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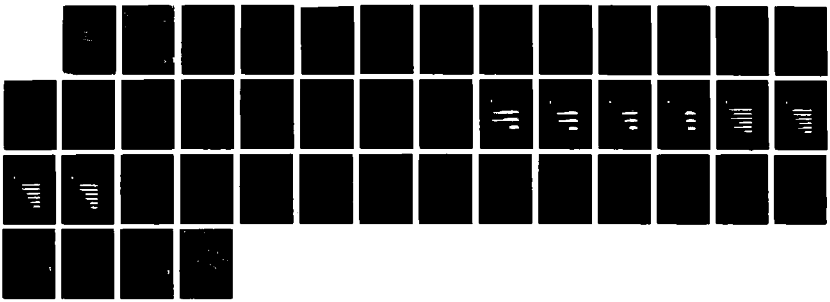

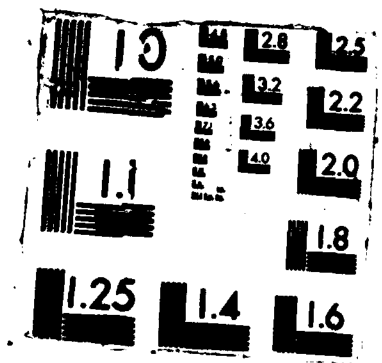
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June 1987
By D. Pendleton and
T. O'Neill
Sponsored By Naval Facilities
Engineering Command

Timber Piling Barrier and Chemical Preservation Annual Costs Comparison

ABSTRACT The currently recommended means of controlling marine borer damage of timber piling by chemical preservative systems are compared with pile barrier systems. Annual costs of untreated, creosoted, arsenical-treated, and dual-treated timber piling are estimated for fender and bearing systems in various geographical regions. Included in these estimates are the maintenance options of pile replacement and barrier system installation. Annual costs are also estimated for chemically-treated or untreated timber prewrapped with polyvinylchloride (PVC), polyethylene (PE), or precoated with polyurethane (PU). It is concluded that the most cost-effective, proven system for timber bearing piles in all regions is creosoted piling (in tropical and subtropical areas also arsenical-treated piling) protected by wrapping with PVC. The most cost-effective system for timber bearing piles, not yet proven by long-term testing, is untreated piling wrapped with PVC or PE or coated with PU before driving. The most cost-effective, proven system for fender piling in all areas is the arsenical-treated piling (in polar regions also creosoted piling) protected by PVC wrap. The most cost-effective, experimental system for fender piling is untreated piling wrapped with PVC. Implications of this analysis on common timber piling usage practices at Naval shore facilities are discussed along with specific recommendations to improve those practices.

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INTRODUCTION

The Navy has historically relied on timber piling for marine construction but its use is in jeopardy. The failure of timber piling caused by marine borers has been and continues to be a major concern. The cost of timber piling included in new military construction projects in 1978 was approximately $25 million in the United States (Ref 1). Because of inflation, the current annual cost of all timber piling used in new military construction and for repair of old structures in the United States and overseas is likely near $50 million. As much as 50 percent of this cost can be attributed directly to damage caused by marine boring organisms. The development and widespread use of concrete bearing piles and recent research into the use of prestressed concrete fender piling arise, in part, from the shortcomings of timber piling. The continued use of timber in the marine environment is contingent on the ability of wood to compete with concrete.

The advantages of using wood in the marine environment include its high strength, relatively low cost, resilience, convenient shape, low conductivity, reliability, availability, and workability. The disadvantages most often cited are its fixed size and limited durability. Concrete piling, in contrast, can be constructed in virtually any diameter desired and are not significantly affected by marine boring organisms. While wood cannot compete with massive concrete bearing piles for large waterfront structures, the advantages of timber still make it a viable option for bearing piles for smaller piers and for most fendering applications. The key to the continued usefulness of timber piling is an effective method of assuring its durability. Such a method now exists.

In the past, the Navy has relied almost exclusively on pressure treatment of timber with creosote to prevent marine borer attack. The development of alternative chemical treatments such as pressure treatment with water-borne arsenical salts or a combination of arsenicals and creosote, are recent attempts to remedy the main problem of creosoted timber, i.e., its susceptibility to the crustacean marine borer, _Limnoria_. These alternative treatments, while effective in prolonging the life of timber, are not without problems. Both alternative processes embrittle wood, dual treatment is more costly, and microbial erosion and leaching eventually render all chemical systems ineffective. The continued reliance on timber piling treated with water-borne salts or creosote (or both) is questionable not only because of the reasons cited above but because the continued use of these preservative systems is in jeopardy. Creosote has been declared an oil by the Environmental Protection Agency (EPA) and, thus, is subject to the same restrictions as other oils. The oil film produced when a recently creosoted pile is driven is a reportable violation of the Water Quality Act of 1971 (Ref 2). The EPA has further declared creosote to be a toxic substance that is detrimental to the environment and has banned over-the-counter sale of this preservative.

Those preservatives often used in lieu of, or with creosote, namely the water-borne salts of copper, arsenic, and chromium, have also been subject to criticism by the EPA and their continued use is questionable. Arsenic used in antifouling paints has been barred because of adverse affects on the marine environment and both copper and chromium salts are considered suspect.

Despite the shortcomings of preservative-treated timber usage in the marine environment and competition from alternative materials, there will be a continued demand for timber piling in the forseeable future. The present facilities constructed with timber piling are often repaired by replacing the old timber pile with a new one. In addition, new construction using timber piling is often relatively inexpensive because of low capital costs. Even more important is the fact that alternatives to chemical timber preservation now exist. Pile wrapping systems are an inexpensive, effective means of eliminating marine borer damage and have extended the durability of wood in the marine environment. These barrier systems for protecting both new and old piling can make the difference between high repair costs due to borer damage and virtually no borer damage. Another advantage of wrapping treated piling is that leaching of chemical preservatives is effectively eliminated, thus, rendering the system more environmentally acceptable.

The economy of pile wrapping systems has been given considerable attention in the past but the Navy is not yet widely using the systems. Part of the reason for the limited use of wraps is that construction of facilities is often not accompanied by a detailed analysis of future repair requirements for timber piling and the relative costs of the various repair options available. Too often, such repair options are considered only when piling begin to fail and cost effective means of protecting the piles are no longer available. By providing a detailed economic analysis of the various chemical preservative and barrier system options, we hope to make the reader aware of the potential savings available by using a pile wrapping plan during or immediately after construction. From a careful consideration of the arguments presented, the reader can determine which timber preservation system and protection or repair option best meets his requirement or, by comparing projected costs with other material options, if using timber is even justified. Where treated timber piling are already in place and deterioration has not reached the point where wrapping is futile, the economic analyses presented remain valid and using the pile wrapping program can be just as effective as a program planned during construction.

PRESERVATION OPTIONS

Chemical Preservatives

Chemicals currently used as preservatives for the Navy's timbers and their application procedures are specified in MIL-P-23613C (Ref 3), which, in turn, refers to specifications developed by the American Society for Testing Materials (ASTM), American Wood Preservers Association (AWPA), and the American Wood Preservers Bureau (AWPB). The maintenance standards and the criteria and policies used in their application are summarized in References 4 and 5.

Navy specifications for chemical treatments for new piling depend on the type and amount of borer damage at the installation site. Piling pressure treated with creosote or creosote-coal tar solutions are recommended where moderate borer activity from shipworms and boring clams (Pholads) is present and where the wood boring crustacean, Limnoria is absent. Piling pressure treated with a water-borne salt, either copper chromium arsenate (CCA) or ammoniacal copper arsenate (ACA), are recommended where Limnoria are a hazard and where Pholads are absent. Dual treatment with a water-borne salt and creosote is recommended where both Limnoria and Pholads are active.

The economics of using timber pile is dependent on the service life of the piling. In general, boring activity within each site is directly correlated with water temperature; pilings are subjected to greater attack in warmer waters. Table 1 presents estimates of the useful life of chemically treated and wrapped piling. The actual useful life of the various chemical treatments is dependent on the numbers and diversity of marine borers, chemical leaching rates, and toxicity. These parameters are affected by water temperature, geographic location, amount of oxygen present, extent and type of pollution, salinity, harbor water circulation, and amount and condition of submerged wood. The useful life of each chemical treatment should be estimated on a site-by-site basis predicated on long-term experience with the treatments in question. Unfortunately, in many areas an estimate of the average life expectancy of even creosoted piling is largely based on guesswork, but the large variance in borer damage among piling with identical treatment and in the same general location makes guesswork highly unreliable. Careful record keeping that includes installation dates, treatment details, replacement dates, and periodic inspection results for piling is vital for determining the average piling useful life and the annual cost of piling employed. Of course, where a particular treatment has never been tried, there are no efficacy records available and the experience of others should be elicited. Although each site is unique and should be independently evaluated, general conclusions about the useful life of treated piling can be drawn from a number of testing programs (Ref 6 through 19) and these form the basis for the estimates given in Table 1.

Another factor rarely considered when determining the economics of chemically treated piling is the effect of these treatments on the mechanical properties of piling. Both resilience and strength of piling may decrease after treatment (Ref 20, 21, and 22). The greatest loss of mechanical properties is caused by dual treatment, followed by a single treatment with water-borne salt; the least reduction of mechanical properties is caused by creosote treatment. A loss of strength increases the number of piling required to meet load-bearing specifications and increased brittleness makes both bearing and fender piles more susceptible to breakage.

