrosion of steel sheet piling have been reported for the U. S. Naval Station, San Diego.

U. S. Naval Air Station, Alameda, California. The only available sheet piling at the Naval Air Station were the walls of Pier 1, a fueling pier, Figure 14. Considerable difficulty was encountered during cutting operations. For example, small underwater explosions of unknown origin occurred while cutting underwater samples from the first pile. The explosions may have been caused by pockets of spilled fuel back of the sheet pile. Additional locations were selected that were remote from any valve pit or fuel line.

Because of the heavy work schedules at Alameda the sample cutting could not be completed during the visit of the NCEL representative. Samples at 3 feet below the mud line could not be obtained.

The piling used for this investigation were in approximately 12 feet of water with a mean tidal range of 4.7 feet. No fouling was present on the piling because of a coating of oil from fueling and small craft operations at the pier. The sheet piling sampled was 1/2 inch thick when installed in 1939, Table I.

Figure 13. Close-up of piling near MLW, San Diego.

Figure 14. Pier 1, Naval Air Station, Alameda.

Twenty samples were cut from the sheet piling of Pier 1 for use in this investigation. The maximum rate of corrosion, 8.6 mpy, occurred in the tidal range approximately two-thirds of the way from MLW to MHW. Weight loss measurements showed that the average corrosion rate in this area is 5.6 mpy. A maximum corrosion rate of 6 mpy occurred at one foot above the mud line and again at the top of the piling about 5 feet above MHW, Appendix C.

An unusually low rate of corrosion, about 0.5 mpy, was found in the splash zone, 2 feet above MHW. Apparently, fuel oil which coated the piling above MHW was not leached away by splash and spray during periods of high tide. As a result a film of fuel oil continuously coated the piling in this area and greatly reduced the corrosion.

After 20 years, the thinnest section of piling was about 3 feet above MLW where about 64 percent of the piling remained, Table II.

Results of a previous survey of corrosion to sheet piling in the San Francisco harbor are available, Appendix A.

Puget Sound Naval Shipyard, Bremerton, Washington. The steel sheet piling at Puget Sound were under cathodic protection, and the piling from which the samples were cut enclosed gravel-filled caissons used for mooring purposes, Figures 15 and 16. A lead for a graphite anode can be seen in Figure 15. After cutting a sample a temporary patch was required to prevent the gravel fill from flowing through the cut hole, Figure 16. The depth of water in the sample area was 40 feet and the mean tidal range was 10 feet. The water temperature varied from 48 - 52 F and the fouling ranged from light in the tidal zone to medium below MLW. The piling was 1/2 inch thick when driven in 1946; cathodic protection was applied in 1954, Table I.

The cathodic protection system was designed by the Hinchman Corporation, Detroit, Michigan, as a permanent installation. Graphite anodes supply rectified AC current to the piling. The estimated cost of the system, including preliminary investigation and design was $45,000. The estimated annual operating cost is $350, and the annual maintenance cost is $450. Approximately 70,000 square feet of steel sheet piling is being protected in the always-wet zones at this cost. The system is checked and adjusted every two months. The voltage to the steel piling is maintained at 0.80 to 0.85 negative. The piling did not contain a protective coating before being driven in 1946, and no maintenance coating has ever been applied.

The maximum corrosion rate of the sheet piling at Puget Sound was 10 mpy in the splash zone 2 feet above MHW; cathodic protection does not extend to this area. A high corrosion rate of 8.5 mpy was shown at 2 feet below MLW in the cathodic protection area, Appendix C.

The minimum piling thickness remaining in the test area was shown to be about 73 percent in the splash zone, Table II. At one foot above MLW a minimum of about 78 percent of the piling was shown to be remaining.

Previous reports on the corrosion to piling at Bremerton were prepared in 1952 and 1956. Copies are available, Appendix A.

Pearl Harbor Naval Shipyard, Pearl Harbor, Hawaii. The area selected for investigation was the Pearl Harbor Naval Shipyard Annex, Section W-22 Waipio Peninsula. The water depth in this area was about 20 feet below MLW and the mean tidal range was 1.2 feet. The water temperature ranged from 72 - 81 F at a depth of 15 feet. No fouling was noted in the tidal zone and medium fouling occurred below MLW and was predominately fauna. The piling had been coated to full length with one coat of 34Yb specification material prior to being driven in 1946. Cathodic protection has not been used on sheet piling in this area of the harbor. The sheet piling had a web thickness of 3/8 inch and a flange of 1/2 inch, Table I. The harbor water in the area of the sample cutting was badly contaminated with sewage.

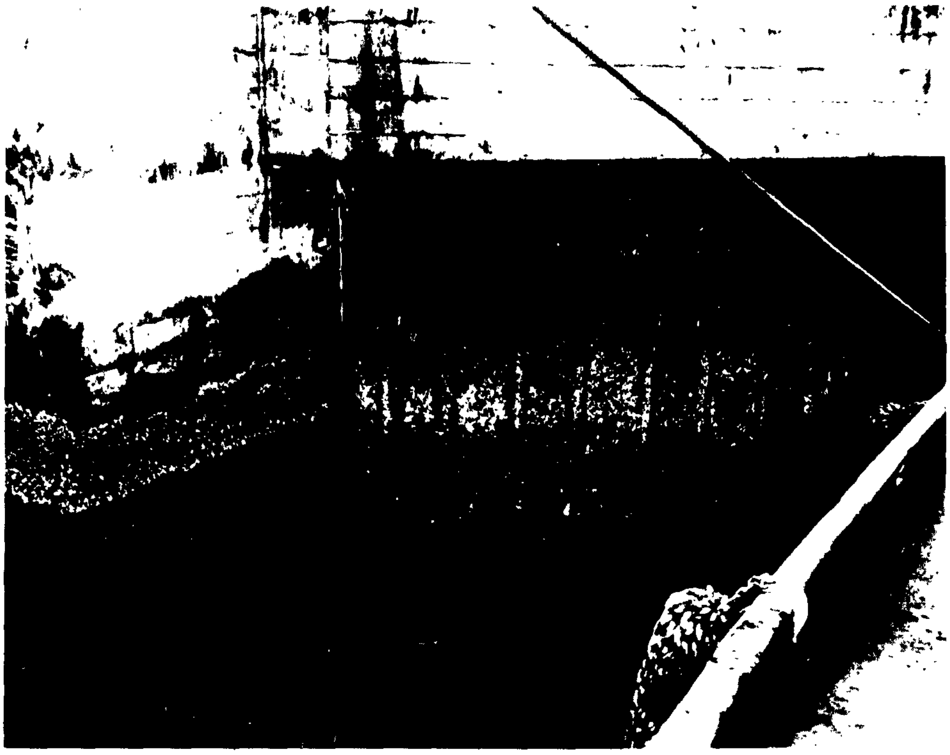

Figure 15. Sheet piling caisson, Puget Sound.

Figure 16. Close-up of piling after removal of sample, Puget Sound.

Twenty-six samples were obtained from the three piles. One sample at 3 feet below the mud line could not be cut because of mud rock. Inspection of the piling and the cut samples showed little or no protective coating remaining above one-half depth of mean low water (afterward called one-half depth). Considerable rusting was observed in the splash and atmospheric zones as shown in Figure 17. As cutting progressed down along the piling below the one-half depth the amount of protective coating remaining on the piling increased. Figure 18 shows the slight pitting on a test sample beneath the protective coating after 13 years at a depth of 18 feet, which was one foot above the mud line.

The maximum corrosion rate of 11 mpy was found near the top of the piling about 6 feet above MHW. Two additional areas with a severe corrosion rate, 10 mpy, were at 2 feet above MHW and at the one-half depth, Appendix C.

The corrosion on one specimen taken at the one-half depth had one large pit. This condition could have been caused by damage to the protective coating followed by accelerated corrosion in this small anodic area. After the major portion of the coating became detached from the piling in the area surrounding the pit, the corrosion became more general and less localized. When the sample was cut, the corrosion products in the pit and in the surrounding area appeared to be uniform. The average corrosion rate from weight loss measurements at the one-half depth was found to be 4 mpy.

The thinnest section of piling after 13 years was near the top of the piling where 52 percent of the original thickness remains, Table II. The splash zone and the anodic zone 2 feet below MLW show a minimum of approximately 65 and 78 percent of the original piling thickness remaining.

No previous surveys of corrosion to sheet piling have been made at Pearl Harbor.

DISCUSSION

The relative amount of steel remaining on the piling at the various sampling locations are presented in Table II. The average figures were obtained from weight loss measurements. The minimum figures were calculated from micrometer measurements on the thinnest section of the test sample, and represent the maximum corrosion in the specified zone. By reference to the average and minimum columns of Table II an estimate can be made of the remaining service life for the piling.

Appendix C shows that, except for the harbors at Boston and Alameda, the corrosion rate of steel sheet piling is most severe in the splash zone. At Boston a sheltered condition existed which decreased the amount of wetting in the splash zone

Figure 17. Sheet piling, Pearl Harbor.

Figure 18. 34Yb coating and test sample, one foot above mud line, Pearl Harbor.

and thus also decreased the corrosion rate. At Alameda the test piling were part of a fueling pier, and the fuel oil floating on the water surface continually wetted the pile and acted as a corrosion inhibitor.

In every instance the maximum corrosion rate in the splash zone is as much as triple the average corrosion rate in the same area.

Of the four harbors where samples were cut in the atmospheric zone near the top of the piling, two showed an increase and two showed a decrease over the corrosion rates 2 feet above MHW in the splash zone. These samples were obtained from about 5 feet above MHW and the corrosion rates demonstrate that the splash zone can extend as high as 5 feet above MHW. The corrosion near the top of the piling is affected by the prevailing wind, the amount of splash and spray, and the presence of overhanging capping, as well as by the presence of a protective coating or oil film. In quiet water the corrosion near the top of the pile would be expected to be less than in the splash zone or just below MHW.

The anodic area, usually found to be 2 feet below MLW, was evident at all harbors except San Diego and Alameda. The anodic condition is caused by a lower oxygen concentration in the sea water than in the tidal area above MLW. The oxygen-poor portion of an oxygen concentration cell is always anodic to the oxygen-rich portion. At San Diego the area about one foot above MLW was frequently scraped by small craft and floating camels which prevented heavy rust scale from forming on the outward face of the piles. Essentially rust-free steel is anodic to steel covered with rust scale and this area therefore is anodic to both the splash zone and to the area 2 feet below MLW which is ordinarily the anode for the splash zone.

The average corrosion rates at one-half depth for the eight harbors were about 3.6 mpy. The maximum rate at one-half depth which was 4.7 mpy occurred at both Coco Solo and Pearl Harbor; the lowest one-half depth corrosion rate was at Alameda, 2.5 mpy.

