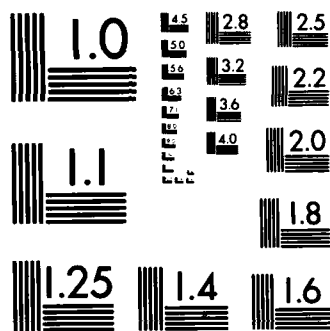


AD-A157 492 COST OF WATER DISTRIBUTION SYSTEM INFRASTRUCTURE
REHABILITATION REPAIR AND REPLACEMENT(U) ARMY ENGINEER
WATERWAYS EXPERIMENT STATION VICKSBURG MS ENVIR.

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AD-A157 492

TECHNICAL REPORT EL-85-5



COST OF WATER DISTRIBUTION SYSTEM INFRASTRUCTURE REHABILITATION, REPAIR, AND REPLACEMENT

by

Thomas M. Walski

Environmental Laboratory

DEPARTMENT OF THE ARMY
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March 1985

Final Report

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report presents data and estimating procedures for predicting the cost of several types of work involved with maintaining water systems, including cleaning and cement mortar lining of pipes, cathodic protection of buried pipes, repair of pipe breaks and leaks, replacing (relaying) water mains, and chemical addition to produce water that is neither corrosive nor scale-forming. This report is intended to serve as a tool for water supply engineers required to develop planning level cost estimates of alternative rehabilitation measures.		

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PREFACE

This report describes work conducted under the Water System Operation, Maintenance, and Rehabilitation Work Unit (CWIS 31794) of the Water Supply and Conservation Research Program. The technical monitors of this program in the Office of the Chief of Engineers were Mr. James Ballif (DAEN-ECE-B) and Mr. Robert Daniel (DAEN-CWP-D).

The report was written at the US Army Engineer Waterways Experiment Station (WES) in Vicksburg, Miss., by Dr. Thomas M. Walski, Water Resources Engineering Group (WREG), Environmental Engineering Division (EED), Environmental Laboratory (EL), WES.

The report could not have been prepared without data provided Dr. Walski from a number of sources. Mr. Scott Biondi of Ameron, Inc., Kenilworth, N.J., provided data on pipe cleaning and lining costs under purchase order DACW39-84-M-0726. Mr. Roger Cimbara of Atlantic Piping Services, Ltd., provided data on the costs of pigging pipes. Additional data on pipe cleaning were provided by Mr. Spencer Cubage of Flowmore Services, Houston, Tex., and Ms. Kay Kerr of Knapp Polly-Pig, Houston, Tex. Mr. George Rubenstahl of the Harco Company, Houston, Tex., provided data on cathodic protection of buried pipes under purchase order DACW39-84-M-1924. Ms. Theresa King of the Water Department of the City of Philadelphia provided data on the cost of repairing pipe breaks and relaying pipes. Dr. Joe Miller Morgan and Ms. Margret M. Brown of Auburn University provided data on the cost of chemical feed for water stabilization, and prepared the first draft of that section.

The report was reviewed by Mr. M. John Cullinane of the Water Supply and Waste Treatment Group of EED and Dr. Morgan. The study was conducted under the general supervision of Dr. Michael R. Palermo, Chief, WREG; Mr. Andrew J. Green, Chief, EED; and Dr. John Harrison, Chief, EL.

Commanders and Directors of WES during preparation and publication of this report were COL Tilford C. Creel, CE, and COL Robert C. Lee, CE. Technical Director was Mr. F. R. Brown.

This report should be cited as follows:

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CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI
(metric) units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
feet	0.3048	metres
gallons (US liquid)	3.785412	cubic decimetres
inches	25.4	millimetres
miles (US statute)	1.609347	kilometres
pounds (mass)	0.4535924	kilograms
pounds (mass) per day	0.4535924	kilograms per day
square feet	0.09290304	square metres
yards	0.9144	metres

COST OF WATER DISTRIBUTION SYSTEM INFRASTRUCTURE
REHABILITATION, REPAIR, AND REPLACEMENT

PART I: INTRODUCTION

Background

1. As water systems throughout the country age, maintenance and rehabilitation of these systems are becoming increasingly important and costly. Cleaning and lining pipes, providing cathodic protection, and chemically stabilizing water are three methods used to prolong the life of existing pipes. Failure to take action to prevent the loss of hydraulic carrying capacity and structural integrity of pipes results in lower pressures, increased energy costs, and more frequent pipe breaks, ultimately hastening the need for replacement.

2. Engineers working with utilities are often called upon to make decisions concerning alternative maintenance and rehabilitation techniques and to estimate the costs for infrastructure projects. While data and methods are available for obtaining good planning level costs for construction of new water supply facilities (Headquarters, Department of the Army 1980; Walski and Lindsey 1982; Walski 1983), there is no similar guidance available for infrastructure rehabilitation work, which has traditionally been considered to be of minor significance. Rehabilitation work is also fairly site-specific, which has tended to discourage anyone from developing generalized planning level cost estimating procedures.

3. Numerous individuals have proposed methods to evaluate alternatives for pipe replacement and rehabilitation (Shamir and Howard 1979; Stafford et al. 1981; Male, Noss, and Moore 1984; Walski 1984c). However, application of these methods is often limited by lack of information on costs.

4. The increased interest in water system infrastructure rehabilitation in recent years has made the lack of cost data and estimating procedures more obvious. Cost data have been developed for items associated with specific studies (US Army Engineer District, Buffalo 1981; US Army Engineer District, New York 1980; Walski and Pelliccia 1981) and some cities have become more concerned with collecting and storing cost data for this kind of work (King

1984a, 1984b). Nevertheless, an engineer preparing estimates has very little guidance on water system rehabilitation costs.

Purpose

5. The purpose of this study was to assemble existing cost data and develop and verify cost estimating procedures for pipe cleaning and lining, cathodic protection of buried pipes, pipe break repair, pipe relaying, and chemical feed for prevention of internal corrosion and scaling. This report is intended to serve as a reference work for water supply engineers faced with the problem of developing planning level cost estimates or selecting from alternative rehabilitation measures.

Overview

6. Each of the latter parts of this report are essentially separate reports on cost estimating for that particular type of work. Therefore, there is no need to read them in order.

7. Part II contains a method for cleaning and cement mortar lining of water mains. Two methods are presented, one which uses unit prices of individual cost items, and a second based on statistical analysis of project data. These procedures are verified against costs of actual projects. Costs of projects in which the pipes are cleaned but not lined are also discussed, and some tips on conducting cleaning and lining projects are presented.

8. Part III contains a description of methods for cathodic protection of buried pipes and an approach to estimating costs for a cathodic protection project. This method is verified against the cost of actual projects.

9. Part IV presents data collected in several cities on the costs of repairing broken pipes and leaks. Some factors affecting costs and time to repair pipe are also discussed.

10. Part V gives cost data on replacement (relaying) of water pipes in older water systems. It also discusses why cost of relaying is generally higher than the cost of laying new pipe in an undeveloped area.

11. Part VI contains data on the cost of feeding chemicals to prevent water from being corrosive or scale-forming. Factors affecting the costs are also described.

Caveat

12. The method for predicting the cost of water system rehabilitation, repair, and replacement presented in this report should provide fairly accurate cost estimates given the general descriptions of potential projects that are usually available before detailed specifications are prepared. The methods work best for "typical" projects. It is the responsibility of the engineer to ensure that the data entered into the methods are accurate and, more importantly, that the cost estimates be corrected for atypical conditions which include, but are not limited to, such considerations as difficult job sites, unusual bidding climates, restrictions on hours worked or methods used, new technologies, and shifts in prices for labor or materials.

PART II: COST OF CLEANING AND LINING WATER MAINS

Introduction

Background

13. As water mains age, they tend to lose their carrying capacity. This can occur in unlined metal pipe carrying aggressive water (relatively low pH) because iron is pulled out of the pipe to form tubercles. When water in any type of pipe is supersaturated with calcium or magnesium (relatively high pH), scale may form on the interior of the pipe. In other cases bacterial growth can occur on pipe walls. All of these mechanisms reduce the internal diameter of the pipe and increase the pipe roughness so that for a given flow, head loss is increased, or for a given hydraulic gradient, flow is decreased. The utility realizes these effects in higher pumping costs, lower pressures, and reduced fire-fighting capability.

14. The carrying capacity of water mains is usually reported in terms of the Hazen-Williams C-factor. New pipes have C-factors on the order of 140. Severely tuberculated pipes can have C-factors as low as 40. The C-factor of unlined metal pipes can be restored to values of approximately 120 by cleaning and cement mortar lining.

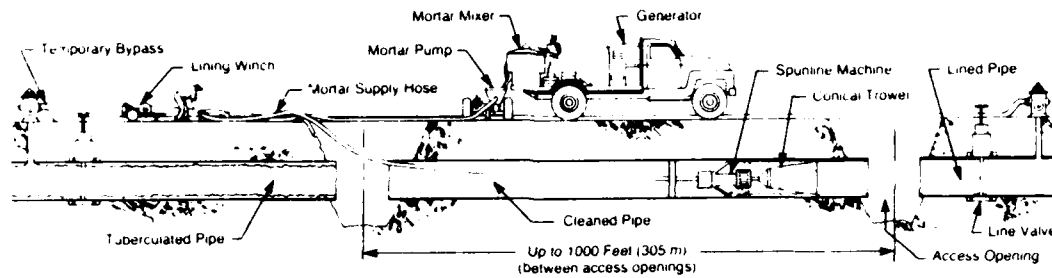
15. The cleaning and lining process consists of either mechanically or hydraulically scraping the inside of the pipe to remove all corrosion products. Once the pipe is sufficiently cleaned and dewatered, a thin lining of cement mortar is centrifugally applied to the pipe and smoothed with a trowel. After the mortar cures, the pipe is inspected, tested (if required), disinfected, and placed back in service. The cleaning and lining process is illustrated in Figure 2-1.

16. When a pipe is out of service during a cleaning and lining project, temporary service lines are often required to provide water to customers in the area. These usually consist of 2- and 4-in.* lines laid along the ground.

17. Small excavations to permit access to the pipe being rehabilitated are required every 500 to 800 ft. For convenience, these excavations should

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

For Pipelines 4 Inches (100 mm) Through 36 Inches (914 mm) in Diameter



For Larger Pipelines to 264 Inches (6.7 m) in Diameter

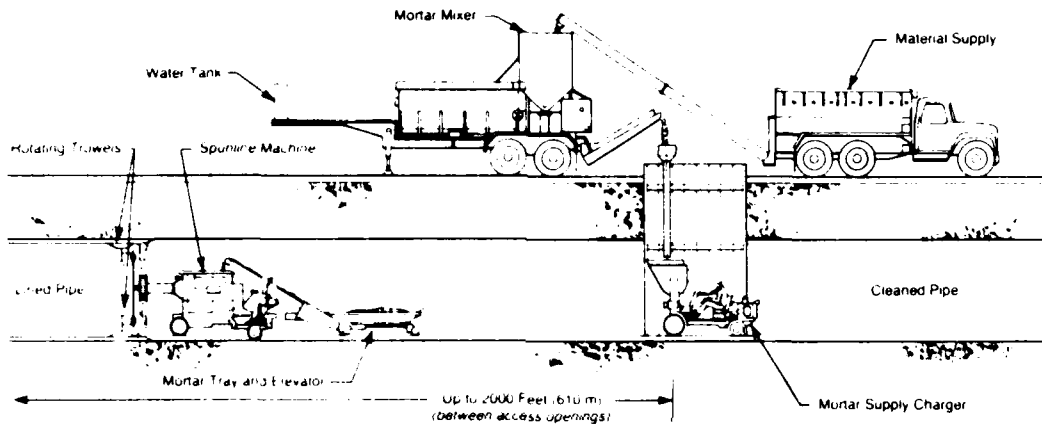


Figure 2-1. Cleaning and lining process

coincide with the location of valves needing replacement and bends which are too sharp to allow the mortar lining machines to operate properly. The section of pipe removed for the equipment to enter is called a "nipple." The nipple sections are usually cleaned and lined manually.

18. While in-place water main cleaning and lining have been practical since the 1930s, most of the literature on the process has been concerned with describing how pipes are cleaned and lined or how C-factors are modified by cleaning and lining. Relatively little attention has been directed toward cost.

19. The earliest documented costs for pipe cleaning and lining were presented by Kavanagh and Clifton (1945) who reported costs of 10s 2d/yd for the Stalwart Process (bituminous lining) for 4- to 7.5-in.-diam pipes (\$14.70 in 1984 US dollars) and 23s 7d/yd for the Tate Process (cement mortar) for 9- to 12-in.-diam pipes (\$34 in 1984 US dollars). The work was performed in Dublin, Ireland, during the late 1930s and early 1940s.

20. The Naval Energy and Environmental Support Activity (NEESA) (1983) and Walski (1982) presented some cost data based on fairly limited studies. Nevertheless, there is no standard procedure for estimating such costs.

Purpose

21. The purpose of this part is to develop a procedure for determining the cost for cleaning and lining water mains. The procedure will enable an engineer to calculate costs that are of sufficient accuracy for planning studies.

Overview

22. Two methods for estimating cleaning and lining costs are developed in the following sections. The first is a detailed unit price method based on determining quantities of excavation, temporary lines, etc., and multiplying by appropriate unit prices. The second procedure is a simpler method based on statistical correlations between features of historical cleaning and lining projects and their costs.

Unit Price Method

23. The unit price method for determining the cost of a cleaning and lining project consists of determining the quantities of excavation, cleaning and lining, bypass piping, and valve replacements and determining the unit prices of each item. The quantities are then multiplied by the appropriate unit prices, summed, and corrected for effects of variations in local labor costs and inflation to obtain the cost of the project. Table 2-1 shows a worksheet for calculating costs using this approach. Each item is explained in more detail below.

Development of cost data

24. Before describing how to use Table 2-1, it is necessary to explain what each item includes and does not include. The costs do not include such items as operating valves to isolate sections of the system, obtaining permits, notifying customers of service interruptions, providing water to the sites, chlorinating and flushing cleaned pipes, and conducting tests to ascertain the roughness of cleaned pipes. Typically, these tasks are performed by the utility or another contractor.

25. Each of the items for which costs are provided in Table 2-1 are

Table 2-1
Cost Estimating Worksheet

Item No.	Item	Unit	Bare Costs				Incl. O&P	Quant	Item Cost
			Labor	Mat'l	Equip	Total			
I	Mobilization	L.S.*	--	--	--	6,000.00	7,500.00		
	Correction for Location								
	Corrected Mobilization Cost								
II	Excavation								
	6- to 24-in. pipe								
	Type A	EA.	575.00	150.00	190.00	915.00	1,190.00		
	Type B	EA.	480.00	120.00	170.00	770.00	1,000.00		
	Type C	EA.	375.00	80.00	145.00	600.00	780.00		
	Type D	EA.	240.00	40.00	100.00	380.00	495.00		
	Sheeting/shoring	EA.	180.00	120.00	--	300.00	390.00		
	30- to 42-in. pipe								
	Type A	EA.	1,150.00	300.00	400.00	1,850.00	2,400.00		
	Type B	EA.	960.00	240.00	350.00	1,550.00	2,015.00		
	Type C	EA.	750.00	160.00	290.00	1,200.00	1,560.00		
	Type D	EA.	500.00	80.00	170.00	750.00	975.00		
	Sheeting/shoring	EA.	270.00	150.00	--	420.00	550.00		
	48- to 60-in. pipe								
	Type A	EA.	1,725.00	450.00	600.00	2,775.00	3,600.00		
	Type B	EA.	1,440.00	360.00	525.00	2,325.00	3,020.00		
	Type C	EA.	1,125.00	240.00	435.00	1,800.00	2,340.00		

(Continued)

* L.S. = Lump Sum.

(Sheet 1 of 3)

Table 2-1. (Continued)

Item No.	Item	Unit	Bare Costs				Incl. O&P	Quant	Item Cost
			Labor	Mat'l	Equip	Total			
III	Type D	EA.	750.00	120.00	255.00	1,125.00	1,460.00		
	Sheeting/shoring	EA.	360.00	150.00	--	510.00	660.00		
	Temporary service								
	2-in. bypass pipe	L.F.	0.78	0.20	0.30	1.28	1.70		
	4-in. bypass pipe	L.F.	1.53	0.60	0.35	2.48	3.20		
	Domestic serv. conn.	EA.	35.00	10.00	--	45.00	60.00		
	Fire serv. conn.	EA.	70.00	60.00	30.00	160.00	200.00		
	Cleaning and cement-mortar lining*								
	4- to 8-in. CIP or WSP	L.F.	4.31	0.33	1.50	6.14	8.00		
	10- to 16-in. CIP or WSP	L.F.	4.55	0.66	1.50	6.71	8.70		
IV	18- to 24-in. CIP or WSP	L.F.	4.78	1.24	1.50	7.52	9.80		
	30- to 42-in. CIP or WSP	L.F.	5.20	2.14	1.60	8.94	11.62		
	48- to 60-in. CIP or WSP	L.F.	5.40	3.09	1.70	10.19	13.25		
	Additional costs of rehabilitation of riveted steel or lockbar steel pipelines; hand cleaning and hand mortaring of rivet rows and lockbars:								
	30- to 42-in. RSP or LSP	L.F.	0.80	0.10	--	0.90	1.17		
	48- to 60-in. RSP or LSP	L.F.	0.90	0.15	--	1.05	1.37		

(Continued)

* CIP = Cast Iron Pipe, WSP = Welded Steel Pipe, RSP = Riveted Steel Pipe, LSP = Lockbar Steel Pipe.

(Sheet 2 of 3)

Table 2-1. (Concluded)

Item No.	Item	Unit	Bare Costs			Incl. O&P	Quant	Item Cost
			Labor	Mat'l	Equip			
V	Valve replacements							
	4-in. gate valve	EA.	146.00	255.00	40.00	550.00		
	6-in. gate valve	EA.	146.00	294.00	40.00	600.00		
	8-in. gate valve	EA.	146.00	409.00	40.00	745.00		
	10-in. gate valve	EA.	204.00	584.00	40.00	1,035.00		
	12-in. gate valve	EA.	204.00	724.00	40.00	1,210.00		
	16-in. butterfly valve	EA.	204.00	1,500.00	65.00	2,210.00		
	18-in. butterfly valve	EA.	263.00	1,834.00	65.00	2,700.00		
	20-in. butterfly valve	EA.	263.00	2,130.00	65.00	3,070.00		
	24-in. butterfly valve	EA.	263.00	2,195.00	65.00	4,050.00		
	Uncorrected total cost (UT)							
	Labor cost index							
	Total corrected for labor cost = 0.5 (1 + L) UT							
	Inflation correction							
	Total cost							

described in the following paragraphs. All costs are given in 1984 dollars. First bare costs and totals are defined.

26. Bare costs include labor, materials, and equipment but do not include contractor overhead and profit (O&P). Labor costs include base wages, fringe benefits, and payroll added costs for a crew composed of four contractors' key employees (technicians) and eight local laborers. Materials are items built into the work, normally sales tax exempt, and disposable items necessary to complete the work. Equipment costs include contractor-owned specialty equipment and equipment rented on site. Total costs are bare costs plus allowance for contractor O&P.

27. Mobilization includes all costs to transport bypass piping, rolling stock, and specialized cleaning and lining equipment and transfer lining technicians to and from the project site. A mobilization cost of \$7,500 represents a typical value, but mobilization costs must be adjusted since a good deal of transportation is involved in mobilization. Table 2-2 gives values that may be used to correct mobilization costs for given locations. Note that data listed in Table 2-2 were provided by a cleaning and lining contractor with offices in southern California and New Jersey. The factors will probably differ for other contractors.

28. Excavation costs are dependent on the size of the pipe, the type of cover, and the need for shoring. Excavation costs for access and valve replacement locations include all costs to excavate, provide street plates, backfill, and perform permanent restoration work. Excavation subcategories are:

- Type A: Removing and replacing 8-in. nonreinforced cement concrete paving base and 2-in. bituminous concrete wearing course.
- Type B: Removing and replacing 6-in. bituminous concrete paving base and 2-in. bituminous concrete wearing course.
- Type C: Removing and replacing 2-in. bituminous concrete paving and compacted subgrade.
- Type D: In nonpaved area involving minimal surface restoration such as topsoiling and seeding.
- Sheeting and shoring: Sheet and shore excavations in accordance with Occupational Safety and Health Administration (OSHA) regulations.