Barrier Systems

Polyvinyl chloride (PVC) is the most extensively used flexible barrier. Initially developed in 1956, its use is designated in NAVFAC Specification TSM B10a (Ref 23). PVC wrap has been recommended as a piling protection method when cross-sectional area loss due to borers reaches 10 to 15 percent (Ref 24). That is satisfactory for fender piles but bearing piles should be wrapped before damage occurs. This is especially important in tropical waters where piling can be completely destroyed within 2 years after the onset of borer attack. Pilings are first cleaned of fouling organisms and then wrapped from just below the mudline to above the high water mark with sheets of 30-mil PVC. Because of the solubility of PVC in creosote, 6-mil polyethylene liners are placed between the piling and PVC when freshly creosoted timber is wrapped. The PVC is tightened around the piling and secured in place. In one patented system, the wrapping is tightened by wooden poles around which the PVC is wrapped and turned by a ratchet wrench. In another patented system, the PVC sheets are custom fitted and edges are joined by a nylon zipper; additional tightening is secured by cinching up any loose folds with straps.

The history of PVC wrapping can best be related by citing the records of the Port of Los Angeles. Their experimental program, initiated in 1956, was the first large-scale use of PVC wrapping. The success of the experimental program in stopping borer activity led the Port to begin, in 1962, the standard practice of wrapping all bearing piling with PVC. Over 10,000 piles were so treated. This ambitious program was stimulated by the resurgence of marine borers as a consequence of successful attempts to clear the harbor of pollutants that had previously kept the borer populations in check. During this 30-year period the Port has maintained records on the status of wrapped pilings. No other port in the nation nor Naval installation has such an informative collection of pertinent records.

The estimated useful life of PVC wrapped piling has been increasing yearly with the continued success of the wrapped piling program conducted by the Port of Los Angeles. It was reported in 1978 (Ref 25) that, despite the potential for damage by the more than 25 tons of floating debris that is collected from the harbor daily, there has been no failure of a wrapped pile. The relative absence of borer damage to wrapped piles has been corroborated by more recent inspections of wrapped bearing piles pulled to facilitate new construction (Ref 26). Between 1982 and 1983, 620 wrapped bearing piles were extracted. Sixty of these piles, most wrapped with 30-mil PVC were randomly selected and evaluated for borer damage. Each pile surface below the wrap had no visible living organisms and the condition of the wood was in each case approximately the same as its condition prior to wrapping. Since most of these piles were originally wrapped in 1968, a service length of at least 15 years for PVC wraps was established. Similar inspections completed in 1986 by the authors and Port engineers have confirmed previous observations. In no case has there been borer damage observed below intact wraps. Of the hundreds of piles inspected, only one wrap was damaged enough to allow borer entry, and another wrap did not adequately cover an attached bolt and thus borer damage continued at that point only. The aluminum alloy nails used to attach the wraps were still intact with little visible corrosion. Piling that had previously sustained heavy damage (in some cases up to 30 percent cross-sectional loss) did not deteriorate further after the wraps were installed.

As yet, the piling wrapped when this program began in 1962 have not been pulled and inspected. There is no reason to believe, however, that inspection results will be any different than those described for piles wrapped in 1968. These results establish at the Port of Los Angeles that the service life of timber piling will be extended at least 24 years if PVC wraps are used. An extended service life of 35 years or more at the Port is probable. This estimate is also considered reliable for warmer waters with greater borer damage potential (Ref 26).

PVC wraps for timber piling have been installed to date at a limited number of military waterfront facilities (Table 2). Interviews with facility engineers and inspection results at these sites have confirmed the experience at the Port of Los Angeles; PVC wraps are an effective means of preventing borer damage.

Polyethylene (PE) film has been extensively used since 1970 by the Port of Los Angeles. Originally used as the initial wrap over creosoted piling to protect PVC from dissolution by creosote, 20-mil thick PE has been used without an overwrap of PVC since 1978 as a wrapping system for new piles. Because of its relatively low resistance to abrasion, a 150-mil high molecular weight PE jacket is usually installed in the intertidal area for protection from floating debris. The application of PE by a heat shrinking technique (developed and patented by the Port of Los Angeles) is less expensive than PVC wraps and, unlike PVC, requires no plasticizers (Ref 27). A major disadvantage is that heat-shrunk PE cannot be used for in-place pile wrapping and is restricted to treating new piles. An even greater disadvantage for the Navy is that the system is not commercially available at the present time, but a "cold" wrap system for in-place pile repair using PE is entirely possible. A number of fender piles extracted and inspected in 1982 and 1983, and many of the piles inspected in 1986 were wrapped with heat-shrunk PE. All of these piles were in excellent condition. Thus, a confirmed estimate of the useful life of PE-wrapped, creosoted piles is currently 8 years but the probable useful life is 35 years or more.

Based on experience at the Port of Los Angeles, unwrapped creosoted piling have a useful life span of about 10 to 15 years. Because of this limited service life, an experimental program was initiated in 1985 using untreated, PE-wrapped fender piles. It is expected that these tests of piles wrapped before driving will demonstrate that chemical preservation of wrapped piles is unnecessary and that the wrap is not unduly damaged by driving.

Elastomeric polyurethane (PU) coatings are a relatively new concept for timber piles but the operating principle is the same, i.e., PU provides a barrier to organisms and oxygen. PU coatings can be quickly and easily applied to the desired thickness and require no attachment hardware that can work loose or corrode after installation. PU coatings can be formulated to cure underwater, and any breach of the coating can be quickly and easily repaired. Polyurethane coatings were applied to 70 untreated fender piles in the Port of Los Angeles prior to driving in 1985. Thus, driving of PU-coated piles is feasible. Independent tests with small panels (Ref 28) have shown that PU is not readily attacked by boring organisms. PU coatings for untreated piling appear to have great promise.

Perhaps the most enduring physical barriers are made of concrete. In fact, in many new construction sites concrete has been selected in lieu of wood, especially where heavy loading is anticipated. Prestressed concrete fendering systems may also soon compete effectively with timber fender piling. In addition, concrete can be used to encase timber piling either before or after driving. The Port of Tacoma used the former method in 1922 and the piling is still in excellent condition today.

Thus, the proven useful life of concrete barriers for timber is now at least 64 years. Concrete is, however, most commonly applied to repair piling when the damage is in excess of 15 percent of the pile's cross-sectional area. Concrete is also used as a replacement for damaged timber piling. The capital investment for concrete repair of timber piling is high, as much as ten times greater than the wrapping systems.

Metallic barriers offer protection against marine borers but their use has been virtually eliminated because of the much lower cost of PVC wrapping. The most common metal used was a 90:10 cupro-nickel alloy in sheets 2 mils thick. The sheets were fastened to the piling with monel or cupro-nickel nails. The copper does offer some antifouling activity from the slow release of copper ions but this advantage is not of great importance for piling. Because such metallic barriers are not economically feasible, they are not included in the cost analysis.

ECONOMIC ANALYSIS

The following economic analysis assumes that an effective inspection program is followed and maintenance is performed on a timely basis. The ideal frequency of marine timber piling inspections at each facility is dependent on inspection costs and deterioration rates. Where the pile deterioration rate is known, the most cost-effective inspection frequency can be calculated (Ref 29). Where the deterioration rate has not been determined, the data in Table 1 may be used in a similar manner to estimate the most cost-effective inspection frequency. In general, inspections should be done more often in warmer waters where deterioration rates are higher. Wrapped piling will require fewer inspections because deterioration will effectively cease. Each inspection should follow the guidelines developed by Brackett (Ref 30).

There are two categories of timber piling used for new construction considered in this analysis: bearing and fender piles. The need for repair or protection of all chemically treated piling is included in the cost estimates. This makes these cost estimates useful for existing piling where various options are being considered. Dolphin piling and piling for seawalls are not considered as such, but the factors involved are similar to fender and bearing piles, respectively. The preservative options for each pile usage category include the presently recommended chemical preservatives, creosote, water-borne salts, and dual treatment. In addition, there are various barrier systems that can be effectively employed, i.e., wraps made from PVC or PE, PU coatings, and concrete.

Various assumptions are made in this analysis. Details of these assumptions as well as details of formula derivations are presented in Appendix A. Costs and interest rates vary and may be different from those assumed. All cost estimates are based on 45-foot Douglas-fir piling. The reader is free to incorporate alternative cost estimates into the formulae presented. The expected life of preservative treated piling also varies and depends on the location. The analysis is thus completed for an estimated life expectancy value for each preservative treatment and for each geographic category as indicated in Table 1.

Bearing Piles

The calculated average annual costs of installing timber bearing piling are presented in Table 3 and Figures 1 through 4. Included are the cost of treatment and repair or protection options for treated and untreated piling installed in tropical, subtropical, temperate, and polar locations. Costs for these piling depend on the treatment, the method of repair or protection and the amount of time before the repair is required, i.e., the durability of the original treatment. Protection by wrapping with PVC is generally required about 2 years before either pile replacement or repair by encasement with concrete and is, therefore, compared on that basis in these tables. The installation of untreated piling protected by PVC wrapping is included in these tables but is not recommended because long-term testing has not yet demonstrated its efficacy. The calculated annual costs of installing bearing piles wrapped with PVC or PE or coated with PU before driving are:

Treatment	Cost/Pile/Yr ($)
None	112
Creosote	149
Arsenical Salt	170
Dual	202

Since such piling are not expected to need repair within 35 years of installation in all geographical categories, only one set of cost values are presented. This set of values can be compared with the calculated costs of treated piling protected by barrier installation or replaced but since long-term testing has also not proven the efficacy of prewrapped or precoated systems they are not yet recommended.