The average corrosion rates at the mud line were below 5.0 mpy, and averaged 2.2 mpy for the eight harbors. The highest average mud line corrosion was at Boston, 4.8 mpy, although two of the three mud line samples cut there were 0.7 and 1.7 feet above MLW, respectively. Thus, at periods of MLW, the higher available oxygen concentrations accelerated corrosion of these two piles.

At one- and three-foot levels below the mud line, the corrosion rates varied only slightly from those which occurred at the mud line. An exception occurs at the San Diego harbor where a high corrosion rate, 10 - 13 mpy, was found 3 feet below the mud line. Local conditions in the harbor at the test site may have produced a high pH or oxygen cell corrosion at this level.

The effects of the cathodic protection used at Bremerton for the last six years cannot be accurately evaluated because the system was installed eight years after the piling were driven. No protective coating was applied to the piling prior to driving and thus corrosion proceeded normally for eight years. The data shown in Table II and Appendix C give the combined results of eight years normal corrosion followed by six years cathodic protection. However, the corrosion rate curves, Appendix C, do show a rather uniform corrosion rate for the full length of the piling with the maximum corrosion rate in the splash zone. In comparison, the corrosion rates at the other harbors show considerable variations in corrosion rates over the full length of the piling.

The findings in this report represent the conditions at the particular test area in each harbor and are not necessarily the conditions existing in all areas of the harbor.

CONCLUSIONS

The corrosion survey of steel sheet piling at eight Naval harbors revealed the following:

1. The maximum rate of corrosion occurs in the splash zone about 2 feet above MHW.

2. A secondary high corrosion rate of slightly less magnitude occurs in the anodic area about 2 feet below MLW.

3. The average corrosion rate at one-half depth is low, averaging about 3.6 mpy.

4. Corrosion rates from about one foot above the mud line to 3 feet below the mud line are generally low, averaging 2.2 mpy at the mud line.

5. The corrosion rates from the mid tide to 3 feet below the mud line were the most uniform at Puget Sound where cathodic protection has been in use for six years.

6. A protective coating applied along the full length of a pile before driving increases the life of the pile especially from MLW into the mud zone.

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APPENDIX A

QUESTIONNAIRE AND LIST OF PREVIOUS SURVEYS

PRELIMINARY DATA REQUIRED FOR USE IN STUDY OF CORROSION OF STEEL SHEET PILING

1. Naval activity, address, and telephone number:

2. Name of person preparing report and telephone extension:

3. Are there locations within the harbor where sheet piling appears to deteriorate most rapidly? Explain. (Use additional space if required to report on this item.)

4. a. Tidal range in area:

   b. Mean high water:

   c. Mean low water:

5. a. Maximum and minimum average water temperature in sheet piling area ________ °F, ________ °F.

   b. Average depth at which temperature was taken ______ ft.

   c. Depth of water in sheet piling area ______ ft.

6. Amount of fouling on sheet piling in:

   a. Splash zone area

   b. Below M.L.W.

   (Designate fouling as: None, light, medium, or heavy)

7. Is fouling predominantly flora (plant) or fauna (animal) in these two areas:

   a. Splash zone area

   b. Below M.L.W.

8. a. Specification or nominal composition of steel used in sheet piling:

   b. Manufacturers name and address:

   c. Nominal thickness of sheet piles______inches.

9. When were sheet piles referred to in question 3 above first installed?

   By whom?

10. Was piling coated prior to installation______?

    To what length?

11. Give complete coating system as follows:

    a. Surface preparation

b. Coating (type or name)	No. of Coats	Thickness (Avg)
Primer		mils
Intemediate		mils
Topcoat		mils
Total Thickness		mils

12. a. Has it been necessary to replace any of the sheet piling located in the area listed in question 3 above?

b. Dates

c. Specification or nominal composition of steel used in replacement piling.

13. a. Was the renewal piling coated prior to installation?

b. Surface preparation

c. Coating (type or name)	No. of Coats	Thickness (Avg)
Primer		mils
Intermediate		mils
Topcoat		mils
Total Thickness		mils

d. Length of each pile coated _____ft.

14. Has any attempt been made to coat piling in place during low tide?

Describe

15. Has cathodic protection been employed?

a. Date system installed.

b. Designed life of system ________ years.

c. Estimated square feet under protection _________ sq. ft.

d. Is it protected on land side _______ , seaward side _______.

16. Who designed and specified system?

17. Type of cathodic protection employed

    a. Impressed current

        1. Source of power (D. C. generator or rectified A. C.)

        2. Anode material used

    b. Sacrificial

        1. Anode material used

18. a. Estimated cost of system installation, including preliminary investigation and design costs.

    b. Estimated annual operating cost of system.

    c. Estimated annual maintenance cost of system.

19. Have design changes been made by maintenance forces since original installation of system?

    a. Major design change (switching from sacrificial to impressed)

    b. Minor design change (change of anode material, changing capacity of system, etc.)

    c. Reason for change (Give dates and cost)

20. What control is exercised over the cathodic protection system?

21. a. Is system checked and adjusted periodically?

    b. How often __________ By whom __________?

    c. Within what range is the voltage and current density controlled?

d. Have any automatic control devices been used ____________________

Type ____

Success ____

22. Opinion of Public Works Department Engineers concerning:

    a. Effectiveness of cathodic protection in prolonging life of piling, considering such areas as:

       Seaward side (Splash zone and Below M.L.W.)

       Land side

    b. Adverse effects resulting from use of cathodic protection

23. Does cathodic protection appear to be an economical method to prevent corrosion? Discuss

24. a. Have there been previous surveys concerned with the corrosion of sheet steel piling at this activity?

    b. Are reports of these surveys available?

25. List any other information which is pertinent to the survey.

The following Previous Reports of Corrosion Surveys are available from the activity:

U. S. Naval Station, Coco Solo, Canal Zone:

Report on "Structural Condition of Piers at U. S. Naval Station," Coco Solo, C. Z.—prepared by DPWO, 15ND in September 1952.

Naval Air Station, Alameda, California:

The Hinchman Corporation, Detroit, Michigan, Contract NBy-23931

Puget Sound Naval Shipyard, Bremerton, Washington:

1. The Hinchman Report, 1952

2. Informal Report by Shipyard, 1956, sample cutouts available

Boston Naval Shipyard, Boston, Massachusetts:

1. A corrosion survey was made in 1950 by Ebasco Services Incorporated, New York.

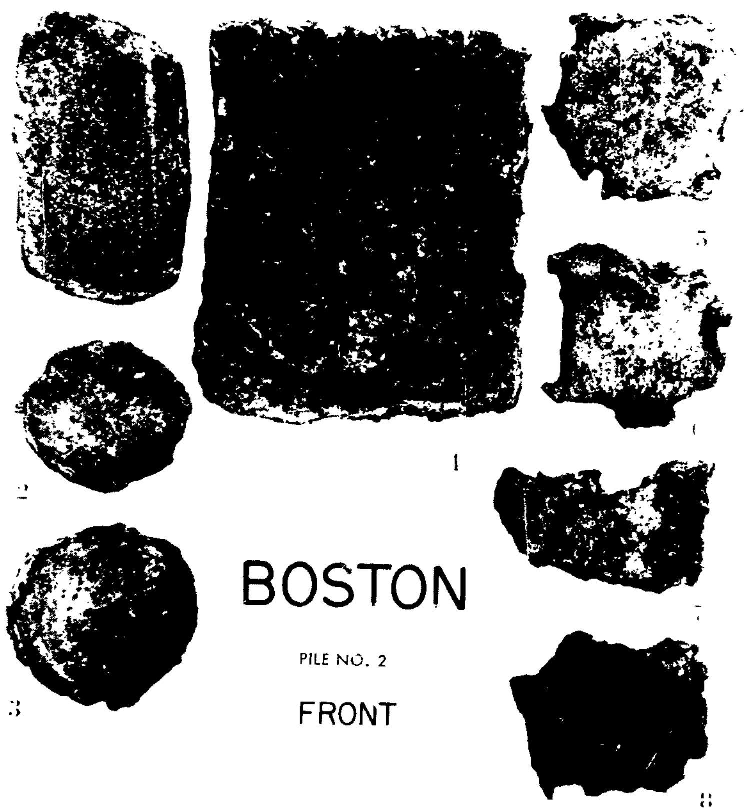
2. A continuing survey of piling thickness started in 1954 is being conducted by Public Works personnel of the Boston Naval Shipyard.

APPENDIX B

PHOTOGRAPHS OF SAMPLES CUT FROM PILES AT EIGHT NAVAL HARBORS

NOTE: Sample numbering starts at the top of the pile and proceeds downward.

For each harbor, all illustrated samples bearing the same number are merely different views or cuts of the same sample.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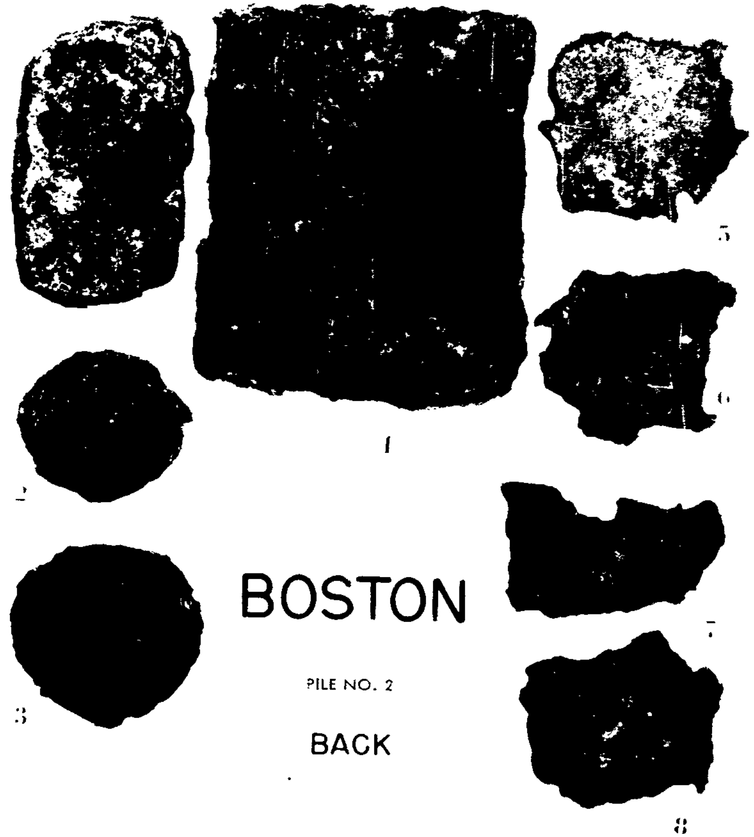
FRONT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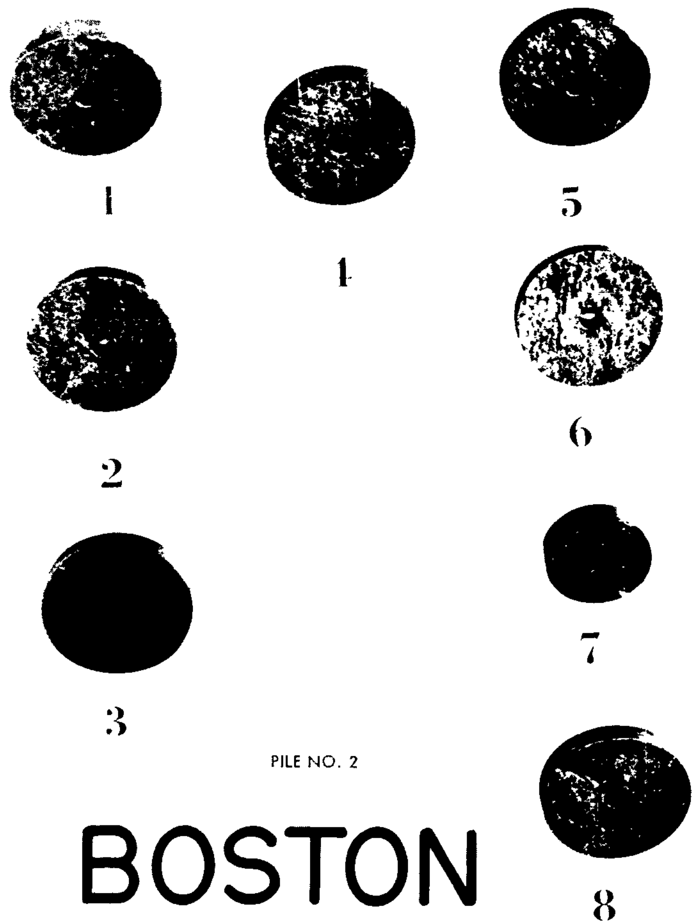