Table 2-2
Cost Adjustment Factors For Mobilization and Labor Costs

<u>State</u>	<u>Mobilization Adj., \$</u>	<u>Labor Cost Index</u>
Alabama	+ 7,500.00	0.92
Alaska	+ 20,000.00	2.12
Arizona	+ 3,000.00	1.16
Arkansas	+ 11,000.00	0.95
California		
Northern	+ 3,000.00	1.55
Southern	- 3,000.00	1.55
Colorado	+ 9,000.00	1.11
Connecticut	- 2,000.00	1.26
Delaware	- 2,000.00	1.29
Florida		
Northern	+ 7,000.00	1.08
Southern	+ 12,000.00	1.08
Georgia	+ 7,000.00	0.90
Hawaii	+ 20,000.00	1.49
Idaho	+ 7,000.00	1.20
Illinois	+ 7,000.00	1.43
Indiana	+ 5,000.00	1.17
Iowa	+ 11,000.00	1.17
Kansas	+ 11,000.00	1.01
Kentucky	+ 5,000.00	1.04
Louisiana	+ 12,000.00	1.08
Maine	+ 1,000.00	1.05
Maryland	No Adj.	1.00
Massachusetts	No Adj.	1.37
Michigan	+ 4,000.00	1.14
Minnesota	+ 12,000.00	1.39
Mississippi	+ 10,000.00	0.83
Missouri	+ 10,000.00	1.23
Montana	+ 9,000.00	1.08
Nebraska	+ 10,000.00	1.03
Nevada	+ 2,000.00	1.50
New Hampshire	No Adj.	1.13
New Jersey	- 3,000.00	1.25
New Mexico	+ 6,000.00	1.04
New York	No Adj.	1.31
North Carolina	+ 3,000.00	0.74
North Dakota	+ 12,000.00	0.97
Ohio	+ 3,000.00	1.39
Oklahoma	+ 11,000.00	1.02
Oregon	+ 5,000.00	1.45
Pennsylvania	No Adj.	1.07
Rhode Island	No Adj.	1.33
South Carolina	+ 4,000.00	0.71
South Dakota	+ 12,000.00	0.84
Tennessee	+ 6,000.00	0.87
Texas	+ 11,000.00	0.93
Utah	+ 4,000.00	1.14
Vermont	No Adj.	1.03
Virginia	+ 1,000.00	0.86
Washington	+ 7,000.00	1.39
West Virginia	+ 1,000.00	1.11
Wisconsin	+ 8,000.00	1.15
Wyoming	+ 7,000.00	0.90
District of Columbia	No Adj.	1.20

Excavations costs are based on the following typical dimensions:

Pipe size in.	Excavation ft wide × ft long × ft deep
6-24	5 × 7 × 4.5
30-42	6 × 8 × 8
48-60	7 × 9 × 10

Costs need to be increased for unusually deep pipe or the need for dewatering.

29. The cost of temporary services depends primarily on the length and diameter of the bypass piping and the number of connections. Temporary service costs include all costs for laying and removing bypass piping, protection of pedestrian and vehicular traffic, domestic service connections at existing meter locations or at hose bibs and fire service connections made by hand excavating, and cutting into existing services.

30. The largest single cost item is the actual cleaning and lining process cost. This must be distinguished from what will be called the cleaning and lining project cost which includes the cleaning and lining process plus mobilization, excavation, temporary services, removal of obstructions, valve replacement, etc. The process cost includes making all required access openings in the pipe; dewatering excavations to avoid water entering the pipe section while cement-mortar lining is in progress; cleaning and cement-mortar lining pipe sections, including access pipe nipples; replacing lined pipe nipples with approved couplings; and, after cleaning and after cement-mortar lining, clearing service laterals having diameter of 2 in. or less with air or water. The lining is assumed to be done in accordance with American Water Works Association (AWWA) standard C-602 (AWWA 1983).

31. Valves are often replaced as part of a cleaning and lining job. Valve replacement costs given in Table 2-1 include all costs to furnish and install new valves exclusive of excavation costs described above. Valve costs are highly dependent on the pipe size.

32. Summing the costs described in the preceding paragraphs gives national average cleaning and lining project costs. Local labor costs can significantly affect these costs. To correct for local labor costs, the following formula (based on the fact that labor accounts for roughly one half of project costs) should be used:

$$TL = 0.5 (1 + L) UT \quad (2-1)$$

where*

TL = cost corrected for local labor, \$

L = local labor cost index

UT = uncorrected project total cost, \$

Some suggested values for labor cost indices are presented in Table 2-2. These values represent the ratio of local to national average costs. Individual utilities in a state may have significantly different values than the average values for that state.

33. The value TL above is given in 1984 dollars. This value can be corrected for inflation by multiplying TL by a ratio of appropriate cost indices, as shown below:

$$CT = TL (\text{current index value}/1984 \text{ index value}) \quad (2-2)$$

where CT equals corrected total cost, \$. One index that is used to correct for temporal changes in cost is the ENR-CC (Engineering News Record Construction Cost Index). It is a simple matter to look up current and 1984 values of the index (4200) and insert them into Equation 2-2 to determine a total.

34. The total cost given by Equation 2-2 reflects what a utility will ordinarily pay a contractor. However, several other costs may be included in a contract. The most common is for "pipe obstructions" which are bends, reducers, and other fittings not indicated in the utility's specifications which require extra excavations. These are usually paid for as separate cost items with a fixed unit price. Typical unit prices range from \$500 for small pipe in an unpaved area to several thousand dollars for large pipe in a congested area. It is rare that costs for removing obstructions amount to even 1 percent of the total project cost.

35. Cleaning and lining contracts may also include installation of new pipe or vaults and replacement of hydrants. The utility usually requires testing of the cleaned and lined pipe to determine the Hazen-Williams C-factor. This enables the utility to determine if the project has restored the C-factor to the value guaranteed in the contract. This testing is usually done by the utility or an independent contractor.

* For convenience, symbols and abbreviations are listed in the Notation (Appendix A).

36. The utility can also reduce the cost of the contract by performing the excavation, backfilling, and paving and by installing and/or providing replacement valves. However, these costs must ultimately be borne by the utility whether payment is made to the contractor or the utility's own employees and suppliers.

Making unit price cost estimates

37. To make an estimate of the cost of the cleaning and lining project, the engineer must first identify the section of pipe to be cleaned and lined, the diameter and type of pipe, and the locations along the pipe at which excavations must be made. The maximum allowable distance between nipple sections is 500 to 800 ft for pipe less than 24 in. in diameter and up to 2,000 ft for larger pipes. This is a convenient time to identify the valves which need to be closed when each pipe section is being cleaned and lined and to determine where service connections and bypass piping are required. The engineer must also decide which valves in the system need to be replaced.

38. Once these tasks have been completed, the engineer then need only fill in the blanks in Table 2-1 to prepare a planning level estimate of cleaning and lining costs.

39. The best way to illustrate how to prepare an estimate is with a hypothetical example. The data for the example are given in Table 2-3 while the solution is presented in Table 2-4.

Verification

40. To verify that the method described in the preceding sections produces accurate estimates of cleaning and lining costs, it was necessary to compare predicted costs with the costs of actual projects. Data were provided on 51 actual projects performed by Ameron, Inc. Pipe sizes ranged from 6 in. to 66 in. Length cleaned and lined ranged from just over 3,000 ft to nearly 90,000 ft. There were as many as 370 excavations per project and over 100 valve replacements in a single project. The mean values and ranges of some of the important parameters are shown in Table 2-5.

41. Costs were calculated for each project using Table 2-1, and compared with the actual costs. The correlation coefficient obtained was 0.95, which indicates a very good correlation. The average absolute difference between actual and predicted costs was 16 percent. The results of the comparison between actual and predicted costs are shown graphically in Figure 2-2.

Table 2-3
Data for Hypothetical Example Unit Price Method

Location: Tennessee

Cast Iron Pipe

12,000 ft of 6-in. pipe
 2,500 ft of 8-in. pipe
 5,000 ft of 12-in. pipe
 2,000 ft of 20-in. pipe

Excavation	
<u>Type</u>	<u>Number</u>
A	5
B	12
C	31
D	5
Shoring required for 5	

30,000 ft of temporary 2-in. bypass
 8,700 ft of temporary 4-in. bypass

Valves	
<u>Size</u>	<u>Number</u>
6	10
8	2
12	2
20	1

ENR = 4,500, Inflation Correction = $4500/4100 = 1.10$
 Labor Correction = 0.87 (from Table 2.2)

Table 2-4
Cost Estimating Worksheet

Item No.	Item	Bare Costs					Incl. O&P	Quant	Item Cost
		Unit	Labor	Mat'l	Equip	Total			
I	Mobilization	L.S.*	--	--	--	6,000.00	7,500.00	L.S.	7,500
	Correction for Location +6,000								
	Corrected Mobilization Cost								13,500
II	Excavation								
	6- to 24-in. pipe								
	Type A	EA.	575.00	150.00	190.00	915.00	1,190.00	5	5,950
	Type B	EA.	480.00	120.00	170.00	770.00	1,000.00	12	12,000
	Type C	EA.	375.00	80.00	145.00	600.00	780.00	31	24,180
	Type D	EA.	240.00	40.00	100.00	380.00	495.00	5	2,475
	Sheeting/shoring	EA.	180.00	120.00	--	300.00	390.00	5	1,950
	30- to 42-in. pipe								
	Type A	EA.	1,150.00	300.00	400.00	1,850.00	2,400.00	0	
	Type B	EA.	960.00	240.00	350.00	1,550.00	2,015.00	0	
	Type C	EA.	750.00	160.00	290.00	1,200.00	1,560.00	0	
	Type D	EA.	500.00	80.00	170.00	750.00	975.00	0	
	Sheeting/shoring	EA.	270.00	150.00	--	420.00	550.00	0	
	48- to 60-in. pipe								
	Type A	EA.	1,725.00	450.00	600.00	2,775.00	3,600.00	0	
	Type B	EA.	1,440.00	360.00	525.00	2,325.00	3,020.00	0	
	Type C	EA.	1,125.00	240.00	435.00	1,800.00	2,340.00	0	

(Continued)

* L.S. = Lump Sum.

(Sheet 1 of 3)

Table 2-4. (Continued)

Item No.	Item	Unit	Bare Costs			Incl. O&P	Quant	Item Cost
			Labor	Mat'l	Equip			
III	Type D	EA.	750.00	120.00	255.00	1,460.00	0	
	Sheeting/shoring	EA.	360.00	150.00	--	660.00	0	
	Temporary service							
	2-in. bypass pipe	L.F.	0.78	0.20	0.30	1.28	30,000	51,000
	4-in. bypass pipe	L.F.	1.53	0.60	0.35	2.48	8,700	27,840
	Domestic serv. conn.	EA.	35.00	10.00	--	60.00	250	15,000
IV	Fire serv. conn.	EA.	70.00	60.00	30.00	200.00	10	2,000
	Cleaning and cement-mortar lining*							
	4- to 8-in. CIP or WSP	L.F.	4.31	0.33	1.50	6.14	14,500	116,000
	10- to 16-in. CIP or WSP	L.F.	4.55	0.66	1.50	6.71	5,000	43,500
	18- to 24-in. CIP or WSP	L.F.	4.78	1.24	1.50	7.52	2,000	19,600
	30- to 42-in. CIP or WSP	L.F.	5.20	2.14	1.60	8.94	0	
	48- to 60-in. CIP or WSP	L.F.	5.40	3.09	1.70	10.19	0	
	Additional costs of rehabilitation of riveted steel or lockbar steel pipelines; hand cleaning and hand mortaring of rivet rows and lockbars:							
	30- to 42-in. RSP or LSP	L.F.	0.80	0.10	--	0.90	0	
	48- to 60-in. RSP or LSP	L.F.	0.90	0.15	--	1.05	0	

(Continued)

* CIP = Cast Iron Pipe, WSP = Welded Steel Pipe, RSP = Riveted Steel Pipe, LSP = Lockbar Steel Pipe.

(Sheet 2 of 3)

Table 2-4. (Concluded)

Item No.	Item	Unit	Bare Costs			Incl. O&P	Quant	Item Cost
			Labor	Mat'l	Equip			
V	Valve replacements							
	4-in. gate valve	EA.	146.00	255.00	40.00	550.00	0	
	6-in. gate valve	EA.	146.00	294.00	40.00	600.00	10	6,000
	8-in. gate valve	EA.	146.00	409.00	40.00	745.00	2	1,490
	10-in. gate valve	EA.	204.00	584.00	40.00	1,035.00	2	2,070
	12-in. gate valve	EA.	204.00	724.00	40.00	1,210.00	0	
	16-in. butterfly valve	EA.	204.00	1,500.00	65.00	2,210.00	0	
	18-in. butterfly valve	EA.	263.00	1,834.00	65.00	2,700.00	0	
	20-in. butterfly valve	EA.	263.00	2,130.00	65.00	3,070.00	1	3,070
	24-in. butterfly valve	EA.	263.00	2,195.00	65.00	4,050.00	0	
	Uncorrected total cost (UT)							347,625
	Labor cost index 0.87							
	Total corrected for labor cost = 0.5 (1 + L) UT							325,029
	Inflation correction 1.10							
	Total cost							357,532

Table 2-5
Data for Actual Projects

Parameter	Mean	Range
Length, ft	23,000	3,100-88,700
No. of excavations	80	6-365
No. of valves	20*	1-108
Length of temporary bypass, ft	25,000**	1,960-16,000
Clean & line process cost	\$347,000	55,500-1,735,000
Clean & line project cost	\$427,000	68,500-2,200,000

* Based on 23 projects with nonzero values.

** Based on 39 projects with nonzero values.

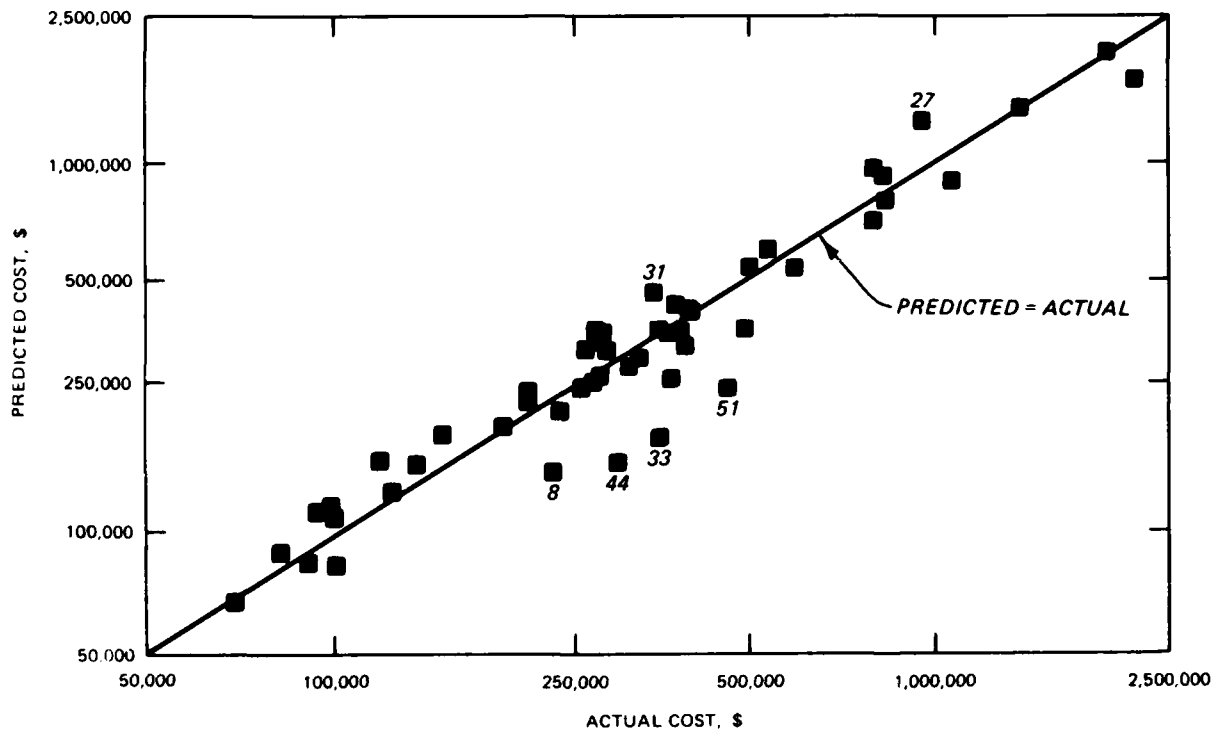


Figure 2-2. Verification for cleaning and lining projects

If correlation were perfect, all of the points would fall on the line identified as "Predicted = Actual."

42. The correlations would have even been better if a few outlier points had been discarded in the analysis. Each of these outliers, however, sheds some light on the factors that influence cost. These outliers are numbered on Figure 2-2. In projects 27 and 31, the utility performed the repaving and installed temporary service connections thus making the reported cost lower than that predicted. In projects 44 and 51, the actual costs were higher than the predicted costs because of the large amount of reinforced concrete paving involved and the phasing of the work. In projects 8 and 33, traffic conditions and interference with other buried utilities made the predicted costs only 63 and 51 percent of the actual costs, respectively.

43. When these outlier points are discarded, the correlation coefficient improves to 0.98, and the average difference between actual and predicted costs is only 12 percent.

44. Overall, the verification showed that Table 2-1 could be used to develop reasonably good estimates of project costs for typical projects, but the engineer must be aware that there are cases in which the costs may be inaccurate.

Statistical Regression Method

45. While the unit price method for determining the cost of cleaning and lining projects is quite accurate, it requires knowledge of the number of temporary services, number of valve replacements, and length of temporary bypass piping. This information may not be available during a planning study. For some preliminary estimates an engineer would like to be able to predict costs based merely on the length and diameter of pipe or number of excavations. Such a method can explain more sources of variation in cost than simply a fixed unit cost of say \$20 per foot since there is considerable variation about such a typical value.

46. What is needed is a simple equation, or set of equations, which can relate project, or process, cost to one or two simple explanatory variables. Such equations can be developed by regression (curve fitting) analysis using data on the 51 projects used earlier for verification.

47. Regression equations developed based on total project costs are presented below first. In subsequent sections, regression equations are developed for individual items of work such as length of bypass lines, cleaning and lining process cost, and valve cost. The cost of these individual items can be combined to give project costs.

48. The goodness-of-fit of the regression equations is measured by the index of determination (R^2). A value of unity indicates perfect correlation, while a value of zero indicates that the independent variables do not explain variation in the dependent variable. The regression equations are based on all 51 projects and therefore contain some projects with unusual features (e.g. repaving performed by utility). This lowered the index of determination for the equations. Power functions (i.e. straight lines on log-log paper) provided the best fit agreement between cost and explanatory variables.

Project cost

49. Regression equations were developed relating total project cost (TC) to the diameter, length of cleaning and lining, number of excavations, and length of temporary bypass piping. The following regression equations, with the corresponding indices of determination R^2 , were developed:

Equation	R^2	
$TC = 6.49 D^{0.55} L^{0.72} TB^{0.24}$	0.85	(2-3)
$TC = 2115 E^{0.84} D^{0.62}$	0.87	(2-4)
$TC = 23.66 L^{0.89} D^{0.29}$	0.81	(2-5)
$TC = 23861 E^{0.65}$	0.65	(2-6)

where

TC = total project cost, 1984 \$

D = diameter of pipe, in.

L = length of pipe cleaned and lined, ft

TB = length of temporary bypass piping, ft

E = number of excavations

For projects in which several different diameter pipes were excavated, a weighted average diameter was used for D in developing the above equations.

50. Because they are based on only a handful of independent variables, the regression equations given above cannot be expected to give as accurate a

prediction of costs as the unit price method, but because of their simplicity, they are attractive. The exponents in the equations also serve as an indicator of economy of scale in projects. For example, if the exponent on an independent variable is near one, costs are highly dependent on that variable, while if they are near zero, costs do not depend highly on that parameter.

51. One interesting observation from Equations 2-3 and 2-5 is that the exponent on length L is not unity. An exponent of unity would make it possible to divide through by L and derive an equation for unit cleaning and lining TC/L in dollars per foot that would be independent of the size of the project. Instead, dividing through by L , in say Equation 2-5, leaves L on the right of the equation with a negative exponent:

$$TC/L = 23.66 L^{-0.11} D^{0.29} \quad (2-7)$$

This means that the unit cost of cleaning and lining decreases with the project size. For example, for a 24-in. pipe, Equation 2-7 predicts a unit cost of \$23.30/ft for a 5,000-ft project and a cost of \$18.09/ft for a 50,000-ft project--a reduction of 22 percent. Another interesting result is that the exponent on diameter D is considerably less than one. This means that it does not cost much more to clean and line a large pipe than a small pipe. This explains why cleaning and lining may be only marginally economical when compared with replacement of small pipes, but it is clearly more economical when compared with replacement of large pipes.

52. One interesting result is the high correlation between number of excavations, diameter, and cost. This indicates that it is not so much the length to be cleaned and lined but rather the number of excavations (which is related to length) that influence cost. Therefore, if an engineer only knew one thing about a job and needed to predict cost, the most crucial thing to know would be the number of excavations. Fortunately, the engineer also knows an average diameter for a project. This additional information greatly improves the estimate.

53. Those using the regression equations must be aware that the equations work best for typical projects and will not be very accurate for projects with unusual features. For example, Equation 2-7 predicts a cost per foot of \$20.47 for 10,000 ft of 20-in. pipe. In the data used to develop the cost equations, there are several projects with approximately this unit cost.

There are however two projects with costs of \$8.57/ft and \$36.32/ft. The first project was performed in a railroad right-of-way. This reduced excavation and eliminated paving costs and no valve replacements were required. The second project involved working among a large number of underground utilities in a congested urban area, and involved difficult excavation, paving, and traffic control. Therefore, while the costs predicted by the regression equations are generally good, there will be special cases in which the engineer must exercise caution in applying the results.