The calculated costs presented in Figures 1 through 4 show that the least expensive, proven approach to timber bearing piling installation in all geographical areas is to use PVC wrapping after installing the treated piling. The cost differences between piling protection with PVC and repair by concrete encasement or replacement are greater in tropical and subtropical areas because the protection or repairs must be accomplished sooner where biodeterioration rates are higher. The greater durability of treated timber in cooler waters reduces the calculated annual costs because of the deferment of maintenance costs. In tropical and subtropical areas, installing creosoted or arsenical treated bearing piles, to be subsequently protected by PVC wrapping, results in comparable annual costs. In contrast, dual treatment is more expensive. In temperate and polar areas, the least expensive approach is to install creosoted piling protected by PVC wrap.

Although not yet recommended because of the absence of data from long-term studies, the use of untreated timber either prewrapped or precoated before driving or wrapped shortly after driving appears to offer significant economic advantages. For all geographical areas, that advantage is an approximate 20 percent reduction of costs compared to the wrapping or coating of creosoted timber. There is little difference between the calculated annual cost of untreated, prewrapped or precoated bearing piling and untreated piling fitted with a wrapping system after installation. The advantage of prewrapped piling is that there is no chance that the required protection will be delayed after installation. Any such delay could prove disastrous. Therefore, if in the future the use of untreated, wrapped piling is a viable option, the most likely recommended procedure would be to wrap or coat the piling before driving.

Fender Piles

The annual cost of fender piling is complicated by breakage. The calculations include the annual expense incurred by this breakage and take into consideration that a diminishing number of the original piling will be attacked by borers. In all cases, greater breakage rates result in greater costs. Where the breakage rate results in an expected life of the piling less than that expected because of borer damage, that portion of annual cost estimates due to biodeterioration are necessarily excluded. In these calculations, the breakage rates of all treated piling are assumed to be the same. That may or may not be the case. The increased brittleness of salt treated piling may increase breakage rates.

The annual cost of installing fender piling (Table 4; Figures 5 through 8) is dependent on geographical location, pile treatment, repair or protection method, and annual breakage rate. The installation of untreated fender piling, while included in Table 4, is not recommended because long-term testing of untreated fender piling, like untreated bearing piling, has not yet been completed. The installation of fender piles prewrapped with PVC or PE or precoated with PU (Table 5) is also not currently recommended for the same reason. These options may be available in the future, however, and cost estimates for untreated piling are presented for comparison with currently proven systems.

Figures 5, 6 and 7 indicate that the least expensive, proven system for fender piling installation and maintenance in tropical, subtropical, and temperate areas and where breakage is less than 10 percent, is the arsenical treated piling protected by PVC wrapping when required. In polar regions the costs of arsenical treated and creosoted piling protected by PVC wrapping are comparable for all breakage rates (Figure 8). Replacing fender piles is more expensive than protecting piles by PVC wrapping in all areas where the need for piling maintenance due to marine borer damage is not eliminated by pile breakage. Of course, if the breakage rate is high enough and the chemical treatment good enough to prevent borer damage before breakage occurs, than the logical option is to replace the broken piles.

The use of untreated, wrapped or coated fender piling, like untreated bearing piling, is not yet recommended because of the lack of long-term testing, but there is a potential economic advantage. In all areas the calculated annual cost of untreated fender piling protected by wrapping is about 10 percent less than the calculated annual cost of treated fender piling protected by PVC wrapping. In polar areas the greatest savings is affected by wrapping untreated fender piling after the onset of borer damage. This savings results directly from the greater durability of untreated timber in colder waters and the delay in required capital expenditures for maintenance. In all other areas, prewrapped or precoated piling is the least expensive option for untreated piling.

CONCLUSIONS

1. Creosote, the currently preferred preservative for timber piling in the marine environment, is environmentally suspect and is relatively ineffective against the marine borer Limnoria.

2. Arsenical salts, chemical alternatives to creosote, are also environmentally suspect, embrittle wood, and may adversely affect its strength.

3. Polyvinyl chloride (PVC) wrap has been conclusively demonstrated by long-term, extensive use at the Port of Los Angeles to be a highly effective means of preventing further marine borer damage to creosoted piling. PVC wrap has extended the useful life of creosoted piling 24 years and will likely extend it more than 35 years.

4. Polyethylene (PE) wrap has been demonstrated at the Port of Los Angeles to be a highly effective means of preventing further marine borer damage to creosoted piling. The PE wrap has extended the useful life of creosoted piling 8 years and will likely extend it more than 35 years.

5. Initial investigations at the Port of Los Angeles have shown that driving timber either prewrapped with PVC or PE or precoated with polyurethane (PU) is feasible and may offer economic advantages to wrapping after installation.

6. Greater savings may be realized by wrapping or coating untreated timber piling. Long-term monitoring of 140 such piling recently installed at the Port of Los Angeles is required before conclusions can be made on its borer resistance.

7. The relative costs of timber piling chemical preservation and maintenance options are dependent on geographical location; piling in warmer water are generally more expensive because of greater borer damage.

8. Our economic analysis indicates that the least expensive, proven approach for timber bearing piling is to protect chemically treated piling (creosoted piling in temperate and polar regions, and either creosoted or arsenical-treated piling in tropical and subtropical regions) with PVC wraps after piling installation.

9. Our economic analysis also indicates that the least expensive, proven approach to timber fendering is to use PVC wrap protection after installing chemically treated piling (arsenical treated piling in tropical and subtropical regions and either creosoted or arsenical treated piling in temperate and polar regions).

10. In tropical and subtropical areas, where repairs of chemically treated piling are soon required, it may be advisable to install prewrapped, treated bearing piling to avoid potentially catastrophic delays in wrapping.

RECOMMENDATIONS

1. Periodically inspect marine timber piling at all Naval facilities for marine borer damage. In general, ideal inspection frequencies are greater in warmer, unpolluted waters and decrease with decreased temperatures and increased pollution.

2. If inspections indicate borer damage is 30 percent or less, the bearing pile may be wrapped from the mudline to the high tide mark with PVC. The load-bearing capacity of the whole structure must be considered. Wrapping the fender piling depends on breakage and borer damage rates.

3. Include a specific plan for bearing pile wrapping with either PVC or PE for all new construction in all geographical areas using timber bearing piles.

4. Include a specific plan for fender pile wrapping with PVC for all new construction in tropical, subtropical, and temperate areas, where the estimated annual breakage rate is less than 10 percent.

5. Bearing piling should be wrapped during construction in tropical and subtropical areas except where an economic analysis has shown that wrapping bearing piling after borer damage becomes evident costs significantly less. In the latter case, a specific inspection and wrapping plan must be implemented immediately after construction.

6. Where it is advisable to prewrap creosoted piling for new construction, 20-mil thick PE is preferred and must extend from below the mudline to the high tide mark. The intertidal area should be further protected by encasement with a 150-mil thick, high molecular weight, PE jacket.

7. Either PE or PVC can be used to prewrap arsenical treated piling for new construction.

8. When advisable to wrap bearing piling after construction, PVC is preferred and should be used before 5 percent damage occurs and must extend from below the mudline to the high tide mark.

9. Specifications based on performance criteria for wrapping systems for timber piling should be developed to assure maximum service life. The experiences of the Port of Los Angeles would be very helpful in this regard.

10. Continued research into the use of wrapped or coated timber piling untreated with chemical preservatives should be a high priority. Not only is there a potentially large economic advantage over presently recommended systems but the chemically untreated, PVC- or PE-wrapped or polyurethane-coated piling are environmentally sound.

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We thank the Port of Los Angeles for their generous cooperation in providing much of the data for this report. Details of a unique technical history, extending over a period of 30 years, were made available to us. In particular, we thank Mr. Donald L. Mosman, Deputy Executive Director; Edward Gorman, Chief Harbor Engineer; and Mr. George Horeczko, Testing Engineer, all from the Port of Los Angeles.

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Table 1. Estimated Average Useful Life of Marine Timber Piling

Geographical Area	Treatment				
	None	Creosote	Arsenical Salt	Dual	PVC or PE Wrap
Tropical	2[a]	7	15	25	35
Subtropical	3	10	20	30	35
Temperate	6	15	25	35	35
Polar	10	25	35	35	35

[a]All numbers = years.