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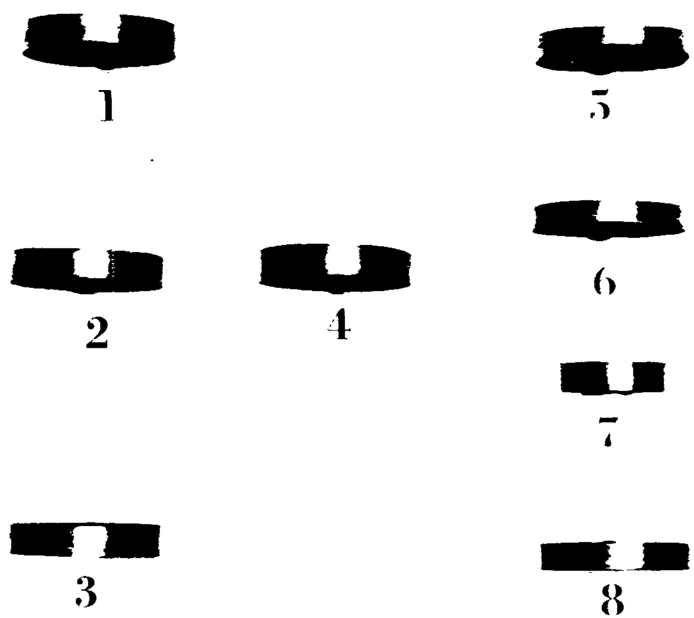

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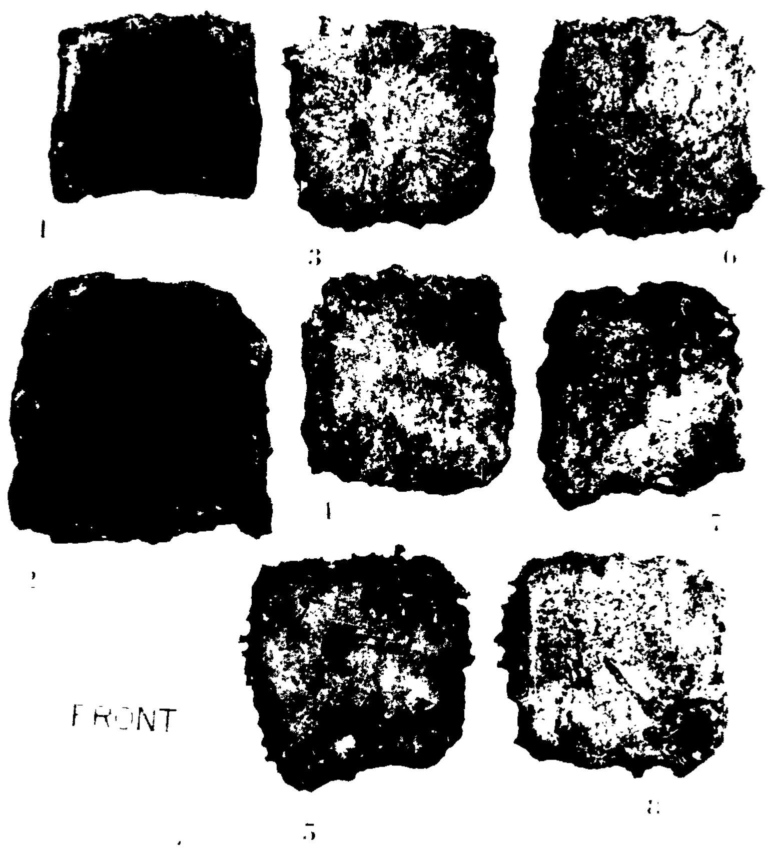
BOSTON



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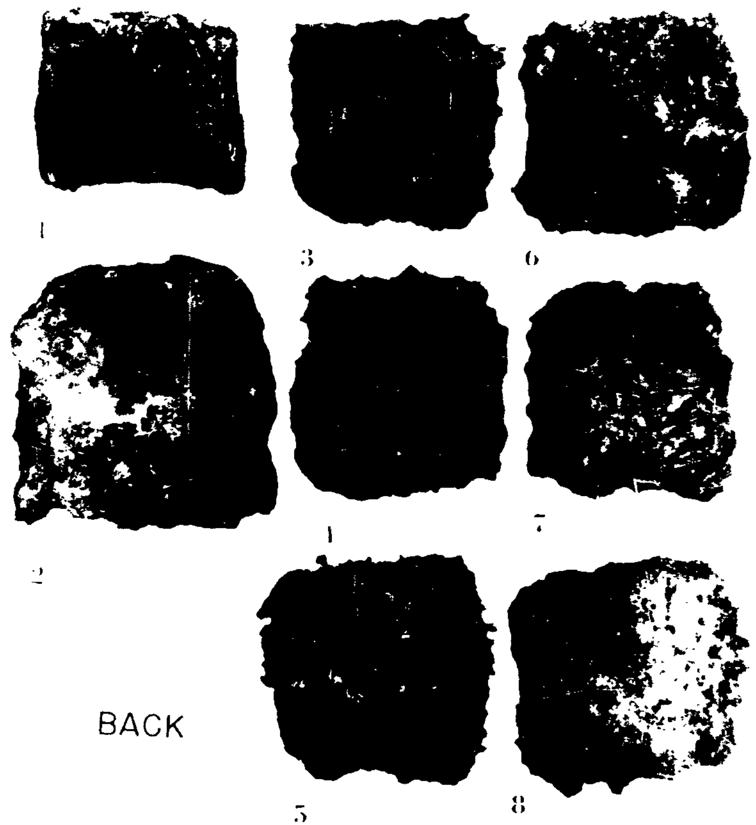

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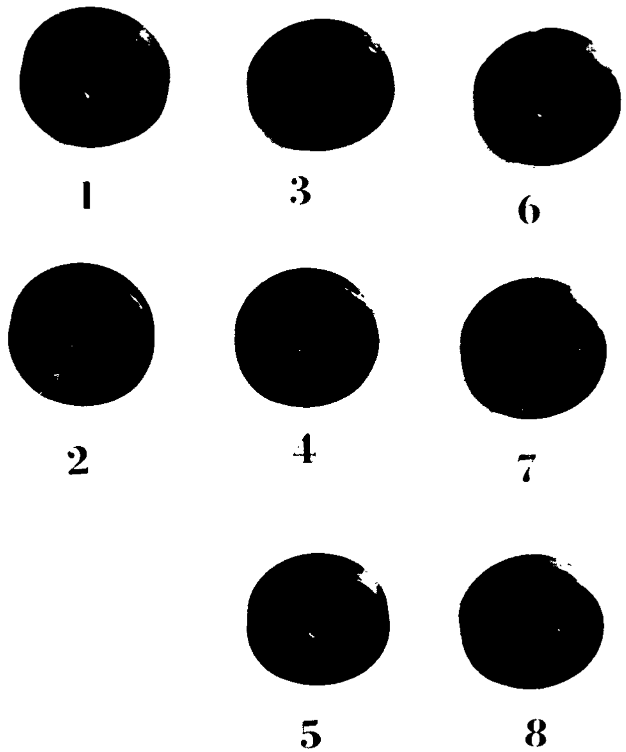

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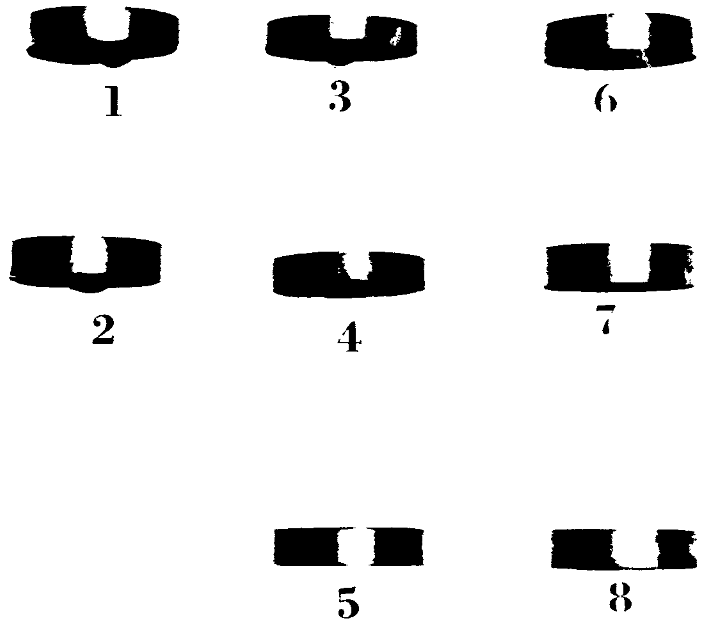