Cleaning, lining, and excavation costs

54. Sometimes the engineer only needs to know the costs associated with the cleaning and lining process plus excavation without other items such as valve replacement, removal of obstructions, and temporary bypass piping. These costs, referred to as LC for lining cost below, are made up essentially of items I, II, and IV from Table 2-1. (The variable TC presented in the previous section included all project costs).

55. Regression equations for predicting cleaning, lining, and excavation costs are given below:

<u>Equation</u>	<u>R²</u>	
$LC = 16.8 L^{0.89} D^{0.35}$	0.84	(2-8)
$LC = 1,672 E^{0.82} D^{0.67}$	0.87	(2-9)
$LC = 22,471 E^{0.62}$	0.61	(2-10)

where LC equals cleaning, lining, and excavation cost, 1984 \$.

56. These equations, which are very similar to Equations 2-3 to 2-7, enable the engineer to generate a cost estimate based on the sum of component costs when the cost of valves and temporary bypass piping lengths is known or can be calculated as described below.

Valve costs

57. Valve replacement cost can be given by the equations below:

<u>Equation</u>	<u>R²</u>	
$VC = 4,146 V^{0.75}$	0.36	(2-11)
$VC = 308 V^{0.89} D^{0.92}$	0.52	(2-12)

where

VC = valve replacement cost, 1984 \$

V = number of valves replaced

Since valve costs are highly dependent on diameter, Equation 2-11 is not a good predictor of costs. By including diameter in the analysis, Equation 2-12 becomes a better predictor of valve costs. The fact that the exponent on V is less than unity indicates that there is some economy of scale in valve replacement.

58. There is usually very little valve replacement in projects involving large pipes. If only projects involving smaller (< 24 in.) pipes are included in developing the equation, the following equation, with a significantly better index of determination, can be developed:

$$VC = 56.8 V^{0.83} D^{1.85} \quad R^2 = 0.76 \quad (2-13)$$

Note the significantly higher exponent on D .

59. Another approach to estimating valve costs is to simply use the unit prices from item V in Table 2-1.

Temporary bypass piping cost

60. The cost of temporary bypass piping can be estimated by referring to item III in Table 2-1 if the number of each type of connection and the size of each line are known. A regression equation that does almost as well is:

$$BC = 15.9 TB^{0.81} \quad R^2 = 0.82 \quad (2-14)$$

where BC equals temporary bypass piping cost, 1984 \$. Dividing through by the length of bypass piping TB , shows that there is some economy of scale in unit bypass piping cost BC/TB :

$$BC/TB = 15.9 TB^{-0.19} \quad (2-15)$$

This equation indicates that if only 1,000 ft of bypass piping is required for a project, the unit cost will be \$4.28/ft, while if 20,000 ft is required the unit cost will be \$2.42/ft.

Costs of Cleaning Only

61. It is not always necessary to cement-mortar line pipes when they have been cleaned. This is especially true of pipe with calcium carbonate scale if the quality of the water being transported is altered so that it is no longer scale-forming.

62. The costs of cleaning only are lower than cleaning and lining for several reasons: (a) lining cost need not be incurred; (b) it is possible to clean longer runs because restrictions on the distance mortar can be pumped are no longer limiting; (3) pipes need not be out of service for several days, thus bypass piping may not be required; and (4) hydraulic pigs need not be launched from excavated nipple sections but can in some cases be launched from hydrants.

63. It is possible to use Table 2-1 to generate costs of a cleaning-only project by not including the excavation, bypass piping, and valve replacement items, and by reducing cleaning and lining costs (item IV) to roughly 70 percent of that listed in the table. This will generally yield cost on the order of \$7.00/ft.

Statistical analysis of pigging cost

64. Data were provided by Atlantic Piping Services, Lmt., on the costs of 56 projects involving cleaning pipes using hydraulic pigs but not relining the pipes. (This is often referred to as "pigging.") The cost data included only the cost of the contractor and not of the utility's own staff required to monitor work, control traffic, operate valves, etc. No temporary bypass piping, valve replacement, or disinfection are included. The projects were conducted in Canada during 1981 through 1984. Costs were adjusted to 1984 US dollars using a multiplier of 0.8.

65. The length cleaned ranged from 50 ft to 12 miles and the diameters ranged from 1.5 in. to 24 in. The cost per foot of pipe cleaned ranged from \$0.26/ft to \$68.40/ft in 1984 US dollars.

66. Before any statistical analyses of the data were carried out, the data were divided into two sets. The first contained all 56 projects while

the second contained only those projects involving potable water distribution line pigging. This set contained data for 36 projects. The 20 projects eliminated from the second set included air lines, process lines contaminated with adhesives, small pipes (2 in.), hospital piping, and in-plant piping.

67. First, the project costs were correlated with project length and diameter (average diameter was used when several sizes were encountered). There was a high correlation between project cost and length as given below:

$$C = 76.4 L^{0.57} \text{ (all projects)} \quad R^2 = 0.69 \quad (2-16a)$$

$$C = 21.0 L^{0.72} \text{ (potable lines)} \quad R^2 = 0.78 \quad (2-16b)$$

where

C = project cost, \$/ft

L = length cleaned, ft

Correlations of project cost with diameter were meaningless since, in general, the largest projects involved long, large-diameter pipe. So, diameter correlated with length (correlation coefficient = 0.53) rather than cost. To circumvent this problem, an attempt was made to correlate diameter with cost per foot of pipe. This resulted in correlation coefficients of 0.05 (all projects) and 0.03 (potable only), which indicates that diameter does not correlate well with unit cost.

68. Next, a multiple regression equation was developed for the potable water lines. It can be given by

$$C = 24.4 L^{0.72} D^{-0.04} \text{ (potable only)} \quad R^2 = 0.86 \quad (2-17)$$

where D equals diameter, in.

69. Equation 2-17 indicates that costs actually decrease as diameter increases. This seems significant until one notes that the confidence limits on the exponent on diameter are 0.59 to -0.67. The partial F-statistic for diameter also indicates that diameter is not useful in predicting cost for these data.

70. The variation in project data is due more to the complexity of the project and ease with which system valves can be operated rather than simply the length and diameter of the pipes encountered. To account for this, the

following formula is suggested for predicting costs in the planning stages of pigging projects:

$$C = a L^{0.72} \quad (2-18)$$

where

$$a = \begin{cases} 6.5, & \text{for very long runs, excellent valves, soft deposits} \\ 18.6, & \text{for valves in good condition, long runs} \\ 30.7, & \text{for average systems} \\ 42.8, & \text{for difficult access, some inoperable valves} \\ 54.9, & \text{for many inoperable valves or valves which cannot be found,} \\ & \text{complicated access or piping, short runs, inadequate water} \\ & \text{pressure} \end{cases}$$

Using Equation 2-18 involves some judgment but it indicates which factors are important in pigging cost. The term "runs" is used to describe the distance between where the pig is launched and where it is retrieved. A "long run" would be a distance in excess of 1,000 ft.

Other data on pigging

71. The cost of cleaning for a large project (60 miles) was given by Cimboras* as \$0.32 per foot for direct onsite contractor costs and \$0.07 per foot for direct utility costs. Cimboras added that the costs depend highly on project-specific conditions and can vary by as much as 500 percent from these representative values. In general, three to four contractor personnel and two to three utility personnel are required for the work. They can clean a mile of pipe in 2 to 3 days.

72. Anderson and Muller (1983) reported that cleaning of a raw water line consisting of 2,200 ft of 60-in. pipe and 1,020 ft of 54-in. pipe cost \$3,900 (\$1.21/ft). Only one pass of the pigs was required because the material on the wall was removed fairly easily.

73. NEESA (1983) stated that costs for hydraulically pigging pipes ranged from \$0.90 to \$2.00 per foot cleaned. These costs, however, are based on conditions very favorable to cleaning.

* Personal communication from Roger Cimboras, Atlanta Piping Services, Ltd., to Kay Kerr, Knapp Poll-Pig, dated 29 October 1984.

74. Costs for one actual project awarded in the fall of 1983 are listed below:

<u>Diameter</u> <u>in.</u>	<u>Cost</u> <u>\$/ft</u>
6	6.725
8	4.35
10	3.65

Note that costs actually decreased for increasing diameter. This is apparently due to smaller pipes having a greater percentage of their cross-sectional area covered with tuberculation, and significantly higher pressures being required to push a pig through a small opening. Unit costs level off above the 10-in. diam and probably begin to increase again for pipes above 20 in. because of larger volumes of water required, larger launchers, and higher cost of pigs.

75. In deciding whether or not to line pipes when they are being cleaned, the utility must weigh the benefits of the lining over cleaning only, against the additional costs of lining. Lining the pipe will: (a) prevent reoccurrence of tuberculation, (b) seal small leaks, and (c) eliminate "red water" problems in the lined sections. It is also possible to chemically treat water to prevent corrosion and scaling. This is discussed in greater detail in Part VI.

Tips for Conducting Pipe Cleaning and Lining Projects

76. The unit costs of a cleaning and lining project can range from as low as \$8/ft to as much as \$60/ft. There are a few considerations in selecting pipes to be cleaned and lined and managing the work which can keep costs down. Some tips for reducing costs are given below:

- a. Be certain that the loss in carrying capacity is indeed due to internal deposits in the pipe. Sometimes low pressures or poor fire flow test results are caused by valves that were mistakenly left closed or partially closed. Conduct loss of head tests and, if practicable, visually inspect the inside of pipes before deciding that cleaning and lining is desirable.
- b. Be certain that the pipes to be cleaned and lined are structurally sound. If a pipe has been breaking frequently, it may

need to be replaced. Check pipe break records and, if possible, visually inspect the pipe for external corrosion and related pitting.

- c. Concentrate on pipes carrying relatively high flows. Friction energy costs are proportional to flow to the 2.85 power. The biggest savings in pumping energy, therefore, can be realized by cleaning and lining large transmission mains. As discussed earlier, it is only slightly more expensive to clean and line a 24-in. pipe than a 12-in. pipe, but the energy savings in the 24-in. pipe will be much greater if the velocities are comparable.
- d. In some cases it may be more economical to replace or parallel smaller pipes (4, 6, and 8 in.) rather than clean and line them. These decisions must be made on a case-by-case basis. It may also be economical to clean, and not line, smaller pipes that have excessive calcium carbonate scale buildup.
- e. Select nipple sections to minimize excavation costs. Costs of a project correlate highly with the number of excavations required. Therefore, the beginning point of a section to be cleaned should be at the end of the previously cleaned section. Try to locate nipple sections out of heavy traffic and preferably where the pipe is covered by asphalt or bare ground rather than reinforced concrete pavement. This will minimize excavation and paving costs.
- f. Cleaning and lining equipment cannot pass through butterfly and check valves, undersized gate valves, and sharp mitre bends. It is usually desirable to locate nipple sections at valves or replace obstructions with "spool" pieces. When a valve is removed and found to be in poor condition, it is best to replace it during the cleaning and lining project since the excavation and paving will have to be done anyway. Valve costs are highly dependent on diameter, so replacing small valves is much more attractive than replacing large valves.
- g. Steel pipes with riveted or lockbar joints require hand cleaning and lining of rivet rows and lockbars. This can increase costs by approximately 10 percent. All other things being equal, it is therefore less expensive to concentrate on steel pipe with welded joints.
- h. Concentrate on sections of pipe with few services. If two pipes are identical except that one has a large number of service connections which require temporary bypass piping, large savings can be realized by cleaning and lining the pipe with fewer services.
- i. If water demands are growing, new piping may be necessary since cleaning and lining can only increase carrying capacity to a certain point. If a large increase in demand is expected, this improvement may not be adequate, and new transmission mains will be required. A computer model of the distribution system may be required to evaluate these alternatives.

- j. Since mobilization costs for cleaning and lining can be large, clean and line as much of the system as financially possible in a given project. For example, two projects involving 5,000 ft will cost roughly 15 percent more than one project for 10,000 ft.
- k. Make certain the portion of the system to be cleaned and lined can be shut down effectively. Before the cleaning and lining contractor arrives at the site, the utility should test all valves which will be operated during the project to ensure they are operating properly.
- l. Take steps to improve water quality. If mains have not been lined, aggressive water can quickly cause regrowth of tubercles in a main. Even when mains have been relined, there are miles of mains, services, and customer plumbing that are not protected. The utility should feed chemicals at the treatment plant to minimize corrosion and scaling (see Part VI).

PART III: ESTIMATING CATHODIC PROTECTION COSTS FOR PREVENTING
EXTERNAL CORROSION OF BURIED METAL PIPES

77. To date a simple procedure for estimating cathodic protection costs has not been developed. The purpose of this part is to provide a method with which an engineer, knowing some facts about the pipe and soil, can produce a planning estimate of the costs to cathodically protect a pipe. The emphasis will be placed on protecting existing, buried, bare water mains, although the methods developed will also have some application for coated or new mains. The following sections contain a definition of corrosion, a discussion of external corrosion control by cathodic protection, development of two methods for estimating cathodic protection costs and verification of the cost estimating method, and a discussion of protective coatings and wrappings.

Corrosion

78. The National Association of Corrosion Engineers (1976) defines corrosion as "the deterioration of a material, usually a metal, because of a reaction with its environment." In the case of metallic piping, Westerback (1982) proposed a more useful definition as "the destructive alteration of a metal caused by the chemical or electrochemical action of its environment."

79. Corrosion attacks ferrous metal water mains by pulling the iron out of the pipe to create an oxidized form of iron. Corrosion can also occur in the reinforcement wire in reinforced concrete pipe. Corrosion weakens the pipe and ultimately results in leaks or breaks with the associated costs for repair, damage, lost water, and eventual pipe replacement. Other piping materials can also deteriorate due to the environment in which it is placed.

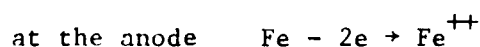
80. Rothman (1981) described the following four basic facts about corrosion of buried iron and steel:

- a. Corrosion is a natural process. The energy imparted to a metal when it is refined wants to be released and the metal wants to revert to its ore. Therefore, the question is not will a metal corrode, but rather at what rate will the corrosion occur.
- b. In a given underground environment, all ferrous metals corrode at the same rate. Tests performed by the National Bureau of Standards (Romanoff 1957) show that the ferrous metals including cast iron, carbon steel, wrought iron, and ductile iron

corrode at essentially the same rate underground. The apparent corrosion resistance of cast iron pipe is attributed to the fact that graphitized cast iron can retain its appearance as a pipe even though much of the iron is gone.

- c. Corrosion is selective and concentrated. The basic corrosion mechanism of iron underground is electrochemical and corrosion is not uniformly distributed over the entire metal surface, but occurs only at anodic areas. It has been found that for pipelines which have had numerous leaks, less than 5 percent of the total surface area of the pipe had been attacked.
- d. Once leaks start to occur in a piping system, they can be expected to continue at an exponentially increasing rate.

81. When iron or steel corrode there is always an anode and a cathode, an electrolyte, and a return circuit. The reactions at the anode and the cathode are:



82. In general, there are two types of corrosion: galvanic and stray current (Rothman 1981). Galvanic corrosion in the ground is caused by dissimilarities between two metals in the ground or dissimilarities with the electrolyte (i.e. the ground). This establishes an electrical cell in which the pipe is the anode for another structure or another point on the pipe. Stray current or electrolytic corrosion is driven by direct current (DC) from an external source. Corrosion occurs where the current leaves the pipe. This stray current condition is referred to as "interference."

83. The intensity of corrosion depends highly on soil resistivity (i.e. the ability of the soil to resist the flow of electricity). Soils with resistivity less than 2,000 ohm-cm are considered corrosive, while soils with resistivity in excess of 50,000 ohm-cm are fairly noncorrosive. Small patches of highly corrosive soil among relatively noncorrosive soil can result in serious corrosion. Schiff (1976) listed characteristics of soil that would indicate it is corrosive:

Characteristics

Black or gray color	Poor aeration
High acidity	Presence of anaerobic microorganisms
High dissolved solids content	Presence of organic material
High moisture content	Presence of sulfides
Low redox potential	
Low resistivity	

The AWWA (1977) mentions many of these factors in discussing soil tests needed to determine if soil is corrosive.

Cathodic Protection

84. The process of supplying electrons to a metal structure at a rate higher than they are lost is called cathodic protection. In other words, the metal structure to be protected is made cathodic with respect to another structure.

85. External corrosion of pipe can be significantly reduced by providing cathodic protection, installing protective wrappings and coatings, and providing a dry inert environment for the pipe by selective bedding or special dewatering. The last two are generally prohibitively expensive for existing pipes. In such a case cathodic protection may be the only solution short of replacement of the pipe with a protected or coated pipe.

86. The benefits of cathodic protection in loss reduction, reduced maintenance, and/or pipe replacement costs must be compared with the cost of cathodic protection to make a rational decision with respect to the alternatives of repair, replacement, or cathodic protection.

87. There are two types of cathodic protection systems: a sacrificial anode (galvanic) type, or an impressed current type cathodic protection system.

88. Sacrificial anode cathodic protection may be achieved by connecting a more active metal, usually magnesium, to the buried metal. Sacrificial anodes are most commonly used on relatively small pipes or large coated pipes installed in relatively low resistivity soils. Their current output is related to their surface area and the soil resistivity. Figure 3-1 shows

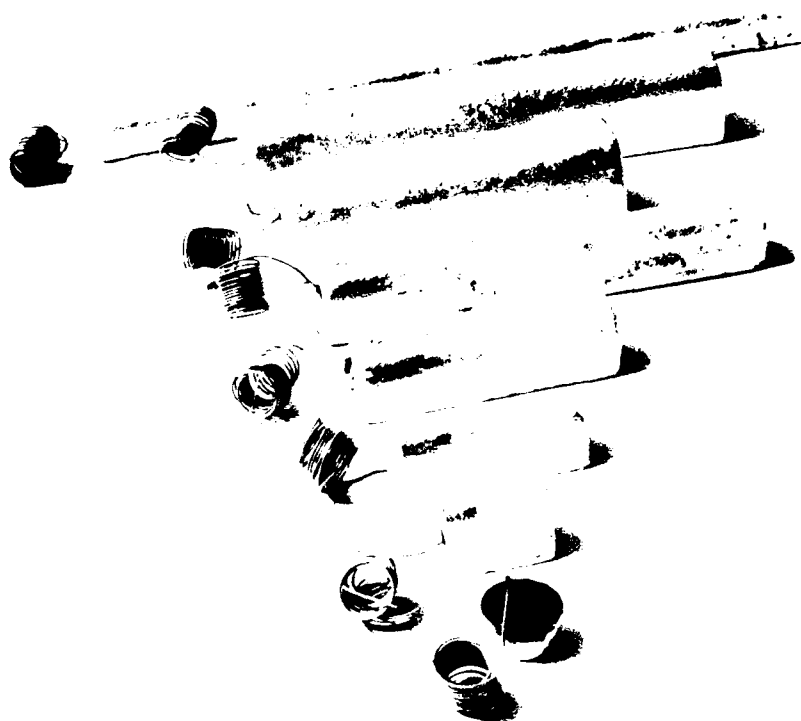


Figure 3-1. Bare magnesium anodes

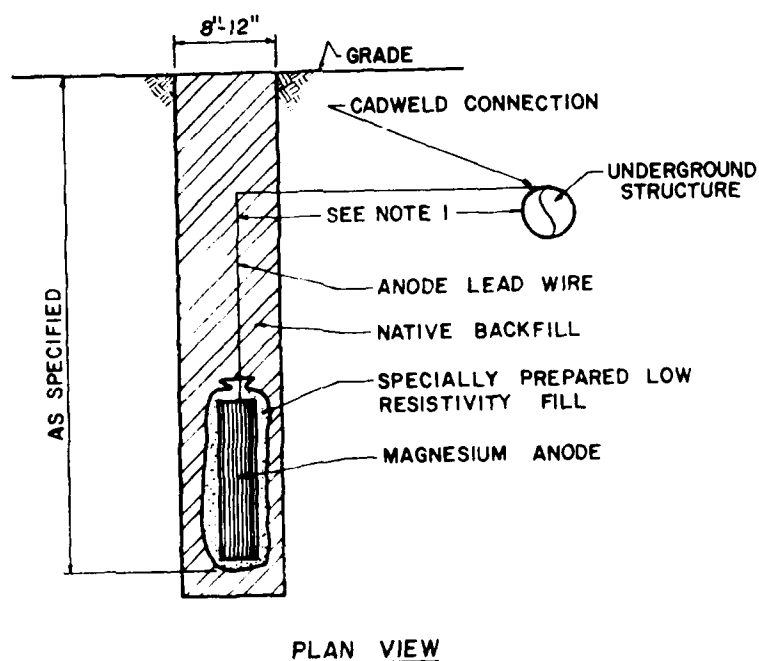
several sizes of anodes. Figure 3-2 shows a bare anode on the right, an anode packed in low resistivity fill in the center, and an anode packed for shipping on the left. Figure 3-3 shows a typical installation.

89. Impressed current cathodic protection consists of rectifying AC current to DC current and impressing the DC current onto the structure to be protected (the cathode) through an anode groundbed. Impressed current systems are most commonly utilized when large amounts of current are required, such as for bare or poorly coated pipelines. Figure 3-4 shows some high silicon cast iron impressed current anodes. Impressed current anodes require DC current, which may be produced from standard AC current using a rectifier such as the one shown in Figure 3-5.