Table 2. Navy and Coast Guard Sites with PVC-Wrapped Timber Piling

Location	Contact
U.S. Navy	
Pier Santa Cruz Island, CA	Mr. Lester Malen Deputy Staff Civil Engineer Code 00-3 Navy Pacific Missile Test Center Point Mugu, CA
Camp Nimitz Bridge San Diego, CA	Mr. Bill Thornton Mooring Engineer Naval Public Works Center San Diego, CA
U.S. Coast Guard	
Pier Newport Beach, CA Pier Terminal Island, CA	Mr. Hux Civil Engineer Coast Guard Civil Engineering District Office Long Beach, CA
Pier Ketchikan, AK (experimental only)	Mr. Bud Morris Civil Engineer Coast Guard Civil Engineering District Office Juneau, AK
Depot Pier Corpus Christi, TX	Mr. Frank Mineo Civil Engineer U.S. Coast Guard Corpus Christi, TX

Table 3. Calculated Average Annual Costs of Marine Timber Bearing Piling Treatment and Repair Options in All Areas

Area	Treatment	Repair Option ($/Pile/Yr) for--		
		PVC Wrap	Pile Replacement	Concrete Encasement
Tropical	None	126	1,223	493
	Creosote	146	414	385
	Arsenical Salt	148	234	276
	Dual	169	199	220
Subtropical	None	122	805	456
	Creosote	138	293	318
	Arsenical Salt	142	189	221
	Dual	166	184	198
Temperate	None	112	391	362
	Creosote	130	205	241
	Arsenical Salt	138	165	187
	Dual	165	176	185
Polar	None	102	231	273
	Creosote	121	144	164
	Arsenical Salt	134	144	153
	Dual	165	176	185

Table 4. Calculated Average Annual Costs of Marine Timber Fender Piling Treatment and Repair Options in All

Area	Treatment	Repair Option ($/Pile/Yr) for--					
		No Breakage		5% Broken/Yr		10% Broken/Yr	
		Wrap	Replace	Wrap	Replace	Wrap	Replace
Tropical	None	126	842	206	861	286	880
	Creosote	139	310	228	349	317	388
	Arsenical Salt	124	170	212	229	300	300
	Dual	136	151	235	235	340	340
Subtropical	None	122	563	201	585	279	607
	Creosote	132	230	220	277	308	324
	Arsenical Salt	118	143	207	212	300	300
	Dual	133	143	235	235	340	340
Temperate	None	112	287	187	318	262	348
	Creosote	124	170	212	229	300	300
	Arsenical Salt	115	129	205	205	300	300
	Dual	132	138	235	235	340	340
Polar	None	102	180	175	220	248	260
	Creosote	115	129	205	205	300	300
	Arsenical Salt	112	117	205	205	300	300
	Dual	132	138	235	235	340	340

Table 5. Calculated Annual Costs of Marine Fender Piling Wrapped with PVC or PE or Coated with PU Before Driving

Treatment	Costs ($/Pile) for--		
	No Breakage	5% Broken/Yr	10% Broken/Yr
None	110	205	300
Creosote	140	250	360
Arsenical Salt	140	250	360
Dual	160	280	400

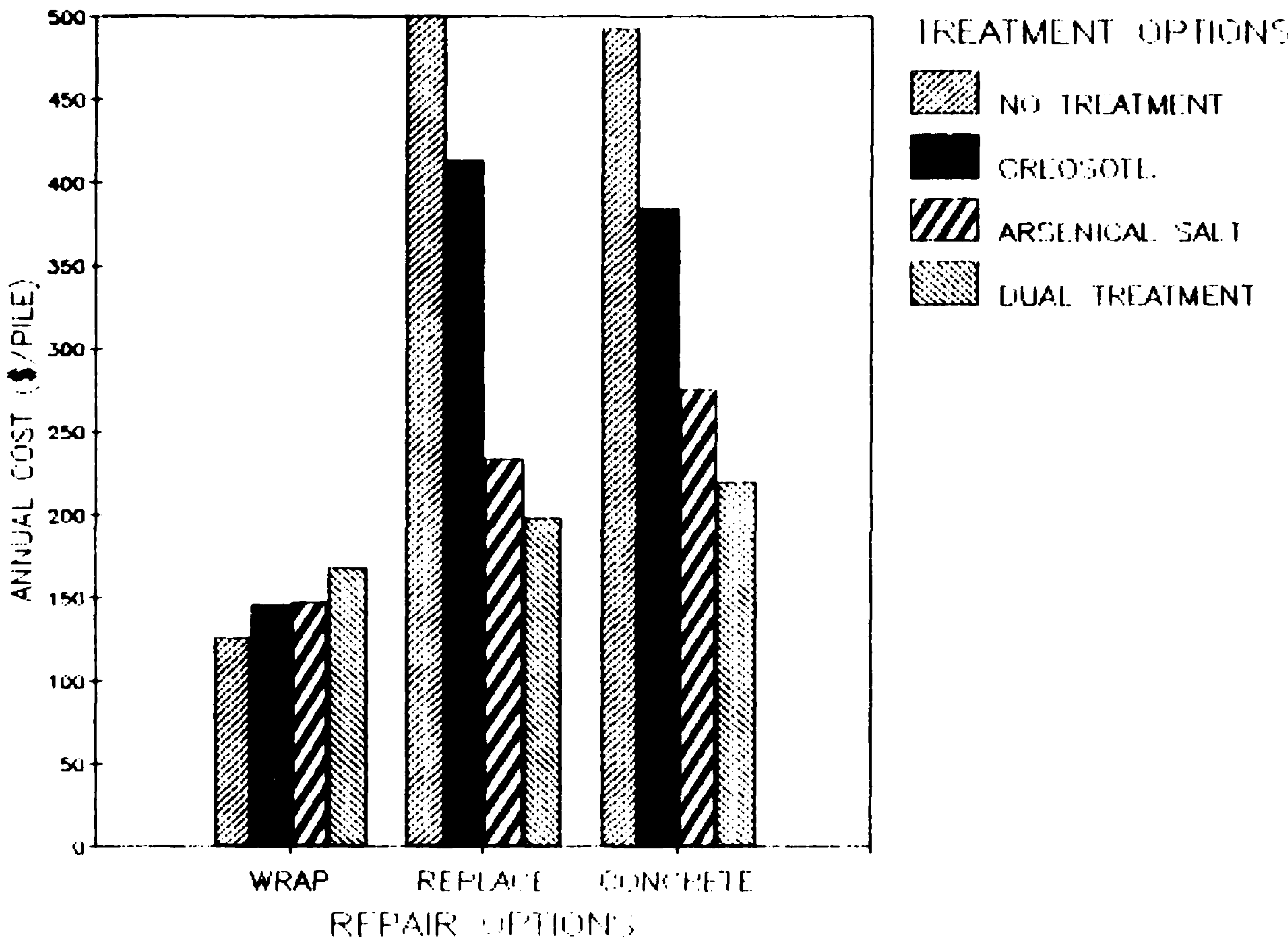

Figure 1. Calculated annual costs of marine timber bearing piling treatment and repair options in tropical areas.

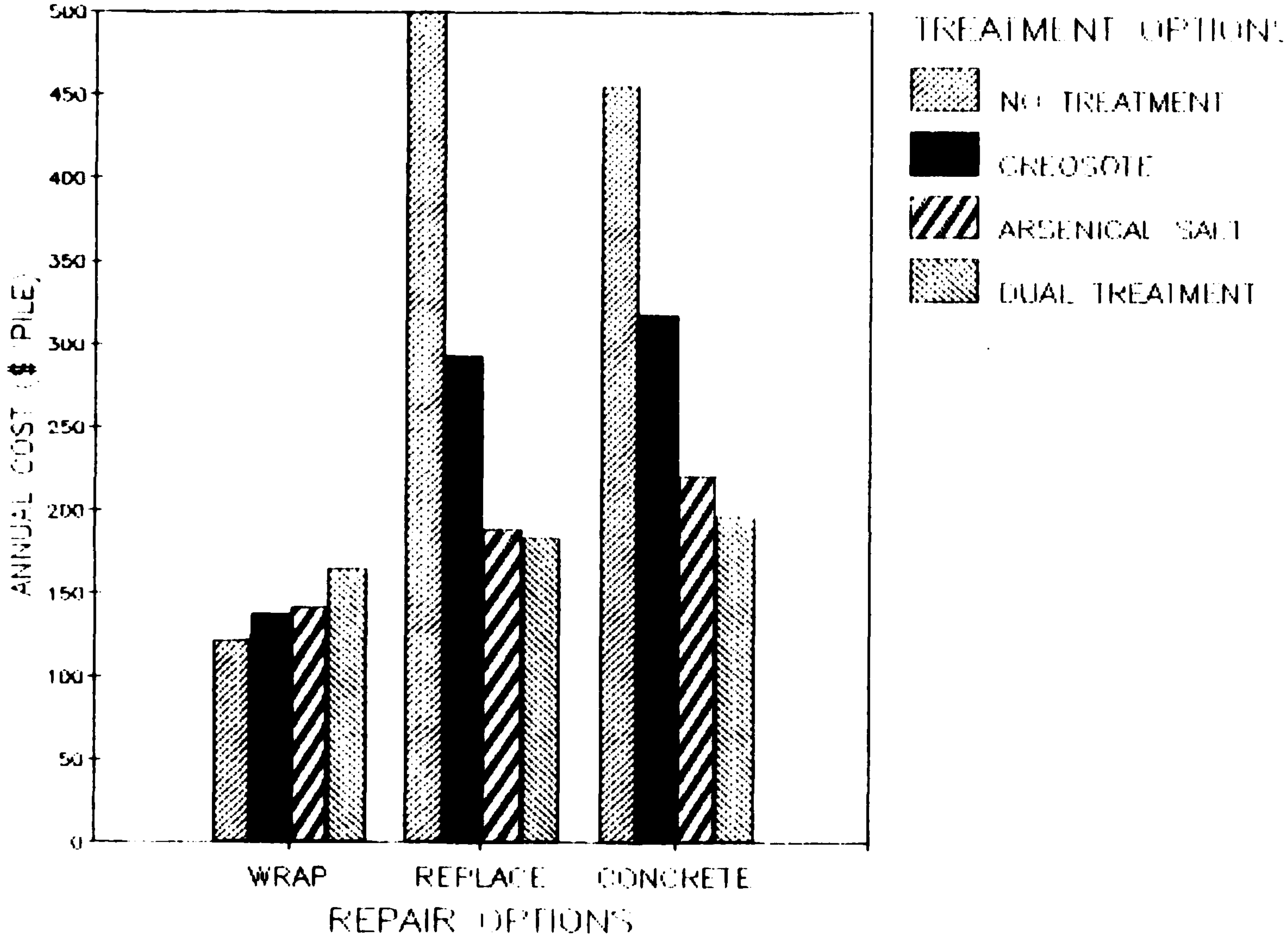

Figure 2. Calculated annual costs of marine timber bearing piling treatment and repair options in subtropical areas.