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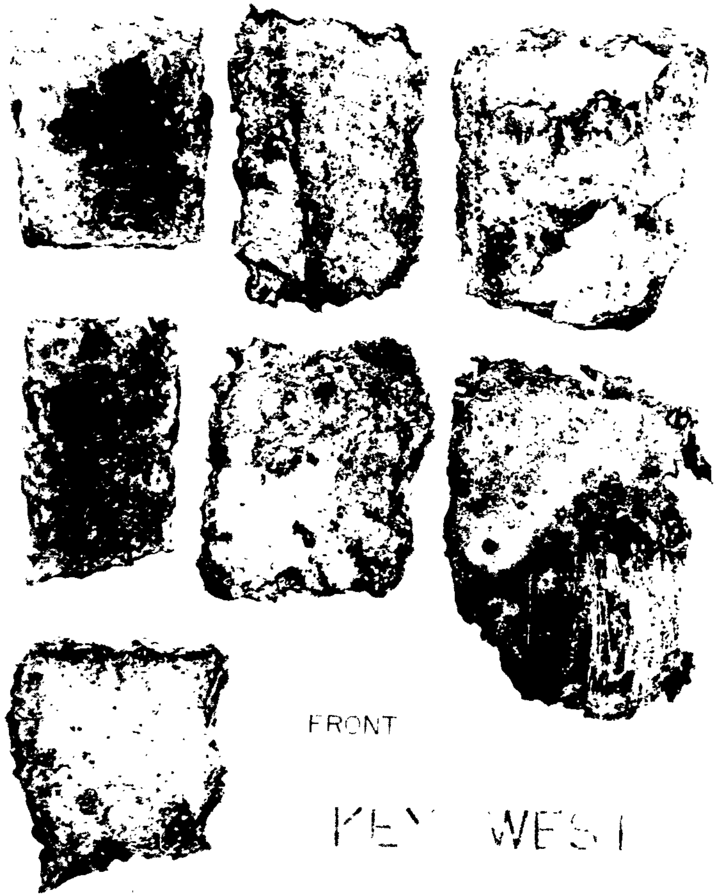
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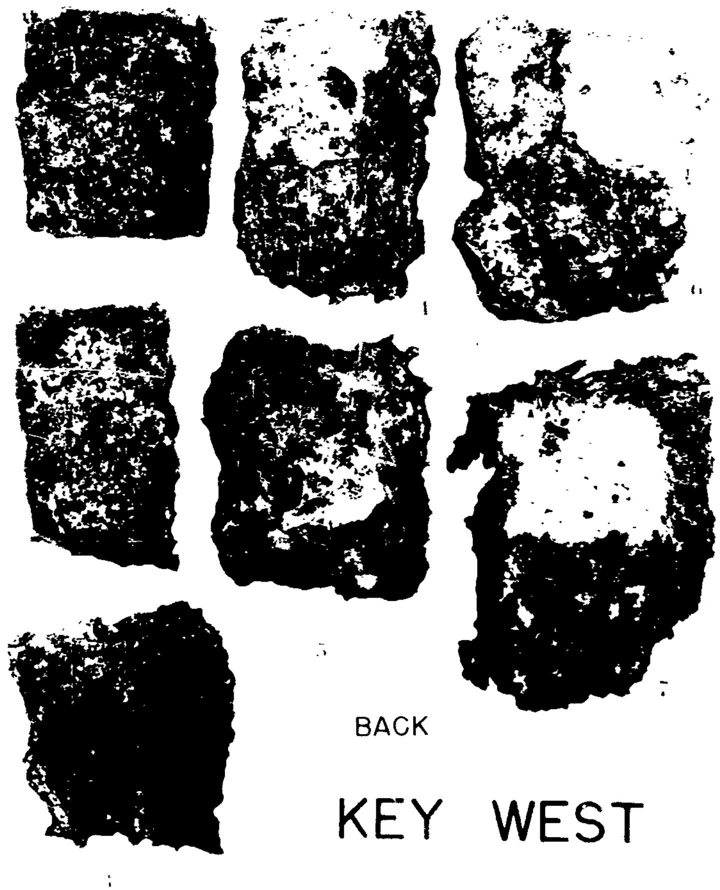
KEY WEST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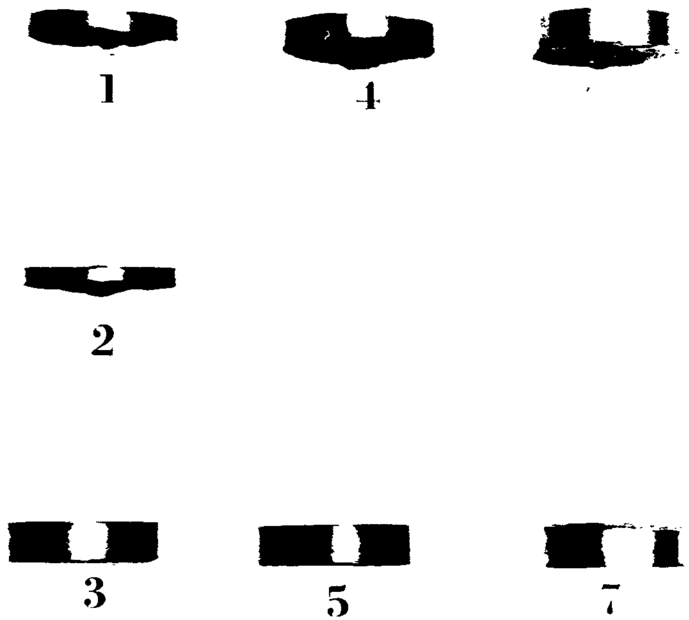

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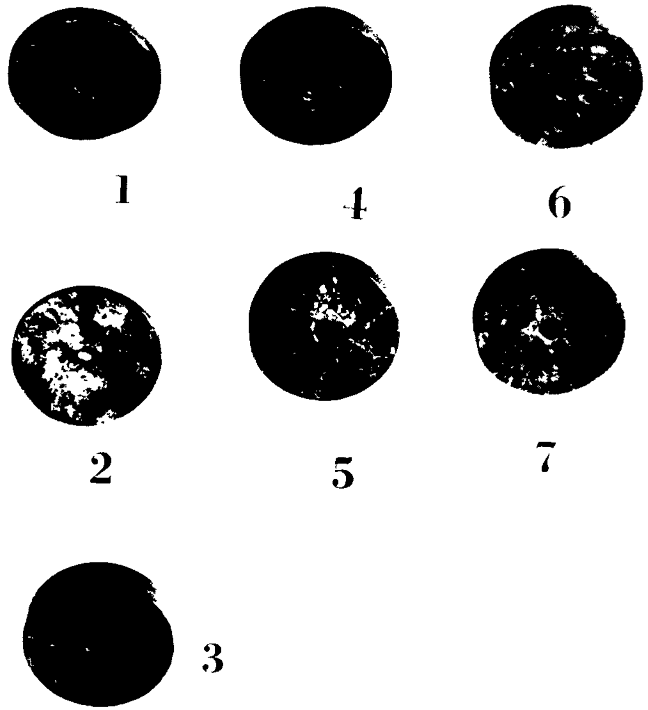