90. Jackson (1980) discussed the relative merits of galvanic (sacrificial anode) and impressed current cathodic protection systems, which are summarized in Table 3-1. Using the following sections, it will be possible to develop cost estimates for the two forms of cathodic protection to determine if the cost of one is much greater than the other.



Figure 3-2. Sacrificial anode (packaged for shipping including fill bag and bare anode)



NOTE

- I. ANODE SHALL BE INSTALLED FIVE FEET ADJACENT TO EACH PIPELINE

Figure 3-3. Typical sacrificial anode installation

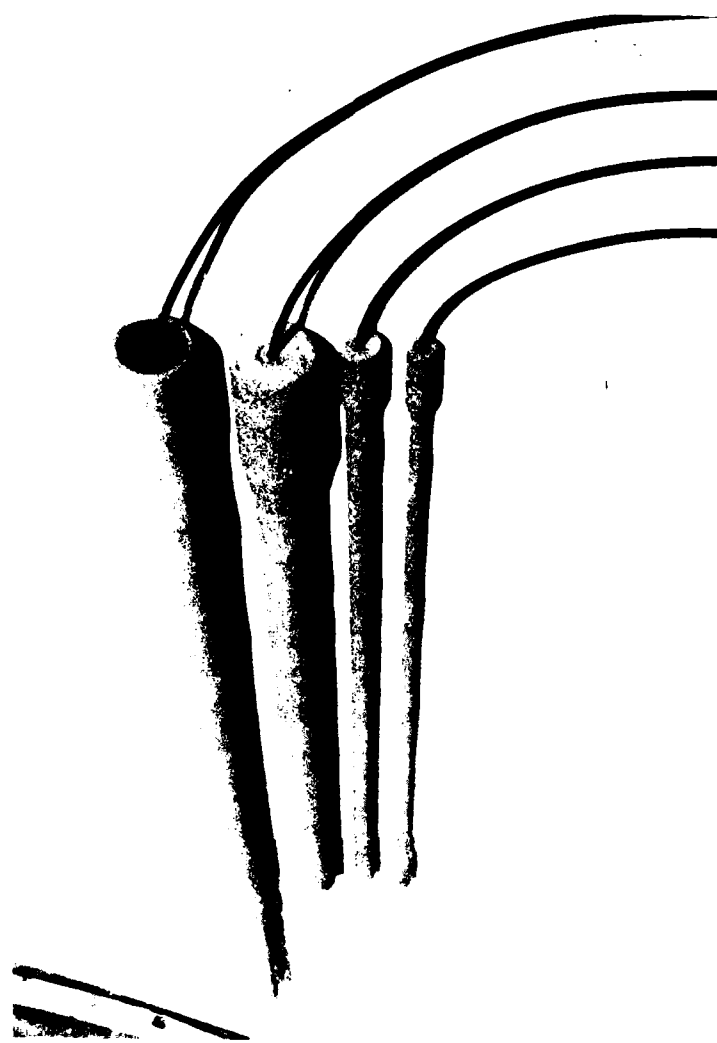


Figure 3-4. Anodes for impressed current system

91. Another factor in determining the type of cathodic protection required is whether electrical continuity exists across the joints in a pipe. If it does not (as is the case with ductile and cast iron pipe), separate anodes are required for each pipe segment, or an electrical bond must be made across each joint. This virtually eliminates impressed current protection for existing pipelines without electrical continuity.

92. The current required for cathodic protection is a function of current density, i.e. current per bare surface area. The larger the effective bare surface area, the more current is required for cathodic protection. For purposes of this report, a current density of 1 milliamperes per square foot (mA/ft^2) is used. This is a common figure for cathodic protection of buried

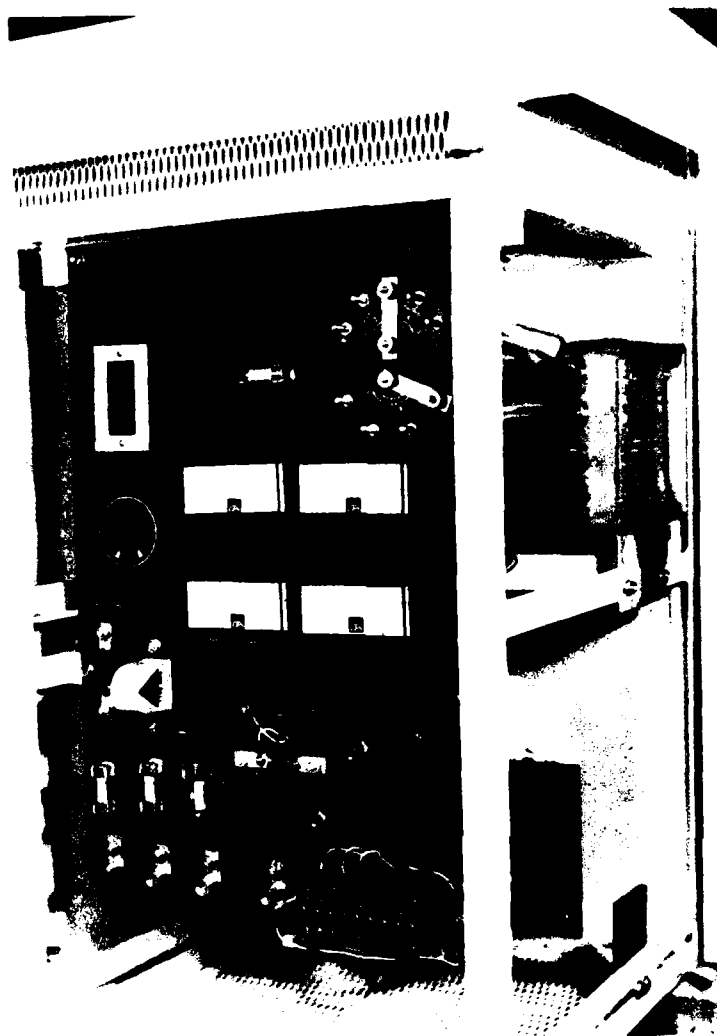


Figure 3-5. Rectifier for impressed current system

ferrous metal. In the case of coated piping, an effective bare area equal to 5 percent of the total surface area can be used for estimating. This is equivalent to an average coating. Coating effectiveness can vary from 1 percent bare for new, well-coated piping to 50 percent bare for old, poorly applied coating.

93. The Department of Transportation's Office of Pipeline Safety has developed regulations for pipelines carrying hazardous materials. These regulations include cathodic protection as part of the requirements for corrosion control. The corrosion mechanisms affecting these pipelines are the same as on water piping. The best practice then for water mains is a good coating and cathodic protection just as in the case for pipes carrying hazardous materials.

Table 3-1
Relative Merits of Galvanic and Impressed Current
Cathodic Protection (Bosich 1970)

<u>Galvanic</u>	<u>Impressed Current</u>
<u>Advantages</u>	
No external power needed	Longer length of pipe
Minimal maintenance cost	Useful in high resistivity soil
Little chance for interference	Adjustable output
No additional right-of-way needed	Produces more current for bare or large pipes
<u>Disadvantages</u>	
Limited power output	Higher maintenance cost
Restricted by soil resistivity	Possible interference problems
Limited configurations	Electrical continuity required

94. The effectiveness of cathodic protection for eliminating pipeline leaks has been documented by Westerback (1982), who showed that the number of leaks from several water pipelines in California was dramatically reduced by installing cathodic protection.

95. A special method of corrosion control for bare pipelines is referred to as "hot-spot" corrosion control. In applying this method, an engineering survey is conducted and the locations of anodes to prevent long line corrosion cells are determined. Sacrificial anodes are then installed at the anodic locations. This does not result in cathodic protection for the entire pipeline, but does provide corrosion control at specific locations.

96. Another method utilizes a statistical analysis of soil resistivity information to determine the most corrosive sections of a pipeline. This information can be used to determine when to cathodically protect only certain sections of pipeline or to schedule sections of pipeline to be cathodically protected.

97. The "hot-spot" and statistical analysis methods are generally utilized on relatively long, large diameter pipelines where the cost of

providing cathodic protection for the entire pipeline cannot be economically justified.

98. Cathodic protection will protect buried pipe from galvanic corrosion and stray current corrosion, when the stray current is not too great. Surveys can determine if the corrosion in a pipe is due to stray current and can determine the magnitude of the stray current. If the stray current is excessive, it must be diverted elsewhere if cathodic protection is to be successful.

Estimating Cathodic Protection Costs

Overview

99. The following sections contain procedures for estimating the costs of cathodic protection projects given some data describing the project. The first method actually involves estimating the number and cost of individual components and summing the costs. This method requires more detailed data and as such can account for many of the factors that affect cost. It is best used when the engineer has a good idea of such items as soil resistivity and availability of power.

100. The second method is based on statistical analysis of cost data from historical projects. The resulting equations give reasonable estimates of cost based on one important design parameter (e.g. length current requirement). Because of the limited number of parameters involved, this method cannot account for unusual conditions requiring atypical design.

101. Occasionally, engineers are asked for quick estimates and would like to have some rules of thumb for estimating costs (e.g. cost per square foot of pipe area). The third section gives some rough rules of thumb to help engineers estimate the order-of-magnitude of costs quickly.

Detailed estimating procedure

102. The following procedure can be used to develop planning level cost estimates for cathodic protection projects. Estimates can be expected to differ from actual costs because of such considerations as project size, contractor workload, competitive climate, and site-specific conditions. Therefore, considerable judgment is required in applying the procedure.

103. To use this procedure, the engineer must know the length of pipe to be surveyed, length of pipe to be protected, diameter of pipe, soil resistivity, effective bare area (100 percent for uncoated pipe), soil resistivity, depth of pipe, type of cover, operation and maintenance (O&M) labor cost, price of energy (for impressed current system), length of power lines required, and whether electrical connectivity exists between pipe sections. The costs are divided into survey, mobilization, anode material, installation (which includes excavation and paving), power lines, rectifiers, O&M labor, and power. Each of the construction items is summed to give first cost while the present worth of O&M labor and power is added to give total present worth cost.

104. The steps involved in the estimating procedure are summarized in the flowchart presented as Figure 3-6. The procedure for estimating each of the major cost items is given in the following sections. Table 3-2 is provided as a worksheet. An example problem is presented and the cost estimating procedure is verified with the data from actual projects.

105. Survey and testing. The cost of the survey includes soil resistivity tests, pipe-to-soil potential measurements, and in some instances current requirement tests and insulation checks. The costs depend on the type of pipe, size of system, presence of other buried utilities, and whether the survey is for a new or existing pipe. The scope can range from taking a

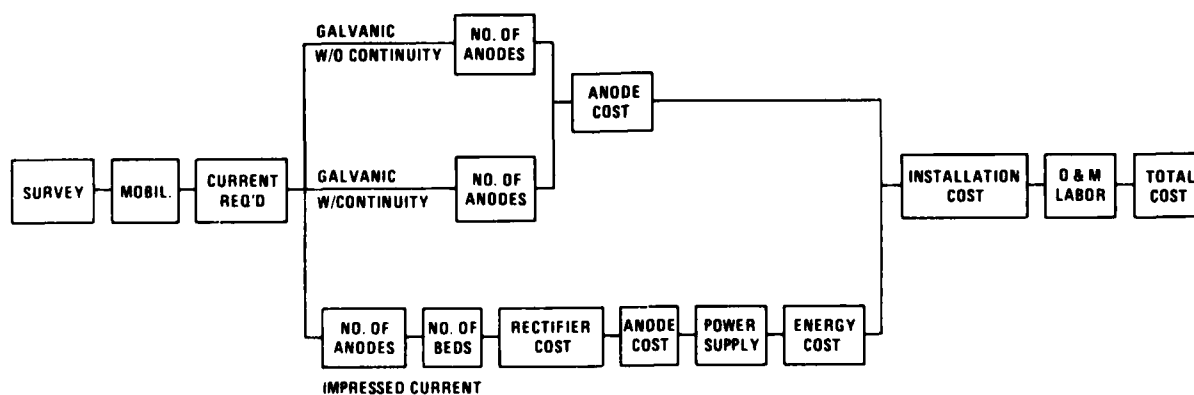


Figure 3-6. Cathodic protection estimating procedure

Table 3-2

Form for Estimating Cathodic Protection Costs

	Cost
Survey (LS) _____ ft	(CS) \$ _____
Mobilization _____	(CM) _____
Length (L) _____ ft; Diameter (D) _____ in.	
Current Requirement (CRA) _____ Amps	
Types of Anodes: Circle I or G	
Number of Anodes (NA) _____	
Material Cost (CA) \$ _____ /anode	
Installation Cost (CE) \$ _____ /anode	
Total Anode Cost (AC) $2.2 * \text{_____} * \text{_____} 0.8$	(AC) _____
Rectifiers (NB) _____ number	(RC) _____
Power Line _____ ft	(PC) _____
Insulation _____ number	_____
Bonding joints _____ number	_____
Inflation correction (_____ /4200) = _____	_____

	First Cost \$ (TC) _____
Labor Cost (OM) _____ man-hr/year, (UL) \$ _____ /man-hr	\$ _____ /year
Power Cost (AR) _____ kWhr/year, (PE) \$ _____ /kWhr	_____ /year
	Total O&M (OM) \$ _____ /year
	Present Worth (PWO) \$ _____

Total Present Worth	\$ _____

handful of soil resistivity measurements to detailed testing, design, and postinstallation testing. The cost equation is as follows:

$$CS = A * LS^{0.87} \quad (3-1)$$

where

CS = cost of survey, 1984 \$

A = coefficient for type of survey

$$= \begin{cases} 6.5, & \text{for detailed surveys, plus design and postinstallation testing} \\ 0.8, & \text{for detailed survey only} \\ 0.3, & \text{for quick surveys} \end{cases}$$

LS = length surveyed, ft

106. Mobilization. Mobilization costs include expenses for transporting equipment, materials, and crew to the job. A reasonable estimate for a typical project is \$1,500. The cost will be lower if the cathodic protection contractor has offices in the immediate area (\$1,000) and will be larger if material and equipment must be shipped to a distant jobsite (\$2,000). Mobilization costs will be considerably higher for remote areas and locations such as Alaska and Hawaii.

107. Current requirements. Before calculating other costs, it is necessary to determine the current requirement for the project in milliamperes (mA). This is based on pipe area, a current density factor of 1 mA/ft², and a parameter indicating the coating effectiveness. Current requirement can be estimated as

$$CR = 0.26 * D * L * EB \quad (3-2a)$$

$$CRA = CR/1000 \quad (3-2b)$$

where

CR = current requirement, mA

D = pipe diameter, in.

* Denotes multiplication.

L = length protected, ft

CRA = current requirement, A

EB = effective bare area

$$= \begin{cases} 1.00, & \text{for bare pipe} \\ 0.50, & \text{for old, poorly applied coating} \\ 0.05, & \text{for typical coating} \\ 0.01, & \text{for new, excellent coating} \end{cases}$$

The coefficient 0.26 is simply pi divided by 12 in./ft. If several different diameter pipes are involved, it is best to estimate CR for each diameter and sum the current requirements for all the different diameters.

108. Anode requirements. The next step is to estimate anode requirements. Different procedures are required for galvanic protection without electrical continuity, galvanic with continuity, and impressed current protection (generally applied only where electrical continuity exists).

109. Anode costs (galvanic without continuity). In the case of pipe with no electrical continuity (typical cast and ductile iron pipes), anodes are usually installed at every other joint, such that each anode protects two pipe sections which have an electrical bond installed across the joint. The number of anodes required can be calculated based on the laying lengths of pipe sections. Ductile and cast iron pipe sections are usually 18 or 20 ft long. The number of anodes required can be given by

$$NS = \frac{L}{2 * LL} \quad (3-3)$$

where

NS = number of sacrificial anodes

L = length protected, ft

LL = laying length, ft

110. If anodes are only being used to protect "hot spots" along a pipeline, NS must be reduced to reflect the fraction of the pipe actually protected. For example, if NS = 200 but the engineer feels only 30 percent of the pipe will need protection, reduce NS to 60 (i.e. 200×0.3).

111. The required current output from an anode can be calculated as

$$CO = \frac{CR}{NS} \quad (3-4)$$

where CO equals current output required for individual anode, mA.

112. The size of the anode which will deliver this current depends on the soil resistivity as given in Table 3-3. Given the soil resistivity and current output, the engineer can then select the best sized anode from Table 3-3. The current output depends on soil resistivity and surface area. The 20-lb anode is longer and thinner than the 32- or 17-lb anode (see Figure 3-1) and can therefore produce more current.

Table 3-3
Current Output from Various Magnesium Anodes

Resistivity ohm-cm	Output (mA) at Indicated Anode		
	32 lb	20 lb	17 lb
500	318	480	300
1,000	159	240	150
2,000	80	120	75
3,500	45	68	43
5,000	32	48	30
10,000	16	24	15
20,000	8	12	7.5
35,000	4.5	7	4.3
50,000	3.2	4.8	3

113. In low resistivity soil, any of the standard sizes can provide adequate current. However, smaller anodes (e.g. 17 lb) providing larger current (e.g. 100 mA) will be used up quickly. In general an anode should be selected that will last for 20 years. The weight of an anode required to provide current for a specific number of years can be estimated using

$$WT = 0.0206 * EL * CO \quad (3-5)$$

where

WT = weight of anode, lb

EL = expected life of anode, years

The coefficient 0.0206 is the effective number of pounds of magnesium anode used up per year per milliamp of output. Actual consumption is 0.0175, but anodes are usually 85-percent efficient.

114. Typically anodes are selected to produce 50 mA. For example, a 36-ft length of 6-in. pipe requires 56 mA. If more than 200 mA per anode is required, it is usually better to use an impressed current system because sacrificial anodes will be used up too quickly.

115. Once the size is selected, the price for that size can be found in Table 3-4.

Table 3-4
Unit Price for Magnesium Anodes

Size lb	Price \$
17	55
20	65
32	86

The unit prices given in Table 3-4 will be combined with installation cost later to give total project costs.

116. Anode costs (galvanic with continuity). If the pipe being protected is electrically continuous, as is the case with welded steel pipes and cast and ductile iron pipes with electrically bonded joints, then the spacing of the anodes is primarily determined by soil resistivity and pipe area to be protected. This type of system is used in remote areas where the cost of providing electricity is prohibitive. Current output is determined from soil resistivity using Table 3-3.

117. Using the current output (CO) and current required (CR), the number of sacrificial anodes (NS) can be determined from

$$NS = \frac{CR}{CO} \quad (3-6)$$

The size of the anode can be selected based on current requirement and expected life as described in the previous section. Given the size, the unit price can be determined from Table 3-4.

118. Anode cost (impressed current). Impressed current systems are usually only economical when electrical continuity exists and power is available. In this type of system, the anodes, which are generally made of graphite, can be clustered in anode beds. Typical spacing of anode beds for bare pipelines is one every 5,000 ft for smaller pipes (≤ 14 in.) and one every 2,500 ft for larger pipes (> 14 in.). For coated pipelines the spacing can be increased by up to a factor of 10 depending on the quality of the coating. For a given project, however, spacing may be determined more by availability of power. In such cases, the number of anode beds should be determined by the number of locations at which power can be supplied.

119. Once the spacing of the beds has been determined, the number of beds can be calculated as

$$NB = \frac{L}{SB} \quad (3-7)$$

where

NB = number of anode beds

SB = spacing of anode beds, ft

NB should be rounded to the next larger integer. This value is used later to determine the cost of rectifiers and power requirements.

120. The current output per anode varies from 500 mA for high resistivity soils to 3,000 mA for low resistivity soils with 1,500 mA being typical. The number of impressed current anodes can therefore be given by

$$NI = \frac{CR}{CO} \quad (3-8)$$

where NI equals the number of impressed current anodes. The number of anodes per bed can be given by

$$NP = \frac{NI}{NB} \quad (3-9)$$

where NP equals the number of anodes per bed. NP should be greater than 5 and less than 50. If it falls outside of that range, the spacing may need to be adjusted.

121. The unit price of a typical graphite anode for an impressed current system is \$65, based on a purchase of 50 anodes.

122. Installation cost. For most pipelines the largest single item is usually installation which includes excavation, placement of anodes, wiring the anodes to the pipe, backfilling, and repaving. The cost depends most highly on the type of ground cover. Typical installation costs are given in Table 3-5 for dry excavation, no shoring, and no significant rock, for a depth of 3 to 5 ft. The last entry in Table 3-5 corresponds to the case in which the anodes are being installed along a new pipe. Only a small amount of additional excavation is required in this case.

Table 3-5
Unit Installation Cost

<u>Cover</u>	<u>Single Anode 1984 \$</u>
Soil or turf	400
Asphalt pavement	500
Concrete pavement	600
New pipeline	250

For depths greater than 5 ft, correct costs using

$$CE = \begin{cases} [1 + 0.1 * (DP - 5)] * BE & \text{for } DP > 5 \\ BE & \text{for } DP \leq 5 \end{cases} \quad (3-10)$$

where

CE = corrected excavation, installation, and repaving cost, \$

BE = base excavation, installation, and repaving cost, \$ (from Table 3-5)

DP = depth of excavation, ft

If dewatering is required, increase cost by 50 percent. Increase cost by another 50 percent if significant rock excavation is required.