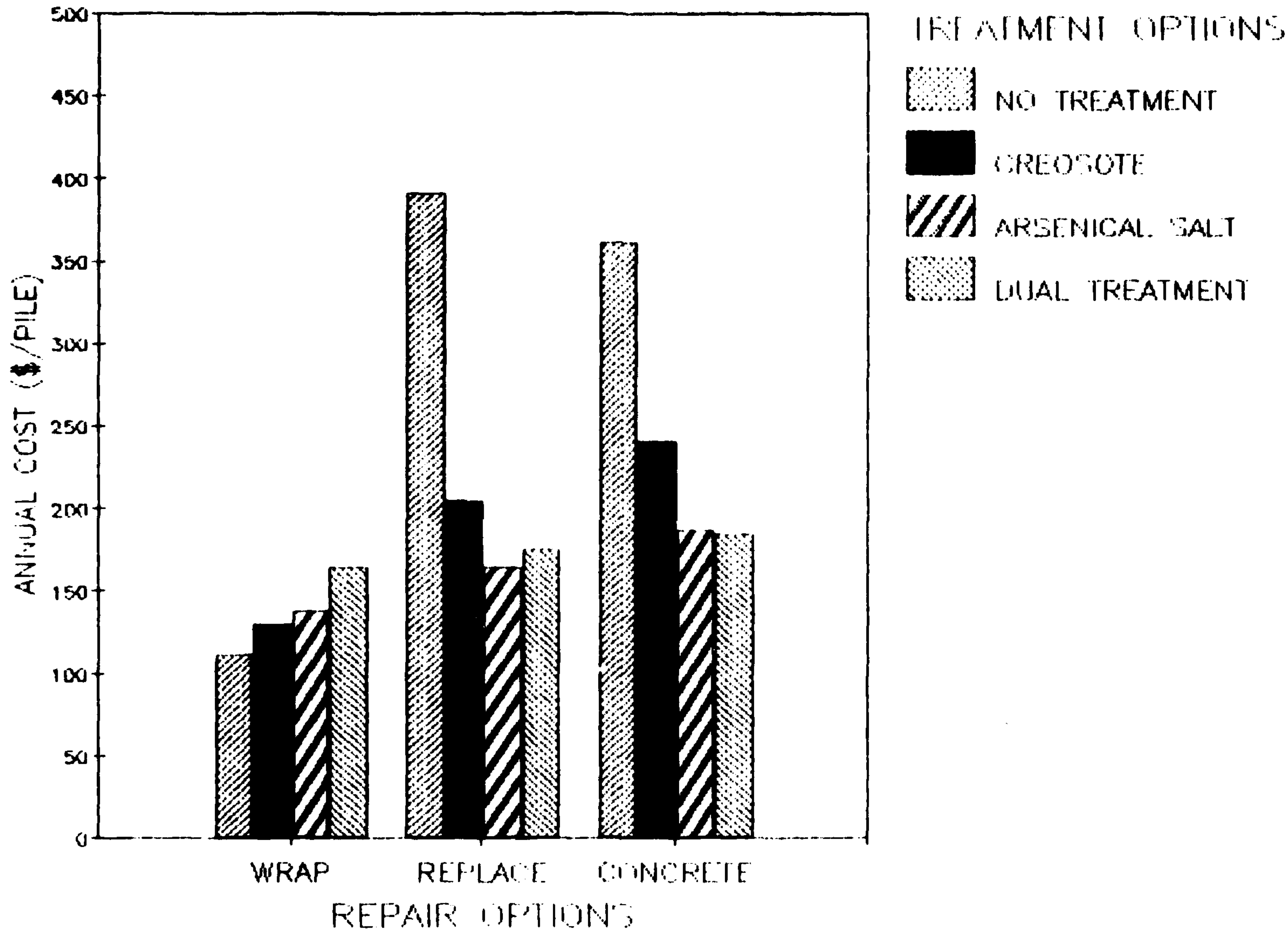

Figure 3. Calculated annual costs of marine timber bearing piling treatment and repair options in temperate areas.

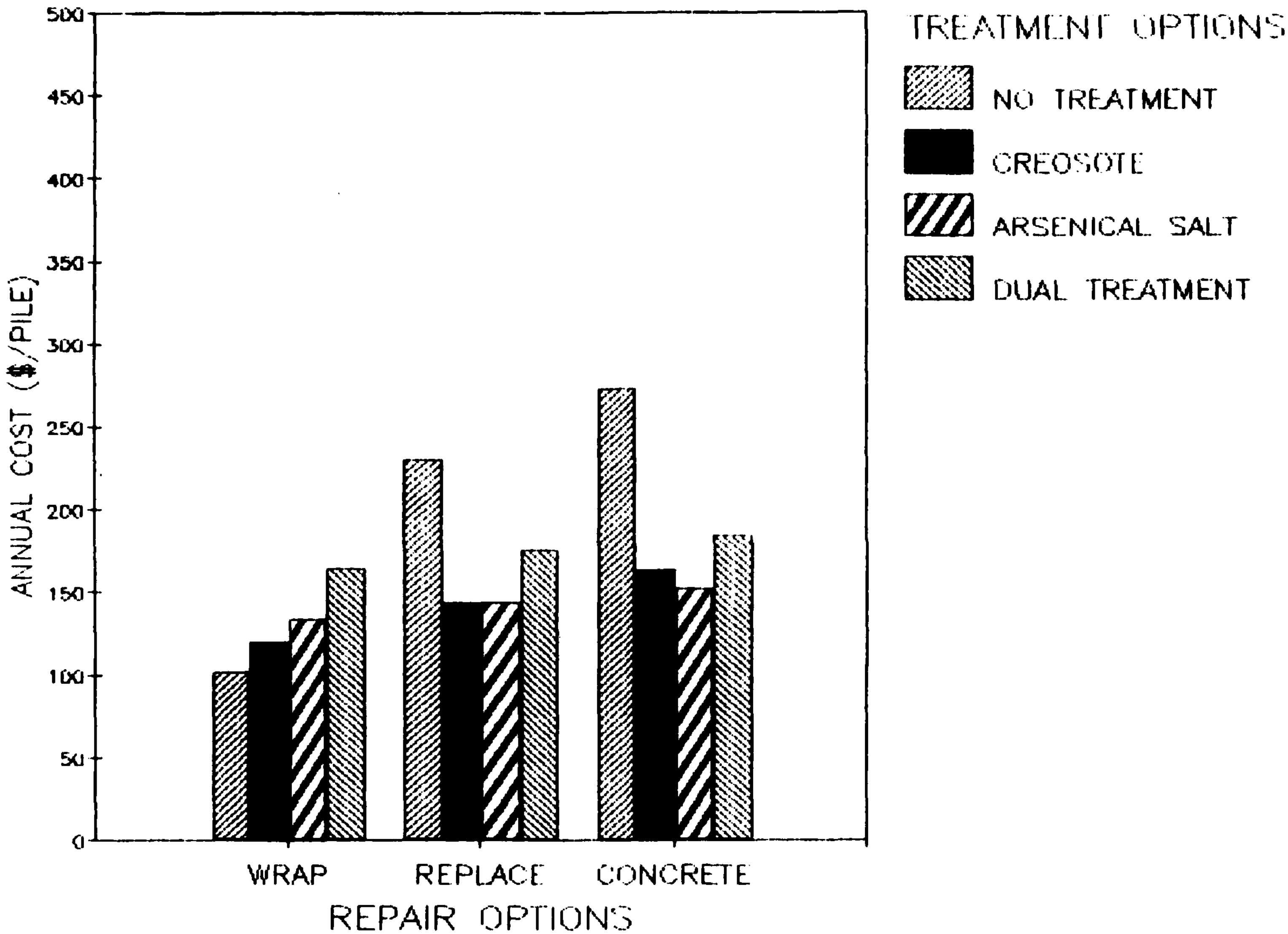

Figure 4. Calculated annual costs of marine timber bearing piling treatment and repair options in polar areas.