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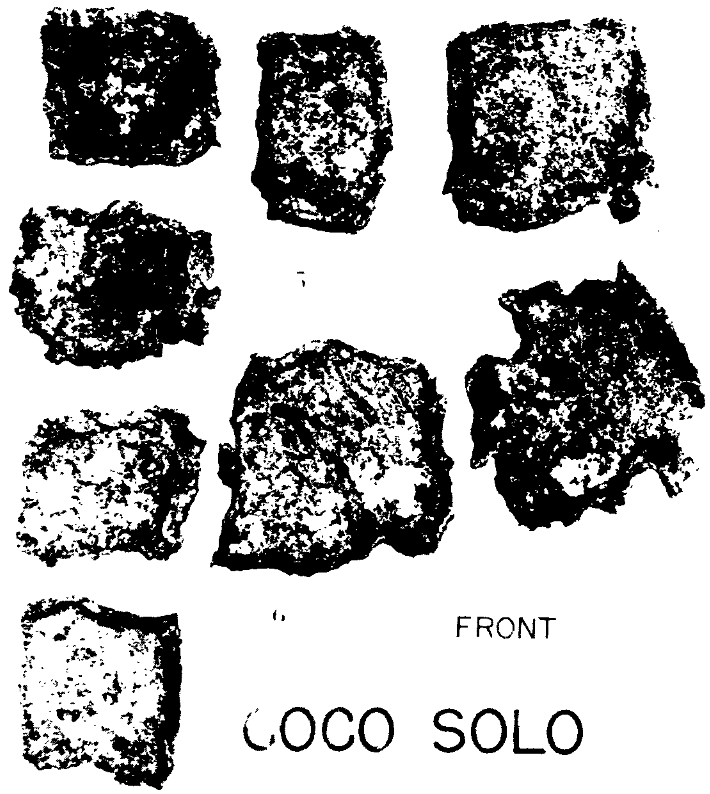
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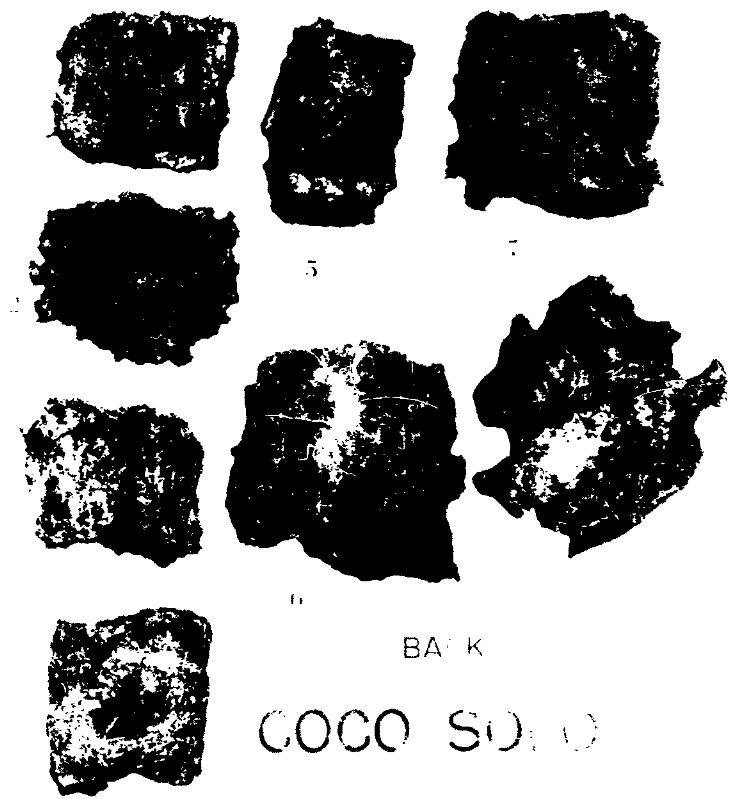
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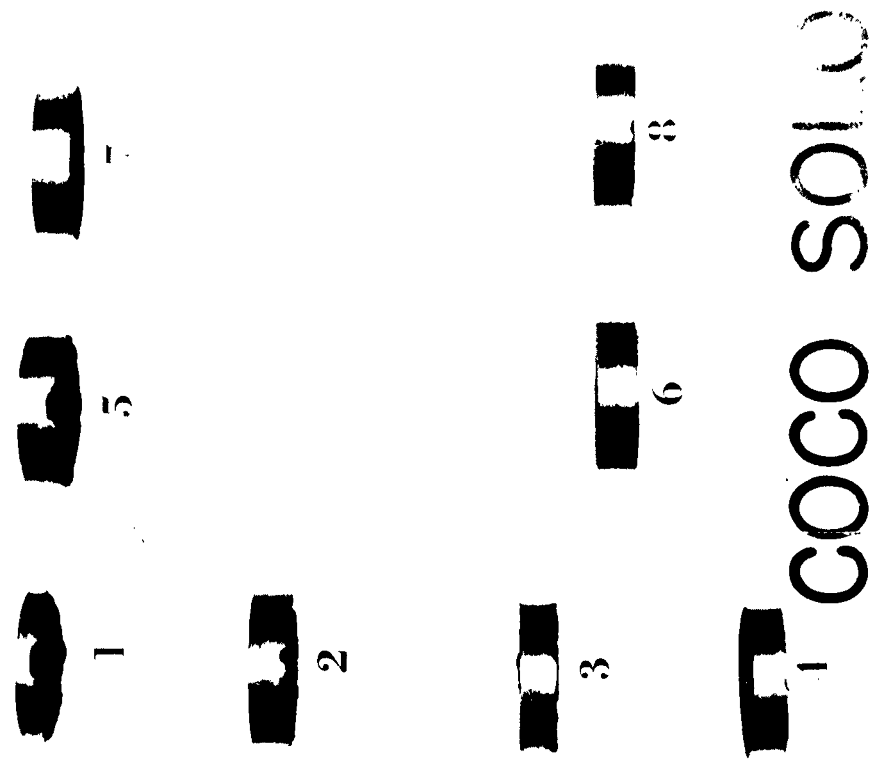
COCO SOLO
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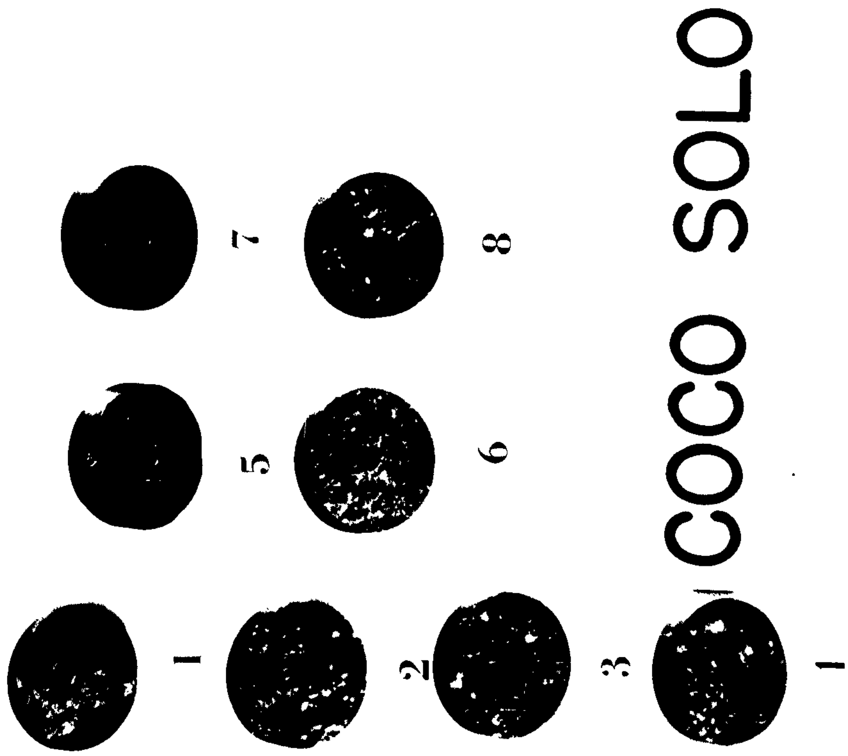
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8
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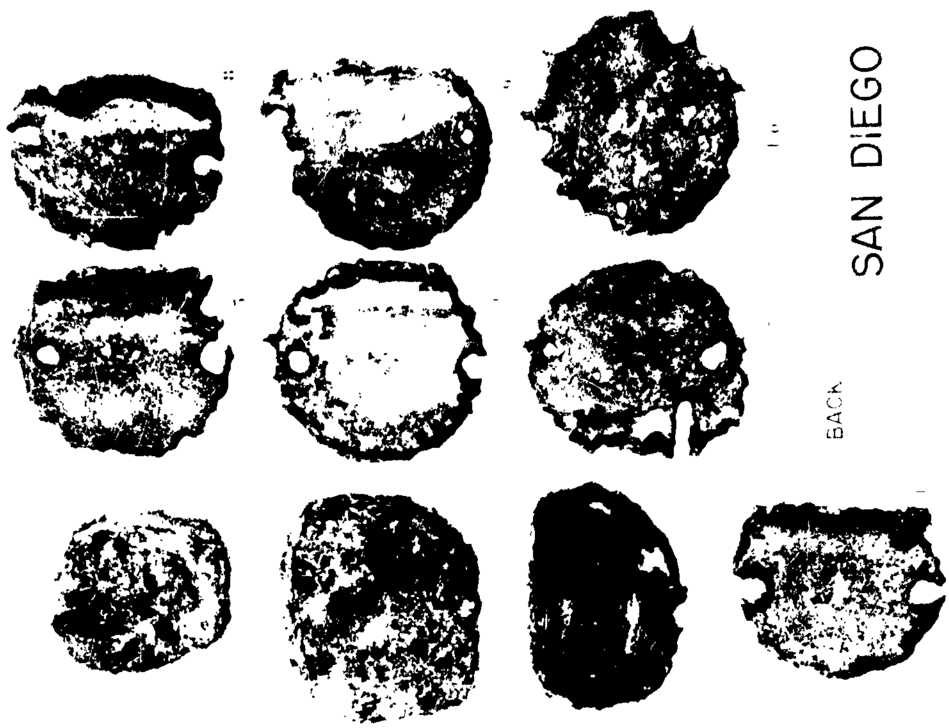
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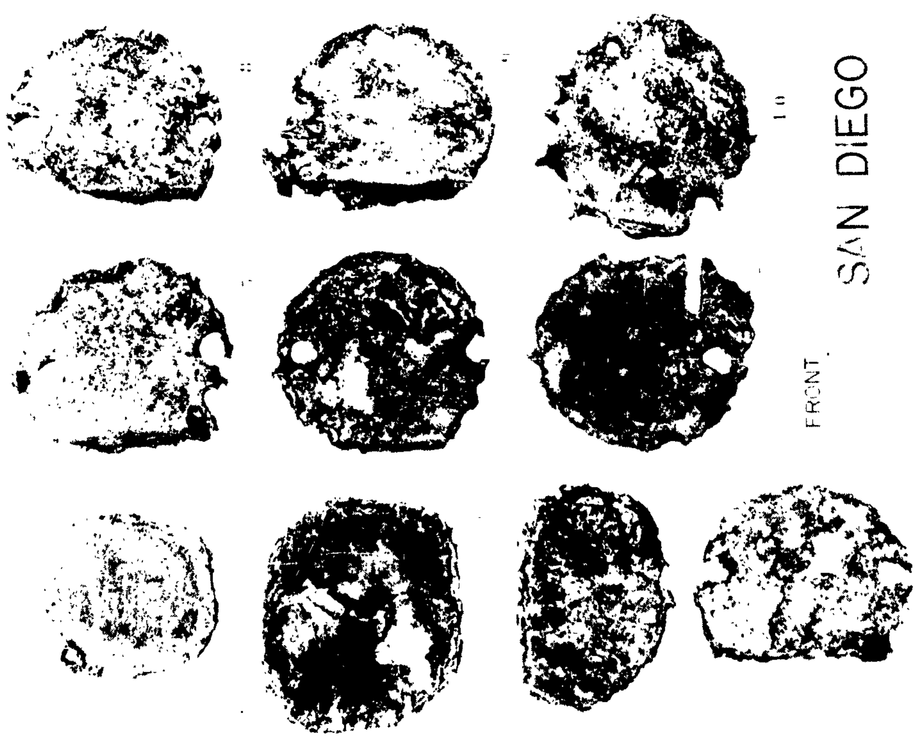
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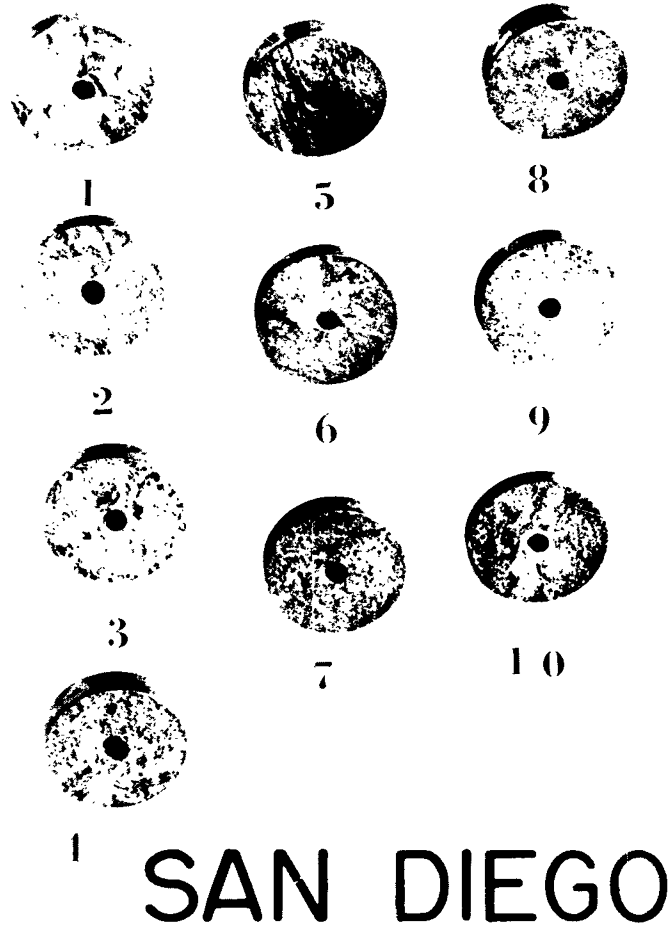
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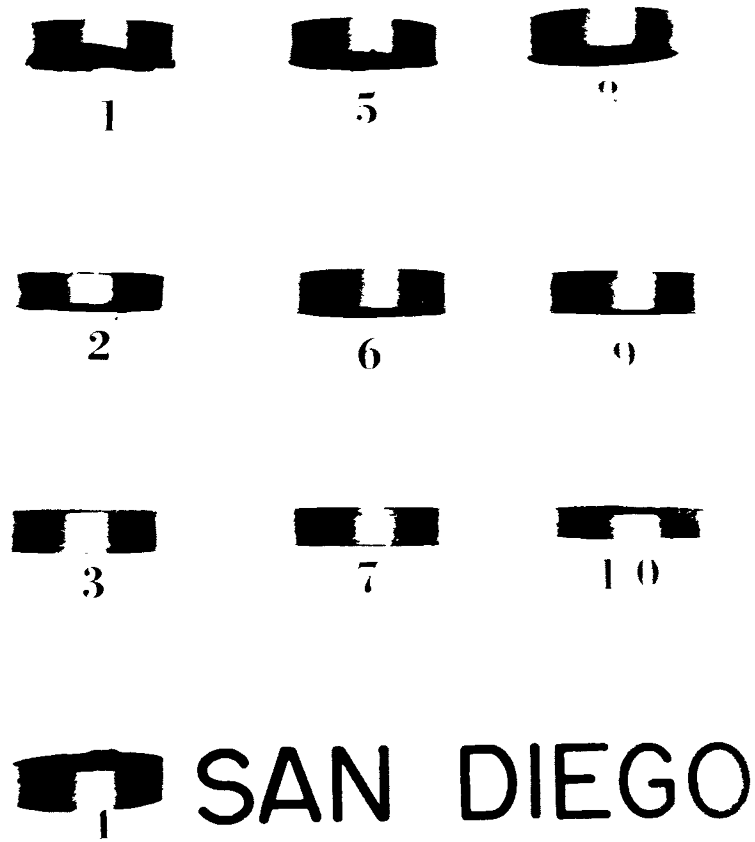
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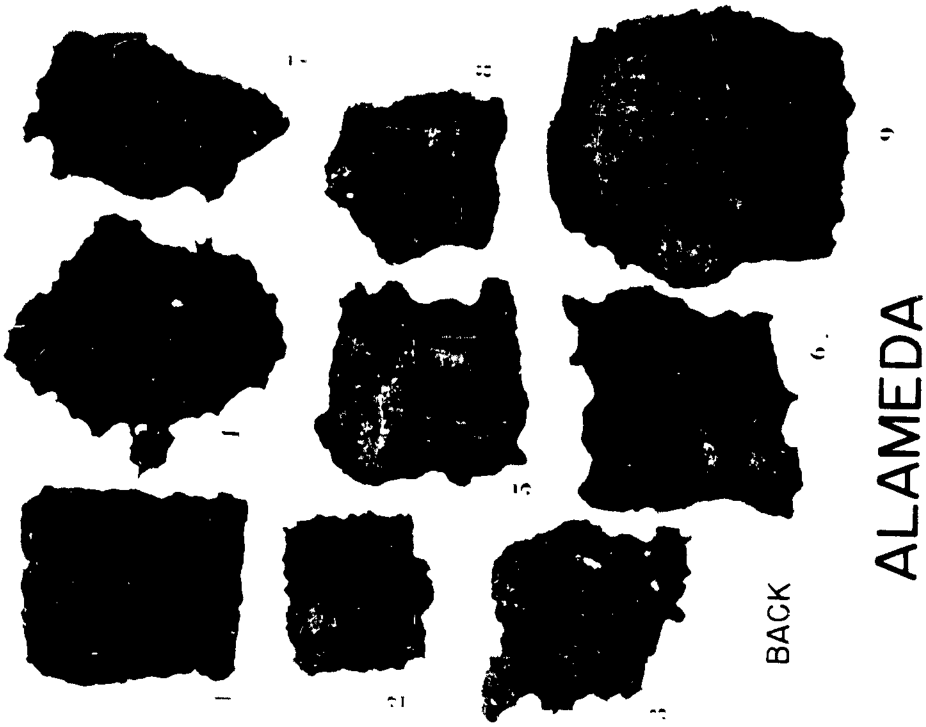
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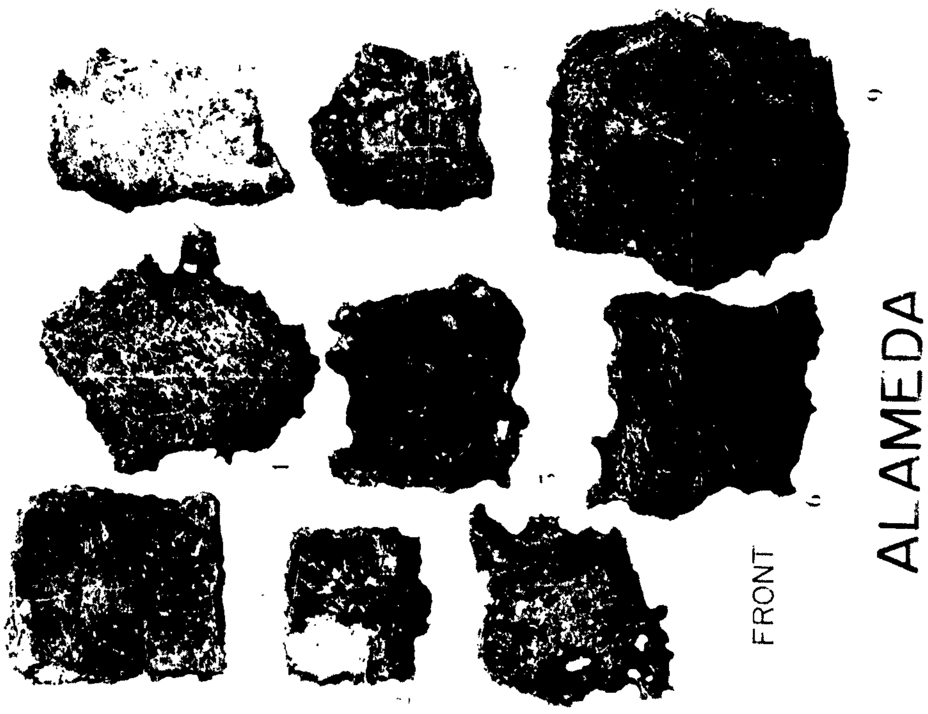
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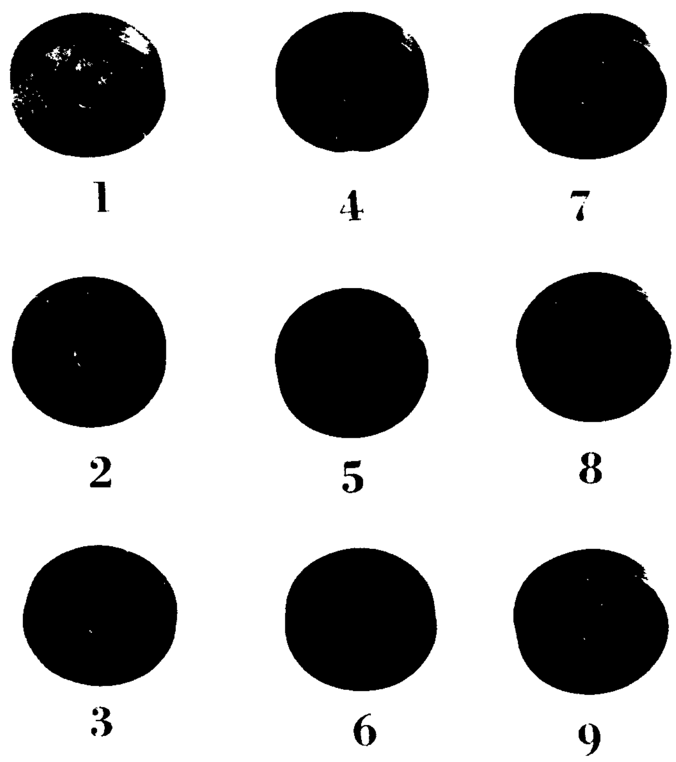