123. When anodes are being installed for new pipelines, the excavation costs are usually included in the cost of installing the pipe. The only extra cost is that of wiring the anodes to the pipe. This is typically \$250 per/anode for sacrificial anodes which are placed within 5 ft of the pipe. The cost for impressed current anodes is only slightly less than the cost given in Table 3-5 for existing pipes because these anodes are usually placed about 100 ft from the pipe to provide better current distribution.

124. Combining material and installation cost. Once the individual anode material and installation cost have been developed, they can be combined and multiplied by the number of anodes to obtain total cost for installed anodes. There are economies of scale involved in anode installation. Data for historical projects indicate that doubling the number of anodes does not double the cost, but increases costs by 75 percent. The data presented earlier for individual anode and installation costs were based on 50 anodes. The equation given below can account for economies of scale in anode material and installation:

$$AC = 2.2 * (CA + CE) * NA^{0.8} \quad (3-11)$$

where

AC = anode material and installation cost, \$

CA = cost of individual anode, \$

CE = cost of excavation, installation, repaving, \$

NA = number of anodes

Note that for NA = 50, AC = 50 * (CA + CE) .

125. Rectifier cost. A rectifier (or set of rectifiers) is necessary to convert AC power to DC power as required for impressed current anodes. There is usually one rectifier per anode bed. The installed cost for rectifiers depends on the current required per bed (in amps) and is listed in Table 3-6.

Table 3-6
Cost for Single Rectifier

<u>Current</u>	<u>Rectifier</u>
<u>A</u>	<u>\$</u>
10	680
20	850
40	1,200

The total cost for rectifiers is therefore:

$$RC = NB * UR \quad (3-12)$$

where

RC = total rectifier costs, \$

UR = cost for single rectifier (from Table 3-6), \$

126. Power supply. In most cases no additional power lines are required and the charge for an electrical meter and hookup to the utility is small. However, in remote areas where power lines must be installed, this can become a major item. The cost can be estimated as \$4.00/ft for wooden pole with single overhead wires over cleared land. However, cost will vary from one power company to another. Where clearing a right-of-way is required, add 50 percent.

127. Bonding joints. In some cases, it may be desirable to install electrical conductivity bonds across joints such as when using impressed current on ductile iron pipe. A typical cost is \$130 per bond. This cost includes excavation and Cadwelding across the joint. When bonding is done as part of installation of galvanic anodes, this cost is included in the anode cost for the joint at which the anode is installed, and should not be double counted.

128. Electrical insulation. Cathodically protected pipe must be electrically insulated from customer plumbing and aboveground structures. For small pipes (1/2 to 2 in.), this cost is roughly \$40 per installation. For larger pipes (3 to 12 in.), this cost is roughly \$60 per installation. The cost to insulate cathodically protected pipe is usually negligible for major transmission mains but can be significant for distribution piping.

129. First cost. Total first cost for a project can be determined by summing the survey, mobilization, anode installation, rectifier, and power costs and correcting for inflation to give:

$$TC = (ENR/4200) (CS + CM + AC + RC + PC) \quad (3-13)$$

where

TC = total first cost for project, \$

ENR = Engineering News Record Construction Cost Index

CS = cost of survey, \$

CM = cost of mobilization, \$

AC = cost of anode material and installation, \$

RC = rectifier cost, \$

PC = power supply cost, \$

The factor ENR/4200 is used to correct costs for inflation. All costs to this point have been in 1984 dollars (ENR = 4200). Other methods besides the ENR can be used to correct for inflation and local cost anomalies.

130. Maintenance labor. While cathodic protection systems operate essentially without human intervention, it is nevertheless worthwhile to check the system to ensure it is operating properly. Maintenance labor can be related to project length by the following equation:

$$MH = 0.86 L^{0.35} \quad (3-14)$$

where

MH = labor, man-hr/year

L = length of pipe protected, ft

These costs include recording rectifier output on a monthly basis, measuring pipe-to-soil potential, and checking current output of galvanic anodes. Rectifiers may be damaged by lightning or vandalism. These costs are not included in Equation 3-14.

131. Power cost. Impressed current cathodic protection systems require electrical energy to operate. The AC power required can be determined from the DC power requirement using the formula:

$$AR = CRA * DV * 8,760 / (E * 1,000) \quad (3-15)$$

where

AR = AC power requirement, kWhr/year

CRA = DC current requirement, A

E = efficiency of converting AC power to DC power, W

DV = DC voltage requirement, V

The conversion efficiency of rectifiers is roughly 70 percent ($E = 0.7$).

132. The DC voltage requirement depends on the current required per anode bed and the groundbed resistance. The usual range of DV is 10 to 60 V with 20 V being typical. This can be given by

$$DV = GR * CRA / NB \quad (3-16)$$

where

GR = groundbed resistance, ohms

NB = number of anode beds

Typical groundbed resistance is on the order of 1 ohm although it can be as high as 6 ohms for high resistivity soils.

133. A more precise formula for determining groundbed resistance is

$$GR = 0.00521 * RH * [\log_e (8 * LA / DA) - 1 + 2 * LA / S * \log_e (NP)] / (NP * LA) \quad (3-17)$$

where

RH = soil resistivity, ohm-cm

LA = length of anode, ft

DA = diameter of anode, ft

S = anode spacing, ft

NP = number of anodes per bed

Typically, LA = 7 ft, DA = 0.7 ft, and S = 15 ft for impressed current anode beds.

134. O&M cost. The O&M cost can be determined by summing the maintenance labor cost and energy cost as shown below:

$$OM = (MH * UL) + (PE * AR) \quad (3-18)$$

where

OM = total O&M cost, \$/year

MH = man-hours labor, man-hr/year

UL = unit cost of labor (including fringes), \$/man-hr

PE = price of electricity, \$/kWhr

$$AR = \begin{cases} \text{AC power requirement, kWhr/year} \\ 0 \text{ for galvanic systems} \end{cases}$$

For economic comparisons, it may be necessary to determine the present worth of O&M costs as shown below:

$$PWO = OM/CRF \quad (3-19)$$

where

PWO = present worth of O&M costs, \$

CRF = capital recovery factor

$$= \frac{i * (1 + i)^N}{(1 + i)^N - 1}$$

i = interest rate

N = design life, years

N is usually on the order of 20 years for most cathodic protection systems.

The interest rate, i, in Equation 3-19 should be expressed as a fraction (e.g. if interest rate is 14 percent, i = 0.14).

135. Replacement cost. To correctly evaluate the project life-cycle cost, the present worth replacement cost should be included. The present worth of replacement can be approximated by:

$$PWR = TC/(1 + i)^N \quad (3-20)$$

where

PWR = present worth of replacement cost, \$

TC = total first cost, \$

In most cases power lines can be salvaged and only a minimal survey is needed, so TC should be reduced accordingly. At present interest rates and a 20-year design life, replacement costs are only a small fraction of first cost.

136. Example problem 1 (galvanic). An 8,000-ft network of 6-in. ductile iron pipe in 18-ft laying lengths is to be cathodically protected. The average soil resistivity is 5,000 ohm-cm and the project is to have a 20-year life. Most of the anodes will be installed under asphalt pavement. Correct the cost to an ENR value of 4500. (See worksheet in Table 3-7.)

137. The cost for a typical survey for 8,000 ft of pipe is \$9,950 using Equation 3-1 with $A = 0.8$:

$$CS = 0.8 * 8,000^{0.87} = \$2,000$$

138. Estimate mobilization as \$1,500.

139. The current requirement can be estimated from Equation 3-2 using $EB = 1$ since the pipe is bare:

$$CR = 0.26 * 6 * 8,000 = 12,500 \text{ mA}$$

$$CRA = 12.5 \text{ A}$$

140. The anodes will be installed at every other joint, so the number of anodes is given by Equation 3-3 as

$$NS = \frac{8,000}{2 * 18} = 222$$

141. The current from each anode can be estimated from Equation 3-4 as

$$CO = \frac{12,500}{222} = 56 \text{ mA}$$

142. From Table 3-3, a 20-lb anode will produce roughly that current in this soil (actually 48 mA). Equation 3-5 gives the weight required for the anode to last 20 years.

$$WT = 0.0206 * 20 * 48 = 20 \text{ lb}$$

Therefore, a 20-lb anode will produce adequate current for the design life.

Table 3-7
Form for Estimating Cathodic Protection Costs
Example (Galvanic)

	Cost	
Survey (LS) <u>8,000</u> ft	(CS)\$	<u>2,000</u>
Mobilization	(CM)	<u>1,500</u>
Length (L) <u>8,000</u> ft; Diameter (D) <u>6</u> in.		
Current Requirement (CRA) <u>12.5</u> Amps		
Types of Anodes: Circle I or G		
Number of Anodes (NA) <u>222</u>		
Material Cost (CI) \$ <u>65</u> /anode		
Installation Cost (CE) \$ <u>400</u> /anode		
Total Anode Cost (AC) $2.2 * \underline{465} * \underline{222}$		<u>60,500</u>
Rectifiers (NB) <u>0</u> number		
Power Line <u>0</u> ft	(PC)	<u>0</u>
Inflation correction $(4500/4200) = \underline{1.07}$		
First Cost \$ (TC) <u>68,500</u>		
Labor Cost (OM) <u>20</u> man-hr/year, (UL) \$ _____ /man-hr	\$	_____/year
Power Cost (AR) _____ kWhr/year, (PE) \$ _____ /kWhr	\$	_____/year
Total O&M (OM) \$ _____/year		
Present Worth (PWO) \$ _____		
Total Present Worth \$ _____		

143. The unit cost for a 20-lb anode is \$65 from Table 3-4 and the cost for installation from Table 3-5 is \$400.

144. The cost for installed anodes is given by Equation 3-11 as

$$AC = 2.2 * (65 + 300) * 222^{0.8} = \$60,500$$

145. The corrected total first cost is given by Equation 3-13 as

$$TC = (4500/4200) (2,000 + 1,500 + 60,500) = \$68,500$$

146. Maintenance labor required can be estimated using Equation 3-14 as

$$MH = 0.86 (8,000)^{0.35} = 20 \text{ man-hr/year}$$

147. Example problem 2 (impressed current). In this problem 20 miles (105,000 ft) of 24-in. welded steel pipe is to be protected using impressed current. Soil resistivity is 2,000 ohm-cm and some dewatering of excavations is required. Approximately 700 ft of power lines is required and the cost of power is 8 cents per kilowatt-hour. Maintenance labor cost is \$12/hr including fringes. Costs should be given in 1984 dollars. Use an interest rate of 12 percent and a design life of 20 years. (See worksheet in Table 3-8.)

148. Costs for a typical survey ($A = 0.8$) can be given by Equation 3-1 as

$$CS = 0.8 * 105,000^{0.87} = \$18,700$$

149. Estimate mobilization as \$1,500.

150. The current requirement can be estimated from Equation 3-2 as

$$CR = 0.26 * 105,000 * 24 = 655,000 \text{ mA}$$

$$CRA = 655 \text{ A}$$

Table 3-8
Form for Estimating Cathodic Protection Costs
Example (Impressed)

	Cost
Survey (LS) <u>105,000</u> ft	(CS)\$ <u>18,700</u>
Mobilization	(CM) <u>1500</u>
Length (L) <u>105,000</u> ft; Diameter (D) <u>24</u> in.	
Current Requirement (CRA) <u>655</u> Amps	
Types of Anodes: Circle <u>I</u> or G	
Number of Anodes (NA) <u>437</u>	
Material Cost (CI) \$ <u>65</u> /anode	
Installation Cost (CE) \$ <u>500</u> /anode	
Total Anode Cost (AC) $2.2 * \underline{565} * \underline{437}$	0.8 <u>161,000</u>
Rectifiers (NB) <u>42</u> number	<u>30,200</u>
Power Line <u>700</u> ft	(PC) <u>2800</u>
Inflation correction $(4200/4200) = 1.0$	
First Cost	\$ (TC) <u>214,200</u>
Labor Cost (OM) <u>49</u> man-hr/year, (UL) \$ <u>12</u> /man-hr	\$ <u>588/year</u>
Power Cost (AR) <u>62,000</u> kWhr/year, (PE)\$ <u>0.08</u> /kWhr	<u>4,960/year</u>
Total O&M (OM)	\$ <u>5,550/year</u>
Present Worth (PWO)	\$ <u>41,000</u>
Total Present Worth	\$ <u>273,500</u>

151. Since soil resistivity is fairly low, each anode will be selected to produce 1.5 A (1,500 mA). Equation 3-8 gives the number of anodes as

$$NI = \frac{655}{1.5} = 437$$

or 1 anode for each 240 ft.

152. The unit cost for anodes material will be \$65.

153. Since some of the anodes beds will be placed in areas needing dewatering during excavation, use an excavation and placing unit cost of \$500.

154. The total cost for installing 437 anodes is given by Equation 3-11 as

$$AC = 2.2 * (500 + 65) * 437^{0.8} = \$161,000$$

155. Anode beds for large pipes are usually spaced every 2,500 ft. According to Equation 3-7 this results in

$$NB = \frac{105,000}{2,500} = 42 \text{ beds}$$

156. The current output per bed can be given by

$$\frac{655 \text{ A}}{42 \text{ beds}} = 15.5 \text{ A/bed}$$

157. From Table 3-6, this results in rectifiers costing \$720 each. Equation 3-12 gives rectifier costs as

$$RC = 42 * 720 = \$30,200$$

158. Power supply costs can be estimated using \$4 per foot of power line as

$$PC = 700 * 4 = \$2,800$$

159. Since the costs are to be given in 1984 dollars, there is no need to correct costs for inflation in Equation 3-13.

$$TC = (18,700 + 1,500 + 161,000 + 30,200 + 2,800) = \$214,200$$

160. The maintenance labor required can be given by Equation 3-14 as

$$MH = 0.86 (105,000)^{0.35} = 49 \text{ man-hr/year}$$

161. In soil with resistivity of 2,000 ohm-cm, it is reasonable to expect a groundbed resistance of 1 ohm. Equation 3-16 gives the voltage at each bed as

$$DV = 1 * 655/42 = 15.5 \text{ V}$$

162. The annual power requirement can be given for conversion efficiency = 0.7 using Equation 3-15 as

$$AR = 655 * 15.5 * 8,760 * 0.7/1,000 = 62,000 \text{ kWhr/year}$$

163. The labor and power requirement can be inserted into Equation 3-18 as

$$OM = 49 * 12 + 62,000 * 0.08 = \$5,550/\text{year}$$

164. The present worth of these annual costs at 12 percent for 20 years can be estimated as

$$PWO = 5,500/0.134 = \$41,000$$

where

$$CRF = \frac{0.12 (1.12)^{20}}{(1.12)^{20} - 1} = 0.134$$

165. Verification of detailed cost estimating procedure. The cost estimating procedures presented earlier can be verified by comparing costs developed using the procedure with costs of actual projects. Harco, Inc., provided data on 23 cathodic protection projects of which 17 contained sufficient detail for use in verification. This included 5 galvanic systems, 10 impressed current systems, and 2 mixed systems. Two projects involved purchase but not installation of anodes. The projects ranged in size from 30 ft of 4-in. pipe to 47 miles of 20-in. pipe.

166. The verification was based on installation costs only as opposed to including testing and power costs for which the project data were not sufficiently detailed and consistent for analysis. The actual project costs were adjusted to 1984 dollars before the comparisons were made.

167. The cost estimates were performed using the method described in the preceding section. Pipe diameter and length were used to determine current requirement. Current requirements were used to calculate anode requirements and hence anode costs. The number of rectifiers was based on the spacing described above.

168. In the first verification calculations, the predicted and actual costs differed significantly. For example, in one project, a large portion of the cost involved bonding joints for an impressed current system although this was not mentioned in the initial project description. Another problem developed when it was assumed in the initial calculation that laying length for pipe was 20 ft. In many cases, the inclusion of valves and fitting reduced this significantly.

169. In another case, the predicted cost was found to be 40 percent higher than actual cost. It was then noticed that the anodes were installed along a new pipeline. When costs for installing anodes along new pipes were used, the agreement between actual and predicted cost was reduced virtually to zero.

170. The most serious difficulty arose from the range of values used for current output from an impressed current system. Initially a value of 0.80 A/anode was used, but many projects differed significantly from this typical value. Actual values ranged from 2.0 to 0.3 A/anode. The estimator, of course, would usually not know which value to use beforehand. In later calculations, an anode output of 1.5 A/anode was used for projects in low

resistivity (<20,000 ohm-cm) soil while 0.5 A/anode was used for projects in high resistivity soil.

171. Once adjustments to the data and design criteria were made in response to the difficulties described above, the costs were estimated again. The average difference between actual and predicted cost was 25 percent. The results are shown graphically in Figure 3-7. Points falling on the 45-deg line indicate agreement between actual and predicted costs.

172. The points in Figure 3-7 tell a great deal about the strengths and weaknesses of the estimating procedure. Most of the points which do not fall on the line correspond to projects with an unusual design or questionable actual cost data.

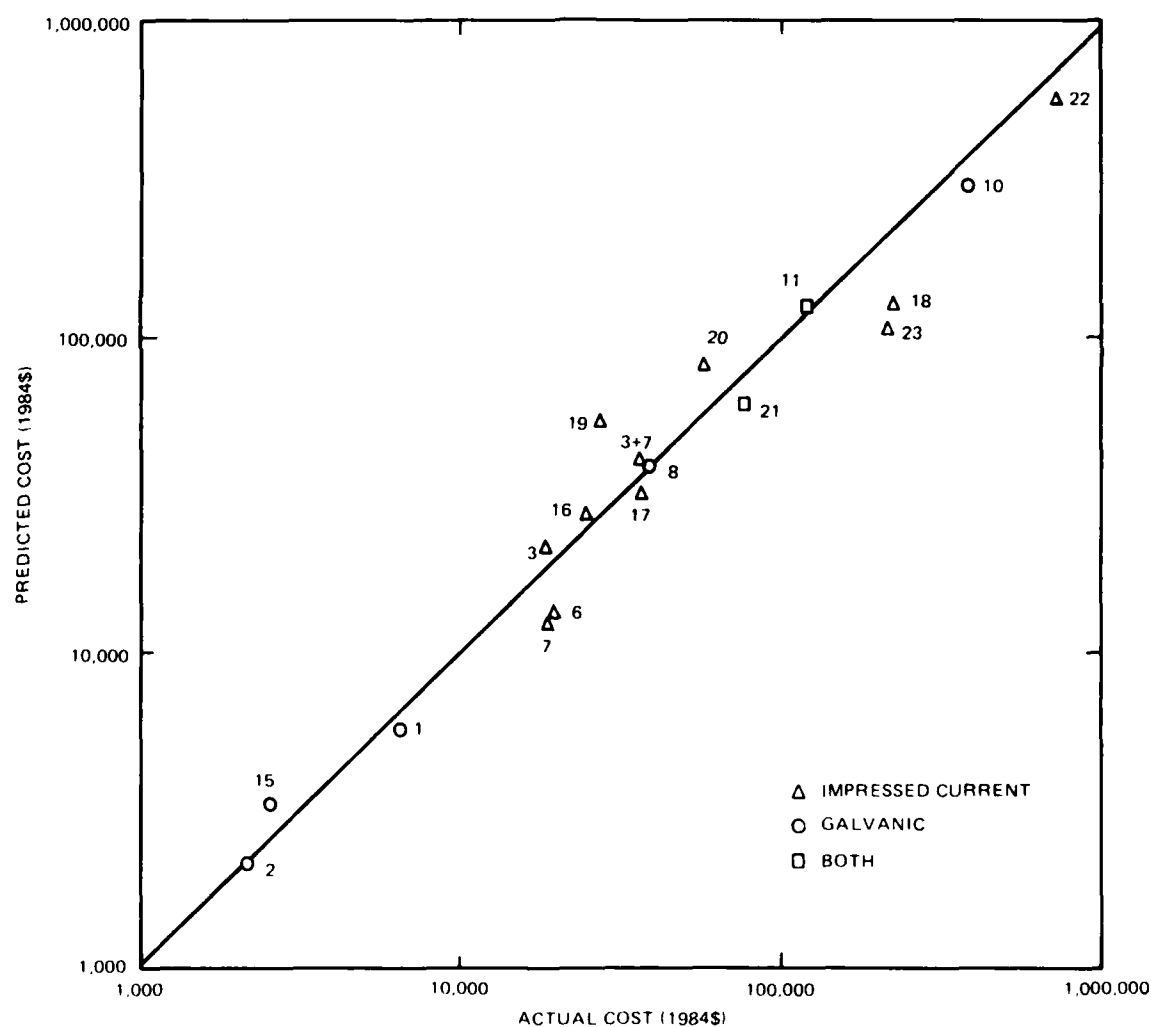


Figure 3-7. Results of verification for sacrificial anode costs

173. For example, projects 3 and 7 were performed for the same owner in the same year. One project involved protecting 40,000 ft of 6-in. pipe while the other involved 10,000 ft of 12-in. pipe. The cost was the same for both projects even though the first project involved twice as many anodes. The estimating procedure was not very accurate for either project. However, when the projects were combined into one, the costs agreed as shown by the point labelled "3+7." Apparently, the contractor was willing to lose money on one job provided he could make it up on another.