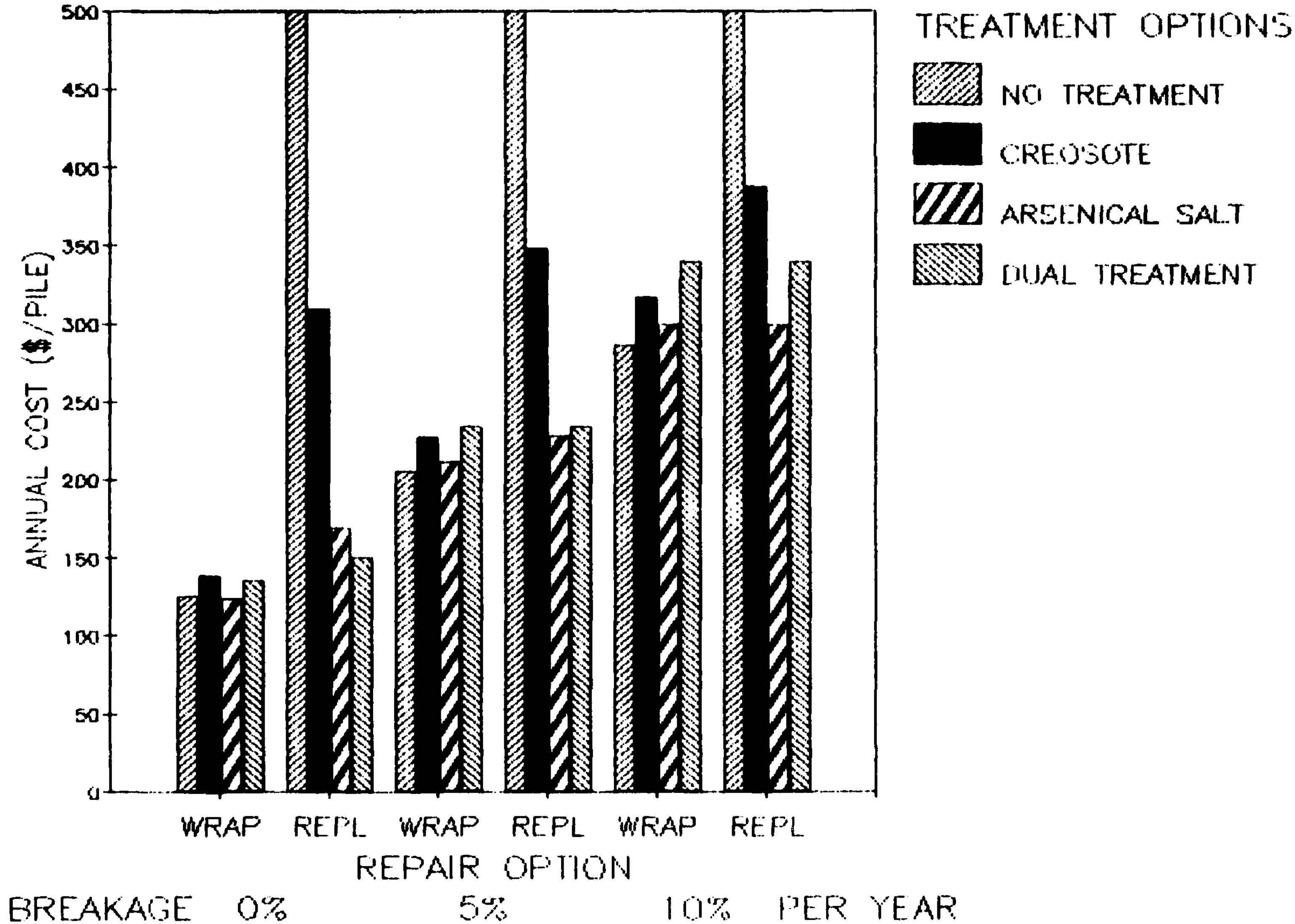

Figure 5. Calculated annual costs of marine timber fender piling treatment and repair options in tropical areas.

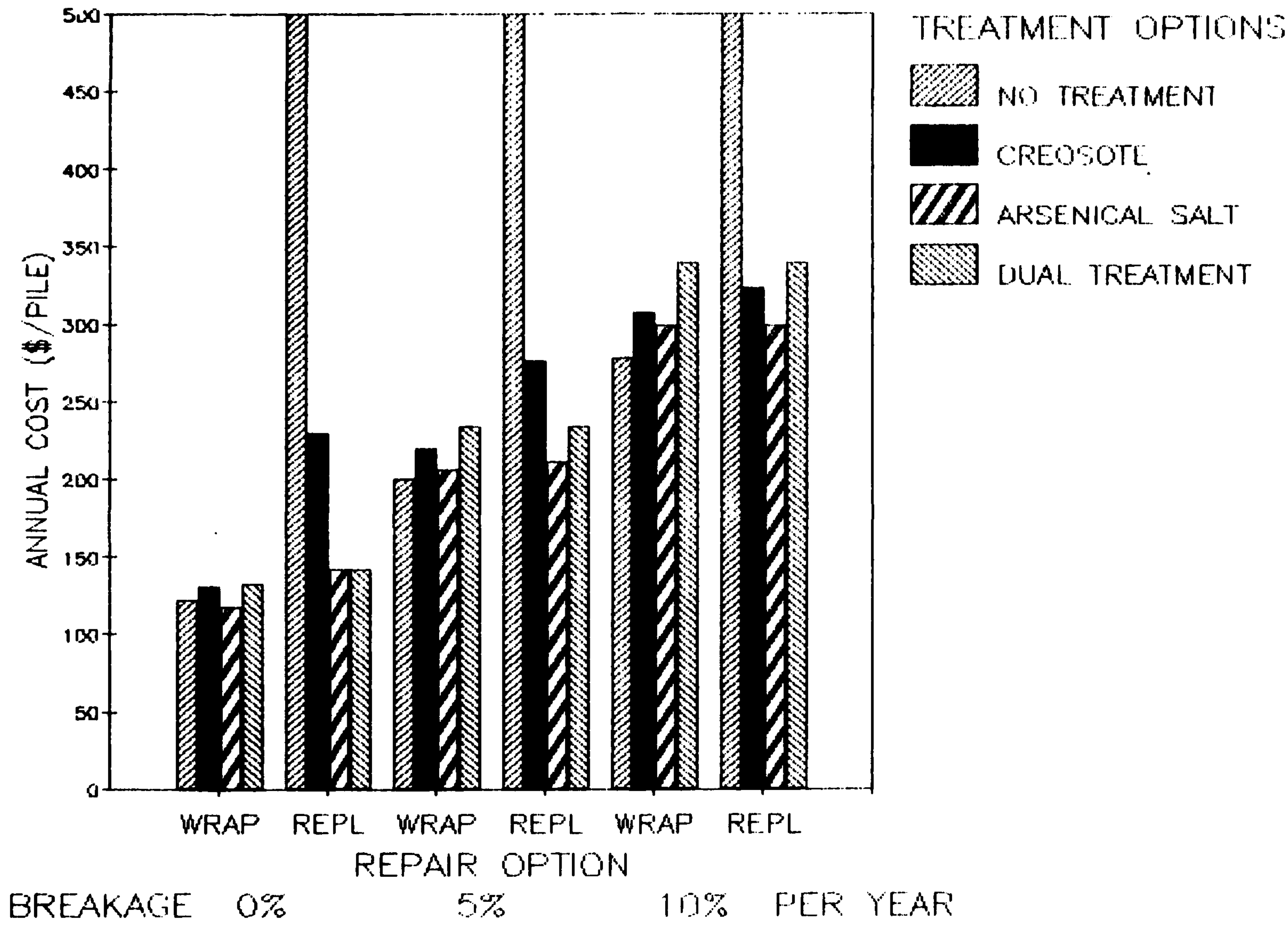

Figure 6. Calculated annual costs of marine timber fender piling treatment and repair options in subtropical areas.