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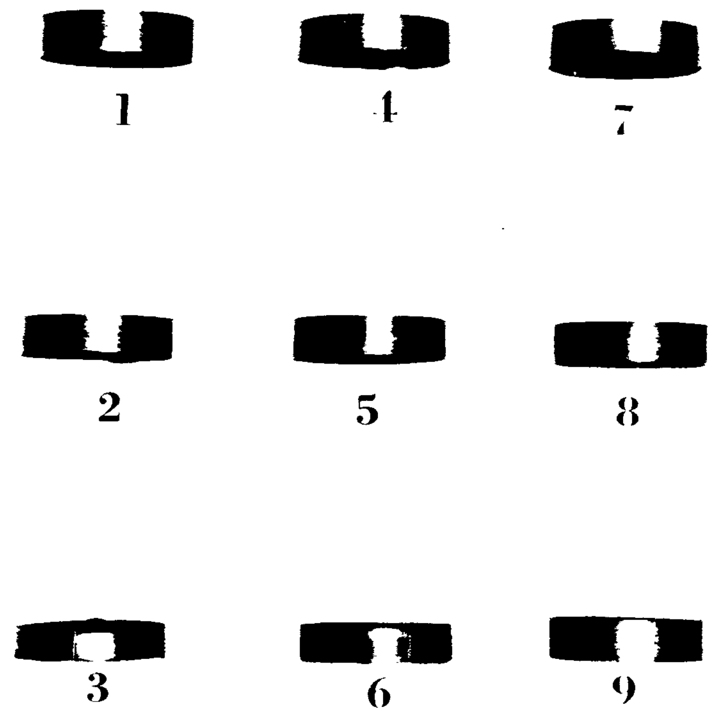
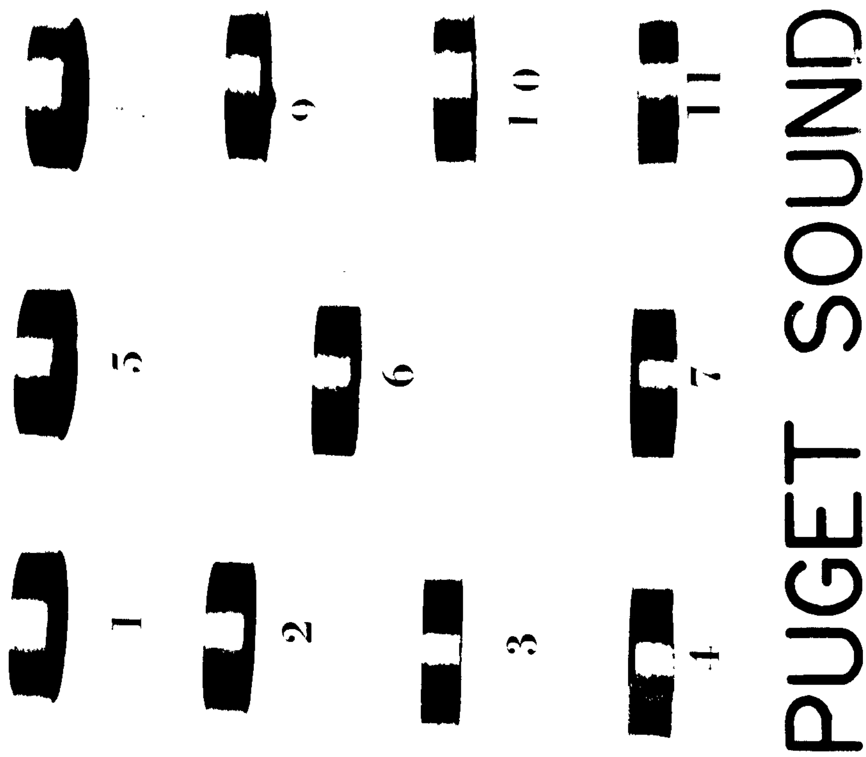