174. In another example, project 23 involved roughly three times the number of anodes as project 19, yet the cost was over 7 times as great even though it was done for the same owner on the same type of pipe in the same area. The estimating procedure predicted that the costs would differ by a factor of three. Again, several projects were performed for this owner over a several year period, and the sum of estimated costs and the sum of predicted costs do not differ greatly.

175. Apparently, much of the disagreement between actual and predicted costs is due to a lack of consistency in the way in which these jobs are bid. This can be caused by varying levels of expected competition, long-term relationships between contractor and owner, and workload of contractor. The estimating procedure apparently gives good values for the contractor's cost plus an average profit.

Statistical estimating procedure

176. The estimating method described earlier should give fairly accurate costs for a wide array of projects. For planning purposes, engineers sometimes want an estimating procedure which can account for the effect of important variables but is much easier to use. Such a procedure can be developed using regression analysis based on costs of completed projects. Because it is so simple, this procedure is less flexible (e.g. bare pipe only) and less able to effectively account for atypical conditions (e.g. varying types of excavation).

177. The statistical equations were developed using data provided by Harco, Inc., for 23 projects. Costs were converted to 1984 dollars. The equations were developed using the STATPRO computer package. The equations are shown along with their index of determination (R^2), which accounts for the fraction of the variance in the dependent variable explained by the equations.

A value of one indicates a good fit of the equation to the data while zero indicates a poor fit.

178. Most of the impressed current systems were installed in Pennsylvania and were fairly large (\$192,000 average cost). In contrast, most of the galvanic systems for which complete data were available were in the south. One was for only \$2,500. Two projects had a mixture of impressed current and sacrificial anodes and could not be used in the regression analysis. Others had to be eliminated because of missing data, so that overall there were only ten complete data sets. Some of the incomplete sets could be used, for example, to develop relationships between number of anodes and current requirement, but not cost.

179. The power formula $y = ax^b$ proved to be the best formula for the regression equations. Linear regressions were performed on transformed data. This tends to give equations which have roughly the same percent error over several orders of magnitude.

180. Testing cost. The cost for testing is similar to that presented earlier (Equation 3-1):

$$CS = 5.32 * LS^{0.87} \quad R^2 = 0.79 \quad (3-21)$$

where

CS = cost of a survey, \$

LS = length surveyed, ft

(Many of the projects included surveying, design work, and postinstallation design work in the testing cost.) An alternative equation is:

$$CS = 641 + 1.46 LS \quad R^2 = 0.83 \quad (3.22)$$

Equation 3-22 indicates that, on the average, the cost for testing is roughly \$641 plus \$1.46 per foot tested.

181. Installation cost. The cost to install a cathodic protection system is a function of the number of anodes, which is a function of the current requirement, which, in turn, is a function of the length and area to be protected. Regression equations were developed for all projects with impressed current systems only, and with galvanic systems only. In the following equations, the project cost represents costs based on both types of systems, while

cost equations based on impressed current and galvanic systems are designated by I and G in parentheses, respectively.

182. The cost is related to the number of anodes by:

All projects

$$CP = 1,322 NA^{0.80} \quad R^2 = 0.78 \quad (3-23a)$$

Impressed

$$CP(I) = 1,429 NI^{0.78} \quad R^2 = 0.75 \quad (3-23b)$$

Galvanic

$$CP(G) = 491 NS \quad R^2 = 0.98 \quad (3-23c)$$

where

CP = cost of project, \$

NA = number of anodes

NI = number of impressed current anodes

NS = number of sacrificial anodes

183. The cost is related to the current requirement in amps by:

All projects

$$CP = 11,668 CRA^{0.53} \quad R^2 = 0.44 \quad (3-24a)$$

Impressed

$$CP(I) = 1,962 CRA^{0.85} \quad R^2 = 0.90 \quad (3-24b)$$

Galvanic

$$CP(G) = 23,496 CRA^{0.66} \quad R^2 = 0.93 \quad (3-24c)$$

where CRA equals the current requirement, A. The current requirement in

Equation 3-24 is given in amperes since it refers to the current requirement for the project. Earlier, the current requirement in milliamperes was designated CR .

184. Since a current of 1 A can protect 1,000 ft² of pipe, Equation 3-24 can be rearranged to give revised estimating equations based on pipe area as shown below:

All projects

$$CP = 300 PA^{0.53} \quad (3-25a)$$

Impressed

$$CP(I) = 5.53 PA^{0.85} \quad (3-25b)$$

Galvanic

$$CP(G) = 246 PA^{0.66} \quad (3-25c)$$

where PA equals pipe area to be protected, ft². The R² values are not given for the above equations since they were derived from Equation (3-24).

185. Cathodic protection costs can also be related to the length of pipe protected by:

All projects

$$CP = 620 L^{0.51} \quad R^2 = 0.27 \quad (3-26a)$$

Impressed

$$CP(I) = 2.94 L^{1.0} \quad R^2 = 0.69 \quad (3-26b)$$

Galvanic

$$CP(G) = 168 L^{0.77} \quad R^2 = 0.94 \quad (3-26c)$$

where L equals length of pipe protected, ft.

186. In general, as one progresses from correlations based on number of anodes, which is directly related to cost, to pipe length, which is more indirectly related to cost, the correlations become poorer. In each step in the design process (length to current requirement to number of anodes) decisions were made by the design engineer based on specific conditions for each project contained in the historical data set. Regression equations cannot account for these differences. Therefore, it is best to make estimates based on knowing the number of anodes rather than simply on pipe length.

187. In almost all cases, the above equations indicate that sacrificial anode systems are more expensive. This may be due in part to the fact that cost data were available for fewer sacrificial systems and one of those systems involved a great deal of asphalt and concrete excavation and paving work, which significantly affected the equations.

188. Number of anodes. An important intermediate step in estimating costs is relating current requirement to number of anodes. The following equations were developed based on historical data:

All projects

$$NA = 16.9 CRA^{0.83} \quad R^2 = 0.51 \quad (3-27a)$$

Impressed

$$NI = 3.04 CRA^{0.94} \quad R^2 = 0.89 \quad (3-27b)$$

Galvanic

$$NS = 17 CRA \quad R^2 = 0.89 \quad (3-27c)$$

The individual equations for sacrificial and impressed current systems show good correlation and have roughly the same exponent. However, the equations

developed when mixing data for the two types of systems show much poorer correlation. This is also true in Equations 3-23 through 3-26.

Rules of thumb for quick estimates

189. While the statistical equations presented in the preceding section give simple formulas for determining cost, some engineers would like some even simpler rules of thumb for very "quick-and-dirty" estimates. Such values are of limited value for anything other than "ballpark" estimates. Table 3-9 gives some factors developed based on the historical data described in the preceding section.

190. The values were developed by inserting the geometric mean of the independent variable into the appropriate regression equation, and dividing the resulting dependent variable by the geometric mean. For example, inserting the geometric mean of length surveyed (69,000 ft) into Equation 3-21 gives a typical survey cost of \$86,400. Dividing by 69,000 ft gives a unit cost of \$1.25 per foot.

191. Table 3-9 is divided into four columns. Values in the second column are for all projects while values in the third and fourth columns are for impressed current and galvanic systems, respectively. Table 3-9 shows that in general it is less expensive to use impressed current. This observation, however, must be tempered by three considerations. First, power is not always available and the cost of installing power lines may make impressed

Table 3-9
Rules of Thumb for Cathodic Protection Estimating
(Cost in 1984 dollars)

<u>Rule</u>	<u>All Projects</u>	<u>Impressed Current</u>	<u>Galvanic</u>
Cost/anode, \$/anode	435	424	491
Cost/current, \$/A	1,550	970	5,460
Cost/pipe area, \$/ft ²	1.5	0.97	5.46
Cost/pipe length, \$/ft	4.3	2.9	33
Current/anode, A/anode	0.29	0.43	0.032
Power/anode, kWhr/year/anode	--	375	--
Power/current, kWhr/year/A	--	250(61)	--
Power/area, kWhr/year/ft ²	--	375	--

current systems unattractive. Second, electrical continuity is required for such a system and the cost of bonding pipes will usually make impressed current uneconomical where electrical continuity does not already exist. Finally, an impressed current system may cause interference currents in other buried structures with the associated costs involved with eliminating these currents.

192. The rules of thumb for estimating power requirements in Table 3-9 are based on Equation 3-15 with a voltage (DV) of 20 V at the rectifier. The power required per ampere of current was converted to power per anode using 1.5 A/anode and to power per square foot using 1,000 mA/ft².

Protective Coatings and Wrappings

193. The rate of corrosion can be significantly reduced by coating or wrapping a pipe. Numerous coatings have been developed from coal tar, asphalt, wax, and epoxy, to name a few. Numerous wraps have also been used.

194. In general, the most commonly used protective covering used in the water industry is a loose fitting, polyethylene film encasement. It consists of an 8-mil (0.008-in.) nominal thickness polyethylene tube or sheet that is wrapped around the pipe at the time of installation.

195. For planning purposes, the cost of polyethylene encasement can be estimated as \$0.05/in. diameter/ft length. Polyethylene encasement is especially attractive for pipes without electrical continuity (e.g. ductile and cast iron) where establishing electrical continuity involves extra cost.

196. Coatings and wrappings must be installed when the pipe is installed. Once the pipe is in the ground, cathodic protection is the only economical way to prevent most external corrosion problems.

PART IV: COST OF REPAIRING PIPE BREAKS

Introduction

197. One of the primary ways in which deterioration of pipes becomes evident is through an increase in the number of pipe breaks. The benefits of pipe replacement programs are often evaluated in terms of savings in costs for pipe break repair (e.g. Shamir and Howard 1979, Walski and Pelliccia 1981). (There are, of course, other benefits from pipe replacement such as reduction in damage and reduction in water loss.)

198. The cost to repair an individual break will vary due to a number of factors, including: size of pipe, location, traffic, depth of pipe, type of pipe, time of day, weather, type of break, ability to isolate break, local labor, equipment and materials costs, type of pavement, land use, and ease with which the break can be found. While data are not available to develop a method for estimating break repair costs as a function of all of the above parameters, existing data can be used to prepare cost functions for estimating these costs as a function of pipe diameter and type of break.

Purpose

199. Several studies have been made to determine pipe break repair costs. The purpose of this part is to present the available data and discuss the factors that affect costs.

Approaches

200. Several approaches have been used to quantify pipe break repair cost. The first is to develop a "typical" pipe repair cost based on the historical record; the second is to develop "synthetic" cost functions based on typical quantities of materials and labor used and typical unit prices; and the third is to develop a cost function based on statistical analysis of historical cost data. All three types of cost data have been reported in the literature and are presented below. In the subsequent sections, costs for repair of minor breaks and times to repair breaks are also presented.

Basis for costs

201. The costs presented in this part reflect the cost to the water utility and do not include the damage caused by breaks, value of lost water, inconvenience to motorists, traffic control by police, and final repaving work

usually done by the street department. All costs have been adjusted to 1983 dollars using the Engineering News Record Construction Cost Index.

Typical Repair Cost

202. Shamir and Howard (1979) used repair costs of \$1,000 with a range of \$500 to \$2,000 in 1977 dollars (\$1,600 with a range of \$800 to \$3,200 in 1983 dollars) for Calgary, Alberta, Canada. They did not discuss in any detail how they arrived at those costs.

203. As part of the New York Infrastructure Study (US Army Engineer District, New York 1980), O'Day et al. (authors of the Infrastructure Study) gave costs of \$7,323 per break as direct costs to the Water Supply Bureau. This cost includes 11 man-days of Water Bureau staff time per break. The New York data also showed an average damage settlement of roughly \$1,000 per break (\$1,460 in 1983 dollars).

204. Stafford et al. (1981) reported that costs for break repair in the period from 1971 to 1978 ranged from \$1,170 to \$1,760 per break for the Cincinnati (Ohio) Water Works. Assuming these costs are in 1975 dollars, this yields 1983 repair costs of \$2,150 to \$3,235 per break.

205. Walski (1984a) reported an average cost of \$2,848 for breaks reported by the Corps of Engineers, Washington Aqueduct Division, during the period 1981 through 1983. The cost data were taken from actual work orders.

Synthetic Cost Functions

206. Another approach to estimating break repair costs is to divide the repair costs into individual items and determine the quantity of each item required for each size break. Then the total cost can be determined by multiplying the unit price of each item by the quantity required and summing the costs. Walski and Pelliccia (1981) developed such data for Binghamton, N.Y., and the US Army Engineer District, Buffalo (1981), presented this type of data for Buffalo, N.Y. The data are summarized in Table 4-1.

207. The Binghamton costs are considerably lower than the Buffalo costs primarily in the items described as "Crew" and "Equipment." After carefully considering the manner in which the data were developed, this author feels the Buffalo costs are more representative of typical repair costs in an urban area.

Table 4-1
Pipe Break Repair Costs (1983 Dollars)

Pipe Diameter in.	Binghamton Costs \$	Buffalo Costs \$
4	718	1,455
6	786	1,558
8	839	1,679
10	896	1,780
12	920	1,872
16	1,266	2,315
18	1,305	--
20	1,415	2,434
24	1,770	2,755
30	--	3,289
36	--	3,485
48	--	4,107

Historical Cost Function

208. As part of its Water Supply Infrastructure Study, the City of Philadelphia (King 1984a) evaluated the actual cost of 416 breaks occurring in the period 1975 to 1981. Costs varied primarily with the pipe diameter and type of break. The time to repair breaks in large diameter pipes in industrial and commercial areas was found to be larger than in residential areas. For smaller mains (<16 in.), the differences in land use were not significant. Repair costs also did not vary with the time of year. In general, atypical costs were attributable to unusual conditions at specific break sites.

209. The data from Philadelphia are presented in Table 4-2. The type of break is significant in explaining break costs because circumferential breaks can be repaired with a clamp while split bell and longitudinal breaks usually require that part of the pipe be cut out and replaced. The amount of pipe replaced is usually much larger for the longitudinal breaks, which require more material and excavation.

Table 4-2
Pipe Break Repair Cost by Type of Break (1983 Dollars)

Pipe Diameter in.	Cost for Indicated Type of Break, \$		
	<u>Circumferential</u>	<u>Split Bell</u>	<u>Longitudinal</u>
6	930	975	1,058
8	895	1,202	1,053
10	1,149	1,380	1,611
12	1,362	1,087	2,516
16-48	2,237	3,904	5,620

Minor Breaks

210. While main breaks are the most serious in terms of damage and repair costs, minor leaks in service lines, curb stops, meters, hydrants, etc., can actually account for more lost water because they can go on for years without being detected. These minor leaks often are detected and repaired as part of a leak detection survey. As such, it is difficult to separate detection and repair costs.

211. Boyle Engineering (1982) conducted a vigorous leak detection and repair study for the State of California in the Petaluma, Poway, and Serrano water utilities. They only repaired 60 leaks and many of these involved simply tightening spud nuts or hydrant nuts. Nevertheless, they did document the costs well. These costs are summarized in Table 4-3, which shows that with the exception of main and lateral repairs, repair costs are quite small. In this work, the cost of repair is often less than the cost of detection which is on the order of \$130 per mile surveyed.

212. Male, Noss, and Moore (1984) reported repair costs for the Westchester (N.Y.) Joint Water Works by type of repair. These costs are summarized in Table 4-4. The entry in the table titled "No Leak Found" refers to the case in which the sound of a leak was detected but the leak could not be located or repaired. The authors reported a leak detection cost of \$280 per leak for the Westchester system and \$1,200 per leak for the Louisville (Ky.) Water Company.

Table 4-3
Cost of Leak Repair (Boyle Engineering 1983)

<u>Type of Repair</u>	<u>Number Reported</u>	<u>Average Cost 1983 \$</u>
Service lateral and service main	4	418
Hydrant lateral	1	298
Curb stops	5	23
Tighten spuds, packing, valves, etc.	45	5
8-in. main leak	1	880
Replace meter	1	98
Replace angle stop	1	50
Repair air release	1	24
Reflare conn pipe	1	32

Table 4-4
Cost of Leak Repair (Male,
 Noss, and Moore 1984)

<u>Type of Repair</u>	<u>Cost 1983 \$</u>
Main	710
Service lateral	714
No leak found	491
Hydrant	80

213. Pilzer (1981) reported that the cost of leak detection and repair in the Gary-Hobart (Ind.) Water Corporation was \$587 per leak in 1983 dollars.

Time to Repair Breaks

214. In some instances, the time to repair a break, which is an indicator of the interruption in service, is of interest to a utility. This time is highly dependent on the ease with which a break can be pinpointed and the pipe segment isolated hydraulically from the remainder of the system. The time also correlates with the size of the broken main and the type of break. Data from Philadelphia (King 1984a) and Binghamton, N.Y. (Walski and Pelliccia 1981), are given in Table 4-5.

215. While the repair times reported in Table 4-5 are typical, there is considerable variance about these averages. King (1984a) reported repair times that ranged from a half hour to over 60 hr. For a break in a 6-in. pipe, King (1984a) reported a standard deviation of 5.0 hr for repair time while for in the 16- to 48-in. range, the standard deviation was 19 hr. This corresponds to roughly ± 60 percent of mean times.

Table 4-5
Time to Repair Breaks (in hours)

Pipe Diameter in.	Philadelphia			Binghamton
	<u>Circular</u>	<u>Split Bell</u>	<u>Longitudinal</u>	
6	8.7	6.9	10.0	11
8	7.7	10.6	9.5	12
10	10.2	13.2	13.2	12
12	12.2	9.4	20.6	13
16-48	21.9	29.7	47.1	--
16	--	--	--	14
20	--	--	--	15
24	--	--	--	16

PART V: COST OF PIPE REPLACEMENT

Introduction

216. Replacement of old pipes with new ones is often required when the old pipes begin to leak or break frequently or have lost a significant amount of their carrying capacity. In order to evaluate whether replacing pipes is economical, it is necessary to be able to estimate the cost of pipe replacement.

217. Replacing old water mains with new ones is sometimes referred to as "relaying" pipe. As will be shown below, the costs of relaying pipe in an urban area are significantly higher than laying new pipe under typical conditions. Abandoning the old pipe, interference with other utilities, small contracts with high mobilization costs, and a large number of service connections tend to contribute to the somewhat high cost.

218. The purpose of this part is to present cost data for replacing water mains in old, urban water systems, and to discuss the factors that would have an impact on the cost. Cost data are presented for two areas:

(a) Philadelphia, and (b) New York and Buffalo.

Cost Data (Philadelphia)

Data

219. The data presented in this part were originally collected and analyzed by the Water Department of the City of Philadelphia (King 1984b) primarily to study relay cost trends with time. The data consisted of the actual bid price, diameter and length of pipe, and date.

220. Two types of projects were included in the data: (a) relay in which only the water mains were relayed, and (b) relay/reconstruction in which both the water main and the sewer were replaced. In relay/reconstruction projects only that portion of the cost attributable to the water main is included, although this breakdown is somewhat arbitrary. In addition, some work was undertaken with the Street Department. The cost of these projects will be discussed separately.

221. Relaying costs consist of all of the costs actually paid to the contractor. These include excavation, abandoning existing pipe, laying new

pipe, reconnecting services, pressure testing, disinfection, backfilling, repaving, and contractor overhead and profit. Portions of some hydrant laterals are also replaced. In general temporary services are not provided. The costs do not include preparation of specifications and inspection. In the Philadelphia project, ductile iron pipe was used exclusively for relays.

222. Most pipe relays in Philadelphia are for 8-in. pipe, although data were also provided for 12-in. relays. During the period 1973 through 1982 there were an average of 32 8-in. relay contracts and 16 8-in. relay/reconstruction projects let annually with an average length of 580 ft and 480 ft, respectively.

223. Cost information was only available to this author as actual price per foot of pipe averaged over all projects in a single year and not on a project-by-project basis. Since the cost data were collected over a 10-year period, costs were first adjusted to 1982 dollars using the Engineering News Record Construction Cost Index for Philadelphia.

224. The average costs corrected for inflation and standard deviations (between years not projects) are presented for eight different types of projects in Table 5-1. As expected, the cost for 12-in. pipes is higher than 8-in. pipe. The difference in cost between the two sizes is not quite as high as one would expect for a 50-percent increase in pipe size, indicating that nonpipe costs are larger in this work than typical pipeline construction.

Table 5-1
Costs for Pipe Relay and Relay/Reconstruction

Pipe Diameter in.	Type of Project	Mean 1982 \$/ft	Standard Deviation 1982 \$/ft	Number of Years	Notes
8	Relay	96.6	11.8	10	
12	Relay	115.5	32.4	10	
8	R/R*	114.4	21.4	10	
12	R/R	149.0	38.3	9	
8	Relay	91.1	8.4	6	w/streets contract
8	R/R	65.9	20.2	5	w/streets contract
18	Reconstruction	152.4	25.6	6	Sewer only
18	R/R	150.1	23.3	6	Sewer only

* R/R = relay/reconstruction (water main portion of water main relay and sewer reconstruction project).

225. Somewhat surprisingly, the cost of the water portion of relay/reconstruction projects is larger than the cost of a relay only project, although the difference is only slightly significant statistically. One would think that since the excavation and repaving work was required for installation of both the water and sewer pipe, the costs would be slightly less for relay/reconstruction projects. The data, however, did not support this.