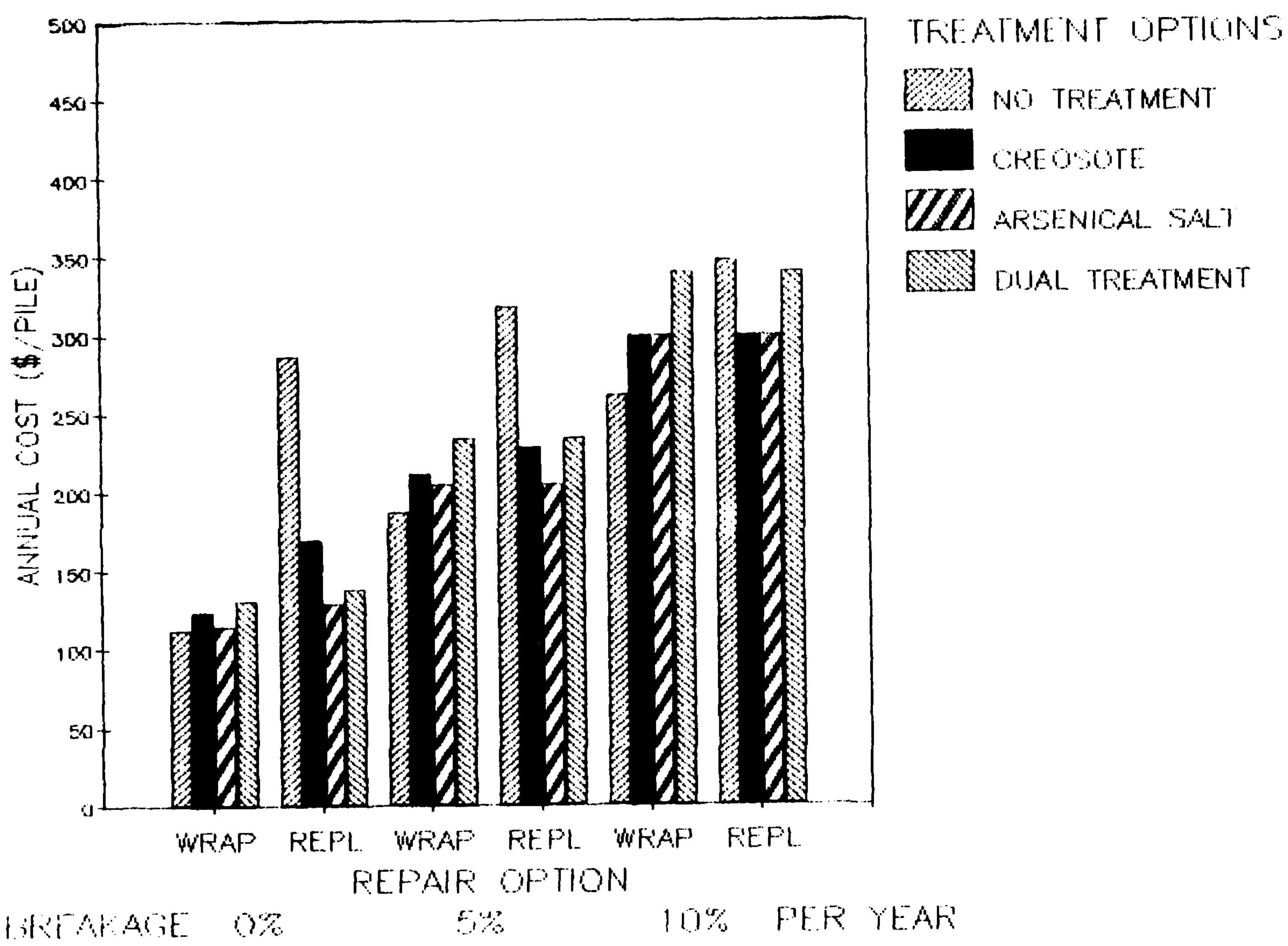

Figure 7. Calculated annual costs of marine timber fender piling treatment and repair options in temperate areas.

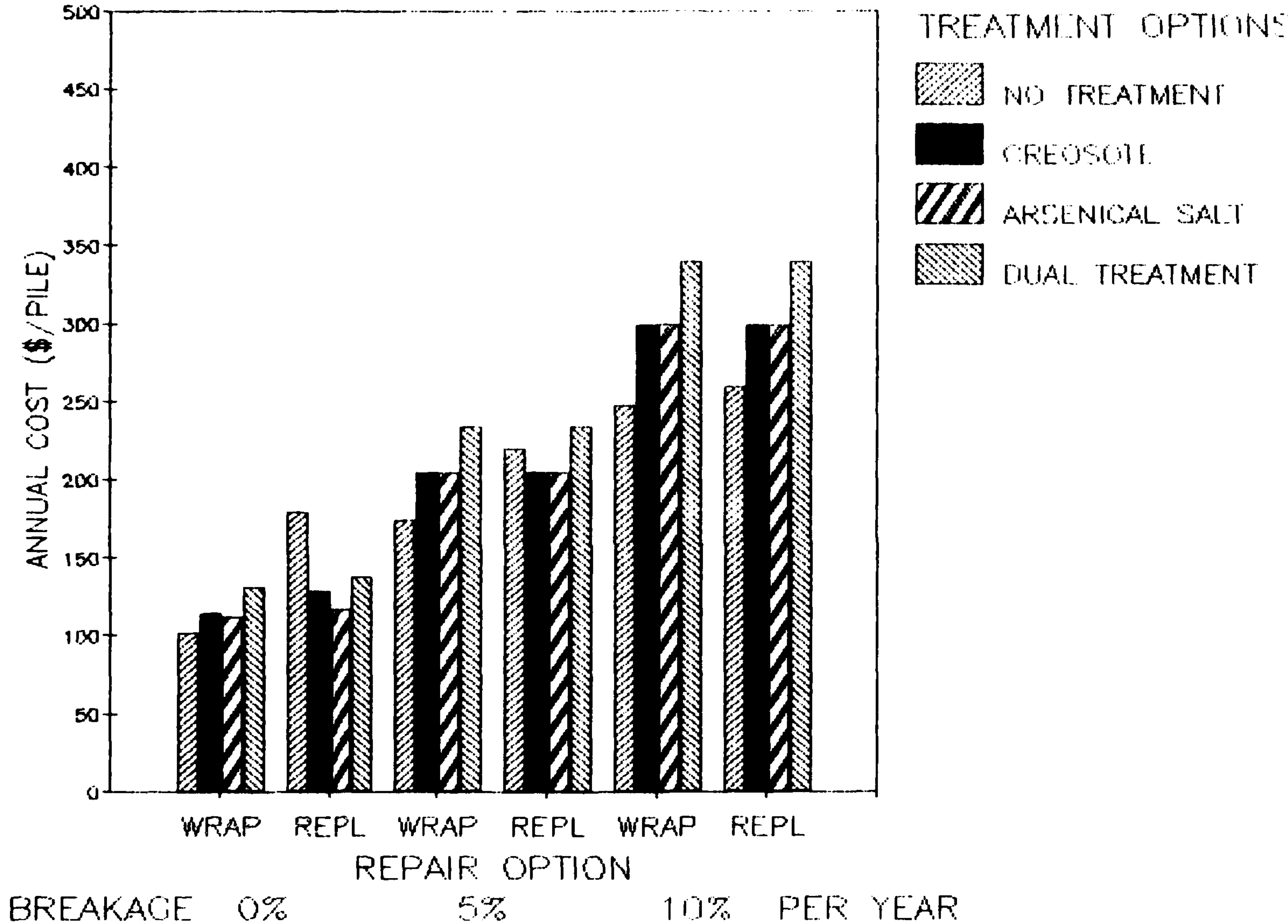

Figure 8. Calculated annual costs of marine timber fender piling treatment and repair options in polar areas.

Appendix A

ANNUAL COST ESTIMATE FORMULAE WITH ASSUMPTIONS

Various assumptions are made in this analysis. Costs and interest rates vary and may be different from those assumed here. The reader is free to incorporate alternative cost estimates into the formulae presented. The expected life of preservative-treated piling also varies dependent on location. The analysis is thus completed for the range of life expectancy values for each preservative treatment and for each geographical area as indicated in Table 1. No analysis is completed for useful life values greater than 35 years because of the increasingly small additional amortized costs beyond that amount of time.

The following nomenclature and assumptions are used for the various models:

AC = Annual cost

i = Interest rate is 10%

C_n = Capital cost of an untreated 45-foot pile is \$800

C_t = Capital cost of a creosoted or arsenical-treated pile is \$1100

C_d = Capital cost of a dual-treated pile is \$1300

C_{tw} = Capital cost of a single-treated pile prewrapped with PVC or PE or precoated with PU is \$1400

C_{dw} = Capital cost of a dual-treated pile prewrapped with PVC or PE or precoated with PU is \$1600

C_w = Capital cost of an untreated pile prewrapped with PVC or PE or precoated with PU is \$1100

A_w = Cost of wrapping a pile after installation is \$450

A_c = Cost of encasing the pile with concrete is \$5000

R_b = Cost of reinstallation of a timber bearing pile is \$1600 (does not include piling cost)

R_f = Cost of reinstallation of a timber fender pile is \$800 (does not include piling cost)

T_n = Estimated useful life of an untreated pile (Table 1)

T_t = Estimated useful life of a treated pile (Table 1)

T_d = Estimated useful life of a dual-treated pile (Table 1)

T_w = Estimated useful life of a wrapped or coated pile is 35 years

T_y = Estimated number of years before repair by wrapping is required (2 years less than indicated in Table 1)

F_c = Added cost factor due to decreased strength of creosoted timber is 1.05

F_a = Added cost factor due to decreased strength of arsenical-treated timber is 1.2

F_d = Added cost factor due to decreased strength of dual-treated timber is 1.25

B = Percentage of fender piles broken per year is 0, 5, or 10

Annual cost estimates for the various options are developed using the above assumptions and generally follow the arguments presented in Reference 31. The formulae developed consider the different points in time when capital expenditures are necessary. This is done by assuming that each policy will be followed indefinitely. With this assumption the cost per year of the initial capital investment is simply the original cost x interest rate. The added cost per year for maintenance is determined by discounting all costs during one repair or replacement cycle back to the present and then calculating the equivalent uniform annual payment over that cycle time. The general form of the equation thus becomes:

$$AC = C \cdot i + (C + R)\left[\frac{1}{1+i}\right]^{t_1}\left[\frac{i(1+i)^{t_2}}{(1+i)^{t_2} - 1}\right]$$

where $\left[\frac{1}{1+i}\right]^{t_1}$ is the present worth factor and t_1 is the amount of time required before maintenance is required.

and $\frac{i(1+i)^{t_2}}{(1+i)^{t_2} - 1}$ is the capital recovery factor and t_2 is the expected useful life of the repair or replacement

The following formulae are presented in the order used in the various tables.