ALAMEDA


11
BACK
PUGET SOUND


11
FRONT
PUGET SOUND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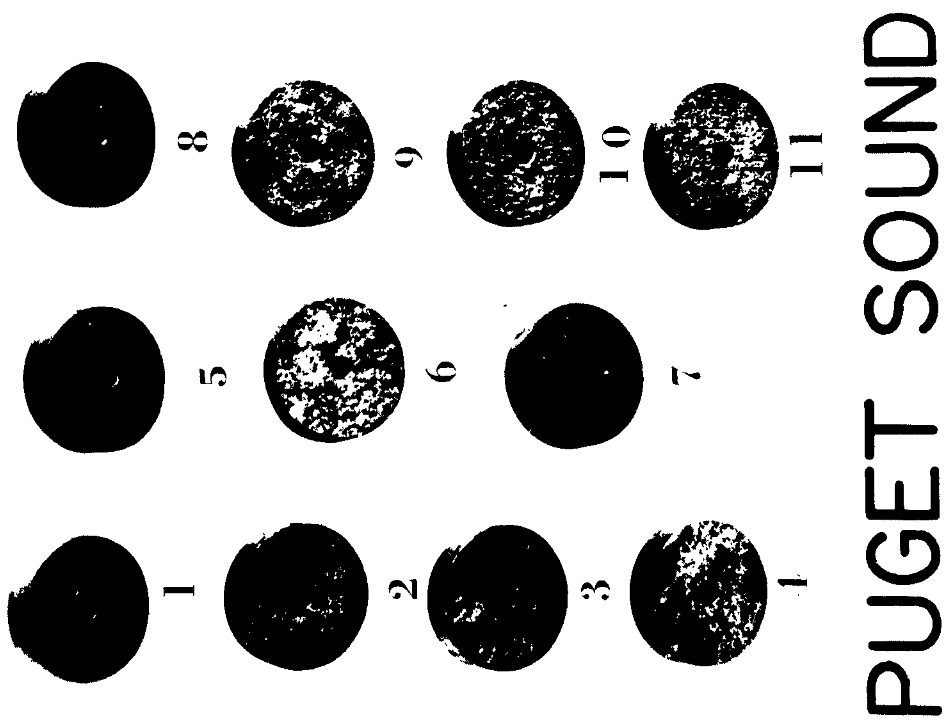
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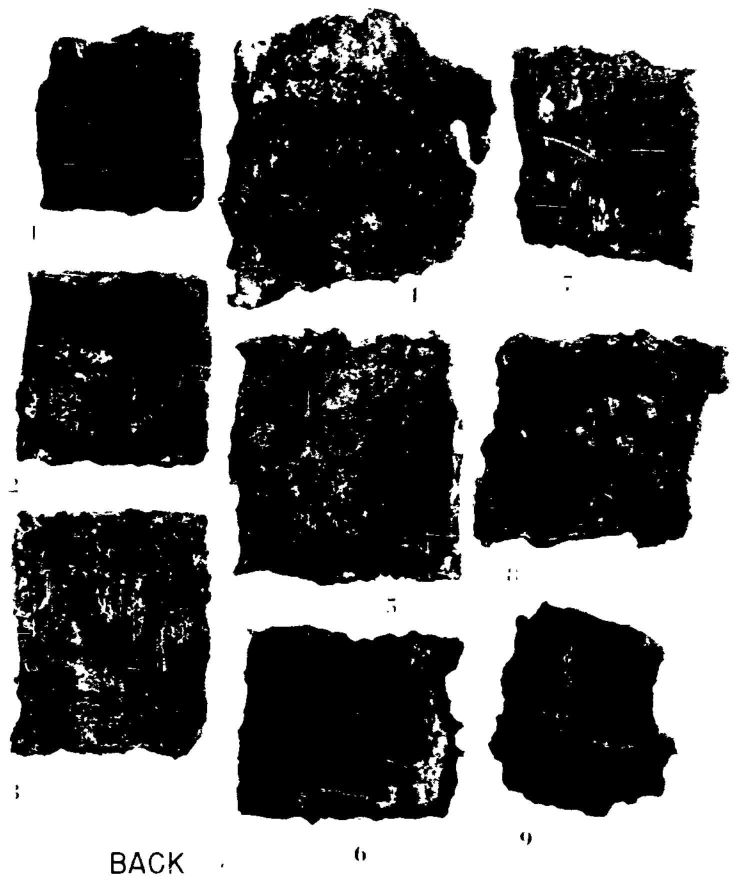
PEARL HARBOR



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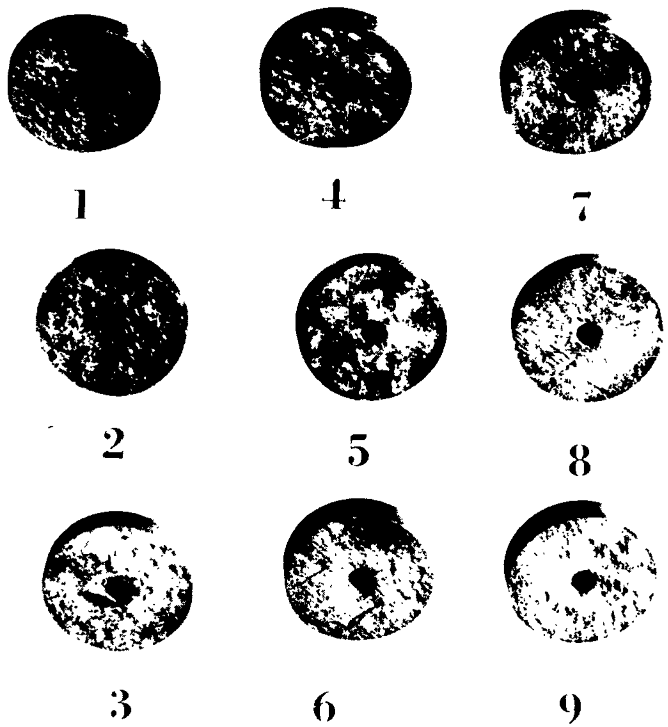

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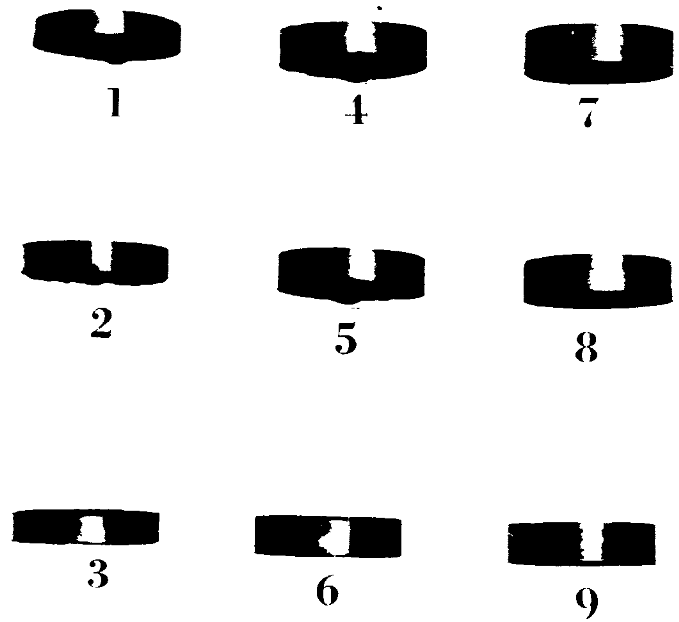
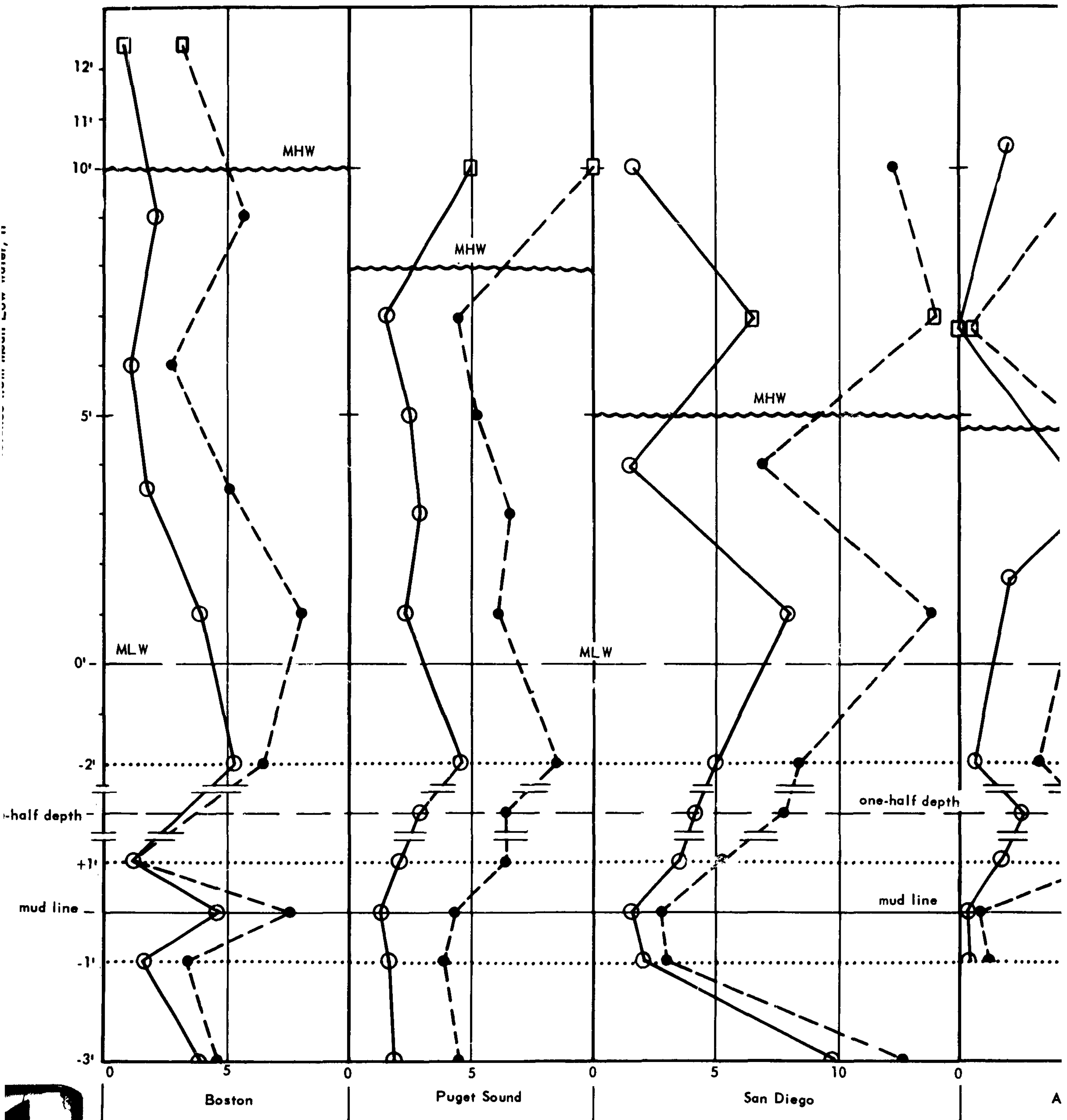