226. One explanation of the higher relay/reconstruction costs is that costs were not allocated correctly between the water and sewer costs. The final two rows of Table 5-1 do not support this as they show that sewer reconstruction costs were virtually the same regardless of whether the sewer was reconstructed alone or as part of a relay/reconstruction.

227. One statistically significant result is that relay/reconstruction costs tend to be much lower when the work is conducted in conjunction with a street department project. Costs of a relay alone were only slightly less expensive when performed with the street department.

228. The data were also tabulated by Pitometer districts of which there are seven in Philadelphia. Costs for 8-in. relays varied from \$92/ft to \$113/ft between the districts with a mean of \$96/ft. The highest cost was for district III which consists of much of the central business district, but even the highest cost was not statistically significantly different from the mean. The City of Philadelphia is currently doing additional work on the factors that affect relay costs.

Implications

229. In cities as highly developed as Philadelphia, which should include most older cities, the costs of relaying water mains are considerably higher than laying new pipe in an undeveloped area. Typical costs in 1982 dollars for new 8-in. pipe with a gate valve every 150 ft could range from \$35/ft to \$60/ft, yet average costs in this study were \$96/ft with some costs much higher. This can be explained by: interference with other buried utilities, the large number and size of service connections, small project size with associated large mobilization costs, thicker pavement, high local labor costs, problems in abandoning and in some cases removing the old mains, and attempts to minimize interference with traffic.

230. These cost items associated with relays do not depend greatly on pipe diameter so that relaying a large main is not much greater than relaying

a smaller main. The only item that varies significantly with diameter is the pipe material itself.

231. In a city as highly developed as Philadelphia even the noncentral city area is fairly highly urbanized, especially those areas that have pipes that are old enough to require relaying. This was borne out by the fact that costs in the heart of the city were only slightly higher than elsewhere. This was partly due to the fact that Pitometer districts are selected based on hydraulic features and not land use. A finer breakdown in districts should reveal some correlation between cost and land use.

232. Relaying pipe in conjunction with sewer reconstruction did not significantly reduce costs, but including relaying with general street and sewer work did reduce cost.

Cost Data (New York and Buffalo)

233. During the New York Water Supply Infrastructure Study, O'Day et al. (US Army Engineer District, New York 1980) developed cost data for relaying water mains in New York City. The costs included the following items: protection and maintenance of traffic, removal of pavement, excavation, sheathing and shoring, removal of existing main, dewatering, maintenance and protection of existing structures, furnishing and placing new main, backfilling using material from excavation, removal and replacement of hydrants and valves, and temporary and permanent restoration of pavements.

234. The costs for New York City are presented in Table 5-2. Costs are not provided for pipes smaller than 12 in. because the current policy in New York is not to install new mains with a diameter smaller than 12 in. Similarly, steel and reinforced concrete pipe are only used for larger mains.

235. Costs were also developed for pipe replacement for Buffalo, N.Y. (US Army Engineer District, Buffalo 1981), based on historic pipe costs in the Buffalo area and in the Dodge Guide. These costs are presented in Table 5-3, and are based on ductile iron pipe.

236. The Buffalo costs are considerably lower than either the New York or Philadelphia costs. The differences may be due to lower labor costs or less complicated excavation in Buffalo. Much of the historical data in Buffalo was for smaller pipe (<20 in.). In these sizes, the costs do not differ greatly between the cities.

Table 5-2
Costs for Pipe Relaying in New York City (1982 \$)

Pipe Diameter in.	Cost for Indicated Pipe, \$/ft		
	<u>Ductile Iron</u>	<u>Reinforced Concrete</u>	<u>Steel</u>
12	106	--	342
20	132	--	--
24	144	--	--
30	354	319	342
36	472	461	496
42	579	561	608
48	685	662	721

Table 5-3
Costs for Pipe Relaying in Buffalo, N.Y. (1982 \$)

Pipe Diameter in.	Cost \$/ft
4	68
6	72
8	77
10	84
12	89
16	115
20	139
24	166
30	205
36	262
48	384

PART VI: ESTIMATING COSTS OF CHEMICAL TREATMENT
FOR INTERNAL CORROSION CONTROL

Introduction

237. Internal corrosion of metallic elements of water distribution systems is an electrochemical process whereby metal dissolves. It has recently been estimated that the total annual cost of internal corrosion of water systems in the United States is in the billions of dollars (Bennett et al. 1979).

238. Several means of minimizing internal corrosion are available: the use of corrosion-resistant materials and/or coatings and linings, insulated couplings between dissimilar metals, impressed cathodic protection, and chemical treatment. Cathodic protection and many coating are only applicable to tanks and other appurtenances. New pipes are generally lined with corrosion-resistant material, but there are still many miles of bare metal pipe in existence today. Lining (as described in Part II) and/or chemical treatment are required to protect these pipes. The two most popular chemical treatment techniques are a process generally known as stabilization, and the use of corrosion inhibitors, both of which are discussed below. Following that discussion is a section on how to estimate chemical treatment cost.

Stabilization for Corrosion Control

239. As used in the potable water supply industry, the term "stabilization" means adjustment of pH, alkalinity, and calcium hardness such that finished water has a slight tendency to precipitate calcium carbonate. Several chemicals can be used for this purpose, but lime (CaO or Ca(OH)_2) and carbon dioxide (CO_2) are usually chosen for larger treatment plants. Many waters can be stabilized with lime alone.

240. As stabilized water flows through a distribution system, precipitation occurs and a thin layer (or film) of calcium carbonate adheres to the inside surfaces of pipes and appurtenances. This film, which often contains other precipitates such as siderite, goethite, and magnetite, limits the rate of corrosion by providing a barrier between the water and potential corrosion sites. Although stabilization is beneficial for virtually all waters, the quality of the film and, hence, the degree of corrosion protection afforded

vary from water to water. Generally, film quality increases with increasing alkalinity, calcium hardness, and velocity of flow in the system. Over the years, the use of stabilization for corrosion control has received considerable attention in the water supply literature (Langelier 1936, 1946; Caldwell and Lawrence 1953; Merrill and Sanks 1977; Pisigan 1981; Singley 1981; Morgan, Walski, and Corey 1984).

241. Factors serving to limit the use of stabilization for corrosion control include the operational difficulty and expense associated with lime and carbon dioxide feeding equipment and the general unavailability, until recently (Morgan, Walski, and Corey 1984), of a simple method for directly estimating the required chemical doses. As a general rule, stabilization can be expected to be an effective corrosion control technique for most larger water systems having skilled operating personnel. For small systems, especially those that do not have a treatment plant, the factors noted above will generally dictate that some other method of corrosion control be used.

Inhibitors for Corrosion Control

242. In the potable water supply industry, the term "corrosion inhibitor" is used to describe any of a number of chemicals that act in some way to interrupt the corrosion process and, thus, slow the rate at which corrosion occurs. Most of the inhibitors commonly used are phosphate compounds that function as both film formers and sequestering agents.

243. When added to water on a continuous basis, film-forming inhibitors cause a very thin protective film to form on the inside surfaces of pipes and attached appurtenances. The nature of the protective coating thus formed varies depending upon the chemical inhibitor used, but, once formed, the thickness generally does not continue to increase to any significant extent. Nevertheless, continuous treatment is necessary to ensure that the film remains intact. Failure to properly maintain the film can lead to serious corrosion problems.

244. Sequestering agents act to form soluble complexes with various metal ions such as calcium, magnesium, iron, and manganese that may be present in water. Depending upon the stability of the complex formed, this can be quite effective in preventing excessive calcium carbonate scale deposits and the discoloration often associated with iron and manganese problems. However,

when used alone, sequestering agents are not effective for corrosion control. In fact, they may contribute to the overall corrosion process by preventing the deposition of corrosion products and, therefore, causing more bare metal to be exposed than would otherwise be the case. Some sequestering agents interact with existing scale deposits to remove them from pipe walls and other internal surfaces. For this reason, it is not uncommon to note an increase in customer complaints related to color and turbidity immediately following the introduction of such chemicals to a water system. Although there are conflicting claims concerning the speed and extent of scale removal, it seems doubtful that excessive deposits can be satisfactorily removed by this method for potable water systems.

245. Important advantages of the use of inhibitors, as compared to conventional stabilization, are that the chemicals are generally more convenient and economical to handle and feed, water quality considerations such as pH are less significant (although pH adjustment is sometimes desirable), other treatment processes are less affected, and mild overdoses will usually not cause serious problems. The ease with which inhibitors may be handled and fed is especially important for smaller systems since they frequently rely on groundwater sources that require only minimal treatment prior to distribution.

246. Unfortunately, the exact mechanisms by which inhibitors work are not yet fully understood. However, it is known that effectiveness often decreases with decreasing flow velocity and increasing pH. Other factors such as alkalinity, hardness, temperature, contact time, and water hammer also have some effect. Therefore, it is difficult to predict if a given inhibitor will work in a given situation and, if so, the optimum dose to use. Thus, most manufacturers and suppliers recommend rather detailed pilot studies to choose the most economical treatment program. Many times such experimentation is carried out without charge to the utility.

247. The use of phosphate compounds for scale prevention and corrosion control in the United States dates from the late 1930s and early 1940s when sodium hexametaphosphate was first used for these purposes. Continuing research since that time has resulted in significant improvements in inhibitor formulations and performance. Presently, the most generally applicable inhibitors are zinc bimetallic polyphosphates. These, as well as the older formulations, are available in both dry and liquid forms. They are usually added to the water to be treated as a dilute solution. Typically, equipment similar

to that used for hypochlorination or for polymer feed to aid coagulation/flocculation may be used.

248. Over the years, corrosion inhibitors (and similar compounds used for various purposes) have received considerable attention in the water supply literature. Early claims concerning the performance of some of the formulations were, no doubt, exaggerated, but more recently a significant body of scientific literature on the subject has developed. Representative technical articles and reports include Illig (1957); Kleber (1965); Powers, Cahalan, and Zalfa (1965); DeBerry, Kidwell, and Malish (1982); McFarland (1983); Boffardi and Schweitzer (1984).

Estimating Chemical Treatment Costs

General approach

249. Cost for chemical treatment can be divided into three main items, regardless of the chemical being fed: (a) capital cost for feed equipment; (b) operation and maintenance (O&M) labor, energy, and supplies; and (c) chemical cost. Capital costs are based on the capacity of the system, while O&M and chemical costs are based on expected feed rates. All costs are then converted into dollars per million gallons treated for comparisons. The overall estimating procedure is summarized in Figure 6-1. Table 6-1 is a sample worksheet.

250. The only other published data on corrosion control cost was developed by Singley, Beudet, and Markey (1984). The costs in this section are consistent with their costs. They also presented data on costs of analytical laboratory services.

Data source

251. Gumerman, Culp, and Hansen (1979) have presented curves that may be used to estimate costs associated with a wide variety of water treatment operations and processes. Subsequently, cost equations were developed from these curves and incorporated into the MAPS computer program described in Engineer Manual EM 1110-2-502 (Headquarters, Department of the Army 1980). A similar approach was utilized to provide the basis for the cost equations presented below.

252. In general, the total cost of a treatment process may be thought of as the sum of the applicable capital and operation and maintenance costs.

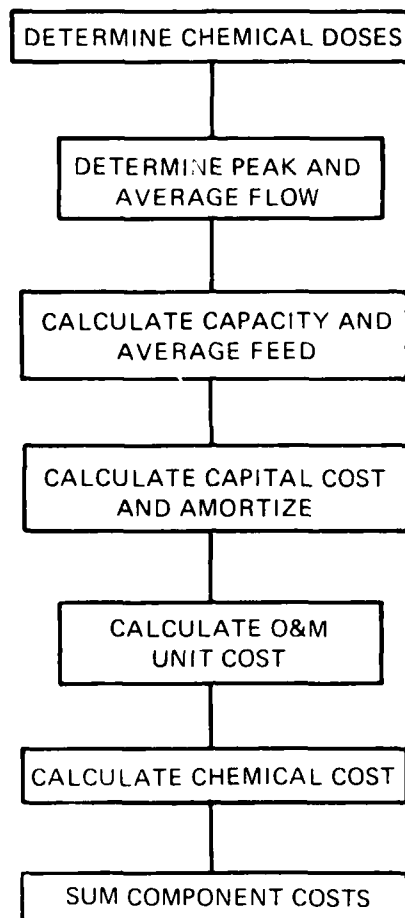


Figure 6-1. Chemical treatment estimating procedure

Both of these categories can be further subdivided into several components if such is desired. For example, the total capital cost of a given water treatment process may be considered to be the sum of the actual construction cost of the process (referred to herein as the treatment process cost) and those costs associated with site work; interface piping; engineering; contractor overhead and profit; land; legal, fiscal, and administrative fees; and interest incurred during construction. In this report, the only category of capital costs considered is the actual process construction cost, or treatment process cost. The reader is referred to the MAPS documentation (EM 1110-2-502) and the original work by Gumerman, Culp, and Hansen (1979) for discussion of how the other components of the total capital cost of a process may be estimated.

Table 6-1
Worksheet for Chemical Treatment Costs

Peak Flow _____	MGD		Average Flow _____	MGD
	Lime (Quick or Hydrated)	Carbon Dioxide	Chemical Inhibitor	Total
Peak Dose* (DOSEP), mg/l	_____	_____	_____	
Ave Dose* (DOSEA), mg/l	_____	_____	_____	
Feed Capacity (CAP), lb/day	_____	_____	_____	
Average Feed (FEED), lb/day	_____	_____	_____	
Feed Equipment				
Initial Cost (CC), \$	_____	_____	_____	
Unit Cost (UNC), \$/MG	_____	_____	_____	_____
Operation and Maintenance				
Annual Cost (OP), \$/year	_____	_____	_____	
Unit Cost (UOM), \$/MG	_____	_____	_____	_____
Chemicals				
Purchase Price (UCHEM), \$/lb	_____	_____	_____	
Unit Cost (CHEM), \$/MG	_____	_____	_____	_____
Total, \$/MG				_____
Interest Rate (I) _____				
Design Life (N) _____				

* Expressed as commercially available product.

Chemical Dose

253. In order to determine the cost of feed equipment and chemicals, the required chemical dose must be known. Lime and carbon dioxide doses can be determined stoichiometrically. Chemical inhibitor doses must be determined through pilot studies although typical values can be used for planning purposes.

254. Lime doses for stabilization can be determined empirically in the laboratory by conducting a series of "marble tests" (AWWA 1971) to determine optimal dose. This is a tedious process. Similarly, the Langlier Index of treated water can be determined and the chemical feed rate can be adjusted until a desirable Index is achieved or raw water quality changes.

255. Given the raw water calcium hardness, alkalinity, pH, temperature, and total dissolved solids, chemical doses to achieve a stable water can also be determined by trial and error using Caldwell-Lawrence diagrams (Merrill and Sanks 1977). Morgan, Walski, and Corey (1984) have developed a set of monograms and a microcomputer program which can be used to determine chemical doses without the need for trial-and-error solutions.

256. Lime and carbon dioxide doses are often expressed in terms of concentration as calcium carbonate (CaCO_3). To convert to concentration of pure chemical multiply by 0.56, 0.74, or 0.44 for quick lime, hydrated lime, or calcium carbonate, respectively. For example, a lime dose of 15 mg/l as CaCO_3 would be equivalent to a dose of 8.4 mg/l (15×0.56) as quick lime.

257. Lime and carbon dioxide doses must be adjusted for the purity of the commercially available chemical. This is done by multiplying the dose by $100/P$ where P is the percent purity of the chemical as commercially available. For example, if the quicklime dose as pure chemical is 8.4 mg/l, the dose as 70 percent pure quicklime is 12 mg/l ($8.4 \times 100/70$) as commercially available quicklime. It is this corrected value that should be used in subsequent calculations in this section. The microcomputer program described in Morgan, Walski, and Corey (1984) makes these corrections as well as displaying the dose as CaCO_3 .

258. Required lime and carbon dioxide doses will vary in response to normal fluctuations in raw water quality. It is recommended that the doses be calculated for the range of observed water quality and the average values be used for the average doses (DOSEA) and the largest be used for the peak doses (DOSEP) in making subsequent calculations. All other things being equal, peak

lime dose will occur in the winter while peak carbon dioxide dose will occur in the summer. For ground-water sources the fluctuations will usually be negligible, while for small surface streams the fluctuations can be large.

259. Chemical costs for inhibitors vary considerably depending upon the specific inhibitor chosen. TG-10 (Calgon Corporation), G-C 21CC (Garratt-Callahan Company), and Shan-No-Corr (Shannon Chemical Company) are fairly typical of the dry-form, phosphate-based inhibitors on the market today. TG-10 is a sodium-zinc phosphate compound (bimetallic glassy phosphate) that is often used at a concentration of around 1 mg/l (8.34 lb/MG) as commercially available product. G-C 21CC is a sodium tripolyphosphate inhibitor usually used at a concentration of 8 to 10 mg/l (66.7 to 83.4 lb/MG) as commercially available product. Shan-No-Corr is a combination of sodium hexametaphosphate, a zinc salt and acid salt. Shan-No-Corr is usually used at a dosage of 1 to 2 mg/l (8.34 to 16.68 lb/MG) as commercially available product. All three of these products act as both film-formers and sequestering agents.

260. Aqua Mag (Kjell Water Consultants, Incorporated) is a liquid-form, linear-chain, sodium polyphosphate compound usually used at a concentration of 0.5 to 1 mg/l (4.17 to 8.34 lb/MG) as commercially available product. Like the dry-form chemicals discussed above, Aqua Mag acts as both a film-former and sequestering agent.

261. Many other inhibitors are available, but those mentioned above are generally representative. McFarland (1983) has presented a general discussion of inhibitors that includes basic information pertinent to some 22 different commercially available products.

262. A major problem associated with estimating the cost of using any inhibitor is estimating the required dosage. While it seems reasonable to assume that inhibitor dosage should be directly related to measurable water quality parameters, few manufacturers or suppliers present a rational method for estimating the required dosage. Instead, pilot studies are virtually always used for this purpose. While this is a logical approach for a utility that is contemplating using an inhibitor for corrosion control, it is of little value to a planner or engineer who wishes to make cost comparisons among many alternatives. This problem is further complicated by the fact that there is no way to predict in advance the actual degree of corrosion protection that will be afforded by any given inhibitor. Thus, one cannot be sure that the alternative approaches being considered are actually equivalent in

terms of their net effects. From the foregoing discussion, it should be obvious that, for a given situation, comparing the costs of alternative chemical treatment corrosion control programs without specific empirical data obtained from pilot studies entails a considerable element of uncertainty.

Feed requirement

263. The cost equations presented in subsequent sections require feed rates and capacities in pounds per day as input. The feed rate depends on the flow rate in million gallons per day (MGD) and dosage in milligrams per liter (mg/l). Two feed rates are needed in the cost calculations: capacity (CAP), and average feed rate (FEED).

264. The capacity refers to the maximum output of the feed equipment and should be based on the conservative assumption that peak chemical dose and peak flow rate occur simultaneously. The capacity can be give by

$$CAP = 8.34 * QP * DOSEP \quad (6-1)$$

where

CAP = capacity of feed equipment, lb/day

QP = peak design flow rate, MGD

DOSEP = peak dose rate, mg/l

265. The actual feed rate is required in the equations for O&M and chemical costs. The actual flow rate and feed rate for the treatment process vary throughout the design life of a project. Ideally, one would calculate costs for short periods during the design life and sum the present worths of these costs. A simpler approach is to pick the average flow as the flow in some year during the design life and use this average in calculations. Walski (1984) gives some guidance on determining this flow. For example, if the actual flow increases linearly over the 20-year design life of a project and the interest rate is 10 percent, the flow 8 years into the design life will give the "correct" O&M costs for planning purposes.

266. The average feed rate can be given as:

$$FEED = 8.34 * QA * DOSEA \quad (6-2)$$

where

FEED = average feed rate, lb/day

QA = average flow, MGD

DOSEA = average dose, mg/l

267. Equations 6-1 and 6-2 are applicable to lime, carbon dioxide, and chemical inhibitors.

Lime feed equipment

268. The cost of lime feed equipment depends on whether hydrated or quick lime is used. The cost of quick lime feed is higher because it requires a slaker. The costs can be estimated using:

$$CC = \begin{cases} 1,880 * CAP^{0.45} & \text{for hydrated lime} & (6-3a) \\ 18,540 * CAP^{0.18} & \text{for quick lime} & (6-3b) \end{cases}$$

where

CC = treatment process cost, \$

CAP = lime feed capacity, lb/day

In general, hydrated lime is used in smaller plants (<1,200 lb/day) while quick lime is used in larger plants although the dividing line is not distinct.