Untreated Bearing Piles Repaired by Replacement:

$$AC = C_n \cdot i + (C_n + R_b)\left[\frac{1}{1+i}\right]^{T_n} \left[\frac{i(1+i)^{T_n}}{(1+i)^{T_n} - 1}\right]$$

Untreated Bearing Piles Protected by Wrapping with PVC:

$$AC = C_n \cdot i + (A_w)\left[\frac{1}{1+i}\right]^{T_n} \left[\frac{i(1+i)^{T_w}}{(1+i)^{T_w} - 1}\right]$$

Untreated Bearing Piles Repaired by Encasement in Concrete:

$$AC = C_n \cdot i + (A_c \cdot i)\left[\frac{1}{1+i}\right]^{T_n}$$

Creosoted Bearing Piles Repaired by Replacement:

$$AC = F_c \left\{C_t \cdot i + (C_t + R_b) \left[\frac{1}{1+i}\right]^{T_t} \left[\frac{i(1+i)^{T_t}}{(1+i)^{T_t} - 1}\right]\right\}$$

Creosoted Bearing Piles Protected by Wrapping with PVC:

$$AC = F_c \left\{C_t \cdot i + (A_w) \left[\frac{1}{1+i}\right]^{T_t} \left[\frac{i(1+i)^{T_w}}{(1+i)^{T_w} - 1}\right]\right\}$$

Creosoted Bearing Piles Repaired by Encasement in Concrete:

$$AC = F_c \left\{C_t \cdot i + (A_c)\left[\frac{1}{1+i}\right]^{T_t}\right\}$$

Arsenical-Treated Bearing Piles Repaired by Replacement:

$$AC = F_a \left\{ C_t \cdot i + (C_t + R_b) \left[\frac{1}{1 + i}\right]^{T_t} \left[\frac{i(1 + i)^{T_t}}{(1 + i)^{T_t} - 1}\right]\right\}$$

Arsenical-Treated Bearing Piles Protected by Wrapping with PVC:

$$AC = F_a \left\{ C_t \cdot i + (A_w) \left[\frac{1}{1 + i}\right]^{T_t} \left[\frac{i(1 + i)^{T_w}}{(1 + i)^{T_w} - 1}\right]\right\}$$

Arsenical-Treated Bearing Piles Repaired by Encasement in Concrete:

$$AC = F_a \left\{ C_t \cdot i + (A_c) \left[\frac{1}{1 + i}\right]^{T_t} \right\}$$

Dual-Treated Bearing Piles Repaired by Replacement:

$$AC = F_d \left\{ C_d \cdot i + (C_d + R_b) \left[\frac{1}{1 + i}\right]^{T_d} \left[\frac{i(1 + i)^{T_d}}{(1 + i)^{T_d} - 1}\right]\right\}$$

Dual-Treated Bearing Piles Protected by Wrapping with PVC:

$$AC = F_d \left\{ C_d \cdot i + (A_w) \left[\frac{1}{1 + i}\right]^{T_d} \left[\frac{i(1 + i)^{T_w}}{(1 + i)^{T_w} - 1}\right]\right\}$$

Dual-Treated Bearing Piles Repaired by Encasement in Concrete:

$$AC = F_d \left\{ C_d \cdot i + (A_c) \left[\frac{1}{1 + i}\right]^{T_d} \right\}$$

Untreated, Prewrapped, or Precoated Bearing Piles Repaired by Rewrapping:

$$AC = C_w \cdot i + (A_w) \left[\frac{1}{1 + i}\right]^{T_w} \left[\frac{i(1 + i)^{T_w}}{(1 + i)^{T_w} - 1}\right]$$

Creosoted, Prewrapped or Precoated Bearing Piles Repaired by Rewrapping:

$$AC = F_c \left\{ C_{tw} \cdot i + (A_w) \left[\frac{1}{1+i}\right]^{T_w} \left[\frac{i(1+i)^{T_w}}{(1+i)^{T_w} - 1}\right]\right\}$$

Arsenical-Treated, Prewrapped or Precoated Bearing Piles Repaired by Rewrapping:

$$AC = F_a \left\{ C_{tw} \cdot i + (A_w) \left[\frac{1}{1+i}\right]^{T_w} \left[\frac{i(1+i)^{T_w}}{(1+i)^{T_w} - 1}\right]\right\}$$

Dual-Treated, Prewrapped or Precoated Bearing Piles Repaired by Rewrapping:

$$AC = F_d \left\{ C_{dw} \cdot i + (A_w) \left[\frac{1}{1+i}\right]^{T_w} \left[\frac{i(1+i)^{T_w}}{(1+i)^{T_w} - 1}\right]\right\}$$

Untreated Fender Piling Repaired by Replacement:

$$AC = C_n \cdot i + (R_f + C_n)(1 - 0.8 \cdot t_n \cdot B)\left[\frac{1}{1+i}\right]^{T_n} \left[\frac{i(1+i)^{T_n}}{(1+i)^{T_n} - 1}\right]$$

$$+ B(R_f + C_n)$$

Untreated Fender Piling Protected by Wrapping with PVC:

$$AC = C_n \cdot i + (A_w)(1 - 0.8\ t_n\ B)\left[\frac{1}{1+i}\right]^{T_n} \left[\frac{i(1+i)^{T_w}}{(1+i)^{T_w} - 1}\right]$$

$$+ B(R_f + C_n)$$

Treated Fender Piling Repaired by Replacement:

$$AC = C_t \cdot i + (R_f + C_t)(1 - 0.8 \cdot t_t \cdot B)\left[\frac{1}{1+i}\right]^{T_t} \left[\frac{i(1+i)^{T_t}}{(1+i)^{T_t} - 1}\right]$$

$$+ B(R_f + C_t)$$

Treated Fender Piling Protected by Wrapping with PVC:

$$AC = C_t \cdot i + (A_w)(1 - 0.8 \cdot t_t \cdot B)\left[\frac{1}{1+i}\right]^{T_t} \left[\frac{i(1+i)^{T_w}}{(1+i)^{T_w} - 1}\right] + B(R_f + C_t)$$

Dual-Treated Fender Piling Repaired by Replacement:

$$AC = C_d \cdot i + (R_f + C_d)(1 - 0.8 \cdot t_d \cdot B)\left[\frac{1}{1+i}\right]^{T_d} \left[\frac{i(1+i)^{T_d}}{(1+i)^{T_d} - 1}\right]$$

$$+ B(R_f + C_d)$$

Dual-Treated Fender Piling Protected by Wrapping with PVC:

$$AC = C_d \cdot i + (A_w)(1 - 0.8 \cdot T_d \cdot B)\left[\frac{1}{1+i}\right]^{T_d} \left[\frac{i(1+i)^{T_w}}{(1+i)^{T_w} - 1}\right] + B(R_f + C_d)$$

Untreated, Prewrapped or Precoated Fender Piles Repaired by Rewrapping:

$$AC = C_w \cdot i + (A_w)(1 - 0.8 \cdot T_w \cdot B)\left[\frac{1}{1+i}\right]^{T_w} \left[\frac{i(1+i)^{T_w}}{(1+i)^{T_w} - 1}\right] + B(R_f + C_w)$$

Creosoted or Arsenical-Treated, Prewrapped or Precoated Fender Piles Repaired by Rewrapping:

$$AC = C_{tw} \cdot i + (A_w)(1 - 0.8 \cdot T_w \cdot B)\left[\frac{1}{1+i}\right]^{T_w} \left[\frac{i(1+i)^{T_w}}{(1+i)^{T_w} - 1}\right] + B(R_f + C_{tw})$$

Dual-Treated, Prewrapped or Precoated Fender Piles Repaired by Rewrapping:

$$AC = C_{dw} \cdot i + (A_w)(1 - 0.8 \cdot T_w \cdot B)\left[\frac{1}{1+i}\right]^{T_w} \left[\frac{i(1+i)^{T_w}}{(1+i)^{T_w} - 1}\right] + B(R_f + C_{dw})$$

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14 Airfields and pavements
15 **ADVANCED BASE AND AMPHIBIOUS FACILITIES**
16 Base facilities (including shelters, power generation, water supplies)
17 Expedient roads/airfields/bridges
18 Amphibious operations (including breakwaters, wave forces)
19 Over-the-Beach operations (including containerization, materiel transfer, lighterage and cranes)
20 POL storage, transfer and distribution
28 **ENERGY/POWER GENERATION**
29 Thermal conservation (thermal engineering of buildings, HVAC systems, energy loss measurement, power generation)
30 Controls and electrical conservation (electrical systems, energy monitoring and control systems)
31 Fuel flexibility (liquid fuels, coal utilization, energy from solid waste)
32 Alternate energy source (geothermal power, photovoltaic power systems, solar systems, wind systems, energy storage systems)
33 Site data and systems integration (energy resource data, energy consumption data, integrating energy systems)
34 **ENVIRONMENTAL PROTECTION**
35 Solid waste management
36 Hazardous/toxic materials management
37 Wastewater management and sanitary engineering
38 Oil pollution removal and recovery
39 Air pollution
44 **OCEAN ENGINEERING**
45 Seafloor soils and foundations
46 Seafloor construction systems and operations (including diver and manipulator tools)
47 Undersea structures and materials
48 Anchors and moorings
49 Undersea power systems, electromechanical cables, and connectors
50 Pressure vessel facilities
51 Physical environment (including site surveying)
52 Ocean-based concrete structures
53 Hyperbaric chambers
54 Undersea cable dynamics

TYPES OF DOCUMENTS

85 Techdata Sheets
86 Technical Reports and Technical Notes
82 NCEL Guide & Updates
☐ None–remove my name
83 Table of Contents & Index to TDS
91 Physical Security

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