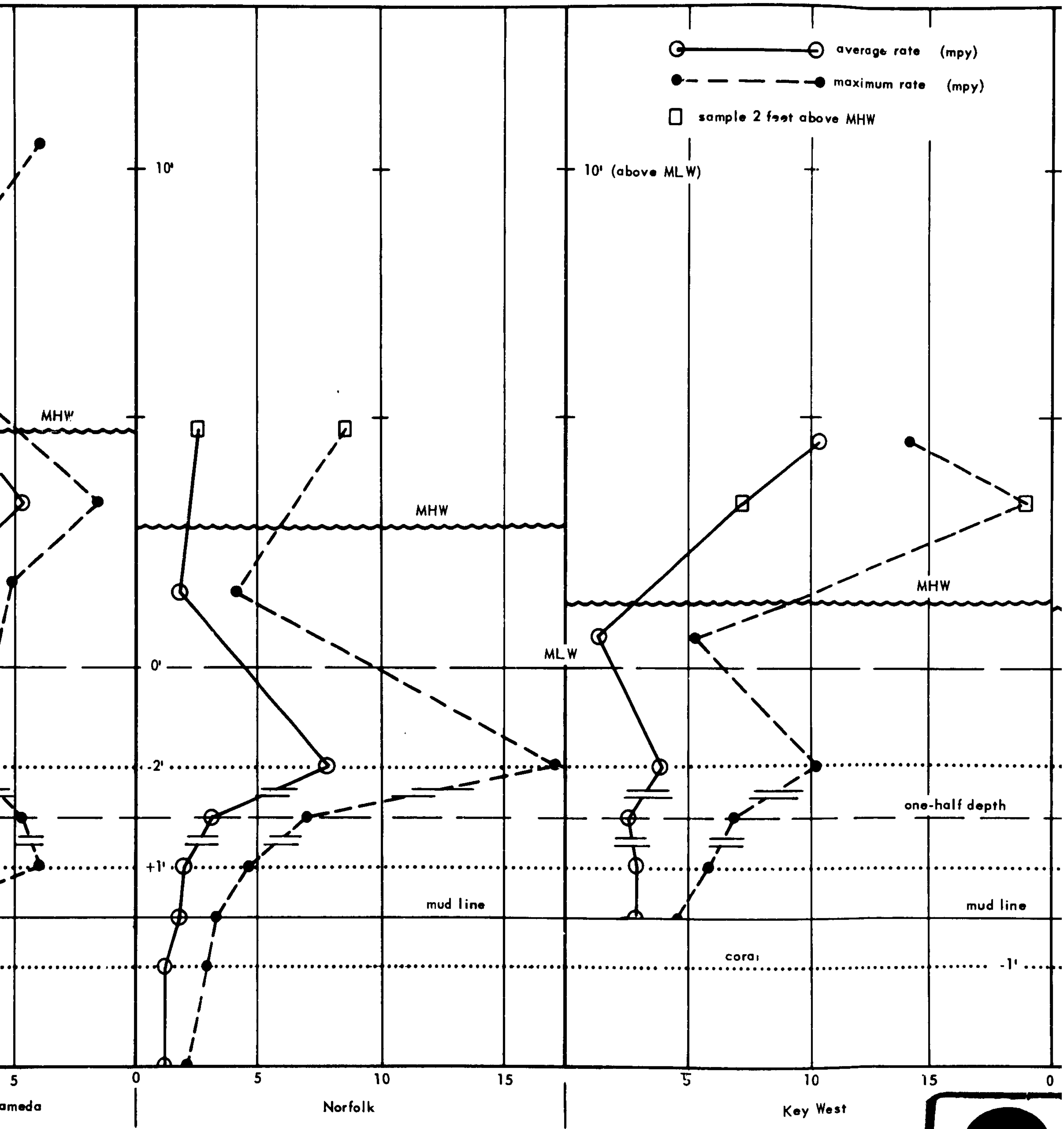
PEARL HARBOR

APPENDIX C

VERTICAL DISTRIBUTION OF CORROSION RATES

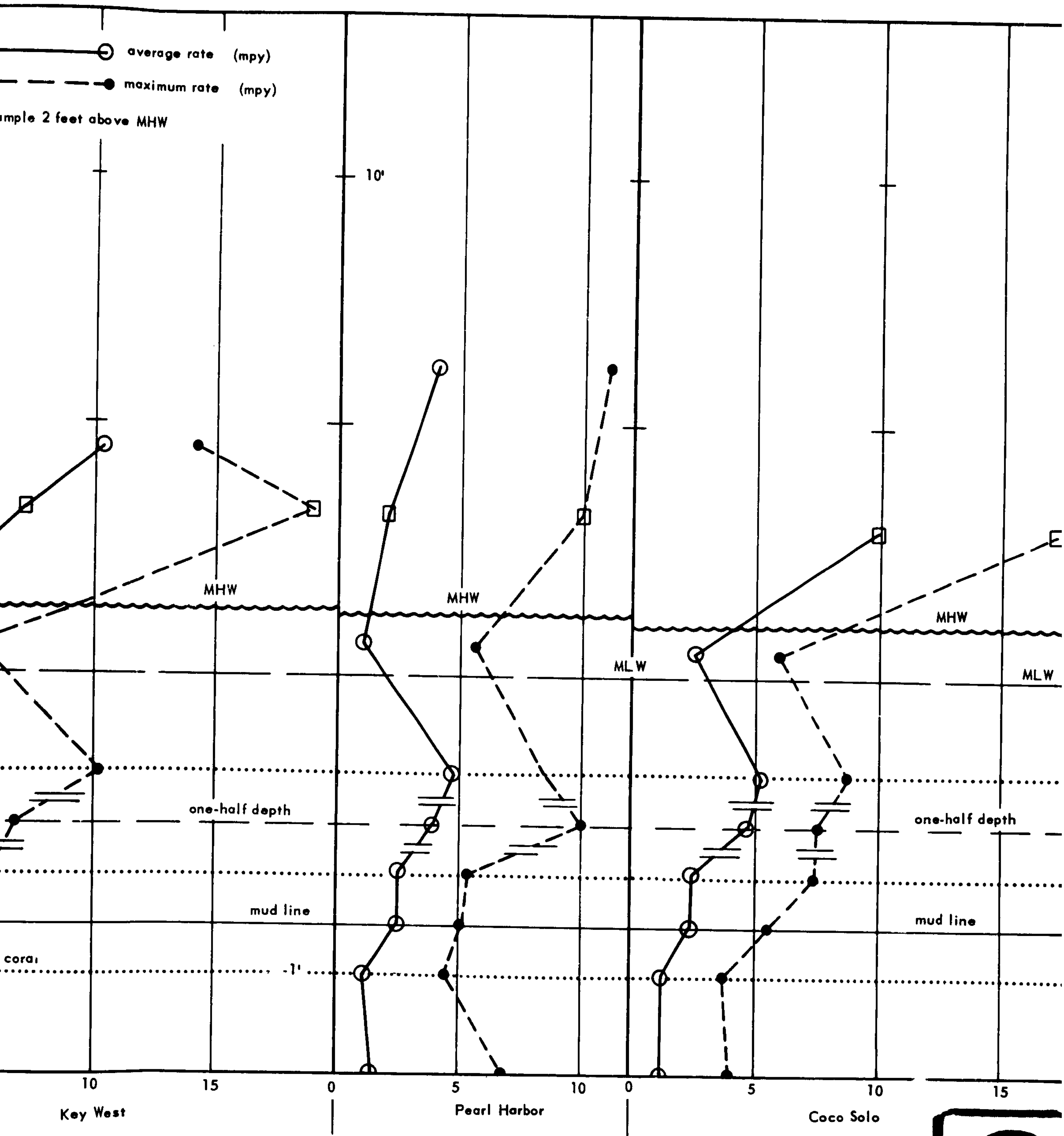


12'
11'
10'
5'
0'
-2'
-half depth
+1'
mud line
-1'
-3'
MHW
MHW
MHW
MLW
MLW
one-half depth
mud line
0
5
0
5
0
5
10
0
Boston
Puget Sound
San Diego
A



average rate (mpy)
maximum rate (mpy)
sample 2 feet above MHW
10'
10' (above MLW)
MHW
MHW
MHW
MLW
0'
-2'
one-half depth
+1'
mud line
mud line
coral
-1'
5
0
5
10
15
5
10
15
0
ameda
Norfolk
Key West

2



average rate (mpy)
maximum rate (mpy)
mple 2 feet above MHW
10'
MHW
MLW
one-half depth
mud line
cora
-1'
10
15
0
5
10
0
5
10
15
Key West
Pearl Harbor
Coco Solo

3

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