Carbon dioxide feed equipment

269. The facilities and equipment needed for carbon dioxide addition are similar to those commonly used for recarbonation following precipitation softening, except that a separate recarbonation basin is not required. The following expressions may be used to estimate the treatment process cost associated with carbon dioxide addition:

$$CC = \begin{cases} 15,900 * CAP^{0.21} & \text{for } 400 < CAP < 1,000 & (6-4a) \\ 3,890 * CAP^{0.42} & \text{for } 1,000 < CAP < 4,000 & (6-4b) \\ 1,780 * CAP^{0.51} & \text{for } 4,000 < CAP < 10,000 & (6-4c) \end{cases}$$

where

CC = treatment process cost, \$

CAP = liquid carbon dioxide feed capacity, lb/day

Equation 6-4 assumes the use of liquid carbon dioxide. Other methods of carbon dioxide addition are considered by Gumerman, Culp, and Hansen (1979) and

in EM 1110-2-502. However, operational flexibility, low maintenance requirements, and high transfer efficiency make liquid carbon dioxide the source of choice in many cases.

Inhibitor feed equipment

270. The equipment and facilities needed to add an inhibitor for corrosion control vary somewhat with the specific inhibitor to be used. For an actual application, the best source of treatment process cost information is the manufacturer or supplier of the inhibitor chosen for use. However, for comparison purposes, it is reasonable to consider the equipment and facilities needed to feed most corrosion inhibitors as essentially the same as those required to feed polymers used as aids to the coagulation/flocculation process. Making this assumption, the treatment process cost associated with the use of an inhibitor may be estimated by means of the following expressions:

$$CC = \begin{cases} 18,000 * CAP^{0.14} & \text{for } 1 < CAP < 50 \\ 6,750 * CAP^{0.27} & \text{for } 50 < CAP < 200 \end{cases} \quad \begin{matrix} (6-5a) \\ (6-5b) \end{matrix}$$

where CAP equals inhibitor feed capacity, lb/day.

Operation and maintenance cost functions

271. Operation and maintenance costs may be thought of as consisting of the sum of all costs incurred in operating a process on a day-to-day basis. This would include such items as materials required for maintenance, energy required to keep the process running, energy required to maintain the proper environment within the building housing the process, labor required to maintain and operate the process, and chemicals to be used. In the original work by Gumerman, Culp, and Hansen (1979), a total O&M cost curve (excluding chemical and building energy costs) and cost curves for each of the individual O&M categories mentioned above (except chemicals) are presented for numerous treatment processes. In the MAPS documentation (EM 1110-2-502), separate O&M cost functions are presented for each of the categories, including chemicals, for most of the treatment processes considered. In this report, O&M costs include labor, process energy, and materials other than chemicals.

Lime feed O&M cost

272. The following expressions may be used to estimate the O&M cost associated with lime addition:

$$OM = \begin{cases} 75 * FEED^{0.64} & \text{for } 240 < FEED < 1,200 & (6-6a) \\ 245 * FEED^{0.47} & \text{for } 1,200 < FEED < 24,000 & (6-6b) \end{cases}$$

where

OM = process O&M cost, \$/year

FEED = lime feed rate, lb/day

Equation 6-6a assumes the use of commercial grade hydrated lime (about 70 percent calcium hydroxide) and Equation 6-6b assumes the use of commercial grade quick lime (about 90 percent calcium oxide).

Carbon dioxide feed O&M cost

273. The O&M cost associated with carbon dioxide addition may be estimated by the use of the expressions presented below:

$$OM = \begin{cases} 700 * FEED^{0.30} & \text{for } 400 < FEED < 1,000 & (6-7a) \\ 311 * FEED^{0.42} & \text{for } 1,000 < FEED < 4,000 & (6-7b) \\ 63 * FEED^{0.62} & \text{for } 4,000 < FEED < 10,000 & (6-7c) \end{cases}$$

where FEED equals liquid carbon dioxide feed rate, lb/day.

Inhibitor feed O&M cost

274. The O&M cost of inhibitor addition may be estimated with the aid of the equations presented below:

$$OM = \begin{cases} 2,900 * FEED^{0.011} & \text{for } 1 < FEED < 20 & (6-8a) \\ 2,284 * FEED^{0.091} & \text{for } 20 < FEED < 200 & (6-8b) \end{cases}$$

where FEED inhibitor feed rate, lb/day.

Chemical cost

275. Chemical cost can be determined based on the average dose and flow rate, as given by:

AD-A157 492

COST OF WATER DISTRIBUTION SYSTEM INFRASTRUCTURE
REHABILITATION REPAIR AND REPLACEMENT(U) ARMY ENGINEER
WATERWAYS EXPERIMENT STATION VICKSBURG MS ENVIR.

2/2

UNCLASSIFIED

T M WALSKI MAR 85 WES/TR/EL-85-5

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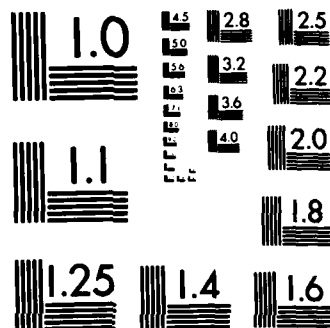
NL



END

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DEC



MICROCOPY RESOLUTION TEST CHART
NBS-1963-A

$$\text{CHEM} = 8.34 * \text{DOSEA} * \text{UCHEM}$$

(6-9)

where

CHEM = unit chemical cost, \$/MG

DOSEA = average chemical dose, mg/l

UCHEM = unit price of chemical, \$/lb

In Equation 6-9, both the dose and the unit price must be expressed in terms of commercially available chemical.

276. In calculating the chemical cost using Equation 6-9, UCHEM should be determined by obtaining quotes from local chemical suppliers. This is desirable because the price of chemicals can vary widely due to shipping costs, new technologies to produce the chemicals, and local competition.

277. Some unit prices for chemicals based on typical 1984 prices are presented below. With one exception, these costs are f.o.b. city of manufacture. These should only be used for rough comparisons or to check on the order-of-magnitude of quotes.

278. The 1984 values are roughly \$0.07/lb for hydrated lime and \$0.04/lb for quick lime in the southeastern United States. Hydrated lime costs more because it is bulkier. However, it does not require slaking, and therefore has lower capital and O&M cost. The price of liquid carbon dioxide ranges from \$0.30/lb for small quantities to \$0.12/lb for large quantities.

279. Prices for the chemical inhibitors vary fairly widely. C-G 21CC costs \$1.13/lb (freight included). Quantity discounts are available. Shan-No-Corr costs from \$0.75 to \$0.60/lb depending on the quantity purchased. TG-10 costs \$2.05 to \$1.71/lb depending on the quantity purchased. Aqua Mag costs from \$0.80 to \$0.70/lb depending on the quantity purchased.

Unit cost

280. The unit cost for chemical treatment can best be expressed in cost per unit volume treated (i.e. dollars per million gallons). The capital cost needs to be amortized first using the capital recovery factor. Unit capital cost can be given by:

$$\text{UNC} = \frac{\text{CC} * \text{CRF}}{365 * \text{QA}} \quad (6-10)$$

where

UNC = unit capital cost, \$/MG

CC = process capital cost, \$

CRF = capital recovery factor

QA = average flow, MGD

The capital recovery factor can be found in amortization tables or determined using

$$CRF = \frac{I(1 + I)^N}{(1 + I)^N - 1} \quad (6-11)$$

where

I = interest rate (as decimal)

N = design life, years

The O&M cost can be converted into a unit cost using

$$UOM = \frac{OM}{365 * QA} \quad (6-12)$$

where

UOM = unit O&M cost, \$/MG

OM = O&M cost, \$/year

281. The unit cost of the individual components can be summed to give the unit cost of chemical treatment:

$$UTR = UNC + UOM + CHEM \quad (6-13)$$

where UTR equals unit cost of treatment, \$/MG.

Updating treatment process cost functions

282. The treatment process cost functions presented above may be updated for inflation by multiplying them by the ratio SCCT/132, where SCCT is the average US Environmental Protection Agency (EPA) small city conventional treatment plant construction cost index for the time period of interest. The 132 in the denominator of the ratio is SCCT for the base time period for the original cost curves (Gumerman, Culp, and Hansen 1979). For the first quarter of 1984 the SCCT was 204.

283. The SCCT Index is actually a municipal wastewater treatment plant index, but it is the most appropriate of the readily available indices. It is published quarterly by EPA and can be found in the Journal of the Water Pollution Control Federation and the Engineering News Record.

284. Alternatively, the equations may be multiplied by the ratio ENR/2843, where ENR is the Engineering News Record construction cost index (base 1913) for the time period of interest. The 2843 in the denominator of the ratio is ENR for the base time period for the original cost curves (Gumerman, Culp, and Hansen 1979). The average ENR for 1983 was 4066. As of September 1984, the ENR was 4174.

285. Chemical costs should not be adjusted using the above indices. Instead, current local chemical costs should be used. In using Table 6-1, it is recommended that the costs be adjusted for temporal and spatial cost variations before putting the values in the table.

Examples

286. Example problem 1. A treatment plant with a design capacity of 10 MGD and an average flow of 7 MGD will use water from a small surface stream. The raw water quality varies through the year as shown below.

	Calcium (as CaCO_3) <u>mg/l</u>	Alkalinity (as CaCO_3) <u>mg/l</u>	<u>pH</u>	Temperature <u>°C</u>
Spring	20	30	7.2	15
Summer	40	40	7.5	25
Fall	40	40	7.4	15
Winter	30	40	7.0	5

The utility would like to stabilize the water using hydrated lime and liquid carbon dioxide which are available at 70 percent and 95 percent purity at \$0.07/lb and \$0.15/lb, respectively. Use a design life of 20 years and an interest rate of 10 percent. Determine the unit cost for treatment. (See Table 6-2.)

287. First, determine the chemical doses for each season using the nomograms in Morgan, Walski, and Corey (1984). These values should be averaged to give average dose and the highest should be used as peak dose (see

Table 6-2
Worksheet for Chemical Treatment Costs
(Example 1)

Peak Flow	<u>10</u>	MGD	Average Flow <u>7</u> MGD			
			<u>Lime</u> <u>(Quick or Hydrated)</u>	<u>Carbon</u> <u>Dioxide</u>	<u>Chemical</u> <u>Inhibitor</u>	<u>Total</u>
Peak Dose* (DOSEP), mg/ℓ	24			11	<u> </u>	
Ave Dose* (DOSEA), mg/ℓ	15			4.6	<u> </u>	
Feed Capacity (CAP), lb/day	2,000			917	<u> </u>	
Average Feed (FEED), lb/day	876			268	<u> </u>	
Feed Equipment						
Initial Cost (CC), \$	57,500			66,600	<u> </u>	
Unit Cost (UNC), \$/MG	2.69			3.13	<u> </u>	5.8
Operation and Maintenance						
Annual Cost (OM), \$/year	5,731			3,745	<u> </u>	
Unit Cost (UOM), \$/MG	2.24			1.47	<u> </u>	3.7
Chemicals						
Purchase Price (UCHEM), \$/lb	0.07			0.15	<u> </u>	
Unit Cost (CHEM), \$/MG	8.76			5.75	<u> </u>	14.5
Total, \$/MG						24.0
Interest Rate (I)	0.10					
Design Life (N)	20					

* Expressed as commercially available product.

tabulation below). These values are expressed first as CaCO_3 and are converted to commercially available chemical by multiplying by 1.06 (i.e. $0.74 * 100/70$) for lime and 0.46 (i.e. $0.44 * 100/95$) for carbon dioxide.

	Dose <u>mg/l Lime</u>	Dose <u>mg/l Carbon Dioxide</u>
Spring (as CaCO_3)	20	24
Summer (as CaCO_3)	6	0
Fall (as CaCO_3)	7	0
Winter (as CaCO_3)	<u>23</u>	<u>16</u>
Average (as CaCO_3)	14	10
Peak (as CaCO_3)	23	24
Average (as commercial)	15	4.6
Peak (as commercial)	24	11

288. The capacities of the feed equipment and average feed rates can be determined using Equations 6-1 and 6-2, respectively.

$$\text{CAP(lime)} = 8.34 * 10 * 24 = 2,000 \text{ lb/day}$$

$$\text{CAP}(\text{CO}_2) = 8.34 * 10 * 11 = 917 \text{ lb/day}$$

$$\text{FEED(lime)} = 8.34 * 7 * 15 = 876 \text{ lb/day}$$

$$\text{FEED}(\text{CO}_2) = 8.34 * 7 * 4.6 = 268 \text{ lb/day}$$

289. Next determine equipment cost. The lime and carbon dioxide feed equipment cost is given by Equations 6-3a and 6-4a, respectively, as

$$\text{CC (lime)} = 1,880 * 2,000^{0.45} = \$57,500$$

$$\text{CC}(\text{CO}_2) = 15,900 * 917^{0.21} = \$66,600$$

The capital recovery factor can be determined from Equation 6-11 as

$$CFR = \frac{0.10 (1.10)^{20}}{(1.10)^{20} - 1} = 0.12$$

290. The unit cost for equipment can then be given by Equation 6-10 as

$$UNC (\text{lime}) = \frac{57,500 * 0.12}{365 * 7} = \$2.69/\text{MG}$$

$$UNC (\text{CO}_2) = \frac{66,600 * 0.12}{365 * 7} = \$3.13/\text{MG}$$

291. The O&M cost can be determined using Equations 6-6a and 6-7a, respectively.

$$OM (\text{lime}) = 75 * 876^{0.64} = \$5,731/\text{year}$$

$$OM (\text{CO}_2) = 700 * 268^{0.30} = \$3,745/\text{year}$$

292. These costs can be converted to unit costs using Equation 6-12

$$UOM (\text{lime}) = \frac{5,731}{365 * 7} = \$2.24/\text{MG}$$

$$UOM (\text{CO}_2) = \frac{3,745}{365 * 7} = \$1.47/\text{MG}$$

293. The chemical unit cost can be determined from Equation 6-9 as

$$\text{CHEM} (\text{lime}) = 8.34 * 15 * 0.07 = \$8.76/\text{MG}$$

$$\text{CHEM} (\text{CO}_2) = 8.34 * 4.6 * 0.15 = \$5.75/\text{MG}$$

294. The unit costs can be summed as shown in Equation 6-13 to give

$$UTR = 5.8 + 3.7 + 14.5 = \$24.0/\text{MG}$$

or 2.40 cents per thousand gallons which is a common way of expressing treatment cost.

295. Example problem 2. Given the same flow rates, design life, interest rate, etc., from problem 1, the utility wants to determine the cost to feed a polyphosphate inhibitor which costs \$1.20/lb. A pilot study showed that a dose of 1.5 mg/l (as commercially available) was usually required, although a dose of 2.0 mg/l may be required at certain times of the year. (See Table 6-3.)

296. Since the doses are already expressed as commercially available chemicals, Equations 6-1 and 6-2 can be used directly:

$$\begin{aligned} \text{CAP} &= 8.34 * 10 * 2.0 = 167 \text{ lb/day} \\ \text{FEED} &= 8.34 * 7 * 1.5 = 88 \text{ lb/day} \end{aligned}$$

297. Feed equipment cost can be determined from Equation 6-5b as

$$\text{CC} = 6,750 * 167^{0.27} = \$26,900$$

Using the capital recovery factor from the previous problem, Equation 6-10 gives the unit capital cost as

$$\text{UNC} = \frac{26,900 * 0.12}{365 * 7} = \$1.26/\text{MG}$$

298. O&M cost can be determined using Equation 6-8b as

$$\text{OM} = 2,284 * 88^{0.091} = \$3,432$$

This gives a unit O&M cost of

$$\text{UCM} = \frac{3,432}{365 * 7} = \$1.34/\text{MG}$$

299. The chemical cost can now be determined using Equation 6-9

$$\text{CHEM} = 8.34 * 1.5 * 1.20 = \$15.0/\text{MG}$$

Table 6-3
Worksheet for Chemical Treatment Costs
(Example 2)

Peak Flow <u>10</u> MGD	Average Flow <u>7</u> MGD			
	<u>Lime</u> <u>(Quick or Hydrated)</u>	<u>Carbon</u> <u>Dioxide</u>	<u>Chemical</u> <u>Inhibitor</u>	<u>Total</u>
Peak Dose* (DOSEP), mg/l	<u> </u>	<u> </u>	2.0	
Ave Dose* (DOSEA), mg/l	<u> </u>	<u> </u>	1.5	
Feed Capacity (CAP), lb/day	<u> </u>	<u> </u>	167	
Average Feed (FEED), lb/day	<u> </u>	<u> </u>	88	
Feed Equipment				
Initial Cost (CC), \$	<u> </u>	<u> </u>	26,900	
Unit Cost (UNC), \$/MG	<u> </u>	<u> </u>	1.26	1.3
Operation and Maintenance				
Annual Cost (OM), \$/year	<u> </u>	<u> </u>	3,432	
Unit Cost (UOM), \$/MG	<u> </u>	<u> </u>	1.34	1.3
Chemicals				
Purchase Price (UCHEM), \$/lb	<u> </u>	<u> </u>	1.20	
Unit Cost (CHEM), \$/MG	<u> </u>	<u> </u>	15.0	15.0
Total, \$/MG				17.6
Interest Rate (I)	0.10			
Design Life (N)	20			

* Expressed as commercially available product.

The total treatment cost can now be given as

$$UTR = 1.3 + 1.3 + 15.0 = \$17.6/MG$$

or 1.76 cents per thousand gallons.

PART VII: SUMMARY

300. Engineers need good cost estimates to plan projects to improve the performance of water distribution systems. Locating the required cost data is time-consuming and may be misleading if the engineer only gets data on one or two projects, data which can be significantly different from the project at hand. This report contains cost data for typical water system rehabilitation projects. The report goes beyond this however to include procedures for estimating costs of projects, and verification of these procedures to determine instances when these procedures may be inaccurate.

301. A detailed estimating procedure for pipe cleaning and lining projects was developed. The difference between costs predicted by this procedure and actual project costs averaged 12 percent. Regression equations for cleaning and lining were developed. Some data on the cost of "cleaning only" projects were also presented.

302. A procedure for estimating the costs to cathodically protect existing, buried metal piping was also developed. The procedure is applicable to both galvanic and impressed current cathodic protection systems. The average difference between actual and predicted cost was 25 percent. Regression equations and some rules of thumb for estimating were also presented.

303. Data were also presented on the cost of repairing pipe breaks and replacing (relaying) water mains in urban areas. Break repair costs depended on the size of the pipe and the type of break. Relaying pipe in urban areas proved to be considerably more expensive than laying the pipe in an uncongested area.

304. Finally, a procedure was developed to estimate the cost of chemically treating potable water so that it will not be corrosive or scale-forming. The costs included chemical feed equipment, operation and maintenance labor, and supplies and chemicals. The procedure is applicable to both chemical stabilization using lime and carbon dioxide and use of chemical inhibitors to prevent corrosion.

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APPENDIX A: NOTATION

A	Coefficient in survey cost equation (Equation 3-1)
AC	Anode material and installation cost, \$
AR	AC power requirement, kWhr/year
BE	Base excavation, installation, and repaving cost, \$
CA	Cost for individual anodes, \$
CAP	Feed capacity, lb/day
CC	Process capital cost, \$
CE	Corrected excavation, installation, and repaving cost, \$
CHEM	Unit cost for chemicals, \$/MG
CO	Current output from single galvanic anode, mA/anode
CM	Cost of mobilization, \$
CP	Cost of project, \$
CR	Current requirement, mA
CRA	Current requirement, A
CRF	Capital recovery factor
CS	Cost of survey, \$
CT	Corrected total cost, \$
D	Diameter of pipe, in.
DA	Diameter of anode, ft
DOSEA	Average dose, mg/l
DOSEP	Peak dose, mg/l
DP	Depth of excavation, ft
DV	DC voltage requirement, V
E	Number of excavations (Part II); conversion efficiency (Part III)
EB	Effective bare area of pipe
EL	Expected life of anode, years
ENR	Engineering News Record Construction Cost Index
FEED	Average feed, lb/day
I or i	Interest rate
GR	Groundbed resistance, ohms
L	Local labor cost index (Part II); length of pipe cleaned and lined, ft (Part II); length of pipe protected, ft (Part III)
LA	Length of anode, ft
LC	Lining costs, \$

LL	Laying length of pipe, ft
LS	Length of pipe surveyed, ft
MH	O&M labor requirement, man-hr/year
N	Design life, years
NA	Number of anodes
NB	Number of anode beds
NI	Number of impressed current anodes
NP	Number of anodes per bed
NS	Number of sacrificial anodes
OM	Process O&M cost, \$/year
PA	Pipe area protected, ft ²
PC	Power line cost, \$
PE	Price of electricity, \$/kWhr
PWO	Present worth of O&M cost, \$
PWR	Present worth of replacement
QA	Average flow, MGD
QP	Peak flow, MGD
RC	Total rectifier cost, \$
RH	Soil resistivity, ohm-cm
R ²	Index of determination
S	Anode spacing within bed, ft
SB	Spacing of anode beds, ft
SCCT	Average EPA small city conventional treatment plant construction cost index
TB	Length of temporary bypass piping, ft
TC	Total material and installation cost, \$
TL	Cost corrected for local labor, \$
UCHEM	Unit price of chemical, \$/lb
UL	Unit cost of labor, \$/man-hr
UNC	Unit capital cost, \$/MG
UOM	Unit O&M cost, \$/MG
UP	Uncorrected unit price of anodes, \$
UR	Unit cost for rectifier, \$
UT	Uncorrected project total cost, \$
UTR	Unit treatment cost, \$/MG

V Number of values replaced
VC Value replacement cost, \$
WT Weight of anode, lb

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